VARIABLE SALINITY DESALINATION DEMONSTRATION PROJECT

Technical Memorandum No. 1
Desalination Technology Research

Project No. E13063

Prepared for:

CITY OF CORPUS CHRISTI, TEXAS

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EXECUTIVE SUMMARY

A review of previous seawater desalination efforts along the Texas Gulf Coast identified an ample record of planning, feasibility, research, and pilot plant studies. This record, stretching as far back as the beginning of state water planning in Texas, provides a wealth of lessons that can be directly applied to the current Corpus Christi Variable Salinity Desalination Demonstration project. This technical memorandum presents a summary of the more relevant studies and the lessons derived from them. A key overarching lesson is that the more challenging issues to implementing a desalination project are not technical in nature. It is clear from the literature that there are no apparent technical impediments to seawater desalination in Texas. The more challenging issues are understanding and communicating why a project is being considered and its economic feasibility.

Here are some of the key lessons learned from past efforts:

Lesson 1: Identify the potential customers early on and understand the nature of their need for seawater desalination supplies. This knowledge provides for a firmer foundation and justification for the project.

Lesson 2: Implement a deliberate stakeholder outreach process. This fosters an environment of trust which helps keep the project focused.

Lesson 3: Develop a communication strategy to discuss project costs in a clear and consistent manner. Cost tends to be the most common question about a desalination project; educating stakeholders about cost factors and their impact on the project facilitates communication on this important topic.

Lesson 4: Develop and communicate potential cost recovery strategies for an eventual production facility. This process may be started on the basis of estimates of likely production volumes and costs and later refined when more accurate projections are available.

Lesson 5: It is advisable to monitor water quality at potential sites for seawater desalination intake facilities. This helps develop back up plans if a particular selected site is later proven unfeasible and an alternate site needs to be considered.

Lesson 6: Develop a sound pilot study protocol and ensure that all necessary skills and team members are committed to the project. A pilot project is a cost-effective way to test competing water treatment options, and to control and learn from potential failures. The pilot plant study protocol lays the foundation for this process.
Lesson 7: Maintain good records to track energy requirements to desalinate seawater. Typically the focus of a pilot study is to identify a pretreatment that provides consistent quality for the reverse osmosis system. However, energy costs may account for as much as 50 percent of the life cycle cost of a seawater desalination production facility which presents the need to carefully document and assess the energy requirement of a desalination system.
BACKGROUND, KEY FINDINGS, AND LESSONS LEARNED

THE VARIABLE SALINITY DESALINATION DEMONSTRATION PROJECT

Seventy percent of Earth is water; most of it is too saline for human consumption. As fresh water supplies become less abundant, the search for new water supplies is inevitably drawn to the most plentiful source of water on the planet and to treatment options for desalination. Desalination is the process of removing salts [1] from salt water to produce fresh water adequate for drinking. According to the International Desalination Association, more than 300 million people around the world rely on desalinated water for some or all of their daily water demand [2].

The City of Corpus Christi, historically reliant on surface water supplies alone, is strategically poised and is acting to take advantage of available saline water resources. The current effort to implement a demonstration desalination facility will provide needed data regarding water desalination as a future water supply option for the Corpus Christi regional system. The project will explore siting and water desalination technology options to produce a reliable and cost-effective water supply from saline sources.

Prior to implementation of the demonstration facility, a thorough process of research, planning, source water characterization, equipment selection, protocol development, and design must be completed. This process is defined in Contract E13063 with the City of Corpus Christi and will be carried out through the development of four technical memoranda. These documents, which will help to pave the way for the Variable Salinity Desalination Demonstration Plant, are titled:

- TM #1 – Desalination Technology Research
- TM #2 – Variable Salinity Desalination Plant Siting Analysis
- TM #3 – Variable Salinity Desalination Plant Technical Criteria
- TM #4 – Variable Salinity Desalination Study Protocol

Technical Memorandum #1 is part of the City’s due diligence process to ensure that previous and relevant work is identified and considered. This memorandum provides an overview of relevant planning and technology issues regarding desalination and aquifer storage and recovery. The literature review encompassed international, national, state and local studies and reports. The following is a summary of key findings and lessons learned. Additional findings are presented at the end of each one of the major sections of this report.
WATER SUPPLY PLANNING

- Water supply diversification is increasingly more important to water planners in Texas. A combination of growing water demands, extended drought and technological improvements compel regional water planners to consider and include water reuse, desalination and aquifer storage and recovery as recommended water management strategies to meet current and future water supply needs.

- Current strategic planning efforts by the City seek to increase the diversity of the region’s water supply by supporting conservation and incorporating reuse, aquifer storage and recovery, and desalination;

- On May 8, 2014 the Coastal Bend Regional Water Planning Group moved to amend the current regional water plan to incorporate seawater desalination as a recommended water management strategy for the Corpus Christi region.

SEAWATER DESALINATION STUDIES

- In 2004, three seawater desalination feasibility studies –by Corpus Christi, Freeport and Brownsville- concluded that: 1) seawater desalination was technically feasible; and, 2) financial assistance was required to ensure affordability of the proposed projects;

- The Corpus Christi Seawater Desalination Feasibility Study researched, assessed, and issued recommendations on most of the topics that will be revisited in this current effort. The report should be incorporated as a working reference to the present project. Key findings from the study include:

  o Using brackish groundwater for source blending was deemed unfeasible due to insufficient availability. The study did not include a detailed investigation of availability and salinity of groundwater sources.

  o Solar and wind power were found to be potentially feasible options for powering a desalination plant but not as reliable or cost competitive as grid power.

  o A consideration of the future use of an open intake and a diffused discharge into the ocean across the Laguna Madre and the island.

  o The highest ranked pretreatment option was dissolved air flotation.

  o Co-locating at the Barney Davis Power Plant had many advantages in terms of use of existing infrastructure. The final recommendation was to use the existing power plant intake even with the higher salinity water from the Laguna Madre. This recommendation was based on a cost evaluation of the alternatives.

  o The report concluded that, “The option for discharge to Oso Bay should be retained for future consideration, but the environmental concerns keep this option from being a likely solution.” The study estimated salinity increases in Oso to be approximately 5%.

- There are valuable lessons to be considered from the Brownsville seawater pilot plant study captured in the TWDB report by Reiss Engineering “Lessons Learned from the Brownsville Pilot Plant Study.” Some of the key findings include several practical recommendations for the design and
operation of seawater desalination pilot plant studies. The report and its recommendations are directly relevant to the current Corpus Christi effort.

- Taunton River and Thames Water Works are examples of medium to large-scale desalination systems drawing raw water from highly variable salinity sources. In both cases, the strategy to address the varying salinity of the source is the use of source water storage as a means of normalizing the source to a target feed water salinity. Additionally, the Taunton River project also utilizes concentrate storage and timed discharge on the high tide to mitigate environmental concerns. The Thames project dilutes its discharge with wastewater effluent at a ratio of 50:1. Where available, using treated wastewater as a diluting stream for concentrate disposal is a competitive option.

**BRACKISH GROUNDWATER DESALINATION**

- The results of the groundwater study for the City indicate the availability of well field locations which are capable of producing between 700 and 20,000 acre-feet-per-year of brackish groundwater (0.62 to 17.8 million gallons per day). Several potential well fields identified in the study are estimated to have total dissolved solids concentrations of less than 3,000 milligrams per liter. Accurate characterization of the brackish groundwater will be required in order to ascertain the long-term sustainability of this resource including the potential occurrence of subsidence as a result of groundwater extractions.

**VARIABLE SALINITY DESALINATION**

- Flexible systems for desalination of variable sources are feasible. There are many ways to convert a seawater system to a brackish water system or vice versa as long as the materials are compatible with the most corrosive water source;

- Industrial applications with variable feed sources can obviously take advantage of flexible treatment systems for treating and recycling their own wastewater without requiring additional permitting;

- Drinking water utilities have a more difficult challenge. Though regulations vary by state, often new approval is needed whenever the water source is changed. Planning for eventual alternative sources would make the approval process more straightforward. The process can be evaluated in the different configurations on alternative sources during the initial approval process.

**DESALINATION TECHNOLOGY ISSUES**

- Although there are multiple proven and emerging desalination methods from which to choose, the technology of choice for municipal, stand-alone applications is reverse osmosis;

- Key issues to ensure the successful implementation of a seawater desalination project include:

  - Comprehensive source water characterization including seasonal variability, presence of oil contaminants, and potential for algal blooms;
  - Selection of an intake system that ensures a sustainable supply of the best source water quality. Impingement and entrapment issues, including new stricter federal regulations
Intake options include open intakes and subsurface intakes. Co-locating – utilizing intake and discharge facilities of a power plant – is an advantageous and cost-saving open intake method that has potential for Corpus Christi; however, if the source water quality is poor, those benefits and savings need to be examined on a life cycle basis to account for added treatment costs and possible increase in membrane replacements;

- Pretreatment refers to the removal of particulates, colloidal, organic, mineral and microbiological contaminants to prevent their accumulation on and consequent loss of performance of the reverse osmosis membrane. There are two general pre-treatment methods: granular media filtration and membrane filtration; there are combinations of these two methods and additions of other components such as dissolved air flotation that can be particularly effective in dealing with more challenging source water.

- It is estimated that as much as 50 percent of the lifecycle cost to produce reverse osmosis permeate is attributed to electric power requirements. Energy demand management, including the use of energy recovery devices and energy optimized desalination processes have become more important and are resulting in more cost competitive systems.

- Most seawater desalination facilities are able to discharge concentrate back to the sea where it is almost immediately diluted by the large volume of available water, leaving marine life undisturbed. A study of the effects of the Tampa Bay Water Desalination Plant’s concentrate discharge found no effect of salinity elevation on a representative ecosystem.

- There is a growing interest in exploring beneficial uses of concentrate. If there is a local demand for a particular mineral in the concentrate, then salt separation might be a practical solution – if not, trucking expense may make it infeasible. If there is a long term beneficial use for saline water in the neighborhood, then it would be wise to tailor the concentrate to meet the requirements for that use. Saline wetlands can be a good solution, but there must be an outlet to the sea. Blending concentrate with reclaimed wastewater for a saline wetlands is an even better solution.

**AQUIFER STORAGE AND RECOVERY**
- There are several brackish and saline aquifers in the Coastal Bend. ASR is possible in these aquifers with the appropriate buffer zone. ASR can be beneficial if the overall groundwater quality can be improved by this storage. However, the storage of high quality water (such as that coming out of a desalination plant) in a brackish/saline aquifer may result in deterioration of the stored water and require additional treatment to meet drinking water standards.

- Corpus Christi has the state’s only ASR Conservation District (See 9.0, Aquifer Storage and Recovery). The Corpus Christi ASR Conservation District has identified the following objectives for ASR in the Corpus Christi area:
  - Seasonal Storage: Store water throughout the year to cover increased demand from May to September.
  - Long Term Storage: Store water from years of high rainfall for use in times of dry weather.
Emergency Storage: Store water as a strategic reserve, especially for the islands in case their supply from the mainland is disrupted.

Streamflow Diversion Mitigation: Store water for use to meet minimum flow requirements for Nueces Bay.

Defer expansion of water system infrastructure by using ASR to meet seasonal and peak water demands;

Stormwater flow and estuary salinity management;

Help meeting large retail customer demands.

A desalination facility and ASR program, in conjunction, may provide some synergy for energy optimization, source water alternatives, and innovation.

COST ESTIMATES FOR SEAWATER DESALINATION

For illustration and planning purposes, the project team developed preliminary cost estimates for 20 MGD seawater desalination production facilities. Additional assumptions and methods used in the development of the cost estimates can be found in Section 8.0.

Total estimated construction costs for the facility, located in Ingleside, is $248 million.

Lifecycle water production costs, at the fence, are estimated to be $4.45 per 1,000 gallons for a plant located in Ingleside.

Lifecycle water production costs, at the fence, are estimated to be $4.35 per 1,000 gallons for a plant located at the O.N. Stevens Water Treatment Plant.

ALTERNATIVE ENERGY SOURCES

Many types of renewable energy resources are inherently uncontrollable and intermittent. Large-scale desalination projects featuring alternative power sources typically utilize grid-connected renewable power systems.

Successful applications of wave power technology were recently demonstrated in Freeport, Texas, and could potentially extrapolate to the Corpus Christi area. The experimental project encountered modest waves ranging in height from 6” to 6 feet and consistently pumped 12 to 18 gallons of seawater per minute at a head pressure of 47 to 54 PSI.

Geothermal energy is better suited to thermal desalination rather than to reverse osmosis membrane processes. However, within the Rio Grande Embayment, there is a source of geothermal water that could potentially be used to produce electricity to offset the power consumption by the Corpus Christi desalination plant. On-site electricity generation using a geothermal resource is not practical.

Even though wind has been proven for powering small autonomous desalination systems without the grid, in large municipal applications, such as for Corpus Christi, grid connectivity is preferred to ensure water supply reliability. Given the offshore wind conditions near Corpus Christi,
wind-power may be considered as an alternative supplemental energy supply for a full-scale desalination plant.

- Photovoltaic solar energy may be used to offset some of the power consumed by the desalination plant in Corpus Christi but will most likely require a large area and result in higher capital costs.
- Concentrating solar power generation relies on direct normal radiation. Direct normal radiation is more limited in areas of higher humidity. According to the National Renewable Energy Laboratory, the concentrating solar resource potential in the area surrounding Corpus Christi is relatively low. Thus, solar (thermal) energy is less likely to be a viable alternative for on-site energy generation.

CONCLUSIONS

Many Texas communities are confronted with the combined challenge of meeting growing water demands while facing the continued threat of drought. The need for increased water supply diversity is more urgent for communities highly dependent on a single source of water. The City of Corpus Christi, with its proactive initiatives to conserve water, reduce demand, and advance reuse, desalination and aquifer storage and recovery strategies, is an example of progressive water development policies that will result in more robust and reliable water supply portfolios.

Desalination has been the subject of many studies in the Corpus Christi region. Several of those studies, and other efforts undertaken in the Lower Rio Grande Valley, provide a valuable basis and reference to the current effort. The 2004 Corpus Christi Seawater Feasibility Study considered and provided recommendations on several of the same issues that will need to be addressed in the present project. Pilot plant studies in the Brownsville Ship Channel and South Padre Island and the constructive critique of those efforts informs the Corpus Christi project with a wealth of practical guidance to improve the effectiveness of the proposed pilot plant study.

Energy is inarguably the greatest single operational cost of a desalination plant. The energy budget of a desalination facility is directly proportional to the salinity of the source water. The greater the salinity, the more energy is required to separate salts from water. The Bureau of Reclamation (Reclamation) has demonstrated the feasibility of the variable salinity concept. The goal of a variable salinity desalination approach is to maximize the use of lower salinity sources while providing for the ability to treat higher salinity sources, such as seawater, when needed. This conjunctive approach is a promising strategy to gain greater firm yields while reducing energy consumption.
An intake that provides a sustainable source of the highest quality water is an important component of a desalination project. The selection of intakes for seawater desalination projects is dominated by the need to provide safeguards to minimize environmental impacts, impingement and entrapment. Previous City of Corpus Christi studies provide useful information on intake options; however, this issue is so important that it should be looked anew.

Alternative energy sources such as wind and wave power are promising but not necessarily more cost effective than obtaining power generated by conventional means. However, alternative power sources may provide a sustainable means to directly or indirectly meet some of the energy requirements of desalination plants.

The City of Corpus Christi is a step ahead in matters of aquifer storage and recovery. However, additional aquifer characterization studies are needed to adequately measure this strategy’s potential. The concept of using ASR as a repository of desalinated water bears no record in the literature. Other opportunities such as a storing surface or reclaimed wastewater in a managed aquifer recharge approach may be more practical and should be considered. However, current regulations require treatment to drinking water standards prior to injection.
1.0 INTRODUCTION

Recognizing that water remains a top priority for the Texas House of Representatives because it remains critical to the Texas economy and its quality of life, House Speaker Joe Straus appointed four water committees in March 2014. One of those committees was the Joint Interim Committee to Study Water Desalination co-chaired by Texas House Representative Todd Hunter of Corpus Christi. This joint committee held meetings in various locations throughout the state, including the City of Corpus Christi, to examine the status of seawater and groundwater desalination in Texas, as well as ways that expanded use of desalinated water could help meet Texas' needs. City of Corpus Christi Mayor Nelda Martínez testified before the committee on the City’s current desalination efforts and the vision to install a desalination facility starting in the year 2016.

The City of Corpus Christi (City), is joining efforts with federal and state agencies, academia, industry, and the Corpus Christi Regional Economic Development Corporation to implement a demonstration desalination facility. This project will provide detailed first-hand information about water desalination as a future water supply option for the Corpus Christi system. The project will explore siting and water desalination technology options to produce a reliable and cost-effective water supply from sources of varying quality and salinity content.

The salinity of the water is measured in terms of dissolved solids content. Based on the salinity content, saline water may be classified as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>Total Dissolved Solids (milligrams/liter)</th>
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<tr>
<td>Fresh</td>
<td>&lt; 1,000</td>
</tr>
<tr>
<td>Brackish</td>
<td></td>
</tr>
<tr>
<td>Mildly Brackish</td>
<td>1,000 to 5,000</td>
</tr>
<tr>
<td>Moderately Brackish</td>
<td>5,000 to 15,000</td>
</tr>
<tr>
<td>Heavily Brackish</td>
<td>15,000 to 35,000</td>
</tr>
<tr>
<td>Seawater</td>
<td>~35,000 &gt;</td>
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Typically, the higher the salinity content of the water, the more energy that is required to separate the salts from the water. The current project will explore a variable salinity desalination approach that would preferentially treat lower salinity sources, when available, but be capable of desalinating seawater or
diluted blend of seawater if needed. The goal is to lower the overall energy requirements of the desalination operation and, thus, improve the long term economics of the project.

The City has long had an interest in desalination. In the early 1980’s the City contracted a study to investigate alternative sources of water supply, including desalination of brackish water and seawater. In early to mid-1990s, as part of the Trans Texas state program, desalination was again considered as a potential water supply source for Corpus Christi. Both of these efforts identified the cost of desalination, relative to other water supply sources, as a reason to relegate its development to a future time, pending technological advances to improve its cost competitiveness [3]. In the late 1990’s the City and others prepared a report entitled “Desalination for Texas Water Supply” focusing on membrane technologies and cost factors for siting desalination plants in the Texas Gulf Coast [4]. Most recently, in 2002, City contracted a feasibility study for a desalination plant in Padre Island [5]; also in 2002, the Texas Water Development Board (TWDB) identified and recommended Corpus Christi as one of three sites with the greatest potential for developing large-scale seawater desalination supplies in Texas [5]. Subsequent to this designation, a feasibility study completed in 2004 confirmed that seawater desalination was technically feasible in Corpus Christi [6]. The study also identified financial challenges to implementing large-scale desalination in the face of less expensive surface water alternatives.

A decade later, with the imminent completion of the Mary Rhodes Phase 2 pipeline extension, almost all of the surface water options for the Coastal Bend region will have been exhausted. A strategic planning effort¹ is currently underway with a goal of increasing the reliability of the water supply system through diversification. This planning effort will include aggressive conservation, large-scale reuse of wastewater for industrial purposes, aquifer storage and recovery, brackish and seawater desalination.

Technical Memorandum #1 provides an overview of pertinent planning, desalination and aquifer storage and recovery information from previous studies; identifies key findings and lessons learned that have resulted from those efforts; and, reviews and summarizes relevant desalination technology issues.

¹ City of Corpus Christi, internal memorandum from Bill Green to Ronald Olson, Resolution for City of Corpus Christi Water Management Plan 2015-2050, May 28, 2014.
2.0 WATER SUPPLY PLANNING AND DESALINATION

Water planning in Texas is based on a bottom-up, consensus-driven approach. The state is divided into 16 regional water planning areas (Figure 1). Each planning area is represented by a planning group that consists of about 20 members representing a variety of interests, including agriculture, industry, environment, public, municipalities, business, water districts, river authorities, water utilities, counties, and power generation. Each planning group evaluates population projections, water demand projections, and existing water supplies available during drought. Based on this information, each planning group identifies who will not have enough water, recommends strategies and projects that could be implemented to obtain more water, and estimates the costs of these strategies and projects. Once the planning group adopts the regional water plan, the plan is sent to TWDB for approval. TWDB then compiles information from the regional water plans and other sources to develop the state water plan. The entire process is open to the public.

State and regional water planning provide a blue print for developing water supplies in Texas; these plans help set funding and project permitting priorities for the State. Thus, understanding the water planning context for desalination water management strategies is relevant to the Corpus Christi desalination initiative. Also, an abundance of previous desalination work informs the current effort with options, costs and feasibility findings. This section provides an overview of state and regional water plans and captures the more relevant lessons from desalination studies pertinent to Corpus Christi.
2.1 STATE WATER PLANNING

From its earliest beginnings in the late 1950s, water planning in Texas has recognized the potential contributions innovative water management strategies, including desalination, can provide to communities around the state. Starting with the first state water plan, issued in 1961, the “reuse of municipal return flows” and “demineralization of brackish water and seawater” were noted and recommended for additional research [7]. In 1965, TWDB commissioned a study of the state’s saline water
sources and identified 11 potential sites for desalination in the state; including two current wholesale customers of the City of Corpus Christi: Beeville and Kingsville [8]. The second state water plan, published in 1968, reflected a growing interest in reuse and desalination. Regarding reuse, the plan recommended “the use of return flows and reclaimable waste waters to the maximum feasible extent.” This plan also recognized the potential of desalination but cited the high cost as a key challenge. It was noted, however, that technological advances were likely to reduce the cost of desalination over time [9]. Sixteen years later, the third state water plan, published in 1984, reported increased use of treated wastewater effluent for irrigation and cooling electric power generators; noting that recycling was “a well-established practice in the industrial sector.” Desalination has since advanced to noticeable production with 71 desalination plants in operation in Texas producing a total of 52 acre-feet per day for municipal and industrial purposes [10].

