Barton Springs Edwards Aquifer Conservation District

Desalination/ASR Feasibility Assessment Project

# REPORT 1

FINAL | March 2018

TBPE No. F-882

Barton Springs
Edwards Aquifer
CONSERVATION DISTRICT

# Barton Springs Edwards Aquifer Conservation District
# Regional Plan for Desalination and Aquifer Storage Recovery

## REPORT 1

## DESALINATION and ASR FEASIBILITY ASSESSMENT

FINAL | March 2018

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Barton Springs Edwards Aquifer Conservation District

Regional Plan for Desalination and Aquifer Storage Recovery

# REPORT 1

# DESALINATION and ASR FEASIBILITY ASSESSMENT

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## Abbreviations

| | |
|---|---|
| AC | Acre |
| AFY | Acre-feet per year |
| ADD | Average Day Demand |
| ASR | Aquifer Storage and Recovery |
| ASRS | ASR Systems, LLC |
| BSEACD | Barton Springs Edwards Aquifer Conservation District or the District |
| Carollo | Carollo Engineers, Inc. |
| Centex | Centex Materials, LP. |
| cf | cubic feet |
| cfs | cubic feet per second |
| CHP | combined heat and power |
| CIP | Capital Improvement Program or cast iron pipe |
| CMWSC | Creedmoor-Maha Water Supply Cooperation |
| ERD | Energy Recovery Device |
| F | Fahrenheit |
| ft | Feet |
| ft-msl | feet above sea level |
| GAC | Granular Activated Carbon |
| gpcd | gallons per capita day |
| gpd/ac | gallons per day per acre |
| gpm | gallons per minute |
| GSUD | Goforth Special Utility District |
| HGL | Hydraulic Grade Line |
| µg/L | micrograms per liter |
| LSI | Langelier Saturation Index |
| MDD | Max Day Demand |
| MF | Microfiltration |
| MG | million gallons |
| mg/L | milligrams per liter |
| mgd | million gallons per day |
| MinDD | Minimum Day Demand |
| MinMD | Minimum Month Demand |
| MMD | Maximum Month Demand |
| msl | Mean sea level |
| MWTP | Membrane Water Treatment Plant |
| Monarch | Monarch Utilities, Inc. |
| PHD | peak hour demand |
| PS | Pump Station |
| psi | pounds per square inch |
| RDM | Regional Dense Member (Zone 12 of Westbay well) |
| RO | Reverse Osmosis |

| | |
|---|---|
| SCADA | Supervisory Control and Data Acquisition |
| SWP | State Water Plan |
| TDS | Texas Disposal Systems, or Total Dissolved Solids |
| TSS | Total Suspended Solids |
| TSV | Target Storage Volume |
| TWDB | Texas Water Development Board |
| UF | Ultrafiltration |
| WRF | Water reclamation facility |
| WTP | Water treatment plant |
| WWTP | Wastewater treatment plant |

## Report 1

# DESALINATION AND ASR FEASIBILITY ASSESSMENT

## Section 1: Executive Summary

The Barton Springs/Edwards Aquifer Conservation District (BSEACD or the District) was formed to conserve, protect, and enhance the groundwater resources in its jurisdictional area, which covers the unconfined (recharge) zone and the confined zone of the Barton Springs segment of the Edwards Aquifer in central Texas.

The Edwards Aquifer has been considered a vast source of inexpensive, high-quality drinking water for many years. However, restrictions have been placed on production from the Edwards in recent years, and rising demands have increased faster than the provision of other additional sources. With the past significant reliance on the Edwards Aquifer, other potential sources warrant further consideration. Potential sources within the boundaries of the BSEACD that are being minimally used, if at all, include the Middle and Lower Trinity aquifers, and the brackish portion of the Edwards. One prospective new water supply source is the large quantity of brackish groundwater in the eastern portion of the District. Texas Disposal Systems is located on this "donut hole" which is outside the jurisdiction of the BSEACD. Multi-port wells installed here have provided data necessary to analyze the feasibility of desalination of the brackish groundwater; management of desalination treatment residuals; and using the treated water for aquifer storage and recovery (ASR).

An evaluation of desalination technologies to lower the total dissolved solids (TDS) of brackish Edwards Aquifer water to drinking water standards found reverse osmosis (RO) membranes to be the most effective option. A two-stage, single-pass RO system may be able to provide water meeting regulatory standards. However, the groundwater contains significant concentrations of boron. Boron does not have a primary or secondary maximum contaminant level, but is known to have negative impacts on plant life, depending on the concentration and plants involved. To remove boron, a second-pass, two-stage RO system would be able to reduce boron levels and help to provide high quality water that may be used for both irrigation and human consumption. For purposes of this feasibility assessment, the desalination facility was sized for 2.5 million gallons per day (mgd) in Phase 1 and 5 mgd in Phase 2, based on estimated yields from three potential brackish groundwater supply wells from the lower producing intervals of the Edwards Aquifer. Generating power from the Texas Disposal Systems landfill gas could meet the energy requirements of the Phase 1 and Phase 2 desalination facility as well as provide additional electricity. Several disposal options for the brine concentrate that is a byproduct of RO were evaluated, and deep well injection into the Trinity Aquifer at the Texas Disposal Systems site was selected as the most cost effective option.

Aquifer storage and recovery (ASR) is the storage of water underground in an aquifer and subsequent recovery of the stored water when needed. For the BSEACD, ASR could create new water supplies in central Texas, meet seasonal variations in water supply and demand, and enhance water supply reliability during droughts. This would be for the District's permittees and potentially for other water users in the surrounding area. A portion of the produced desalinated drinking water would be stored during winter months when demands are low. During summer peak demand months and droughts, the stored water would be recovered from the ASR wells and added to the desalination supply, helping to meet peak demands exceeding the capacity of the desalination treatment plant. ASR wells would be located within the TDS "donut hole" area, storing water in the upper producing intervals of the Edwards Aquifer, which is brackish at this location.

Feasibility study level capital and operation & maintenance (O&M) costs for the desalination system, wellfield collection system, various concentrate disposal alternatives, an aquifer storage and recovery (ASR) system, as well as a landfill gas combined heat and power facility were developed for two distinct phases: 1) a desalination facility with a production capacity of 2.5 mgd; 2) a desalination facility with a production capacity of 5.0 mgd. These costs were used to develop five financial forecast scenarios, exclusive of ASR. The lowest cost of the evaluated scenarios is $6.51 per 1,000 gallons of production in the first year of operation for a 5 mgd desalination facility with a landfill gas to energy cogeneration facility and concentrate disposal in Trinity Aquifer injection wells. The 30-year life cycle cost for a 5 mgd desalination facility powered by traditional grid sources with concentrate disposal in Trinity Aquifer injection wells is $8.20 per 1,000 gallons. The 30-year cost of an ASR project for water produced by the 5 mgd desalination facility is $0.38 per 1,000 gallons.

# Section 2: Background

## 2.1 Introduction

The 70th Texas Legislature passed Senate Bill 988 in 1987 and created the Barton Springs/Edwards Aquifer Conservation District (BSEACD or the District) as a Groundwater Conservation District (GCD), with a directive to conserve, protect, and enhance the groundwater resources in its jurisdictional area. Under its enabling legislation, the District's jurisdictional area is bounded on the west by the western edge of the Edwards Aquifer outcrop and on the north by the Colorado River. The eastern boundary is generally formed by the easternmost service area limits of what are now the Creedmoor-Maha, Aqua-Texas Water Services, and Goforth Water Supply Corporations. The District's southern boundary is generally along the established groundwater divide or "hydrologic divide" between the Barton Springs and the San Antonio segments of the Edwards Aquifer. The area covers the unconfined (recharge) zone and the confined zone of the Barton Springs segment of the Edwards Aquifer, but not its contributing zone. It includes the locations of all wells in the Barton Springs segment, and also the locations of the natural outlets of the aquifer at Barton Springs and several other smaller springs along the Colorado River.

The Edwards Aquifer has been considered a vast source of inexpensive, high-quality drinking water for many years. However, restrictions have been placed on production from the Edwards in recent years, recognizing the potential impacts of over-pumping on water-supply wells, water quality, springflow, and endangered species. Water suppliers have been working to diversify their sources of water, but rising demands (as demonstrated in the 2017 State Water Plan) have increased faster than the provision of other additional sources. With the past significant reliance on the Edwards Aquifer, other potential sources warrant further consideration.

Potential sources within the boundaries of the BSEACD that are being minimally used, if at all, include the Middle and Lower Trinity aquifers, and the brackish portion of the Edwards. Wells within the Middle and Lower Trinity have been used regularly within the District, but their yields are significantly less compared to the production of wells in the Edwards, and water quality can be marginal or poor enough that treatment or blending is necessary. BSEACD has installed multiport monitor wells to study the Edwards, Upper Trinity, and Middle Trinity aquifers. One potential new water supply source is the large quantity of brackish groundwater in the eastern portion of the District. The multi-port wells provide data necessary to analyze the feasibility of desalination of the brackish groundwater; management of desalination treatment residuals; and using the treated water for aquifer storage and recovery (ASR).

In 2013, the 83rd Texas Legislature passed Senate Bill 1532 to promote research into the desalination of brackish groundwater and aquifer storage and recovery in the Edwards Aquifer. This Feasibility Assessment describes the results of research authorized by SB 1532 and investigates and evaluates the engineering and financial feasibility of desalination and ASR as water management strategies. This assessment develops and evaluates delivery scenarios and infrastructure costs, as well as the market for water supply from these water management strategies. Using data obtained from the District’s multiport monitoring wells, this assessment also evaluates potential impacts to the freshwater/saline water interface in the Edwards Aquifer. Projected costs for desalination and brine disposal are presented based on projections for energy production or energy cost offsets from landfill gas waste-to-energy generation.

## 2.2 Purpose

The Texas Water Development Board (TWDB) offers Regional Facility Planning Grants, available for local planning feasibility studies. This Desalination and ASR Feasibility Assessment falls under the category of determining availability of current/future water supplies. The purpose of this study was to assess the feasibility of implementing two water management strategies using waste-to-energy power to offset the electrical demands of these strategies. The Feasibility Assessment is an effort to address potential future water shortages within the Barton Springs segment of the Edwards Aquifer.

Carollo presented information on the purpose of this report in two public presentations that can be found in Appendix G – Presentations.

## 2.3 BSEACD, Study Area and "Big 6" Permittees

A list of potential entities searching for additional water supply was developed using data acquired from BSEACD (as shown in a table located in Appendix F1 – BSEACD Permittee List and Drought Compliance). This list includes the Tier 3 water users that are greater than >= 120 million gallons per year (MGY), which are also referred to as the "Big 6":

1. Creedmoor-Maha Water Supply Cooperation (CMWSC)
2. City of Buda
3. Goforth Special Utility District (GSUD)
4. City of Kyle
5. Centex Materials, Lp. (Centex)
6. Monarch Utilities, Inc. (Monarch)

In addition to the Big 6, the City of Austin was also determined to be a potential candidate for future water supply because of the proximity of their existing water supply system near the project site. The City of Austin owns a 42 inch water transmission line that is in close proximity to the site and will be discussed further in this report. This water line is shown on the map in Appendix A – Maps (Figure 2).

It's also worth noting that BSEACD is not a water purveyor and does not intend to build, drill, or manage the proposed system outlined in this report. Although the District does intend to contribute to the effort, it is assumed that the entity looking to receive water supply would operate and build the proposed facility. This report will remain a public document to ensure it stays available to any entities that may be able to move forward.

In an effort to collect information on water sources, projections, and future water supply/demand, the BSEACD emailed out a list of questions to each of the Big 6 entities. This emailed information stated:

> *"As part of the Regional Facilities Planning grant that we received from TWDB, the District and our subcontractor, Carollo Engineers, are pulling together data to indicate water needs for this area. We are focusing on the six largest District permittees. Hopefully, most of these numbers will be readily at hand.*
>
> - *What are your current average and peak day demand (mgd)?*
> - *What are your current source(s) of water supply (Edwards Aquifer, Trinity Aquifer, Austin, etc.)?*
> - *What are your projected average and peak day demands, and associated year?*
> - *What are your potential future supplemental water sources, and do you have information on future water supply?*
> - *Do you have any available information on current or projected water costs?*
> - *Can you provide information on infrastructure and interconnections, existing and planned? Do you offer this in a GIS format, or if not, what is the best way to get this information from you?*
>
> *Please let me know if you have any questions about these questions. Thank you for your help with this project."*

The district received no direct response to these questions from any of these entities. Limited information was gathered from the City of Buda and the City of Kyle through previous studies that had been completed (Documented in Appendix F). BSEACD contacted the General Manager (GM) at CMWSC and Monarch but never got a response. Centex responded that they are self-sufficient and will not have any water demands in the future.

The vicinity of the study area along with municipal and utility boundaries are shown on Figure 1 in Appendix A – Maps.

## 2.4 Edwards Aquifer Rules

The District operates within a framework of statutes, plans, rules, and policies. The legal framework for administering groundwater rights in Texas has been the common law "Rule of Capture" wherein the owner of land may drill a well to withdraw groundwater and use that groundwater for any purpose. For many decades, the Rule of Capture was considered inviolate, and the only change made in this law during that time was to ensure that the water was put to beneficial use and was not wasted.

Although the Rule of Capture remains in effect, in the 1950s the Texas Legislature began authorizing the establishment of local groundwater conservation districts (GCDs). GCDs, like the BSEACD, are the state's legal method of groundwater management and they are specifically authorized to modify how the Rule of Capture is to be applied within their boundaries as part of a comprehensive, approved groundwater management plan. GCDs may limit aquifer withdrawals in order to conserve, preserve, and protect groundwater or groundwater recharge, and to prevent waste of the groundwater resource or groundwater reservoirs in their jurisdiction.

The BSEACD boundary is shown in Figure 2.1 (below). The boundary shown in Figure 2.1 represents the Authority's boundary over the Edward's Aquifers; the actual BSEACD jurisdictional boundary is larger. Texas Disposal Systems (TDS) is surrounded by, but legislatively independent from the BSEACD. As such, groundwater management in this area is not governed by the BSEACD framework, and therefore called the "donut hole."

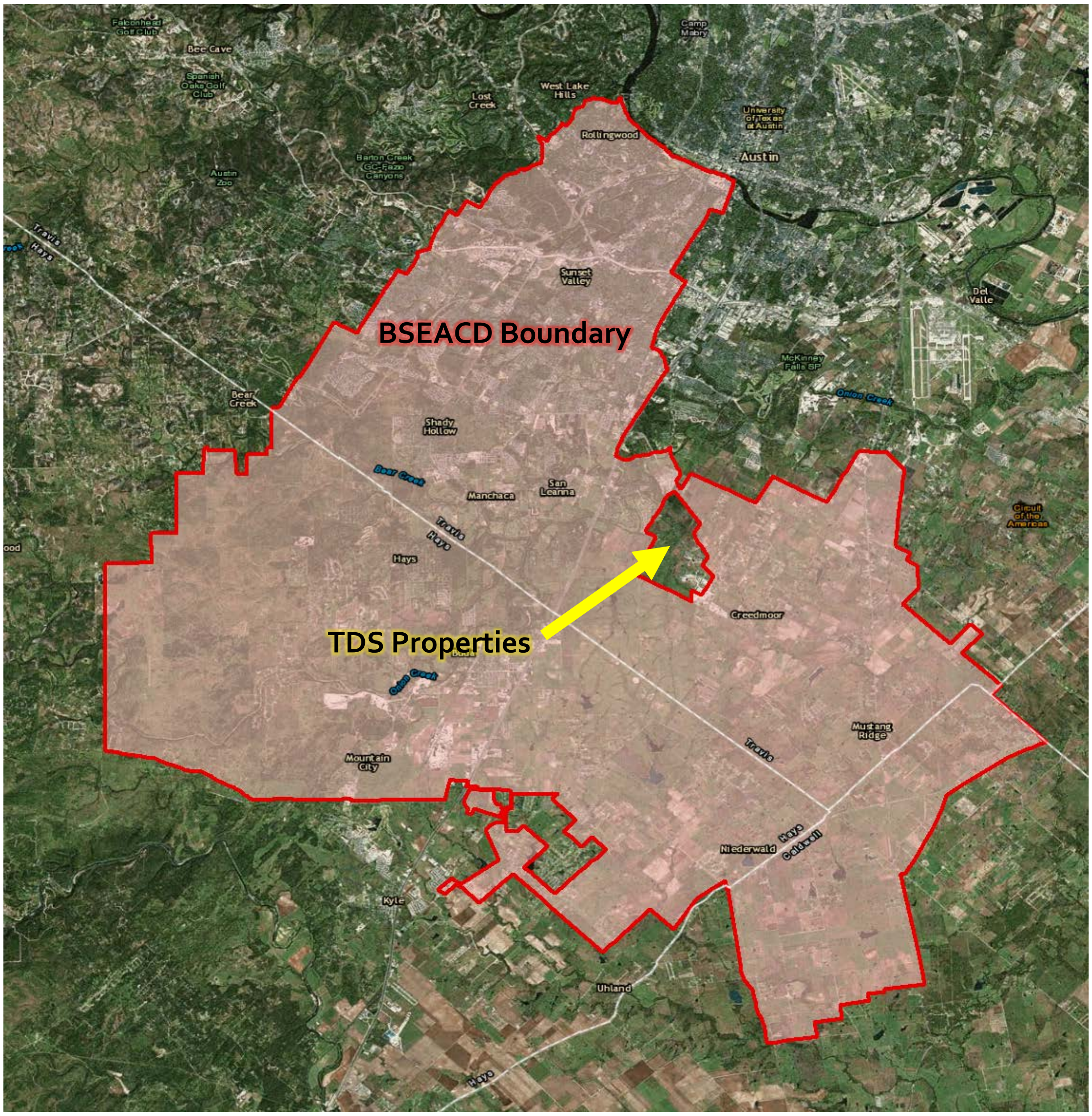


Figure 2.1 BSEACD Boundary Area

## 2.5 Saline Multiport Monitoring Well

In addition to the analysis conducted in this report, BSEACD installed a multiport monitoring well to allow collection of groundwater samples from multiple zones from the top of the Edwards Aquifer and extends into the uppermost Upper Glen Rose below the Edwards. This well employs the Westbay Multilevel Groundwater Monitoring System, an advanced monitoring well system that utilizes, after drilling and certain down-hole logging, a specialized down-hole water-level measurement and withdrawal system. The well system allows for measurements and samples to be collected from discrete zones in the well to evaluate both potentiometric and geochemical relationships among the zones, on a continuing basis. This well was specifically designed to provide data that was used in the analysis of hydraulic and water-chemistry properties of the Saline Edwards and Middle Trinity aquifers in the area near TDS. The multiport well can also be used as an observation well for subsequent aquifer testing of both the Middle Trinity and Edwards aquifers, and will be used as part of a future permanent monitoring system.

The initial report from the multiport well includes the results from a beginning round of sampling and analysis of groundwater from the well. Sampling was conducted by District staff and the samples were analyzed by accredited laboratories. The groundwater samples were analyzed for a suite of geochemical parameters that are important for hydrogeologic characterization, evaluation of desalination facility and ASR operations. A continuing sampling and analysis program will be part of the future monitoring system. The result of the initial sampling and analyses needed for the hydrogeologic characterization and operational evaluations are included in this Feasibility Assessment.

## 2.6 Desalination

The proposed water source for the desalination of brackish water is the Saline Edwards Aquifer located on the TDS property. The Saline Edwards Aquifer contains brackish groundwater with total dissolved solids (TDS) of approximately 17,000 mg/L in productive zones. An evaluation of desalination technologies to lower the TDS of this water to drinking water standards found reverse osmosis (RO) membranes to be the most effective option. Water quality data collected from the multiport monitoring well on the TDS property was input into an RO membrane modeling software to determine treatment requirements.

A two-stage, single-pass RO system may be able to provide water meeting regulatory standards. However, the groundwater contains significant concentrations of boron. Boron does not have a primary or secondary maximum contaminant level, but is known to have negative impacts on plant life, depending on the concentration and plants involved. To remove boron, a second-pass, two-stage RO system would be able to reduce boron levels and help to provide high quality water that may be used for both irrigation and human consumption. For purposes of this feasibility assessment, the desalination facility was sized for 2.5 million gallons per day (mgd) in Phase 1 and 5 mgd in Phase 2, based on estimated yields from three potential brackish groundwater wells. Generating power from the TDS landfill gas could meet the energy requirements of the Phase 1 and Phase 2 desalination facility as well as provide additional electricity.

Desalination produces a brine concentrate that will require disposal. Several disposal options were evaluated as part of this feasibility study. The alternative that was selected as the most cost effective was deep well injection into the Trinity Aquifer at the TDS site. This alternative assumed that the Trinity Aquifer has a TDS concentration over 10,000 mg/L. Other deep well injection alternatives include piping the concentrate to new disposal wells in Caldwell County or existing wells in the Salt Flat (Edwards) Field to the south. Deep well injection for desalination brine disposal has been successful in other projects. For example, the Kay Bailey Hutchison Desalination Facility in El Paso conveys the brine 22 miles away. Zero liquid discharge technologies were also evaluated and found to be cost prohibitive.

## 2.7 Aquifer Storage and Recovery

Aquifer storage and recovery (ASR) is the storage of water underground in an aquifer and subsequent recovery of the stored water when needed. Water is injected through a well in a suitable aquifer during times when water of suitable quality is available for storage. The water is recovered, usually from the same well or wells. Over 500 ASR wells are operational nationwide, at more than 120 different wellfields in at least 20 states. Many more ASR wells and wellfields are operational overseas. In Texas, some ASR wellfields have been operational for almost 30 years. Some of the long-term ASR wells in Texas are located in at El Paso and the City of Kerrville. Twenty-nine different applications of ASR have been identified to date, however the most common applications are to ensure water supply reliability during droughts; to meet seasonal variations in water supply and demand, and to provide water supplies during emergencies such as failure of long pipelines.

For BSEACD, the opportunity is primarily to create new water supplies in Central Texas, meet seasonal variations in water supply and demand and to enhance water supply reliability during droughts. This would be for the District's permittees and potentially for other water users in the surrounding area. The proposed desalination plant would operate continuously at a steady rate. A portion of the produced desalinated drinking water would be stored during winter months when demands are low. During summer peak demand months and droughts, the stored water would be recovered from the ASR wells and added to the desalination supply, helping to meet peak demands exceeding the capacity of the desalination treatment plant. Additional water from the desalination plant or potentially from other sources could be stored in the same wells to help meet water supply reliability goals during severe droughts for the BSEACD permittees and also potentially for others.

ASR wells would be located within the TDS "donut hole" area, storing water in the upper producing intervals of the Edwards Aquifer, which is brackish at this location. Desalination supply wells would produce from the lower producing intervals of the brackish Edwards aquifer. A semi-confining layer separates the upper and lower portions of the aquifer and the wells would be located to achieve a sufficient separation distance so that ASR operations and production well operations impacts would be minimized

### 2.7.1 Risk Management and Phasing

Phased development effectively manages risk, such as current uncertainty regarding individual well yields, aquifer hydraulic characteristics, concentrate disposal options or potential changes in the legal and regulatory framework.

Successful ASR implementation is best achieved by development in phases. Lessons learned in each phase are then incorporated into plans for the next phase. In the first phase, test wells would be constructed to confirm potential individual well yields and aquifer hydraulic characteristics. Test wells would include one full-sized ASR well and one full-sized production well, plus several monitor wells.

For the desalination facility, phasing is also beneficial. However, economies of scale are such that the structure is typically sized for potential ultimate capacity while membrane racks are provided to meet initial demands. As demands increase, additional membrane racks are added within the existing facilities.

# Section 3: BSEACD Water Supply and Demand

## 3.1 Permittees

The BSEACD has groundwater well permits issued to 91 customer entities totaling a permitted annual volume of 8,765 ac-ft per year. These entities are generally classified as municipal, domestic, commercial, and agricultural users; several of the municipal entities are identified water user groups in the 2017 Texas State Water Plan (2017 SWP).

## 3.2 Water Sources and Variability, Existing and Projected

The BSEACD regulates groundwater use from all aquifers in its jurisdictional area, primarily the Edwards Aquifer. The BSEACD has also granted some groundwater permits for use of the Trinity Aquifer. For discussion purposes of water supply, the focus area is solely on the Edwards Aquifer water supplies in Travis and Hays counties under jurisdiction of the BSEACD. In 2015, the jurisdictional area of the BSEACD was legislatively expanded to include additional area in Hays County for regulation of the Trinity Aquifer. This expanded area is not considered in the estimation of the groundwater supplies and demands.

BSEACD is located in Hays and Travis counties and is split between Regional Water Planning Groups K and L. Existing and future groundwater supplies are estimated from the 2017 SWP for the Edwards Aquifer in Travis and Hays Counties.

Table 3.1 Projected Groundwater Supplies

| | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 |
|---|---|---|---|---|---|---|
| Edwards Aquifer(1) | 12,274 | 12,229 | 12,190 | 12,152 | 12,103 | 12,052 |

Note:
(1) Edwards Aquifer supplies are shown in ac-ft per year.

As indicated previously, the primary objective for any ASR program at BSEACD would most likely be to provide seasonal storage, storing water during low demand (winter months) and recovering water during peak demand (summer months). However, to the extent that BSEACD may need to restrict local groundwater production during severe droughts, additional water volume could be stored in the ASR facility, providing a reserve storage capacity that is not governed by the regulatory restrictions on groundwater withdrawals from freshwater portions of the Edwards and Trinity aquifers.

## 3.3 Water Demand and Variability, Existing and Projected

Existing groundwater demands of the District are identified by quantifying all of the District's groundwater permits. Future groundwater demands are calculated as the water user group demand projections from the 2017 SWP and the existing permitted groundwater contracts for the remaining entities. The future demand estimates are low with respect to expected future BSEACD water supplies because the water user groups may have additional water supply sources to meet portions of their forecasted demand.

Table 3.2 Existing and Projected Groundwater Supplies

| Existing | 2020 | 2030 | 2040 | 2050 | 2060 | 2070 |
|---|---|---|---|---|---|---|
| 8,765 | 14,639 | 18,596 | 21,787 | 23,963 | 26,403 | 29,158 |

Note:
(1) Groundwater supplies are shown in ac-ft per year.

During each year, water demand will vary seasonally. For current project purposes, this variability is assumed to be as follows:

Ratio: Maximum Day Demand / Average Day Demand = 1.7 mgd
Maximum Month Demand / Average Day Demand = 1.3 mgd
Minimum Day Demand / Average Day Demand = 0.4 mgd

This is important for estimating the Target Storage Volume (TSV) for ASR wells. It is assumed that the desalination plant would operate at a steady rate of 5.0 MGD and includes sufficient redundancy of membranes and other process elements so that this rate can be maintained continuously without regularly scheduled downtime for major maintenance, repairs and periodic membrane replacement. Effective integration of ASR and desalination could then meet peak system demands of up to 7.2 MGD for the duration of a summer peak demand period.

## 3.4 Water Quality and Variability

The desalination model is based on water quality data provided from the multiport monitoring well (TWDB State Well Number 5858305) located at the southwest corner of the TDS property. The well was drilled in August 2016 to a depth of 1,100 feet. The well was completed with measurement and sampling ports in 18 zones, most of which are in the Edwards group. Zones 4-11 of the Saline Edwards Aquifer have sufficient hydraulic conductivities for groundwater production. Table 3.3 summarizes water quality data for zones 4-11 of the Saline Edwards Aquifer sampled in the fall of 2016, based on a total of 8 samples (one sample per zone). Input to the desalination model assumes an equal volume of water from each of these eight zones.

Table 3.3 TWDB State Well 5858305 Water Quality Statistics for Zones 4-11

| Parameter | Units | Minimum | Average | Maximum |
|---|---|---|---|---|
| Alkalinity, Bicarbonate Dissolved (mg/L), LAB | mg/L | 143 | 252 | 297 |
| Alkalinity, Carbonate Dissolved (mg/L), LAB | mg/L | 20 | 20 | 20 |
| Alkalinity, Hydroxide Dissolved (mg/L), LAB | mg/L | 20 | 20 | 20 |
| Alkalinity, Phenolphthalein (mg/L) | mg/L | 20 | 20 | 20 |
| Alkalinity, Total (mg/L AS CACO3) | mg/L | 143 | 252 | 297 |
| Aluminum, Dissolved (ug/L AS AL) | ug/L | 4 | 7 | 10 |
| Anion/Cation Chg Bal, Percent | Pct | -3 | 1 | 4 |
| Antimony, Dissolved (ug/L AS SB) | ug/L | 2 | 2 | 4 |
| Arsenic, Dissolved (ug/L AS AS) | ug/L | 8 | 10 | 11 |
| Barium, Dissolved (ug/L AS BA) | ug/L | 4 | 10 | 18 |
| Beryllium, Dissolved (ug/L AS BE) | ug/L | 1 | 3 | 5 |

Table 3.3 TWDB State Well 5858305 Water Quality Statistics for Zones 4-11 (continued)

| Parameter | Units | Minimum | Average | Maximum |
|---|---|---|---|---|
| Bicarbonate ION, Calculated (mg/L AS HCO3) | mg/L | 175 | 308 | 362 |
| Boron, Dissolved (ug/L AS B) | ug/L | 5130 | 7656 | 8850 |
| Bromide, Dissolved, (mg/L AS BR) | mg/L | 52 | 62 | 72 |
| Cadmium, Dissolved (ug/L AS CD) | ug/L | 1 | 3 | 5 |
| Calcium, Dissolved (mg/L AS CA) | mg/L | 773 | 1007 | 1110 |
| Carbonate ION, Calculated (mg/L AS CO3) | mg/L | 0 | 0 | 0 |
| Chloride, Dissolved (mg/L AS CL) | mg/L | 6240 | 8274 | 9610 |
| Chromium, Dissolved (ug/L AS CR) | ug/L | 1 | 3 | 4 |
| Cobalt, Dissolved (ug/L AS CO) | ug/L | 1 | 4 | 6 |
| Copper, Dissolved (ug/L AS CU) | ug/L | 2 | 22 | 51 |
| Deuterium, Expressed as PERMIL VSMOW | 0/00 | -29 | -28 | -27 |
| Fluoride, Dissolved (mg/L AS F) | mg/L | 2.80 | 3.09 | 3.79 |
| Hardness, Total, Calculated (mg/L AS CACO3) | mg/L | 3834 | 4856 | 5284 |
| Iron, Dissolved (ug/L AS FE) | ug/L | 50 | 236 | 2500 |
| Lead, Dissolved (ug/L AS PB) | ug/L | 1 | 3 | 5 |
| Lithium, Dissolved (ug/L AS LI) | ug/L | 3350 | 3995 | 4720 |
| Magnesium, Dissolved (mg/L AS MG) | mg/L | 457 | 562 | 615 |
| Manganese, Dissolved (ug/L AS MN) | ug/L | 2 | 4 | 140 |
| Mercury, Dissolved (ug/L AS HG) | ug/L | 0 | 0.20 | 0.20 |
| Molybdenum, Dissolved (ug/L AS MO) | ug/L | 1 | 1.88 | 2.00 |
| Nitrate Nitrogen, Dissolved, Calculated (mg/L AS NO3) | mg/L | 0 | 0.08 | 0.10 |
| Nitrite Plus Nitrate, Dissolved (mg/L AS N) | mg/L | 0 | 0.08 | 0.10 |
| Oxygen-18, Expressed AS PERMIL VSMOW | 0/00 | -4 | -3.96 | -3.79 |
| pH (STANDARD UNITS), FIELD | SU | 7 | 6.71 | 6.76 |
| Phosphorus, Dissolved (mg/L AS P) | mg/L | 0 | 0.02 | 0.04 |
| Potassium, DissolveD (mg/L AS K) | mg/L | 98 | 123 | 137 |
| Residual Sodium Carbonate, Calculated |  | 0 | 0 | 0 |
| Selenium, DissolveD (ug/L AS SE) | ug/L | 41 | 50 | 65 |
| Silica, Dissolved (mg/L AS SI02) | mg/L | 11 | 18 | 28 |
| Silver, Dissolved (ug/L AS AG) | ug/L | 5 | 29 | 50 |
| Sodium Adsorption Ratio, Calculated (SAR) |  | 24 | 26 | 28 |
| Sodium, Calculated, Percent | Pct | 64 | 66 | 66 |
| Sodium, Dissolved (mg/L AS NA) | mg/L | 3340 | 4220 | 4660 |
| Specific Conductance, Field (Umhos/Cm At 25c) | Micr | 22200 | 24513 | 26200 |
| Strontium, Dissolved (ug/L AS SR) | ug/L | 18900 | 22238 | 24800 |
| Strontium, Isotope of Mass 86 And 87 Ratio | N/A | 1 | 1 | 1 |

Table 3.3 TWDB State Well 5858305 Water Quality Statistics for Zones 4-11 (continued)

| Parameter | Units | Minimum | Average | Maximum |
|---|---|---|---|---|
| Sulfate, Dissolved (mg/L AS SO4) | mg/L | 2070 | 2329 | 2540 |
| Temperature, Water (CELSIUS) | C | 24 | 25.2 | 26 |
| Thallium, Dissolved (ug/L AS TL) | ug/L | 1 | 3 | 5 |
| Total Dissolved Solids , Sum Of Constituents (mg/L) | mg/L | 13541 | 16707 | 18622 |
| Uranium, Natural, Dissolved (ug/L AS U) | ug/L | 1 | 3 | 5 |
| Vanadium, Dissolved (ug/L AS V) | ug/L | 1 | 2 | 2 |
| Zinc, Dissolved (ug/L AS ZN) | ug/L | 5 | 9 | 10 |

The above water quality data was collected from one sampling well at one point in time and could vary across the TDS property and over time. Below Zone 12 of the multiport monitoring well, this brackish groundwater has an average TDS of close to 17,000 mg/L, approximately half that of seawater. This is referred to as the "lower Edwards Aquifer." Levels of calcium, sulfate, iron, and silica could lead to scaling. Other potentially problematic species for treatment and concentrate disposal include arsenic and boron. Zone 12 is a semi-confining layer, approximately 22 feet thick, known locally as the "Regional Dense Member (RDM)." Above Zone 12 is the "Upper Edwards Aquifer," which is proposed for use for ASR storage. Average TDS of this upper aquifer is approximately 9,000 mg/l TDS.

For current project purposes, it is assumed that production wells in the Lower Edwards Aquifer would each produce 1,500 gallons per minute (gpm) and that ASR wells in the Upper Edwards Aquifer would each produce 500 gpm. Construction and testing of wells will be needed to confirm or modify these estimates.

## 3.5 Infrastructure and Interconnections, Existing and Planned

The most relevant interconnections for the proposed project are potable water transmission pipelines. Maps in Appendix A – Maps (Figure 2) shows proximity to existing water and wastewater lines in the area, including an existing adjacent 42-inch potable water transmission pipeline. This 42-inch main water is part of the City of Austin's water distribution system and runs along Bradshaw Road to the west of TDS property.

## 3.6 Desalination Planned Capacity and Phasing

The desalination facility is planned to ultimately treat a feed flow of 6.48 mgd, the total from three wells pumping 1500 gpm each. At a recovery of 76 percent, this 2-pass desalination facility will have a product flow of 4.94 mgd and a concentrate flow of 1.54 mgd.

The 5 mgd production desalination facility design was scaled down to 2.5 mgd based on cost curves to provide a cost estimate for a smaller initial facility that could eventually reach a buildout to 5 mgd. The 2.5 mgd facility might be more realistic than a 5 mgd facility if well production levels or consumer demand are lower than initially anticipated.

The assumed well production rates referenced in this report are conceptual in nature and were used only to establish a desalination feed water supply target for conceptual designs. If implemented, the alternatives described herein could be modified to supply larger or smaller volumes of water based on production data from test wells to be drilled before the detailed design phase.

## 3.7 Wellfield Phasing

As described in Section 3: Hydrogeology, individual well yields are currently unknown. Construction and testing of full-size test wells will be required to confirm these yields. However, data has been obtained from the multiport monitoring well at the site, providing a reasonable basis for estimating preliminary well yields. For the producing interval in the upper Edwards Aquifer, a reasonable estimate for planning purposes is 500 gpm. This would be the interval selected for ASR wells since it is relatively thin, has lower salinity and reasonable vertical confinement. For the producing interval in the lower Edwards Aquifer, a reasonable estimate for planning purposes is 1,500 gpm. This interval is much thicker, has higher salinity and limited vertical confinement, and would be utilized for brackish water production wells supplying the desalination plant.

During the initial phase of wellfield development, at least two demonstration wells and four monitor wells would be constructed, as follows:

- **ASR Demonstration Well AD-1**: Northeast corner of the site; completed in the upper Edwards Aquifer producing interval.
- **ASR Monitoring Well AM-1:** Located 200-300 feet from AD-1; completed in the upper Edwards Aquifer producing interval.
- **ASR Monitoring Well AM-2**: Located 200-300 feet from AD-1; completed at the top of the lower producing zone of the brackish lower Edwards Aquifer (Zone 11 of the multiport monitoring well).
- **Production Demonstration Well PD-1**: Southwest corner of the site; completed in the lower Edwards Aquifer producing interval. It would make more sense to put the initial Production Demonstration Well at the Desal Plant, reducing or eliminating the need for a long pipeline to a test well.
- **Production Monitoring Well PM-1**: Located close to PD-1, completed in the upper Edwards Aquifer producing interval.
- **Production Monitoring Well PM-2:** Located close to PD-1, completed in the lower Edwards Aquifer producing interval to support aquifer pump tests analysis.

Additional wells may also be constructed during the initial phase, such as an exploratory hole to the Lower Trinity Aquifer to determine whether it may be suitable for disposal of concentrate from the desalination plant.

During subsequent phases of wellfield development, two more ASR wells and two more production wells would be constructed, as shown on the map in Appendix A – Maps (Figure 3). As shown in the map, ASR wells in Alternative A would extend along the northeastern side of the TDS site, in a straight line, spaced about 1000 feet apart. Production wells would extend along the western side, providing maximum separation distance between the two sets of wells, not only about two miles horizontally but also vertically. The actual ASR and production well locations will be refined based on demonstration well data and available sites during a design phase. A thin confining layer separates the upper and lower portions of the Edwards Aquifer. Total installed ASR well capacity would be 1,500 gpm (2.2 mgd) from a total of 3 wells. Firm yield of the ASR wells, with one well out of operation, would be 1,000 gpm (1.4 mgd).

Total installed production well capacity would be 4,500 gpm (6.5 mgd) from a total of 3 wells. Firm capacity of the production wells, with one well assumed to be out of operation, would be 3,000 gpm (4.3 mgd). Desalination production well capacity required is estimated at about 6.8 mgd. Either a fourth production well or slightly higher production than 1,500 gpm will be required from each of the three currently planned production wells.

The anticipated well locations are shown on the map in Appendix A -Maps (Figure 3).

## 3.8 Target Storage Volume (TSV)

The Target Storage Volume (TSV) for the ASR wells on the TDS site is the sum of the volume required for recovery to meet BSEACD water needs, plus the volume required for a buffer zone to separate the stored drinking water from the surrounding brackish water. The buffer zone is like the walls of a tank. Once formed, the buffer zone is not pumped out. It is a one-time addition of water to the well and is often considered to be an element of the well construction and development cost. Initially forming and maintaining a buffer zone at many other ASR sites in brackish, limestone aquifers has been effective at controlling arsenic concentrations and meeting other water quality criteria in the recovered water. The buffer zone volume is initially estimated to equal the recovered water volume for this site, preliminarily estimated at 130 MG.

Based on similar ASR sites, a preliminary estimate of the TSV for the first phase of ASR wellfield development is 130 MG (400 acre feet) to meet seasonal peak water demands. Two years would probably be required to achieve the TSV. Target recovery would occur during three months of the year at 500 gpm, resulting in recovery of 65 MG. For a single ASR well during the first year of operations, recharge would occur for up to seven months of the year at about 400 gpm (0.6 mgd), resulting in storage of up to approximately 100 MG during October to April. About half of this water would then be recovered, providing 500 gpm for up to 69 days. The difference of about 50 MG during the first year would be left underground, helping to form the buffer zone. The final buffer zone volume would be achieved during the second year, enabling recovery of stored water at 500 gpm for 90 days.

The assumed recharge flow rate of 400 gpm is a preliminary estimate pending construction and testing of an initial ASR well. Recharge specific capacity (gpm per foot of water level rise) is almost always less than recovery specific capacity (gpm per foot of water level decline). For a deep, consolidated limestone aquifer such as is present at the TDS site, a ratio of 80 percent is a conservative initial estimate. Available recharge pressure will depend upon the discharge pressure from the desalination plant or from the 42-inch pipeline. Available drawdown during recovery will depend upon several factors, including the leakance of the Zone 12 Regional Dense Member which comprises the lower confining layer for ASR operations. ASR wells are typically operated so that the drawdown that can be provided by pumping the well exceeds the increase in water levels during recharge periods, so that any particulates clogging the ASR well can be periodically purged to waste by backflushing the well.

Experience gained during the first two years of ASR operations would then provide a firm basis for adjusting the TSV for the initial well so that water quality standards and goals are met when the ASR wellfield is expanded to three wells in the second phase. At that time, the TSV would be reevaluated so that it achieves not only seasonal objectives but also drought reliability objectives. A greater volume would be stored, capable of sustaining recovery during a sustained drought. Providing water supply reliability during a repeat of the Drought of Record (DOR) is a possible goal for BSEACD, although great benefit would also be achieved with a less ambitious objective. The DOR lasted 10 years, however even during that period there were rainfall events, some of which were substantial. Such events would be opportunities for ASR recharge.

A detailed analysis of water supplies, water demands, interlocal agreements, water reliability goals and other factors would be required to prepare an estimate of the TSV required for subsequent phases of ASR wellfield expansion, however it is likely to be on the order of a few thousand acre feet. With the City of Austin 42-inch pipeline as a potential connecting artery, the TDS site could be one of several ASR wellfields serving BSEACD and the City of Austin.

### 3.8.1 Seasonal Variation in Demand

ASR storage of desalinated drinking water during five winter months and recovery of the stored water during three summer months is a reasonable preliminary operating scenario for planning purposes.

For a seasonal water storage program, the duration of recovery would typically vary from 60 to 120 days, based upon experience at other ASR wellfields. For current planning purposes, an ASR recovery period of 90 days is assumed.

### 3.8.2 Long-term Storage, or "Water Banking"

After the first two years of operations at the initial ASR well and estimation of the TSV for an expanded wellfield, the operations schedule would most likely be adjusted to match actual monthly variability in distribution system water supplies and demands, not only for BSEACD but perhaps also to meet a portion of the water needs for other water providers in the area. The 5.0 MGD supply of water from the desalination plant would be steady except for approximately every five years when reverse osmosis membranes would need to be replaced. Demand and supply from the transmission and distribution system would be variable, depending in part upon ASR objectives and duration of recovery.

For an expanded ASR wellfield, it is reasonable to assume that a second ASR objective of providing long term storage, or "water banking," would be established, in addition to meeting seasonal variability in demand. The rate of ASR recovery, assumed to be 2 mgd, is assumed to be constant. A higher recovery rate may also be appropriate. The duration of recovery would still be variable. There would be several extended recovery periods over a drought duration of several years. Based upon analysis of this variability at other Texas locations, the longest duration of a continuous recovery period might be several months to almost a year, interspersed with shorter-than-normal recharge periods. The steady supply of drinking water from the desalination plant would tend to moderate variability in ASR operations.

# Section 4: Hydrogeology

## 4.1 Overview of BSEACD Hydrology Report

Brian A. Smith, Brian B. Hunt, and Bruce Darling of BSEACD, coauthored a report titled "Hydrogeology of the Saline Edwards Zone, Southeast Travis County, Central Texas," completed in October 2017. The study area location map is shown below in Figure 4.1. Portions of their report were used to assume hydrogeology elements for our recommendations in this report. This section gives a brief overview with excerpts from the report, which is attached in full as Appendix E – Hydrogeology Report.