The 75th Texas Legislature Senate Bill 1, the basis for contemporary water planning in Texas, has further encouraged development of a more diverse water supply portfolio. Water planning rules direct regional water planners to provide “specific recommendations of water management strategies based upon identification, analysis, and comparison of all water management strategies the regional water planning group determines to be potentially feasible including reuse of wastewater and desalination” [11]. Meeting current and projected water needs in the state requires that all potential water management strategies be considered.

The current state water plan, Water for Texas, 2012 State Water Plan [12] explicitly states that “In serious drought conditions, Texas does not and will not have enough water to meet the needs of its people, its businesses, and its agricultural enterprises”. As one of the fastest growing states in the nation, the Plan notes that the population of Texas is expected to increase 82 percent between 2010 and 2060 from 25.4 to 46.3 million people. At the same time, existing water supplies are anticipated to decrease by an estimated 10 percent. This reduction is the result of loss of storage volume in existing reservoirs and decline in groundwater availability.

Under drought of record conditions, the State Water Plan 2012 projects additional water supply needs of 8.3 million acre-feet by the end of the 2060 decade. The regional water planning groups have recommended strategies that, if implemented, will provide 9.0 million acre-feet per year of additional water supplies by 2060. Desalination is one such strategy recommended by regional water planning
groups to meet future water needs. Three regional water planning groups (H, L, and M)\textsuperscript{2} recommended 125,514 acre-feet per year of seawater desalination by 2060. Five regional water planning groups (E, F, L, M, and O) recommended 181,568 acre-feet per year of brackish groundwater desalination by 2060. Region N had not included desalination as a recommended water management strategy in its approved 2011 Regional Water Plan [13]; however, as noted in Section 2.2, the regional water planning group initiated an amendment to the 2011 Regional Water Plan to include desalination as a recommended water management strategy. The minor amendment was approved by both the regional water planning group and the Texas Water Development Board.

The 1961 State Water Plan did not specifically recommend water management strategies to be implemented as do modern plans. The 1961 plan, however, provided projections of additional water requirements providing a sense of the water supply tools that were under consideration at the time. Acknowledging the differences in terms, Figure 2 illustrates the increased diversity of the water supply portfolio in Texas over the water planning history of the state.

![Figure 2-Water Supplies in Texas State Water Planning](image)

2.2 REGIONAL WATER PLANNING

The City of Corpus Christi is located in Nueces County, one of the eleven counties addressed by the Coastal Bend Regional Water Planning Group (Region N). The 2011 Coastal Bend Regional Water Plan outlines future water needs of the region and recommends water management strategies to meet projected

\textsuperscript{2} See Figure 1 for names and locations of regional water planning areas.
deficits [13]. Currently, there are four major wholesale water suppliers in the region: the City of Corpus Christi, San Patricio Municipal Water District (SPMWD), South Texas Water Authority (STWA), and the Nueces County WCID #3. The City of Corpus Christi is by far the largest, supplying 77 percent of the region’s water in 2000 and selling resources to both SPMWD and STWA. This percentage is expected to increase to 93 percent by 2060. The Coastal Bend Region depends mostly on surface water sources for municipal and industrial use, which together constituted 85 percent of the region’s total water consumption in 2000. The other 15 percent is predominantly consumed for agricultural purposes. Altogether, surface water sources account for more than 75 percent of the region’s existing water supply.

Corpus Christi relies on two sources of surface water: the Choke Canyon Reservoir/Lake Corpus Christi System in the Nueces River Basin and Lake Texana on the Navidad River in Jackson County. According to the 2011 Region N Water Plan, Corpus Christi has 205,000 acre-feet-per-year of safe yield water supplies from Choke Canyon Reservoir, Lake Corpus Christi, and Lake Texana. With the completion of Mary Rhodes Phase II, the system will also draw water from the Lower Colorado River basin. Despite these supplies, Region N is projecting a shortage of 9,393 acre-feet per year in 2020 for the City as a wholesale provider. By 2060, the City of Corpus Christi is estimated to need 54,357 acre-feet per year of additional water supply based on existing treatment plant and raw water supply constraints. Of this amount, 39,517 acre-feet per year will be due to raw water supply shortages. These projected deficits can be attributed to anticipated population increases and corresponding increases in water demand. The region’s population is expected to rise by 63.7 percent between 2010 and 2060 and total water use is expected to rise 57.8 percent in the same time frame. In addition to the anticipation of population growth, industrial demand on the water supply is also projected in the Region N Plan. If projected water needs are not met, the estimated regional economic impact is $57.2 million per year in 2010, $1.6 billion per year in 2030, and $7.8 billion per year in 2060. [14]

The Region N Plan details the anticipated demands and shortages for each water user group (municipal, manufacturing, mining, steam-electric, irrigation, and livestock), as well as the recommended strategy to meet those additional needs. In 2010, mining use was predicted to account for about half of the region’s water needs but by 2060, water needs are dominated by manufacturing. The discovery and development of Eagle Ford Shale in the region has resulted in an unprecedented industrial boom that continues to attract entrepreneurs to the area. The Eagle Ford Shale, now considered the largest oil and gas play in the world, was first tapped in 2008 and directly impacts approximately 20 counties in South Texas. By 2022, the estimates for regional economic impact are $89 billion and 127,000 full time jobs. [15]
Water required by hydraulic fracturing in the development of Eagle Ford Shale oil and gas resources and the operation of industrial giants such as TPCO America Corp., NuStar Energy, and the Voestalpine Group was not considered in the 2011 Regional Water Plan and will increase stress on the existing water supply. According to the Corpus Christi Regional Economic Development Corporation (CCREDC), $6.58 billion in potential industry investment is targeted for the Corpus Christi Region. [16] In order to retain and continue to attract industry to the area, it will be necessary to implement additional water supply strategies to keep supply reliably ahead of demand. Frequently, a sweeping recommendation given to meet each water need has been to increase the contracted amount of water obtained from the wholesale provider in question or to develop additional water supplies for the City of Corpus Christi. A more detailed breakdown of water management strategies analyzed twenty different options for increasing water supplies, including seawater desalination [14].

The examination of seawater desalination in the regional water plan co-sited a 25 MGD desalination plant with the Barney M. Davis Power Station in Corpus Christi. This selection was made with the intention of using once-through cooling water from the power plant as the influent to the desalination plant; thus providing significant cost savings by utilizing the power plant’s existing intake structure. The regional water plan also examined three different treatment processes: distillation, electrodialysis reversal, and reverse osmosis. Distillation and electrodialysis were quickly eliminated as impractical due to the intensive energy requirements. Additionally, distillation was not considered since “there are no distillation processes in Texas that can be shown as comparable installations.” However, distillation and electrodialysis could become cost effective if the desalination facility is located near an industrial area able to provide sufficient waste heat to offset the high energy consumption of each process. Considering the selected site, it was concluded reverse osmosis would be the only applicable treatment process and that “the current domestic and worldwide trend seems to be for the adoption of reverse osmosis when a single purpose seawater desalting plant is to be constructed.” While the water source (seawater from the Gulf of Mexico) is assumed be unlimited in quantity and have zero cost prior to extraction; the regional plan sited the following concerns regarding the feasibility of desalination that need to be taken into consideration: generally high costs (between $1,349 and $1,929 per acre-foot), disposal of the concentrated brine stream, permitting/construction of the concentrate pipeline, environmental impact on bays/estuaries, the ability to blend desalted seawater with other water sources in the distribution system, high power requirements, availability of skilled operators, and general permitting efforts.
Regional planning groups in Texas are now engaged in the fourth round of post Senate Bill 1 planning. The TWDB requires each regional water planning group to develop a scope of work including evaluation of “potentially feasible water management strategies to meet projected needs” [11]. The scope of work submitted by the Coastal Bend Region identifies improved conservation as the top regional priority. The evaluation of seawater desalination, as listed under the development of new surface water supplies, will be updated based on new supply estimates and costs. These updates will include on-going local study information. As in the 2011 Regional Water Plan, the evaluation in the 2016 Plan will assume that the desalination facility will be sited adjacent to the Barney Davis Power Station. However, the scope notes that “if specific site evaluations are needed for the 2016 Plan, additional funding might be needed to complete evaluations consistent with other water management strategy evaluations.”

Even though seawater desalination was examined in detail as a potential water management strategy for the Coastal Bend region, it was included in the regional water plan as an alternate strategy and not a recommended strategy. This distinction becomes important when considering state funding opportunities for desalination projects. The City requested and gained approval from the Coastal Bend Regional Water Planning Group to amend the 2011 Plan and show desalination as a recommended strategy³. This request underscores the City’s commitment to the pursuit of desalination and their continued dedication to secure the means to meet long term water supply needs. On August 14, 2014 the planning group approved submitting a request for a minor amendment to TWDB to revise saltwater desalination from an alternative water management strategy to a recommended water management strategy. In the meantime, the City of Corpus Christi, as a Wholesale Water Provider, is continuing to evaluate seawater desalination program options, including variable desalination programs and combining with brackish groundwater resources. The results of these on-going studies will be considered during development of the 2016 Coastal Bend Regional Water Plan.

2.3 OTHER REGIONAL AND LOCAL PLANNING

At the local level, water planning has long had a focus on water desalination. A review of earlier desalination studies by Wurbs [3] notes that in the early 1980’s, the City of Corpus Christi was investigating alternative sources for supplementing existing water supplies; these included reuse of treated municipal wastewater and desalination of brackish water and seawater sources. Wurbs cited a 1984 report by report

³ Coastal Bend Regional Water Planning Group meeting of May 8, 2014.
Stone & Webster and DSS Engineers which noted that desalination and tertiary treatment systems are viable water supply alternatives and concluded that “whether desalination or industrial use of municipal wastewater should be incorporated into the water supply programs of the City of Corpus Christi depends upon the comparative economics of these measures relative to the other water supply options that were being considered by the City.”

A decade later, in 1995, a TWDB Trans Texas report for the Corpus Christi region [15] similarly considered desalination and water reuse strategies. This report concluded that “While desalination in the greater Corpus Christi area is an expensive alternative, it should not be ruled out for future consideration. Desalting may merit further consideration when there are no other viable alternatives, when the costs of desalted seawater are comparable or lower than the cost of other new water supplies, or when desalination can make water available in the shortest time frame.”

In the year 2000, the City of Corpus Christi and others completed a report on desalination that provided a comprehensive overview of desalination technology and the economic importance of siting for desalination plants [4]. The report examined the cost impact on seawater desalination of source water salinity, source water fouling potential, proximity to product water demand center, concentrate disposal, raw water intake power cost, and proximity to sensitive environmental features. A summary of this report is included in the Appendix.

In 2002 the City of Corpus Christi commissioned a study to examine water alternatives to supply up to 5 million gallons per day of supplemental water to Padre and Mustang Islands [16]. The study consisted of a feasibility analysis and siting plan for a desalination project on Padre Island. The project considered a reverse osmosis desalination facility to treat brackish groundwater from Chicot Aquifer well field, deep well injection of concentrate and development of an aquifer storage and recovery system. This report provides a holistic approach to the initial development of a desalination project. Although the feasibility assessment is a decade old, the report provides valuable background information on desalination technologies, site assessment, permitting considerations, outreach efforts and much more.

Other desalination-specific planning studies were conducted after 2003 and these are covered in the next section.
2.4 WATER SUPPLY PLANNING – KEY FINDINGS

- Nearly six decades of water planning in Texas have produced an increasingly more diversified mix of water management strategies.
- Water desalination has gained prominence in Texas water planning, from an early recognition of its potential as a water supply option to a necessary water management strategy that addresses current and future water supply needs.
- Regional water planning and other studies have consistently characterized desalination as a water supply option to be pursued when other less costly options are exhausted.
- On May 8, 2014 the Coastal Bend Regional Water Planning Group moved to amend the current regional water plan to incorporate seawater desalination as a recommended water management strategy for the Corpus Christi region.
- Current strategic planning efforts by the City seek to increase the diversity of the region’s water supply by supporting conservation and incorporating reuse, aquifer storage and recovery, and desalination.

3.0 SEAWATER DESALINATION STUDIES

3.1 TEXAS SEAWATER DESALINATION INITIATIVE

According to the TWDB, there are 200 brackish desalination facilities in operation in Texas. Of these, 46 are public water supply facilities rated at 25,000 gallons per day or more for a total installed capacity of 123 million gallons per day. As a testament to the growing relevance of desalination, 75 percent of this installed capacity has been added over the last decade. Additionally, the regional water planning groups have recommended increasing the installed capacity by 310,000 acre-feet per year by the end of the 2060 decade. As dramatic and sudden as these developments are, compared to the magnitude of saline water resources, the potential for water desalination in Texas has barely been scratched.

Texas has more than 360 miles of coastline along the Gulf of Mexico providing access to a seemingly endless supply of seawater. Inland, more than thirty aquifers are spread across the state containing an ample supply of brackish groundwater estimated to exceed 2.7 billion acre-feet. Capturing this potential has been a recurring interest for Texas since the beginning of drought contingency water planning efforts in 1957.

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4 TWDB verbal testimony before the Joint Desalination Committee, June 16, 2014, Austin.
To further investigate this limitless resource Governor Rick Perry instructed TWDB in 2002 to develop recommendations for implementing a large-scale demonstration of seawater desalination. The TWDB recommended Corpus Christi, along with Brownsville and Freeport, as leading sites for executing large-scale demonstration seawater desalination projects [5]. This initiative resulted in feasibility-level studies, development of a desalination permitting roadmap and two seawater desalination pilot plant studies.

### 3.2 2004 SEAWATER DESALINATION FEASIBILITY STUDIES

In September 2003, the TWDB awarded regional water facility planning grants to the City of Corpus Christi, the Brownsville Public Utilities Board and the Brazos River Authority to conduct feasibility studies of seawater desalination. The purpose of these studies was to assess the technical feasibility of seawater desalination, assess combined uses of seawater and brackish groundwater sources as a means of enhancing the cost-competitiveness of a desalination project, determine the cost of the projects, identify a target customer base for the projects, and identify the requirements for implementing the projects. In the case of the City of Corpus Christi proposal, the customer base identification included consideration of water trading upstream in the Nueces and Lower Colorado rivers to customers such as the City of San Antonio.

The feasibility studies confirmed the technical feasibility of large-scale seawater desalination at all three locations. The studies identified financial challenges and incentives that would be required to implement the projects and maintain the financial integrity of the respective water utilities. Also, the feasibility reports pointed to the need to collect source water data and conduct pilot plant studies to better ascertain the technical requirement for seawater desalination at the chosen locations. These issues are discussed in further detail ahead in the memorandum. Table 2 provides a summary of the key findings of these studies as reported by the TWDB in its 2004 Biennial Report on Seawater Desalination [6].

TWDB recommended to the 79th Texas Legislature consider supporting a continuation of the Seawater Desalination Initiative by funding the implementation of pilot and other seawater desalination related studies. In 2005, the 79th Texas Legislature appropriated the funds requested from the TWDB to continue the program. This funding made it possible for the TWDB to provide grant funding for two seawater pilot plant studies: the Brownsville Ship Channel Study ($1.34 million grant; total project cost $2.3 million) and the South Padre Island Study ($231,000 grant; total project cost $779,000).
Table 2-Highlights of the Desalination Feasibility Studies [18] [19] [20]

<table>
<thead>
<tr>
<th>Project</th>
<th>Corpus Christi (Sponsor: City of Corpus Christi)</th>
<th>Brownsville (Sponsor: Brownsville Public Utilities Board)</th>
<th>Freeport (Sponsor: Brazos River Authority)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Customer(s)</td>
<td>Corpus Christi Regional System. Surplus fresh water capacity in the system resulting from implementation of the seawater desalination project was intended to be traded upstream in the Nueces and Lower Colorado rivers to customers such as the City of San Antonio. This issue was explored but failed to gain traction with potential upstream partners.</td>
<td>Brownsville Public Utility Board’s (PUB) system (initial capacity) and neighboring cities in Cameron and Hidalgo counties (Final capacity). Although the customer base existed for the project, the ability of these customers to pay for the project was a challenge (see below).</td>
<td>The Brazosport Water Authority system. The premise for this project was to replace surface water supplies with seawater desalination supplies in the Brazosport Water Authority System. Although the opportunity to realize this vision existed, the cost of the project exceeded other available options for the targeted customer.</td>
</tr>
<tr>
<td>Capacity</td>
<td>25 million gallons per day – Reverse osmosis</td>
<td>25 (initial capacity) to 100 (final capacity) million gallons per day-Reverse osmosis</td>
<td>10 million gallons per day-Reverse osmosis. Future expansions of up to 50 million gallons per day, and potentially greater, would expand the area served by the desalination plant to northern Brazoria and eastern Fort Bend counties as demands in those areas increase.</td>
</tr>
<tr>
<td>Site</td>
<td>Barney Davis Power Plant. However, due to hyper salinity of the Laguna Madre and environmental concerns for discharging at Oso Bay, the study recommended open ocean intake and diffused open ocean discharge.</td>
<td>Brownsville Ship Channel</td>
<td>Dow Chemical Complex. The project’s concept was to treat river water preferentially to lower the produced water cost and, when river water was not available, to shift to treatment of seawater. The disposal of concentrate would also benefit from use of existing permitted discharge infrastructure.</td>
</tr>
<tr>
<td>Capital cost</td>
<td>$197 million</td>
<td>$151 million</td>
<td>$93.1 million</td>
</tr>
<tr>
<td>Operation and maintenance cost</td>
<td>$17.5 million/year</td>
<td>$11.8 million/year</td>
<td>$7.3 million/year</td>
</tr>
<tr>
<td>Power cost</td>
<td>6.5 cents per kilowatt-hour</td>
<td>5.45 cents per kilowatt-hour</td>
<td>N/A (Energy costs estimated to be 43 percent of O&amp;M)</td>
</tr>
<tr>
<td>Required financial incentives</td>
<td>Assuming $5 million/year from water sales to San Antonio, the City of Corpus Christi estimated that, in order to maintain a zero impact to its customer base from the implementation of the desalination project, a subsidy of $24 million per year, equivalent to $1,055 per acre-foot was needed to implement this project.</td>
<td>Brownsville PUB estimated that, in order to maintain the affordability of its water utility rate, a subsidy of $13.8 million per year, equivalent to $494 per acre-foot was needed to implement this project. This level of subsidy assumed that by the year 2010 the water utility rate for the Brownsville PUB system would be approximately $2.50/1,000 gallons; the subsidy corresponded to the difference between this projected rate and the estimated unit cost of the seawater desalination facility.</td>
<td>The Brazos River Authority estimated that a subsidy of approximately $8 million per year, equivalent to $765 per acre-foot was necessary to adjust the cost of desalinated water down to the level available via alternative or existing sources of drinking water.</td>
</tr>
</tbody>
</table>
3.3  2004 CORPUS CHRISTI SEAWATER FEASIBILITY STUDY

The feasibility study [18] considered a 25 million gallons per day reverse-osmosis plant scheduled to begin operations in the year 2010. This proposed production volume was consistent with the State’s goal of creating a large-scale demonstration of seawater desalination. Although at the time of the study the City could not justify adding this capacity to its system, the proposal considered water trade-offs with upstream cities as a possible use and justification for the project. Other factors favoring the City’s proposal included: regional water supply system, presence of a strategic port, large industrial customer base, documented history of long-range water planning, proximity to water demand centers, potential to supply future customers.

The proposed site for the seawater desalination facility was the Barney Davis Power Plant, located approximately one mile from the Corpus Christi water distribution system. This site was one of five considered on the basis of available land area, seawater intake permit, proximity to concentrate discharge location, proximity to customers and host facility’s owner interest in co-siting a desalination facility. Favorable factors for using the Barney Davis location included: proximity to the water distribution system, use of existing seawater intake infrastructure and the use of cooling plant effluent for diluting concentrate. Challenges associated with this site are the high salinity of the source water (Laguna Madre) and potential environmental issues from discharging concentrate into Oso Bay.

Also, the Barney Davis Power Plant changed ownership during the course of the 2004 study which created uncertainty as to the possible use of that location for siting a seawater desalination facility\(^5\). However, this issue was satisfactorily resolved and the site was considered the leading option for installing the proposed 25 million gallon per day facility. Following are key issues related to the assessment and selection of intake, pretreatment and concentrate management options in this study:

3.3.1  Intake

As noted, co-location was one of three options considered in the 2004 Corpus Christi desalination study: the existing Barney Davis Power Plant shared intake; open sea intake; and infiltration type intakes. The intake selection was based on raw source location, quality, environmental impacts, intake technology, and costs. Consideration was given to the cost and complexity of construction of raw water lines through

\(^5\) Topaz Power is the current owner of the Barney Davis Plant.
environmentally sensitive areas such as Padre Island, Corpus Christi Bay, Red Fish Bay, or the Laguna Madre.

Initially, the existing Barney Davis Power Plant intake was not included in the evaluation due to plant ownership issues and its uncertain future, and the hyper salinity of Laguna Madre. Blending with brackish groundwater was considered but deemed infeasible based on lack of availability of groundwater of suitable quality. Ultimately with the plant ownership resolved, the Barney Davis Power Plant intake was included and the project alternatives were optimized. It was noted that the benefits of using the existing intake were partially off-set by the cost of treating the higher salinity source.

The open sea intake concept included 2 miles of 42 inch diameter high-density polyethylene pipe extending into the Gulf of Mexico to be installed by wet-dredging, backfilling, and armoring with rock. The intake itself would be comprised of two risers with intake screens extended 7 feet above the sea floor. Screening facilities with an air blast system for cleaning and a raw water pump station were located on shore.

Three types of infiltration systems were considered: caissons (beach wells); linear collection wells; and Rainey collectors. All three types of infiltration rely on the natural soils to provide filtration and can significantly reduce pre-treatment requirements, though their long term viability is unknown and very site specific. At least 40 beach wells, possibly 60 feet deep, were estimated to be required to supply the 55 million gallons per day of raw seawater. The linear collection wells buried parallel to the shoreline were estimated to require six caissons with a total of 39,000 feet of horizontal collector pipes. Beach wells and linear collection wells were not considered further due to questionable long-term reliability, cost, high maintenance requirements, and large onshore land area requirements. Six Rainey collector intakes were estimated with 39,000 linear feet of horizontal collectors extending radially from each caisson. The caisson requires excavation but the horizontal collectors can be jacked out from each caisson and the installation can be much less intrusive to the environment.

The conclusion from the intake options evaluation was that the existing Barney Davis Power Plant intake was the optimal intake choice due to: shared use, cost savings, permitted use, and elimination of an expensive intake into the Gulf of Mexico and raw water pipeline through Laguna Madre and Padre Island. The only negative factor noted was the hyper salinity of the source water that would increase capital and operating costs and partially off-set the benefit provided by the existing intake. The existing Barney Davis
Power Plant intake was recommended subject to a final agreement with the power plant owners. The open sea intake was considered the next most viable alternative.

3.3.2 Pretreatment

The 2004 Corpus Christi Seawater Desalination Feasibility Study included a review, assessment and selection of pretreatment options. The screening of pretreatment options was performed on the basis of worst-case water quality: turbidity could be greater than 20 NTU; red tides or algae could be present for a significant period of time; there may be variations in temperature of the raw water; there may be moderate total organic carbon; greater than 25 mg/l of coagulant may be required; hurricanes may cause severe water quality excursions; and the density of seawater may affect the performance of the pretreatment processes. The screening sought a pre-treatment process that would be robust enough to handle expected worst-case variations in water quality and still provide acceptable water quality for the reverse osmosis process. Additional assumptions are that the processes should be space efficient to reduce land requirements and facilitate siting of the plant, and be well proven in drinking water treatment applications. The following pretreatment options were considered:

- Direct filtration (eliminated prior to pre-screening as not applicable)
- Conventional flocculation, sedimentation, and filtration
- Solids contact clarification (Accelerator™) and filtration
- Plate or tube settler clarification and filtration
- Pulsator or Superpulsator clarification and filtration
- Dissolved air flotation (DAF) clarification and filtration
- Micro-sand enhanced clarification and filtration
- Ultrafiltration using immersed membranes (Zenon)
- Infiltration galleries

After the pre-screening process, which is described in detail in the feasibility report, four pre-treatment options were considered for detailed evaluation (including life-cycle costs):

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6 Please refer to Desalination Technology, Section 6.4, Pretreatment for additional information on these technologies.
1. Plate or tube settler clarification with filtration
   (+) Considered the baseline alternative due to prior use in seawater reverse osmosis pretreatment
   (+/-) Residuals of 0.1 to 0.5 percent solids.
   (-) Susceptible to thermal variation
   (-) Limited in treating high turbidity or algae (phytoplankton)
   (-) Plate or tube openings can become blocked by solids or algae causing poor performance

2. Dissolved air flotation clarification with filtration
   (+) Low clarified turbidity and exceptional performance
   (+) No need for a polymer
   (+) Not susceptible to thermal variation
   (+) Proven as the premier clarifier for treating algae (phytoplankton)
   (+) Residuals of up to 2.0 percent or greater solids
   (+) Residuals may be directly dewatered without further thickening
   (+) Dissolved air flotation can be stacked over the filtration process reducing the overall footprint
   (+) One seawater reverse osmosis plant using dissolved air flotation at the time of the study
*Stacked dissolved air flotation was evaluated in the alternative.
*Dissolved air flotation is considered the most robust and favorable high rate clarification process evaluated in the study.

3. Ultrafiltration using immersed membranes (Zenon)
   (+) Physical removal of solids, particles, algae, and pathogens
   (+) Demonstrated effectiveness for providing water with a low silt density index
   (+) Possibly reduces recovery cleaning and extends membrane life
   (+) Can replace both clarification and filtration
   (-) Limited experience for seawater reverse osmosis pretreatment
*GE Zenon Zeeweed 500D was considered in the study.

4. Infiltration galleries using the Rainey collector
   (+) Replaces all forms of seawater reverse osmosis pretreatment
   (-) Infiltration galleries are an “intake” system but considered here as a means of pretreatment.

All 4 alternative options above were developed on each of the two desalination facility sites based on selecting compatible intakes, off-site piping, and common elements (reverse osmosis and appurtenant
processes) using a weighted prioritization method and the following decision criteria: Total life cycle cost; reliability; and, complexity of implementation.

Overall results were:

- Infiltration intake pretreatment alternative was the lowest cost but had poor reliability and high complexity;
- Tube and plate settlers and dissolved air flotation pretreatment had similar life cycle costs but dissolved air flotation was deemed more reliable and robust;
- The immersed membrane approach was the most costly option but scored favorably in reliability and complexity of implementation;
- Dissolved air flotation was the optimum pre-treatment option for the Corpus Christi Desalination Project;
- The study noted that membrane pretreatment by ultra or micro filtration should be reconsidered in the future due to the possibility of developments that could reduce membrane system costs.

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Note: Dissolved air flotation is a proven robust technology with advantageous features such as high surface loading rates; ability to achieve low clarifier turbidities without polymer use; ability to treat large algae concentrations. This technology has been selected for testing as part of the Corpus Christi Variable Salinity Desalination Project.
3.3.3 Concentrate Management

Assuming a seawater salinity of 35,000 milligrams per liter and a permeate recovery rate of 50 percent the resulting byproduct concentration would be approximately 70,000 milligrams per liter. The following potential options for byproduct disposal were considered and evaluated:

1. Deep Well Injection
   a. 25-30 wells8 spaced at .25 mile apart with approximate injection capacity of 1.0 million gallons per day.
   b. High injection pressure of approximately 1,000 psi
   c. Not considered further due to very high cost ($97 million).

2. Evaporative Lagoons
   a. Required a land area of 38,000 acres.
   b. Estimated to cost $2.0 billion
   c. Not considered further.

3. Offshore Discharge
   a. Considered to be the most straightforward and reliable method of byproduct disposal.
   b. Conceptualized as co-located in the same trench with the raw water intake but diverging at the end to attain separation.
   c. Estimated a 2.0 mile off shore distance.
   d. Estimated a separation distance of 0.25 miles (1400 ft.).
   e. Estimated a depth of 40 ft.
   f. Relies on the Texas Coastal Current to aid in mixing and dispersion.
   g. Discharge to the Gulf of Mexico may garner environmental support.
   h. Dispersion modeling should be used to further refine the discharge location.

Discharging the byproduct to a wastewater treatment plant was also considered but quickly rejected due to the volume of byproduct being significantly greater than the local wastewater treatment plant effluent and adverse impact of the discharge on the salinity of Oso Bay.

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8 Existing disposal wells in the area for disposal of chemical industry byproducts are typically in the 5,000 feet depth range.
Membrane-thermal zero liquid discharge was not considered due to expected high cost, lack of an identified market for byproduct salts. One local company having a need for 300,000 mg/L feed stock for their process was considered but rejected as an alternative due to the uncertain long-term viability of the company.

Discharge to the Barney Davis Power Plant cooling water stream which flows through cooling ponds prior to discharging into Oso Bay: The Barney Davis Power Plant discharge to Oso Bay is considered beneficial and already of higher salinity. The byproduct stream was estimated to increase the salinity of the discharge to Oso Bay by about 5 percent. This option represented considerable cost savings compared to other alternatives for byproduct disposal. Therefore both the off shore discharge (open sea outfall) and discharge to the Barney Davis Power Plant cooling water were evaluated in detail in the study. It was recommended that the option for discharge to Oso Bay should be retained for future consideration, but the environmental concerns keep this option from being a likely solution.

3.3.4 Other Findings and Lessons Learned

Other issues considered in the feasibility study include:

- Combined uses of seawater and brackish water. The study relied on salinity results from a previous desalination study, existing log data, and the interpretation of a professional hydrogeologist. The report concluded that using brackish groundwater for blending was not cost effective. This same result was determined with blending with either the feed water or the byproduct water.

- Potential partnerships for implementing a large-scale project. The focus of this item was in considering public private partnerships as a means to implementing a large-scale project. The report concluded that such a consideration was premature at the time of the study.

- Potential customers for surplus water. A premise of the 2004 study was to consider a project sized in the 25 million gallons per day range. In 2004, such a project would have created a surplus water supply. The study considered several water sales options at a conceptual level and included a potential sale of surplus water to San Antonio in its estimates.

- Power sources. Both conventional and alternative power sources were investigated during the course of this feasibility study. Conventional power sources are referred to as the purchase of retail power at competitive rates from the electric power grid. Alternative energy sources consist of developing a power source using wind or solar energy specifically designed to meet the power requirements of the desalination facility. Wind-generated power appeared to be close in cost for the desalination plant. However, disadvantages such as non-controllable nature of the resource, marginal cost-effectiveness at the available power rate structure and uncertainties about a potential suitable location, the cost of the land for a wind generation facility, and the cost of transmission to the
desalination facility represented significant unknown costs at the time of the study. Solar power was considered, but the conceptual costs for solar power on the scale needed for the large scale desalination facility were an order of magnitude higher than either conventional power or wind-generated power.

3.4 PILOT STUDY: BROWNSVILLE SEAWATER DESALINATION PROJECT

In 2004, the Brownsville Public Utilities Board executed a seawater feasibility study (See Table 2) similar in scope to the 2004 Corpus Christi Seawater Desalination Feasibility Study. The strength of the Brownsville proposal laid in the fact that additional supplies were critically needed to supplement the surface water supply obtained from the Rio Grande River, which had failed to reach the ocean in 2001. This context provided added priority to the seawater desalination proposal and the request by the Brownsville Public Utilities Board for financial assistance from the State to execute a pilot plant study.

A partnership between the TWDB and Brownsville Public Utilities Board developed and operated a seawater desalination pilot plant from February 2007 to July 2008 [21]. The pilot plant, located on the Brownsville Ship Channel, treated seawater from the channel for 18-months and evaluated process performance, water quality, and various equipment manufacturers. Once the study was completed the temporary facility was decommissioned.

3.4.1 Site Selection

Two alternative site locations were considered for the pilot facility: Boca Chica Beach (coastal) and the Brownsville Ship Channel (inland approximately 11 miles). Although the raw water quality was expected to be generally poorer at the ship channel site, the pilot facility was located there because of power supply, cost, security, and access considerations. As such, the site represents a worst-case scenario for source water quality for desalination.

3.4.2 Pretreatment Equipment Evaluation

Pilot study results indicate that a treatment system consisting of microfiltration followed by reverse osmosis and post-treatment is capable of treating raw seawater from the Brownsville Ship Channel to a quality that meets all primary and secondary water quality standards without the need for additional treatment. Post treatment requirements include a combination of chemicals such as caustic soda (pH control), sodium bicarbonate for alkalinity, and calcium chloride for addition of calcium. This combination of chemicals will produce stable, non-corrosive water.
Four equipment manufacturers participated in the pretreatment evaluation at the Brownsville pilot plant. One packaged media filtration system and three membrane filtration systems were tested. These included:

- EIMCO, a packaged dual media filtration system
- GE Zenon Ultrafiltration
- Norit Ultrafiltration
- Pall Microfiltration

Of these systems, only the Pall membrane satisfactorily meet the pretreatment criteria.

3.4.3 Reverse Osmosis Equipment Evaluation

Three reverse osmosis membranes from two manufacturers were tested during the operation of the pilot plant. DOW and Toray membranes were piloted and evaluated against a set of performance selection criteria in order to determine their acceptability in a possible full-scale desalination application. All membranes were successful in meeting project goals and deemed acceptable for use in a full-scale facility.

3.4.4 Concentrate Disposal

To facilitate a preliminary design of a multi-port diffuser outfall for the concentrate stream of the proposed full-scale seawater desalination plant, the Cornell Mixing Zone Expert System (CORMIX) model was used to simulate various discharge scenarios. CORMIX is a software system for the analysis, prediction, and design of aqueous toxic or conventional pollutant discharges into diverse water bodies. The system’s major emphasis is on predicting the geometry and dilution characteristics of the initial mixing zone so that compliance with water quality regulatory constraints may be evaluated.

The modeled discharge location was approximately 1/2 mile offshore from Boca Chica beach, approximately 2 miles north of the mouth of the Rio Grande. Field measurements were made on two occasions at five locations in the vicinity. Water depths at these sampling sites ranged from 25 to over 50 feet. The discharge modeling used 25 feet depth as the disposal depth –minimum depth to protect from ship traffic.
In summary, the results show that the concentrate discharge plume is completely mixed from substrate to surface (cross-section view), and that concentrations are reduced to near ambient conditions within 125 ft. of the diffuser.

Deep well injection was determined to be economically unfeasible.

The Brownsville Seawater Pilot Plant Study was an ambitious and pioneering undertaking in Texas. The study generated valuable knowledge and specific lessons for future pilot plant studies. These lessons are discussed ahead.

3.5 LESSONS LEARNED FROM THE BROWNSVILLE PILOT PLANT STUDY

TWDB contracted Reiss Engineering Inc. (REI) to provide Seawater Pilot Services to support the TWDB’s desalination pilot study program [22]. This included identification of lessons learned from the Brownsville seawater desalination pilot plant study. The study generated a better understanding of the intensity of the operations and maintenance requirements of a seawater desalination facility. Following is a summary of findings/lessons from the study:

3.5.1 Pilot Unit Operations

- Operating the pilot study was more difficult than expected. Personnel and resources were difficult to plan prior to implementation of the study because the project was expanded to include four different pretreatment units.

- A pilot study team should plan for the on-site personnel as a full-time employee to ensure the success of the pilot study; ideally, operating department representatives, including operators, should be assigned and involved in all phases of the pilot plant facility operation.

- Roles and responsibilities during a pilot study should be clearly defined and understood by the team prior the pilot unit start-up.

- Pilot plant personnel should be trained by each treatment unit vendor representative to ensure proper operation of the units.

- Enclosure of equipment is preferred to protect the equipment against corrosive conditions, but on the other hand, the costs associated with constructing an enclosure may be prohibitive. Therefore, the pilot study team will have to balance costs versus advantages and disadvantages of an enclosure.
3.5.2 Intake Siting

- Pilot testing at a selected location using a proposed treatment process train represents a proof of concept evaluation. Pilot-scale testing over an extended period allows direct and scalable assessment of the suitability of an intake location and its associated raw water quality. Intake siting is important as it directly determines the quality of raw water and subsequent treatment requirements.

- The north shore of the Brownsville ship channel site minimized raw water pipeline costs and transmission to the Brownsville distribution system, and provided access to power and other needed infrastructure. However, the tradeoff was a poorer source water quality that needed advanced pretreatment. The intake site experienced wide variations in raw water quality, particularly sediment loading.

- For future projects in Texas, thorough sampling of raw water quality can be used to screen sites in advance of pilot testing at a low cost. Specific emphasis on sediment loading in particular is of critical value as it is directly related to the level of pretreatment that will be required. It is important to recognize the relationship between sediment loading and its impact on pretreatment requirements, operational reliability, and project costs.

3.5.3 Pretreatment Systems

- Pretreatment systems can vary considerably and directly affect water treatment plant sustainability. Multimedia filtration and membrane filtration options are two competing approaches with the optimal solution remaining a project-specific answer. Conventional filtration systems can provide the benefit of lower capital costs but are typically reserved for high quality, low sediment source waters. Microfiltration and ultrafiltration systems typically provide very high quality filtrate but at a higher cost.

- The Brownsville pilot study evaluated alternative pretreatment processes. These included a conventional dual media flocculation-clarification-filtration system and three microfiltration and ultrafiltration units.

- The conventional system consisted of a rapid mix basin, two flocculation chambers, and a clarifier equipped with plate settlers. Ferric chloride was used to coagulate the water supply. Following the conventional system was a single-stage, dual-media (silica sand and anthracite) filtration system. The conventional system’s performance was not acceptable. During the operational testing period it only provided a satisfactory effluent quality 12 percent of the time. The conventional system was unable to produce a filtrate of acceptable quality to feed a seawater reverse osmosis system and was eliminated from consideration. This experience exemplifies the issues of using conventional filtration systems on near shore, high sediment loading water sources.

- The use of raw water sampling to determine sediment loading can be an effective screening tool to ensure appropriate selection of pretreatment technologies that warrant further consideration at pilot-scale.
Microfiltration and ultrafiltration systems used included the Norit, Zenon, and Pall systems. These systems are membrane filters capable of reducing turbidity to near or below detection limits, thereby eliminating any issues of plugging of the downstream reverse osmosis system. These systems do not necessarily require use of coagulant. However, without the use of coagulants these systems (nor conventional filtration) do not reduce dissolved organic carbon (DOC), and therefore any assimilable organic material in the raw water will pass to the reverse osmosis system and can cause biological fouling. In addition, the microfiltration and ultrafiltration systems themselves can foul due to high sediment loading so it is critical that sustained operational performance be demonstrated by any microfiltration or ultrafiltration system under consideration.

The microfiltration and ultrafiltration systems experienced a series of mechanical difficulties, extended downtime, and fouling issues. These experiences are not uncommon but were particularly prevalent with this pilot study. One observation regarding this project when compared to other pilot studies is that the scope of the pilot was particularly large, with four pretreatment technologies, two reverse osmosis systems, and a large array of project implementation tasks requiring attention. In addition, there was significant reliance upon the equipment manufacturers to facilitate operational process engineering decision-making.

For future pilot studies, the ability to rapidly interpret and respond to pilot results, particularly pretreatment system performance, is important. The scope of the project must be balanced with the expertise and resources of the project team. Also important is to incorporate vendor participation in the development of operational protocols prior to start-up.

3.5.4 Desalination System

The Brownsville pilot study included the use of two reverse osmosis systems. These systems used 8-inch diameter elements in a full, seven element array. This represents a typical configuration for the first pass of a large-scale seawater desalination system. No second pass system was tested.

The systems incurred significant down-time primarily due to mechanical difficulties and lack of filtrate from the pretreatment units. These issues are common for pilot studies and may have been enhanced in this instance due to the significant scope of the Brownsville pilot study.

The reverse osmosis systems were subject to biological fouling as presented in the final report. Operational times between cleaning were generally on the order of 70 to 90 days, compared to a typical design criterion of cleaning no more frequently than once every 90 days. The cause of the biological fouling was not determined but alternatives to potentially control biological fouling in future studies were presented by the project team.

The reverse osmosis elements used in the study were found to be irreversibly fouled. While the duration between chemical cleanings approached acceptable targets, the ability to chemically clean the membrane to restore performance is as important as the rate at which it fouls.

For future Texas seawater desalination projects, the ability of a reverse osmosis system to meet cleaning frequency targets as well as the ability to restore performance following a chemical
cleaning is of critical importance. In addition, when using 8-inch diameter membranes, it is important to ensure that an adequate quantity of pretreated water will be available to supply the reverse osmosis unit.

3.5.5 Finished Water Quality

- The permeate total dissolved solids for the Brownsville pilot study ranged from 132 to 320 mg/L. Chloride concentration ranged from 69 to 161 mg/L. These results demonstrate production of fresh water and are generally acceptable.

- Additional testing should include boron (in addition to bromide) and re-equilibration effects, among others.

- Defining finished water quality objectives up front is critical to ensuring that the pilot is designed appropriately and that the pilot ultimately does meet those objectives. While the Brownsville pilot study has not yet evaluated post treatment (and re-equilibration in particular), this topic remains a key factor in any regional water distribution system.

3.5.6 Permitting

- Given the complex nature of a seawater desalination system, the level of pilot information should likely be well beyond that currently required by the Texas Commission on Environmental Quality (TCEQ). As seen in the pilot study, repeatability of the test success (as defined by Stages 2 and 3 of the TCEQ requirements) was not always feasible due to the ever changing water quality of the source water.

- As was addressed in the Brownsville pilot study, it is recommended that future pilot studies in the State of Texas include 12 months of operation to capture seasonal differences in raw water quality.

- The study was designed to evaluate two concentrate disposal options: disposal into the Gulf via diffusion and outfall and disposal via a deep well injection. Both were found technically feasible, but since the concentrate disposal into the Gulf was more cost-effective than the deep well injection, the disposal to the Gulf was the option recommended for concentrate disposal.