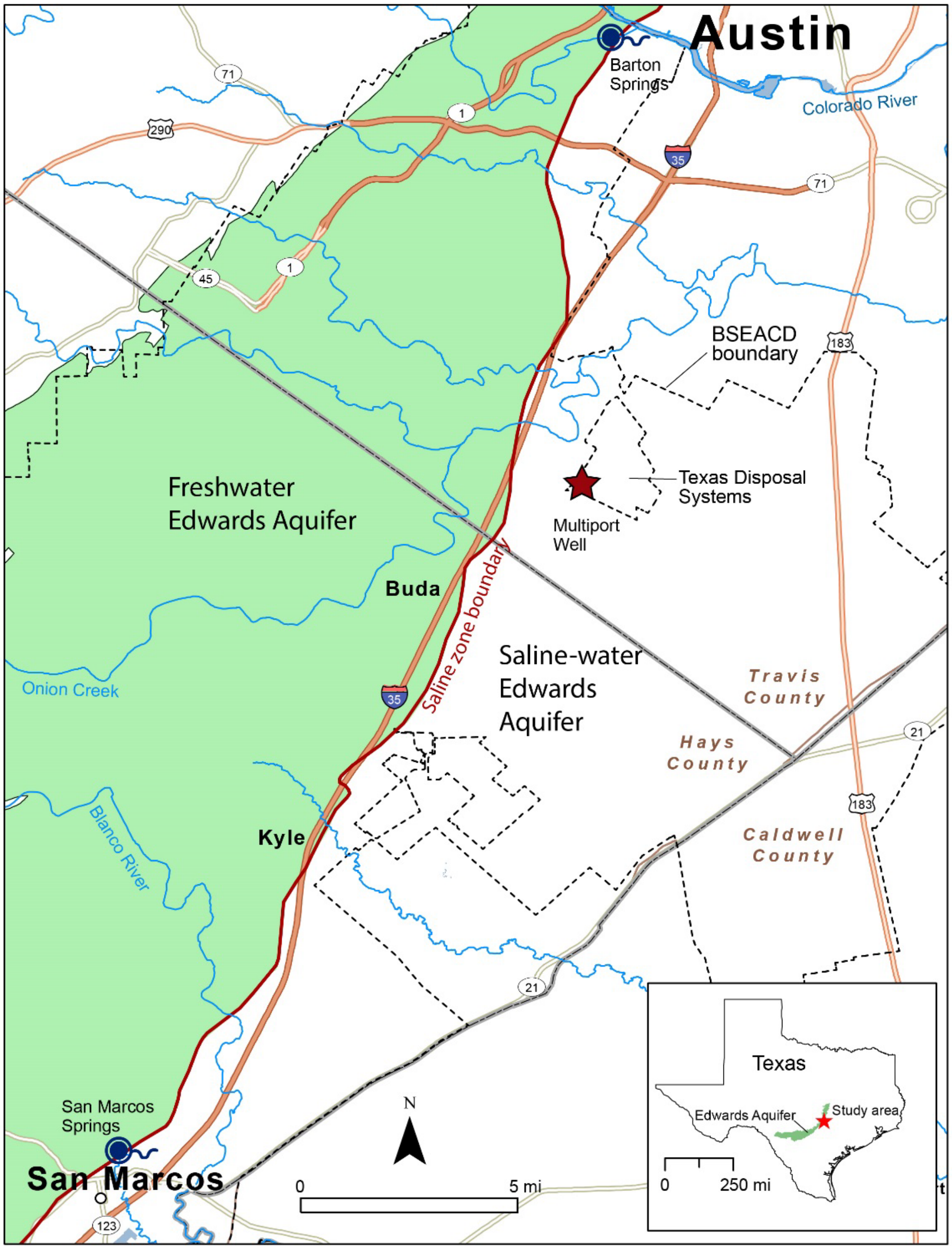


Figure 4.1 Hydrogeologic Study Area Location Map

The saline Edwards Aquifer is defined as the Edwards Group rock units that contain water with greater than 1,000 mg/L total dissolved solids. The saline Edwards Aquifer occurs east (in the Austin area) and south (in the San Antonio area) of the freshwater Edwards Aquifer. Because of limitations placed on pumping the freshwater Edwards Aquifer, the saline Edwards Aquifer has been viewed as a potential alternative source of water for desalinization or as a reservoir for aquifer storage and recovery (ASR). Given the closed system of the saline Edwards Aquifer, a combination of desalinization and ASR may be a sustainable strategy. BSEACD and other groundwater conservation districts regard the saline zone as an alternative water supply that poses little threat to the freshwater Edwards, and could in fact can lessen demands placed upon it.

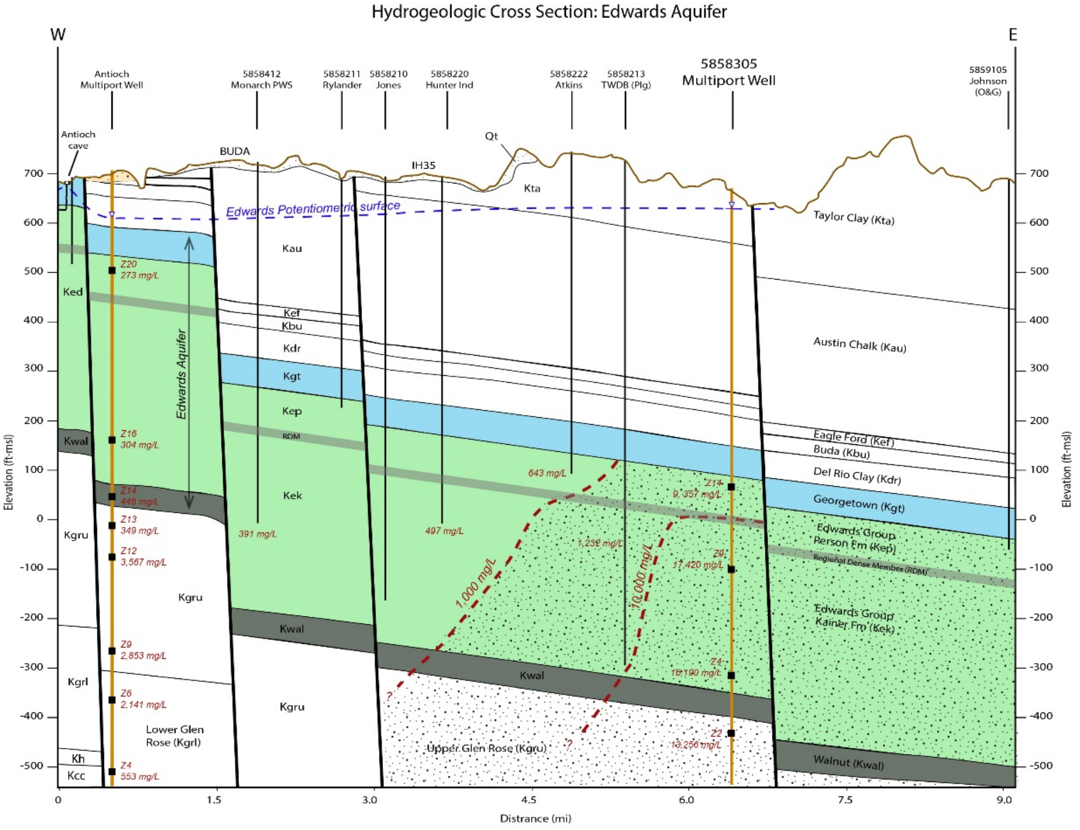


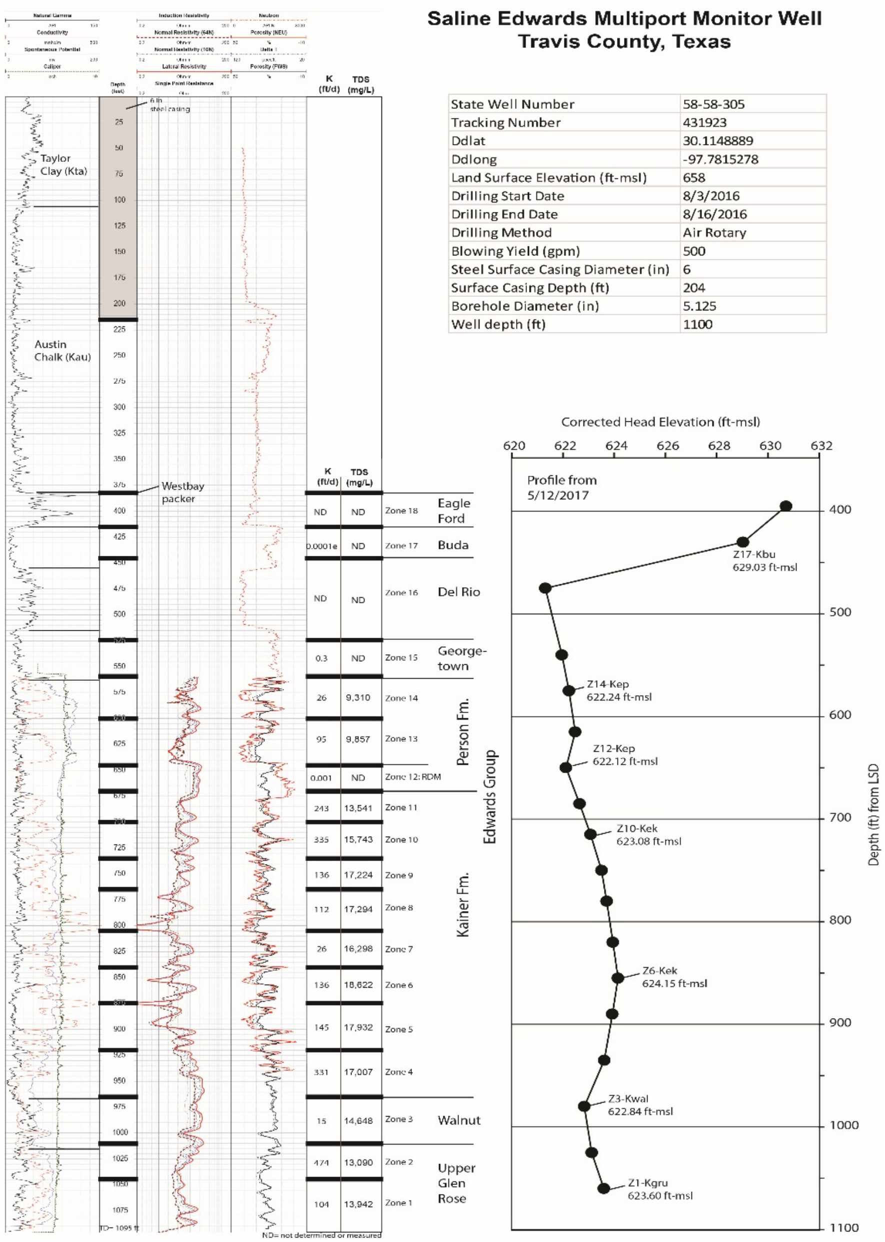
Figure 4.2 Hydrogeologic Cross Section: Edwards Aquifer

The installation of a multiport monitor well, and the data it provides, is central to the hydrogeologic characterization of the saline Edwards Aquifer and is the focus of the BSEACD hydrology report. The multiport well provides detailed hydrogeologic data that are critical for characterizing the saline Edwards Aquifer in the study area. Some conclusions from this study include:

- Heads are generally higher in the saline Edwards than the freshwater Edwards Aquifer, with a potential for flow toward the freshwater/saline-water interface.
- Vertical flow potential is variable. There is downward flow potential from the upper Edwards (Person) to the lower Edwards (Kainer Fm), and there is upward flow potential from the Upper Glen Rose to the lower Edwards (Kainer Fm).
- The overlying geologic units (Georgetown, Del Rio, Buda, Eagle Ford) confine the underlying saline Edwards Aquifer.
- The Person (111 feet thick) and Kainer Formations (292 feet thick) of the Edwards Group appear to be hydrologically isolated from each other due to the regional dense member (22 feet thick), as determined by this study and as noted in other publications.
    - The regional dense member is likely to provide some confinement between the Person and Kainer Formations over a large area.

- The upper Edwards (Person Fm) has an average transmissivity of 2,400 $ft^2$/d. The Kainer has an average of 7,100 $ft^2$/d.
- Estimates indicate relatively high-yielding wells are possible in the saline Edwards, with yields greater than 1,000 gpm. This is consistent with other studies.
- Saline waters are sodium-chloride waters with a range in TDS of 9,000 to 17,900 mg/L. The Kainer Formation had the highest TDS, followed by the Upper Glen Rose and then the Person Formation.
- Results from the multiport monitor well suggest that the saline Edwards Aquifer can serve as a reservoir for ASR and as a source of water for a desalination facility.

A figure of the multiport monitoring well is shown below in Figure 4.3.



Saline Edwards Multiport Monitor Well
Travis County, Texas

| | |
|---|---|
| State Well Number | 58-58-305 |
| Tracking Number | 431923 |
| Ddlat | 30.1148889 |
| Ddlong | -97.7815278 |
| Land Surface Elevation (ft-msl) | 658 |
| Drilling Start Date | 8/3/2016 |
| Drilling End Date | 8/16/2016 |
| Drilling Method | Air Rotary |
| Blowing Yield (gpm) | 500 |
| Steel Surface Casing Diameter (in) | 6 |
| Surface Casing Depth (ft) | 204 |
| Borehole Diameter (in) | 5.125 |
| Well depth (ft) | 1100 |

| K (ft/d) | TDS (mg/L) | | |
|---|---|---|---|
| ND | ND | Zone 18 | Eagle Ford |
| 0.0001e | ND | Zone 17 | Buda |
| ND | ND | Zone 16 | Del Rio |
| 0.3 | ND | Zone 15 | Georgetown |
| 26 | 9,310 | Zone 14 | Person Fm. |
| 95 | 9,857 | Zone 13 | |
| 0.001 | ND | Zone 12: RDM | |
| 243 | 13,541 | Zone 11 | Kainer Fm. |
| 335 | 15,743 | Zone 10 | |
| 136 | 17,224 | Zone 9 | |
| 112 | 17,294 | Zone 8 | |
| 26 | 16,298 | Zone 7 | |
| 136 | 18,622 | Zone 6 | |
| 145 | 17,932 | Zone 5 | |
| 331 | 17,007 | Zone 4 | |
| 15 | 14,648 | Zone 3 | Walnut |
| 474 | 13,090 | Zone 2 | Upper Glen Rose |
| 104 | 13,942 | Zone 1 | |

ND= not determined or measured

Figure 4.3 Saline Edwards Multiport Monitor Well

# Section 5: Desalination

## 5.1 Desalination of Saline Groundwater from the Edwards Aquifer

The conceptual design for the desalination of saline groundwater from the Edwards Aquifer begins with the well field siting and collection system. Options for desalination treatment and disposal of the resulting concentrate are evaluated. Energy requirements from desalination treatment models are compared to predict the energy required to operate the facility.

### 5.1.1 Well Field and Collection System

Zones 4-11 from the multiport well information are in the lower Edwards Aquifer and are characterized by abundant amounts of saline groundwater. The three proposed desalination production wells will be sized to pump 1,500 gpm each from the lower Edwards Aquifer. The desalination production wells will be located along the western side of the TDS property with one north, one central, and one south near the existing multiport monitoring well, as shown in Appendix A – Maps (Figure 3). The actual production well locations will be refined based on demonstration well data and available sites. Hydraulic communication between the upper and lower Edwards is expected to be limited because of the regional semi-confining unit and the horizontal distance between the ASR wells and the production wells. The distance between the ASR wells and saline production wells will tend to minimize the head differential across the semi-confining unit. As shown on in Appendix A -Maps (Figure 3), ASR wells located at the Alternative A site would have significantly greater separation distance from the production wells compared to Alternative B.

Well pumps will be installed in the production wells to extract groundwater and deliver it to the desalination facility. Wellhead construction will consist of valves and piping, gravel paving, and fencing. An estimated 1.5 miles of 14-inch HDPE pipe will be required to convey groundwater from the wells to the desalination facility. It is assumed that the well pumps will have sufficient power to pump the water to the desalination facility. It is possible that water levels for the production wells could steadily decline with time due to pumping; however, sign specific well performance data and tests will provide additional information when the wells are drilled.

### 5.1.2 Desalination Treatment Options

Desalination technology options may be defined as pressure-driven, electrically-driven, and thermal. Reverse osmosis (RO), electro dialysis reversal (EDR), and multi-effect distillation (MED). Each technology is briefly described below.

RO membranes are the standard recommended treatment technology for desalination of brackish water. RO is a desalting process that rejects dissolved constituents and produces a concentrated reject stream. When used for groundwater desalination, the main treatment objective is typically the removal of dissolved solids. Brackish groundwater typically has a low concentration of total suspended solids (TSS) and membrane pretreatment (such as microfiltration (MF) or ultrafiltration (UF)) is not required. Typically, disposable cartridge filters are installed directly upstream of the RO membranes to protect the membranes from any small particles. One-pass RO systems are standard for brackish water desalination, but two-pass systems in which the product water from the first pass is feedwater for a second pass are sometimes required to deal with high TDS or problematic contaminants.

EDR is a desalting process that applies an electric current directly to a “stack” of alternating semipermeable membranes. These membranes allow either cations or anions to pass through, creating alternate compartments of brine and product water. EDR is well suited to treat slightly brackish groundwater, but is usually not the best choice for water with TDS over 10,000 mg/L. EDR also results in a waste concentrate stream requiring disposal.

MED is commonly used in seawater desalination plants. MED units consist of multiple stages, or effects, maintained at decreasing levels of pressure and temperature. As the pressure drops at each stage, so does the temperature required to boil water. The steam collected from boiling water at each stage is used to heat the next stage, saving energy. MED is more energy efficient than other thermal evaporative technologies due to the beneficial use of waste heat in the boiling process, but its energy costs remain high compared to those for RO and EDR. Other thermal desalination technologies may be used in zero liquid discharge applications (see Section 4.1.3.6).

RO membrane systems are the most commonly used desalination technology for drinking water applications. Based on the water quality data for the Edwards Aquifer at this location, RO membranes are recommended for the desalination process.

### 5.1.3 Conceptual Desalination Design

A conceptual design[1] for desalination was developed for a 5 mgd reverse osmosis (RO) membrane water treatment plant (MWTP). Average groundwater quality from Table 2.3 was input to the model for an influent TDS of approximately 17,000 mg/L. Flows in this section refer to the 5 mgd Phase 2 MWTP, and can be halved for the Phase 1 2.5 mgd MWTP.

#### 5.1.3.1 Pre-Treatment

Pretreatment of the pumped groundwater will include injection of sulfuric acid and antiscalant followed by cartridge filtration. The acid and antiscalant are used to minimize inorganic scaling on the membranes. The scaling potential of the RO concentrate limits water recovery from the system. High levels of sulfate and carbonate in the brackish groundwater are concentrated in the brine stream, resulting in oversaturation of calcium sulfate and calcium carbonate. Antiscalant modeling software[2] was used to determine the proper antiscalant dosage to feed to maximize recovery. An antiscalant that provides a high level of sulfate inhibition was assumed for use in this application to reduce the calcium sulfate scaling potential allowing up to 80 percent system recovery.

The Langelier Saturation Index (LSI) is a calcium carbonate solubility-derived index, which indicates the tendency for water to precipitate dissolved calcium carbonate as scale. A maximum LSI of 2 to 2.5 for the RO concentrate is recommended to prevent scaling. Setting the upper limit for LSI in the concentrate at 2.5 results in maximum recoveries of 78 percent and 76 percent, respectively, for the one-pass and two-pass models[3].

Cartridge filtration will be used for additional particle removal to protect the RO membranes from particles larger than 5 microns.

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[1] Toray Design System 2 (Toray DS2) software was used

[2] Avista Advisor Ci was used

[3] Based on Toray DS2 model output

### 5.1.3.2 Membrane Treatment

Challenges regarding boron levels in the groundwater and scaling in the concentrate drove the MWTP design. Models were developed for a one-pass RO system without effective boron removal. Therefore, a two-pass system was modeled that reduced boron to below guideline levels.

Boron is not regulated by the EPA, but the World Health Organization has set a preliminary limit of 0.5 mg/L for drinking water based on reproductive dangers and suspected teratogenic properties[4]. Additionally, boron causes leaf damage to sensitive plants and crops at levels of more than 0.3 mg/L in irrigation water[5] and reduces fruit yield. RO systems at or near neutral pH do not effectively remove boron, but increasing the pH significantly improves boron removal. The one-pass RO model developed here projects a product water boron concentration of 2.1 mg/L, which would not be suitable for all types of agriculture and could threaten human health. Therefore, a two-pass RO model with chemical addition to increase pH to 11 before the second pass was developed. The two-pass model projects a safe product water boron concentration of 0.1 mg/L, at the cost of adding chemical addition and RO units for a second pass and achieving a lower recovery.

The one-pass RO system was designed to recover 78 percent of 4,500 gpm of feedwater with low-energy seawater RO membranes, resulting in 3,510 gpm of product water and 990 gpm of concentrate. Figure 4.1 below shows the process flow diagram for this model from the Toray Design System 2 software. A total of 144 RO vessels with 6 elements each are split into two stages, with 96 in the first and 48 in the second. The product water has a TDS of 101 mg/L. A generic turbocharger with 71 percent efficiency was included in the model as an energy reduction device (ERD). A turbocharger uses excess pressure from the high pressure concentrate stream to reduce the feed pump energy required to achieve the membrane feed pressure.

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[4] World Health Organization (WHO), Guidelines for drinking-water quality, 2nd ed. Addendum to Vol. 1. Recommendations. Geneva, 1998. pp. 4-6.

[5] Environmental Protection Agency (EPA). 1975. Preliminary investigation of effects on the environment of boron, indium, nickel, selenium, tin, vanadium and their compounds. Vol. 1. Boron. US Environmental Protection Agency Rep. 56/2-75-005A.

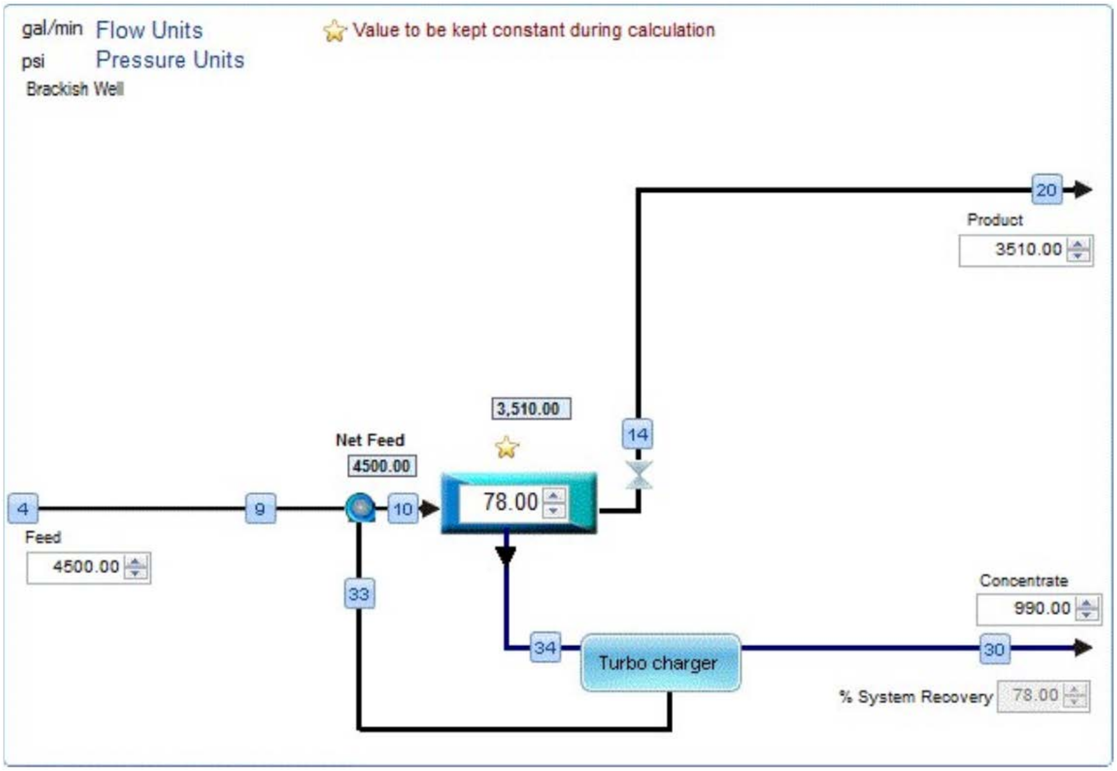

Figure 5.1 One-Pass RO Model Conceptual Process Flow Diagram – Using Toray DS2

The two-pass RO system was designed to recover 76 percent of 4,500 gpm of feedwater with:

- **Pass One:** low-energy seawater RO membranes with a total of 180 RO vessels containing 6 elements each, split into two stages – 120 RO vessels in the first stage and 60 RO vessels in the second stage
- **Pass Two:** low-pressure brackish water RO membranes with a total of 120 RO vessels containing 6 elements each, split into two stages – 80 vessels in the first stage and 40 vessels in the second stage

This two-pass system is expected to result in 3,429 gpm of product water and 1,071 gpm of concentrate. Figure 4.3 below shows the process flow diagram for this model from the Toray Design System 2 software. Chemical addition after pass one raises the pH to enhance boron rejection. The product water has a TDS of 7 mg/L. A generic turbocharger with 71 percent efficiency was included in the model as an energy reduction device (ERD).

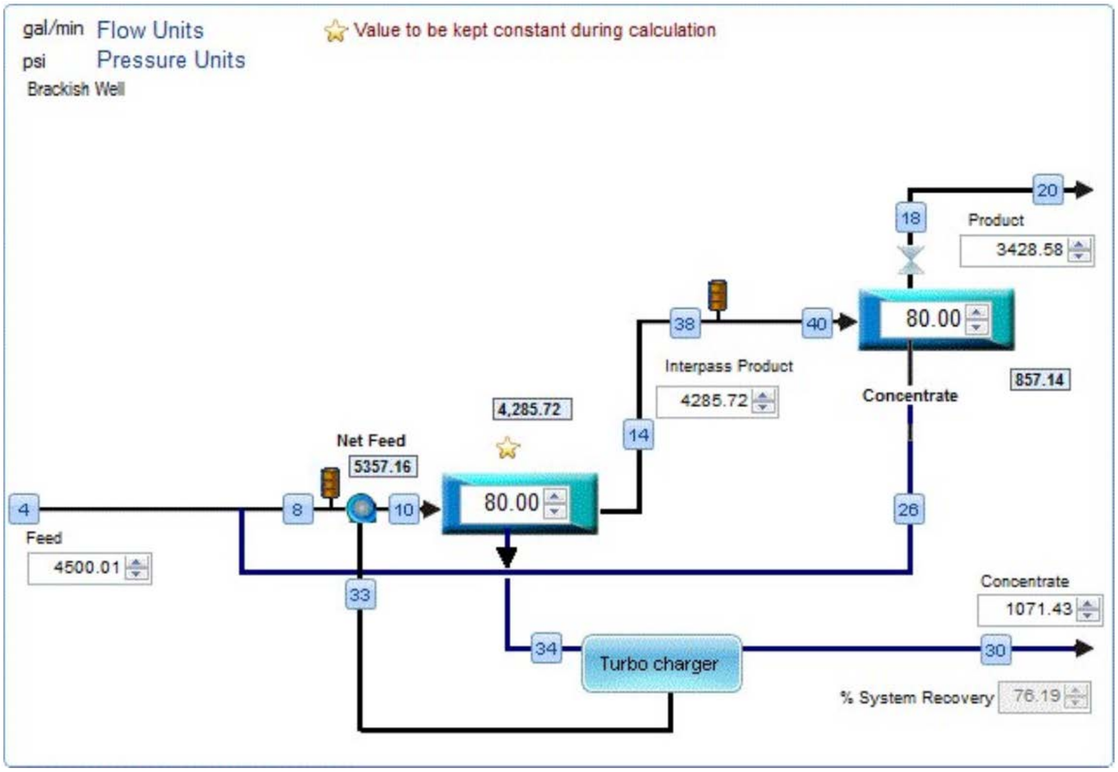
gal/min Flow Units
psi Pressure Units
Brackish Well
Value to be kept constant during calculation
Feed 4500.01
Net Feed 5357.16
Interpass Product 4285.72
Product 3428.58
Concentrate 1071.43
% System Recovery 76.19

Figure 5.2 Two-Pass RO Model Conceptual Process Flow Diagram – Using Toray DS2

Figure 5.3 below shows a simplified process flow diagram from well to distribution for the overall two-pass RO process that would produce a good quality water.

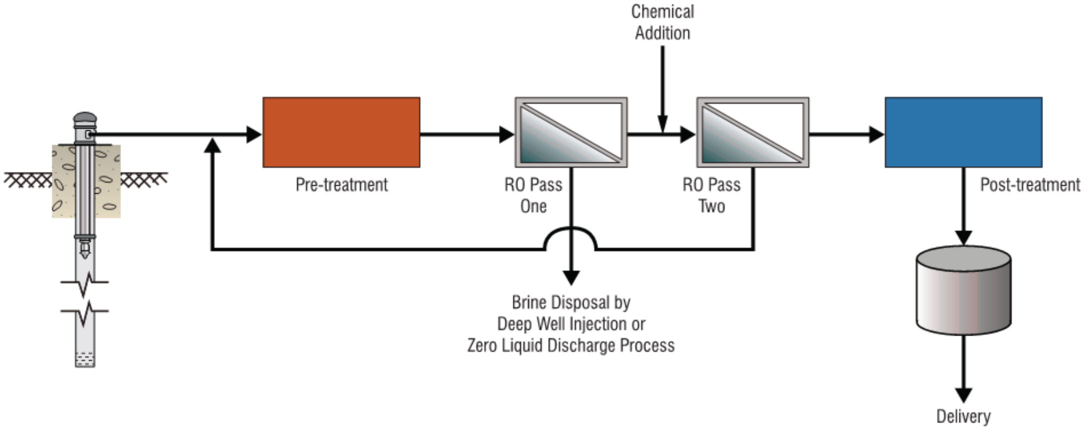

Figure 5.3 Overall Process Flow Diagram with Two-Pass RO

#### 5.1.3.3 Post-Treatment

Minerals are often added to water after RO treatment for stability in conveyance and use:

- The one-pass RO system's product water has a low pH of 4.8 that requires addition of lime or caustic soda in post-treatment to increase stability.
- The two-pass RO system's product water has high pH and low TDS that will require post-treatment adjustment. The product water's high pH of 10.4 requires acid and calcium carbonate addition in post-treatment to stabilize for drinking water distribution or for ASR recharge. The expected TDS of 7 mg/L requires mineral addition for stability.

Post-treatment of the water provided for ASR storage may also be needed to condition the aquifer so that physical, microbial and geochemical reactions do not occur or can be controlled to acceptable levels through operational measures. Possible measures might include disinfection, pH adjustment, and/or alkalinity adjustment, plus formation and maintenance of a buffer zone.

#### 5.1.3.4 Concentrate Disposal

Several alternatives were examined for disposal of the brine from the desalination process:

1. Deep Well Injection
    - Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County.
    - Trinity Injection Wells on TDS Property.
    - Edwards Injection Wells in Caldwell County.
2. Zero Liquid Discharge

#### 5.1.3.5 Deep Well Injection

Concentrate disposal via deep well injection involves conveying the brine to the well site and into a porous, confined, subsurface rock formation at a high enough pressure to overcome the well backpressure. Deep well injection requires drilling a new well unless a suitable abandoned oil or gas well within pipeline range can be found.

Wells for injection of waste typically require an Underground Injection Control (UIC) permit along with close site monitoring. Texas has issued a General Permit authorizing the use of a Class I injection well to inject nonhazardous desalination concentrate or nonhazardous drinking water treatment residuals (TAC §331.201). Authorization under the General Permit requires submittal of a Notice of Intent to the TCEQ executive director addressing the required items specified in the General Permit (TAC §331.203). Hazardous constituents are constituents identified in Appendix VIII of 40 Code of Federal Regulations Part 261 that have been detected in groundwater in the uppermost aquifer underlying a regulated unit and that are reasonably expected to be in or derived from waste contained in a regulated unit (TAC §335.159). The Groundwater Protection Standard defined in TAC §335.158 is that hazardous constituents detected in groundwater do not exceed the concentration limits under TAC §335.160. Under this standard, the concentration of injected brine constituents must not exceed the background level of that constituent in the injection zone or must not exceed the value shown in Table 5.1, if the background level of that constituent is below the value in Table 5.1.

Table 5.1 Max Concentration of Constituents for Groundwater Protection (TAC§335.160) 4-11

| Constituent | Maximum Concentration (mg/L) |
|---|---|
| Arsenic | 0.05 |
| Barium | 1.0 |
| Cadmium | 0.01 |
| Chromium | 0.05 |
| Lead | 0.05 |
| Mercury | 0.002 |
| Selenium | 0.01 |
| Silver | 0.05 |
| Endrin | 0.0002 |
| Lindane | 0.004 |
| Methoxychlor | 0.1 |
| Toxaphene | 0.005 |
| 2-4-D | 0.1 |
| 2, 4, 5-TP Silvex | 0.01 |

The deep well injection alternative location for brine disposal will be selected based on background water quality relative to the brine.

This report assumes conservative injection well pressure requirements of 350 psi. Pressure requirements could vary widely depending on the local geology and need to be confirmed when a site is selected.

Based on reports[6,7] regarding injection wells in the region, the desalination project would likely require two injection wells sized at approximately 500 gpm each to dispose the full 1.5 mgd of concentrate generated with 76 percent recovery of 6.5 mgd of feedwater.

*Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County.* Use of one or more of the existing gas injection wells in the area should be investigated as a potentially less-costly alternative to drilling new injection wells. Several abandoned oil and gas wells in the Salt Flat (Edwards) Field have been repurposed as brine injection wells. However, the Salt Flat Field is approximately 35 miles from the proposed desalination facility. The capital and O&M costs for a concentrate pipeline this long are substantial. Additionally, piping brine this distance could lead to issues with brine stability and scaling due to the long residence time in the pipeline. Another issue is that many of these abandoned wells are very old and have mild steel casings that have likely rusted, or may do so if conveying brine.

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[6] Acquisition and Development of Selected Cost Data for Saline Storage and Enhanced Oil Recovery (EOR) Operations, U.S. Department of Energy National Energy Technology Laboratory, May 2014

[7] 2008 Joint Association Survey on Drilling Costs, American Petroleum Institute, April 2010

*Trinity Injection Wells on TDS Property.* Injection wells on TDS property into the Trinity Aquifer could be possible if the aquifer contains salinity greater than 10,000 mg/L. Aquifers of only moderate salinity with TDS of less than 10,000 mg/L are considered Underground Sources of Drinking Water (USDW) and not allowed to receive concentrate. Since the Trinity Aquifer underlies the saline Edwards Aquifer, there is a chance that the Trinity Aquifer is saline as well. Samples from a test well will be needed to verify the TDS concentration and other water quality parameters as well as the presence of suitable thickness of permeable sands.

Appendix A – Maps (Figure 3) shows a potential site for injection wells into the Trinity Aquifer on TDS property, approximately 1 mile east of the proposed desalination facility.

*Edwards Injection Wells in Caldwell County.* If deep well injection does not happen on the TDS property then another location will need to be located. Based on legislative rules the injection site would have to be outside of the county. The closest site for the injection wells to the east would be in Caldwell County and would require at least 11 miles of pipeline. Land could be acquired to drill injection wells into the saline Edwards Aquifer.

#### 5.1.3.6 Zero Liquid Discharge (ZLD)

Additional advanced treatment could reduce the volume of the concentrate stream or achieve a zero liquid discharge (ZLD) while recovering a larger portion of the brackish groundwater for potable use. The Water Research Foundation (WRF) sponsored a study on Zero Liquid Discharge Desalination in 2011[8]. Thermal desalination is used for conventional ZLD, but has a high energy cost. Treating RO concentrate to reduce its membrane fouling potential and then desalinating the treated concentrate with a second set of membranes, such as RO or electrodialysis, can achieve ZLD at a lower energy cost, depending on TDS. The 5 mgd, 2-pass brackish desalination facility with a projected recovery of 76 percent would produce 1.54 mgd of concentrate with a TDS of approximately 72,000 mg/L. According to the 2011 WRF study, thermal desalination was found to be less expensive than electrodialysis for concentrate streams with TDS of 5,300 mg/L and greater. Therefore, the ZLD cost estimate in this report is for thermal distillation with an evaporator and crystallizer. A brine concentrator is typically a mechanical water evaporator that works on single-effect evaporators usually under vacuum to lower the flash point of the liquid, using steam to heat brine solutions and promote water evaporation. Heat released from condensing steam is transferred to the brine solution via a heat exchanger, which boils the brine solution. Water evaporators may be expanded upon using multiple stages to increase the overall efficiency, and economy, of the treatment process. Advantages of using water evaporators include the production of high purity water and independence from climatic conditions. Evaporators are very effective at reducing a brine solution to a very concentrated level. TDS levels may be as high as 250,000 mg/L at a recovery of 90 to 99 percent. Reject brine tends to be very corrosive and requires evaporators to be constructed of very durable and high quality materials such as stainless steel and titanium.

Crystallizers are similar to water evaporators in that the brine stream is heated to aid in water evaporation. However, in the case of crystallizers, the waste brine enters a heated vertical vortex chamber where brine solutions evaporate in the vapor phase, causing salts to drop out in crystalline form.

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[8] Zero Liquid Discharge Desalination (Project #4163), Water Research Foundation, June 2011.

*Potential Minerals Recovery.* With a ZLD approach to concentrate disposal, the concentrate would be treated further by advanced distillation until the residue is comprised of solid salts, to be disposed in the landfill. However, an opportunity should be investigated to recover any salts or minerals that have potential economic value. Enviro Water Minerals Company, Inc. (EWM) built the first commercial facility in the U.S. to recover minerals from RO concentrate for beneficial use. The facility incorporates several technologies including RO, nanofiltration, and electrodialysis reversal. Feed water to the facility includes a blend of 1 mgd of brackish groundwater (2,500 mg/L TDS) and 1.25 mgd of concentrate (13,000 mg/L TDS) from the Kay Bailey Hutchison Brackish Groundwater Desalination Plant in El Paso (located on the adjacent property). The EWM facility produces caustic soda, hydrochloric acid, gypsum, magnesium hydroxide, and 2.1 mgd of potable (less than 700 mg/L TDS) water. The potable water is sold back to El Paso Water Utilities.

Additional technologies are available for commercial salt recovery but have no known commercial installations:

The SAL-PROC process is a simple technology based on chemical precipitation reactions to recover commercial salts.[9] It sequentially extracts dissolved elements from saline waters as chemical products in crystalline, slurry, and liquid forms. This process is well-suited to brackish inland brines since it increases water recovery, eliminating disposal costs. SAL-PROC is patented but has not been widely tested on an industrial scale.

Zero discharge desalination (ZDD) technology recovers commercial salts with a series of processes that are currently available individually.[9] Studies estimate 76-100 percent water recovery and indicate that it could be economically feasible. ZDD capital costs are high due to the multiple technologies of electrodialysis, brine concentrators, crystallizers, and brine purification treatments required for the process. ZDD is patented for sea and brackish water but has not undergone much testing by industry.

#### 5.1.3.7 Evaporation Ponds

Other disposal options besides deep well injection exist, but are expected to be more costly. Evaporation ponds concentrate brine in a surface impoundment as water evaporates. The sunny, semi-arid climate of Central Texas is suitable for this concentrate disposal method, but it would require a large land area dedicated to evaporation ponds, construction of an impermeable liner, and regulatory approval. Additionally, any loss of water from these systems is essentially a loss of product water because water is evaporated rather than reclaimed. Evaporation pond costs may become excessive when concentrate flow rates exceed 0.2 mgd, even with high evaporation rates.

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[9] Morillo, Jose; Jose Usero; Daniel Rosado; Hicham El Bakouri; Abel Riaza; Francisco-Javier Bernaola. *Comparative study of brine management technologies for desalination plants.* Desalination 336 (2014) 32-49.

#### 5.1.3.8 Research at Texas A&M

Attached in Appendix B – Texas A&M ZLD is correspondence along with supporting documentation (a white-paper and Laredo pilot report) that was completed by Mark Holtzapple and others that outlines advanced vapor-compression desalination processes. This process, albeit not yet commercialized, has the potential of reducing the overall cost of the desalinated water vs. alternative methods by offsetting and significantly reducing the total cost of disposal of concentrate by maximizing the yield of potable usable water from the inlet saline water source. This is an emerging technology that the District could consider in the future.

### 5.1.4 Plant Siting

The preliminary plan is to site the desalination plant on an available parcel of TDS-owned property. The map in Appendix A – Maps (Figure 4) shows a preliminary site location at the northwest corner of TDS-owned property, near the northern preliminary desalination production well site along the western edge of TDS property. The location of the plant site was setback from the road by 500 feet per TDS instructions. This location would also allow for proximity to the 42 inch main water line from the City of Austin, shown in Figure 2 (Appendix A), for a possible connection. As shown in the map, this location for the desalination facility is free of development and accessible by Bradshaw Road.

The available land at the preliminary site location could accommodate at least a six acre main site for the desalination facility and three acre storage pond used to contain off-specification water discharged from the membrane WTP, as shown in Appendix A – Maps (Figure 4) This pond could also be used to hold test water during construction and start-up and to accelerate evaporation. The pond could also be used to store pump test water from demonstration test wells, production wells and/or ASR wells. This water will be brackish so cannot be discharged to the environment.

# Section 6: Energy through Cogeneration

## 6.1 Energy Requirements and Availability

One advantage of locating this project on the TDS facility is the excess gas generated by the landfill. This excess gas can be converted into electricity and utilized to power the project through the development of a cogeneration plant. Carollo was able to obtain limited information about the disposal gas collection system from TDS. The information that was gathered on their system is presented in Appendix C – TDS. This generally included phone conversations, email correspondence, and an Executive Summary dated 1-19-17 that provided some insight into the gas collection system.

The energy requirements for the preliminary design for a 5.0 mgd desalination facility is shown in Table 6.1. A 2011 study concluded that energy costs can contribute up to 40 percent of the operating cost of a membrane desalination facility[10]. This same study also found that installing an energy recovery device (ERD) on the RO concentrate stream can achieve 24 percent energy savings. The RO desalination system was modeled with and without an ERD, as shown in Table 6.1. A generic turbocharger with 71 percent efficiency was included in the Toray DS2 model. A turbocharger uses excess pressure from the high pressure concentrate stream to reduce the feed pump energy required to achieve the membrane feed pressure. This modeled ERD reduces energy requirements 20 percent and 15 percent, respectively, for the 1-pass and 2-pass RO systems modeled.

Table 6.1 Desalination Energy Requirements

| | 1-Pass RO | 2-Pass RO (Boron removal) |
|---|---|---|
| Pump Power without ERD (kW) | 1878 | 2379 |
| Pump Power with ERD (kW) | 1511 | 2013 |
| Unit Power without ERD (kW-hr/kgal) | 8.92 | 11.56 |
| Unit Power with 71 percent efficient ERD (kW-hr/kgal) | 7.17 | 9.79 |
| Energy reduction with ERD | 20 % | 15 % |

Table 6.2 shows energy requirements for the various concentrate disposal alternatives assuming 76 percent RO recovery resulting in a concentrate flow of 1080 gpm. The zero liquid discharge (ZLD) energy requirements are based on an energy consumption of 125 kW-hr per 1000 gallons of feedwater treated to power an evaporator and crystallizer. The ZLD power requirements are many times higher than those for deep well injection. Deep well injection power requirements are based on pressure requirements for pumping to injection sites and overcoming well backpressure.

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[10] MacHarg, John P. (2011). Energy Optimization of Brackish Groundwater Reverse Osmosis Desalination; Affordable Desalination Collaboration. TWDB Contract Report Number 0804830845: Austin, TX, USA.

Table 6.2 Concentrate Disposal Energy Requirements

| | Zero Liquid Discharge | Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County | Trinity Injection Wells on TDS Property | Edwards Injection Wells in Caldwell County |
|---|---|---|---|---|
| Power (kW) | 8,100 | 403 | 239 | 285 |
| Power Use (kW-hr/day) | 194,400 | 9,671 | 5,726 | 6,849 |

### 6.1.1 Combined Heat and Power from Landfill Gas

It is the intent of this report to demonstrate the ability to utilize the landfill gas to generate electricity to power the desalinization equipment as well as other loads required for the project. Landfill gas production and composition were estimated by others and are used in this report without additional validation. Table 6.3 shows the values obtained from others for the development of this report.