3.6 FEASIBILITY AND PILOT STUDY: SOUTH PADRE ISLAND SEAWATER DESALINATION PROJECT (LAGUNA MADRE WATER DISTRICT)

The feasibility and pilot study on seawater desalination in South Padre Island provides a good foundation direction on planning, siting, and carrying out these types of projects along the Coastal Bend [23].

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9 Stage 2 refers to the continued operation of the pilot treatment process for a minimum period of 90 days; stage 3 refers to the operation of the pilot treatment system after a major cleaning event to observe its recovery performance.
Laguna Madre Water District (LMWD) study and subsequent final report include evaluations on siting, source water characterization and quality, process selection, and desalination costs.

3.6.1 Intake Structure

An evaluation of potential intake locations included the collection and analysis of data from TCEQ Water Quality Stations to predict source water quality for the pilot facility. It was determined that the Gulf of Mexico would most likely supply a more consistent raw water quality and minimize the environmental impact of a full-scale raw water intake. The decision to use the Gulf instead of the Bay also directed the siting evaluation.

The project team concluded that an intake pipe, equipped with a passive inlet screen, should convey seawater to a wet well where it would be screened one more time prior to being pumped through the desalination process. It was hypothesized that the passive intake screen and screening on the pump intake would reduce impingement of marine biology and provide relatively low-maintenance screening for raw water.

3.6.2 Pretreatment

During the pilot study, it was determined that pre-treatment performance should be monitored by measuring silt-density index and either turbidity or particle counts. The results of the pretreatment evaluation led the project team to conclude that a combination of screening and micro- or ultra-filtration was preferable over conventional dual media filtration pretreatment as it produces a more consistent pretreated water quality.

3.6.3 Desalination

Electrodialysis and Electrodialysis Reversal can be effectively and economically used for desalination of source water up to approximately 10,000 mg/L of total dissolved solids. At higher total dissolved solids concentrations, the team concluded that reverse osmosis would be the most economically feasible desalination process. However, if the plant could be co-located with a facility which produces a significant amount of waste heat, thermal distillation processes should also be considered.

The reverse osmosis process at South Padre Island was estimated to require approximately 23 kilowatt-hours (kWh) of electricity for every thousand gallons treated. The final report made a recommendation
for improving energy efficiency through the conservation and capture of brine pressure utilizing one of the following:

- PX Pressure Exchanger
- Hydraulic Pressure Booster
- Pelton Impulse Turbine

3.6.4 Permitting

The following permits and agencies were considered for the South Padre Island Desalination Pilot:

- USACE – construction in navigable waters.
- US Fish and Wildlife Services
  - Endangered Species Act Consultation
  - Fish and Wildlife Coordination Act Consultation
- National Marine Fisheries Service
  - Endangered Species Act Consultation
  - Manguson-Stevens Fishery Conservation and Management Act Consultation
- US EPA
- TCEQ
  - Texas Land Application Permit
  - Underground Injection Control Permit
  - TPDES Storm Water Permit
  - TPDES Construction Storm Water Permit
  - Water Rights Permit
  - Texas Public Water System Permit by Rule
  - Water Quality Certification (Section 401 and Section 404)
- Texas Parks and Wildlife
  - Protected Species Consultation
  - Fish and Wildlife Coordination Act Consultation
  - Sand and Gravel Permit
- Texas Historical Commission
Antiquities Permit
National Historic Preservation Act Consultation

Texas General Land Office
Coastal Zone Management Act
Right of Way – Easement

Texas Department of Transportation
Highway alteration permit for construction of an access road which connects to a TXDOT road.

3.7 SEAWATER DESALINATION INITIATIVE – OTHER STUDIES

In addition to the seawater feasibility studies previously discussed, the state has conducted and/or funded several other projects of direct relevance to the current City of Corpus Christi effort:

- 2004 Biennial Report on Seawater Desalination, Volume II: Technical Papers, Case Studies and Desalination Technology Resources, [24]. This is a compilation of white papers discussing various key desalination related issues, the availability and development of saline water sources in Texas, and desalination technology topics including10:
  - An Overview of Seawater Intake Facilities for Seawater Desalination (Tom Pankratz)
  - Potential for Thermal Desalination in Texas (John Tonner)
  - The Importance of Pilot Studies in the development of large-scale seawater desalination plants (C. Robert Reiss)
  - Fundamentals of Membranes for Water Treatment (Alyson Sagle and Benny Freeman)
  - Integration of Power Generation and Water Desalination Operations (Neil Callahan)
  - The Importance of Energy Recovery Devices in Reverse Osmosis Desalination (Boris Liberman)
  - Review of Concentrate Management Options (Mike Mickley)
  - Please Pass the Salt (R. Mace, J.P. Nicot, A.H. Chowdhury, A. R. Dutton, S. Kalaswad)
  - Economic Siting Factors for Seawater Desalination Projects along the Texas Gulf-Coast (Mark Graves and Ken Choffel)

10 These documents are accessible and downloadable from the TWDB, Desalination Web page: http://www.twdb.texas.gov/publications/reports/numbered_reports/doc/R363/Report363.asp
Permitting Roadmap for Seawater Desalination Facilities in Texas Using Reverse Osmosis Processes (Howard E. Steiman)

Cost Guidance for Seawater Desalination Facilities in Texas (Jonathan Dietrich and Christopher Robert)

- Development of Permitting and Development Decision Model for Desalination Projects in Texas [25]. This study provided permitting guidance and a decision model for desalination projects in Texas. The report listed 20 major permits and approvals for a seawater desalination plant and associated transmission lines. According to the study, the amount of time required to complete a permitting process ranges from 18 to 24 months. However, for both the Brownsville Ship Channel and the South Padre Island pilot plant studies, the permitting for the pilot plant studies alone took from 6 to 12 months. Due in great extent to its location near protected areas, the South Padre Island study involved additional permitting steps that further delayed the actual start of the piloting phase.

- Texas Desalination Data Base [26]. The report presents detailed information on public water systems in Texas that are currently engaged in desalination and includes a Web-based database application of existing public water system desalination plants.

3.8 TAMPA BAY WATER DESALINATION PLANT

Water managers and planners with Tampa Bay Water (TBW) initiated a desalination effort in the late 1990s in order to ensure supply for the region’s long-term water demand. The project was completed in 2007 and is the first large-scale seawater desalination project constructed in the United States. Operating at capacity, the plant is capable of producing 25 MGD of drinking water from seawater.

3.8.1 Project Delivery Method

The initial Request for Proposals and contract for this project were structured so that a single entity or partnership would design, build, operate, and own the desalination plant. The agreement also allowed TBW to purchase the facility after 30 years, or earlier if necessary. The engineering and construction partner on the first contract went bankrupt and a subsequent partner was unable to acquire project financing due to a poor bond rating. After navigating the financial and contract issues, the project settled into a design-build-operate agreement and ownership would be solely retained by TBW.

Under the latest agreement, TBW pays the operator, American Water-Pridesa, $7 M per year for fixed operating and maintenance costs in addition to separate payments for variable operating costs which include chemicals and utilities. This allows TBW to reduce production of the plant if cheaper alternative sources are available.
3.8.2 Project Capital and Water Production Costs

Initial capital cost estimates for the desalination plant and the 15-mile pipeline to connect it to the water system was estimated to be $110 million. After construction, however, numerous deficiencies were identified which required significant improvements. The final capital cost of the project was $158 million, more than 40% above the initial estimates.

In 1999, Heller reported in the St Petersburg Times the project developer’s commitment for a 30-year average wholesale price of water of $2.08 per 1,000 gallons ($678 per acre-foot) [27]. However, project developers were unable to deliver on initial cost estimates and the production of water has varied dramatically since the project was completed in 2007. In 2012, Cooley and Ajami, citing personal communication with Lynda Vatter [28] reported that these impacts elevated unit costs of production to $3.99 per 1,000 gallons ($1,300 per acre-foot) if the plant is operating at its 25 MGD capacity. It is expected that TBW will purchase only 11 MGD, on average, which will further increase the unit production costs to $1,600 per acre-foot ($4.91 per 1,000 gallons). This is more than twice as much as the original estimate.

3.8.3 Lessons Learned

- This plant’s pretreatment system had to undergo substantial modifications in order to achieve a consistent performance. Pilot studies are a critical step in selecting and testing a pretreatment system that can deliver consistent quality for the reverse osmosis process. It is possible that some of the operational deficiencies that had to be corrected in this project could have been identified through pilot testing and thus avoid the delays and added costs to the project;

- Anticipate the transfer of ownership at any point of the project and consider what actions will be taken if transfer occurs;

- Exercise caution when transferring ownership under a Design-Build-Own-Operate-Transfer contract. The new owner must recognize that they are assuming many of the risks associated with the project;

- Ensure that those submitting proposals have relevant desalination project experience.

- Minimize demand risk by implementing cost-effective water supply alternatives prior to the development of the project;

- Consider establishing a minimum operating contract, rather than a take-or-pay contract, to allow the water supplier to adjust production of the plant if cheaper alternatives become available.
3.9 CARLSBAD DESALINATION PLANT

Poseidon Resources (Poseidon) is currently building a 50 MGD desalination plant co-located with the Encina Power Station in Carlsbad, California. Project planning was initiated in 1998, a demonstration plant was built in 2003, and permitting for full-scale construction was completed in 2009 [29]. The facility in Carlsbad is expected to begin producing water by 2016.

The permitting process for this facility took 6 years\(^\text{11}\). Key permits included: California Department of Public Health Wholesale Drinking Water Permit, California Coastal Commission Coastal Development Permit, State Lands Commission Amendment to Intake and Outfall Lease, Regional Water Quality Control Board NPDES Permit and Waste Discharge Requirements, and City of Carlsbad Environmental Impact Report, Precise Development Permit, Redevelopment Permit, Habitat Management Plan Permit, Coastal Development Permit (pipeline), Development Agreement, and Specific Plan Amendment.

3.9.1 Project Delivery Method

Poseidon is developing this project under a design-build-own-operate-transfer agreement and joint venture between subsidiaries of Kiewit Corporation and J.F. Shea Construction, Inc. for engineering, procurement, and construction of the desalination plant as well as a 10-mile pipeline. IDE Americas, Inc. has been contracted to perform the reverse osmosis design and operate and maintain the facility for a period up to 30-years.

3.9.2 Project Capital and Water Production Costs

The water purchase agreement, released for public review in September 2012, provided detailed capital cost estimates for the project. According to these figures, the total capital cost of the facility and related projects is $984 million [30]. Capital costs include the following:

- $528 million (54%) for planning, permitting, design, construction, mitigation and legal costs associated with the desalination plant.
- $163 million (16%) for construction of a 10-mile pipeline to transport product water to the distribution system.

\(^{11}\) This process included 5 local discretionary approvals, 4 state agency discretionary approvals, 21 Public Hearings with 85 hours of testimony, dozens of technical studies, 14 legal challenges, and unanimous support of state & federal legislative delegations and hundreds of letters of support.
• $80 million (8%) for indirect costs for water system improvements, including relining and rehabilitating a 5.5-mile section of the distribution pipeline and modifying another treatment plant in the system.

• $213 million (22%) for financing the project. This includes interest during construction, financial bond costs, and other financing costs.

Excluding grants and subsidies received by the San Diego County Water Authority (SDCWA), the unit cost for water production has been estimated between $2,000 and $2,300 per acre-foot ($6.13 to $7.06 per 1,000 gallons) in 2012 dollars (SDCWA 2012a).

3.9.3 A Lesson in Risk Allocation

One of the key elements in the agreement between Poseidon and the SDCWA is the allocation of risk among project partners. Project-related risks are defined and divided between Poseidon and the SDCWA as illustrated in the Table below.

<table>
<thead>
<tr>
<th>Risk Description</th>
<th>Poseidon</th>
<th>SDCWA</th>
</tr>
</thead>
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<tr>
<td>Force Majeure Events</td>
<td>X (Insurable)</td>
<td>X (Uninsurable)</td>
</tr>
</tbody>
</table>

3.10 TAUNTON RIVER DESALINATION PLANT

The Taunton River Desalination Plant [31, 32] is located on the western shore and fourteen miles north of the mouth of the Taunton River, Massachusetts. The facility is designed to provide 3.2 million gallons per day to the City of Brockton. The $56 million project was delivered via a design-build-own-operate-transfer scheme under a 20 year take or pay delivery contract between the project developer and the City. The plant was commissioned in 2008 and, due to a dramatic reduction in water demand, has not operated at full capacity for long and has experienced long periods of idleness.
In many ways this project and the design of the treatment process was much more complicated than a typical seawater desalination project because of the wide range of water quality conditions that must be treated. The feed water source for the plant is provided by the tidally influenced Taunton River. Depending on the tide stage, the salinity of the source may range from 200 to 12,000 milligrams per liter while organics and suspended solids also vary widely. During the fresh water season the main treatment issue is very high TOC and DOC and disinfection byproducts control. The plant relies on an ultra-filtration pretreatment system (Zenon Zeeweed™).

The plant’s intake system is designed to operate in a batch mode. Raw water is drawn at a low salinity point (lower tides) and stored (up to 12-hours of feed supply needs). At high tide, reverse osmosis concentrate is discharged (with dilution if necessary) when it more closely matches the river’s higher salinity conditions at around 8,000 milligrams per liter of dissolved solids.

### 3.11 THAMES GATEWAY WATER TREATMENT WORKS

The Thames Water’s Gateway Desalination plant also draws water from a tidally influenced source: the Thames River [33, 34]. The 40 million gallons per day plant is located on the north bank of the Thames River in the east London Borough of Newham. The cost of the facility was $410 million. As with the Taunton case, feed water is drawn from the estuary targeting lower salinities; in this case 11,000 milligrams per liter or about a third of seawater salinity. This strategy results in a much lower energy demand to desalinate the water.

The screening consists of a copper-nickel passive wedge wire screen with an aperture size of 3mm. The screens will be periodically cleaned using an air scour system. The intake structure will also include an Acoustic Fish Deterrent which is turned on 10-15 minutes prior to the start of the intake pumps and a raw water quality monitoring station. Raw water is stored in a 40 million gallon salinity buffer tank.

The pretreatment consists of coagulation, flocculation, and sand filtration followed by a Norit X-Flow ultrafiltration system. Concentrate from the plant will be blended with treated effluent discharge from the nearby Beckton Sewage Treatment Works (the largest sewage treatment plant in the United Kingdom) at a dilution factor of approximately 50, so its salinity will be lower than the river itself.

In addition to the source salinity management strategy, a number of innovative measures have been included to minimize the specific energy consumption of the plant, including: Using variable speed drives on the reverse osmosis feed pumps reduces energy wastage through permeate throttling; the use of
Pelton turbines to recover energy from the reject stream; innovative electrical engineering including the use of higher voltage transmission (33 kV as opposed to 11 kV), water cooled switch gear as opposed to air cooling and intelligent assemblies, which can monitor electrical energy use and efficiency to switch off non-essential power use during peak demands, and optimize running plant to the most efficient available.

### 3.12 SEAWATER DESALINATION STUDIES – KEY FINDINGS

- The Texas Seawater Desalination Initiative launched in 2002 was a bold policy that reflected strong interest of the State to develop seawater desalination supplies. Although the initiative did not accomplish its primary goal (to install a large-scale demonstration seawater desalination plant in Texas) the effort resulted in studies that substantially advanced the desalination agenda in Texas;

- In 2004, three seawater desalination feasibility studies -- by Corpus Christi, Freeport and Brownsville- concluded that: 1) seawater desalination was technically feasible; and, 2) financial assistance was required to ensure affordability of the proposed projects;

- The Corpus Christi Seawater Desalination Feasibility Study researched, assessed, and issued recommendations on most of the topics that will be revisited in this current effort. The report should be incorporated as a working reference to the present project. Key findings from the study include:
  - Using brackish groundwater for source or byproduct blending was not feasible due to lack of available brackish groundwater with appropriate levels of total dissolved solids;
  - Solar and wind power were found to be potentially feasible options for powering a desalination plant but not as reliable or cost competitive with grid conventional power;
  - The final recommendation for the Barney Davis Plant co-location was to use the exiting intake by co-locating with the Barney Davis Power Plant;
  - The highest ranked pretreatment option was dissolved air flotation followed by clarification and granular media filtration.

- There are valuable lessons to be considered from the Brownsville seawater pilot plant study captured in the TWDB report by Reiss Engineering “Lessons Learned from the Brownsville Pilot Plant Study.” Some of the key findings include:
  - Roles and responsibilities during a pilot study should be clearly defined in a pilot study protocol and be understood by the team prior the pilot unit start-up.
  - Enclosing equipment to protect against corrosive conditions is highly advisable;
  - Sampling of raw water quality can be used to screen sites in advance of pilot testing at a low cost;
  - Conventional filtration systems can provide the benefit of lower capital costs but are typically reserved for high quality, low sediment source waters. Microfiltration and ultrafiltration systems typically provide very high quality filtrate but at a higher cost;
The ability of a reverse osmosis system to meet cleaning frequency targets as well as restoring performance following a chemical cleaning is of critical importance.

- Taunton River and Thames Water Works are examples of systems drawing raw water from highly variable salinity sources. In both cases, the strategy to address the varying salinity of the source is the use of source water storage as a means of normalizing the source to a target feed water salinity.

4.0 BRACKISH GROUNDWATER DESALINATION

Groundwater with salinity concentrations between 1,000 mg/L and approximately 10,000 mg/L is generally categorized as a brackish supply. It is estimated that Texas has 2.7 billion acre-feet of groundwater with salinity concentrations in that range [17]. As drought conditions and water resources become more critical issues for the state, brackish groundwater has been increasingly developed as a raw water supply for drinking water.

4.1 CORPUS CHRISTI GROUNDWATER

The City commissioned a groundwater study of the brackish groundwater resources contained in the Gulf Coast Aquifer System [35]. In the Corpus Christi vicinity, the Gulf Coast Aquifer System is more than a mile thick and contains significant quantities of groundwater at depths of less than 1,000 feet.

The groundwater consultant prepared the study and report utilizing geophysical logs, resistivity logs, and spontaneous potential logs as well as countless available data sources with historical well and groundwater data. Based on the geophysical logs, a process was developed to estimate the total dissolved solids concentration of groundwater in a specific location. This process involves approximation of resistivity values for groundwater based on information in the database and converting that to an estimate of salinity. While this tool does provide a convenient and cost effective method for estimating salinity in groundwater without drilling new wells, it has a relatively significant margin of error and is based on data which is impacted by variations in:

- Aquifer porosity
- Cementation (type and degree)
- Makeup of the formation (rock, sand, clay)
- Temperature gradient and stratification
- Ionic chemistry of the groundwater
The results of the groundwater study for the City indicate the availability of well field locations capable of producing between 700 and 20,000 acre-feet-per-year (0.62 to 17.8 million gallons per day) of brackish groundwater. Several potential well fields identified in the study are estimated to have total dissolved solids concentrations less than 3,000 mg/L, which is less than 1/10th the concentration found in seawater. Figure 3 depicts total dissolved solids concentrations from Texas Water Development Board well water quality data in the Corpus Christi area.

Subsidence—the gradual caving in or sinking of an area of land—is an issue that may impact groundwater availability. A report by the U.S. Geological Survey (USGS) entitled “Hydrogeology and Simulation of Groundwater Flow and Land-Surface Subsidence in the Northern Part of the Gulf Coast Aquifer System, Texas, 1891–2009”, identified as “Scientific Investigations Report 2012–5154, Version 1.1, December 2013” addresses subsidence issues related to the withdrawal of groundwater from the Gulf Coast aquifer system, consisting of the Chicot, Evangeline and Jasper aquifers. The conclusion of the report is:
“Therefore, the dewatering caused by the depressurization of the clay layers combined with clay-grain realignment reduces the porosity and groundwater-storage capacity of the clay layers, which in turn allows them to inelastically and permanently compact.” In other words, the withdrawal of groundwater from the inter-bedded clay formations in the Gulf Coast aquifer system is the precipitating factor for land surface subsidence. The subsidence modeled in the USGS report, mentioned previously, is primarily for Harris and Montgomery Counties and may not be useful for the Corpus Christi area. The Phase I groundwater report by INTERA did not model or estimate subsidence.

Since it is the dewatering process that causes the consolidation (compaction), it may not matter whether the groundwater withdrawn is fresh or brackish. Based on this, the excessive withdrawal of groundwater from the Gulf Coast aquifer system, including the withdrawal of brackish groundwater, may raise subsidence concerns.

4.2 **TWDB BRACKISH GROUNDWATER CHARACTERIZATION DATABASE**

A common challenge to developing brackish groundwater desalination is the lack of information on brackish aquifers. A 2003 TWDB study laid the foundation for estimating brackish groundwater volumes in Texas [17]. However, TWDB notes that “the study was by design regional in scope, limited in areal extent, and narrow in its assessment of groundwater quality” [36].

The TWDB has compiled the most extensive library of groundwater information in the state. It is estimated that the TWDB Groundwater Database contains information on 10-20 percent of all active wells in Texas [35]. Some of the wells with information logged in the database are monitoring wells used by the TWDB to track water quality and level in aquifers across the state. These data logs include water level, water quality, and information on well construction and other geological highlights.

The database of groundwater information also contains significant information pertaining specifically to brackish groundwater resources. The management of this portion of the database is delegated to the Brackish Resource Aquifer Characterization System (BRACS). The BRACS program is intended to map and characterize the brackish groundwater resources in Texas and help assess the viability of brackish groundwater aquifers for use as groundwater supplies for desalination initiatives.

Information pertinent to Region N and Corpus Christi, including aquifer production and estimated costs is summarized below [17].
4.2.1 Region N – Coastal Bend Aquifers

1. Major:
   a. Carrizo-Wilcox (3,641 wells)
      1) Availability – Low
      2) Productivity – Moderate
      3) Cost of Water Production - High
   b. Gulf Coast (6,973 wells)
      1) Availability – Moderate
      2) Productivity – Moderate to High
      3) Cost of Water Production – Low
      4) Subsidence is a primary concern of developing brackish groundwater resources from this aquifer.

2. Minor and Other:
   a. Yegua-Jackson (706 wells)
      1) Availability – Low
      2) Productivity – Low
      3) Cost of Water Production – Moderate to High

4.2.2 Costs

In 2013 TWDB staff posted a review of six Texas brackish groundwater desalination plants completed in the last decade and arrived at the following conclusions [37]:

- Capital cost ranged from $2.03 to $3.91 per gallon of installed capacity;
- Operation and maintenance costs range from $0.53 to $1.16 per 1,000 gallons of water produced;
- Power rates ranged from 5.9 to 8.35 cents per kilo-Watt per hour; and
- Total life cycle production cost of water ranges from $1.09 to $2.40 per thousand gallons or $357 to $782 per acre-foot.

Figure 4 summarizes these results.
4.3 NATIONAL GROUND WATER ASSOCIATION

The National Ground Water Association published an Information Brief regarding Brackish Groundwater Desalination efforts and findings in the United States. The concise document contains several valuable facts which are summarized below.

- Desalination supplies less than 1 percent of potable water in the United States but grew about 40 percent from 2000 to 2005.
- The Underground Injection Control program was established to manage disposal and reuse of concentrates and brines resulting from the desalination of brackish groundwater and oilfield-produced water.
- The average lifecycle cost for treating 1,000 gallons of brackish groundwater in the United States is $2.00
4.4 BRACKISH GROUNDWATER DESALINATION – KEY FINDINGS

- The results of the groundwater study for the City indicate the availability of well field locations which are capable of production between 700 and 20,000 acre-feet-per-year of brackish groundwater. Several potential well fields identified in the study are estimated to have total dissolved solids concentrations of less than 3,000 milligrams per liter;
- A thorough characterization of the brackish groundwater aquifer is of foundational importance to predicting the availability of brackish groundwater;
- Subsidence potential needs to be part of the assessment of brackish groundwater availability.

5.0 VARIABLE SALINITY DESALINATION

Variable Salinity Desalination (VSD) refers to a desalination process which is optimized to treat a wider range of source waters with different salinity concentrations [37]. The goal of VSD is to preferentially treat lower salinity sources (more economic) while available and shift to seawater when needed (more expensive). Ideally, a VSD system would be capable of treating both brackish and seawater, or a strategic blend of the two sources. From 2009 to 2013 Reclamation and others\(^\text{12}\) engaged in a review of variable salinity desalination and its potential applications in Texas. The objective of these efforts was to test the concept of adaptable treatment systems for variable source water through a design study and subsequent pilot test of an adaptable design configuration. The results of this test were published by Reclamation in 2014 as Report #176 and is available through Reclamation’s Desalination and Water Purification Research Publications.

Many water sources are problematic for potable water supply as they vary in quality over time, such as in tidal reaches on coastal rivers. In other situations, water needs to be treated intermittently from a variety of sources. Either water from several sources is brought to a common treatment location, or equipment is moved to the source of contaminated water such as in the case of centralized produced water treatment and small scale industrial waste treatment.

\(^{12}\) Reclamation, Southmost Regional Water Authority, Laguna Madre Water District, NorrisLeal Engineers, Singapore Public Utilities Board and Texas Water Development Board.
Over a period of years, communities that use groundwater may find the salinity increase due to seawater intrusion or declining aquifer levels. In any of these scenarios, the treatment process and equipment need to be adaptable to a wider range of source water qualities.

Potential adaptations are to increase or decrease recovery, operating pressure, flows, and chemical doses, or to design systems to be easily re-configured to adapt to changing conditions. This study was intended to explore and test the potential for membrane systems to be adapted to a wide range of water quality.

The objective of the Variable Salinity Source Desalination project described in Report #176 was to test the concept of adaptable treatment systems for variable source water through a design study and subsequent pilot test of an adaptable design configuration. The first phase of the project evaluated design concepts using a manufacturer’s design program with mildly scaling brackish water for the lower concentration feed water and standard seawater for the high concentration feed water. These water types were used to simulate possible applications in which a somewhat challenging groundwater would be used for part of the year and seawater would be used for the balance of the year. Typically, the brackish water would be desalted in a two-stage system (reject brine from a first stage is fed to a second stage to extract additional permeate) and the seawater would be treated in a single-stage system, see Figure 5. The basis for evaluation of designs was the recommendations of the membrane manufacturer as incorporated into their design program. Flow diagrams of apparatus that could be converted with reasonable simplicity from one mode of operation to the other were generated.

![Figure 5 - Stages of a Reverse Osmosis Desalination Process](image)
Reclamation modified its Expeditionary Unit Water Purifier (EUWP) to conduct the testing. The EUWP was originally designed to meet purified water needs in areas with challenging water sources with high total dissolved solids, turbidity, and/or hazardous contamination during emergency situations when other water treatment facilities are incapacitated or non-existent. The EUWP is a compact, portable water purification system developed for serving many people during long deployments and disaster response. The system is designed to produce 100,000 gallons per day and be transportable in a C-130 aircraft. To ensure removal of nuclear, biological, and chemical contaminants to a safe limit, the system has an optional second permeate pass which was not used for this evaluation. Maximum hydraulic recovery for brackish water is 65 percent. Key innovations applied in the EUWP are:

- High flux ultrafiltration membrane cartridges
- Innovative staging of reverse osmosis membrane modules
- Small system energy recovery to pressurize a parallel array without a booster pump

Reclamation staff modified and operated the EUWP for six weeks in 2013 at the Southmost Regional Water Authority (SMRWA) Regional Desalination Plant in Brownsville, Texas, on brackish groundwater at 75 percent recovery without energy recovery. Then the system was moved to a site on South Padre Island for testing on Gulf seawater at 50 percent water recovery with the energy recovery device back in service. However, as drainage at the site was inadequate, testing could not be carried out for the purposes of this study. Instead, performance of the pilot system at the SMRWA Plant is compared to its performance while treating water from the Mississippi Delta, brackish wastewater, and brackish groundwater, all using the original system design as well as to the performance of the SMRWA Plant.

The design study revealed that a wider range of product flow and feed pressure are available. A design was proposed for a flexible brackish water system that can be adapted to treat seawater. Alternatively a
seawater system, such as the single stage EUWP seawater system, can be adapted to operate as a two stage brackish water system. The projections indicate that flexible designs are feasible in a variety of ways.

The pilot testing portion of the project revealed that the performance of the system in its modified configuration at 75 percent recovery compared favorably with performance in its original configuration treating brackish water at 50 - 60 percent recovery. In summary, key results were:

- Conversion to two stage system. An adaptor made to bypass the energy recovery device worked well with minimal pressure drop between stages
- Power requirements. As the high-pressure pump is the only energy draw for the reverse osmosis system, there was no significant change in power usage. Total power consumption was 7.4 kilowatts per thousand gallons (kW/kgal) of permeate which is comparable to power consumption for similar average bulk concentration feed water for the same equipment.
- Product water quality. Product water total dissolved solids concentration was lower than would be expected with brackish water membrane. Total permeate average dissolved solids concentration for stages 1 and 2 were 27.5 and 42.5 milligrams per liter, respectively, compared to approximately 120 milligrams per liter for 75 percent recovery with brackish water membrane.
- Operational issues switching configuration. There was some difficulty in switching the bypass piping back to the energy recovery device connections. The titanium high pressure lines had shifted during transport in the bypass configuration. However, a permanent valve to re-direct flow would not present this problem.

5.1 VARIABLE SALINITY DESALINATION – KEY FINDINGS

- Flexible systems for desalination of variable sources are feasible. There are many ways to convert a seawater system to a brackish water system or vice versa as long as the materials are compatible with the most corrosive water source;
- Power requirements are related to the incoming salinity and water recovery. Energy recovery devices are essential for maintaining efficiency when treating seawater or highly brackish sources;
- Industrial applications with variable feed sources can obviously take advantage of flexible treatment systems for treating and recycling their own wastewater without requiring additional permitting;
- Drinking water utilities have a more difficult challenge. Though regulations vary by state, often new approval is needed whenever the water source is changed. Planning for eventual alternative sources would make the approval process more straightforward. The process can be evaluated in the different configurations on alternative sources during the initial approval process;
- Source water characterization is a critical step for implementing a variable salinity desalination approach.
6.0 DESALINATION TECHNOLOGY ISSUES

The purpose of this section is to provide a brief refresher of key desalination concepts and technologies that may be relevant to the present project.

6.1 SOURCE WATER QUALITY

Desalination is the process of removing salts from water to produce fresh water [1]. The more dissolved solids in the water the saltier it is. The salinity of water is commonly measured in parts per million or milligrams per liter. Depending on the level of dissolved solids saline water may be classified as follows:

<table>
<thead>
<tr>
<th>Type</th>
<th>Total Dissolved Solids (milligrams/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh</td>
<td>&lt; 1,000</td>
</tr>
<tr>
<td>Brackish</td>
<td></td>
</tr>
<tr>
<td>Mildly Brackish</td>
<td>1,000 to 5,000</td>
</tr>
<tr>
<td>Moderately Brackish</td>
<td>5,000 to 15,000</td>
</tr>
<tr>
<td>Heavily Brackish</td>
<td>15,000 to 35,000</td>
</tr>
<tr>
<td>Seawater</td>
<td>~35,000 &gt;</td>
</tr>
</tbody>
</table>

In addition to salinity, an important water quality distinction for water desalination purposes is the source of the water. Thus, saline water in the 1,000 to 10,000 milligrams/liter range is referred to as brackish water and it may be further defined as brackish groundwater or surface brackish water. Source water drawn from the ocean is referred to as seawater and its salinity is typically reported in the vicinity of 35,000 milligrams/liter with wide variations depending on the location and season. While brackish groundwater may require a minimum degree of conditioning and cartridge filtering to capture formation sand, surface brackish and seawater sources typically require full surface water treatment prior to the desalination process.

Knowing what constituents are in the source water is important to desalination processes. Specifically, designers need information about the occurrence of constituents that may result in deposition of chemical and organic matter on the reverse osmosis membranes, a phenomenon referred to as fouling in the literature. Types of fouling mechanisms include scaling, colloidal fouling, bio-fouling and organic fouling. To control and reduce the extent of membrane fouling much can be done in the area of pretreatment
upstream of the reverse osmosis membrane in providing better quality feed water [38]. The next section of the report discusses pretreatment.

Source water quality characterization is a foundational step in the planning and design of desalination facilities. In the case of seawater desalination projects, the characterization effort spans over several months of data collection to capture diurnal and seasonal variations in the source water. For brackish groundwater projects, the source water quality studies often include modeling to project source water quality changes in response to increased extraction from the aquifer. Table 5 below lists typical water quality parameters to include in pretreatment water characterization studies.

<table>
<thead>
<tr>
<th>Source Seawater Quality Parameter</th>
<th>Pretreatment Issues and Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity (NTU)</td>
<td>Levels above 0.1 NTU are indicative of high potential for fouling. Spikes above 50 NTU for more than 1 hour would require sedimentation or DAF treatment prior to filtration.</td>
</tr>
<tr>
<td>Total Organic Carbon (mg/l)</td>
<td>If below 0.5 mg/l – biofouling is unlikely. Above 2 mg/l – biofouling is very likely.</td>
</tr>
<tr>
<td>Silt Density Index (SDI)</td>
<td>Source seawater with SDI levels consistently below 2 year-around indicate no pretreatment is needed. SDI &gt;4 pretreatment is necessary.</td>
</tr>
<tr>
<td>Total Suspended Solids (mg/l)</td>
<td>This parameter is needed to assess the amount of residuals generated during pretreatment. Does not correlate well with turbidity beyond 5 NTU.</td>
</tr>
<tr>
<td>Iron (mg/l)</td>
<td>If iron is in reduced form (ferrous- Fe +3 or ferric – Fe + 2), seawater reverse osmosis membranes can tolerate up to 2 mg/l. If iron is in oxidized form (Fe (OH)3), concentration &gt; 0.05 mg/l would cause accelerated fouling.</td>
</tr>
<tr>
<td>Manganese (mg/l)</td>
<td>If manganese is in the reduced form (Mn+2), seawater reverse osmosis membranes can tolerate up to 0.1 mg/l. If manganese is in the oxidized form (MnOH), concentration &gt;0.02 mg/l would cause accelerated fouling.</td>
</tr>
<tr>
<td>Silica (mg/l)</td>
<td>Concentrations higher than 20 mg/l may cause accelerated fouling. Analyze for colloidal (unreactive) silica if concentration &gt; 20 mg/l.</td>
</tr>
<tr>
<td>Oil and Grease (mg/l)</td>
<td>Concentrations higher than 0.02 mg/l would cause accelerated fouling.</td>
</tr>
<tr>
<td>Chlorine (mg/l)</td>
<td>Concentrations higher than 0.01 mg/l would cause reverse osmosis membrane damage.</td>
</tr>
<tr>
<td>Temperature (ºC)</td>
<td>T ≤ 12 ºC would cause significant increase in unit energy use. T ≥ 35 ºC may cause accelerated mineral scaling and biofouling. T &gt; 45 ºC may cause irreversible reverse osmosis membrane damage.</td>
</tr>
<tr>
<td>pH (units)</td>
<td>Typical pH of seawater is 7.6 to 8.3. pH &lt; 4 and pH &gt; 11 may cause membrane damage.</td>
</tr>
</tbody>
</table>
Although a comprehensive discussion of source water characterization is beyond the scope of Technical Memorandum #1\textsuperscript{13}, it is important to discuss, albeit briefly, the issue of algal blooms. Algal blooms are not uncommon in the Texas Gulf Coast (see Error! Reference source not found.7) and reverse osmosis desalination facilities can be severely impacted by the presence of algal cells in feed water.

![Figure 7 – Red Tide Event in Corpus Christi Bay in 1986 (Photo courtesy of Dr. Wesley Tunnel, Harte Research Institute for Gulf of Mexico Studies at Texas A&M University – Corpus Christi)](image)

Recognizing the growing importance of this topic, the 2013 International Desalination Association’s Yearbook [39] included a discussion of algae blooms and desalination; following is a summary of this discussion. Algae are a common source of fouling matter. Harmful algal blooms (HAB) are challenging for reverse osmosis seawater desalination plants. HABs refer to fast-growing algal blooms that make toxic chemical byproducts that concentrate in the tissues of fish or shellfish. Animals and humans who eat shellfish may become sick or suffer severe respiratory problems including paralytic shellfish poisoning. Certain phytoplankton species contain reddish pigments; when they bloom, the water often appears to...

\textsuperscript{13} The following references provide a good primer on water quality issues: Desalting Handbook for Planners (2003), Bureau of Reclamation; Water Desalting Planning Guide for Water Utilities (2004), American Water Works Association; and, Desalination Engineering Planning and Design (2013), Nikolay Voutchkov.
be colored red, hence the term ‘red tide’. However, scientists prefer referring to the blooms as HABs and consider the term ‘red tide’ to be a misnomer as the phytoplankton species that are harmful may never reach the densities required to discolor the water and the events are not associated with tides. Although the number and severity of HABs are increasing, they remain highly unpredictable in terms of where and when they occur and their duration, intensity and impact on desalination plant operation. A survey of desalination experts conducted by the Water Desalination Report noted that although all of the experts contacted were aware of the potential impacts of an algal bloom on desalination plant operations, many did not have first-hand experience. Experts agreed that deeper intakes help minimize the risk of algal blooms. Also, a well-designed filtration system is a necessary component and dissolved air flotation is the preferred tool to deal with algal blooms. Microfiltration and ultrafiltration, a lower flux, and plant temporary shutdown are cited as useful strategies. Some believe the use of chlorophyll analyzers can offer earlier warning.

6.2 DESALINATION METHODS

Desalination methods are generally classified into thermal (distillation) processes and membrane desalination processes. Thermal desalination technologies are based on heating the source water to produce water vapor which generates fresh water through condensation. Thermal desalination is often integrated with power generation which may result in higher energy efficiency than achieved when electricity and desalting seawater are generated separately. Membrane-based desalination methods rely on semipermeable membranes to separate water from dissolved minerals. Seawater desalination by reverse osmosis is often the lowest cost method of desalting seawater in a stand-alone process, especially for lower salinity waters [41]. There are other methods such as ion exchange, freeze-thaw, membrane distillation, humidification/dehumidification, and processes using various sources of energy such as solar, wind, geothermal and wave energy. These processes generally are not sufficiently developed for large-scale implementation [42].

A variation in the use of thermal technologies is the use of hybrid systems. The hybrid desalting concept is the combination of two or more processes in order to provide better environmental solutions, lower energy consumption, and a lower water cost product than either alone can provide [43]. Awerbuch reports that “early suggestions for hybrid desalination were based upon elimination of the requirement for a second pass to the reverse osmosis process so that the higher-salinity reverse osmosis product could be combined with the better quality product from a multi-stage flash plant.” A new alternative combines
multi-stage flash with reverse osmosis and a power generation process; this may provide for higher system recoveries, smaller seawater intakes, greater flexibility in meeting product water quality, including Boron, by blending permeate streams and using a single pass reverse osmosis.

Another hybrid scheme that has gained attention because of its great potential is pairing forward osmosis with reverse osmosis. In 2011 the TWDB studied the potential use of high salinity reverse osmosis concentrate as a draw solution in a forward osmosis process to remove water from wastewater or other impaired water for volume minimization. The study included cost modeling, which indicated that the use of forward osmosis-reverse osmosis was not cost competitive when compared to tertiary treatment of wastewater using an advanced treatment process including membrane filtration followed by reverse osmosis and ultraviolet disinfection. The study projected that development of commercial forward osmosis membranes designed for forward osmosis-reverse osmosis systems may improve the economics of this particular approach [44].

Although there are multiple proven and emerging desalination methods from which to choose, the technology of choice for municipal, stand-alone applications is reverse osmosis. A recent detailed survey of 30 seawater desalination facilities worldwide funded by the Water Research Foundation concluded [45]: “Although thermal desalination is the oldest technology, desalination of seawater using reverse osmosis process has begun to take hold since its invention four decades ago and has dominated the market as the preferred technology during the last two decades.” The International Desalination Association reports contracted desalination capacity has now reached 21.1 billion gallons per day. Sixty-three percent of all installed capacity is membrane based. Figure 8 provides a breakdown of the global desalination capacity in 2013 by desalination method [39].
The scope of the present City of Corpus Christi desalination effort—and the subject of Reclamation’s award to the City—is based on a variable salinity reverse osmosis desalination concept. Variable salinity desalination is a relatively recent development and it targets situations where sources may experience a wide range of water salinity variation. In the case of Texas, consideration of desalination in estuary-influenced coastal areas is a prime example of a situation where a desalination facility designed to span a broad range of salinities would be applicable. Interest in exploring this potential in Texas motivated TWDB and Reclamation to examine variable salinity applications in Texas, see Section 5, Variable Salinity Desalination, for additional information. As part of the Corpus Christi Variable Salinity Desalination project Reclamation is providing funding and active technical assistance. The project will further the knowledge on variable salinity desalination and will help the City in its pursuit of cost-effective desalination water supplies.

6.3 SEAWATER INTAKES

Seawater intakes are the first step in the water desalination production process. As the first step in the pretreatment process, the intake will affect a range of feed water quality parameters and determine the performance of downstream process systems [47]. A desalination project intake is designed to provide a
A seawater desalination plant with the best possible source water quality and in the desired quantities. For a brackish groundwater desalination project, the intake takes the form of a well-field. For seawater desalination projects, the choices are more ample and commonly classified as open intakes or subsurface intakes.

Intake strategies are case-specific and merit the most careful consideration. Referring to open intakes but arguably applicable to the intake selection in general, Missimer et al. note “The design, modeling, ecological investigations, and general permitting activities that are required can represent between 5 and 50 percent of the capital cost of the entire [seawater plant] facility. It is possible that intake-related issues and costs may determine the overall feasibility and performance of the membrane plant itself” [48].

An issue that dominates the intake selection process is the need to minimize environmental impacts. Key issues are impingement and entrainment. Impingement and entrainment are a subject to federal regulation by USEPA Clean Water Act, Section 316 b concerning cooling water intakes [49] which sets a standard for seawater desalination intakes. The US Fish and Wildlife Services and the National Marine Services define impingement and entrainments as follows: “Impingement is the entrapment of any life stages of fish and shellfish on the outer part of an intake structure or against a screening device during periods of intake water withdrawal. Entrainment is defined as any life stages of fish and shellfish in the intake water flow entering and passing through a cooling water intake structure and into a cooling water system, including the condenser or heat exchanger” [50].