Table 6.3 Landfill Gas Production and Composition

| | Value | Units |
|---|---|---|
| Gas production per Well | 18 | Million cubic feet per year |
| Number of Production Wells | 118 | |
| Gas Composition | | |
| Methane | 55 | Percent |
| Carbon Dioxide | 39.4 | Percent |
| Oxygen | 1.14 | Percent |

It is recommended that the owner obtain a detailed gas report to prepare a more detailed estimate for the cost and operation of a cogeneration system. The values suggested by others and shown on this table are typical and average and are assumed to be suitable for this project.

Based on the information shown in Table 6.3, the gas production can be estimated at 58.2 Million cubic feet per day or 40,410 standard cubic feet per minute.

#### 6.1.1.1 Landfill Gas Collection and Conveyance

For the purposes of this report, it is assumed that the landfill gas collection and conveyance is done by others and that the landfill gas is delivered to the project site. Figure 6.1 below shows the typical schematic for landfill gas collection and processing.

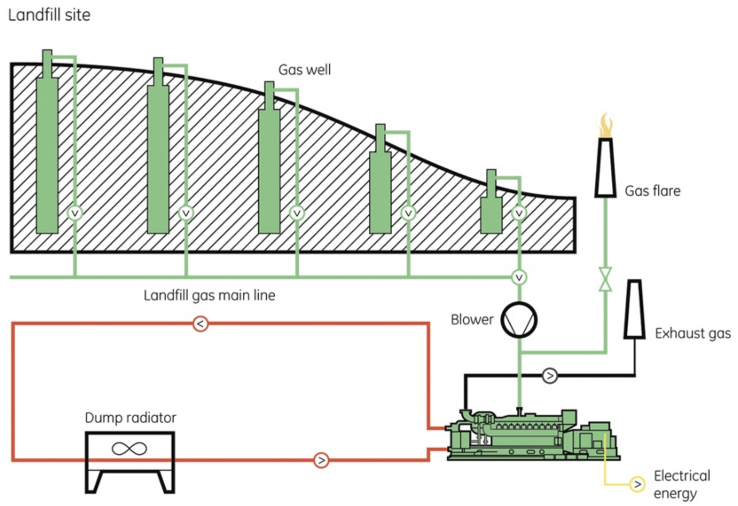

Figure 6.1 Typical Landfill Gas Collection and Conversion to Energy Schematic

### 6.1.1.2 Cogeneration System Components

One of the critical areas for the successful long term operation of a combined heat and power (CHP) system is gas conditioning. These systems remove harmful contaminants from the gas that reduce the life expectancy of the engines. All modern engines require gas conditioning for warranty validation.

Figure 6.2 below shows a typical gas conditioning skid.

A gas treatment skid contains the following:

- Hydrogen sulfide scrubber.
- Moisture removal system.
- Siloxane scrubber.
- Chiller.
- Blower(s).

### 6.1.1.3 Biogas Utilization Technologies

A multitude of biogas utilization technologies are available for landfills. The most appropriate for the purposes of this project are engine generators as these have the highest electrical yields and have been a proven technology for the use in landfill gas.

Figure 6.2 Gas Conditioning Skid

A new cogeneration engine generator includes the following:

- Cogeneration engine generator.
- Jacket water heat recovery system:
    - Pumps.
    - Heat exchangers.
- Exhaust heat recovery system:
    - Heat exchanger.
- Heating hot water recirculation system:
    - Pump.
    - Heat exchanger.
- Electrical equipment.
- HVAC equipment.
- Waste coolant and lube oil maintenance systems.
- Building (Optional) may be housed in vendor supplied enclosures.

### 6.1.2 Cogeneration Engine Selection

Cogeneration engine size selection is typically based on available biogas, volatility in biogas production, and average plant power demand. Based on powering the brackish production wells, the ASR wells, the desalination facility, and any one of the three injection well concentrate disposal alternatives, the total process connected load will be approximately 2.2 MW for Phase 1. Based on additional electrical requirements for building HVAC, lighting and other parasitic loads, the generator sizing was determined to be two 1,500 KW generators with a full standby unit to provide power during a generator failure or maintenance period for one of the other generators. Adding a second set of two 1,500 KW generators with another standby unit would satisfy the total process connected load of approximately 4.5 MW for the selected processes in Phase 2. It was not considered that these generators would be pushing power back to the grid or that they would be used to parallel the utility. Therefore, the costs of interconnecting the power generators to the utility have not been considered.

Generator engines are manufactured in discrete sizes (633 kW, 858 kW, 1137 kW, etc.) and are limited to a 50 percent turndown. Based on the landfill gas production of 58.2 Million cubic feet per day it is not expected that the system will need additional gas from natural gas and it was assumed that the engines would have ample supply of gas.

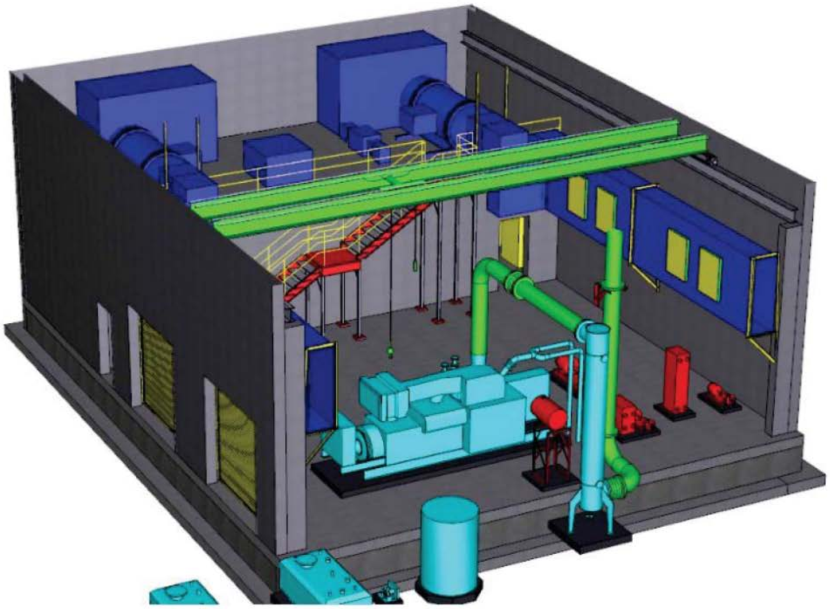

Figure 6.3 Typical Cogeneration System Installation

Alternatively, a self-contained generator unit may be provided to reduce the building and HVAC costs.

Figure 6.4 Self-Contained Generator Sets

# Section 7: Aquifer Storage Recovery (ASR)

## 7.1 ASR Objectives

To date, 29 different objectives for ASR wellfields have been identified for ASR programs in more than 20 states and several countries overseas. The three most common objectives are seasonal water storage; long-term storage, or "water banking," and emergency water storage. A recommended approach at the beginning of any ASR program is to identify objectives of potential interest and rank them in order of priority. This then provides a logical basis for location of ASR wells and for selection of one or more appropriate water storage aquifers or intervals of aquifers.

For this project, the focus is greatly narrowed. The location is predetermined in that it is somewhere within the TDS site. Additional future ASR locations are possible outside the TDS site, within the BSEACD jurisdictional area, and perhaps also within the City of Austin service area. However, they are beyond the scope of this project. The potential aquifer for ASR storage is not limited to the brackish Edwards aquifer, however that is the principal focus of this investigation. Future testing may show that units of the Trinity Aquifer may also be suitable for ASR storage beneath the TDS site. However, the depth to the top of this potential storage interval is estimated at 1,825 feet. A test well to this depth would be needed to determine whether this formation may be suitable for ASR storage. If the total dissolved solids concentration of water in the Sligo formation is greater than 10,000 mg/l, this formation would be more useful for brine disposal from the reverse osmosis desalination plant. If it is less than 10,000 mg/l then the formation would be of no value for brine disposal but could be useful for ASR storage, either instead of or in addition to storage in the brackish Edwards aquifer. Sligo formation thickness is unknown at this location, however the formation is probably tightly confined above and below, which is a favorable characteristic for ASR storage in brackish aquifers or for concentrate disposal.

With the location and aquifer defined, the proposed objectives and assumed order of importance are:

1) Seasonal storage
2) Long-term storage for droughts

Additional objectives may be considered at such time as the first ASR well has achieved full operational capacity and the potential water purveyor is ready to consider addition of ASR wells.

### 7.1.1 Preliminary Feasibility Assessment

The level of detail in this feasibility assessment is constrained by the lack of data on hydraulic and geochemical characteristics of the brackish Edwards aquifer, which is the target aquifer for ASR storage. The multiport monitoring well provides useful data on water quality and water levels, and an indication of relative hydraulic conductivity at different depth intervals, however it does not support firm conclusions regarding individual well yield, aquifer hydraulic characteristics, mineralogy and other geochemical characteristics. A demonstration well, monitor wells and probably a core hole will be required to obtain this data.

The level of detail for an ASR preliminary feasibility assessment is also constrained by lack of data regarding trends and seasonal variability in water demand for water users within the

BSEACD regulatory area. As indicated previously, water use is provided in terms of acre-feet per year but no information is available regarding how that demand varies during the year.

A typical ASR feasibility assessment would address the following factors:

- Identification and ranking of objectives.
- Water supply, trends and variability.
- Water demand, trends and variability.
- Source water quality, trends and variability.
- Hydrogeology.
- Target Storage Volume.
- Site selection and conceptual design.
- Preliminary cost estimate.
- Environmental, regulatory, legal and institutional issues.

Each of these factors is addressed in this and other sections of this report, to the extent achievable with available data.

### 7.1.2 Well and Wellfield Conceptual Design

Three ASR wells are assumed to be needed, each designed to produce 500 gpm. Installed capacity will total 1,500 gpm (2.2 mgd). Some losses will occur due to well interference during an extended recovery period so the combined yield of the wellfield is assumed to be 2.0 mgd. Firm ASR recovery capacity with the largest well out of service would be 1,000 gpm, or 1.5 mgd.

ASR wells would be cased to about 550 ft and completed open hole to about 640 feet.

A thin confining layer separates the upper portions of the brackish Edwards aquifer (Zones 13 and 14 in the multiport monitoring well) from the lower portions of the aquifer (Zones 4 to 11). This confining layer (Zone 12) is about 22 feet thick and is believed to be regionally present, however its vertical hydraulic conductivity is not known. The upper portion of the aquifer has a total dissolved solids concentration of 8,900 to 9,300 mg/l. The lower portion ranges in salinity between 13,100 and 18,600 mg/l.

Individual ASR well yields will need to be sufficiently low so that upconing of more saline water from the lower portion of the brackish Edwards aquifer will be minimized during extended ASR recovery periods. This will probably entail balancing water levels in the ASR wells and in the lower portion of the aquifer beneath the ASR wells so that any head difference between them is downward during ASR recharge periods, and downward to almost neutral during ASR recovery periods. The baseline head difference is currently slightly downward across the confining layer.

The Edwards aquifer in the project area is not expected to have any significant natural recharge. Continuous production from the brackish water production wells supplying the desalination plant is expected to cause a slow, steady decline in water levels, particularly in the lower portion of the aquifer. This may tend to steadily increase potential ASR recharge and recovery rates and would also steadily increase the pumping heads required for the production wells.

ASR well spacing should be far enough apart to minimize well interference and associated reduction in combined yield, yet close enough to achieve coalescence of the storage bubbles around individual wells when the Target Storage Volume has been achieved. This helps to improve recovery efficiency. Assumed well spacing is 800 feet pending construction and testing of demonstration wells and monitor wells to establish aquifer hydraulic characteristics. This assumed well spacing is based upon experience at other ASR wellfields in brackish limestone aquifers.

Location of ASR wells would be near the north corner of the TDS property, as shown in Appendix A – Maps (Figure 3). This location would provide lateral separation from the three brackish water supply production wells, which would be located at the southwest corner of the TDS property. The ASR wellfield location would also be at least three miles downdip from the "1,000 mg/l total dissolved solids" line, which is the interface between fresh water and brackish water at the top of the Edwards aquifer.

Individual well recharge capacity is assumed to be 400 gpm. This is a conservative estimate, based upon 80 percent of the assumed production capacity. The current depth to static water level is assumed to be 45 feet, based on data from the multiport monitoring well. This will rise by several feet when the brackish water in the well is displaced by less dense recharge water. Wellhead pressure during recharge will typically be maintained within a range of 2 psi to 20 psi, providing up to about 80 to 90 feet of total head on the aquifer. Much of this will comprise regional and local mounding around the wellfield and individual wells, with the remainder comprising head required to transfer the recharge water into the aquifer at the well bore.

Alternative materials of construction for the inner casing would be PVC 304 stainless steel or fiberglass. Mild steel is usually inappropriate for ASR wells due to enhanced corrosion potential. Epoxy-coated mild steel casing is another option however that is subject to corrosion at casing welds and pinholes in the epoxy coating, and is easily damaged by drilling below the casing and by pulling and setting pumps. The objective is to avoid causing rust that would flow downhole into the storage aquifer, contributing to particulate and microbial well clogging.

There are several reasons why the initial ASR well is larger diameter than would normally be required for a design recovery flow rate of 500 gpm. If the well yield is potentially more than 500 gpm, this provides flexibility to accommodate the higher flow rate. Larger diameters tend to provide higher yields to wells than might be anticipated based on theoretical considerations. Furthermore, downhole velocity in the well casing will be sufficiently slow so that any entrained air bubbles will tend to rise and be vented at the wellhead, rather than moving downhole and air binding the aquifer near the well. Experience at the initial ASR well will guide design of subsequent ASR wells.

The initial ASR well would be equipped with a pump, motor, variable frequency drive, downhole flow control valve, wellhead piping, valves and appurtenances. This would provide flexibility to accommodate a broad range of anticipated potential operating conditions. Lessons learned from operation of the initial ASR well would be integrated into the design and operation of the subsequent ASR wells.

Table 7.1 shows laboratory water quality analysis of a sample collected from Zone 13 of the Westbay well on 29 March 2017. This sample should be representative to slightly high for a sample pumped from Zones 13 and 14, corresponding to the full thickness of the upper Edwards aquifer overlying the Regional Dense Member, which is the semi-confining layer between the upper and lower portions of the Edwards aquifer. Zone 14 at the top of the upper aquifer is slightly fresher than Zone 13. At such time in the future as mineralogic data may become available from cores in the upper Edwards aquifer at this site, it should be possible to conduct a geochemical analysis to indicate whether any subsurface geochemical reactions may be anticipated as a result of ASR operations, due to mixing between recharge water, native groundwater, and minerals in the aquifer. Any such reactions might include mobilization of metals, dissolution of limestone, or precipitation reactions that could make a well more productive or more subject to clogging. ASR operations at other wellfields in brackish limestone aquifers have been able to successfully manage such geochemical reactions.

Table 7.1 TWDB State Well 5858305, Quality Stats, Zone 13 (Upper EA), Sampled 3-29-2017

| Parameter | Units | Result |
|---|---|---|
| Alkalinity, Bicarbonate Dissolved (mg/L), LAB | mg/L | 256 |
| Alkalinity, Carbonate Dissolved (mg/L), LAB | mg/L | <20 |
| Alkalinity, Hydroxide Dissolved (mg/L), LAB | mg/L | <20 |
| Alkalinity, Phenolphthalein (mg/L) | mg/L | <20 |
| Alkalinity, Total (mg/L AS CACO3) | mg/L | 256 |
| Aluminum, Dissolved (ug/L AS AL) | ug/L | <5 |
| Anion/Cation Chg Bal, Percent | Pct | -4.85% |
| Antimony, Dissolved (ug/L AS SB) | ug/L | 1.32 |
| Arsenic, Dissolved (Ug/L AS AS) | Ug/L | 3.97 |
| Barium, Dissolved (ug/L AS BA) | ug/L | 11.6 |
| Beryllium, Dissolved (ug/L AS BE) | ug/L | <1 |
| Boron, Dissolved (ug/L AS B) | ug/L | 4290 |
| Bromide, Dissolved, (mg/L AS BR) | mg/L | 30.1 |
| Cadmium, Dissolved (Ug/L AS CD) | Ug/L | <1 |
| Calcium, Dissolved (mg/L AS CA) | mg/L | 569 |
| Chloride, Dissolved (mg/L AS CL) | mg/L | 3460 |
| Chromium, Dissolved (ug/L AS CR) | ug/L | 3.03 |
| Cobalt, Dissolved (ug/L AS CO) | ug/L | <1 |
| Copper, Dissolved (ug/L AS CU) | ug/L | 2.23 |
| Fluoride, Dissolved (mg/L AS F) | mg/L | 3.12 |
| Iron, Dissolved (ug/L AS FE) | ug/L | <50 |
| Lead, Dissolved (ug/L AS PB) | ug/L | <1 |
| Lithium, Dissolved (ug/L AS LI) | ug/L | 2090 |
| Magnesium, Dissolved (mg/L AS MG) | mg/L | 322 |
| Manganese, Dissolved (ug/L AS MN) | ug/L | 11.4 |

Table 7.1 TWDB State Well 5858305, Quality Stats, Zone 13 (Upper EA), Sampled 3-29-2017 (continued)

| Parameter | Units | Result |
|---|---|---|
| Mercury, Dissolved (ug/L AS HG) | ug/L | <0.2 |
| Molybdenum, Dissolved (ug/L AS MO) | ug/L | <1 |
| Nitrite Plus Nitrate, Dissolved (mg/L AS N) | mg/L | <0.02 |
| Phosphorus, Dissolved (mg/L AS P) | mg/L | <0.02 |
| Potassium, Dissolved (mg/L AS K) | mg/L | 70 |
| Selenium, Dissolved (ug/L AS SE) | ug/L | 30.4 |
| Silica, Dissolved (mg/L AS SI02) | mg/L | 12.5 |
| Silver, Dissolved (ug/L AS AG) | ug/L | <500 |
| Sodium, Calculated, PERCENT | PCT | 66 |
| Sodium, Dissolved (mg/L AS NA) | mg/L | 2660 |
| Strontium, Dissolved (ug/L) AS SR | ug/L | 17,200 |
| Sulfate, Dissolved (mg/L AS SO4) | mg/L | 2590 |
| Thallium, Dissolved (ug/L AS TL) | ug/L | <1 |
| Total Dissolved Solids , Sum of Constituents (mg/L) | mg/L | 16707 |
| Uranium, Natural, Dissolved (ug/L AS U) | ug/L | <1 |
| Vanadium, Dissolved (ug/L AS V) | ug/L | <1 |
| Zinc, Dissolved (ug/L AS ZN) | ug/L | <5 |

### 7.1.3 Potential for ASR outside TDS study area

There is no fundamental reason why ASR could not be implemented outside the TDS study area, instead of or in addition to ASR within the study area. A recently completed ASR feasibility assessment for Buda (CH2M, 2017) is but one example of how such a program might be implemented, storing water in the Trinity aquifer. Several other potential ASR locations probably exist within the BSEACD jurisdictional area. The close proximity of the 42-inch treated drinking water pipeline along Bradshaw Road on the northwest side of the TDS site potentially opens up the opportunity for ASR operations to also meet regional water management needs, not just BSEACD. Extra water available during winter months from a variety of sources serving the City of Austin and BSEACD could be stored underground. Recovery of this water when needed could meet a broad variety of regional water management objectives. Two taps in the 42-inch water transmission pipeline, and an interlocal agreement between BSEACD and the City of Austin, could potentially provide benefits for both agencies.

## 7.2 Proposed Demonstration Test Program

### 7.2.1 Coring and Geochemistry

A recommended approach for many, but not all, ASR sites is to obtain a continuous wireline core through the aquifer proposed for ASR storage. Typically, the core hole also includes portions of the overlying and underlying confining layer. Based upon analysis of cores, drill cuttings and geophysical logs, core samples are selected and analyzed to determine their mineralogic content and their geochemical characteristics. Geochemical modeling is then conducted, evaluating the mixing of recharge water and ambient groundwater in the presence of aquifer minerals. Results of the geochemical modeling indicate whether the resulting reactions may dissolve or precipitate reaction products, cause clay swelling, or remain neutral. This is an expensive and time-consuming process, so it is not always implemented at every ASR site. Where other ASR wells are operating nearby in the same aquifer, or where other sources of data are available that narrow the uncertainty regarding aquifer mineralogy and water quality, the marginal value of coring may be reduced. For the TDS site, the multiport monitoring well provides useful data on water levels and water quality, and relative hydraulic conductivity. However, it does not provide data on mineralogy.

Two alternate approaches may be considered. The first is to construct a continuous wireline core hole from about 500 feet to 700 feet, obtaining cores from the upper Edwards Aquifer plus adjacent portions of the overlying and underlying confining layers. Selected cores would be analyzed at a core lab to determine the lithology, mineralogy and geochemistry. Results from the core lab would be modeled to evaluate potential geochemical reactions that may occur during ASR operations. It would provide a solid basis for permitting, construction, testing and operation of an ASR test well. Subsequent monitoring of water quality during recharge and recovery operations would indicate the significance of any subsurface geochemical reactions.

The second approach would be to not do the coring, core analysis and modeling. The substantial cost saving for these operations would be applied toward ASR well construction, well equipping and testing. The test results would provide real operating data, which is more reliable than modeling based on analysis of a few selected cores. Operating results would instill high confidence in the usefulness and reliability of the resulting data. A full-sized ASR demonstration well test should be considered, and would require a permit for construction. Monitoring of water quality would be conducted to determine whether recovered water meets drinking water standards. This is a higher risk, but not an uncommon approach. Extensive successful experience exists with ASR storage of drinking water in brackish, confined, karst limestone aquifers, particularly in Florida and South Carolina. More than 25 operating ASR wellfields are storing drinking water in such aquifers. Operating procedures have been developed that lead to successful ASR, particularly relating to attenuation of arsenic and meeting other drinking water standards. For current planning purposes, it is assumed that cores are obtained.

#### 7.2.1.1 ASR Test/Monitor Well Construction

*Edwards Aquifer.* The ASR test well would likely have a nominal 16-inch Certalok PVC SDR17 inner well casing (ID 14.3 in; OD 17.4 in). Casing depth would be 560 feet. A 12-inch hole would be drilled out to 650 feet. (or the top of the Zone 12 confining layer) and then developed to achieve acceptable turbidity. Depths and casing diameters for subsequent ASR wells would be adjusted based upon experience at the first ASR well. Alternate inner casing materials of construction that should be considered include fiberglass (FRP) and 304 stainless steel. Mild steel casing is inappropriate for ASR wells due to the higher propensity for corrosion, resultant well clogging, and increased difficulty for handling more frequent and longer duration backflushing flows to control well clogging. Other possible materials of construction include high-strength, low alloy (HSLA) steel casing, and epoxy-coated steel casing.

Well development water will be approximately 9,000 mg/l TDS. This water may need to be pumped into frac tanks and then trucked or pumped to an acceptable location, either within the TDS landfill site or possibly offsite. Closed-circulation disposal of drilling and well development fluids is not a favorable solution since this would tend to clog the ASR demonstration well and reduce well yield. A possible solution would be to conduct well development at a relatively low production rate, and then defer further well development until after interim recharge with about 20 MG of fresh water has been completed. Developed water would then be fresh and can be discharged to a local drainage system. The interim recharge water could come from the 42-inch pipeline or could come from the phase one desalination plant. Obtaining water from a tap in the 42-inch pipeline would enable initial ASR well construction and testing to proceed in parallel to construction of the desalination plant.

Acidization of the ASR well open borehole should be considered, as a supplemental measure to enhance well yield. If this option is selected, care will be needed to ensure that the acidization process does not adversely impact the confinement properties of the Zone 12 middle confining layer.

A storage zone monitor well would be constructed about 200 to 300 feet from the initial ASR well. Casing depths and materials of construction would be the same as for the ASR well, however casing diameters would be smaller. Surface casing would be 12 inches and the inner casing would be 6 inches.

A second monitor well would be constructed, cased to just below the confining layer separating the upper and lower portions of the Edwards aquifer. It would be open to Zone 11. This monitor well would detect changes in water level and water quality just below the confining layer, serving as a "sentinel well" for any upconing of brackish water into the ASR storage zone during an extended ASR recovery period. It will also provide useful data on leakance of the confining layer, which will be important for subsequent aquifer simulation modeling. A small monitoring interval, just below the middle confining layer (Zone 12) would minimize the increased potential for upconing of more saline water from deeper intervals of the lower aquifer, moving through the wellbore of the monitor well.

Each of the above monitor wells would be equipped with a small pump for sampling, and a transducer for measuring water levels.

#### 7.2.1.2 ASR Well Hydraulic Testing

Upon completion of well construction and development, a representative sample of the ambient baseline groundwater quality would be pumped from each ASR well and monitor well with a submersible pump. Samples will be collected following standard well sampling protocols. Samples would be analyzed for the analytes listed in Table 3.3. Field measurements would include conductivity, pH, temperature, dissolved oxygen (DO), and oxidation reduction potential (ORP). DO and ORP would need to be measured in the field with a closed-cell sampling apparatus to ensure reliability of the data.

Recharge of drinking water into the ASR well would then be initiated. The intention is to store a sufficient volume of drinking water so that subsequent baseline pump testing would result in discharge of fresh water without unacceptable environmental degradation. An assumed recharge volume is about 20 MG, requiring approximately one month of continuous recharge. This "interim recharge" would be achieved using temporary piping and wellhead facilities.

An 8-hour step-drawdown pumping test would be conducted at three or four different, increasing flow rates, with measurement of flow rates and water level response at the ASR well and at the monitor wells in the storage zone and in the deep monitor well, plus a shallow monitor well, if constructed.

Following water level recovery to static conditions, a 36- hour constant rate pumping test would be conducted at a flow rate selected based upon hydraulic performance during the step-drawdown pumping test. For current purposes, this is assumed to be 500 gpm. Samples would be collected periodically during recovery. Field measurements of conductivity would be obtained, confirming that water discharged to the environment is fresh. The pump test data would be analyzed to determine transmissivity, storativity and leakance. Any apparent leakance would be assumed to be through the lower confining unit (Zone 12 of the multiport monitoring well), not through the overlying clay layer. If a shallow monitor well is constructed, any measured leakance could be apportioned between the overlying and underlying confining layers.

#### 7.2.1.3 Production Well Hydraulic Testing

Similar well construction, interim recharge and testing procedures would be implemented for the brackish water production wells supplying the desalination plant. A larger interim recharge volume may be needed to ensure that pumped water would be fresh and could be discharged to the local environment during pump testing. Estimated flow rate is 1,500 gpm for 36 hours, plus the 8-hour step drawdown test. Alternatively, the water produced during test pumping of the production wells could be pumped to the pond at the desalination plant site.

### 7.2.1.4 Well Equipping and Wellhead Facilities

It is assumed that ASR well equipping and wellhead facilities would include a vertical turbine pump and motor, set deep in the well casing so as to provide for a significant depth to pumping water level. The pump would be water-lubricated.

Wellhead facilities are assumed to include a well house or enclosure with piping, valves and fittings that provide for:

- Well recharge, recovery, and periodic backflushing to waste.
- Trickle recharge flow during any extended storage periods exceeding about one week.
- Air Vacuum control and air release control.
- Flow, water level and pressure measurement.
- Sampling.
- Operation of the downhole flow control valve.

The well site would also include typical wellhead facilities, such as drainage, lighting, power supply, emergency power supply, variable frequency drive, electrical controls, telemetry and SCADA facilities, disinfection of recovered water, and appropriate site access

Piping would be needed to connect the desalination and ASR facilities and conveying produced water to existing transmission and distribution pipelines within the BSEACD service area. The existing 42-inch transmission pipeline may be available for use, which would reduce the cost of the transmission piping. Target Storage Volume

During the first year of operations at the ASR Demonstration Well, a preliminary Target Storage Volume (TSV) would be established, based upon results of initial testing to determine the well specific capacity (SCp) during production and specific capacity during injection (SCi). For current planning purposes, it is assumed that the production rate would be 500 gpm and the injection/recharge rate would be 400 gpm.

As indicated previously, an initial TSV of 130 MG is estimated. This would supply 500 gpm for 90 days. The initial TSV would be the sum of the stored drinking water volume and the buffer zone volume. It is assumed that a portion of the initial TSV volume would be purchased from the City of Austin and conveyed from the 42-inch pipeline to the ASR Demonstration Well. Subsequent recharge flows would be from the desalination plant.

Two years would probably be required to form the TSV and to conduct cycle testing. During the first year following completion of well construction and initial pump testing, interim recharge would be conducted to form the first part of the TSV. Depending on how many months are available between the start of recharge and the following summer, more or less water may be stored. Half of the stored water would be recovered during summer months. This water would initially be discharged to waste. If recovered water quality is shown to meet drinking water standards, a portion of the recovered water could be directed to the potable water supply system. The remaining stored water would remain underground, forming part of the buffer zone. Following the first summer season, recharge would resume until the TSV has been achieved, most likely prior to the following summer. A typical summer recovery period would then be conducted, recovering 500 gpm for 90 days but leaving the buffer zone intact. The volume of water in the buffer zone should never be recovered since it is analogous to the walls of a storage tank.

Because of the anticipated relatively high salinity of the storage aquifer (9,000 mg/l TDS), it is likely that some minor loss of stored water may occur due to density stratification, with fresher water tending to migrate vertically upward and “pancaking” beneath the overlying clay confining layer. This will tend to pull in more saline water from the base of the storage aquifer, just above Zone 12 (Regional Dense Member, or middle confining layer). To the extent that Zone 12 has some leakance, additional saline water may migrate into the storage aquifer from beneath Zone 12, due to the head difference occurring across Zone 12 during ASR recovery periods. This head difference will tend to reduce with time as water levels in the lower aquifer decline. Initial ASR testing will help to define the hydraulic response of the aquifer system to ASR operations and also to desalination production well operations.

Upon completion of cycle testing at the ASR Demonstration well, the TSV would be revised to incorporate additional ASR wells and also to reflect additional goals and objectives for ASR storage. The ASR storage volume could be increased substantially so that, in addition to meeting seasonal variations in demand, the desalination/ ASR facility could also meet all or a significant portion of water needs during a severe drought, or during a repeat of the Drought of Record. Several other potential ASR objectives should also be considered at that time, potentially affecting the TSV but not requiring any additional construction of ASR facilities beyond the three planned ASR wells.

### 7.2.2 Aquifer Simulation Model

Aquifer simulation modeling will be an important tool to evaluate potential water level and water quality response to ASR and brackish water supply well operations. The program of demonstration and monitor wells will provide a baseline for development of an aquifer simulation model. The model would then be updated after the first year or two of wellfield operations, prior to expanding the wellfields to their planned ultimate capacity.

# Section 8: Economic Feasibility Assessment

## 8.1 Phased Expansion Program

Successful ASR implementation is best achieved by development in phases. Lessons learned in each phase are then incorporated into plans for the next phase. In the first phase, demonstration wells would be constructed to confirm potential individual well yields and aquifer hydraulic characteristics. Demonstration wells would include one full-sized ASR well and one full-sized production well, plus several monitor wells.

For desalination, phasing is also beneficial, however economies of scale are such that the structure is typically sized for potential ultimate capacity while membrane racks are provided to meet initial demands. As demands increase, additional membrane racks are added within the existing facilities.

Phased development effectively manages risk, such as current uncertainty regarding individual well yields, aquifer hydraulic characteristics, concentrate disposal options or potential changes in the legal and regulatory framework.

The project is designed for a 2.5 mgd desalination facility for Phase 1 with buildout to a 5 mgd facility for Phase 2. Costs were developed for Phase 2 as described below and scaled down for Phase 1. Table 8.1 summarizes Phase 2 costs and power requirements for the wellfields, desalination facility, brine disposal alternatives, and landfill gas combined heat and power system.

The desalination facility would operate at a steady rate, all year long, every year. Seasonal variations in demand would be met from the ASR wells, supplementing peak supplies by 2.2 mgd. Total peak supply from the desalination/ASR facility would therefore be 7.2 mgd.

Table 8.1 Desalination Cost Estimate

| | Wellfield | | | Desalination System | Concentrate Disposal Alternatives | | | | Landfill Gas Combined Heat and Power |
|---|---|---|---|---|---|---|---|---|---|
| | Brackish Wells (3 production + 2 monitor) ($M USD) | Brackish Wellfield Piping and Wellheads ($M USD) | ASR Wells, Wellheads, and Wellfield Piping ($M USD) | RO with Boron Removal 5 mgd production ($M USD) | Zero Liquid Discharge ($M USD) | Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County ($M USD) | Trinity Injection Wells on TDS Property ($M USD) | Edwards Injection Wells in Caldwell County ($M USD) | Four 1.5 MW Generators ($M USD) |
| **Capital ($M)** | | | | | | | | | |
| Equipment | | $0.5 | | $60.2 | $60.0 | | | | |
| Pipeline | | $1.2 | | | | $26.2 | $1.2 | $7.7 | |
| Pump Stations | | | | | | $8.7 | $6.6 | $6.6 | |
| Wells | $5.3 | | | | | | $10.0 | $10.0 | |
| **TOTAL** | **$5.3** | **$1.7** | **$7.1** | **$60.2** | **$60.0** | **$34.9** | **$17.8** | **$24.3** | **$54.2** |
| **O&M ($M/yr)** | | | | | | | | | |
| Pump Station O&M | | | | | | $0.16 | $0.12 | $0.12 | |
| Pipeline O&M | | $0.01 | | | | $0.19 | $0.01 | $0.06 | |
| Equipment O&M | $0.05 | | $0.11 | $3.60 | $1.80 | | | | |
| Full-time Personnel | | | | Included in Eqpmt O&M | $0.15 | | | | |
| Power ($0.10 per kW-hr) | $0.59 | $0.00 | $0.10 | $2.70 | $7.10 | $0.35 | $0.21 | $0.25 | |
| **TOTAL** | **$0.64** | **$0.01** | **$0.21** | **$6.30** | **$9.05** | **$0.70** | **$0.34** | **$0.42** | **$0.23** |

Table 8.1 Desalination Cost Estimate (continued)

| | Wellfield | | | Desalination System | Concentrate Disposal Alternatives | | | | Landfill Gas Combined Heat and Power |
|---|---|---|---|---|---|---|---|---|---|
| | Brackish Wells (3 production + 2 monitor) | Brackish Wellfield Piping and Wellheads | ASR Wells, Wellheads, and Wellfield Piping | RO with Boron Removal 5 mgd production | Zero Liquid Discharge | Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County | Trinity Injection Wells on TDS Property | Edwards Injection Wells in Caldwell County | Four 1.5 MW Generators |
| **Power Use** | | | | | | | | | |
| kW-hr/yr | 5,886,720 | | 972,000 | 27,000,000 | 70,956,000 | 3,530,000 | 2,090,000 | 2,500,000 | |
| kW-hr/day | 16128 | | 10800 | 73,973 | 194,400 | 9,671 | 5,726 | 6,849 | |
| kW | 672 | | 450 | 3,082 | 8,100 | 403 | 239 | 285 | Generates 6000 kW |

Notes:

- Costs in Millions of Dollars per Year
- Costs include contingency; general contractor overhead, profit, and risk; and engineering, legal, and administrative fees
- Assumes 76% recovery with 1069 gpm of concentrate flow
- Landfill Gas Combined Heat and Power costs include $0.5M for gas piping and $0.1M for electrical lines

## 8.2 Capital Costs

### 8.2.1 Brackish Production Wells

Brackish production well costs were based on a similar project done in Hilton Head, South Carolina, beginning with bids received in 2012. Unit quantities were adjusted to match the TDS site and unit prices were increased by 16% (3% per year for five years). Contingency of 30% and engineering, legal, and administrative fees of 10% were added.

The estimated cost for the three brackish water production wells is $3,232,000. This was based on 24-inch OD PVC casing and includes pumps, motors and downhole control valves. Texas drillers may prefer 304 SS casing, in which case a smaller diameter would suffice, but at higher cost per foot of casing. These are assumed to be open borehole wells.

The estimated cost for two monitor wells, one in the lower Edwards aquifer and one open to Zone 13 in the upper Edwards aquifer, both located near the southwest corner of the TDS property, is $460,000.

Brackish wellfield piping costs to deliver the water to the desalination facility were estimated based on 1.5 miles of 14-inch PVC piping.

### 8.2.2 Desalination Facility

The preliminary cost estimate for equipment and installation for a 5 mgd two-pass RO facility including adders of 30 percent for contingency and 20 percent for engineering/administration fees is $60.2 million. Included in this cost estimate are a chemical storage and injection systems, cartridge filters, RO equipment, a building, degassifiers, process electrical and instrumentation, a high service pump station and reservoir, yard piping, and site work.

### 8.2.3 ASR

Appendix H – ASRS presents a preliminary estimate of the capital costs for construction of ASR wellfield facilities. The ASR program is presented in two phases of construction: 1) an initial demonstration phase with a single, 500 gpm, ASR well and two monitoring wells, plus associated facilities, and 2) a second phase with expansion to three ASR wells with a combined recovery capacity of 1,500 gpm.

Although not shown in this analysis, consideration should be given to constructing and testing of all three ASR wells during the initial phase. Two of the wells would then be utilized for supplemental monitoring purposes during Phase One testing, and would then be capped. This would achieve economies of scale for well construction. The two additional ASR wells would be equipped during the second phase.

Capital cost estimates include construction costs plus a 30 percent contingency, reflecting the considerable uncertainty associated with ASR conceptual wellfield design at this location. Engineering and hydrogeological consultant costs are also included. These include engineering design and permitting of ASR facilities, including coordination with similar activities for the desalination plant and production wells; engineering construction services and resident observation; training and startup of operations, and operational assistance during the first year of operations. Hydrogeological consultant services include well design and permitting assistance; resident observation services during coring, well construction and testing; preparation of a well completion report, summarizing all data collected during well construction and testing; and preparation of an aquifer simulation model. Effective integration of engineering and hydrogeological consultant services is essential for ASR wellfield success.

Total estimated capital cost for Phase 1 is $3.7M. Combined estimated capital cost for both phases is $7.1M.

### 8.2.4 Concentrate Disposal

Deep well injection costs included the pipeline, pump stations, and injection wells. Costs include adders of 30 percent for contingency; 20 percent for general contractor overhead, profit, and risk; and 15 percent for engineering, legal, and administrative fees.

Pipeline costs were developed based on pipeline route distances from the preliminary desalination facility location to potential deep well injection sites:

- 37.4 miles to Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County
- 1.7 miles to Trinity Injection Wells on TDS Property
- 11.0 miles to Edwards Injection Wells in Caldwell County

Conveying 1.5 mgd of brine concentrate requires a pipeline diameter of 12 inches. High-density polyethylene (HDPE) piping is standard since it resists brine's corrosivity. A conservative backpressure of 350 psi is assumed at the injection wellheads. A cost curve was used to develop costs for booster pump stations to convey the brine and overcome the wellhead backpressures.

A screening level cost estimate of $5 million per 500 gpm injection well is provided based on two primary sources. First, a May 2014 report of the U.S. Department of Energy (USDOE) National Energy Technology Laboratory[11] references injection well drilling and completion costs of $5 million for a 7,500 foot well based on a 2008 American Petroleum Institute survey of drilling costs in the oil and gas industry.[12] Second, San Antonio Water System (SAWS) recently completed installation of its first Class I UIC-permitted injection well as part of its Brackish Groundwater Desalination Program. SAWS reported a project cost of $4.83 million for the injection well test program. The test well was completed to a depth of 5,300 feet and has a 450 gpm injection rate. Based on this data, the desalination project would likely require two injection wells sized at approximately 500 gpm each to dispose the full 1.5 mgd of concentrate generated with 76 percent recovery of 6.5 mgd of feedwater. Therefore, the cost of the brine disposal wells themselves is expected to be on the order of $10 million.

The cost, including contingency and engineering/administration fees, of a ZLD system to dispose of 1.5 mgd of brine waste is $60 million, based on the cost of a similar 1.5 mgd system. Included in this cost estimate are brine concentrator equipment, crystallizer equipment, process electrical and instrumentation, yard piping, and site work.

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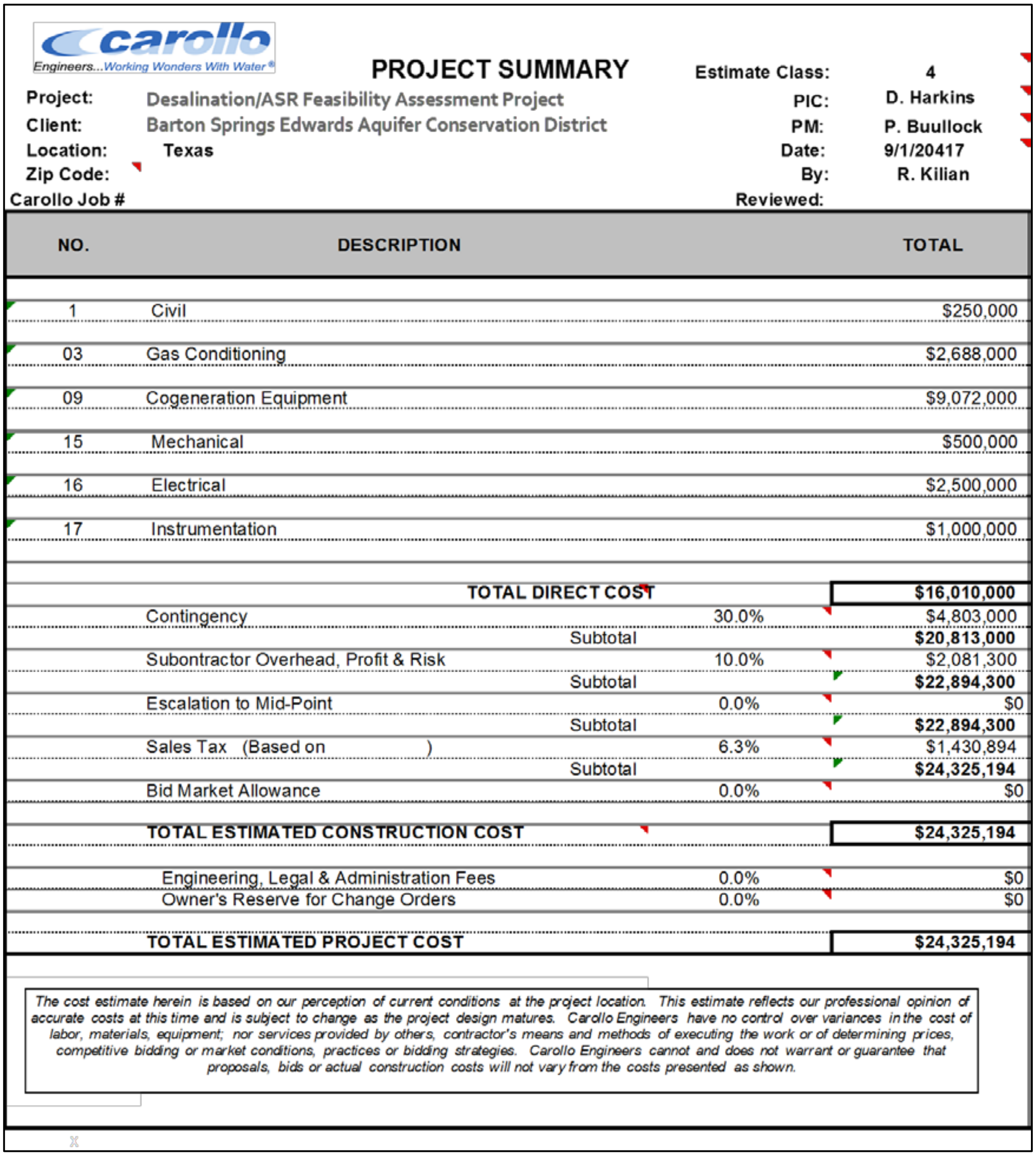
[11] Acquisition and Development of Selected Cost Data for Saline Storage and Enhanced Oil Recovery (EOR) Operations, U.S. Department of Energy National Energy Technology Laboratory, May 2014

[12] 2008 Joint Association Survey on Drilling Costs, American Petroleum Institute, April 2010

### 8.2.5 Cogen Facility

The following cost estimate was prepared as a budgetary estimate to include the project elements identified herein:

Table 8.2 Cogen Cost Estimate



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**PROJECT SUMMARY**

| | | | |
|---|---|---|---|
| **Project:** | Desalination/ASR Feasibility Assessment Project | **Estimate Class:** | **4** |
| **Client:** | Barton Springs Edwards Aquifer Conservation District | **PIC:** | **D. Harkins** |
| **Location:** | **Texas** | **PM:** | **P. Buullock** |
| **Zip Code:** | | **Date:** | **9/1/20417** |
| | | **By:** | **R. Kilian** |
| **Carollo Job #** | | **Reviewed:** | |

| **NO.** | **DESCRIPTION** | | **TOTAL** |
|---|---|---|---|
| 1 | Civil | | $250,000 |
| 03 | Gas Conditioning | | $2,688,000 |
| 09 | Cogeneration Equipment | | $9,072,000 |
| 15 | Mechanical | | $500,000 |
| 16 | Electrical | | $2,500,000 |
| 17 | Instrumentation | | $1,000,000 |
| | **TOTAL DIRECT COST** | | **$16,010,000** |
| | Contingency | 30.0% | $4,803,000 |
| | Subtotal | | **$20,813,000** |
| | Subontractor Overhead, Profit & Risk | 10.0% | $2,081,300 |
| | Subtotal | | **$22,894,300** |
| | Escalation to Mid-Point | 0.0% | $0 |
| | Subtotal | | **$22,894,300** |
| | Sales Tax (Based on ) | 6.3% | $1,430,894 |
| | Subtotal | | **$24,325,194** |
| | Bid Market Allowance | 0.0% | $0 |
| | **TOTAL ESTIMATED CONSTRUCTION COST** | | **$24,325,194** |
| | Engineering, Legal & Administration Fees | 0.0% | $0 |
| | Owner's Reserve for Change Orders | 0.0% | $0 |
| | **TOTAL ESTIMATED PROJECT COST** | | **$24,325,194** |

*The cost estimate herein is based on our perception of current conditions at the project location. This estimate reflects our professional opinion of accurate costs at this time and is subject to change as the project design matures. Carollo Engineers have no control over variances in the cost of labor, materials, equipment; nor services provided by others, contractor's means and methods of executing the work or of determining prices, competitive bidding or market conditions, practices or bidding strategies. Carollo Engineers cannot and does not warrant or guarantee that proposals, bids or actual construction costs will not vary from the costs presented as shown.*

## 8.3 Operating Costs

Operating costs include facility operation, maintenance, labor, and power. Chemical and power costs are the main components of facility operation costs. The price of power is assumed at $0.10 per kilowatt-hour.