Although capacity is a concern regarding subsurface intakes, these types of intakes are advantageous in addressing impingement and entrainment issues and providing a generally constant quality of source water. The State of California, through the State Water Resources Control Board is currently advancing an amendment to the Ocean Plan whereby subsurface intakes are required unless it is determined infeasible based on an analysis of approved criteria [52]. Some economic analysis indicate that Economic analyses have shown that although capital cost of subsurface intakes are higher, operating costs of a seawater desalination facility can be reduced by 5 to 30 percent by using subsurface intake systems [51].

Since the completion of the 2004 Corpus Christi Seawater Desalination Feasibility Study, which considered multiple intake options, including subsurface alternatives, there have been important developments that merit consideration for the current project. One is the completion of the Dana Point Slanted Well investigation and the other is regarding piloting research of a constructed subsurface drain system by Long Beach Water Department.
Slant well technology was the subject of a 2009 Reclamation study project at Dana Point, California [52]. To remove the problem of impingement and entrainment from the seawater intake design, and as a way to include pretreatment with the intake process, a slant well was demonstrated at Dana Point. The project required a site-specific feasibility investigation, including a geophysical survey, geotechnical borings, a test well and monitoring wells, and an aquifer pumping test. The test slant well was constructed using the dual rotary method. The well was 350 feet long and 12 ¾ inches in diameter and was drilled at an angle of 23 degrees below horizontal from the beach out into the sea through the ocean floor. The well cost around $1.1 million and produced 13 acre-feet per year with a specific capacity of 77 gallon per feet per minute over a 5 day constant rate pumping test. Silt density index measurements averaged 0.58, salinity was only 2,600 milligrams per liter since fresh water infiltrates through the ground in the area of the well from the San Juan Creek. Other benefits of a slant well are that there is neither ocean construction nor visual impacts to the beach area.

Texas, the Laguna Madre Water District South Padre Island Seawater Desalination project considered a slant well alternative to an open intake for its pilot plant study [23]. However, the hydrogeology of the area was considered unfavorable and the District opted for an open sea intake.

Long Beach Water Department has been operating a 0.3 million gallons per day demonstration project since 2007 and added an under-ocean floor intake and discharge system in 2008. The system operates like a slow sand filter, employing slotted PVC collection screens buried beneath a minimum cover of five feet of sand. As of early 2011, the project was testing a 3,000 ft² intake bed located approximately 200 feet offshore at infiltration rates from 0.05 to 0.15 gpm/ft² and a discharge rate up to 0.20 gpm/ft². At that time, the project manager reported that the system was producing water as expected, and observed no growth of organisms observed in the visual wet well following the filters. Impingement and entrainment was minimized; there were no clogging issues, as defined by a decrease in water production after adjusting for seasonal temperatures. The California Coastal Commission granted an extension to continue testing until 2017 [53, 54].

Open seawater intakes, in co-location with existing power generation facilities using once-through cooling have been an attractive option and are in use in the two largest seawater desalination plants in the US. Some of the advantages for this approach include the ability to rely on the power plant intake to supply the feed water for the seawater desalination plant; if the feed water is drawn from the cooling plant effluent, the higher temperature of the discharge can result in an increased efficiency in the reverse
osmosis process; last, the option of commingling the concentrate discharge with the power plant effluent allows for an immediate diffusion of the concentrate. The Tampa Bay Water Seawater Desalination Plant and Carlsbad, California desalination project illustrate this desirable feature of a large-scale seawater desalination project: the ability to use an existing power facility’s intake to furnish raw water and also dilute the desalination plant’s concentrate by combining and discharging with the effluent from the power plant. The US EPA rules regulating impingement and entrainment may limit these types of colocation opportunities in the future.

A primer on seawater intakes (and a reference to this section) is available through the Texas Water Development Board Web Site, under the 2004 Biennial Report on Seawater Desalination, Volume II, Technical Papers, An Overview of Seawater Intake Facilities for Seawater Desalination Projects by Tom Pankratz.

### 6.4 PRETREATMENT

Pre-treatment systems are designed to condition the water to minimize the potential for membrane fouling and ensuring an efficient operation. There are two broad categories of pretreatment systems: conventional granular media filtration and membrane filtration. Both granular media and membrane filtration pretreatment technologies may offer advantages or face challenges depending on the source seawater quality and origin. Therefore, selecting the most suitable pretreatment technology for a project should be based on a comprehensive performance and life cycle cost analysis, and when possible, side-by-side pilot testing. Pilot testing should target time frame encompassing events that could create pretreatment challenges such as algal blooms, intake area dredging, heavy ship traffic, rainfall season, etc. [55].

Although conventional granular media pretreatment has been widely used for seawater and brackish water reverse osmosis plants, variations in feed water can limit the effectiveness of conventional pretreatment. Conventional granular media filtration processes involve coagulation, flocculation and pH adjustment) followed by conventional granular media (anthracite and sand) filtration. Often, colloids and suspended particles pass through conventional pretreatment and contribute to reverse osmosis membrane fouling [56]. Use of microfiltration and ultrafiltration membrane technologies for desalination pretreatment is relatively recent but the results are very promising. Industry estimates indicate that half of new reverse osmosis installations are featuring microfiltration or ultrafiltration pre-treatment [57]. Ultrafiltration membranes have found wider application for seawater pretreatment mainly because they
usually provide better removal of suspended organics, silt and pathogens from the source seawater; additionally, membrane pretreatment with ferric chloride coagulation is also able to remove dissolved organics and marine microorganisms, which typically cause membrane fouling\textsuperscript{14}.

Depending on the type of intake, the first component of the pretreatment system consists of coarse screens followed by finer screens to remove large debris, first, and smaller particles second. In some high turbidity cases, sedimentation tanks may be used. In other cases, the use of dissolved air flotation in combination with either media or membrane filtration, is an effective tool to remove floating particulate foulants such as algal cell, oil, grease, and other light solid contaminants that cannot be effectively removed by sedimentation or filtration [58]. A recent survey of pretreatment practices in seawater desalination [42] found that the pretreatment used in seawater facilities varied considerably. Facilities using subsurface intakes showed minimal pretreatment; other facilities used direct single stage media filtration, direct two-stage media filtration, use of various clarification processes (dissolved air flotation or lamella clarifiers), and microfiltration. Several facilities had to modify the original pretreatment systems because of their inadequacy to provide reverse osmosis feed water of sufficient water quality, or because of changes in raw water quality that were not anticipated during design (such as algal blooms).

There have been three seawater pilot plant studies performed in Texas in recent times.\textsuperscript{15} Following is a brief discussion of the pretreatment options considered by each one of these projects.

6.4.1 San Patricio Municipal Water District

Around 2001, Reclamation funded a research project to evaluate the performance of membrane pretreatment versus conventional pretreatment for seawater reverse osmosis desalination, in terms of improved pretreated water quality and impact on reverse osmosis performance; and to determine life-cycle cost benefits of membrane pretreatment compared to conventional granular media pretreatment. The pretreatment units tested included Zenon Zeeweed 1000 ultrafiltration, Norit ultrafiltration, Hydranautics Hydracap ultrafiltration, Memcor CMF microfiltration, Pall microfiltration and, conventional granular media pretreatment consisting of coagulant addition and multi-media filtration (sand, anthracite and garnet) [61, 62].

\textsuperscript{14} Personal communication with Larry VandeVenter (Jorge Arroyo, 7/24/14)

\textsuperscript{15} Previous seawater desalination efforts in Texas include the 1961 seawater desalination plant in Freeport, often cited as the first seawater desalination production facility in the United States; and, around the same time, a facility operated at Port of Mansfield.
The pilot facility was operated from April 2002 to June 2003. The results from the study indicate the following:

- Membrane filtration produced much clearer water than conventional filtration
- The conventional granular media pretreatment pilot resulted in a 6-week cleaning frequency, at a flux of approximately 12.5 gallons per foot$^2$ per day; the membrane filtration pretreatment reverse osmosis unit did not require cleaning during the piloting;
- One of the more important findings from the pilot study is the caution that must be practiced in using membrane filtration for reverse osmosis pretreatment when chlorinated backwashes are utilized in the filters as remnants of chlorine could become in contact with the reverse osmosis membranes and damage them;
- The cost evaluation indicated that the operating costs for desalination facilities using membrane filtration was consistently less than the operating cost for facilities using media filtration as pretreatment.

6.4.2 Brownsville Ship Channel

The Brownsville Seawater Desalination Pilot Plant Study [64] utilized an open intake on the Brownsville Ship Channel. Although the site had several advantages such as power supply, cost, security, and access considerations, the source water quality was poor. The location of the intake was impacted by ship traffic which stirred up sediments and cause dramatic spikes on turbidity. An alternative site was located in Boca Chica which provided access to better quality water but lacked access to utility services and was far from the Brownsville distribution system. Thus, for Brownsville, the ship channel site represented a worst-case source water quality-testing scenario.

![Figure 9 – Brownsville Ship Channel Intake (Photo copied from [64])](image-url)
The pilot facilities included a packaged dual media filtration (Eimco) and several membrane-based systems: GE Zenon Ultrafiltration, Norit Ultrafiltration, and Pall Microfiltration. Only Pall microfiltration successfully completed the pilot study.

**Figure 20 – Pilot Plant Facility Layout (Copied from [64])**

### 6.4.3 South Padre Island

The South Padre Island Pilot Plant Study by the Laguna Madre Water District [23] used an open ocean intake, granular media filters and a Pall microfiltration system. The report recommended a membrane pretreatment system for the proposed full-scale facility including upstream pre-screening provided by an Arkal Spin Klin Disc Filter. DOW FilmTec was recommended as the primary reverse osmosis membrane.
6.5 ENERGY MANAGEMENT

More than 33% of the cost to produce water using reverse osmosis technology is attributed to the electric power requirements [61] and most of that energy consumption can be attributed to the high pressure pumps, as illustrated in Figure 31. An important design goal of reverse osmosis systems is to minimize energy consumption. Energy saving strategies focus on use of high efficiency pumping, energy recovery devices, use of advanced membrane materials, application of new technologies, and renewable energy utilization.

An example of energy use optimization has been provided by the Affordable Desalination Collaboration (ADC). ADC tested and demonstrated state of the art isobaric energy recovery technology for seawater application at the Port Hueneme Naval Base, California and demonstrated an optimized reverse osmosis process achieving specific energy consumption of 11.28 kW-Hr/1,000 gal [62]. The TWDB awarded funding to ADC to develop and test an optimized brackish water reverse osmosis design. The project achieved a 14 percent energy savings compared to a similar system but without energy recovery, and 24 percent compared to a traditional design without energy recovery or inter-stage boost [63].

![Figure 11 – Schematic Test Model for Optimized Brackish Water Reverse Osmosis System Design (Source: TWDB-Affordable Desalination Collaboration, Contract Number 0804830845)](image-url)
Energy recovery systems are a key component of energy management strategies in large-scale facilities. There are two general types of energy recovery devices commonly used in reverse osmosis desalination processes: centrifugal devices and positive displacement devices. Centrifugal devices include reverse running pumps, Pelton impulse turbines, hydraulic turbochargers, and hydraulic pressure boosters. Positive displacement devices include pressure exchangers and dual work exchangers.

Another energy management tool focuses on the use of pump centers to service multiple reverse osmosis desalination trains (the default case being sizing pumps on per train basis). This particular approach is exemplified in the Ashkelon Desalination Plant in Israel. Dr. Boris Liberman examined this concept in a paper included in the 2004 TWDB collection of technical papers on desalination [64].

The previously referenced Water Research Foundation report encountered that all studied facilities employed energy recovery strategies. Most commonly, facilities used turbochargers or Pelton turbines. Facilities built in the last five years used positive displacement devices which result in lower specific energy consumption.

### 6.6 CONCENTRATE MANAGEMENT

The dissolved solids that are rejected in a desalination process are carried out of the system as high concentration brines. The literature refers to these brines as concentrate. Concentrate management is one of the more critical issues for large-scale seawater desalination projects [65]. Although the salinity contained in concentrate discharges from seawater desalination plants is a more concentrated version of
the original source, the disposal streams from seawater desalination plants are classified as industrial wastewater. Missimer and Pankratz [66] note that “this classification causes the disposal of concentrate to be more heavily scrutinized than domestic wastewater and limits disposal options.....Despite the rather large body of research conducted on the marine discharge of concentrate, the permitting process is still long and arduous and commonly results in protracted legal challenges (e.g., Tampa Bay Water).” The more recent Carlsbad project further corroborates this assertion. For its part, the State of Texas has rules in place to regulate the disposal of concentrate; these rules are discussed in Section 7 of this technical memorandum.

The disposal method of choice for large-scale seawater desalination facilities is surface water disposal. For inland facilities the choices are more varied. Figure 13 summarizes the different methods currently in use and their frequency of their use from a survey of 234 inland desalination facilities in the United States [67]. Figure 14 illustrate the types of concentrate methods in use in Texas as of 2004 [26].

Below is a brief explanation of the different methods summarized from Reclamation’s Desalination and Water Purification Research Program, Report # 155.
6.6.1 Surface water discharge

This is the most common concentrate management practice, primarily because this method frequently has the lowest cost and most plants are located relatively near surface water. The primary environmental concern is compatibility of the concentrate with the receiving water. Dissolved gases and lack of oxygen can also be concerns for concentrate disposal. If the groundwater contains hydrogen sulfide, hydrogen sulfide in the concentrate must be suitably reduced before its discharge to prevent negative effects.

At a meeting with TCEQ, in May 2013, the City was informed that discharge of brine concentrate into Nueces Bay is unlikely to be permitted. The Nueces Bay Power Center discharge has used the assimilated water quality capacity of the Bay. The limiting parameter for this capacity was zinc.

6.6.2 Sewer

Sanitary sewer discharge of a small volume of concentrate usually represents a low cost disposal method with limited permitting requirements. The adequacy of sewer capacity and wastewater treatment plant capacity must be addressed. In addition, wastewater effluent quality will change but must still comply with the wastewater treatment plant’s discharge permit. If the concentrate salinity and flow levels are
significant, impacts of salinity on the biological efficiency of the wastewater plant should be considered. Discharge to sewer is used more often with smaller and medium sized plants than larger plants due to the effects of larger volume concentrate on the wastewater treatment plant system.

6.6.3 Land application

Land application can provide a beneficial reuse of water when membrane concentrates are applied to vegetation, such as irrigation of lawns, parks, or golf courses. Factors associated with land application include the water quality tolerance of target vegetation to salinity, the ability to meet ground water quality standards, the availability and cost of land, percolation rates, and irrigation needs. An assessment of the compatibility with target vegetation is conducted, including assessment of the sodium adsorption ratio, trace metals uptake, and other vegetative and percolation factors. Regulations governing ground water quality and protection of drinking water aquifers are investigated to confirm the acceptability of this alternative. The key cost factors of this disposal method are the costs of land, the storage and distribution system costs, costs of dilution water, and the irrigation system installation costs, which in turn are driven by the concentrate volume and salinity. Spray irrigation is used for very small systems due to limited economy of scale.

6.6.4 Deep well injection

Deep well injection is a disposal option in which liquid wastes are injected into porous subsurface rock formations. The aquifer/rock formation receiving the waste must possess the natural ability to contain and isolate it. Injection wells are classified into five different types:

- Class I wells, which are used for deep injection, are regulated by the TCEQ but the Texas Railroad Commission (RRC) reviews and comments on Class I applications;
- Class II wells, which are related to energy byproducts, are regulated by the RRC;
- Class III wells, which are used to extract minerals other than oil and gas, are regulated by the TCEQ or the RRC, depending on the type of well;
- Class IV wells are generally banned, but may be authorized by the TCEQ or the United States Environmental Protection Agency (USEPA) in certain environmental cleanup operations;
- Class V wells, which are used for many different activities, are regulated by either the TCEQ or the RRC, depending on the type of well.

Injection wells for disposal of concentrate are Class I or Class V.
Regulatory considerations for deep well injection or other subsurface injection alternatives include the transmissivity and total dissolved solids concentration of the receiving aquifer and the presence of a structurally isolating and confining layer between the receiving aquifer and any overlying Underground Source of Drinking Water. Deep wells are not feasible in areas subject to earthquakes or where faults are present that can provide a direct hydraulic connection between the receiving aquifer and an overlying potable aquifer. A tubing and packer design is commonly required to allow monitoring of well integrity. One or more small-bore monitoring wells in proximity to the disposal well are also typically required to confirm that vertical movement of fluid has not occurred. The capital cost for deep well injection is higher than surface water disposal, sewer disposal, and land application in cases where these alternative methods do not require long transmission pipelines. Disposal to deep wells is usually restricted to larger volume concentrates where economies of scale make the disposal option more affordable. Geologic characteristics are not appropriate for deep well injection in many areas of the United States. A backup means of disposal must be available for use during periodic maintenance and testing of the well.

Injection wells are commonly used by the oil and gas industry in Texas. The Kay Bailey Hutchison Brackish Groundwater Desalination Plant, El Paso, and the San Antonio Water System’s Brackish Groundwater Desalination Plant – under construction – rely on underground injection. In Corpus Christi, a feasibility study examining desalination in Padre Island [16] considered deep-well injection and concluded that it was a favorable option pending a more in-depth analysis including source water characteristics, concentrate composition, chemical compatibility and disposal pressures to be obtained through direct sampling.

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16 For reference purposes, the cost of the injection wells for the San Antonio project was reported at $9.4 million.
6.6.5 Evaporation pond

Solar evaporation is a viable alternative in relatively warm, dry climates with high evaporation rates, level terrain, and low land costs. Regulations typically require an impervious lining and monitoring wells, which will increase costs of evaporation ponds. With little economy of scale, evaporation ponds are usually used only for small volume concentrates. The sizing of an evaporation pond is a function of the evaporation rate. Location with high evaporation rates, low precipitation rates and inexpensive land are more favorable locations for these types of disposal methods. A TWDB study of evaporation ponds shows evaporation pond surface areas for a 1 million gallon per day desalination facility ranging from 70 to 175 acres [73]. A City feasibility study of desalination in Padre Island estimated area requirements of 1,300 acres for a 5 million gallon per day desalination facility [16].

6.6.6 Zero Liquid Discharge

Zero liquid discharge systems such as thermal evaporators, crystallizers and spray dryers are available to reduce concentrate to a solid product for landfill disposal. However, the cost for these thermal systems is typically much higher than the cost for the desalination membrane facility, both from a capital and operating (energy) perspective, making this disposal option infeasible except for very small concentrate flows.

6.6.7 Pilot Studies and Research

Most seawater desalination facilities, including the Tampa Bay Water and the Carlsbad plants, are able to discharge concentrate back to the sea where it is almost immediately diluted by the large volume of available water leaving marine life undisturbed [66]. The National Research Council [69] cites a study conducted to estimate the effects of the Tampa Bay Water Desalination Plant’s concentrate discharge by selecting a parallel site in Antigua. The study found no effect of salinity elevation on the tropical reef ecosystem.

In spite of the noted research, salinity impact of open ocean discharge is a common concern. For many years, there has been a concern about salinity levels in the local bays and estuaries, particularly Nueces Bay, Oso Bay and the Upper Laguna Madre. For example, Nueces Bay plays a role as a nursery area for gulf shrimp which is considered salinity sensitive; Oso Bay and the Upper Laguna Madre are considered salinity sensitive due to oyster production and fishing. Thus, open ocean discharge options will need to carefully consider these issues as part of the alternative site assessments.
6.6.8 Beneficial Use of Brine

There is a growing interest in exploring beneficial uses of concentrate. The review team included a recently completed study by the Water Reuse Foundation, entitled *Beneficial and Nontraditional Uses of Concentrate* [70]. The document provides an overview of desalination concentrate issues, location specific, regulatory economic, regional salt balance, major ion toxicity, and human and ecological risk factors. It examines traditional disposal methods for how they affect the same set of issues. Traditional modes are surface discharge, sewer discharge, deep well injection, evaporation, and rapid infiltration.

The report discusses beneficial innovative and nontraditional uses of concentrate and their implementation, regulatory, cost, human health and ecological risk factors and applicability to overall basin salt management. The processes considered are oil well field injection, solar ponds, land application and irrigation, zero liquid discharge, aquaculture, wetland creation and restoration, constructed wetlands treatment, along with some other minor uses (blending with storm or wastewater, recreation, transport of mineral resources, subsurface storage, sodium hypochlorite generation, cooling water, dust control & deicing. Salt separation methods are examined including efforts underway during the study, the market for salts, and an economic analysis. Table 6 provides a summary of major salts that could be extracted from desalination brines and their application.