### 8.3.1 Brackish Production Wells

Brackish well O&M costs were estimated at 1% of capital costs for pipeline maintenance plus power costs.

### 8.3.2 Desalination Facility

Desalination equipment operation and maintenance (O&M) for 5 mgd was estimated to be $6.3 million annually. This includes RO membrane replacement allowance spread over the annual O&M cost. Also included in this cost estimate are pumping power (RO feed and interstage pumps, degassifiers, high service pumps), chemicals, equipment maintenance, laboratory testing, operation labor (1 plant superintendent, 4 operators; all full-time personnel).

### 8.3.3 ASR

Operating costs for ASR wellfields comprise primarily electrical power costs; laboratory analytical and other monitoring costs; disinfection and any other chemical additions, such as for pH adjustment (if needed); and routine operation and maintenance costs for wellfield equipment, data collection and reporting, etc. Since ASR operations are typically seasonal, costs are typically higher during summer months and other recovery periods, and are lower during winter months and other times when recharge is occurring. Monitoring costs are typically much higher during the first year or two of operations, particularly during the demonstration testing period. Once an Underground Injection Control (UIC) operating permit has been issued by TCEQ, it is reasonably expected that monitoring intensity will reduce and operating costs will decline. Based upon experience at other ASR wellfields, a preliminary estimate of ASR operating costs for the TDS site is $50,000 per mgd of recovery capacity, per year. For a design recovery capacity of 2.2 mgd, this would amount to $110,000 per year.

Interim recharge for the first ASR demonstration well is assumed to utilize water from the City of Austin 42-inch pipeline, which would need to be purchased. That cost is not included in the above estimate of O&M costs. Subsequent recharge water would presumably come from the desalination plant. This could be in a separate pipeline along Bradshaw Road or another alignment within the TDS property, or could perhaps share conveyance capacity within the 42-inch pipeline, metering flows into and out of the pipeline during ASR recharge and recovery periods.

### 8.3.4 Concentrate Disposal

Deep well injection operating costs include pump station O&M, pipeline O&M, and power costs. Pump station O&M costs are estimated at 2.5 percent of pipeline capital costs, and consist of labor and maintenance costs of pump stations, storage tanks, meters and SCADA systems. Pipeline O&M costs are estimated at 1 percent of capital costs, and consist of pipeline labor and maintenance costs. Power costs are based on energy requirements as shown in Table 8.1.

ZLD equipment O&M cost was estimated to be $10.3 million annually. Included in this cost estimate are power (brine concentrator and crystallizer), equipment maintenance, and operation labor (3 operators; all full-time personnel).

### 8.3.5 Cogen Facility

Typical O&M for a cogeneration facility ranges between 1.5-3.5 cents per kilowatt. A gas analysis would be necessary to understand details such as media replacement rates and engine maintenance requirements. A high level O&M estimate of $115,000 per year for two 1.5 MW generators has been doubled for the Phase 2 cogeneration facility shown in Table 8.1.

## 8.4 Estimate Accuracy

For this evaluation, a Class 4 cost estimate was developed to determine budget level project costs. Per AACE International (formerly the Association for the Advancement of Cost Engineering), Class 4 estimates are developed with a low level of design definition and are appropriate for feasibility studies. All capital costs shown in Table 8.1 include contingency; general contractor overhead, profit and risk; and engineering, legal, and administration fees.

In examining options in regard to cost, several important cost mitigating factors should be recognized:

- Because this is a planning study, estimated costs are conservative and include a construction contingency for unanticipated costs.
- Carollo is unable to account for fluctuation in cost of material, labor components or unforeseen contingencies. The cost estimate has been prepared prior to the finalization of any actual construction plans and specifications and, therefore is subject to change.
- The opinion of probable construction cost (OPCC) was made on the basis of professional experience and qualifications. It represents Carollo's best judgment as a professional design consultant familiar with the construction industry.
- The OPCC is a preliminary cost estimate only. Experience indicates that a fewer number of bidders may result in higher bids, conversely an increased number of bidders may result in more competitive bids.
- The cost to complete each task should be considered high-level and subject to change as detailed information (survey, environmental, permitting, funding, etc.) is developed. Methods of analysis used in the development of the cost estimate are consistent with a planning level of this detail.
- The cost required to complete each bid item is intended only as 1) a guide for preliminary and follow-on detailed engineering and 2) a basis for preliminary estimate of time to complete the intended modifications. While procedures consistent with this cost estimate are generally employed, approximations and engineering judgment was used because of the planning level nature of this exercise and the unpredictability of specific cost items.

# Section 9: Financial Forecasting

## 9.1 Background

NewGen Strategies and Solutions (NewGen) served as a sub-consultant to Carollo Engineers (Carollo) regarding the desalination feasibility assessment for the Barton Springs Edwards Aquifer Conservation District (BSEACD). The purpose of this section is to develop a financial forecast that identifies the cost of developing a desalination facility. Detailed financial tables can be found in Appendix D – NewGen.

Carollo provided capital and operation & maintenance (O&M) costs for the desalination system, wellfield collection system, various concentrate disposal alternatives, an aquifer storage and recovery (ASR) system, as well as a landfill gas combined heat and power facility. It is important to note that cost estimates were provided under two distinct scenarios: 1) a desalination facility with a production capacity of 2.5 mgd; 2) a desalination facility with a production capacity of 5.0 mgd).

## 9.2 Assumptions

The assumptions underlying the capital construction costs, operation and maintenance costs, financing costs, and inflation factors are summarized in the subsequent sections.

## 9.3 Capital Construction Costs

Table 9.1 below summarizes the capital construction costs developed by Carollo and used by NewGen in developing the various financial forecast scenarios. These costs are detailed in Schedule 1 and Schedule 2 (Appendix D).

Table 9.1 Capital Construction Costs

| | 2.5 mgd | 5.0 mgd |
|---|---|---|
| Desalination Facility | $ 41,500,000 | $ 60,200,000 |
| Wellfield[(1)] | 6,959,560 | 6,959,560 |
| **Subtotal** | **$ 48,459,560** | **$ 67,159,560** |
| Concentrate Disposal[(2)] | | |
| 1. Zero Liquid Discharge | $ 40,000,000 | $60,000,000 |
| 2. Existing Salt Flat (Edwards) Field Injection in Caldwell County | $ 31,935,510 | $ 34,910,211 |
| 3. Trinity Injection Wells on TDS Property | $ 10,519,955 | $ 17,750,981 |
| 4. Edwards Injection Wells in Caldwell County | $ 17,025,253 | $ 24,256,279 |

Table 9.1 Capital Construction Costs (continued)

| | 2.5 mgd | 5.0 mgd |
|---|---|---|
| Landfill Gas Combined Heat & Power Facility(3) | $ 27,417,713 | $ 54,175,427 |
| ASR(4) | $ 3,687,120 | $ 7,076,160 |

Notes:
(1) Includes capital costs for brackish wells, wellfield piping, and wellheads.
(2) Carollo evaluated four potential concentrate disposal alternatives.
(3) The landfill gas combined heat & power facility would allow the use of methane to power the desalination facility and wellfield.
(4) Includes ASR wells, wellheads, and wellfield piping.

## 9.4 Operation & Maintenance Costs

Table 9.2 summarizes O&M costs for both the 2.5 mgd and 5.0 mgd scenarios which include pipeline, pump station, and equipment operation and maintenance, as well as full-time salary expenses. Please note that power costs are not included in these estimates and are provided in subsequent tables. These costs are also detailed in Schedule 1 and Schedule 2 (Appendix D).

Table 9.2 Annual O&M Costs

| | 2.5 mgd | 5.0 mgd |
|---|---|---|
| Desalination Facility | $ 2,350,000 | $ 3,600,000 |
| Wellfield(1) | 61,666 | 61,666 |
| **Annual Subtotal(2)** | **$ 2,411,666** | **$ 3,661,666** |
| Concentrate Disposal(3) | | |
| 1. Zero Liquid Discharge | $ 1,350,000 | $ 1,950,000 |
| 2. Existing Salt Flat (Edwards) Field Injection in Caldwell County | $ 294,182 | $348,072 |
| 3. Trinity Injection Wells on TDS Property | $ 87,074 | $127,491 |
| 4. Edwards Injection Wells in Caldwell County | $ 134,214 | $ 174,631 |
| Landfill Gas Combined Heat & Power Facility(4) | $ 115,000 | $ 230,000 |
| ASR(5) | $ 55,307 | $ 110,000 |

Notes:
(1) Includes maintenance costs for pipeline and miscellaneous equipment.
(2) The desalination facility and wellfield operation and maintenance costs are constant throughout each financial scenario, however total costs vary between production capacities of 2.5 mgd and 5.0 mgd.
(3) Carollo evaluated four potential concentrate disposal alternatives.
(4) The landfill gas combined heat & power facility would allow the use of methane to power the desalination facility and wellfield.
(5) Includes equipment maintenance for ASR wells.

## 9.5 Power Costs

As part of the project scope, the Project Team was tasked with evaluating several power alternatives, which are summarized below. Carollo provided cost estimates for each power alternative.

- Traditional Energy Source (Coal and Gas) – $0.10 per kW-hr
- Renewable Energy Source (Photovoltaic Solar Energy) – $0.11 per kW-hr[13]
- Landfill Gas Power – No Cost[14]

Table 9.3 summarizes power costs estimated for a desalination facility with a production capacity of 2.5 mgd. These costs are further detailed in Schedule 1 (Appendix D).

Table 9.3 Power Alternatives at 2.5 mgd Plant Annual Costs

| | Traditional Energy ($0.10 per kW-hr) | Renewable Energy (0.11 per kW-hr) | Landfill Gas – Methane (No Cost) |
|---|---|---|---|
| Desalination Facility | $ 1,350,000 | $ 1,485,000 | $ 0 |
| Wellfield | 294,336 | 323,770 | 0 |
| **Subtotal** | **$ 1,644,336** | **$ 1,808,770** | **$ 0** |
| Concentrate Disposal | | | |
| 1. Zero Liquid Discharge | $ 3,547,800 | $ 3,902,580 | $0 |
| 2. Existing Salt Flat (Edwards) Field Injection in Caldwell County | $ 176,500 | $ 194,150 | N/A |
| 3. Trinity Injection Wells on TDS Property | $ 104,500 | $ 114,950 | $ 0 |
| 4. Edwards Injection Wells in Caldwell County | $ 125,000 | $ 137,500 | N/A |
| Landfill Gas Combined Heat & Power Facility | N/A | N/A | $ 0 |
| ASR | $ 32,400 | $ 35,640 | $ 0 |

Table 9.4 summarizes power costs estimated for a desalination facility with a production capacity of 5.0 mgd. These costs are further detailed in Schedule 2 (Appendix D).

---

[13] Carollo performed a benchmarking analysis comparing the kW-hr cost differential between conventional energy source (i.e. fossil fuels) and renewable sources of energy (i.e. photovoltaic solar energy) and found that renewables, on average, were 7.55% more expensive. In order to be conservative, Carollo recommended using a 10% increase in cost for renewable energy sources.

[14] For the purposes of this analysis, it is assumed that reimbursement to TDS for gas produced at their landfill will be zero ($0).

Table 9.4 Power Alternatives at 5.0 mgd Plant Annual Costs

| | Traditional Energy ($0.10 per kW-hr) | Renewable Energy (0.11 per kW-hr) | Landfill Gas – Methane (No Cost) |
|---|---|---|---|
| Desalination Facility | $ 2,700,000 | $ 2,970,000 | $ 0 |
| Wellfield | 588,672 | 647,539 | 0 |
| **Subtotal** | $ 3,288,672 | $ 3,617,539 | $ 0 |
| Concentrate Disposal | | | |
| 1. Zero Liquid Discharge | $ 7,095,600 | $ 7,805,160 | $0 |
| 2. Existing Salt Flat (Edwards) Field Injection in Caldwell County | $ 353,000 | $ 388,300 | N/A |
| 3. Trinity Injection Wells on TDS Property | $ 209,000 | $ 229,900 | $ 0 |
| 4. Edwards Injection Wells in Caldwell County | $ 250,000 | $ 275,000 | N/A |
| Landfill Gas Combined Heat & Power Facility | N/A | N/A | $ 0 |
| ASR | $ 97,200 | $ 106,920 | $ 0 |

## 9.6 Financing Costs

The Texas Water Development Board (TWDB) offers several funding programs for various water projects. The funding mechanisms listed below are just two examples of funding opportunities through TWDB.

- **Texas Water Development Fund (DFund) Program:** DFund is a state funded loan program that does not receive federal subsidies, and is thus not to subject to federal oversight. The DFund enables the Board to fund multiple eligible components in one loan to borrowers. Eligible applicants include all political subdivisions of the state (at tax exempt rates). Financial assistance for water supply projects may include planning, design, and construction for wells, pumping facilities, and storage reservoirs and tanks. Although not exclusively mentioned in the DFund project eligibility description, a financial representative at TWDB did mention that a desalination project may also be eligible for funding through this mechanism.
- **State Water Implementation Fund For Texas (SWIFT) Program:** SWIFT was created by the Texas Legislature to provide affordable, ongoing state financial assistance for projects identified in the State Water Plan. The program assists communities in developing cost-effective water supplies by providing low-interest loans, extended repayment terms, deferral of loan repayments, and incremental repurchase terms. Eligible applicants include any political subdivision with a project included in the adopted regional water plan that will be included in the state water plan. Eligible projects include conservation and reuse, desalinating groundwater and seawater, developing reservoirs and well fields, etc.

Table 9.5 lists the illustrative lending rates used by the TWDB as of September 29, 2017. Please note that actual rates will vary depending on length, time of closing, and structure. Furthermore, other lending options not summarized in this study are eligible through TWDB.

Table 9.5 TWDB Lending Rates

| | Term | Rates |
|---|---|---|
| Development Fund (Tax Exempt) | 30 Years | 3.83% |
| State Water Implementation Fund for Texas (Tax Exempt) | 30 Years | 0.71% |

For the purposes of this analysis, NewGen utilized the terms of the Development Fund (DFund) as this is a more conservative approach. In addition, an issuance fee of 0.25% was utilized in the debt calculation.

## 9.7 Other Funding Options

Coordination with the regional water planning group and inclusion of the project as a recommended strategy in the regional and SWP are prerequisites for SWIFT eligibility. If SWIFT is considered as a funding option, the BSEACD would need to take next steps to establish eligibility.

If this project is to be used to accommodate current demands (rather than future growth), this project may be also eligible for a loan through the Drinking Water State Revolving Fund, which provides cost savings similar to SWIFT funding but is not limited to projects in the SWP. Additional cost savings could be achieved by utilizing the program's "Green Subsidy" (e.g. use of landfill gas to provide power for energy efficiency). The U.S. Environmental Protection Agency's (EPA) guidance details four types of projects that are categorically eligible for Green Project Reserve funding:

- Water Efficiency
- Energy Efficiency
- Green Infrastructure
- Environmentally Innovative

The TWDB offers subsidized funding to eligible projects with green component costs greater than or equal to 30% of the total project cost. Eligible projects may receive up to 15% in principle forgiveness of the green component costs. The available amount of green subsidy is limited.

These other funding options were not considered in this funding analysis, but should be considered as cost-savings measures by the BSEACD in the future.

## 9.8 Inflation Factors

NewGen utilized the economic projections from the Blue Chip Economic Indicators (BCEI) to determine appropriate inflation escalators for use within this financial forecast. Operation and maintenance costs were increased by 2.2 percent annually, which is consistent with the consumer price index (average census) projections.

## 9.9 Methodology

In addition to analyzing the financial impacts of developing a desalination facility utilizing a production capacity of 2.5 mgd and 5.0 mgd, NewGen also evaluated the costs associated with developing a desalination facility under various power source options, disposal concentration alternatives; as well as further quantified the cost of developing an aquifer storage and recovery (ASR) project for water produced by the desalination facility.

To minimize the number of cost options presented in this analysis, NewGen modeled the following scenarios at both 2.5 mgd and 5.0 mgd production capacities.

Table 9.6 Scenario Matrix

| | Scenario A | Scenario B | Scenario C | Scenario D | Scenario E |
|---|---|---|---|---|---|
| Facility | Desalination System without LF Gas CHP Facility | Desalination System without LF Gas CHP Facility | Desalination System without LF Gas CHP Facility | Desalination System with LF Gas CHP Facility | Desalination System with LF Gas CHP Facility |
| Disposal Alternative | Trinity Injection Wells | Edwards Injection Wells | Existing Salt Flat Field Injection Wells | Trinity Injection Wells | Zero Liquid Discharge |
| Power Source | Traditional | Traditional | Renewable | Methane | Methane/Traditional |

NewGen would note that the costs associated with an ASR project are not included in these scenarios. NewGen does provide a financial analysis for the ASR facility separately in the following section.

## 9.10 Results

NewGen conducted the analysis utilizing two financial approaches. One compares the cost per 1,000 gallons in the first year of operation and the other measures the total life-cycle cost over 30 years and 50 years of operation, respectively.

Table 9.7 lists the cost per 1,000 gallons of treated water in the first year of operation for Scenarios A – E. Schedule 3 and Schedule 4 (Appendix D) detail these costs per 1,000 gallons in 2017.

Table 9.7 Cost per 1,000 Gallons in 2017(1), (2)

| | 2.5 mgd | 5.0 mgd |
|---|---|---|
| Scenario A | $ 8.31 | $ 6.62 |
| Scenario B | $ 8.78 | $ 6.87 |
| Scenario C | $ 10.14 | $ 7.55 |
| Scenario D | $ 8.21 | $ 6.51 |
| Scenario E | $ 15.31 | $ 12.70 |

Notes:
(1) In 2017 US Dollars.
(2) Assumes 100% operating capacity

Table 9.8 shows the total life-cycle cost of operating the project facilities at 30 and 50 years. It is important to note that the life-cycle costs appropriately reflect the same number of gallons treated under each option evaluated. Due to the high volume of scenarios captured in this analysis, only Scenario A and Scenario E were captured in the total life-cycle cost analysis.

Table 9.8 Life Cycle Cost Analysis (1), (2), (3)

| | 2.5 mgd | 5.0 mgd |
|---|---|---|
| Scenario A | | |
| 30-Year | $ 10.15 | $ 8.20 |
| 50-Year | $ 10.52 | $ 8.72 |
| Scenario E | | |
| 30-Year | $ 18.53 | $ 15.51 |
| 50-Year | $ 18.87 | $ 16.05 |

Notes:
(1) In 2017 US Dollars.
(2) Assumes 100% operating capacity.
(3) Cost per 1,000 Gallons.

## 9.11 Aquifer Storage and Recovery (ASR) Analysis

NewGen also conducted a financial forecast quantifying the cost of the development of an aquifer storage and recovery (ASR) project for water produced by the desalination facility. If the ASR utilizes a traditional power source, the cost per 1,000 gallons is estimated to cost between $0.31 and $0.38 per 1,000 gallons over the total life of the project. Table 9.9 summarizes the total life-cycle analysis for the ASR project.

Table 9.9 Life Cycle Cost Analysis (1), (2), (3)

| | 2.5 mgd | 5.0 mgd |
|---|---|---|
| ASR Facility | | |
| 30-Year | $ 0.36 | $ 0.38 |
| 50-Year | $ 0.31 | $ 0.33 |

Notes:
(1) In 2017 US Dollars.
(2) Assumes 100% operating capacity.
(3) Cost per 1,000 Gallons.

ASR wellfields are typically evaluated in terms of capital cost per gpd of recovery capacity, reflecting their primary application for meeting peak and emergency demands with high reliability. For an estimated capital cost of $7.1 million, peak capacity would be increased from 5 mgd desalination capacity to 7.2 mgd using desalination plus ASR. The unit capital cost for this supplemental supply is $3.23 per gpd of recovery capacity.

The typical range for ASR wellfields is $0.50 to $2.00 per gpd of recovery capacity, with a best estimate of about $1.15. The high end of the range is typically associated with low yield wells, small numbers of wells, deep wells and initial wells in a wellfield. The low end of the range is typically associated with high yield wells, large wellfields, relatively shallow wells and wellfield expansions. The projected unit capital costs for the ASR wellfield are relatively high, but should be compared with other water supply alternatives that achieve comparable yields with comparable levels of reliability.

# Section 10: Additional Considerations and Recommendations

## 10.1 2009 Test Well

Little information is currently available regarding the construction of this test well in 2009, other than that the open borehole collapsed after it was deepened below the Regional Dense Member, which corresponds to Zone 12, the confining layer evident at the Westbay monitor well. The collapse is presumed to be due to inadequate depth and/ or grouting of the well casing, rather than encountering a layer of unconsolidated sands and gravels in the brackish Edwards aquifer. As currently constructed, this well will provide a short-circuit for movement of water between the ASR storage zone and the production interval supplying the brackish water production wells. Any such short circuit would tend to reduce ASR recovery efficiency and eventually recirculate desalinated water to the brackish water supply wells for the reverse osmosis treatment plant. Any available information from well construction should be reviewed carefully, including any driller logs. The test well needs to be drilled out to the original depth, then plugged and abandoned with neat cement grout, from the bottom to land surface. This task should be undertaken as part of the initial program for construction of test wells and monitor wells.

It is recommended to redrill, plug and abandon the 2009 test well at the TDS site. That well collapsed after penetrating through the confining layer that separates the upper and lower producing intervals of the Edwards Aquifer, leaving a short circuit for movement of saline water between the two intervals.

## 10.2 Water Supply from the City of Austin

Additionally, water supply for testing the ASR demonstration well could potentially be obtained from the adjacent City of Austin 42-inch treated drinking water pipeline which runs along Bradshaw Road, adjacent to the northwest side of the TDS site. This would require installing two taps in the line. When the desalination plant has been constructed and placed into operation, it could supply the initial ASR test well and also the expanded ASR wellfield in subsequent expansion phases. The taps in the 42-inch pipeline could then be used for desalination supply and also for ASR recovery, supplying both BSEACD and City of Austin, pursuant to an operating agreement that would be needed. Providing such taps in the 42-inch pipeline would facilitate parallel construction and testing of desalination facilities and wellfield facilities.

### 10.2.1 Additional Test Well

A test well should be constructed to the Sligo formation in the Trinity aquifer, at an estimated depth of about 1,825 feet at the top of the aquifer. This would probably be located within the ASR wellfield area, reflecting the greater probability that the water quality in this aquifer is less than 10,000 mg/l total dissolved solids and therefore this aquifer would be unsuitable for concentrate disposal. That would make this well a potentially suitable ASR well. If, on the other hand, further investigations suggest a greater likelihood that this aquifer may be suitable for concentrate disposal, the well should probably be relocated to the vicinity of the brackish water production wellfield and the associated desalination plant.

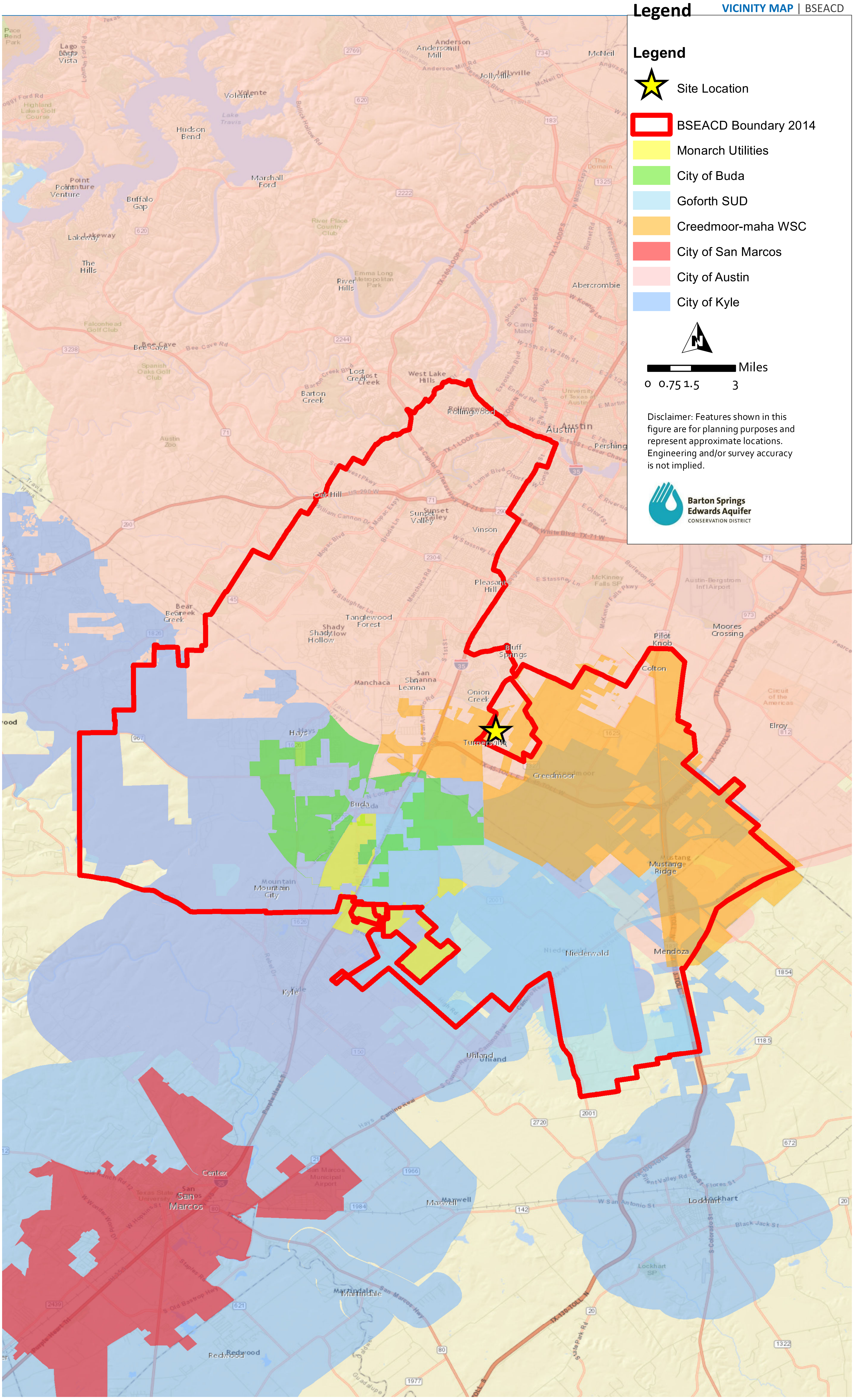
The test well would be cased to the top of the Sligo formation and would extend open hole to the base of the formation. Casing material of construction would be fiberglass or 304 stainless steel. The design of the well would likely depend to some extent upon the primary intended long term objective of this test well, whether for ASR purposes or concentrate disposal purposes. A reasonable assumption is that the inner casing nominal diameter would be at least 12-inches, which would be appropriate for recharging and recovering water or recharging concentrate at flow rates of several hundred gallons per minute.

## 10.3 Desalination Pilot Testing

The RO system design criteria are based on results from membrane and antiscalant manufacturers' models. This approach is typical for a conceptual-level feasibility study. The models are a good source of preliminary hydraulic and water quality performance data. However, with the high TDS, boron, and scale forming potential of the raw groundwater, validation of the design and operational criteria with a pilot study is recommended. In addition, including an evaluation of alternative RO operating criteria and desalination equipment with a pilot study may help lower capital and operating costs of the full-scale system.

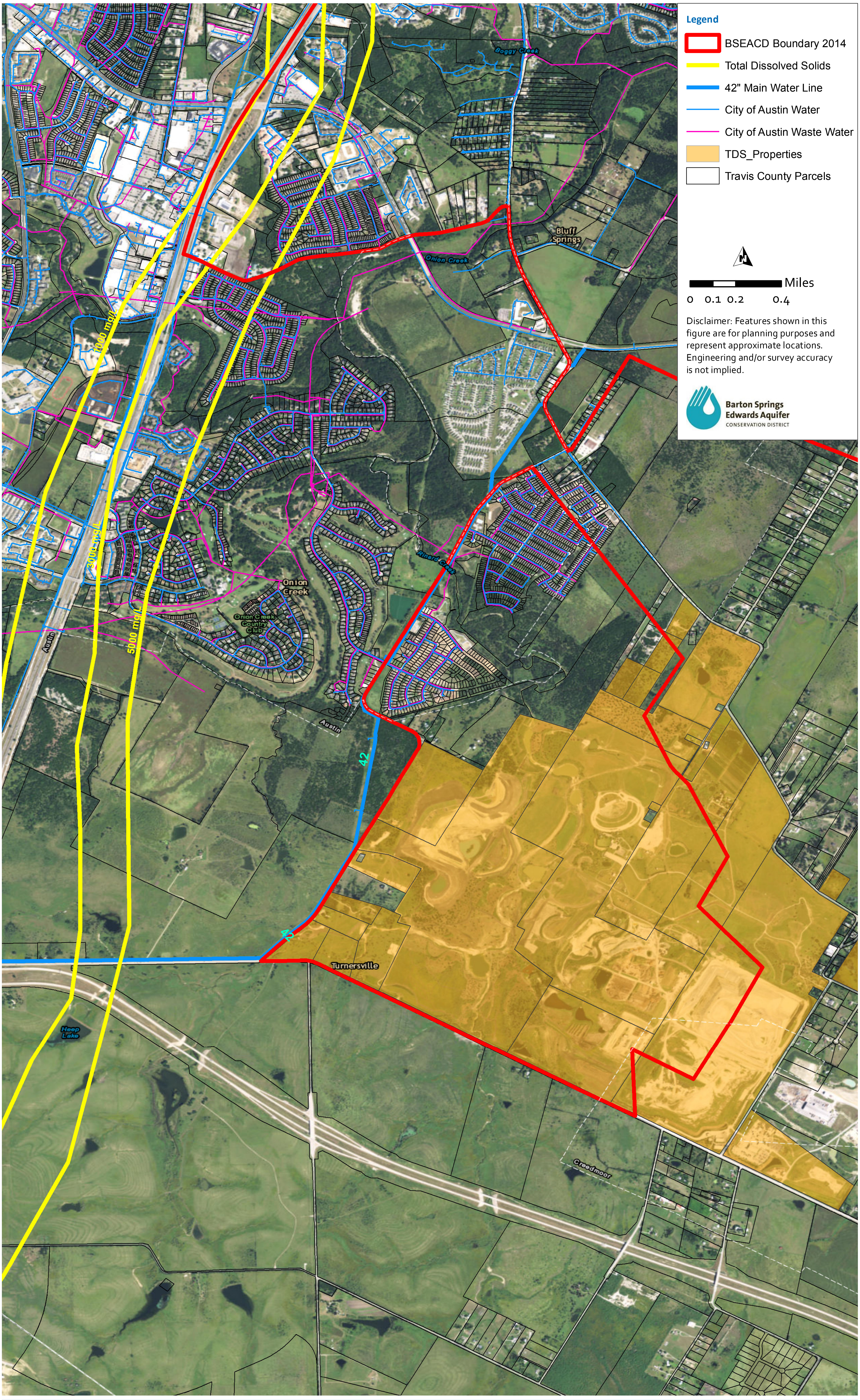
# Appendix A

# MAPS



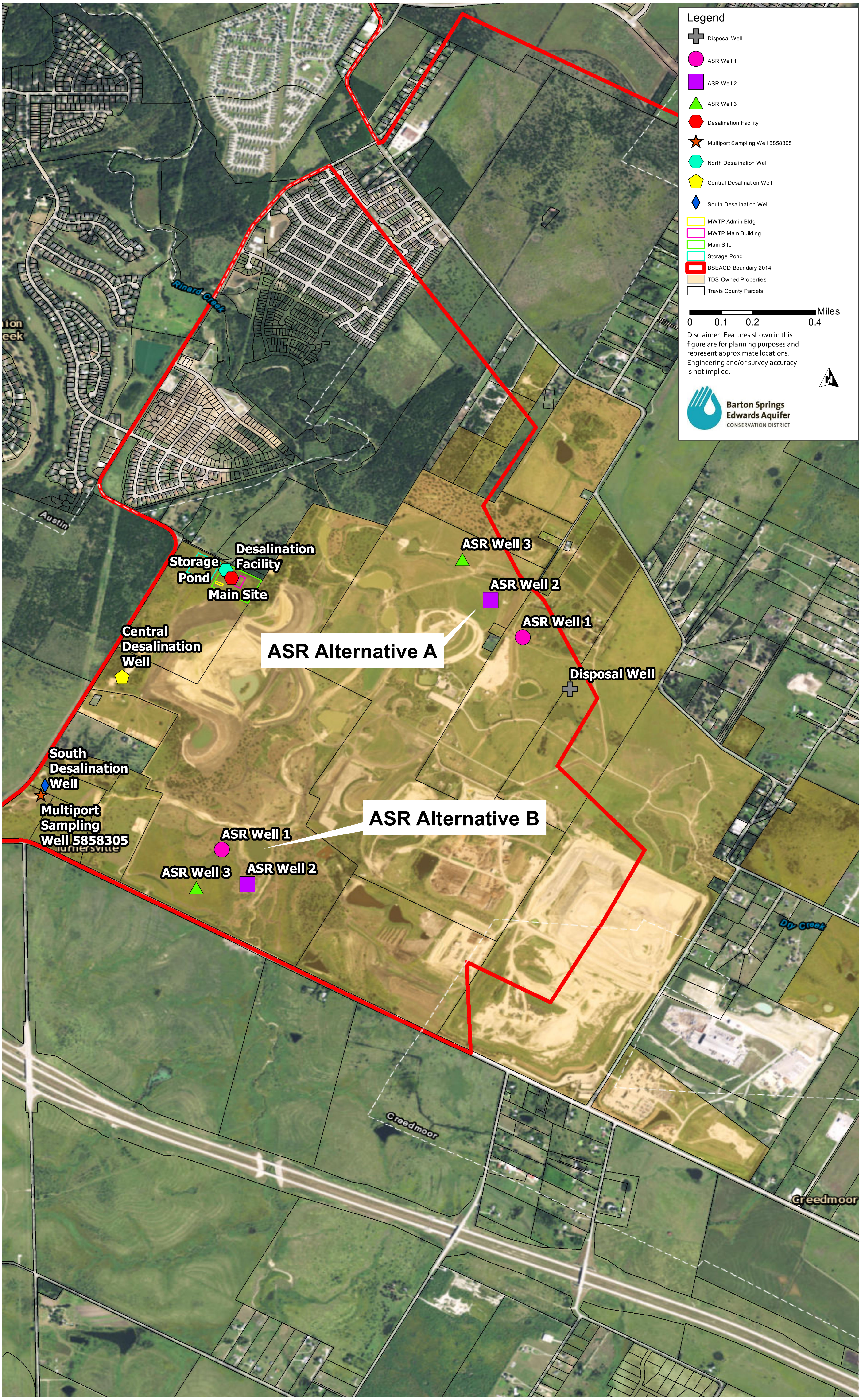
Disclaimer: Features shown in this figure are for planning purposes and represent approximate locations. Engineering and/or survey accuracy is not implied.

Figure # 1 Vicinity Map



Disclaimer: Features shown in this figure are for planning purposes and represent approximate locations. Engineering and/or survey accuracy is not implied.

Figure # 2 | General Information Map



Disclaimer: Features shown in this figure are for planning purposes and represent approximate locations. Engineering and/or survey accuracy is not implied.

Figure # 3 | General Layout

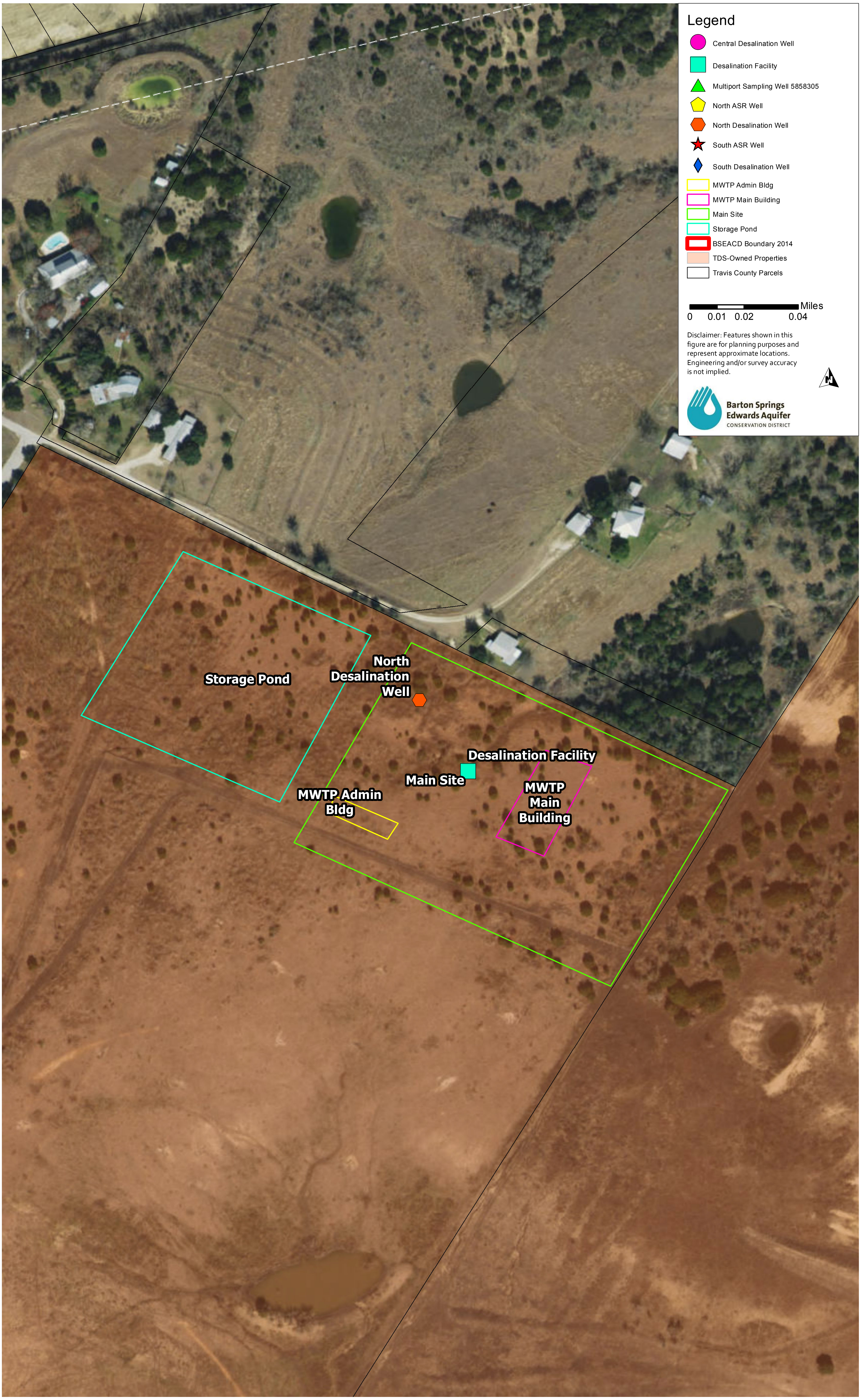


Figure # 4 | Site Layout

## Appendix B

# TEXAS A&M ZLD

**Emailed on:** April 12, 2017

**Sent from:** Mark Holtzapple to Philip Bullock, David Pyne,

**CC:** David Harkins, Jeff Stovall , Justin Sutherland and Mefouts12@gmail.com

**Time: 5:28 p.m.**

**Contents:** BSEACD-Brine Disposal

---

**In detail, the email read as follows:**

Philip,

I enjoyed our conversation today.

As promised, I have attached the following:

- White paper that describes our advanced vapor-compression desalination process
- Report that describes the pilot studies performed in Laredo

I should note that the Laredo project had a number of successes, but it required addition funds to make it fully successful. Unfortunately, both parties ran out of funds and were unable to continue perfecting the hardware. Fortunately, I learned a tremendous amount from that experience and have updated the technology to overcome the problems encountered during construction.

Thanks,

Mark

**Attachments:**

- **Advanced Vapor Compression**
- **Final Report Laredo AdVe Pilot Plant (Final Compressed)**

# Vapor-Compression Desalination

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College Station, TX 77843-3122, m-holtzapple@tamu.edu

20 March 2016

## Background

By 2050, the global population is expected to reach 9 billion, almost a 4-fold increase in one century.[1] Although population is growing rapidly, freshwater supplies are not. Of the total water on earth, only 0.007% is readily accessible freshwater.[4] By 2025, 1.8 billion people will live in water-scarce regions, and 5.4 billion will live in water-stressed regions.[4] Recent water shortages in California have highlighted the importance of this problem.

There is a nearly infinite supply of water in the oceans, which can be desalinated to meet human needs. Fortunately, desalinated water does not require a long distribution pipelines to reach consumers. Of the global population, 40% lives within 100 km of the ocean,[2] and in the United States, 40% of the population lives in counties that border the ocean.[3]

## Desalination Technology

Below is a brief summary of key desalination technologies:

***Multi-stage flash (MSF)*** – Seawater is preheated in a heat exchanger. High-pressure steam completes the heating process. Then, the hot seawater is sent to a series of chambers, each operated at a successively lower pressure. In each chamber, steam flashes and is used to preheat the incoming seawater (Figure 1).

***Reverse osmosis (RO)*** – Seawater is pressurized and forced through a membrane that passes only water, leaving concentrated brine behind (Figure 2).

***Vapor-compression desalination (VCD)*** – The steam above salt water is compressed and sent to a heat exchanger where it condenses. Heat that passes through the heat exchanger wall causes more water to evaporate from the salt water leaving concentrated brine behind (Figure 3).