<table>
<thead>
<tr>
<th>Salt Name</th>
<th>Some Application Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium Carbonate</td>
<td>Paper coating pigment; filler for plastics and rubbers, special inks, paints, and sealants</td>
</tr>
<tr>
<td>Gypsum</td>
<td>Remediation of sodic soils; manufacture of building products</td>
</tr>
<tr>
<td>Gypsum magnesium hydroxide</td>
<td>Wastewater treatment; pH buffering; soil conditioning for sodic soil</td>
</tr>
<tr>
<td>Calcium chloride</td>
<td>Dust suppression; road base stabilization; sodic soil remediation; cement and concrete stabilizer; construction industry</td>
</tr>
<tr>
<td>Glacerite</td>
<td>Potassium fertilizer</td>
</tr>
<tr>
<td>Magnesium hydroxide</td>
<td>Water and wastewater treatment; environmental; animal stock feed; feedstock for magnesium metal production; fire retardants and refractories; acid neutralization</td>
</tr>
<tr>
<td>Magnesium carbonate light</td>
<td>Fire retardant; feedstock for magnesium metal production; filler for paper manufacturing, rubber and paint</td>
</tr>
<tr>
<td>Caustic soda</td>
<td>Many industrial applications; basic feedstock for chemical processes, pH adjustment, etc.</td>
</tr>
<tr>
<td>Halite</td>
<td>Food and industrial processes; chloralkali production; many industries require bulk salt supply</td>
</tr>
<tr>
<td>Soda ash</td>
<td>Water treatment; chemical industry;</td>
</tr>
<tr>
<td>Salt Name</td>
<td>Some Application Areas</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Thenardite</td>
<td>Surfactant manufacture; detergent manufacture; glass manufacture; remediation of calcareous soil</td>
</tr>
<tr>
<td>Sodium hypochlorite</td>
<td>Disinfection; chemical industries; pool chlorine</td>
</tr>
<tr>
<td>Sodium chlorate</td>
<td>Paper bleaching; chemical industries</td>
</tr>
</tbody>
</table>

Two past studies have immediate relevance to the present Corpus Christi effort: The 2003 Padre Island Desalination Plant Feasibility Analysis and Siting Plan [16] and the 2004 Corpus Christi Seawater Desalination Feasibility Study [18].

The Padre Island Study opted for deep well injection to be co-sited with the reverse osmosis facility to control transmission costs. A vertical well in the Catahoula Aquifer could be sited at either the Padre Island Pump Station or at the NCWCID4 Pump Station. This option is available to the South Padre Island project given its relatively small production capacity of 1 million gallons per day. Similarly, a gulf outfall could be placed along the coast of the island, at a strategic location to control transmission costs. A transmission line from a reverse osmosis facility site located at the Padre Island Pump Station could run along the length of Packery Channel and meet with an outfall near the City-leased Texas General Land Office site.

Another issue pertaining to discharges is the matter or disposal of cleaning solutions such as low acid or caustic chemicals used to remove minerals and bio film fouling off the membranes. In the specific case of the Corpus Christi Variable Salinity Desalination Demonstration there will be two chemical cleaning groups. One group results from the enhanced flux maintenance (weekly) and chemical clean-in-place (monthly to every 90 days). The second group refers to the chemical clean-in-place of the (monthly to every 90 days). The caustic and acids are neutralized and are commonly discharged to sanitary sewer; in some cases, cleaning byproducts are stored and hauled off by a chemical disposal company; discharged with a permit; or disposed using lagoon evaporation on site.

6.6.9 Concentrate Management Conclusions

As expected there is no one perfect solution for concentrate management. However, it is clear that solutions must be developed locally, incorporating local resources, needs for water and recoverable products, and local regulations. If there is a local demand for a particular mineral in the concentrate, then salt separation might be a practical solution – if not, trucking expense may make it infeasible. If there is a
long term beneficial use for saline water in the neighborhood, then it would be wise to tailor the concentrate to meet the requirements for that use. Saline wetlands can be a good solution, but must incorporate outlet to the sea.

6.7 DESALINATION TECHNOLOGY ISSUES - KEY FINDINGS

- There is enough written about desalination technology to fill several libraries. This review narrowed down the research by focusing on recent literature and on issues that have gained prominence, perhaps, since the completion of the 2004 Corpus Christi Seawater Feasibility Study.
- Although there are multiple proven and emerging desalination methods from which to choose, the technology of choice for municipal, stand-alone applications is reverse osmosis.
- A particular interest for membrane desalination processes is identifying the occurrence of constituents that may cause a loss of membrane performance by fouling. A source of fouling and growing cause of concern for designers is the presence of algae. Warmer ocean temperatures facilitate more frequent and new types of algal blooms.
- Deeper intakes and well-designed filtration systems help minimize the risk of algal blooms; dissolved air flotation is a preferred tool to manage algae events; microfiltration and ultrafiltration, temporary lower flux and plant temporary shutdown are cited as useful strategies.
- Impingement and entrapment issues, including new stricter federal regulations (Section 316 (b) of the Clean Water Act) pertaining to the design and operation of intakes structures enactment of regulations, continue to dominate the selection of intake strategies.
- Subsurface intakes are advantageous in addressing impingement and entrapment and provide a generally constant quality of source water (slant wells and under-ocean floor systems have been researched and are promising strategies).
- The major drawback of subsurface intakes continues to be the production capacity; these methods may be better suited for medium to small-sized facilities.
- Co-locating with an existing seawater intake facility – such a seawater cooled power generator - is an advantageous and cost-saving intake method; however, if the source water quality is poor, those benefits and savings need to be examined on a life cycle basis to account for added treatment costs and possible increase in membrane replacements.
- Conventional granular media filtration pretreatment has been widely used for seawater and brackish water reverse osmosis plants; however, variations in feed water can limit the effectiveness of conventional granular media pretreatment for seawater applications. Use of microfiltration and ultrafiltration membrane technologies for desalination pretreatment is relatively recent but the results are very promising.
- More than 33 percent of the cost to produce water using reverse osmosis technology is attributed to the electric power requirements.
The Affordable Desalination Collaboration tested and demonstrated state of the art isobaric energy recovery technology for seawater application achieving specific energy consumption of 11.28 kW-Hr/1,000 gal which is comparable with the energy required to transport water from Northern to Southern California using the California State Water Project [71]. Other successful energy management tools focus on the use of pump centers to service multiple reverse osmosis desalination trains.

Most seawater desalination facilities are able to discharge concentrate back to the sea where it is almost immediately diluted by the large volume of available water, leaving marine life undisturbed. A study of the effects of the Tampa Bay Water Desalination Plant’s concentrate discharge found no effect of salinity elevation on a representative ecosystem.

Brine concentrate disposal modeling for the Brownsville seawater pilot study showed that concentrate levels were back to ambient conditions within 125 feet of the discharge diffuser.

There is a growing interest in exploring beneficial uses of concentrate. If there is a local demand for a particular mineral in the concentrate, then salt separation might be a practical solution. If not, trucking expense may make it infeasible. If there is a long term beneficial use for saline water in the neighborhood, then it would be wise to tailor the concentrate to meet the requirements for that use. Saline wetlands where there is an outlet to the sea can be an attractive option. Blending concentrate with wastewater for a saline wetlands is an even better solution.

### 7.0 REGULATORY ISSUES

In 2005, recognizing the lack of precedent in Texas regarding seawater desalination, the TWDB awarded a contract to RW Beck to examine permitting issues that would apply to seawater desalination in Texas and develop a permitting roadmap for seawater desalination in Texas. The following is replicated from a summary of the study [72]:

- The issues associated with permitting seawater desalination facilities using reverse osmosis processes can be complex and confusing. Since only a limited number of actual facilities with regulatory approval are available for use as models in the United States, there is also limited stakeholder guidance for permitting. In fact, the lack of guiding precedent and the resultant uncertainty that regulators face when making decisions related to permit conditions are often cited as major impediments to the successful implementation of desalination projects.

- Seawater desalination facilities using reverse osmosis processes facilities all share some common features. They include a seawater intake system, a reverse osmosis treatment process, and a means for concentrate disposal. In addition, they usually require a transmission pipeline to convey the product water to the municipal bulk storage or distribution system. As a result, the major
regulatory issues associated with these types of facilities generally include a needs assessment\textsuperscript{17} for the facility, seawater intake impacts, concentrate disposal effects, construction impacts, and product water transmission pipeline routing. Other regulatory issues also often exist, since these facilities typically have ancillary features such as membrane cleaning systems, backup power, chemical storage silos, wastewater treatment systems, and storm water collection and control systems. As a result, issues related to waste disposal and air emissions must be considered as well.

- A tabular summary of the major permits identified in this report as required for desalination facilities in Texas is attached in Appendix D.

Additionally, in 2011, the Brownsville Public Utilities Board, jointly with the Laguna Madre Water District, conducted a comprehensive scoping review of permitting requirements for implementing the Brownsville and South Padre Island seawater desalination projects [73]. Appendix D of the report discusses and informs on permitting requirements and strategies for meeting those requirements. Appendix D is attached to the present technical memorandum and will be summarized for inclusion in the final version of this document.

The Texas Commission on Environmental Quality (TCEQ) rules currently place desalination and reverse osmosis technology review under the category of “innovative/alternate treatment,” defined as any treatment process that does not have specific design requirements in §290.42(a)-(f). However, TCEQ has discontinued their previous brackish groundwater desalination and filtration membrane guidance documents and no longer requires pilot testing for these systems. TCEQ is currently in the process of developing design criteria for desalination and reverse osmosis technology. The criteria development is going through the formal rule change procedure. This will afford the opportunity for the City’s input into final TCEQ design criteria as a stakeholder.

7.1 PUBLIC DRINKING WATER

This section will address the issues associated with using the water produced as part of the Public Water System (PWS) from either the desalination pilot program or a full-scale operation. Under 30 TAC Chapters 290, the TCEQ governs PWSs.

\textsuperscript{17} A needs assessment is part of the requirements stated in TCEQ rules, Chapter 290.39, Public Water Systems, General Provisions, Submission of Plans, Engineering Report.
7.2 WATER RIGHTS

This section will address the issues associated with procuring rights to the surface water anticipated for use under both the pilot program and under a full-scale operation. Under 30 TAC Chapters 295 and 296, the TCEQ governs the appropriation of state water. In 30 TAC §297.1(50), “State water” includes water in “every bay or arm of the Gulf of Mexico”. To use sea water or brackish surface water for desalination, the owner or operator of the desalination plant will have to appropriate the right to use that water for a consumptive use through the TCEQ water rights permitting program. This will apply even if that water is diverted through an existing intake structure, because it is a different use.

7.3 SURFACE DISCHARGE

This section will address the issues associated with obtaining authorization to discharge wastes to surface water under both the pilot program and under a full-scale operation. Under 30 TAC Chapters 281, 305, 307 and 308, the TCEQ governs the discharge of wastes into state water. To obtain authorization to discharge the concentrate or any other waste from the desalination process, the owner or operator will have to obtain authorization through an individual permit issued by the TCEQ.

7.4 SUBSURFACE DISCHARGE

This section will address the issues associated with obtaining authorization to discharge wastes to the subsurface under both the pilot program and under a full-scale operation. Under 30 TAC Chapters 331, the TCEQ governs the injection of wastes into the subsurface. To obtain authorization to inject the concentrate or any other waste from the desalination process, the owner or operator will have to obtain authorization through either an individual or General Underground Injection Control (UIC) permit issued by the TCEQ. Specifically, the TCEQ issued UIC General Permit N. WDWG010000, “General Permit to Dispose of Nonhazardous Brine from a Desalination Operation or Nonhazardous Drinking Water Treatment Residuals into a Class I Well” on November 19, 2012, to be effective for a term of ten (10) years. [Exhibit C] The benefit of this general permit to the effort is that is can significantly reduce the permitting timeframe for an injection well to handle concentrate. This may be beneficial for a pilot study.

7.5 REGULATORY ISSUES – KEY FINDINGS

- There are a number of regulatory and permitting issues associated with appropriating surface water (either seawater or brackish surface water) for use in desalination.
There are a number of regulatory and permitting issues associated with securing brackish groundwater for use in desalination, including potential permitting by the CCASRCD if the extraction wells are located within its jurisdiction.

- There are a number of regulatory and permitting issues associated with the surface discharge of concentrate.

- There are a number of regulatory and permitting issues associated with the subsurface discharge of concentrate.

### 8.0 COST ESTIMATES FOR SEAWATER DESALINATION

The modern history of desalination has been dominated by dramatic technological developments resulting in lower costs to desalinate water. Although the industry is unlikely to experience additional significant declines in costs, the relevance of desalination is aided by the increase in the cost of other water supplies, as illustrated in Figure 66. Although these cost trends are useful references, they do not satisfy the need to determine the actual cost of a specific project.

![Figure 66 – Seawater Reverse Osmosis Cost Trends (copied from [79])](image)

Desalination costs vary considerably by location based on a number of issues including feed water source, feed water quality, plant size, process type and design, cost of power, intake type, pre- and post-treatment processes, concentrate disposal method, regulatory issues, land costs, and conveyance of water to and from the plant. The total production cost of desalinated water includes the cost of capital and operation.
and maintenance costs. Debt service costs are a function of the total capital cost of the project, the interest on the capital, and the loan payback period. The operation and maintenance costs are a function of chemical, power, equipment replacement, and labor costs. Power cost have a substantial impact on the life cycle costing of seawater desalination facilities; comparing costs for different facilities without disclosing the power cost basis can be misleading. Figure 77 illustrates commonly recognized desalination cost factors.

### Figure 77 - Key Factors for Capital and Operation and Maintenance Costs of a Desalination Facility [80].

Another important differentiating factor regarding desalination cost figures is the developmental stage of the project: estimating the cost of a project in the planning phase is far less accurate than determining the cost of a completed project which can be more easily documented on the basis of audited reports. Compounding the challenge for estimating seawater desalination costs in Texas is the fact that no facilities have been installed in the state to date to serve as a documentable reference.

Project delivery method also can make a substantial difference in the cost of a project as risk factors and risk tolerance are a basis for structuring water purchase agreements between a project developer and an off taker. Globally, most large-scale seawater desalination facilities are developed by alternate project
delivery methods. This includes the three larger scale seawater desalination facilities in the United States: Tampa Bay Water, Taunton River and Carlsbad.

The project team prepared a preliminary cost estimate for illustration purposes for a 20 million gallons per day seawater desalination plant in Ingleside. The estimated construction cost for this facility is approximately $248 million. Assuming a cost of power of $.06 per kilo-Watt/hour, and capital funded over 30 years at 3 percent interest, the lifecycle water production cost for this facility at the fence would be $4.45/1,000 gallons. A similar facility located at the O. N. Stevens site with similar energy and capital cost assumptions yields a water production cost of $4.35/1,000 gallons at the fence.

9.0 AQUIFER STORAGE AND RECOVERY

Aquifer storage and recovery (ASR) refers to the process of using injection wells to store water underground in a suitable aquifer and extracting it through the same wells, on an as-needed basis. In order to develop an ASR well, water is injected into an existing aquifer until an adequate buffer zone is formed that will contain the stored water without interaction with native groundwater. The formation of this buffer zone maintains the water quality of the stored water regardless of the existing water quality in the aquifer. Given this attribute, brackish aquifers are candidates for ASR.

There was no literature found regarding ASR systems storing desalinated water. A probable reason is the cost of desalination and the fact that the stored water may necessitate additional treatment once it is extracted for use as a potable supply. ASR, however, is commonly used in water reuse schemes, where highly treated wastewater effluent is injected for storage and later extracted for beneficial use. A possibility to be explored, although not strictly referred to as ASR, is the use of reclaimed wastewater for injection in managed aquifer recharge schemes and later used for beneficial uses after the appropriate treatment is provided. However, current regulations would require advanced treatment to drinking water standards prior to injection.
ASR is typically used as a storage option for water in lieu of conventional storage methods such as reservoirs and ground storage tanks. Benefits of ASR include:

- Small footprint for use in urban or suburban settings and environmentally sensitive areas.
- Possibly enhances use of underutilized brackish aquifers.
- In certain applications, provides cost savings over additional surface water supplies.
- Seasonal, long-term and emergency (strategic reserve) storage.
- Augment peak water supply capacity.
- Improving system water quality by maintaining distribution system flow during low demand months.
- Defer expansion of water system infrastructure by using ASR to meet seasonal and peak water demands.
- Peak flow scalping.
- Streamflow diversion mitigation.
- Stormwater flow and estuary salinity management.
- Supplement in meeting large retail customer demands.
- Water conservation from elimination of evaporation losses.
- Reclaimed water management.
- Rainwater harvesting.
- Small carbon footprint.
- Environmentally attractive.
- Higher security and water protection from tampering.

Despite being an economically viable option for water storage, currently less than 4 percent of the nation’s operational ASR well fields are located in Texas. However, ASR wells have been operated successfully in Texas for many years. In particular, the three systems which are presented in Table 7 have reported successful operation using three different types of source water. In all 3 cases, expectations were exceeded and public acceptance has been excellent. In general, legal and regulatory matters, as opposed to technical issues, presented the biggest challenge.

### Table 7-ASR Facilities in Texas [Modified From [74]]

<table>
<thead>
<tr>
<th>Component</th>
<th>SAWS (60 MGD)</th>
<th>Kerrville (2.65 MGD)</th>
<th>EPWU (10 MGD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2004</td>
<td>1995</td>
<td>1985</td>
</tr>
<tr>
<td>Source Water</td>
<td>Groundwater</td>
<td>Treated River Water</td>
<td>Treated Wastewater</td>
</tr>
<tr>
<td>Storage</td>
<td>400-600 feet Carrizo</td>
<td>495-613 feet Lower Trinity</td>
<td>300-835 feet Hueco Bolson</td>
</tr>
<tr>
<td>Issues</td>
<td>Single pipeline Distribution system limitations</td>
<td>Litigation during permitting Lack of source water</td>
<td>Original well design Customers for reclaimed water</td>
</tr>
<tr>
<td>Expansion Plans</td>
<td>Part of 50-year Mgmt. Plan Evaluating TSV</td>
<td>Adding 3rd ASR well WTP; expansion in Regional Plan</td>
<td>Expanding Fred Hervey Water Reclamation Plant; Constructing 4th spreading</td>
</tr>
<tr>
<td>Cost</td>
<td>$238 million ($0.87 per gallon) N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

The U.S. Army Corps of Engineers is conducting ASR demonstration projects in Florida which involve capturing excess high flow and using ASR to store the water for future retrieval during low flow periods. The unique approach demonstrates the ability to lightly treat the water injected into the ASR using direct filtration and ultraviolet disinfection, and takes advantage of the natural purification of the ASR. This has the potential to significantly reduce the cost of some ASR systems. A fact sheet is included in the Appendix.

### 9.1 CORPUS CHRISTI AQUIFER STORAGE AND RECOVERY CONSERVATION DISTRICT

The Corpus Christi Aquifer Storage and Recovery Conservation District (CCASRCD) is the only specific ASR district in Texas and covers portions of Aransas, Kleberg, Nueces, and San Patricio Counties. The enabling statute for the CCASRCD, as contained in the Texas Special District Local Laws Code, Title 6, Water and Wastewater, Subtitle H, Districts Governing Groundwater, Chapter 8811, indicates that the CCASRCD has
been granted all of the powers of a Groundwater Conservation District (GCD) under TWC Chapter 36. As such, in addition to regulating the injection of water for ASR purposes, the CCASRCD could otherwise regulate withdrawal as allowed under Texas Water Code, Chapter 36. Although the board of the CCASRCD is appointed by the City of Corpus Christi City Council, the CCASRCD is a separate entity with its own independent jurisdiction.

The CCASRCD has identified the following objectives for ASR in the Corpus Christi area:

- **Seasonal Storage:** Store water throughout the year to cover increased demand from May to September.
- **Long Term Storage:** Store water from years of high rainfall for use in times of dry weather.
- **Emergency Storage:** Store water as a strategic reserve, especially for the islands in case their supply from the mainland is disrupted.
• Streamflow Diversion Mitigation: Store water for use to meet minimum flow requirements for Nueces Bay.
• Defer expansion of water system infrastructure by using ASR to meet seasonal and peak water demands;
• Stormwater flow and estuary salinity management;
• Help meeting large retail customer demands.

The streamflow objective established by CCASRD is unique in that it has not been considered by other Texas entities. The district requires a 5-year action plan for the implementation of an ASR program. In previous studies, the city has investigated the construction of ASR wells on North Padre and Mustang Islands as part of a proposed desalination project. According to the District’s Management Plan, the development of two well fields with a total target storage volume of approximately 3,700 acre-feet and a total recovery capacity of about 7.5 MGD are intended for implementation.

9.2 ASR APPLICATION IN CORPUS CHRISTI

For application in Corpus Christi, much can be learned from ASR projects in large entities in the State of Texas. These case studies provide a basis for determining potential capital and operational costs, while also highlighting some factors for the City of Corpus Christi to consider if they are interested in pursuing ASR for storage. In addition, consideration specifically for the CCASRCD and interests in the Corpus Christi area must be understood.

There are several brackish and saline aquifers in the Coastal Bend. ASR is possible in these aquifers with the appropriate buffer zone and ASR can be beneficial if the overall groundwater quality can be improved by this storage. However, the storage of high quality water (such as that coming out of a desalination plant) in a brackish/saline aquifer may be of concern if the water quality of the stored water is negatively impacted to the extent that it must be retreated. The more common practice involves treating reclaimed wastewater to drinking water standards and storing it for retrieval in an ASR. An additional consideration would be to inject reclaimed wastewater in a managed aquifer recharge system for drinking water treatment at a future date. However, current regulations would require advanced treatment to drinking water standards prior to injection.

After injection, water is not confined by property boundaries and water rights or water ownership questions can be prominent. Fortunately, the CCASRCRD defines ownership in its Rules and Regulations.
According to Rule 5.5, “Water injected into an aquifer storage area is owned by the person who injected the water and is not percolating groundwater.”