Figure 4 shows the distribution of global desalination capacity, much of which is located in the Middle East. Figure 5 shows that membrane technologies (primarily RO) dominate the United States. Thermal technologies (primarily MSF) dominate the Middle East, which has about 47% of global desalination capacity.[5]

In 1958, the first commercial MSF plant was built and in 1982, RO became commercial.[7] Both of these technologies were predated by VCD, which was practiced during World War II to desalinate water for submarines and diesel-powered ships.[8] Since 1969, the Israeli company IDE has installed over 260 VCD units worldwide with reported availabilities of 96–98% with minimal corrosion or fouling.[9] Their units operate at low temperature (<70°C) and low pressures (<0.3 atm). Because the vapor density is very low, the compressor must be extremely large.[9]

## Costs of RO and MSF

Table 1 summarizes the costs of RO and MSF. RO is less expensive and therefore is being installed at a much higher rate than thermal methods, such as MSF (Figure 6). In 2010 and after, the cost of RO ranged from \$0.63 to \$2.43/m$^3$ (Figure 7). Since 2001, the general cost trend is upward.

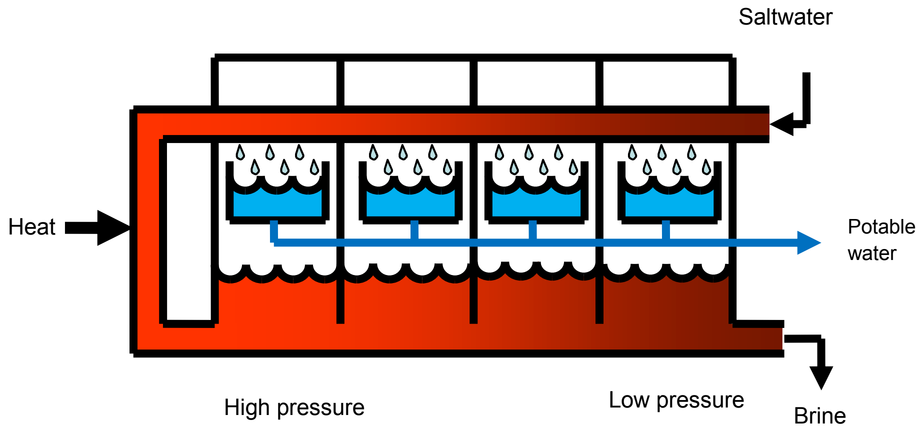

**Figure 1.** Multi-stage flash.

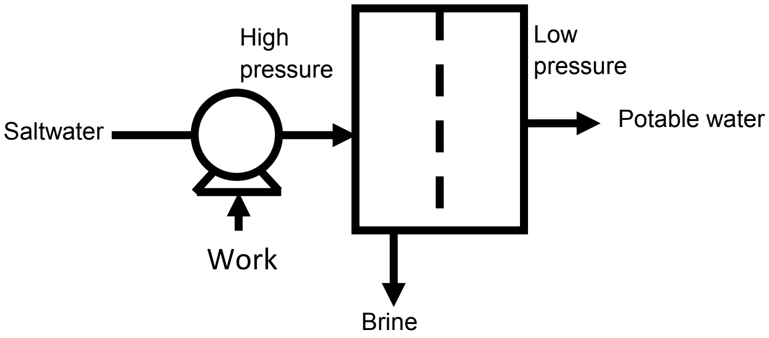

**Figure 2.** Reverse osmosis.

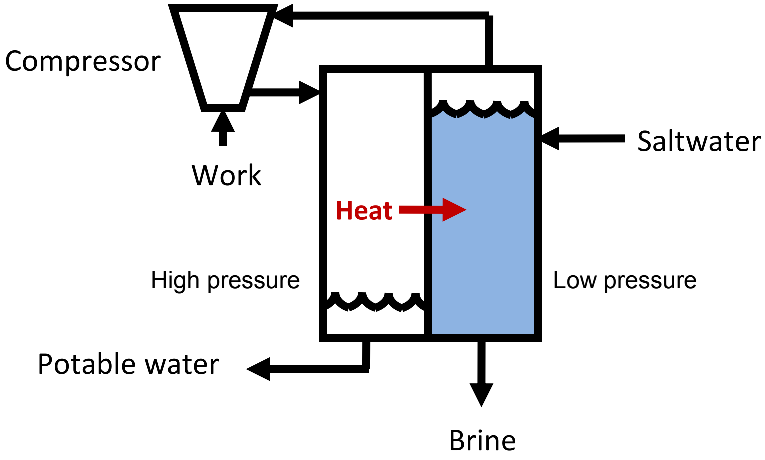

**Figure 3.** Vapor-compression desalination.

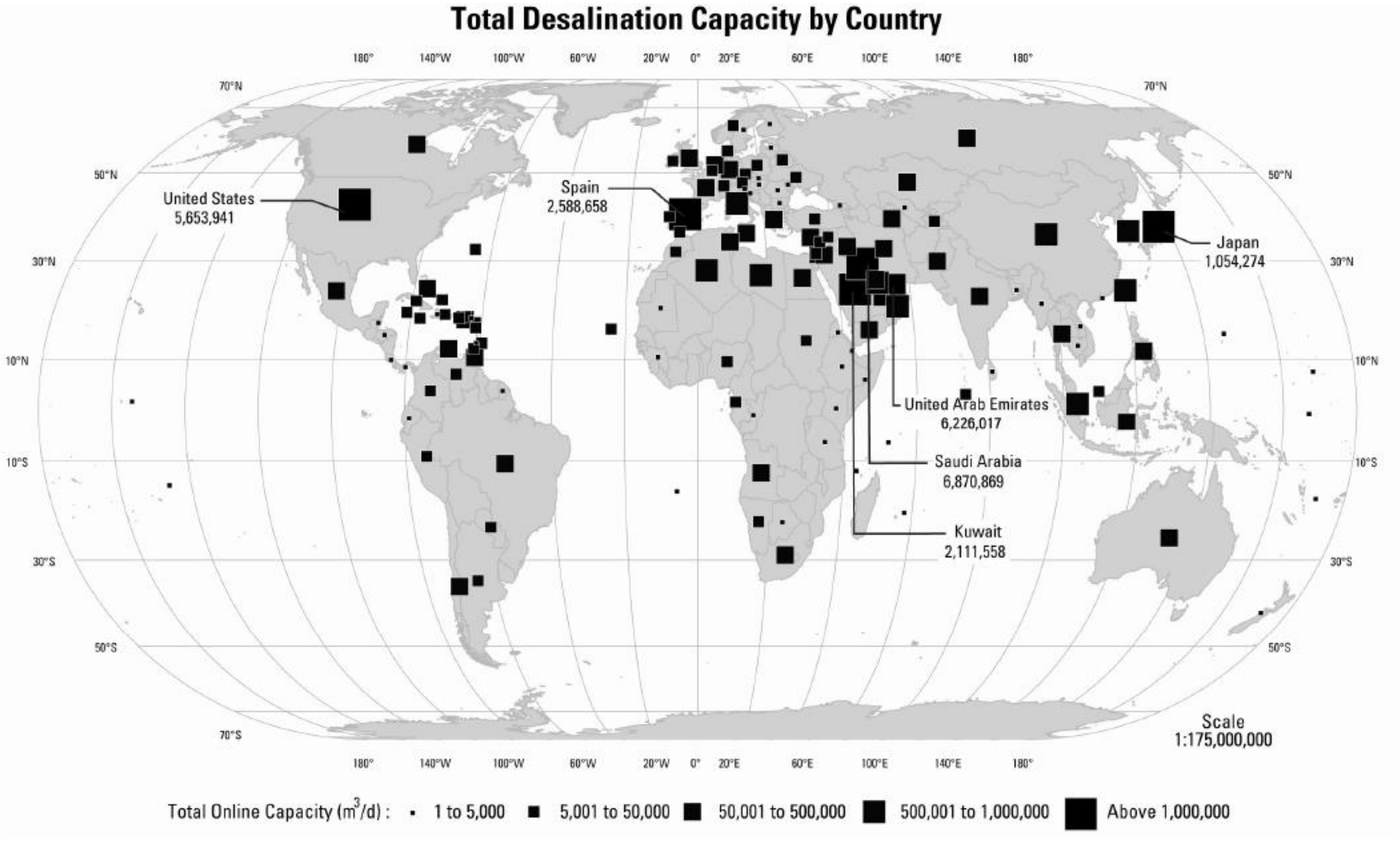

**Figure 4.** Global desalination capacity.[5]

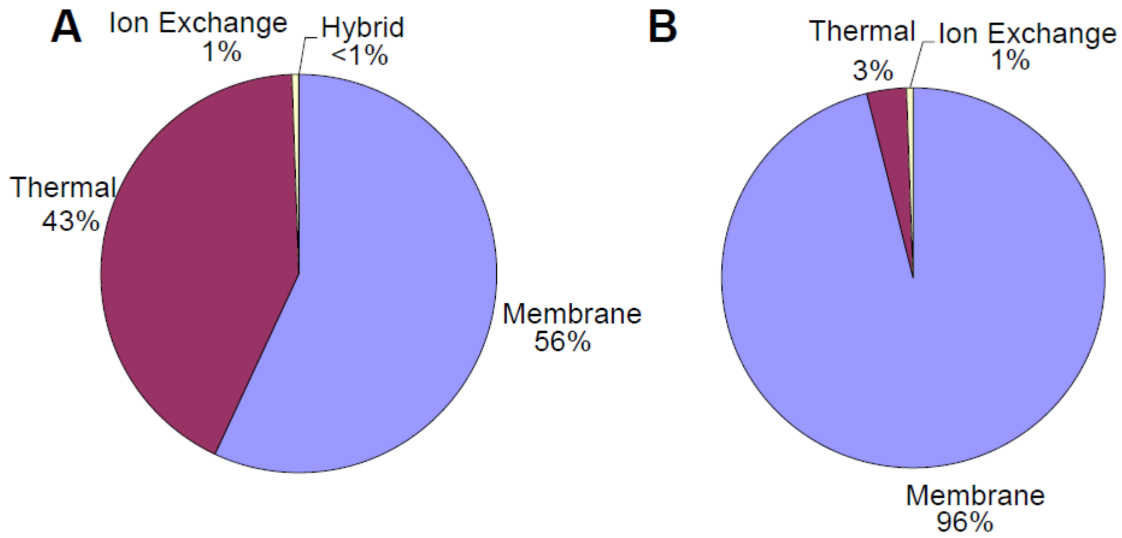

**Figure 5.** Distribution of desalination methods (A) globally and (B) United States.[5]

**Table 1.** Estimated cost for reverse osmosis (RO) and multi-stage flash (MSF)

| | RO ($/m$^3$) | MSF ($/m$^3$) |
|---|---|---|
| Annualized capital costs | 0.15 | 0.29 |
| Parts/maintenance | 0.03 | 0.01 |
| Chemicals | 0.07 | 0.05 |
| Labor | 0.10 | 0.08 |
| Membrane replacement | 0.03 | 0.00 |
| Thermal energy | 0.00 | 0.27 |
| Electrical energy ($0.05/kWh) | 0.23 | 0.19 |
| Total | 0.61 | 0.89 |

Assumptions:

- Year = 2006
- Capacity = 100,000 m$^3$/day
- Interest rate = 6%
- Payback = 20 years

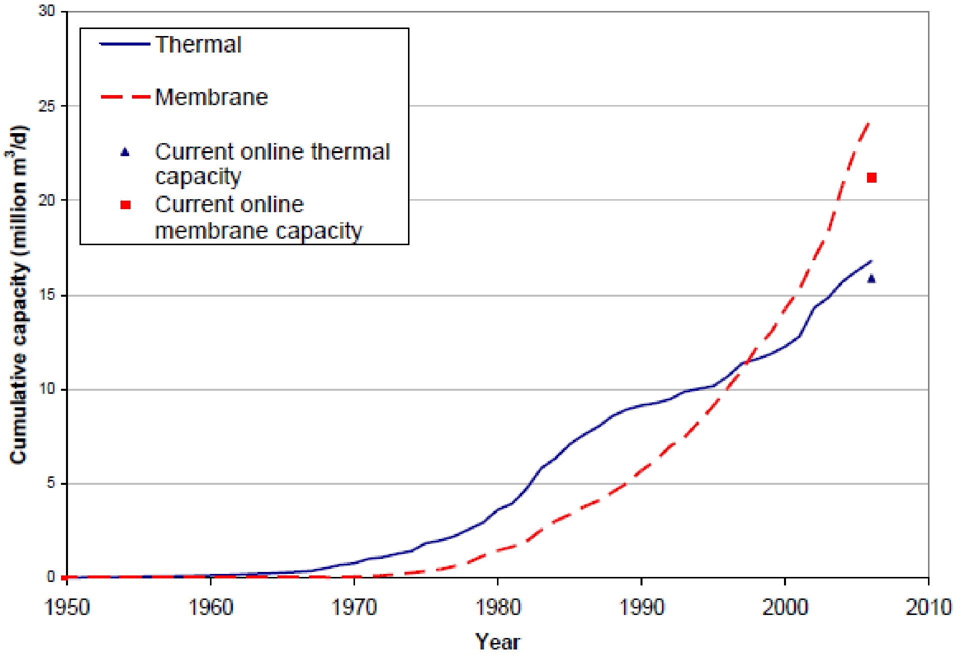

**Figure 6.** Global installed desalination capacity.[5]

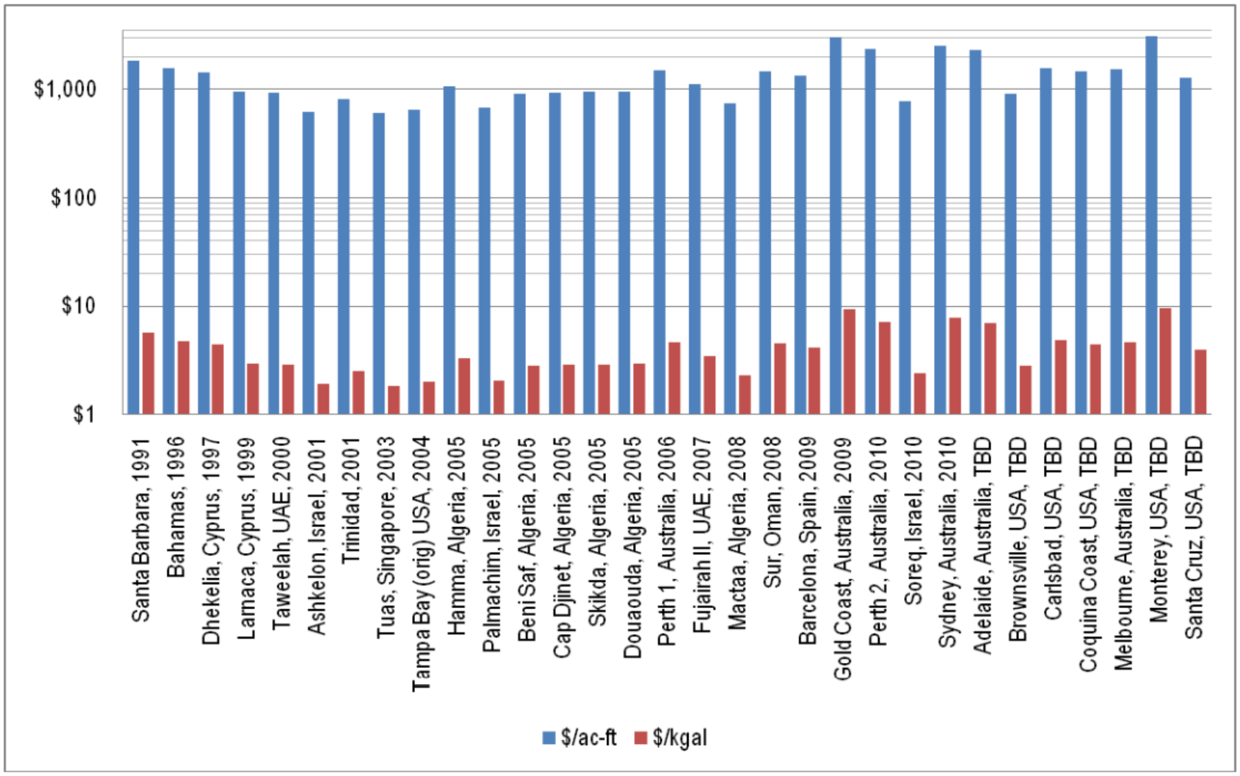

**Figure 7.** Historical cost of RO.[10]

## Advanced Vapor-Compression Desalination

Figure 8 shows a schematic of Advanced VCD. A heat source (e.g., combustion, waste heat, solar, nuclear) produces high-pressure steam that powers a series of turbines to produce shaft work. The shaft work can produce electricity, or directly drive compressors in the vapor-compression system.

Raw seawater is pretreated to remove carbonate and sulfate, both of which are scale-forming components. The water pH is adjusted to about 4.3 so that carbonate is converted to carbon dioxide, which can be removed readily by stripping. Then, sulfates are removed via ion exchange.[11] Interestingly, the spent ion exchange resin is regenerated using the brine discharged from the desalination system, thus no chemicals are consumed.

Using sensible heat exchangers, the pretreated water is heated to 177.87°C. Then steam is directly added to heat the water to 180°C so it can be fed to the latent heat exchangers. The source of the steam is a combination of steam bled from the expanders and steam produced in desuperheaters. Because steam is being bled from the expanders, make-up water is required.

Steam that evaporates in the first latent heat exchanger is compressed. The superheated steam produced from the compression is removed by spraying atomized saturated liquid water into a desuperheater, which is a simple pipe with enough residence time to vaporize the atomized saturated liquid water. The water vaporized in the desuperheater contributes to the steam that heats the incoming water to 180°C. The saturated steam exiting the desuperheater is fed to the condenser of the latent heat exchanger to produce distilled water. The heat of condensation passes through the heat exchanger wall and becomes the heat of evaporation that evaporates steam from the salt water. The heat is recycled repeatedly using a small amount of shaft power provided to the compressors. The compressor pressurizes the heated steam to the required pressure so that heat can transfer through the heat exchanger walls.

The brine produced in the first latent heat exchanger has a higher salt content than seawater. This concentrated brine is fed to the second latent heat exchanger where the process is repeated. In Figure 8, five latent heat exchangers are shown, but more or fewer can be employed. Increasing the number of heat exchangers improves energy efficiency because the process more closely approximates reversible evaporation.

The concentrated brine and distilled water that exit the latent heat exchangers is hot and high pressure. The sensible heat exchanger exchanges heat with the incoming seawater. After the sensible heat exchanger, the high-pressure water passes through a turbine that recovers pressure energy in the form of shaft work. The brine and distilled water exit 2.13°C warmer than the incoming seawater. This slight temperature rise comes from the net energy input in the form of shaft power and a small amount of bleed steam from the expanders. The fact that the process produces such a modest temperature rise is a testament to its energy efficiency.

The process described in Figure 8 has the following "advanced" features:

- The latent heat exchangers operate at high temperatures and pressures, which greatly improves heat transfer coefficients.[12, 13]
- Dropwise condensation is employed in the latent heat exchangers, which greatly reduces the required temperature difference (0.2°C) and improves energy efficiency.
- High-efficiency positive-displacement compressors are employed.
- Novel sensible and latent heat exchangers are employed, which are effective, but inexpensive.

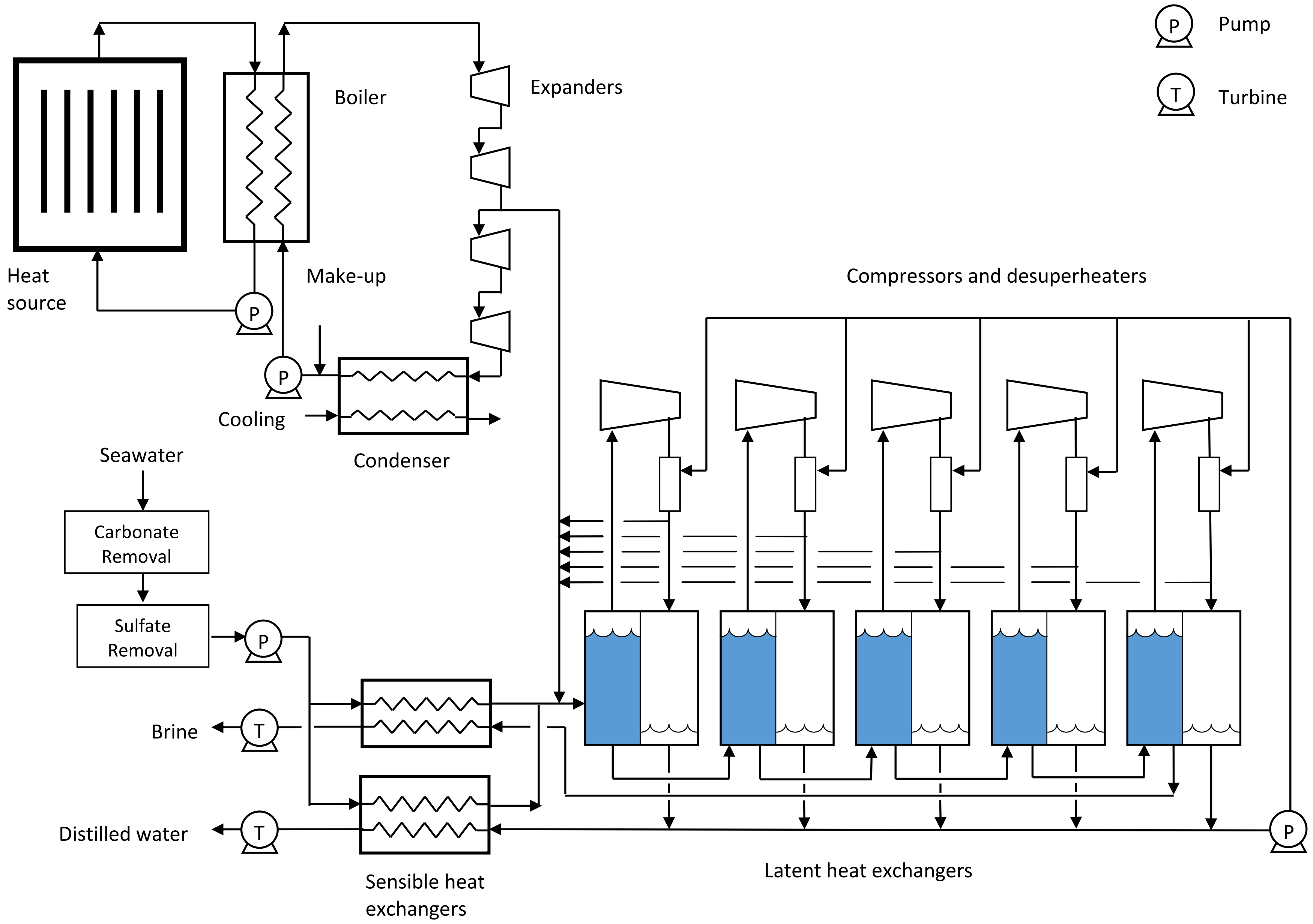

**Figure 8.** Advanced vapor-compression desalination.

## Economics of Advanced Vapor-Compression Desalination

A thorough economic optimization has been performed for Advanced VCD, and is available as a separate report. The key assumptions follow:

- Freshwater production of each module = 40,000 $m^3$/d = ~10 million gallons per day
- Annual operation = 7920 h = 330 days
- Incoming seawater temperature is 25 °C
- Five-stage process recovers 74% of water
- Turbines and pumps operate with efficiencies of 80%
- Blowers operate with efficiencies of 90%
- Circulation pump power assumed to be 200 kW
- Modular units can be repeated to increase capacity
- Lang factor of 3.68 is based on modular units that are constructed in a factory
- Finance with a 30-year municipal bond at 2.8% annual interest rate
- Grid price of electricity = $0.05/kWh (California, 2014, Figure 9)

Tables 2 to 4 document the water selling price is **$0.39/$m^3$**, which is an attractive price. Because of the drought, in the Fresno-based Westlands Water District, raw water costs have soared from $0.11 to $0.89/$m^3$. North of Sacramento, the Western Canal Water District is selling it for double the usual price: $0.40/$m^3$. The estimated cost of $0.39/$m^3$ is less than 30% of the retail price of water in California cities (Table 5).

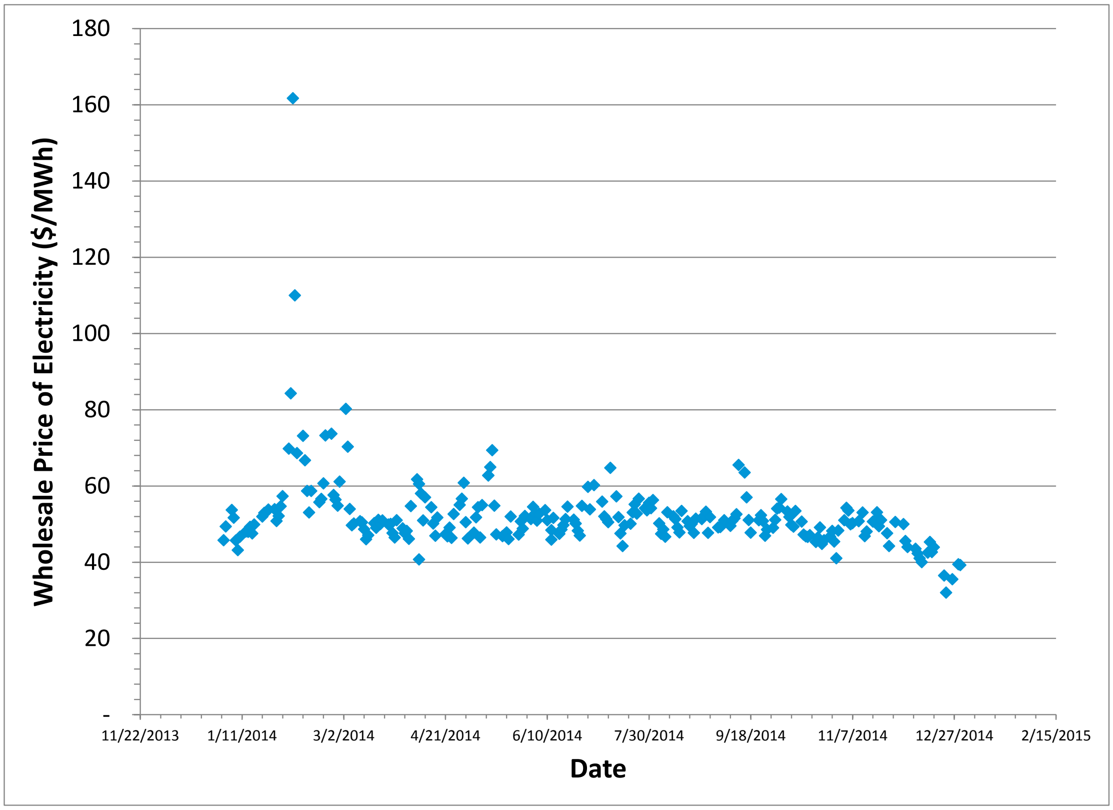

**Figure 9:** Wholesale price of electricity in Southern California (SP-15).[14] Year = 2014.

**Table 2.** Capital cost of one module (40,000 $m^3$/d).

| Equipment | Equipment Cost | Lang Factor | Installed Cost |
|---|---|---|---|
| Latent Heat Exchanger | $672,158 | 3.68 | $2,473,541 |
| Sensible Heat Exchanger | $1,049,929 | 3.68 | $3,863,739 |
| Blower | $1,654,006 | 3.68 | $6,086,742 |
| Pump/Turbine | $290,000 | 3.68 | $1,067,200 |
| Circulation Pump | $290,000 | 3.68 | $1,067,200 |
| Desuperheater | $10,000 | 3.68 | $36,800 |
| Carbon Dioxide Stripping Towers | – | – | $1,500,000 |
| **TOTAL** | **$3,966,093** | | **$ 16,095,222** |

**Table 3.** Utility consumption for each piece of equipment.

| Equipment | Shaft Power (kW) | Steam (kW) |
|---|---|---|
| Latent Heat Exchanger | – | 382 |
| Sensible Pump | 495 | – |
| Blower | 4482 | – |
| Intake Pump | 840 | – |
| Turbine | –540 | – |
| Circulation Pump | 200 | – |
| **TOTAL** | **5477** | **382** |

**Table 4.** Estimated costs of desalinated water.

| | Cost ($/$m^3$) | Cost ($/yr) |
|---|---|---|
| Bond | 0.060 | 793,022 |
| Insurance (0.007/yr × FCI) | 0.009 | 112,667 |
| Maintenance (0.04/yr × FCI) | 0.049 | 643,809 |
| Electricity ($0.05/kWh)* | 0.164 | 2,160,360 |
| Heat ($0.0166/kWh) † | 0.0037 | 49,351 |
| Labor (8 workers @ $70,000/yr) | 0.042 | 560,000 |
| Sulfate removal | 0.064 | 840,167 |
| **TOTAL** | **0.392** | **$5,159,376** |

*Average cost of electricity on the California grid.

†Assume electricity production is 33% efficient

**Table 5.** Retail price ($\$/m^3$) in various California cities.

| City | Los Angeles* | San Diego | San Francisco |
|---|---|---|---|
| Residential starting price | 1.94 | 1.38 | 1.93 |

* Malibu

### Risks

The primary risk associated with Advanced VCD results from operating at high temperatures (180°C). The Israeli company IDE purposely operates at low temperatures (70°C) to avoid potential scaling; however, this comes with two major penalties: (1) very large compressor, and (2) poor heat transfer coefficients. Advanced VCD overcomes these penalties, but has the potential for the heat exchanger surfaces to scale from carbonates and sulfates. This risk can be mitigated as follows:

- Remove carbonates by acidification and stripping. (This cost is incorporated in the economic analysis.)
- Remove sulfates by selective ion exchange. (This cost is incorporated in the economic analysis.)
- Seed the brine with calcium sulfate to promote precipitation on the seed crystals rather than heat exchange surfaces. This technology is described by Mickley.[6]
- Incorporate devices that encourage precipitation in the bulk rather than surfaces. Such a device is manufactured by Colloid-A-Tron.
- Circulate rubber balls that scour and clean heat exchanger surfaces.
- Design the heat exchanger for easy disassembly and cleaning.

### Energy Costs

Advanced VCD is very energy efficient. The work required to separate water from salt is 3.28 $kWh/m^3$ (Table 3). Figure 10 shows that the theoretical minimum is 1.3 $kWh/m^3$, so the process is 40% efficient. Table 6 compares the energy cost of desalination to other energy costs associated with procuring water. Note that the energy cost of Advance VCD is less than the range reported for desalinating seawater (last row, Table 6).

### Conclusion

Using the grid price of electricity in California ($0.05/kWh), Advanced VCD is estimated to produce water for $\$0.39/m^3$. This cost is substantially less than RO ($\$0.63$ to $\$2.43/m^3$), the current best-available technology. RO is a mature technology and is unlikely to have major cost reductions; in fact, the cost curve is increasing (Figure 7). To achieve lower costs, new technologies such as Advance VCD must be developed.

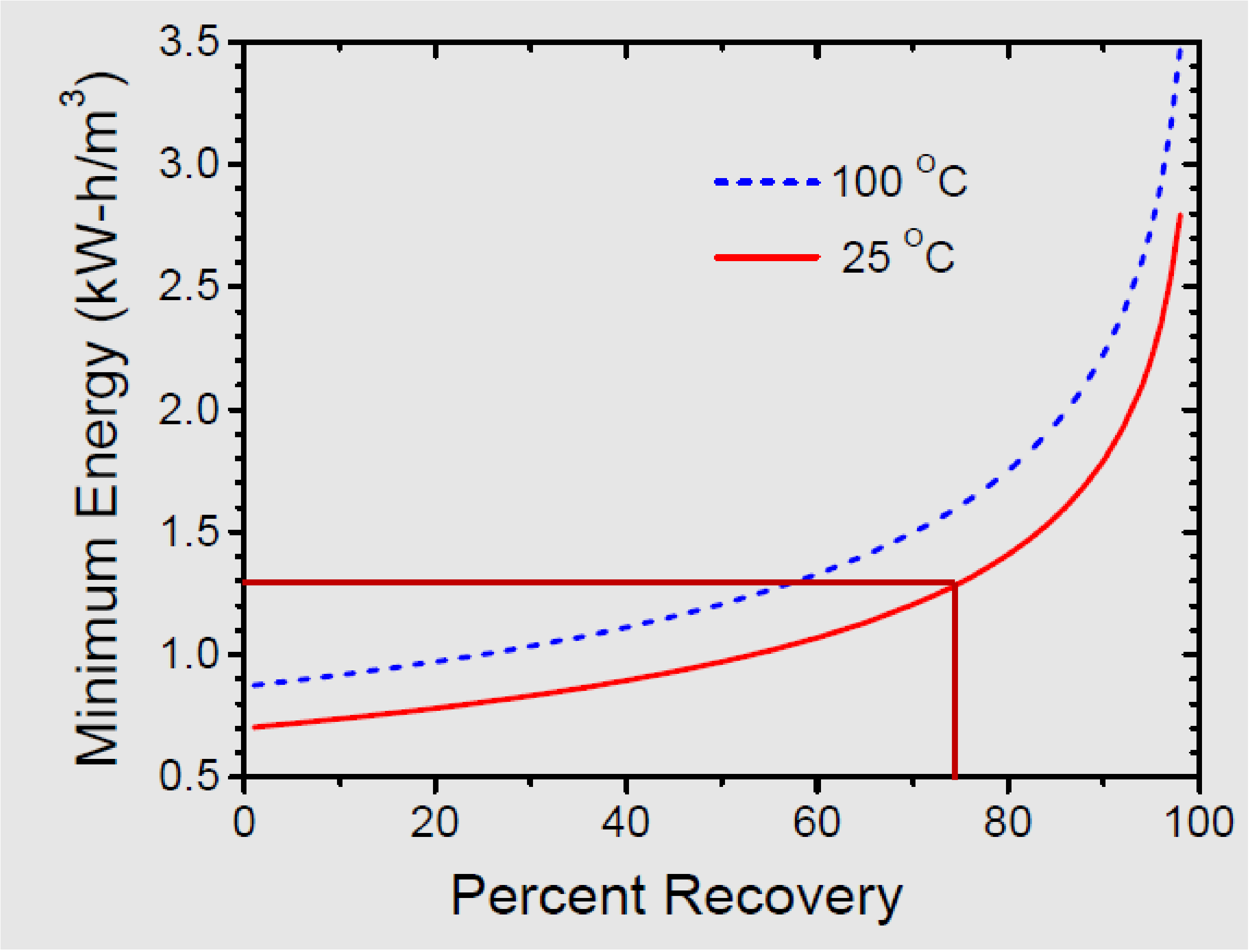

**Figure 10.** Theoretical minimum energy to separate water from seawater.[5]

**Table 6.** Energy costs associated with procuring water in California[5]

| **Water Source** | **Energy Cost (kWh/m$^3$)** |
|---|---|
| Pumping groundwater 120 ft | 0.14 |
| Pumping groundwater 200 ft | 0.24 |
| Treatment of surface water | 0.36 |
| Brackish water desalination | ~0.3 to 1.4 |
| Water recycling (no conveyance) | ~0.3 to 1.0 |
| Conveyance of water (Colorado River aqueduct to San Diego) | 1.6 |
| Conveyance of water (San Francisco Bay Delta to San Diego) | 2.6 |
| Seawater desalination (no conveyance) | ~3.4 to 4.5 |

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2011

# Final Report
# Advanced Vapor Compression Desalination Pilot Project for the City of Laredo, Texas

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# ACKNOWLEDGMENTS

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We also recognize the important contributions of Texas Systems and Control of Tomball, Texas in the detail design and construction of the pilot plant, especially Dennis Abramson and Greg Bear.

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# 1.0 EXECUTIVE SUMMARY

The Brackish Water Desalination Project was initiated to test, develop and enhance the Advanced Vapor Compression technology developed by Texas A&M University. The project called for supplying the City of Laredo with a Demonstration Unit incorporating the Advanced Vapor Compression technology. The contract was awarded to the Texas Engineering Experiment Station and subcontracted to Terrabon, Inc., the exclusive licensee of the technology from Texas A&M. The project entailed the design and construction of the demonstration unit as well as commissioning and operation of the unit at the City of Laredo's Santa Isabel Water Plant.

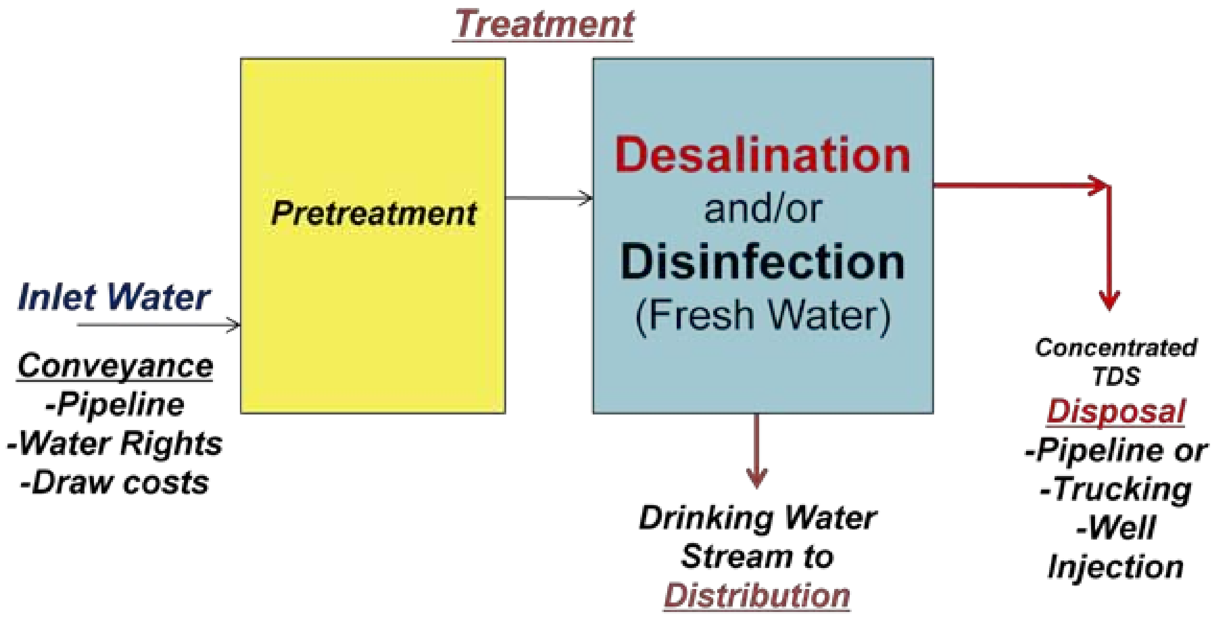
The project cost $2.8 Million to build and test, of which the City funded 56% and Terrabon the remaining 44% of the cost.

The result of the Project is that the technology has been demonstrated to be of economic benefit to the City of Laredo in the event the City's supplemental water supply strategy includes saline groundwater sources in the Laredo region. The use of AdVE technology will reduce the overall cost of desalinated water vs. alternative methods by offsetting and significantly reducing the total cost of disposal of concentrate by maximizing the yield of potable usable water from the inlet saline water. The higher the inlet salinity, the greater the economic benefit to the City of Laredo. Additionally, though not estimated in this analysis, is the significant benefit to the City of Laredo of greater yield of potable water in a water scarce environment.

The demonstration unit had a target water production of 50,000 gallons per day (gpd) but did not meet that capacity for a number of reasons, also detailed herein. The unit can produce approximately 10,000 gpd.

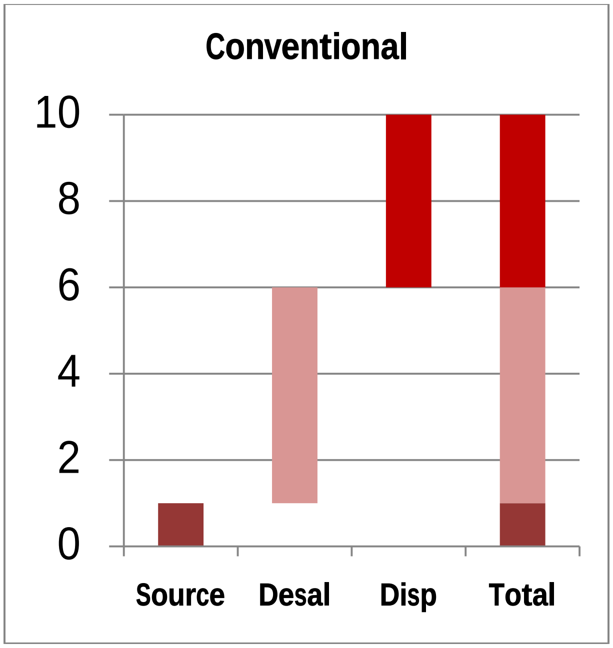
In the desalination process there is always a residual portion of the water that has to be disposed which carries the concentrated salt from the inlet water. This residual portion is called the waste stream and due to the high cost of ultimate disposal of this stream it should be minimized by maximizing the production ratio of water from the inlet to the usable potable flow. Further, the waste stream, because of its high salt concentration, must be disposed in accordance with State regulation, typically requiring the injection into designated deep disposal wells. The total disposal costs associated with the waste stream include conveyance costs, either via pipeline or trucking, and disposal well injection costs. These disposal options are all very costly, so reducing the waste stream volume saves the City capital and/or operating costs. It was assumed that pipeline conveyance will be used for disposal since the use of trucking can be five to ten times more costly than pipeline depending on the distance to the disposal injection wells.

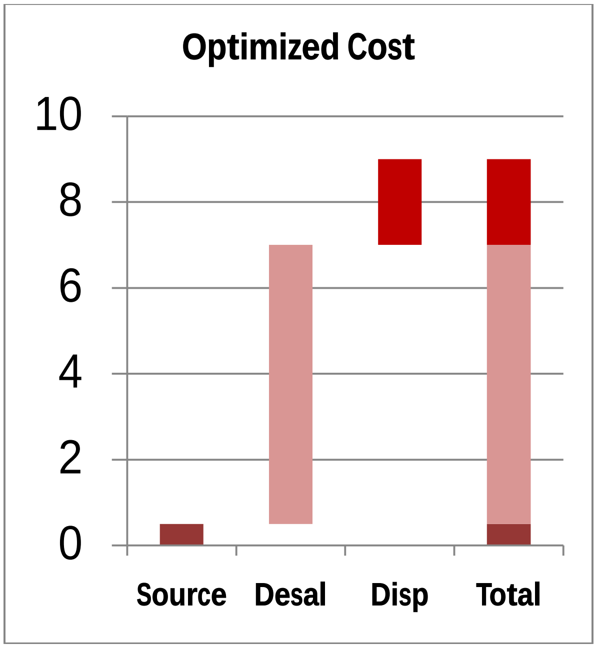
Below is a depiction of a typical Water Treatment Process. The various steps in the chain define the components of the total cost of potable water production.



As seen above, when the inlet water is saline, or above the salt concentration of 1,000 parts per million set by the State as the maximum for potable use, the desalination step needs to be inserted in the process to remove the salts. That process generates the disposal flow as a byproduct to carry the now concentrated salts away for disposal.

In general, the total cost of the desalination process includes capital and operating costs incurred from the 1) incremental flow of source water brought in to carry the concentrated salts to disposal, 2) the desalination of the stream itself, and 3) the disposal of the waste stream. The use of AdVE, while increasing the capital cost of treatment, reduces the overall cost of water by reducing the cost of concentrated water disposal.





There are various technologies for desalination, of which Reverse Osmosis (RO) is the most commonly used. Though RO is the lowest cost desalination technology, its shortfall is the large disposal stream it generates thus driving up the cost of concentrate disposal as well as the waste of scarce water.

The combination of first stage use of RO with a second stage use of AdVE provides significant cost savings by reducing the cost of disposal. A cost comparison study is provided in this report comparing various options for desalination.

AdVE, in combination with RO, provides the City of Laredo the lowest cost of desalinated water!

The participation in the development of the AdVE technology provides the City of Laredo the primary benefit of a robust water desalination technology that enables the conversion of the maximum amount of saline ground water to potable water at the lowest total cost per gallon.

A secondary benefit to the City and region is the furthering of a technology that can be used to recycle return flow water in Eagle Ford Shale gas fracking operations and thus reduce the volume of the City's limited potable water to this industrial sector. This potential application of the AdVE technology needs significant additional study to address the removal of other constituents in the oil and gas field flow back frac water. Further, in the water scarce environment of Laredo with limited resources and growing population demand, maximizing potable water from saline aquifers is invaluable.

As an additional benefit, the City of Laredo and Webb County will receive royalty free use of the AdVE technology including any technology development and improvements made by Terrabon for a period of 20 years for all AdVE systems delivered in Webb County before end of 2031.

# 2.0 INTRODUCTION

According to the Texas Water Development Board's 2007 Water Plan, the State of Texas will require an additional 8.8 million acre-feet of water per year by 2060 [1]. This statistic is well known by the City of Laredo which is experiencing the largest growth in the city's history [2]. This report describes a research and development effort funded by the City of Laredo to address this looming water shortage by economically utilizing the significant amount of brackish groundwater available to the City [3].

The Artie McFerran Department of Chemical Engineering at Texas A&M University has developed two technologies that, when combined, have the potential to significantly reduce the cost of brackish water treatment in conjunction with conventional reverse osmosis technologies. The first technology is an Advanced Vapor Compression Desalination process that is significantly more efficient than conventional vapor compression desalination [4]. The other technology is a high-efficiency compression technology called the StarRotor [5]. The Terrabon Corporation has licensed the Advanced Vapor Compression Technology and is commercializing it into a product called AdVE (Advanced Vapor Evaporation). The StarRotor technology is being commercialized by the StarRotor Corporation. The new compression technology is integrated into the Terrabon AdVE Pilot System described in this report.

The City of Laredo faces significant challenges in securing sufficient water supplies for the future. It is estimated that significant shortfalls in surface water, as well as rights to this water, exist which will stress the ability of cities along the middle and lower Rio Grande to secure adequate supplies of water [6]. The City chose to invest funding in this technology to evaluate the feasibility of using brackish ground water to cost-effectively address their future water shortage.

# 3.0 BACKGROUND

## 3.1 Laredo Water Needs

The City of Laredo is in the unique position of enjoying sustained population and economic growth even during the current national economic recession. The 2011 TWDB Region M Water Plan projects Webb County's population to increase from 257,649 in 2010 to 721,586 in 2060. The corresponding projected water demands in Laredo for this interval are 39,558 acre-feet/year in 2010 and 124,038 acre-feet/year in 2060, a 313% increase! Accordingly, the City of Laredo is wisely evaluating all possibilities to meet future demands. Primary strategies being vetted include: 1) securing additional potable water rights, primarily through conversion of irrigation rights, 2) increased conservation initiatives to lower per capita water demand, 3) reuse and recycling of treated wastewater effluent, 4) development of groundwater (non-brackish aquifers), and 5) development of groundwater (brackish and saline).

Each of these strategies has its own unique "pros and cons". Expanded acquisition of surface water rights takes advantage of the City's demonstrated proficiency in treating this source. Conversely, continuing solely on an expansion of surface water rights and related treatment infrastructure leaves the city vulnerable to the ever present potential of the next "drought of record". Simply put, contractually held water rights cannot create water that is not present in the river system. Surface water expansion is also dependent on Mexico's compliance with required discharges into the Rio

Grande in accordance with the 1906 and 1944 international water compacts. This has been a topic of heated diplomatic dialog in the recent past.

Conservation and reuse strategies are very viable to augment future water supplies but cannot, on their own, secure the City's water future.

Pursuing non-brackish groundwater, primarily from the Carrizo-Wilcox formation in adjacent counties, is a good option in that it requires little treatment but there are risks and possible difficulties in securing a long term commitment from groundwater rights holders and the related groundwater conservation districts in conjunction with a costly conveyance system.

The use of locally available brackish or saline water reduces the need for long and expensive conveyance systems and takes advantage of a little utilized resource. Thus, treatment of this currently little used groundwater as a component of future supply is an attractive supplemental option for the City IF the brackish supply can be treated in an economical manner.

## 3.2 Desalination Technology Overview

Desalination (the removal of salt from salty or brackish water), is one of the fastest growing industries within the water sector. Terrabon's research has shown that the use of desalinated water has grown at 13+% annually from 2006 to 2010 in arid areas such as the Middle East, North Africa, Northeast China, Spain, and the Southwest United States.

Brackish water is broadly defined as having salt content, or total dissolved solids (TDS), in the range of 1,000 to15,000 milligrams per liter (mg/L) equivalent to the same parts per million (ppm), or 0.1 to 1.5% by weight in water. For comparison, seawater has a typical salt concentration of 3.5% by weight or 35,000 ppm or mg/L.

The TCEQ has a salt concentration limit of 1,000 ppm for drinking water with a preferred level of 300 to 800 ppm. The water from the Rio Grande now used in Laredo has a concentration of around 800 ppm with seasonal variations related to rainfall.

In 2008, it was reported that the existing desalination capacity in the United States was 1,500 million gallons per day [7]. While this is a large number, it is only 0.4% of the total water used in the nation. By far, the largest amount of desalinated water is produced by reverse osmosis (RO); 80% of Texas' installed desalination capacity is RO [8]. Arroyo and Shirazi report that the cost for brackish groundwater desalination using RO ranges from $1.26 to $2.60 per thousand gallons of product [9]. These figures do not include the total cost of rejected water disposal, or the initial supply of that water to the treatment facility. Seawater desalination is much more expensive ranging from $3.59 to $5.77 per thousand gallons [10]. These numbers do not include conveyance cost. The cost of brackish and low salinity water treatment typically exceeds the average cost of fresh (less than 1,000 ppm) ground or surface water treatment systems by 30% to 50%. But when surface water supplies cannot meet the municipal demand generated by population and industrial growth reliably year after year, recourse to ground water sources, sometimes brackish, is necessary.

Desalination technologies can be categorized into three basic categories: thermal, filtration, and ion exchange [11].

Thermal desalination technologies are distillation methods and will remove almost all impurities from water and include multistage flash (MSF) distillation, multiple effect distillation (MED), and mechanical vapor compression (MVC). Distillation has been used to purify water for centuries; however, applying heat to boil water to then condense the steam to water, i.e. distill, is a very energy intensive process. Both the MSF and MED distillation methods require external heat inputs, such as from a boiler, to provide the heat necessary for the process and are typically applied in large capacity projects in conjunction with power generation facilities to utilize waste heat.

The thermal technology discussed in this report is a mechanical vapor compression distillation technology (MVC) and is typically applied to water desalination with salt concentrations in excess of the capabilities of RO, which is limited to inlet concentrations of just above seawater or around 45,000 ppm. In mechanical vapor compression method, there is no external source of heat. Heat in the system is injected through the mechanical compression of steam. Briefly, the process is a loop whereby the inlet salty water is boiled using the energy from condensing steam. The boiled steam is compressed to a higher energy level. That added energy is then used to boil the inlet salty water as noted above. As the compressed steam releases its energy back to the salty water, it condenses back to water. This has the advantage of being highly efficient and the significant improvements to the process by Texas A&M University allows much higher efficiency and improved economic operation of the vapor compression process. The advantage of thermal desalination technology is that it can produce higher percent of desalinated product water from the inlet raw water flow and accept a much larger variation in source water quality than conventional ground and surface water treatment technologies. In a high water scarcity environment, extracting the largest amount of potable water from the available water is of utmost importance.

Filtration desalination technologies include reverse osmosis (RO), electro-dialysis (ED), electro-dialysis reversal (EDR), and nano-filtration (NF). All of these filtration technologies use semi-permeable membranes to remove salt ions from the product stream. These membrane technologies are the method of choice for brackish and seawater desalination. Their main drawback, though, is the sensitivity of the membranes to water quality to avoid scaling and failure of the membranes. The pretreatment system designed for the specific characteristics of the inlet water is critical to the performance of membrane systems. Varying water quality levels due to seasonal flow or rainfall can wreak havoc on the performance of RO systems. The range in use of RO in terms of inlet salt concentration is from 1,000 up to 45,000 ppm. Desalination of liquids in excess of 45,000 ppm typically requires a thermal process. A second drawback of RO systems is the low ratio of conversion of inlet flow to potable flow thus generating a high waste stream requiring disposal.

When using RO for a very low inlet water salinity, the waste concentrate stream may be less than the upper limit for RO of 45,000 ppm. In these cases a second stage RO can be used to further extract usable water from the first stage reject flow and reduce the overall system concentrate flow to disposal.

Ion exchange technologies are generally used for industrial and pharmaceutical water conditioning and demineralization and can only remove very small amounts of salt from water, generally already much lower than acceptable drinking water levels.

## 3.3 Introduction to the AdVE Technology

The AdVE Advanced Vapor Compression technology from Texas A&M is an innovative and significant improvement over existing Mechanical Vapor Compression technology in terms of lower power consumption and higher product water recovery ratio. It is efficient water evaporation to extract steam and leave the concentrated salts behind, and then distillation to recover the product water from the steam.

The AdVE technology is based on 20 years of technology development at Texas A&M University. Texas A&M holds patents on the heat exchanger design and the process integration for AdVE, and has exclusively licensed this technology to Terrabon, Inc.

AdVE uses low-cost, high capacity, high efficiency compressors and electric motors as well as non-fouling heat exchangers to desalinate brackish and salty water. The AdVE technology is based on the following core innovations:

- Higher heat transfer coefficients achieved by means of a patented drop-wise condensation process

- Proprietary coating technology which enables higher condensation rates

- Higher operating temperatures and pressures than traditional reverse osmosis technology, resulting in lower capital and operating costs

Vapor compression is a reliable and robust desalination technology that is attractive because of its ability to treat a wide range of salt concentrations and water quality. However, compared to other major desalination technologies such as reverse osmosis, mechanical vapor compression has had relatively high operating and capital costs.

Vapor compression desalination, as seen in Figure 1, refers to a distillation process where the evaporation of salt water is obtained by the application of heat delivered by compressed vapor instead of a boiler. Since compression of the vapor increases both the pressure and temperature of the vapor, it is possible to use the latent heat, the energy rejected during condensation of the vapor to liquid/condensate, to generate additional vapor on the low pressure brine or salty side of the exchanger.

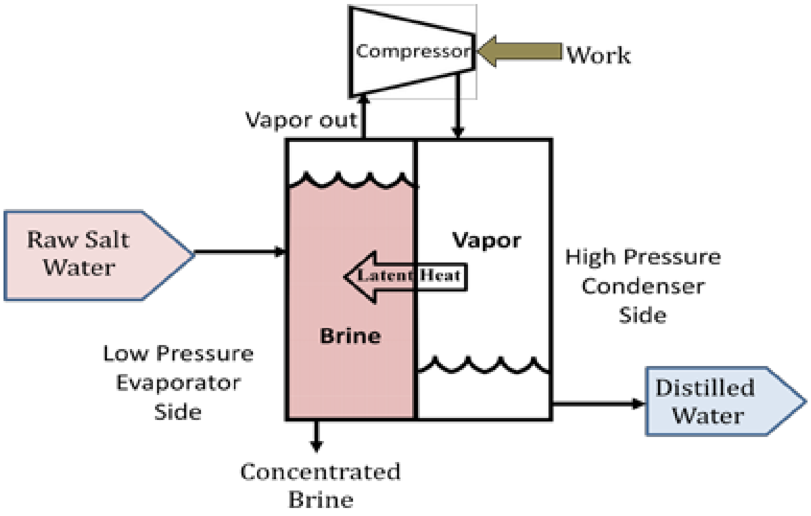


**Figure 1. Mechanical Vapor Compression/Distillation [12]**

As shown in Figure 1, water vapor boiled off the salty water is compressed by means of mechanical Work from an electric motor-driven compressor in most cases. This process is designated as mechanical vapor compression (MVC). As vapor is generated, it is passed over to a heat exchanging condenser which returns the vapor to water. The resulting fresh water is moved to storage while the heat removed during condensation is transmitted to the remaining brine feedstock.

The vapor compression process is the more efficient distillation process available in the market today in terms of energy consumption and water recovery ratio for higher than seawater salinity liquids. AdVE is a significant improvement on this performance. As the system is electrically driven, it is considered a "clean" process, it is highly reliable and simple to operate and maintain.

AdVE incorporates new innovative developments in compressor and evaporator designs making it possible to reduce energy consumption so it is a more competitive alternative. Texas A&M University has developed an advanced vapor-compression desalination system (AdVE) that operates at high temperatures. Advanced sheet-shell latent heat exchangers promote dropwise condensation allowing small temperature and pressure differentials between the saturated boiling liquid and the condensing steam, hence reducing the energy requirements. This newer system consists of a sequence of non-scaling evaporators arranged so feed water flows countercurrently to the steam energy flow, recovering heat from the condensation process of the steam to water. A high efficiency compressor provides the compression work required to return saturated steam to the initial stage of the evaporator process.

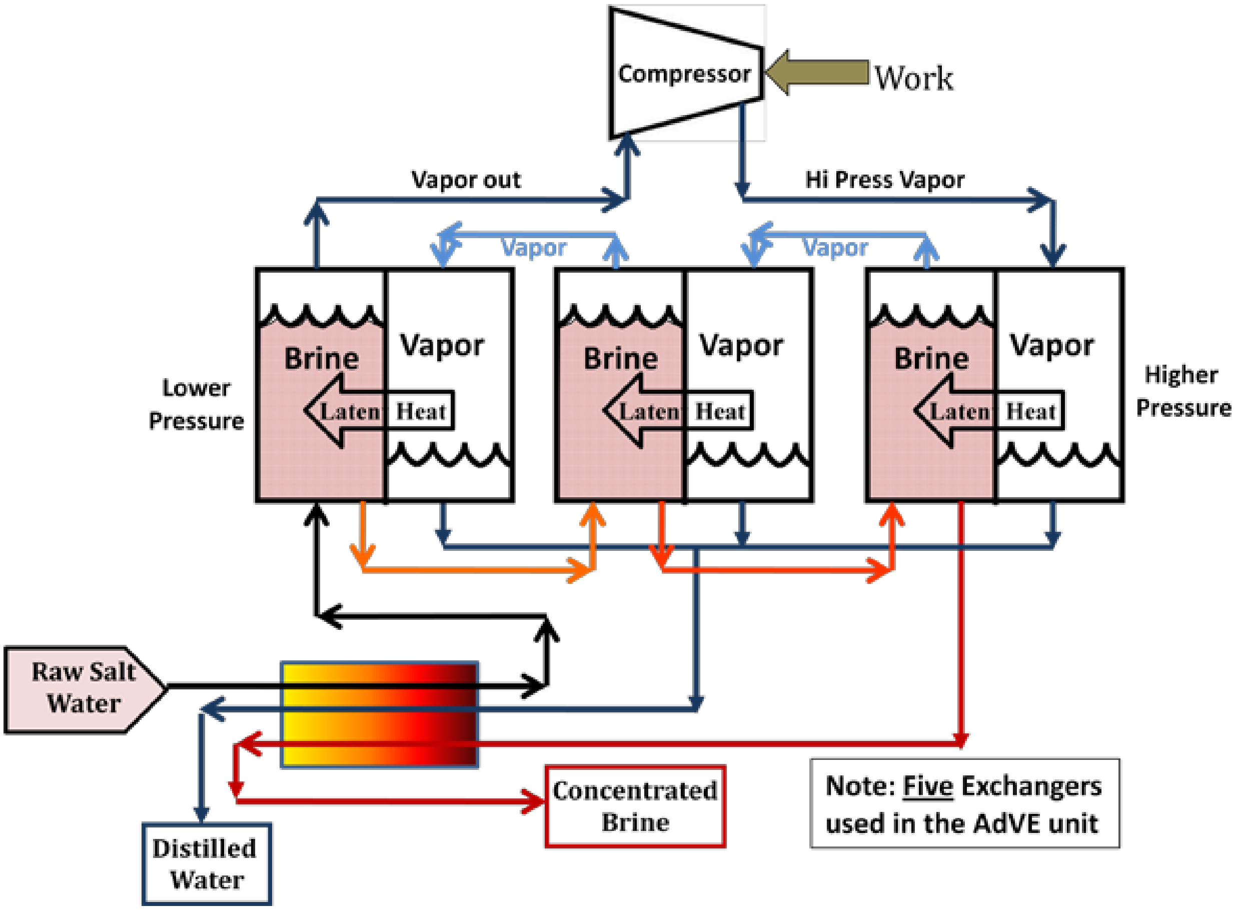


**Figure 2. AdVE Advanced Vapor Evaporation [13]**

Figure 2 shows the AdVE Advanced Mechanical Vapor Compression / Evaporation desalination system. In this example, three evaporator/condenser stages are illustrated, but fewer or more could be employed [13]. The left-most evaporator is at the lowest pressure and it takes in the raw inlet water and its steam feeds the compressor. The right-most evaporator is at the highest pressure taking in the steam from the compressor. This exchanger discharges the rejected highly concentrated brine flow. The work added through the compressor from the electric motor increases the energy content of the steam vapor. The saturated high-pressure steam then enters the condensing side of the right-most evaporator. As this steam condenses, it releases its latent heat, the heat of phase change from vapor to liquid, and evaporates water on the boiling side, thereby producing steam that can be fed to the middle evaporator to also condense. In the middle evaporator, the steam condenses, releasing more heat as the steam condenses, which in turn causes more steam to be produced on the boiling water side of that exchanger. This steam then enters the left-most evaporator where it condenses and evaporates water from the boiling side. The water evaporated from the boiling side enters the compressor, as previously described.

To preheat the feed to the evaporators, a sensible heat exchanger is employed, which exchanges thermal energy between the incoming feed water and the discharged distilled water and concentrated brine. As shown in Figure 2, the preheated feed water is fed to the left-most evaporator. In a countercurrent series manner, the brine exiting the left-most evaporator is directed to the middle evaporator and the brine exiting the middle evaporator is directed to the right-most evaporator. As the brine flows from left to right, it becomes ever more concentrated.

# 4.0 PROJECT OBJECTIVES

## 4.1 Laredo Requirements

The overall objective of the project was to validate the performance of the AdVE technology at scale; e.g. the production of treated water. The first objective was to design, construct, and install a 50,000 gallon per day brackish water advanced vapor compression desalination unit. The second objective was to verify performance of the design in field conditions at a brackish water well site provided by the City of Laredo. The City defined several requirements for the system in support of the overall objectives: 1) operation of the existing RO plant at the selected well site would not be compromised; 2) the system design must be transportable; 3) the system produces potable water; and 4) consider the uses of the system for the City of Laredo after the demonstration is concluded.

The benefits that the City of Laredo received from this project include a validation of the technology; allowing the City to develop and complete specifications for advanced vapor compression desalination water treatment systems to the industry and possibly acquire additional water treatment capacity through this method.

## 4.2 Technology Demonstration Objectives

Technology demonstration objectives include the following: 1) verification that the unit's produced water meets state and federal drinking water standards, 2) the unit is robust and demonstrates consistent production and efficiency without significant pretreatment, 3) the unit has a high percent of recovery of treated water and a corresponding low percent of flow as brine waste effluent, and 4) the unit has lower energy use per unit of treated water than other phase change technologies,

# 5.0 DESIGN OVERVIEW

## 5.1 System Overview

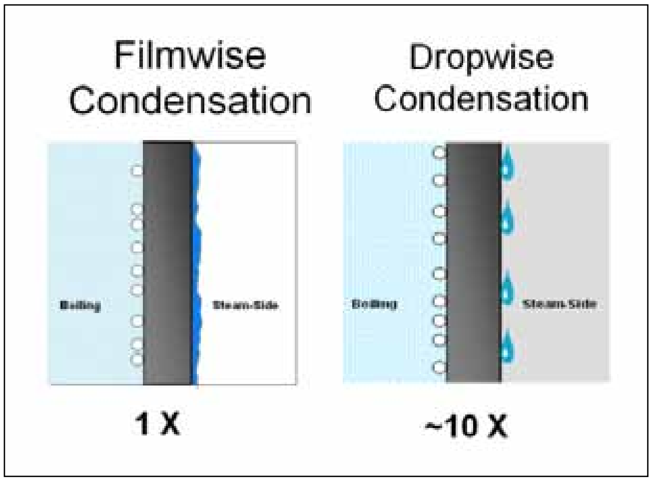
The heart of the AdVE Pilot System is the heat exchanger. The evaporator side generates the steam by the boiling of the brine or salty feed water using the heat released from steam condensing to water, or condensate, in the condenser side. There are five evaporators in the system. It is this condensate that is the product of the desalination process. The heat exchangers are of a type called plate and frame where the heat flow occurs across a plate of metal from the hotter medium to the colder medium. Figure 1 shows a vapor compression plate and frame evaporator along with the fluid and heat flows.

In Figure 1, hot salt water very close to its boiling point is introduced to the evaporator. The line down the middle represents the heat transfer plate. Steam generated from boiling of the brine enters the compressor, which increases its pressure and temperature. The steam, at a high pressure and temperature, enters the high pressure side, or the condenser side, of the heat exchanger. The heat from the high temperature steam as it condenses to water and releases its latent heat flows across the plate and heats the salt water so that it boils. In a continuous cycle of boiling to steam and condensing back to water, the salt is left behind in the increasing concentration the brine.

The compressor raises the pressure of the steam which also increases the temperature of the steam. As heat leaves to steam across the plate to the brine side, the steam cools off. This cooling condenses the steam back to liquid and produces the condensate. The only energy added to the system is the power necessary to run the compressor.

## 5.2 Heat Exchanger

The evaporators in the pilot system used the innovative plate and frame type evaporator outlined in the patents. Each plate is a 2-foot square of copper that is dimpled to provide structural strength. The plates are coated in a proprietary hydrophobic coating. This coating prevents the condensate from creating a film on the plates during the condensation process and forces the condensate to form droplets as seen in Figure 3. This increases the amount of heat transferred from the steam into the brine and increases the efficiency of the process. Figure 4 shows the plate design from Dr. Holtzapple at Texas A&M University.



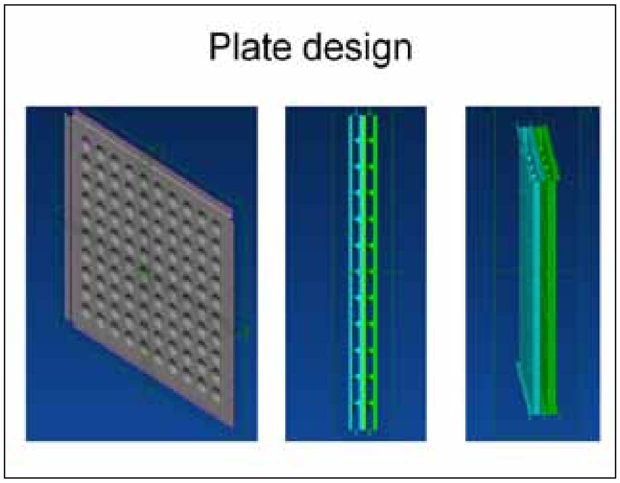


**Figure 3. Drop-wise Condensation**

**Figure 4. Conceptual Evaporator Plate Design [14]**

The plates are mounted back to back as shown in the center illustration of Figure 4. The plates form parallel paths for the steam and condensate and the brine in the other direction. These paths can be seen clearly in the right illustration of Figure 3. The horizontal path between the plates is for the high temperature/pressure steam while the vertical paths are for the flow path for the brine. Figure 5 shows a cross section of the plates in the exchanger shell. The levels of the boiling brine and the steam condensate are seen as well.

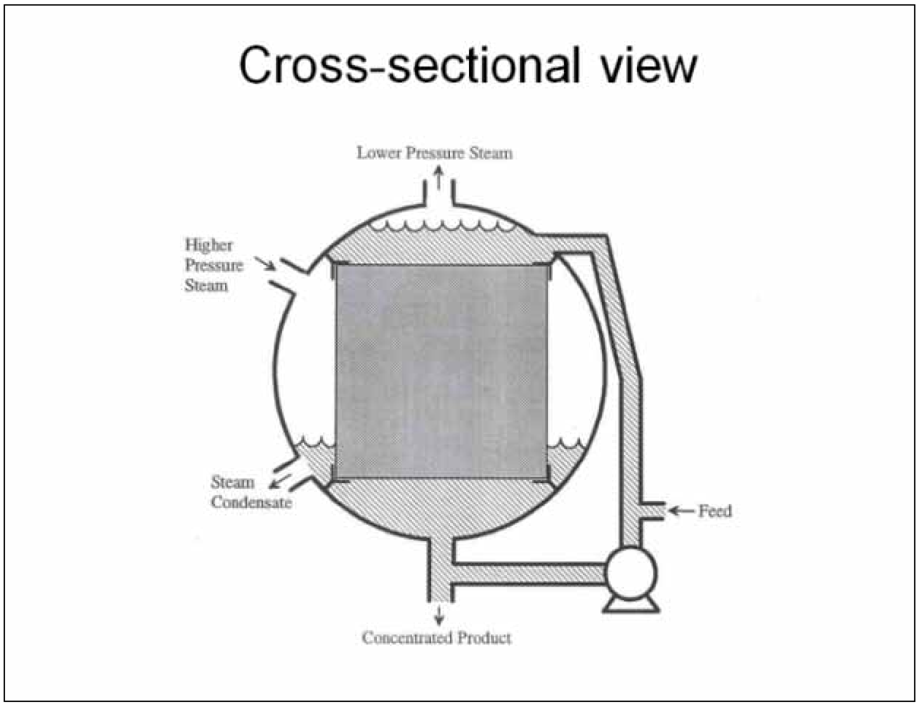


**Figure 5. Cross Section of an Evaporator [15]**

The plate pack was assembled using 80 copper coated plates and stainless steel spacers separated by viton gaskets, compressed with torque bolts and seals along the outside edges. Figures 6 and 7 show the coated plates and plate pack (prior to installation in an evaporator) respectively.

Non-Coated 1'x1' Experimental Plate

Coated 2' x 2' Production Plate

**Figure 6. Non-Coated and Hydroscopic Coated Plates**

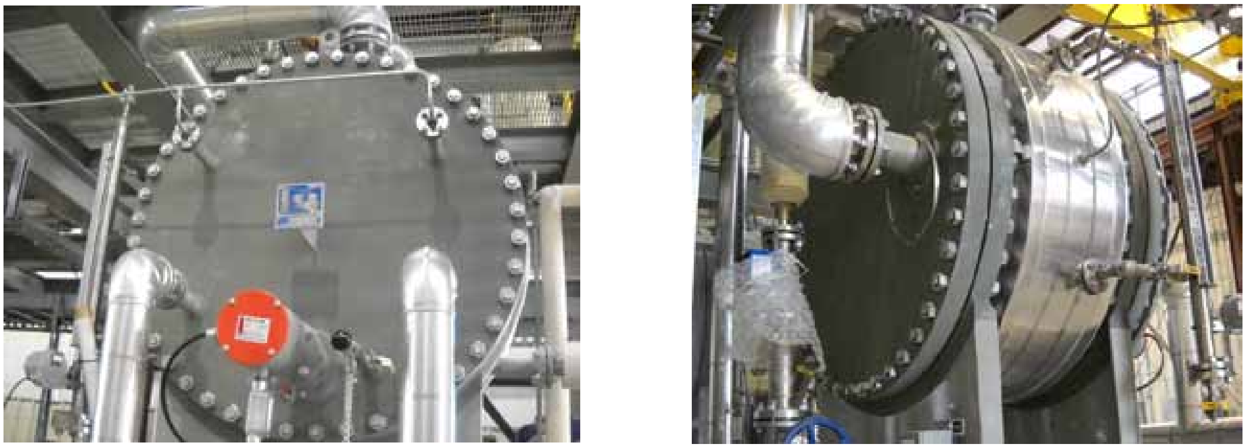
Plate Pack (Side View) Plate Pack (Top View)

**Figure 7. Plate Pack to be Installed in Evaporator**

The evaporator plate pack is installed in an evaporator shell that provides sealing of the corner edges of the plate pack and provides input and output manifolds for the brine and steam flow. Figure 7 shows the evaporator shells under construction and after assembly.

Evaporator Shell & Internal Seal Edges

Installing Plate Pack



Assembled Evaporator (Front View)

Assembled Evaporator (Back/Side View)

**Figure 8. Evaporator Shell Construction and Assembly**

## 5.3 StarRotor Compressor

The major source of energy input for the system is the compressor. As steam is compressed, that is, creating increased pressure, the temperature increases which is necessary for the vapor compression process to work. The compressor chosen for the pilot plant was the StarRotor Compressor. This compressor was also developed by Dr. Holtzapple and was designed and built by the StartRotor Company [16]. The design of the compressor requires a 30kW motor to drive the compressor. The specifications of the compressor are 3500lbs/hr steam flow at a compression ratio of 1.1 (suction to discharge increase). The StarRotor is a rotary compressor that uses offset “star-shaped” cams to create an increase in pressure by trapping gas in a volume and then making the volume smaller. A diagram of the StarRotor compressor is shown in Figure 9. The rotors both rotate, but the center of rotation for the inner rotor is offset from the outer rotor. The rotors do not actually touch, but the amount of internal leakage from volume to volume is very small and does not affect the efficiency of the device.

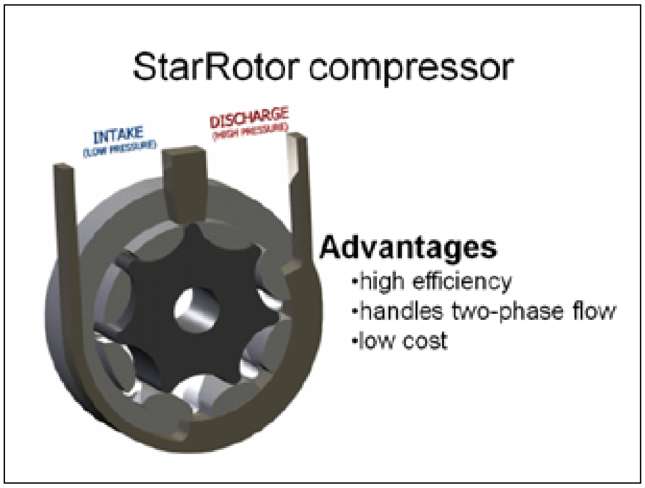


**Figure 9. StarRotor Compressor Diagram [17]**

The actual compressor is fairly small compared to a more conventional design meeting the same pressure and volume requirements. Figure 10 shows the StarRotor compressor both at the StarRotor facility and mounted on the Pilot Plant Skid.

StarRotor Compressor (on left)

StarRotor Compressor Installed

**Figure 10. StarRotor Compressor**

## 5.4 Application of the Technology to the Skid

The overall system diagram is shown in Figure 11. Five evaporators were needed to produce the required amount of condensate product. A 15’ x 50’ skid platform was constructed to mount the system and all the required subassemblies. This conceptual diagram shows the five evaporators connected in series. Pressure and temperature drops incrementally from right to left in the evaporators.

The skid itself has two levels. The bottom level houses the evaporators, heat exchangers, pumps, and controllers. The second level houses the compressor and its motor, ancillary piping, an air compressor, and the top of the carbon dioxide scrubber. Figure 12 through Figure 20 are pictures of the skid showing various aspects of the system. The pictures are from the final testing at the Texas System and Controls facility (where the skid was built) and the others are at the Santa Isabel well site in Laredo.

For the testing, a steam generator was rented to be used to decrease the time required to heat up the unit to test temperature. It was also used to test plate efficiency of saturated steam versus the StarRotor compressor, looking for the impact of compressor superheat on the heat transfer.

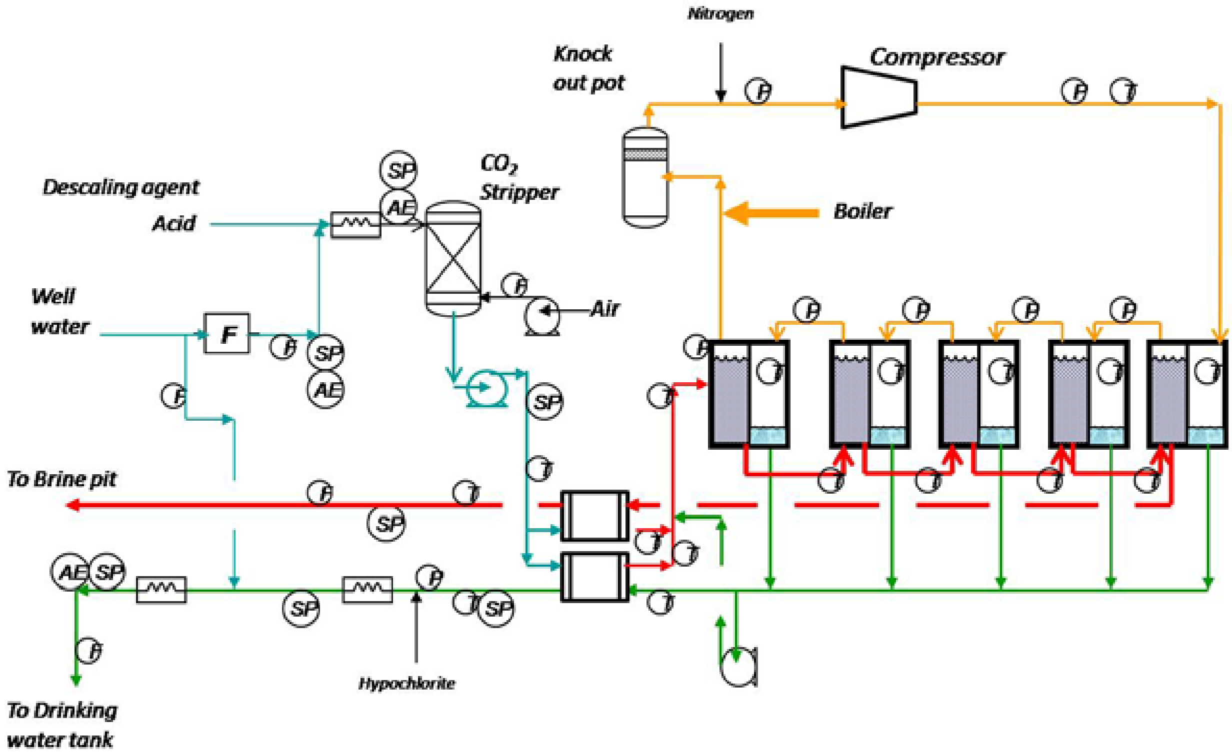


**Figure 11. Pilot Plant System Diagram**

Figure 12. AdVE Laredo Pilot Plant at TSC Prior to Insulation

Figure 13. Installed Evaporators

Figure 14. Sensible Heat Exchanger to Preheat Incoming Raw Water

Figure 15. Brine Recirculation Pumps and Chemical Treatment Tank

Figure 16. Star Rotor Compressor Installed on Top Platform

Figure 17. Pilot Plant Control Panel

Figure 18. Carbon Dioxide Scrubber

Figure 19. Fuel Oil Steam Plant for Start-up Testing

Figure 20. Start-up and Supplemental Heater in an Evaporator

## 5.5 Pilot System Location

The pilot plant is installed at the Santa Isabel well site northwest of Laredo on Mines Road (FM 1472). This location is shown in Figure 21. The well site also hosts a 30,000 gallon per day Reverse Osmosis (RO) water treatment plant. Both the skid and the RO plant are serviced by a brackish water well capable of supplying about 100 gallons per minute of water with a total dissolved solids (TDS) content of 1200 milligrams/liter (mg/L).

The RO plant at the site services a 200,000 gallon finished water tank that provides water to a small number of customers. The well is serviced by a 13 stage submersible pump capable of producing 100 gpm.

The well depth is 1800 feet and the water temperature from the well is around 150°F. Brine from the RO plant is stored in the brine pit in back of the plant building and is disposed via tank truck to the Laredo waste water system. The amount of brine from the AdVE plant is small compared to the reject of the RO plant and does not significantly impact brine transport operations. Figures 22 through 26 show the RO plant and well site.

**Figure 21. Santa Isabel Well Site**

**Figure 22. Santa Isabel Well (Note the old Submersible Pump on the Ground)**

**Figure 23. Finished Water Tank**

**Figure 24. RO Plant Building**

**Figure 25. RO Plant Membrane Rack**

**Figure 26. Brine Pit**

The AdVE Pilot Plant is situated to the west of the RO plan building and is installed on a concrete pad. The electric service for the skid is provided by a transformer in the RO plant control center. The well water input stream is connected at the input of the RO plant and both the RO plant and the AdVE pilot plant (running in steady state) can be run simultaneously. The AdVE brine reject stream is connected to the brine pit via a manhole behind the RO plant. The product stream can be attached to the output to the tank upon approval from the Texas Commission on Environmental Quality (TCEQ) but is now diverted to the adjacent arroyo.

Figures 27 through 36 outline the installation at the Laredo Santa Isabel well site and the connections made to the existing infrastructure.

**Figure 27. AdVE Skid Concrete Pad Framing**

**Figure 28. Completed AdVE Concrete Pad Adjacent to RO Plant Building**

**Figure 29. Skid Base Installation**

**Figure 30. Skid Upper Platform Installation**

Figure 31. Laredo Site Assembly Complete

Figure 32. Well Water Input to the System

Figure 33. Product Line to Arroyo

Figure 34. Output to Arroyo (with Sample Spigot)

Figure 35. Brine Output Line to Brine Pit

Figure 36. Chemical Tanks for Pre-Treatment of Well Water

# 6.0 RESULTS

## 6.1 Project Cost Analysis

The total project cost was approximately $2.8 million with the City of Laredo providing 56% funding ($1.55 million) and the remaining 44% contributed by Terrabon. The first phase of the project to design and construct the 50,000 gallon per day advanced vapor compression unit began in March 2009 in Houston, TX. Texas Systems and Controls (TSC), a global provider of custom skid mounted units served as the detail designer and manufacturer of the plant. With the help of Terrabon's engineering team, evaporator internal plate pack was assembled at Excel stamping. A critical component of the system, an efficient, compact compressor was engineered by Star Rotor Corporation located in Bryan, TX. Engineering design, building and construction was completed in a 14 month period with unit walk down on May 2010. Approximately 70% of the total project cost was spent during initial engineering, building and construction phase.

The duration of the project is divided into 4 different campaigns for cost analysis purposes.
Campaign 1: Building and construction
Campaign 2: Initial startup at TCS
Campaign 3: Data collection at Laredo (3 exchangers and steam)
Campaign 4: Data collection at Laredo with complete assembly (5 exchangers)

The data collection phase for the project is divided into two parts. First the initial runs at Texas Systems from March 2010 to May 2010 and second, performance verification of the design in field conditions in Laredo from August 2010 through March 2011. The unit was shipped to the Santa Isabel water treatment facility on July 20th 2010. During initial testing efforts at TSC, unanticipated issues regarding feed saturation arose and were remedied with engineering modifications. During the testing phase at the Santa Isabel water treatment plant in Laredo, various mechanical issues like gasket and plate pack failure were encountered and successfully managed.

Costs incurred during various campaigns of this project are tabulated below in Table 1.

A detailed discussion of data/trends captured during these campaigns and analysis is provided in the Results section of this report. Some key outcomes have been summarized in the Lessons Learned section in detail. The following issues had a larger impact on the overall project cost and schedule.

- Initial engineering modifications needed at TSC to deal with feed saturation issues
- Need for an external steam boiler to facilitate start up
- Mechanical issues related to gaskets, plate pack
- Adverse effects related to fouling
- Presence of inert compounds in the water
- Operational difficulty maintaining thermal imbalance
- Condensate management issues (steam traps)
- Presence of superheat (when operating with compressor)
- Insufficient recirculation

**Table 1. Spending Analysis - Cost of Various Components/Activities**

| | | | Campaign 1 | Campaign 2 | | Campaign 3 | Campaign 4 |
|---|---|---|---|---|---|---|---|
| Dates | | | April 09 to Feb 10 | March 10 to July 10 | June 10 to Dec 10 | Aug 10 to Dec 10 | Jan 11 to March 11 |
| Duration | | | 10 months | 5 months | | 5 months | 3 months |
| Key milestone | | | Construction | Data collection at TCS | | Data collection | Data collection |
| Location | | | Houston - TCS | Houston - TCS | | Laredo | Laredo |
| Activity description | | | Building and construction | | Gasket/plate pack issues | 3 Exchangers+Steam | with 5 exchangers |
| Shop labor | $ 719,822 | 26% | $ 518,272 | $ 57,000 | $ 11,550 | $ 88,000 | |
| Material | $ 738,206 | 27% | $ 590,565 | $ 86,000 | | $ 61,641 | |
| Engineering | $ 249,557 | 9% | $ 154,557 | $ 58,000 | | $ 37,000 | |
| Operations manual | $ 4,590 | 0.2% | $ 4,590 | | | | |
| HAZOP | $ 6,250 | 0.2% | $ 6,250 | | | | |
| Gaskets+Plates+Misc | $ 284,316 | 10% | $ 273,821 | | $ 10,495 | | |
| Insulation | $ 67,830 | 2% | $ 67,830 | | | | |
| Consolidation | $ 83,434 | 3% | $ 83,434 | | | | |
| Star rotor | $ 112,000 | 4% | $ 112,000 | | | | |
| | **$ 2,266,005** | 82% | | | | | |
| American water | $ 187,000 | 7% | $ 102,000 | | $ 20,000 | $ 65,000 | |
| External boiler | $ 43,000 | 2% | | | | $ 33,000 | $ 10,000 |
| Additional work | $ 50,000 | 2% | | | $ 27,000 | $ 27,000 | $ 8,000 |
| Travel | $ 20,000 | 1% | | | | $ 13,333 | $ 6,667 |
| Contract consulting | $ 169,000 | 6% | | $ 56,000 | | $ 80,000 | $ 33,000 |
| NSF certification fee | $ 18,500 | 1% | $ 18,500 | | | | |
| | **$ 487,500** | 18% | | | | | |
| Total | **$ 2,753,505** | 100% | $ 1,931,819 | $ 257,000 | $ 69,045 | $ 404,974 | $ 57,667 |
| | | | 70% | 9% | 3% | 15% | 2% |
| **Laredo Funding** | **$ 1,549,000** | **56%** | | | | | |
| **Terrabon Funding** | **$ 1,204,505** | **44%** | | | | | |

This project was a first attempt to transform a research level concept into a real world, commercial scale application. Important lessons were learned through various mechanical/engineering issues encountered during the experience.

## 6.2 System Performance Summary

### 6.2.1 System Design Specifications:

The desalination plant design called for the production of drinking water from brackish well water by reducing the salinity in the feed water to potable levels. Use of the AdVE technology will desalinate to a very low salinity in the product water, allowing well water to be back blended with the pure treated water to achieve increased throughput of drinking water at potable water standards.

The plant is designed to meet the performance specifications shown in Figure 37.

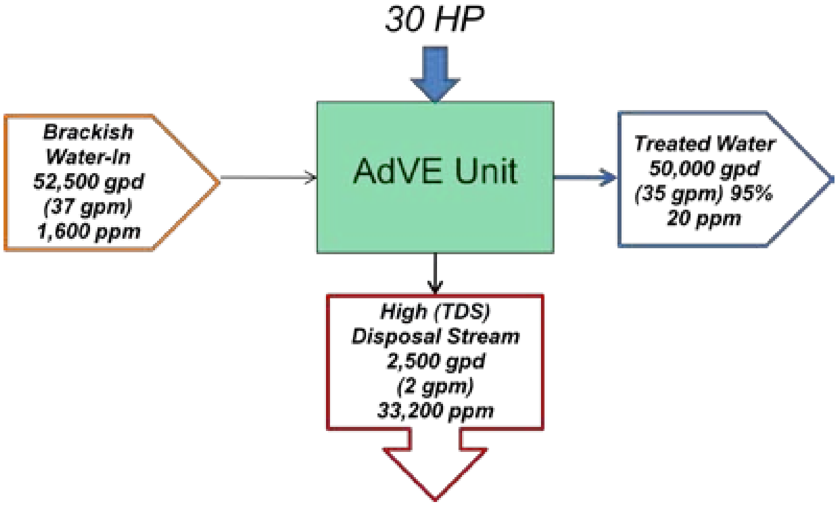


**Figure 37. System Design Specification**

### 6.2.2 Actual System Performance

The actual system performance fell short of the design due to a number of reasons explained later in this report in section 6.3 Lessons Learned. The finished water that was produced from the unit was sampled and analyzed in the local lab. The results showed that the total TDS of incoming well water (1,600 ppm) was reduced to about 40 ppm. Overall this is a good result but higher than the expected 20 ppm. The deviation is a result of the leaks in the heat exchanger plate seals contaminating the steam side with well water.