9.3 ASR AND DESALINATION

When used together, numerous benefits could be realized through ASR and desalination synergy in Corpus Christi. These possible process improvements include, but are not limited to:

- Surplus surface water can be stored when available and made available for treatment in the variable salinity desalination facility when energy is most economically available;
- Development of a water reserve for strategic water resource planning;
- Utilization of excess power for water production. This is particularly beneficial if the desalination facility is co-located with power production.
- Raw water can be treated when its quality is more desirable and economical. During times of poor raw water quality (for example in the event of algal blooms, higher than optimal suspended or dissolved solids, etc.), water from the ASR system can be drawn to meet demand.

While many attractive advantages may be possible when implementing ASR with the Corpus Christi Variable Salinity Desalination project, many unknowns exist about the feasibility of such a system. One of the most significant issues in regards to the efficacy of this process is the extent to which a sufficient buffer zone can be accumulated in the ASR zone to prevent native brackish groundwater from contaminating the treated and stored water. Several potentially suitable aquifers have been identified but their proximity to the desalination plant will greatly affect theapplicability of using ASR.

9.4 CCASRD RULES AND REGULATIONS

The first express statutory authorization to use ASR in Texas was House Bill (HB) 1989 in 1995. While the framework for the rules have been laid out, several improvements can be made to protect the concerns of utilities. Mainly, rules need to be enacted that both facilitate the maximum benefits of ASR and protect the water once it has been injected for storage. If the water is not adequately protected, the full benefits of ASR cannot be realized. The following additions have been recommended in previous studies for inclusion into Texas regulation [74]:

- Seasonal and scalping permit authorizations;
- Further guidance to groundwater conservation districts for how to deal with ASR projects;
- Additional changes to specific rules to allow more entities to use ASR on a limited basis.
Rules specific to the CCASRCD are limited. Based on a document review of the District’s management plan, the following two rules are apparent:

- A new well shall not be within 50 feet of an adjacent landowner. (Rule 5.2)
- Any use of ASR in the district must first be approved through a temporary permitting process. (Rule 8.1)
- Ownership of water is retained by the party storing the water. (Rule 5.5)
- Production of water in areas designated for municipal settling is not allowed. (Rule 6.5)

9.5 SAN ANTONIO WATER SYSTEMS (SAWS) ASR IMPLEMENTATION

Six locations and five separate aquifer systems for ASR were evaluated by SAWS before selecting the Carrizo-Wilcox Aquifer option in 2004 [74]. This location was selected since it provided the lowest costs for transmission, site development and operation. The Twin Oaks ASR Facility, located 30 miles south of San Antonio, was then developed by SAWS to capture surplus water during wet months and store it underground for drought management and emergency relief. Water is injected into a semi-confined sand aquifer, forming a large water bubble. During times when groundwater levels are high, water from the Edwards Aquifer is disinfected to meet drinking water standards and then pumped to the Carrizo-Wilcox Aquifer for storage. A total of 29 high capacity ASR wells and three native Carrizo-Wilcox Aquifer pumping wells were installed using flooded reverse circulation and mud rotary techniques. Well tests were conducted between 500 to 3,500 gallons per minute (gpm). Individual well pumping yields were ultimately designed around a range of 1,800 to 2,500 gpm. Recharge capacities range from 1,200 to 2,000 gpm.

The Carrizo-Wilcox Aquifer has slightly elevated concentrations of iron, manganese, and hydrogen sulfide, so a storage, treatment, and pumping system was built to treat the recovered water and deliver up to 60 million gallons per day back to San Antonio. To date, recovered ASR water and native Carrizo water have been passed through the treatment plant because of the inability to by-pass the plant with water from the ASR wells.

However, the recently-completed Phase 2 construction included the facilities necessary to by-pass water recovered from the ASR wells. The ASR facilities have been mostly used for banking the recharged water, achieving a cumulative storage volume of over 87,000 acre feet as of December 2010. Recovery pumping augmented local water supplies during the recent drought. The recovered water from the ASR wells has not required retreatment, other than disinfection. The wells are backwash-pumped as needed to maintain
recharge efficiency. As stated above, water pumped from the three Carrizo production wells requires full treatment, including disinfection.

The SAWS Twin Oaks ASR Facility is the third largest ASR well field in the United States, behind Las Vegas Valley Water District, which has 157 mgd of recovery capacity, and also Calleguas Metropolitan Water District, California, which has 68 mgd of recovery capacity. Following is a discussion of the ASR operations at this site, addressing issues of interest to TWDB and Texas water utilities.

The SAWS ASR well field has performed well, recharging a substantial volume of water and recovering water to help meet needs during the recent drought. Extended operation under design conditions (60 mgd) has not been demonstrated because of the inability to distribute this volume of water in non-peak periods. When distribution system improvements have been made, it will be possible to recover water at higher rates.

Most significantly, recovery of stored water to date has not required retreatment other than disinfection to meet target drinking water standards.

9.6 ASR TCEQ REGULATORY SUMMARY

ASR wells are subject to the Texas Water Code Chapter 11, Texas Water Code Chapter 27 and TCEQ’s Chapter 331 Underground Injection Control Rules (30 TAC CH 331).

9.6.1 Related Texas Legal Definitions:

- **30 TAC §297.1(5) Aquifer Storage and Retrieval Project** - A project with two phases that anticipates the use of a Class V aquifer storage well, as defined in 331.2 of this title (relating to Definitions), for injection into a geologic formation, group of formations, or part of a formation that is capable of underground storage of appropriated surface water for subsequent retrieval and beneficial use;

  - **30 TAC §331.184(e)** limits injections into an ASR to only inject water meeting drinking water standards;

- **30 TAC § 331.2(8) Aquifer storage well**-- A Class V injection well used for the injection of water into a geologic formation, group of formations, or part of a formation that is capable of underground storage of water for later retrieval and beneficial use.

30 TAC CH 331 (Underground Injection Rules)

Class V Wells Using ASR subject to Subchapters:
A - GENERAL PROVISIONS
H - STANDARDS FOR CLASS V WELLS
K - ADDITIONAL REQUIREMENTS FOR CLASS V AQUIFER STORAGE WELLS

9.6.2 Operating Requirements (§331.184)

- (a) All Class V aquifer storage wells shall be operated in such a manner that they do not present a hazard to or cause pollution of an underground source of drinking water.
- (e) The quality of water to be injected must meet the quality criteria prescribed by the commission’s drinking water standards as provided in Chapter 290 of this title (relating to Water Hygiene) [30 TAC Chapter 290]. Adopted May 29, 1996 Effective June 28, 1996

9.6.3 Protecting Water Quality of Receiving Aquifer

Texas Water Code §11.154 (c) ... The commission shall consider whether:

- (1) the introduction of water into the aquifer will alter the physical, chemical, or biological quality of native groundwater to a degree that the introduction would:
  - (A) render groundwater produced from the aquifer harmful or detrimental to people, animals, vegetation, or property; or
  - (B) require treatment of the groundwater to a greater extent than the native groundwater requires before being applied to that beneficial use;
- (2) the water stored in the receiving aquifer can be successfully harvested from the aquifer for beneficial use; and
- (3) reasonable diligence will be used to protect the water stored in the receiving aquifer from unauthorized withdrawals to the extent necessary to maximize the permit holder's ability to retrieve and beneficially use the stored water without experiencing unreasonable loss of appropriated water.

9.7 NATIONAL GROUNDWATER ASSOCIATION

The NGWA published a fact sheet on ASR with a summary of important information and findings on the application of ASR in the United States. The concise document includes the following pertinent information:

- Globally, groundwater resources dwarf surface water supplies.
- Approximately 78% of community water systems and nearly all of rural America, use groundwater-supplied water systems.
- Approximately 42% of the nation’s agricultural irrigation water is obtained from groundwater.
ASR has been used in many different applications, including:

- Supplement drinking water and surface water supplies
- Augment stream water and lake levels during dry season
- Recharge aquifers to augment agricultural water supplies
- Storage of industrial water (cold water in winter, hot water in summer) to modulate cooling water temperatures for industrial process control

Benefits of ASR:

- No evaporative loss
- Small footprint for use in built-out urban/suburban settings or in environmentally sensitive areas
- Can improve water quality
- Enhances the utilization of brackish aquifers
- Can be more cost-effective than surface water supplies

The first ASR well began operation in Wildwood, New Jersey in 1969

In 2009, the EPA inventory identified 543 ASR wells were in operation nationwide

9.8 AQUIFER STORAGE AND RECOVERY – KEY FINDINGS

There are several brackish and saline aquifers in the Coastal Bend. ASR is possible in these aquifers with the appropriate buffer zone. ASR can be beneficial if the overall groundwater quality can be improved by this storage. However, the storage of high quality water (such as that coming out of a desalination plant) in a brackish/saline aquifer may result in deterioration of the stored water and require additional treatment prior to final municipal use;

- The buffer zone is normally formed only one time, usually near the beginning of ASR operations, while the recovered water volume is recharged and recovered as needed. For karst, brackish, limestone aquifers the buffer zone volume is typically about half of the total stored volume; however, for a fresh, confined, sandstone aquifer such as the Carrizo-Wilcox aquifer in Texas, the buffer zone would most likely be considerably less than half of the total stored volume.

- There are a number of regulatory and permitting issues associated with using ASR including the permitting and operation of the ASR wells as Class V wells under the TCEQ Underground Injection Certification program and the permitting of wells by the CCASRCD if they are located within its jurisdiction.
10.0 ALTERNATIVE ENERGY SOURCES

The large energy requirement for the production of fresh water from desalination processes is a major environmental, as well as economic, concern that has been a factor in limiting more widespread use of desalination. Energy is the largest single operational cost for a desalination plant and accounts for approximately 45% of the cost of producing water [75]. Due to the substantial energy demand, there is often interest in reducing the greenhouse gas emissions resulting indirectly from the production of fresh water from desalination processes. Therefore, integrating desalination processes, directly or indirectly, with renewable energy has the potential to mitigate both the greenhouse gas emissions and economic impact of the large energy consumption required for desalination.

Many types of renewable energy resources are inherently uncontrollable and intermittent [81]; therefore, the ability to reliably supply water on demand is a concern for renewable energy powered desalination plants. Large-scale desalination plants typically utilize grid connected renewable power systems that are supplied during high renewable energy production times. Renewable power is sold to the grid and during low renewable energy production times, the desalination plant can rely –partially or completely- on conventional power supplies from the grid.

In the past, the cost of harvesting renewable energy was high compared to the cost of grid electricity and the majority of desalination plants that utilized renewable energy were small systems with capacities less than 0.013 MGD (50 m³/d) and were located in areas where grid power is not available [76]. However, an increasing emphasis on developing renewable energy resources in the form of federal tax credits (renewable energy credits) and state level policies along with improved technologies has resulted in a reduced cost of developing renewable energy and more opportunities to power desalination with renewable sources.

The following is a summary of different types of renewable energy that can be combined with reverse osmosis and their respective potential for Corpus Christi. Additional detailed information on each energy source is included in the Appendix, Alternative Energy Sources for Desalination.

10.1 WAVE ENERGY

Wave energy is an expanding technology that can be produced from tidal movement offshore or breaking waves onshore. Wave energy can reduce the power required for electrically driven pumps either by generating electricity or by directly driving high pressure pumps. Wave energy can be used to generate
electricity with or without connection to the grid. It can also be used to directly pressurize the feed stream of a desalination process, such as reverse osmosis, nanofiltration, or vapor compression. When using direct power to mechanically drive pumps, continuous operation with varying supply of wave energy requires “smart” control systems to adjust the reverse osmosis process depending on the incoming power supply. An estimate of the wave resource in the Gulf of Mexico is 14 kW per meter of wave front. Wave energy is considered to have high energy conversion efficiency; studies have shown over 80% energy conversion efficiency is possible. There are many types of wave-energy conversion devices that have been tested and are being commercialized. Some of the technologies undergoing commercialization include: Wave Dragon, McCabe Wave Pump, Oyster, SEADOG®, and CETO. A small, 2,000 gallons per day, wave-powered reverse osmosis desalination plant was built in India in 2004 [77].

There is potential for wave energy to serve the project. Successful sea trials have been conducted using the SEADOG® technology in Freeport, TX fairly close to Corpus Christi. During the Gulf trial, the SEADOG® encountered modest waves ranging in height from 6 inches to 6 feet and consistently pumped 12 to 18 gallons of seawater per minute at a head pressure of 47 to 54 PSI. Other testing of the SEADOG® confirmed that the device could withstand 20 foot waves and winds exceeding 50 miles per hour [reference: Available from: http://inri.us/index.php/SEADOG]. The lessons learned from those trials may be applied to the Corpus Christi project.

### 10.2 GEOTHERMAL ENERGY

Geothermal energy comes from the heat within the earth. Geothermal reservoirs contain hot water or steam and occur in areas where the magma comes close enough to the surface to heat groundwater. Low temperature (less than 100 °C) geothermal resources can be used for direct heating. High temperature geothermal resources, with temperatures greater than 100 °C are used to generate electricity. For desalination processes, geothermal energy can be used to heat the feed water for a thermal desalination process. Hot water from a geothermal source can also be used directly as the feed to a desalination process. For membrane applications, high temperature geothermal resources could be used to generate electricity for operating reverse osmosis. The Rio Grande Embayment has a large collection of geopressed-geothermal resources and there is potential to generate electricity to offset the energy consumption by the Corpus Christi desalination plant. However, due to the long distance between the Rio Grande Embayment and the Corpus Christi plant, it is unlikely that this resource could be utilized to generate electricity on-site.
Geothermal energy is better suited to thermal desalination rather than reverse osmosis membrane processes. However, within the Rio Grande Embayment, there is a source of geothermal water that could be potentially used to produce electricity to offset the power consumption by the Corpus Christi desalination plant. On-site electricity generation using a geothermal resource is not practical.

10.3 WIND ENERGY

Wind can be used to generate electricity with or without grid connection to power desalination treatment processes. Wind can also be used to generate mechanical energy to directly power piston pumps for desalination processes. Offshore wind resources are suitable for wind power generation in the area surrounding Corpus Christi with an average wind speed of 8.5 to 9.0 m/s at a height of 80 meters. Onshore conditions are not as favorable to economical wind power generation due to a lower average wind speed of 7.0 m/s and possible contention from environmental and military organizations.

Wind energy for powering desalination, particularly reverse osmosis, is a fairly well established practice. The Sydney desalination plant, located in Sydney, Australia is a notable example of a reverse osmosis plant powered by renewable energy credits from wind power. The Sydney desalination plant began operation in 2010 and provides up to 15% of the City’s entire drinking water supply (approximately 66 MGD). A wind farm was built in Bugendore that supplies approximately 450 gigawatt-hours per year of equivalent power to power the desalination plant, offsetting the power demand. Small-scale autonomous wind-powered reverse osmosis systems have been tested and prototyped since the 1980s. Large, municipal scale desalination plants involving wind power have also been documented. These systems are connected to the grid in order to ensure delivered water availability despite the intermittent availability of the wind resource. During high wind times, excess wind power is supplied to the grid and during low wind times, the desalination plant draws power from the grid.

Even though wind has been proven for powering small autonomous desalination systems without the grid, for large municipal applications, such as Corpus Christi, grid connectivity is preferred to ensure water supply reliability. Given the offshore wind conditions near Corpus Christi, wind-power may be considered as an alternative supplemental energy supply for a full-scale desalination plant. Siting of wind power farms needs to consider potential impacts to migratory birds.
10.4 SOLAR ENERGY (PV)

Photovoltaics (PV) used in solar energy production are a mature technology that have been in commercial use for more than 50 years. Grid connected systems have been in use for over 20 years. Historically, the high cost associated with manufacturing the PV panels has inhibited more widespread use of PV. However, improved efficiency and reduced capital costs have contributed to more widespread use of PV. PV processes convert solar radiation to direct current (DC) electricity using specific types of semiconductors. The DC electricity can be used directly or converted to alternating current (AC) electricity. PV can be used to generate electricity to power the desalination process. Solar radiation conditions for the production of electricity from photovoltaics for the area surrounding Corpus Christi is moderate, 5.0 to 5.5 kWh/m²/d.

Solar energy is being considered in other desalination plants across the county. In preliminary documents for the Carlsbad desalination plant, the use of PV is mentioned to offset a small portion of the energy required for the plant. The preliminary plans mentioned covering the 50,000 ft² building that will house the treatment equipment with solar panels. This system is expected to generate approximately 777 (Megawatt hours per year) MWh/y of electricity with a net carbon footprint reduction of 193 metric tons of CO₂ per year. The total power use for the plant is 246,000 MWh/y; therefore, the portion of the power offset due to solar is expected to be less than 1% and reduce the carbon footprint by 1.4%. The anticipated cost of power generation using the PV system is 47.2 cents/kWh, which is 5 times higher than the cost of power supplied from the electric grid.

PV may be used to offset some of the power consumed by the desalination plant in Corpus Christi but will most likely result in higher capital costs. The most conventional option would be placing solar panels on the rooftops of the process equipment buildings but this would only be able to generate a small portion of the power consumed by the plant. Purchasing solar power renewable energy credits may also be an option. Also, as is the case with wind power generation, solar power facilities need to consider potential impacts to migratory birds.

10.5 SOLAR ENERGY (THERMAL/CONCENTRATING)

In addition to PV, solar energy can be used for other forms of energy generation. Most commonly, solar thermal energy is used to preheat the feed streams for thermal desalination processes; however, solar energy can also be concentrated to produce steam that is then converted to electricity using turbines. The electricity generated can then be used to supply electricity to run reverse osmosis pumps. Parabolic troughs and solar towers are examples of solar collector technology.
Concentrating solar power generation relies on direct normal radiation. Direct normal radiation is more limited in areas of higher humidity [78]. According to the maps developed by the National Renewable Energy Laboratory, the concentrating solar resource potential in the area surrounding Corpus Christi is relatively low [79]. The concentrating solar resource potential in the area surrounding Corpus Christi is relatively low and for this reason this type of renewable energy is not likely to be a viable alternative for on-site energy generation for the project.

10.6 FUEL CELL TECHNOLOGIES

A Fuel Cell is an electrochemical power source. It supplies electricity by combining hydrogen and oxygen electrochemically without combustion. It is configured like a battery with an anode and cathode. Unlike a battery, it does not run down or require recharging and will produce electricity, heat and water as long as fuel is supplied [80]. Hydrogen is supplied to the cell and is split into protons and electrons at the anode. The electrolyte allows the protons to travel to the cathode, but blocks the electrons, forcing them to flow to the cathode by way of an external circuit. Oxygen at the cathode combines with the protons to form water. The flow of electrons through the external circuit creates electricity.

At the closure of this review, no documentation was found on current use of fuel cell for water desalination.

10.7 IMPLEMENTATION OF RENEWABLE ENERGY POWERED DESALINATION

The Environmental Protection Agency (EPA) has a Green Power Partnership that assists organizations with procuring electricity generated from renewable resources. Purchasing green power is a way to reduce the environmental impacts associated with conventional electricity use. Working with EPA through the Green Power Partnership ensures that green energy purchases meet nationally accepted standards supported by EPA.

Renewable energy certificates are tradable instruments that can be used to meet voluntary renewable energy targets as well as to meet compliance requirements for renewable energy policies. A REC is a certificate that represents the generation of one megawatt-hour (MWh) of electricity from an eligible source of renewable energy. Each REC denotes the underlying generation energy source, location of the generation, and year of generation, environmental emissions, and other characteristics associated with the generator. RECs represent a claim to the environmental attributes associated with renewable energy
generation [26]. The program website is:


Many entities in the State of Texas are currently working through the EPA Green Power Partnership to purchase renewable energy. There are different renewable electricity products that can be purchased. EPA has a Green Power Locator tool that can identify retailers who sell green energy products in a given area.

The 2004 Corpus Christi Seawater Desalination Feasibility Study [18] examined alternative power sources and concluded that wind was marginally cost effective based on the 2004 rate structure; suitable location for wind or solar power was unknown; cost of land and transmission for wind or solar power was unknown; and, costs of solar power were an order of magnitude higher than for wind or conventional power.

10.8 ALTERNATIVE ENERGY SOURCES – KEY FINDINGS

- Many types of renewable energy resources are inherently uncontrollable and intermittent. Large-scale desalination projects featuring alternative power sources typically utilize grid-connected renewable power systems;

- Successful applications of wave power technology were recently demonstrated in Freeport, Texas, and could potentially extrapolate to the Corpus Christi area. The experimental project encountered modest waves ranging in height from 6” to 6 feet and consistently pumped 12 to 18 gallons of seawater per minute at a head pressure of 47 to 54 PSI;

- Geothermal energy is better suited to thermal desalination rather than to reverse osmosis membrane processes. However, within the Rio Grande Embayment, there is a source of geothermal water that could potentially be used to produce electricity to offset the power consumption by the Corpus Christi desalination plant. On-site electricity generation using a geothermal resource is not practical;

- Even though wind has been proven for powering small autonomous desalination systems without the grid, in large municipal applications, such as for Corpus Christi, grid connectivity is preferred to ensure water supply reliability. Given the offshore wind conditions near Corpus Christi, wind-power may be considered as an alternative energy supply for the desalination plant;

- Photovoltaic solar energy may be used to offset some of the power consumed by the desalination plant in Corpus Christi but will most likely result in higher capital costs;
The concentrating solar resource potential in the area surrounding Corpus Christi is relatively low and for this reason solar (thermal) energy is not likely to be a viable alternative for on-site energy generation.
11.0 REFERENCES

[37] INTERA, "Gulf Coast Aquifer Groundwater Study for the City of Corpus Christi: Phase 1," INTERA, 2014.