The actual Laredo Unit best performance in operations is as follows:

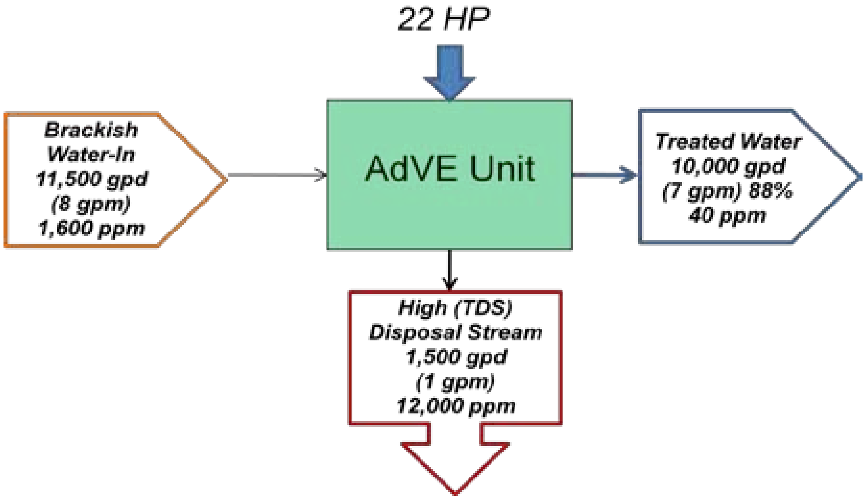


**Figure 38. Actual Performance of Laredo Pilot Plant**

### 6.2.3 Potential System Performance with Improvements

Based on the observations and improvements that have been identified in section 6.3 Lessons Learned, it is anticipated that the Laredo AdVE unit can consistently perform as follows:

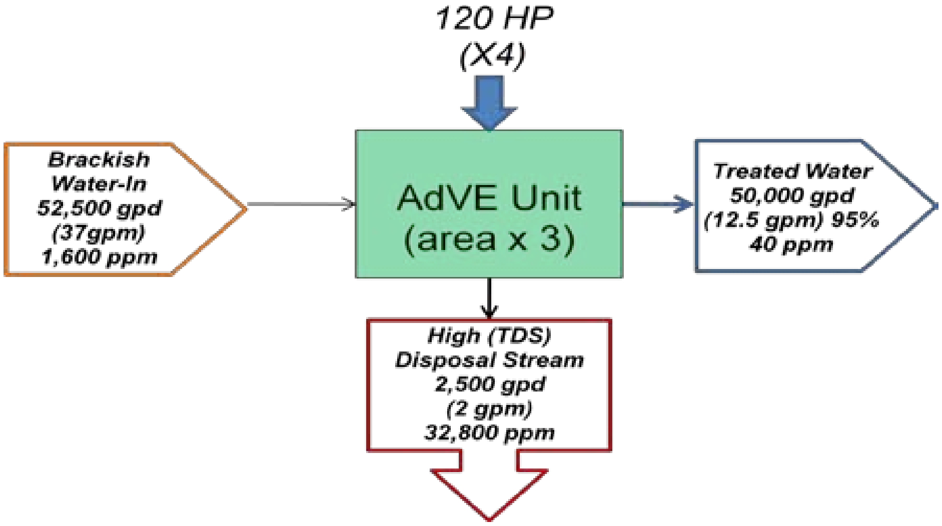


**Figure 39. Laredo System Improvement Potential**

## 6.3 Lessons Learned

The problems encountered during testing can be categorized into several headings. The fixes for each problem are detailed in this section.

### 6.3.1 Heat Exchanger Performance:

We found the heat flow or flux across the exchanger plates was lower than design effectively making the unit undersized for the product flow we planned. In addition we had serious problems with exchanger internal seal leaks that caused some if the steam to flow across into the brine and not condensing providing conflicting data at times. Additionally we had fouling of the plates from the lubricating oil used in the compressor. The compressor is an innovative design with very high efficiency that uses a lubricant that mixes with the steam being compressed. This oil mixed with the steam and flowed into the exchangers, and with time built up on the exchanger plates and reduced the heat flow and therefore the efficacy of the exchanger plate, reducing the effectiveness of the drop-wise condensation feature of the exchanger.

The heat exchanger performance was measured in three ways: 1) the seal integrity between the well water side and the steam vapor side to prevent migration of salt water to the pure steam side, 2) the resistance of the special technology coating to scale build up, and 3) the heat transfer properties between the steam and the well water/brine.

Seal Integrity – The scale up of the plate technology from the lab scale single plate in a chamber to the future view from the inventors has been a technical challenge. Initial efforts to build a multi-plate test unit at Texas A&M were unsuccessful as leakage could not be prevented. There were issues with the coating needing to be applied to each plate individually and the methods to provide a space between the plates and a seal. The Laredo design team took some measured risks to develop this as the project construction was proceeding.

The heat exchanger used for the Laredo unit was constructed using viton GF gaskets and stainless steel spacers between the plates to create the space and sealing area. This turned out to be a good design in that the tear down of the E-204 unit showed that these gaskets stuck to the spacers and plates after heat was applied.

Where the heat exchanger experienced issues was in the end seal between the plate pack and the vessel head. Because the plate back is not a rigid object (containing over 1000 viton GF gaskets between all the plates), the seal on the end needed to be flexible enough to adjust to the thermal cycles and the pressure differential between the steam side and the brine. There have been numerous failures of this seal, both internally between the chambers, and externally. Most unit downtime has been attributed to this seal failure.

As a last trial, conventional vessel gaskets were used to seal the steam pressure from leaking to the environment, a problem encountered with the flexible gaskets as the internal pressure reached 40 PSIG. These were applied to the last two evaporators and were found to also seal internally between the chambers adequately enough to function in the making of condensate. This enabled the last unit runs to be done with all effects in service.

Performance: The initial leak rate for the first fabricated units was not zero, so a specification of 5 gal/hr was established, approximately equal to 2% of the unit capacity. The first five heat exchangers met these criteria and ranged from 0.5 to 4 gal/hr of leakage. As run time increased, the leak rate increased. The evaporators have a leak rate at ambient temperatures of 20 gal/hr and 5 gal/hr at hot (boiling) temperatures.

Scale Resistance – The technical claim was that the hydrophobic coating not only would promote dropwise condensation, but would also prevent scale formation and increase the useful life of the heat transfer surface. So far, the performance data from coupons inside the heat exchangers suggests that the scale does stick to the coating and other scale reduction technologies need to be applied.

Heat Transfer Properties – Performance data on each heat exchanger was conducted as it was in operation. Unfortunately, due to seal failures, only two heat exchangers were used for the bulk of the exchanger evaluations.

Overall heat transfer for the Laredo units was shown to be on average approximately 60% of the lab scale unit when comparing similar conditions. Figure 40 shows the calculated heat flux for the units compared to the project lab values.

The calculated heat transfer coefficients ranged between 800 and 2000 BTU/hr °F and are higher than conventional plate exchangers (500-1000 BTU/hr °F). Figure 40 also demonstrates the heat transfer at the different operating pressures of the unit.

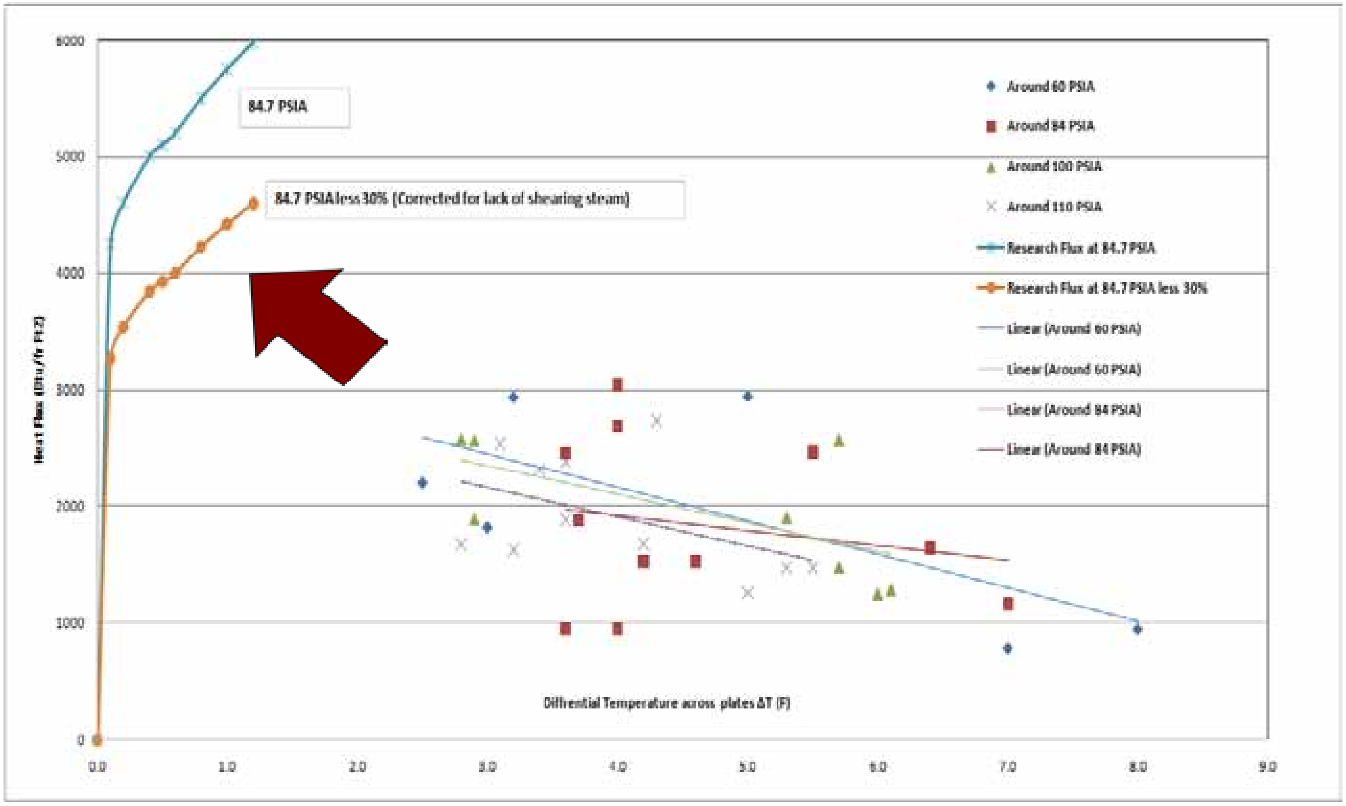


**Figure 40. Achieved Heat Transfer Compared to Laboratory Results**

Conclusions: Overall the heat exchanger performance was better than conventional plate and frame heat exchangers that typically operate at heat flow of around 1,000 BTU/hr-ft$^2$, but not to the capacity of the expected from the lab of 10,000 to 18,000 BTU/hr-ft$^2$. The lower performance is related to the higher than expected differential temperatures that were seen in the heat exchangers and the resulting higher differential pressure across the plates. It is deduced that the scale and plate seal failures contributed heavily to this loss of performance.

As seen in Figure 40, the curves on the left were the lab target values and the data points in the center were the actual results seen. The actual data clearly showed a trend to achieve higher heat flux values at lower differential temperatures, but not as high as the lab data would indicate. The system was able to achieve significantly higher flux values than typical heat exchangers by a factor of approximately three, but with a potential of upwards of five times with the corrective actions detailed herein as the arrow shows.

### 6.3.2 Star Rotor Compressor

The compressor performance was measured based on energy consumption and overall water production from the unit. Overall the compressor performance was in line with expectations and was able to operate in a variety of ranges based on the test runs. The following table shows the water production versus expected compressor operating performance:

**Table 2. StarRotor Compressor Design vs. Achieved**

| **Criterion** | **Design** | **Achieved** |
|---|---|---|
| **Compression Ratio** | 1.1 | 1.5 |
| **Max Speed achievable** | 3600RPM | 2400RPM |
| **Steam Flow** | 3500lbs/hr | 1300lbs/hr |

The results show that the excessive pressure drop of the entire system limited the ability to raise the speed of the compressor and the overall system pressure, reducing production capability.

Conclusion: The Star Rotor Compressor performed to the expected values from the performance data of the compressor test runs. The issue in the overall production of finished water is the overall pressure drop across the system. For the Laredo unit, the higher than designed pressure drop and temperature differential increased the compression ratio and reduced the overall water production. Because of this higher pressure differential required of the compressor, the overall RPM speed of the compressor was limited by the compressor motor torque and horsepower.

The energy consumption per gallon of water will be higher as well due to the same heat exchanger performance issues noted above.

### 6.3.3 Finished Water Heat Recovery

The finished water (condensate) that is discharged from the heat exchangers is collected and used to heat the incoming feed water to recover heat (cross exchange). The performance is measured based on the difference in temperature between the incoming hot condensate and the outgoing well water feed to the first heat exchanger. The performance was as follows:

- The overall temperature difference between the condensate and feed was on average about 6°F when flows were operating consistently. This is in line with the plate and frame manufacturers estimates on performance

- The overall temperature of the well water feed to the first heat exchanger was lower than anticipated due to the control strategy designed into the unit. The steam traps require a minimum pressure drop to remove the condensate from the steam side of the heat exchangers. The back pressure was lowered to improve the condensate removal, but in turn caused a lower temperature of the feed. This lower temperature also created issues in the performance of the plates on the heat exchangers.

### 6.3.4 Design Improvements

Evaporator Design and Seals – The largest issue with the Laredo unit has been the seal design for the evaporator plates. As a prototype, it has provided much data on fabrication methods, gasketing, etc. The future of evaporator design based on the patented Texas A&M University technology is still in question. Applications for high temperature multistage evaporation using commercial plate and frame heat exchangers similar to the patented design are being considered.

Star Rotor Compressor Oil – Part of the design of the Star Rotor compressor requires the process gas to be compatible with the lubrication oil. The design of the compressor components need to also take into account the potential of corrosion based on the process fluids plus start up and shutdown scenarios. For the Laredo unit, carbon steel bearings were in an environment where water and oxygen can be present, creating potential rust failures. Secondary nitrogen was provided to keep the environment oxygen free to prevent this from occurring. Another issue was the unexpected presence of oil in the steam side of multiple heat exchangers. A change in compressor type can eliminate these issues but at the cost of additional energy.

Steam desuperheating – There are two areas where the steam is superheated, that is, has a higher temperature than that of boiling water, and the efficiency of the plates is reduced. The first is in the compressor discharge. The Laredo unit uses a spray desuperheater that can reduce the heat to +4 °F (above the boiling point). The technology inventors have now expressed that this is too high. Reaching saturation requires packed beds and can contribute to additional pressure drop in the system and increased energy consumption. The second area is superheat from boiling point elevation. This did not present an issue in Laredo but would be expected at higher salt concentrations.

Condensate Management – For the condensate return and cross exchange, the temperature needs to be as high as possible to conserve heat balances and utilize the most steam for evaporation. The steam trap system will be replaced with a level pot and feed to downstream heat exchangers to recover additional steam and heat the feed to saturation.

Electric Heaters vs. Steam Generator – The Laredo design uses electric heaters to raise the water and steam pressures to boiling for start up as well as maintaining some base heat in the system. Because the water is boiling, the system experienced electric heater failures where an element in a bayonet shorts out due to excessive heat at the boiled water surface. To improve on the heat up time and to overcome the electric heater issues, Terrabon rented a steam generator for some portion of the unit testing. A special heater has been designed to eliminate this failure mode for use in future designs.

Inert Management – Inerts (e.g. nitrogen) can significantly reduce the heat exchanger performance as they build up in the system. Purging these inerts also reduces overall heat balances and will drop the system pressures over time. More work is needed for purge heat recovery to reduce the impact on inert removal as the unit is operating.

Ease of Maintenance – Because of the issues with the heat exchangers, there was more of a need to develop a hard piped bypass capability to be able to operate the unit at reduced capacity while maintenance is being performed. Future AdVE units will have heat exchanger bypass capability that can do this on line.

Corrosion – It is anticipated that the Laredo unit will have a finite life due to high temperatures and chloride stress corrosion. Through all the testing that has been done to date, there is no evidence that corrosion is significant. It is fortunate that the well water is very low in free chlorides, as this will prolong any corrosion issues and allow for extended life. Units in the future will use titanium and Teflon lined pipes/vessels for corrosion resistance.

Fouling Control – The CO2 stripper has not been tested yet so there are no conclusions at this time. The colloid-a-tron device that was inserted in the recirculation stream seemed to coalesce the carbonates into a mush rather than a solid that caked onto the surface of the exchanger body. This caking helped to keep some of the carbonate away from the exchanger plates which would have further restricted the heat flow. Water softeners are also being considered as an alternate method of fouling control.

Start Up and Shut Down – Control of the system was adequate, however, situations were encountered that were outside the parameters of the control system which caused delay due to numerous control system restarts and consultations with the control system programmers. Future designs need to include simple control loops and interlocks with operating procedures for start up and shut down. Some of these were added as the demonstration project progressed.

## 6.4 Proposal to Upgrade Demonstration Unit

Due to the technical reasons described above the demonstration unit will deliver 10,000 gallons per day. Two alternatives are available for the City of Laredo to enhance the capability of the unit.

Well Water Applications: Upgrade the unit to the capacity of 50,000 gallons per day using the existing well water at the Santa Isabel well site, or equivalent salinity feed water of around 1,600 ppm.

Harsh Water Applications: Upgrade the unit to desalinate much higher salinity feed water such as fracture flow back water from the local oil and gas fields in South Texas. Due to the many additional constituents in the feed water in these applications, the technical and commercial viability of this option is very risky and expensive and not recommended, albeit a brief discussion of the issues involved is provided.

Alternative 1: Well Water Applications at Santa Isabel or similar.

The critical upgrades needed to meet this objective are listed generally below:

- Increase the cross-sectional area of the exchangers by approximately three times. Given the existing equipment in the skid now, the most economical method is to add new industrial exchangers.
- The compressor will have to be upgraded to deliver four times greater differential pressure and its motor will have to be replaced with one four times larger.
- An oxygen stripper will need to be added to enhance scale control of the plates and enhance the heat transfer capability and elongate the time between cleaning service.
- The electric start up heaters will need to be replaced to avoid corrosion and shorting of coils from the corrosive effects of the saline water at high temperature.
- The changes above will require piping and wiring and insulation changes.
- The upgrade will require re-engineering to assure the changes are executed correctly
- The unit itself will need to be transported back to Houston for retrofit and taken back to Laredo and reinstalled.

The budgetary estimate to accomplish the upgrades listed above is $1.7 Million.

Alternative 2: Harsh Water Applications as from the oil fields of South Texas.

The substantial changes required for this application are driven by the much harsher chemistry of the water to be treated that need to be considered for the performance of the AdVE unit. This harsh water requires the protection from high corrosion of all wetted surfaces of equipment and piping, and if the surfaces cannot be protected, the base material will have to be changed to titanium to withstand the corrosive effects of high temperature chlorides. Also the constituents in the water may have to be removed with pretreatment to prevent fouling of the exchanger plates or affect the process adversely. Therefore the upgrades required are similar to those above, plus:

- Further increasing the cross-sectional area of the exchangers to accommodate the boiling point elevation of the higher salinity water. These will require a plate material change to titanium as coating or lining these plates for corrosion protection will completely negate the heat transfer capability of the exchangers.
- The differential pressure capacity of the compressor will have to be increased much more than required for Alternative 1 to accommodate the boiling point elevation of the higher salinity water that cause higher pressure differentials in the exchangers. This may drive the power requirement up by eight vs. the four noted above. Engineering work will have to be done to correctly determine the power requirement.
- The piping and all vessels in contact with the brine solution will have to be lined or coated with anti corrosion layer of Teflon or similar material to protect the base metal from corrosion.

Due to the technical uncertainty of this modification, a budgetary estimate for the upgrade cannot be provided. The amount of effort required is uncertain due to the extent of the technical challenges. An upgrade to the existing demonstration unit for Harsh Water Applications is not recommended.

# 7.0 ECONOMIC BENEFIT OF THE PROJECT TO LAREDO

The use of AdVE technology provides the City of Laredo with a significant benefit in the treatment of water sources from alternative or secondary groundwater sources with salinities in excess of the TCEQ limits for potable use. The best application of AdVE is not as the single desalination step, but as a complementary second step in the desalination process. These benefits are realized from the reduced total cost of water by significantly lowering the disposal cost of waste concentrated brine.

AdVE, in combination with RO, provides the City of Laredo the lowest cost of desalinated water for potable use. First stage use of RO, the lowest cost desalination technology for low salt concentrations with a second stage use of AdVE provides significant cost savings by reducing the cost of disposal of waste water, an unavoidable reject stream from the desalination process.

An economic comparative analysis of various water desalination systems scenarios for alternative or secondary waters for various salinities in $/kgal produced. The water quality produced in all cases is potable. The system scenarios are:

1) RO in two passes,
2) RO with ADVE for 2nd pass,
3) AdVE only in one pass, and
4) RO only one pass.

It can be seen that the combination of AdVE treating the reject from the first pass RO provides a lower total cost vs. RO in two passes. Though capital costs are higher, the NPV is lower due to lower O&M costs stemming from much lower well injection disposal costs.

Facility costs and the conveyance cost for the base 5 mgd are not included in the comparative analysis, as they are the same for all cases. Included are the capital cost of the equipment, the annual operating O&M costs, and the incremental cost of the rejected water and related conveyance capital and O&M costs from the raw water well source to the disposal wells. The base assumptions for the economic study are provided in the Appendix 2.

Maximizing water recovery is where the benefit to Laredo from AdVE is derived. This is of great value to the City of Laredo given the great scarcity of water in nearby sources.

The table below the chart details the annual savings in operating costs of the RO with AdVE treatment scheme over the two-pass RO system. It can be seen that the annual savings on a Present Value basis outweigh the extra capital expenditures.

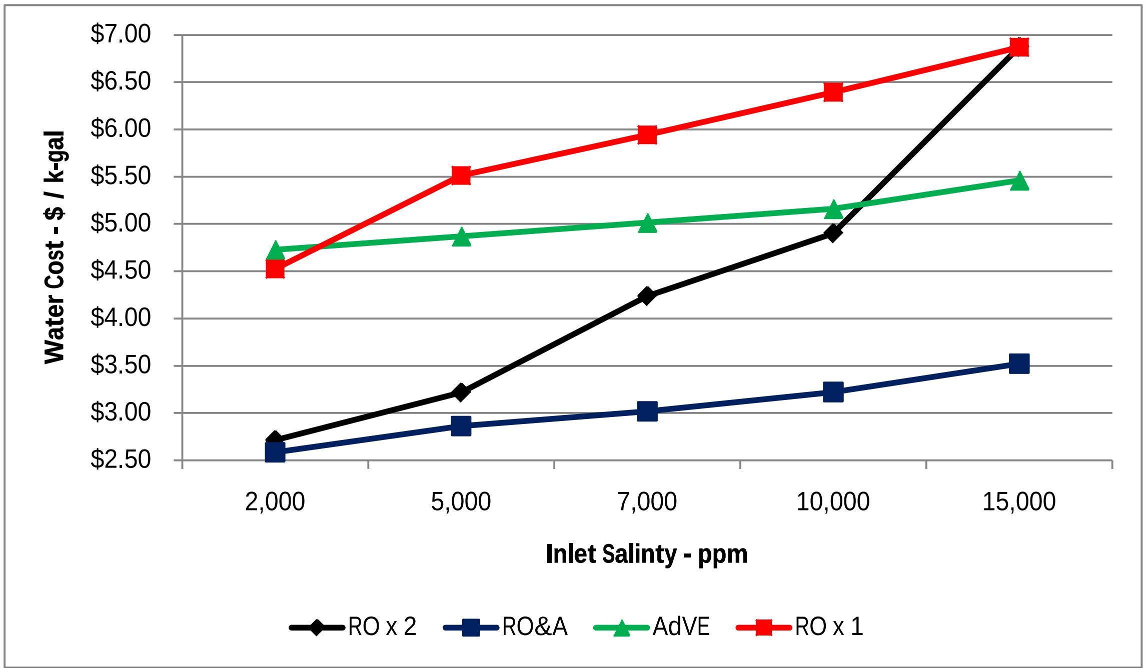


**Figure 41. Comparisons of RO and AdVE Combinations (5 mgd Plant Basis)**

**Table 3. Annual Savings Using RO & AdVE vs. ROx2 – 5mgd Plant ($Millions)**

| Inlet PPM | O&M Savings per Yr | Increased Capital vs. ROx2 | PV: Annual Savings @ 5% | NPV |
|---|---|---|---|---|
| 2000 | $0.38 | ($2.76) | $4.68 | $1.91 |
| 5000 | $0.82 | ($3.33) | $10.18 | $6.84 |
| 7000 | $2.33 | ($2.16) | $29.09 | $26.93 |
| 10000 | $3.15 | ($2.84) | $39.25 | $36.40 |
| 15000 | $6.08 | $0.75 | $75.73 | $76.47 |

# 8.0 CONCLUSIONS

As described in this report, the original hypothesis, that the AdVE would provide a cost effective alternative to reverse osmosis, has been disproved. However, it was found that when coupled as a second stage to a first stage of RO, the reduced cost of disposal of concentrated brine makes AdVE an attractive investment when treating higher salinity source waters or in treating RO rejection streams in water limited areas. This pilot test also validated the laboratory demonstrated science and identified the engineering design issues that will be solved in subsequent generations of this technology. The main obstacle to obtaining the laboratory demonstrated heat transfer rates was seal leakage between the vapor and boiling sides of the heat exchanger. The seals employed will be redesigned in the next generation.

Overall, the City of Laredo benefited from its investment. It was demonstrated that AdVE, in combination with RO, provides the City the lowest cost of desalinated water and the highest ratio of saline water converted to potable water. This lowest cost is achieved through the much reduced annual total cost of disposal of the high salinity waste stream water. An additional benefit to the City and region is the advancement of a technology that can be used, with further engineering work, to recycle return flow water in Eagle Ford Shale gas fracking operations and thus reduce the volume of the City's limited potable water to this industrial sector. Further, in the water scarce environment of Laredo with limited resources and growing population demand, maximizing potable water from little used saline aquifers is invaluable. AdVE is a significant tool in Laredo's toolbox to address their water requirements for the foreseeable future.

# 9.0 ENDNOTES

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[3] Kalaswad, S, Arroyo, J. et al., *Guidance Manual for Brackish Groundwater Desalination in Texas*, Texas Water Development Board, Austin, TX, April 2008.

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[9] Ibid.

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[14] Holtzapple, 2008

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[17] Holtzapple, 2008.

# APPENDIX 1:  PROJECT PARTNERS

## City of Laredo

The City of Laredo was the funding agent for this project.  Laredo is located on the Rio Grande River in southwestern Webb County in South Texas, about 150 miles southwest of San Antonio and 135 miles west of Corpus Christi.  Founded in 1755, Laredo has become a critical Principle Port of Entry for the United States and Mexico with over $367 billion per year in international trade flowing through the port.  The City has over 40 million square feet of distribution and warehouse space and over the past 5 years averaged over 2 million loaded truck border crossings per year.  This activity has spurred substantial growth with the 2008 population of Laredo standing at 233,152 and the average growth since 1980 around 34% every 10 years [12].  Laredo’s water usage is 60 million gallons per day and the system is rapidly expanding.  Currently, the only source of water for the City of Laredo is the Rio Grande River [13].  At the end of the project, the City of Laredo will have outright ownership of the demonstration facility royalty free and have preferential rights on negotiation of a commercial scale desalination facility with Terrabon AdVE, LLC.

## The Texas A&M University System

The Texas A&M University System is one of the largest and most renowned systems of higher education in the nation.  The TAMUS family consists of ten universities and eight state agencies that serve more than 85,000 students and reaches 3.5 million people each year through its service mission.  Research projects underway today by system universities and research agencies total $397 million.  Texas A&M University is ranked as the third largest university in the nation along with the largest engineering undergraduate college in the country.  It is one of the select few national institutions to hold the triple designation of land, sea, and space Grant University.  Two components of The Texas A&M University System are involved in this project:  The Texas Engineering Experiment Station (TEES) and the Artie McFerrin Department of Chemical Engineering (ChemE).

The Texas Engineering Experiment Station is one of three engineering state agency affiliated with the Texas A&M University System.  TEES is the engineering research agency for the State of Texas with the mission to identify and conduct research in areas critical to the State's economic development and quality of life; to promote new technology and entrepreneurship; to leverage and network human, physical, and financial resources; and to enhance and strengthen education in Texas.  TEES addresses the specific technological problems our society now faces and will face in the future. The Texas Center for Applied Technology (TCAT) is the center responsible for managing this project.  TCAT is an industrially funded center and, as a link between university expertise and public and private sector clients, is in a unique position to be able to harness new and emerging technologies for clients in both the private and public sectors.

TEES/TCAT was the prime grantee for this effort and was responsible for the overall management of the project and coordination of all grant team activities.  TCAT provided financial control for the project and was responsible for all reporting.  TEES Office of Sponsored Research issued a subcontract to Terrabon AdVE, LLC and TCAT provided managerial oversight of the team members in their activities related to this project.  TCAT used agency methods and procedures to track expenditures and worked with the City of Laredo and the project team members to identify, arrange for, and supervise qualified contractors to install the prototype system at the selected site.

The Artie McFerrin Department of Chemical Engineering at Texas A&M University is one of the largest, fully accredited chemical engineering programs in the country, with an undergraduate program that ranks 13th nationally, among public institutions. The research performed by the faculty and graduate students ranges from fundamental to applied technology. The faculty features 25 tenure/ tenure track members, including three endowed chairs, nine endowed professorships, one endowed faculty fellowship, one regents professor and five CAREER award recipients. Department research expenditures for fiscal year 2009 totaled $9.6 million. Dr. Mark Holtzapple, Professor of Chemical Engineering, is the inventor of the technology implemented by this project. The Holtzapple Lab is dedicated to the research and development of the sustainable and renewable technologies which, when implemented on a commercial scale, will impact future fuel, chemical, food, and water production. Currently, Dr. Holtzapple and his group are working to commercialize these technologies with their industry partner Terrabon, Inc.

### Terrabon AdVE, LLC

Terrabon, Inc. is the holding company for three technology subsidiaries commercializing licensed technologies from Texas A&M University. Terrabon, Inc. is developing technologies for refining gasoline from non-food biomass, converting protein-bearing waste products to animal feeds and adhesives, and specifically to this project, commercializing advanced vapor compression desalination technology to produce potable water. Terrabon, Inc, is the recipient of $2.75 million Texas Emerging Technology Fund investment. The subsidiary, Terrabon AdVE, LLC (known as Terrabon in this report) is the technology provider for this project through various licenses with the Artie McFerrin Department of Chemical Engineering at Texas A&M University. Terrabon provided the test and production systems for the demonstration plant and coordinated with TEES and the City of Laredo in the installation and operation of the demonstration plant.

### Texas Systems and Controls

Texas Systems and Controls (TSC) was the detail designer and manufacturer of the Advanced Vapor Compression desalination plant. TSC is a global provider of custom skid-mounted systems each engineered to their customer's exact requirements and worked under a subcontract to Terrabon. TSC is based in Tomball, northwest of Houston, Texas.

### American Water - Applied Water Management, Inc.

Applied Water Management, Inc., a subsidiary of American Water, headquartered in Hillsborough, NJ, offers award-winning, customized solutions to real estate developers, industrial clients, and new and expanding communities. They provide their clients with safe, reliable, long-lasting and highly-efficient solutions to suit individual water and wastewater needs. Operating under a subcontract to Terrabon, AWM was responsible for Laredo site preparation and for the operation, maintenance, monitoring and validation of the commercial viability of the demonstration plant during the project.

### Walden Consulting

Steve Walden is a former director of the Water Utilities Division at the Texas Commission on Environmental Quality (TCEQ) and has been consulting on university based water research projects since his retirement from TCEQ at the end of 2003. Mr. Walden was engaged by Terrabon independently of the contractual structure of the project to assist in the commercialization of the

Advanced Vapor-Compression Evaporation (AdVE) technology by locating industrial partners to fund and collaborate with Terrabon on enhanced skid versions for their respective market sector, creating regulatory compliance strategies and dialog with regulators for the Laredo and other projects under discussion, identifying investors that might co-own AdVE and collaborate with Terrabon, and creating an overarching commercialization strategy for the technology. His contribution to the project included consulting on submissions to TCEQ and providing assistance to AWM in developing the test protocols for both TCEQ and NSF-61 compliance certification.

# APPENDIX 2:  COMPARATIVE EVALUATION ASSUMPTIONS

5 mgd plant, Capacity factor of 80%, operating factor of 90%
No conveyance to the facility nor facility costs considered, as they are the same for all options
Comparison included:
Treatment equipment capital and O&M costs
RO Capital Cost = $1M / mgd, O&M costs of $1.80 / k-gal
AdVE Capital Cost = $5M / mgd, O&M costs of $3.50 / k-gal
Source water incremental costs one scenario vs. the other
Reject pipeline equipment capital and O&M costs
Reject disposal costs per scenario.
Source Well site to facility distance: 10 miles
Disposal well site from facility: 10 miles
Disposal well injection costs:  $12 / kgal
Facility life: 20 years for depreciation cost , Rate for PV of 5%

# APPENDIX 3:
# PRESENTATION TO THE CITY OF LAREDO: BRACKISH WATER DESALINATION DEMONSTRATION PROJECT, MARCH 14, 2011

Renewable Energy Solutions

Developing advanced biofuels for an energy hungry world

## Brackish Water Desalination
## Demo Unit
## AdVE - Advance Vapor Compression

## City of Laredo

Revision: **March 14, 2011**

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## *Agenda*

1. Executive Summary
2. Water Treatment & Desalination Process
3. AdVE's role in Laredo Water Strategy
4. Comparative Economic Analysis of Brackish Water Treatment
5. Benefits to the City of Laredo from the AdVE development
6. Project Overview, Results, Recommendations

Appendix
1. Desalination Technologies
2. Comparative Economic Analysis, 4 scenarios by inlet TDS

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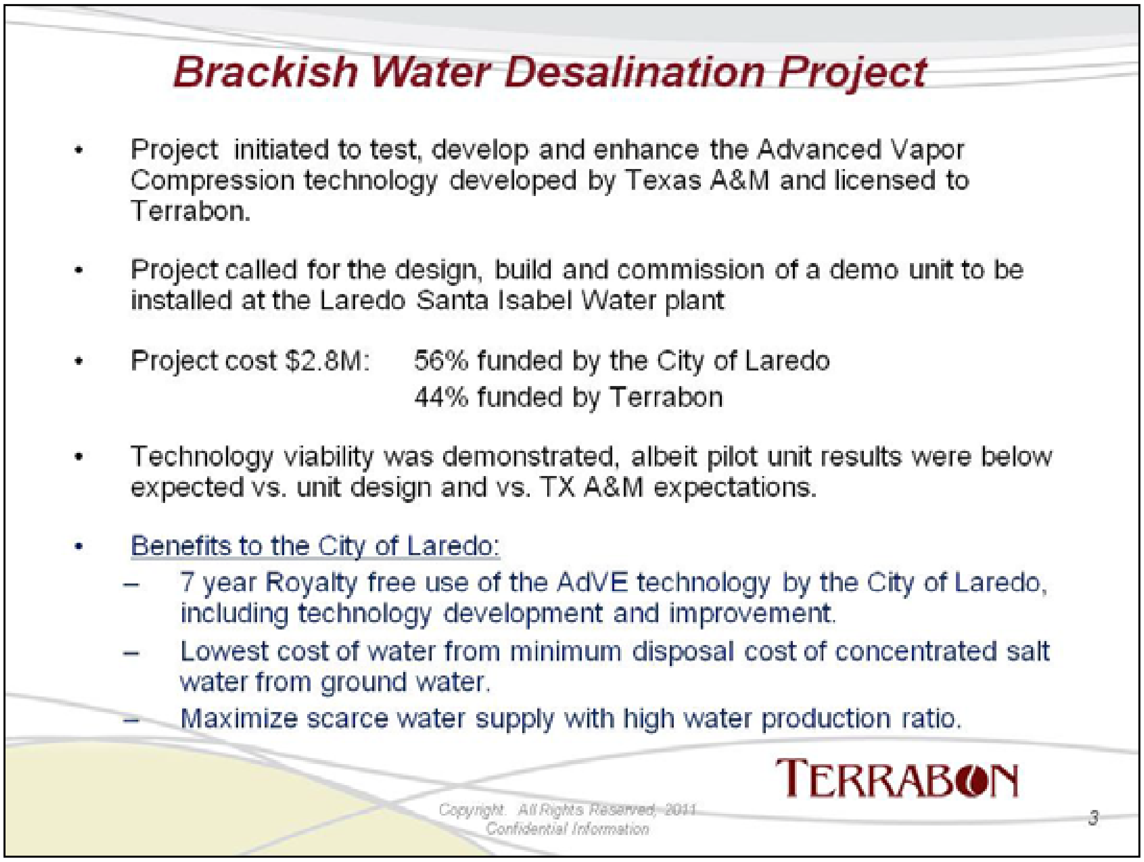

## Brackish Water Desalination Project

- Project initiated to test, develop and enhance the Advanced Vapor Compression technology developed by Texas A&M and licensed to Terrabon.
- Project called for the design, build and commission of a demo unit to be installed at the Laredo Santa Isabel Water plant
- Project cost $2.8M: 56% funded by the City of Laredo
  44% funded by Terrabon
- Technology viability was demonstrated, albeit pilot unit results were below expected vs. unit design and vs. TX A&M expectations.
- Benefits to the City of Laredo:
  - 7 year Royalty free use of the AdVE technology by the City of Laredo, including technology development and improvement.
  - Lowest cost of water from minimum disposal cost of concentrated salt water from ground water.
  - Maximize scarce water supply with high water production ratio.

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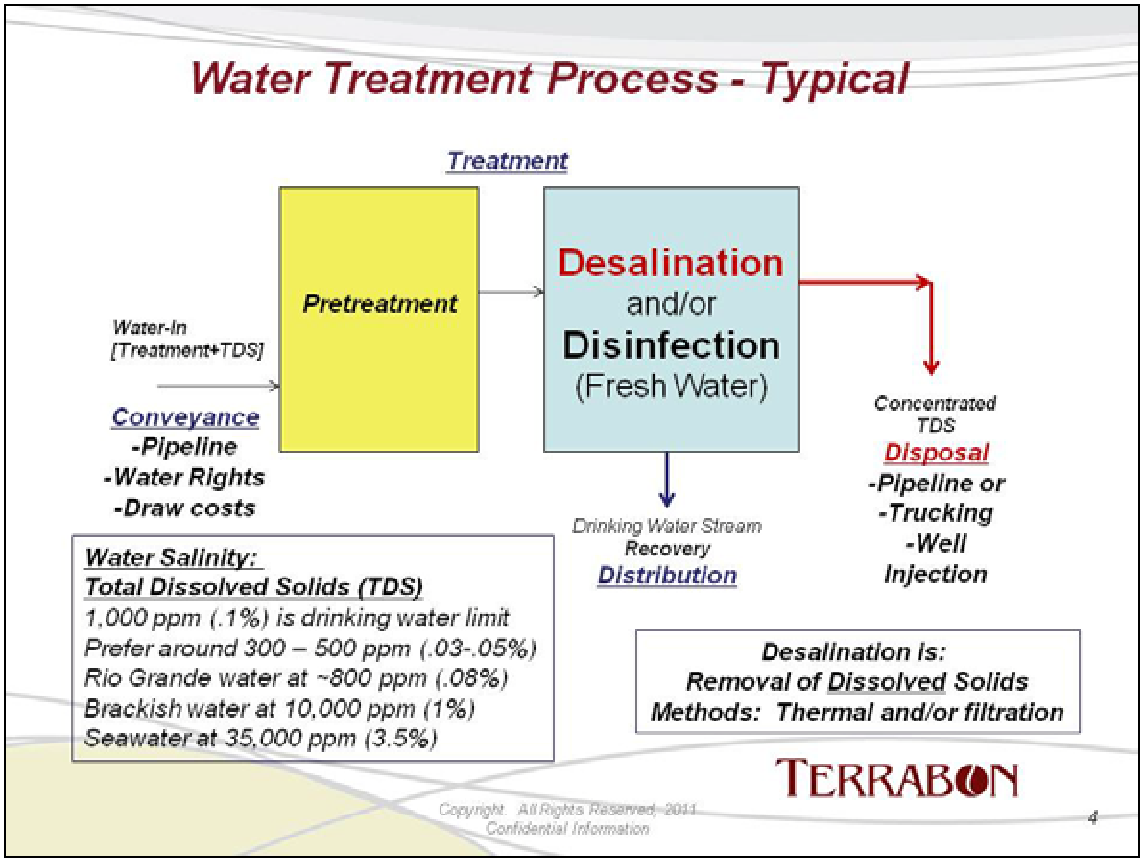

## Water Treatment Process - Typical

**Treatment**

Water-In
[Treatment+TDS]

**Pretreatment**

**Desalination**
and/or
**Disinfection**
(Fresh Water)

**Conveyance**
**-Pipeline**
**-Water Rights**
**-Draw costs**

Concentrated
TDS
**Disposal**
**-Pipeline or**
**-Trucking**
**-Well**
**Injection**

Drinking Water Stream
Recovery
**Distribution**

***Water Salinity:***
***Total Dissolved Solids (TDS)***
*1,000 ppm (.1%) is drinking water limit*
*Prefer around 300 – 500 ppm (.03-.05%)*
*Rio Grande water at ~800 ppm (.08%)*
*Brackish water at 10,000 ppm (1%)*
*Seawater at 35,000 ppm (3.5%)*

***Desalination is:***
***Removal of Dissolved Solids***
***Methods: Thermal and/or filtration***

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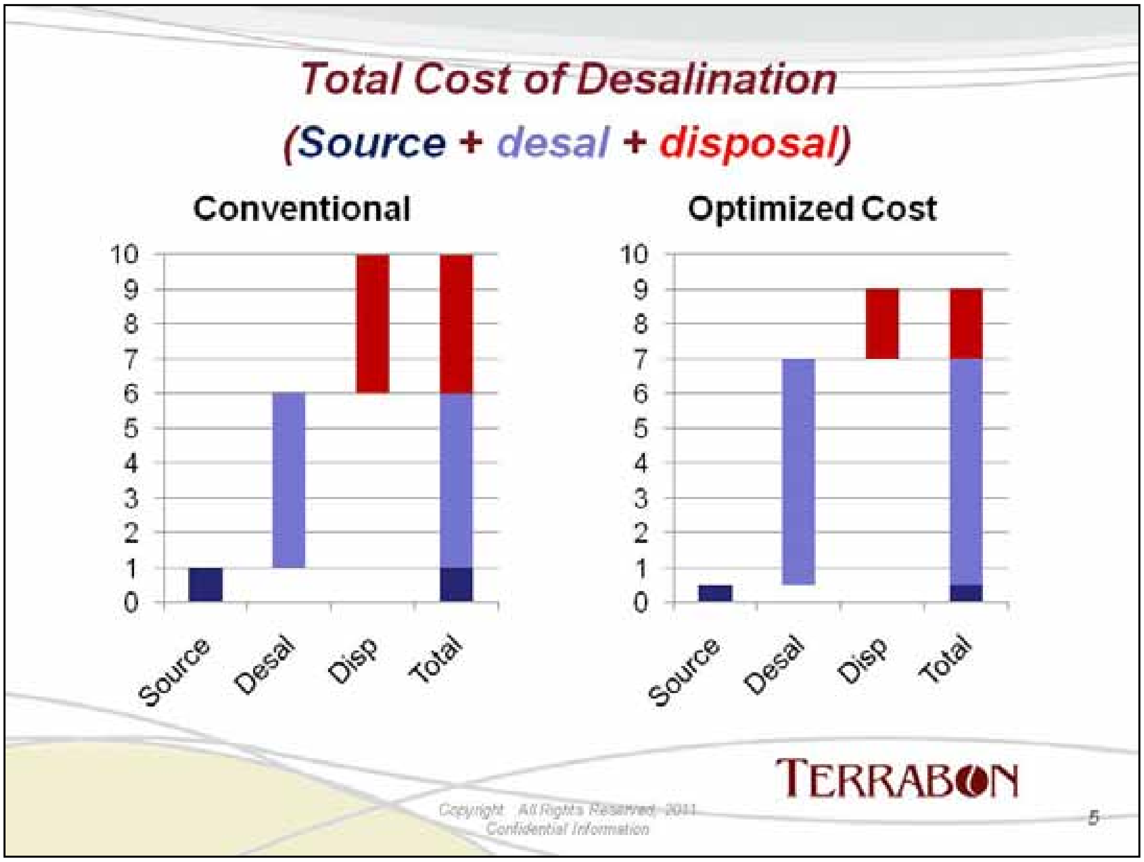

## Total Cost of Desalination

## (Source + desal + disposal)

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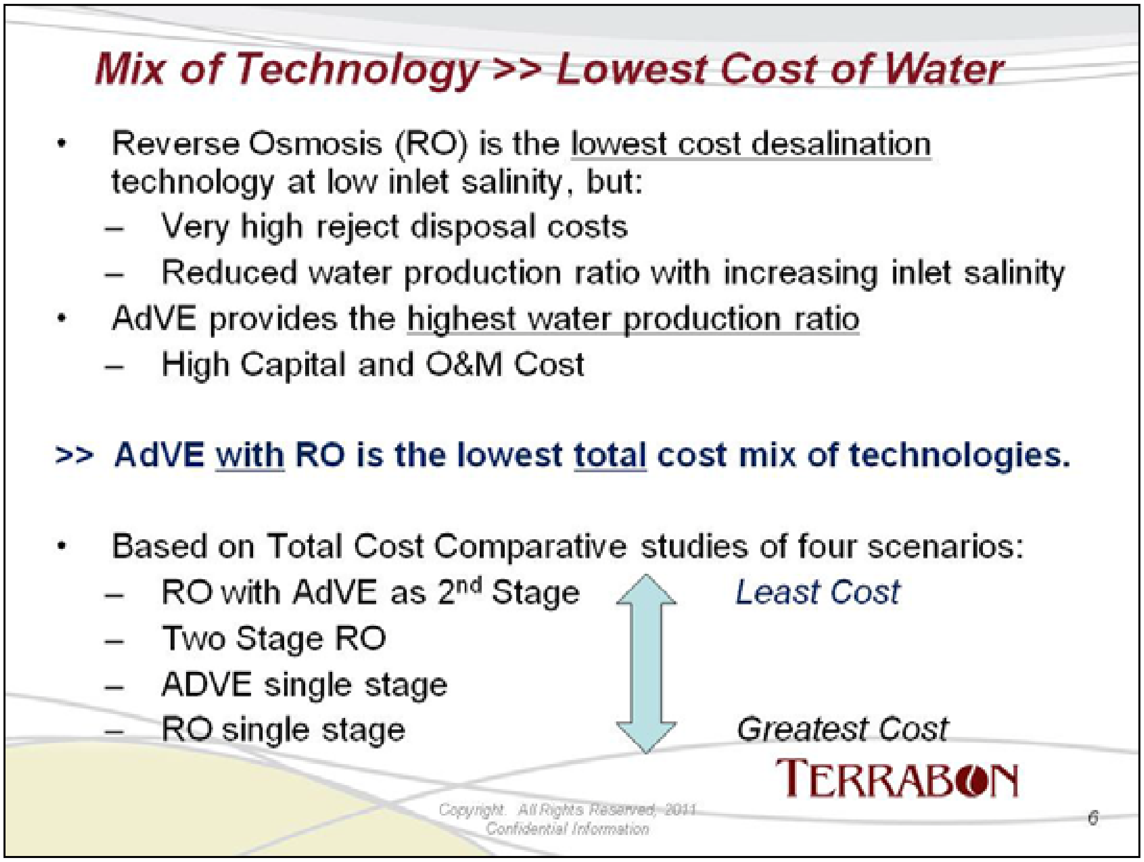

## Mix of Technology >> Lowest Cost of Water

- Reverse Osmosis (RO) is the lowest cost desalination technology at low inlet salinity, but:
  - Very high reject disposal costs
  - Reduced water production ratio with increasing inlet salinity
- AdVE provides the highest water production ratio
  - High Capital and O&M Cost

**>> AdVE with RO is the lowest total cost mix of technologies.**

- Based on Total Cost Comparative studies of four scenarios:
  - RO with AdVE as 2nd Stage
  - Two Stage RO
  - ADVE single stage
  - RO single stage

*Least Cost*

*Greatest Cost*

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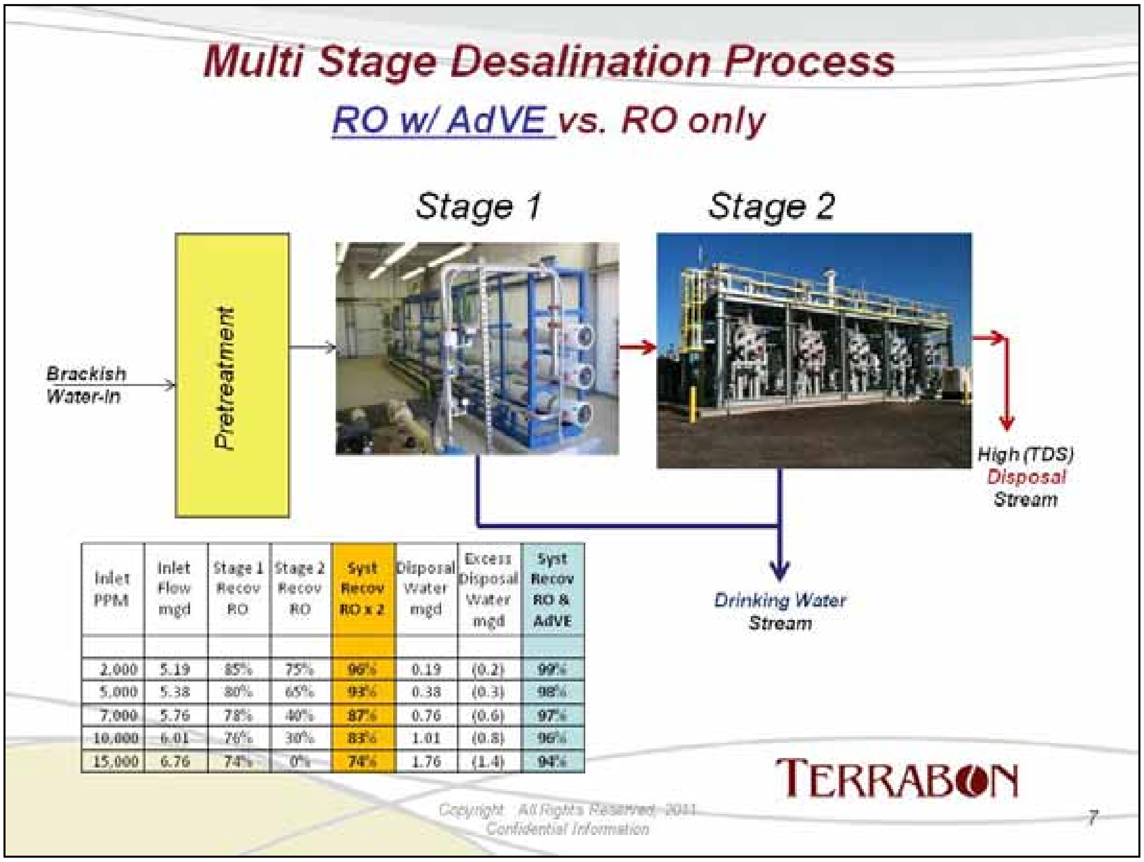

## Multi Stage Desalination Process

### RO w/ AdVE vs. RO only

Stage 1

Stage 2

Brackish Water-In

Pretreatment

High (TDS) Disposal Stream

Drinking Water Stream

| Inlet PPM | Inlet Flow mgd | Stage 1 Recov RO | Stage 2 Recov RO | Syst Recov RO x 2 | Disposal Water mgd | Excess Disposal Water mgd | Syst Recov RO & AdVE |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| 2,000 | 5.19 | 85% | 75% | 96% | 0.19 | (0.2) | 99% |
| 5,000 | 5.38 | 80% | 65% | 93% | 0.38 | (0.3) | 98% |
| 7,000 | 5.76 | 78% | 40% | 87% | 0.76 | (0.6) | 97% |
| 10,000 | 6.01 | 76% | 30% | 83% | 1.01 | (0.8) | 96% |
| 15,000 | 6.76 | 74% | 0% | 74% | 1.76 | (1.4) | 94% |

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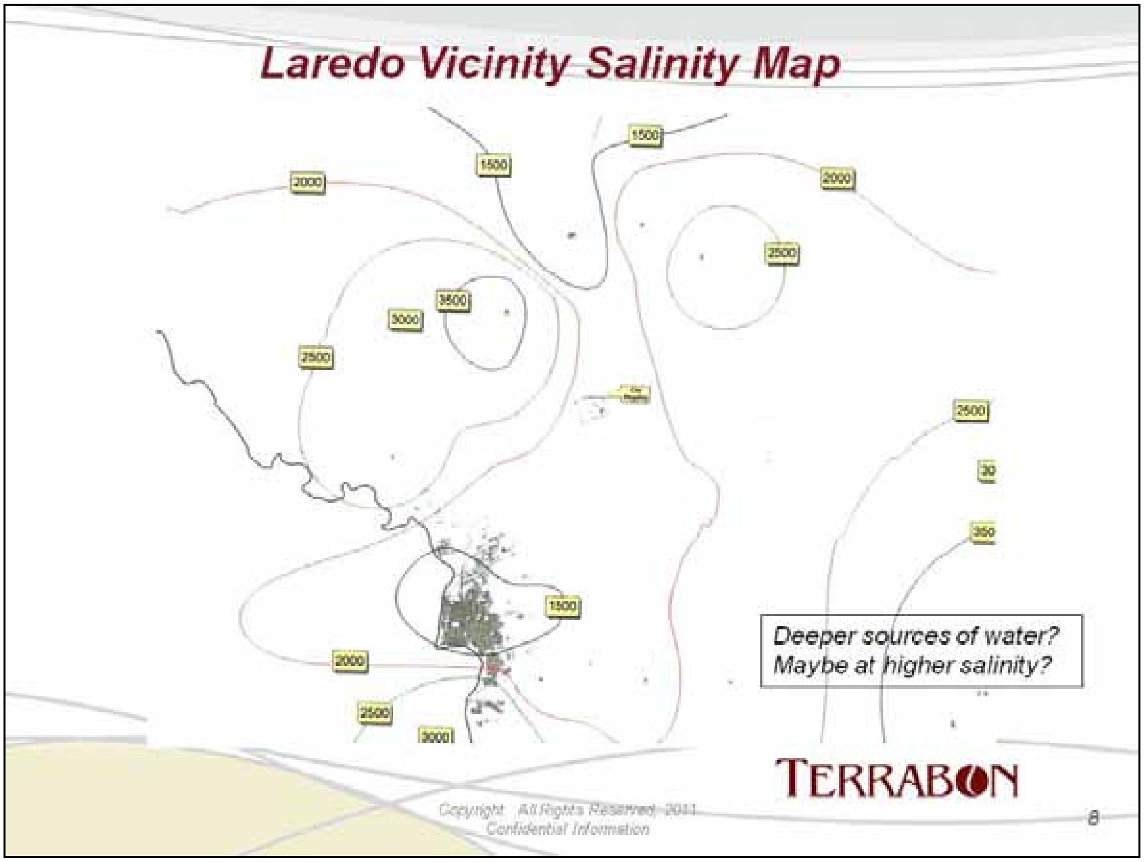

## Laredo Vicinity Salinity Map

Deeper sources of water?
Maybe at higher salinity?

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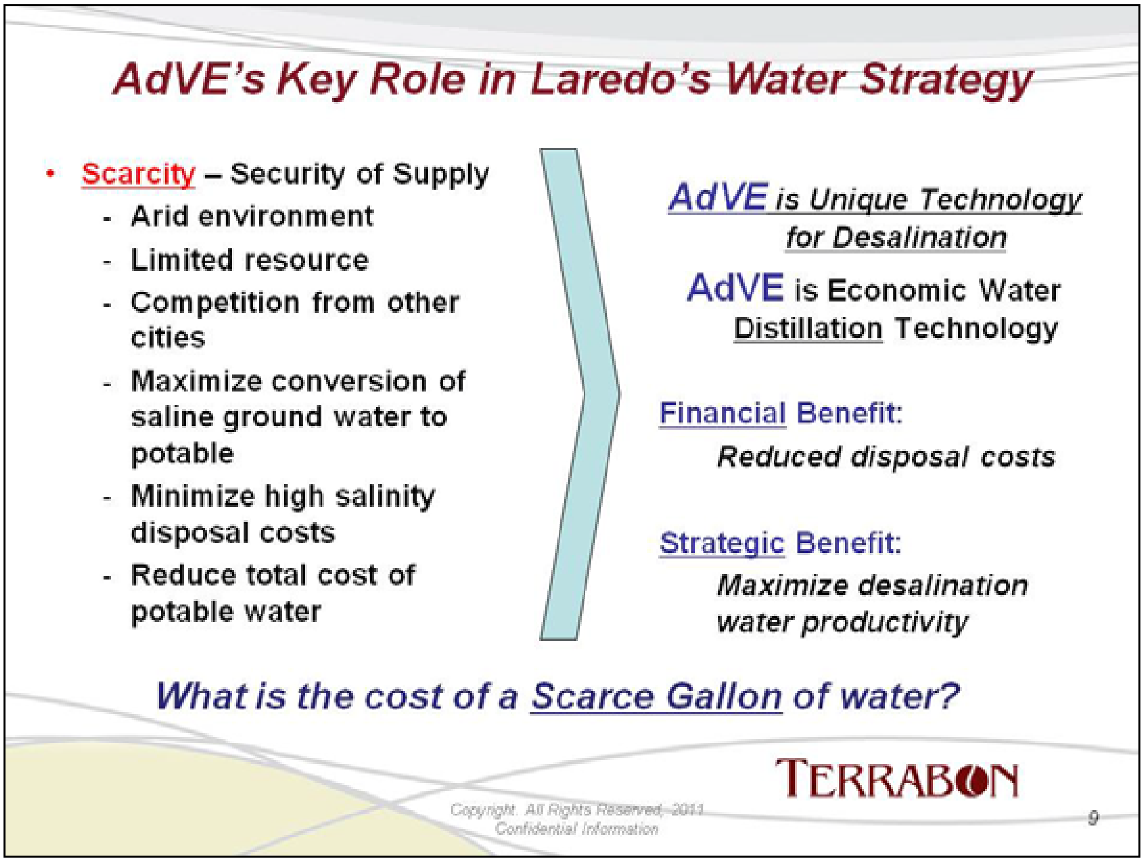

## AdVE's Key Role in Laredo's Water Strategy

- Scarcity – Security of Supply
  - Arid environment
  - Limited resource
  - Competition from other cities
  - Maximize conversion of saline ground water to potable
  - Minimize high salinity disposal costs
  - Reduce total cost of potable water

*AdVE is Unique Technology for Desalination*

AdVE is Economic Water Distillation Technology

**Financial Benefit:**

*Reduced disposal costs*

**Strategic Benefit:**

*Maximize desalination water productivity*

*What is the cost of a Scarce Gallon of water?*

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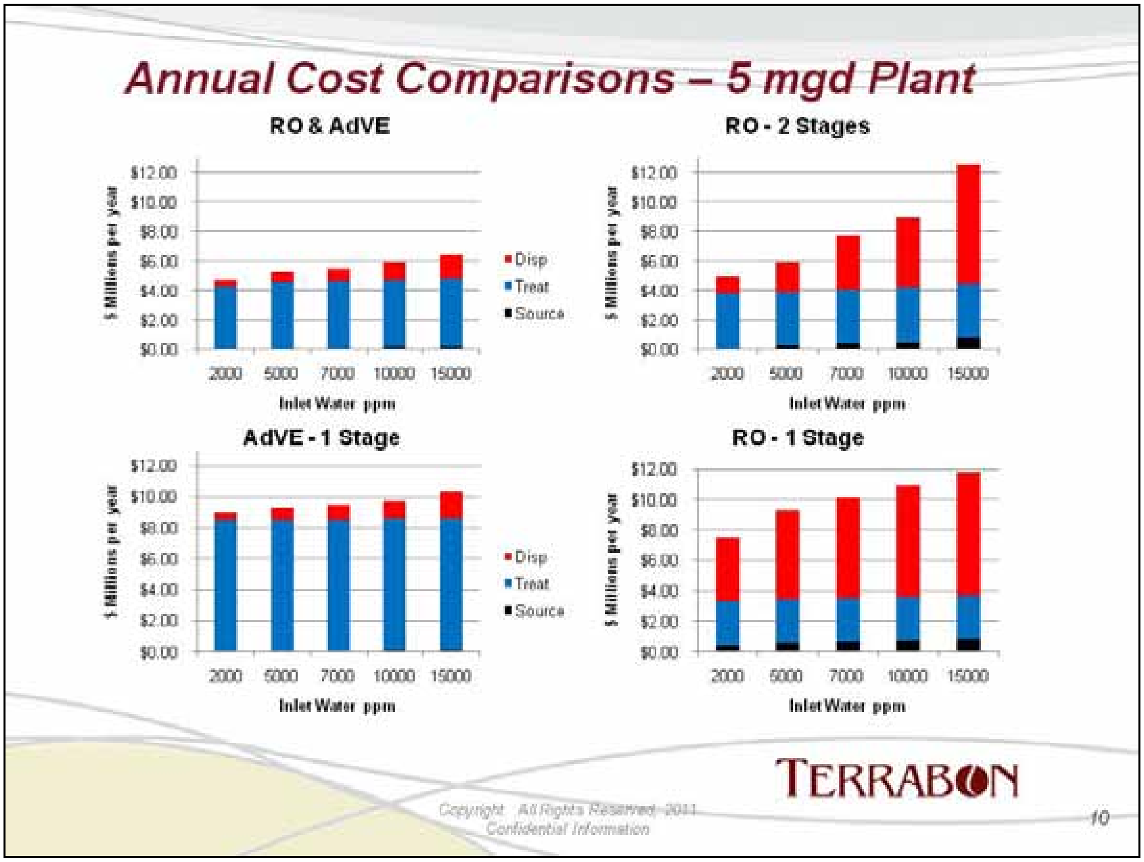

## Annual Cost Comparisons – 5 mgd Plant

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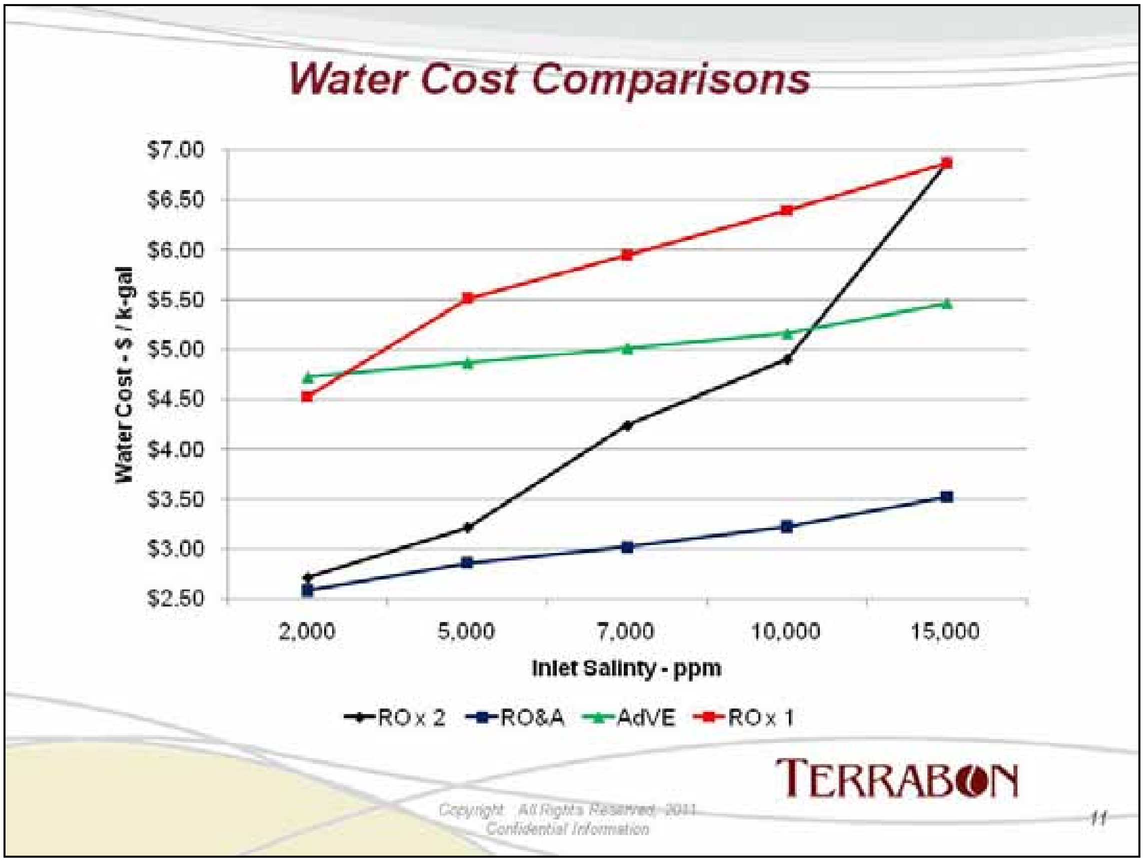

## Water Cost Comparisons

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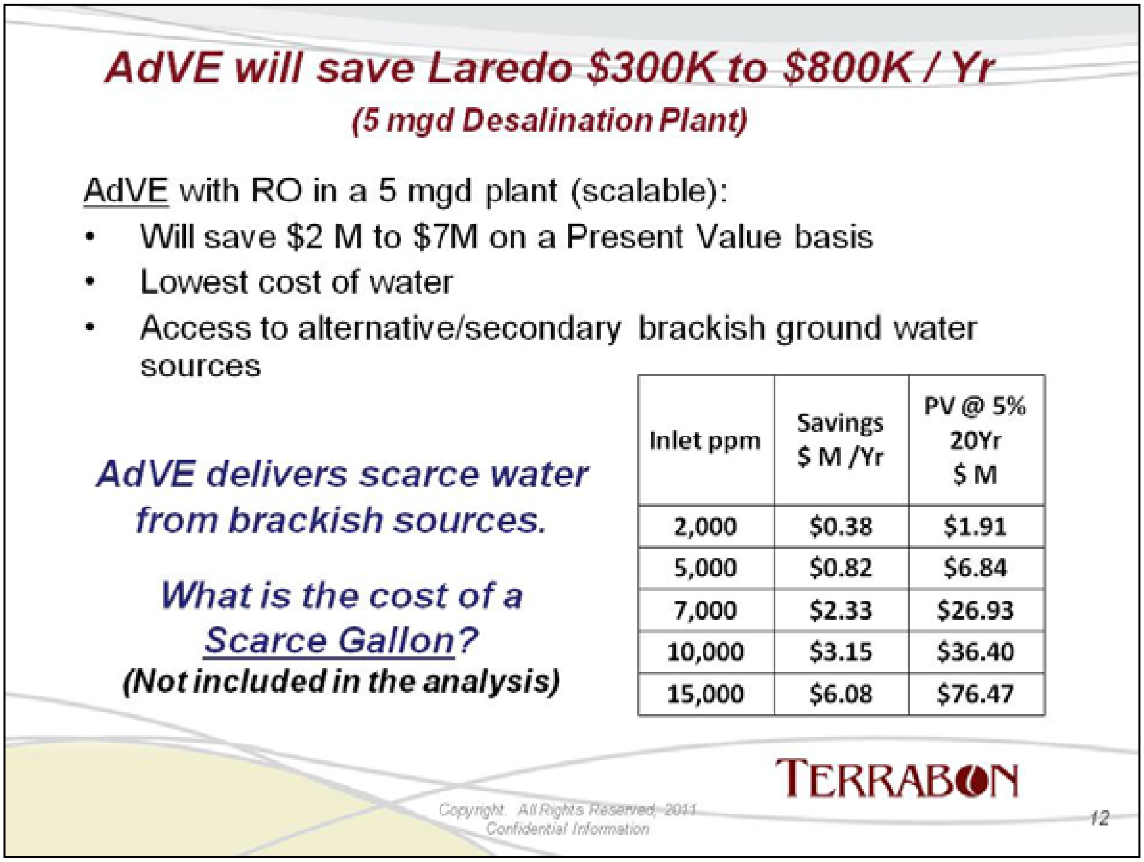

## AdVE will save Laredo $300K to $800K / Yr

### (5 mgd Desalination Plant)

AdVE with RO in a 5 mgd plant (scalable):

- Will save $2 M to $7M on a Present Value basis
- Lowest cost of water
- Access to alternative/secondary brackish ground water sources

*AdVE delivers scarce water from brackish sources.*

*What is the cost of a Scarce Gallon?*

***(Not included in the analysis)***

| Inlet ppm | Savings $ M /Yr | PV @ 5% 20Yr $ M |
|---|---|---|
| 2,000 | $0.38 | $1.91 |
| 5,000 | $0.82 | $6.84 |
| 7,000 | $2.33 | $26.93 |
| 10,000 | $3.15 | $36.40 |
| 15,000 | $6.08 | $76.47 |

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# Brackish Water Desalination Project

## Overview, Results, Recommendations

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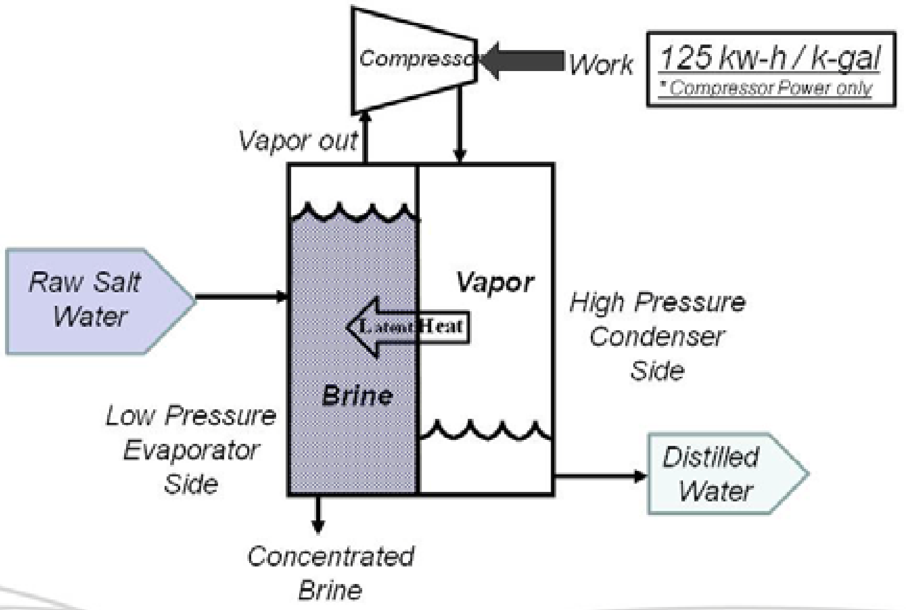
# Vapor Compression



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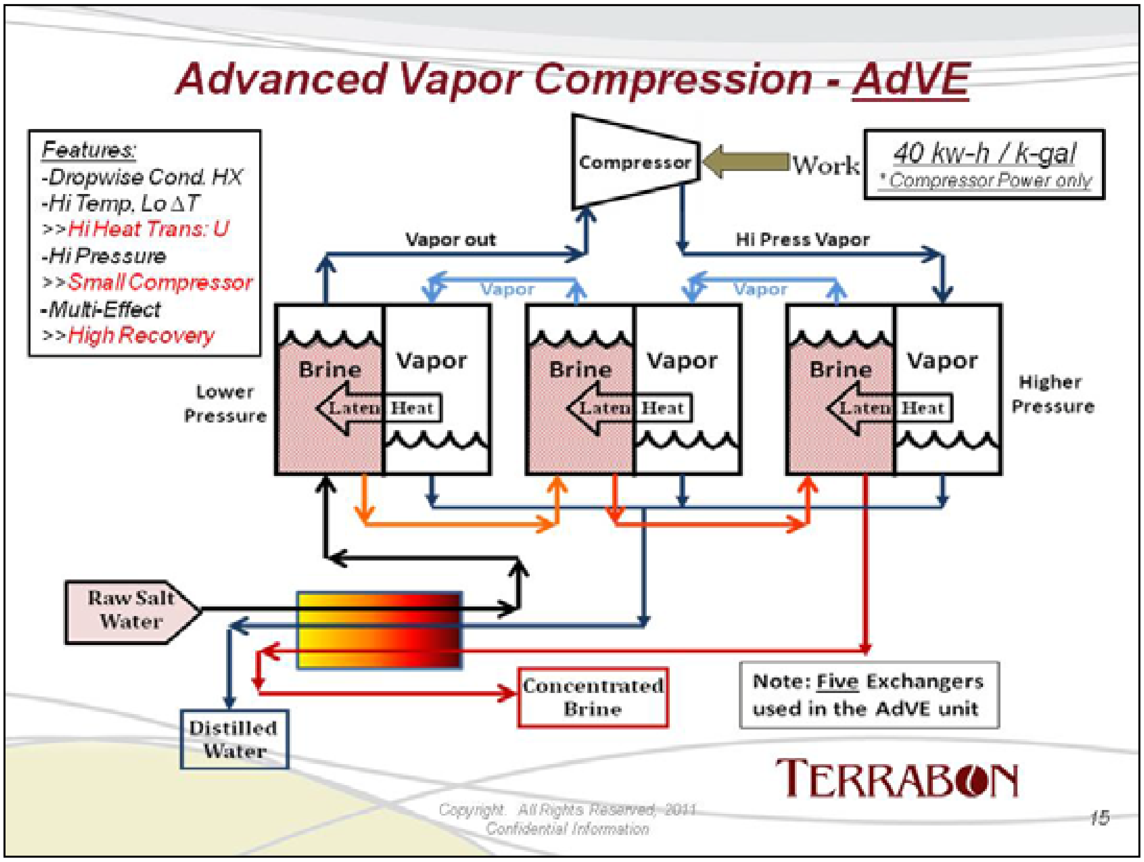

## Advanced Vapor Compression - AdVE

*Features:*
- *Dropwise Cond. HX*
- *Hi Temp, Lo ΔT*
>>*Hi Heat Trans: U*
- *Hi Pressure*
>>*Small Compressor*
- *Multi-Effect*
>>*High Recovery*

*40 kw-h / k-gal*
** Compressor Power only*

Note: Five Exchangers used in the AdVE unit

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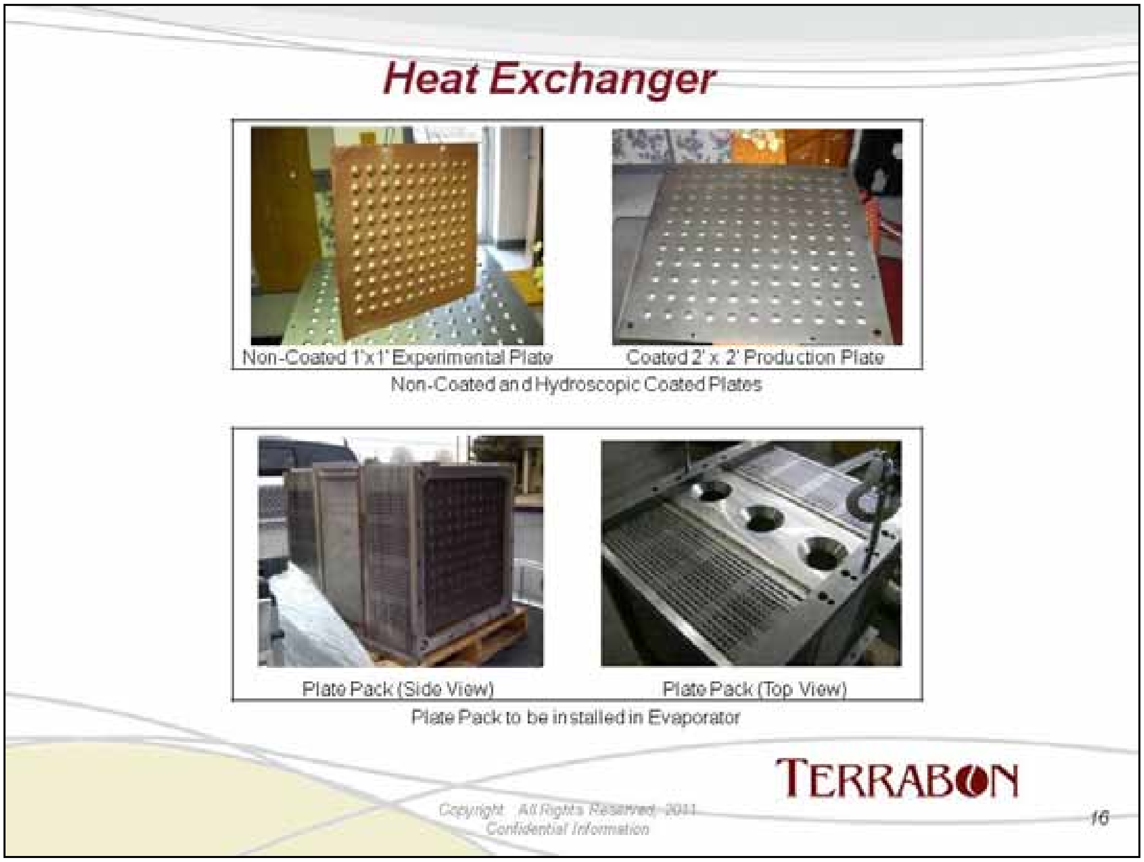

## Heat Exchanger

Non-Coated 1'x1' Experimental Plate

Coated 2' x 2' Production Plate

Non-Coated and Hydroscopic Coated Plates

Plate Pack (Side View)

Plate Pack (Top View)

Plate Pack to be installed in Evaporator

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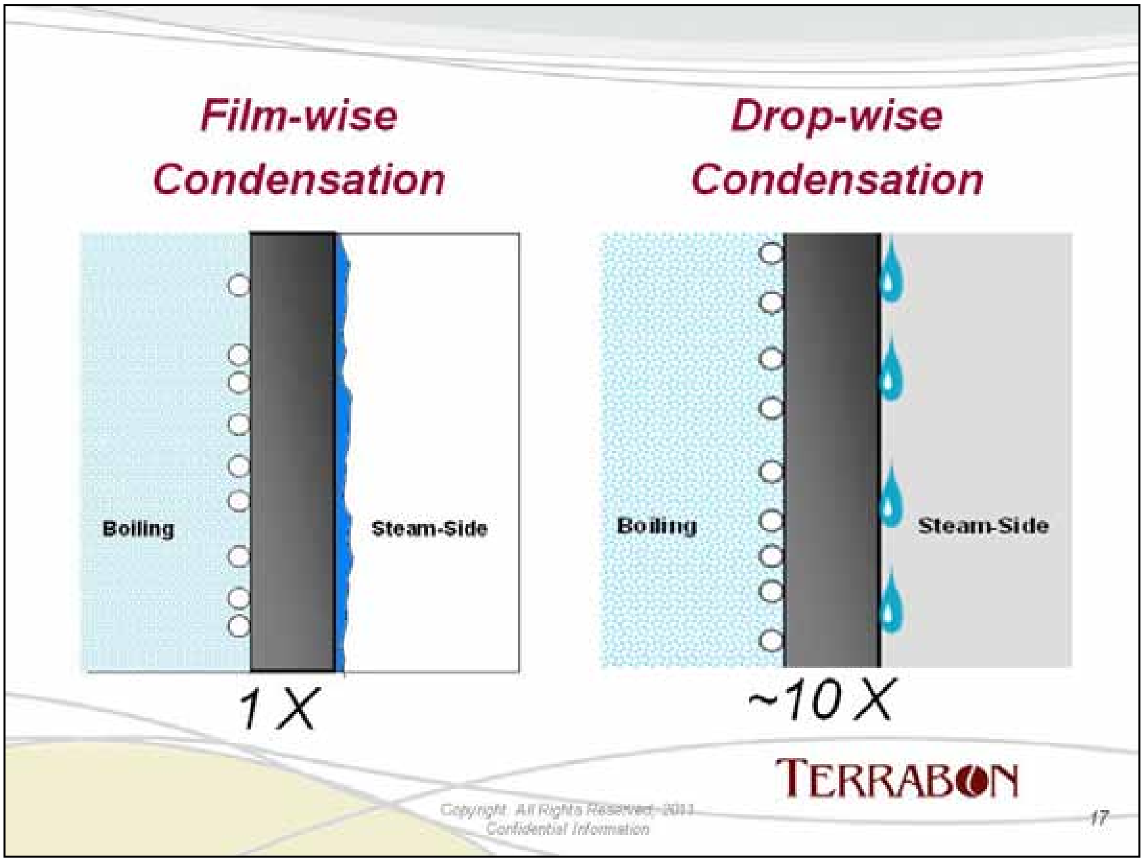

## Film-wise Condensation

## Drop-wise Condensation

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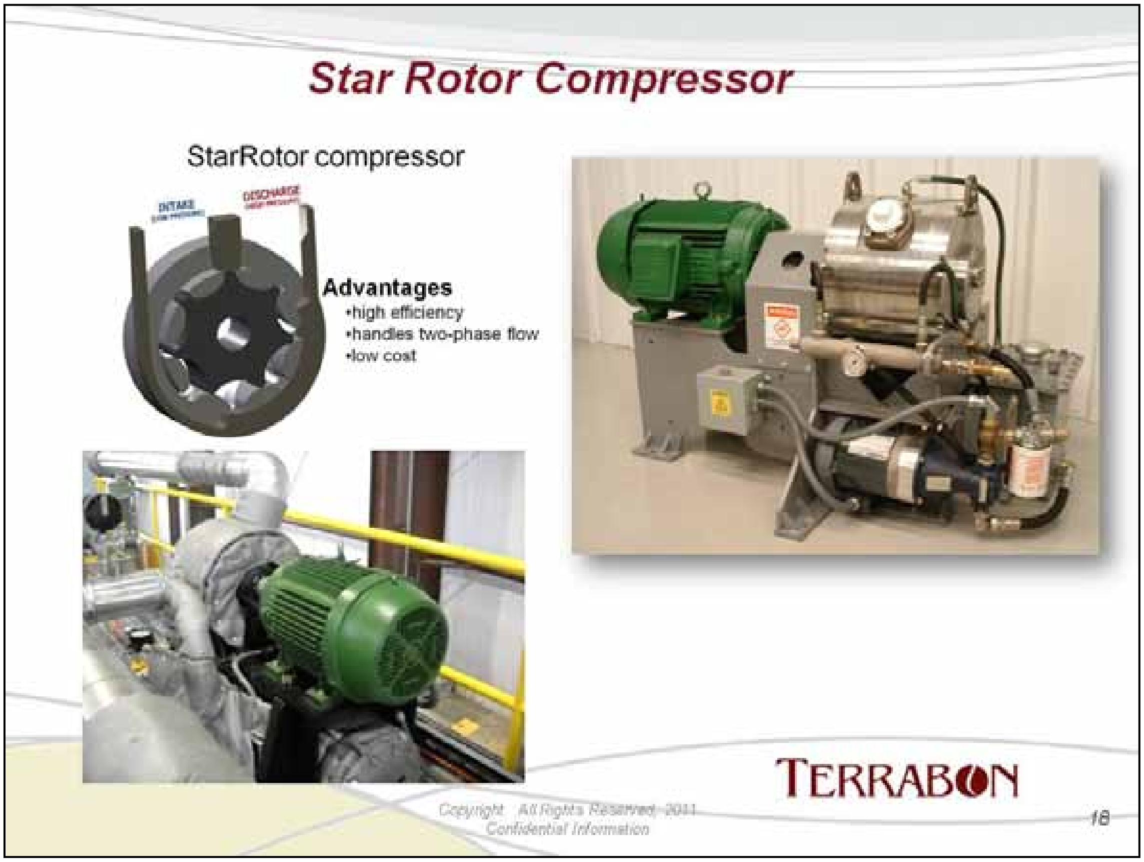

## Star Rotor Compressor

StarRotor compressor

**Advantages**
- high efficiency
- handles two-phase flow
- low cost

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## Assembled AdVE Unit in Laredo

Santa Isabel Well Site

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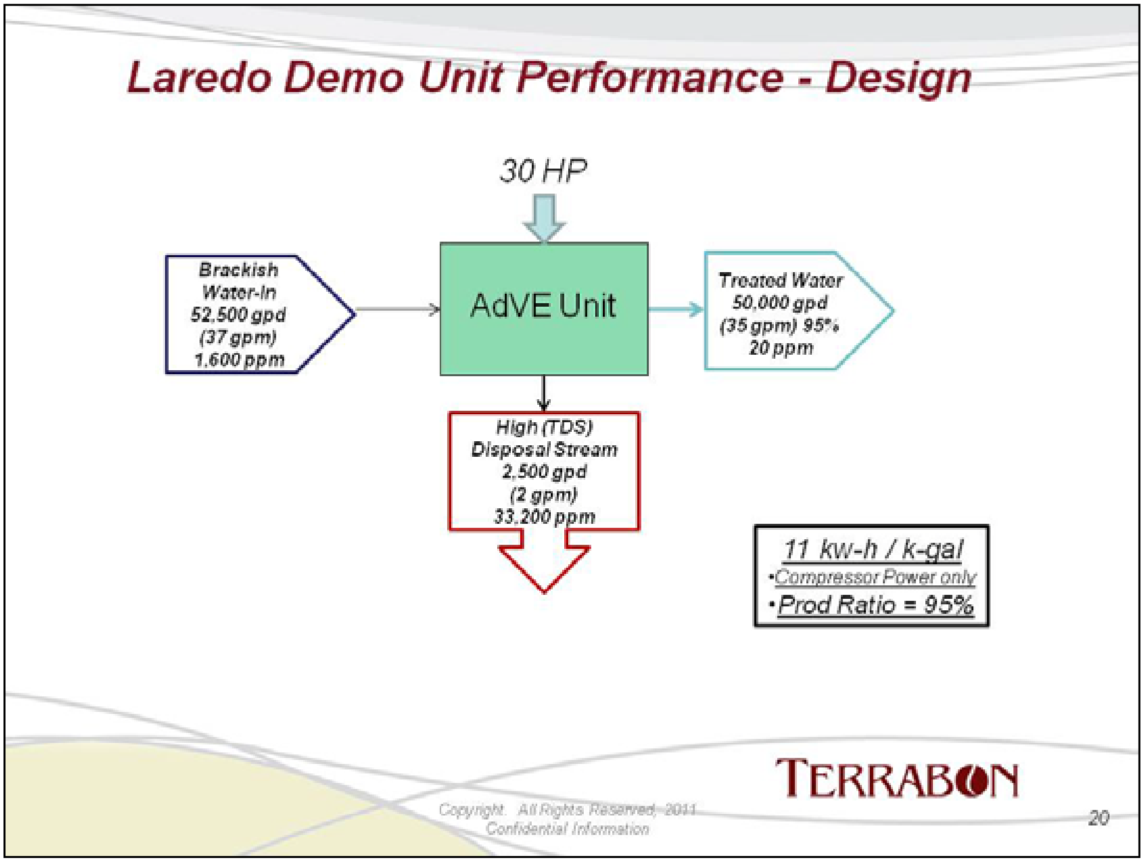

## Laredo Demo Unit Performance - Design

30 HP

**Brackish Water-In**
**52,500 gpd**
**(37 gpm)**
**1,600 ppm**

AdVE Unit

**Treated Water**
**50,000 gpd**
**(35 gpm) 95%**
**20 ppm**

**High (TDS)**
**Disposal Stream**
**2,500 gpd**
**(2 gpm)**
**33,200 ppm**

11 kw-h / k-gal
- Compressor Power only
- Prod Ratio = 95%

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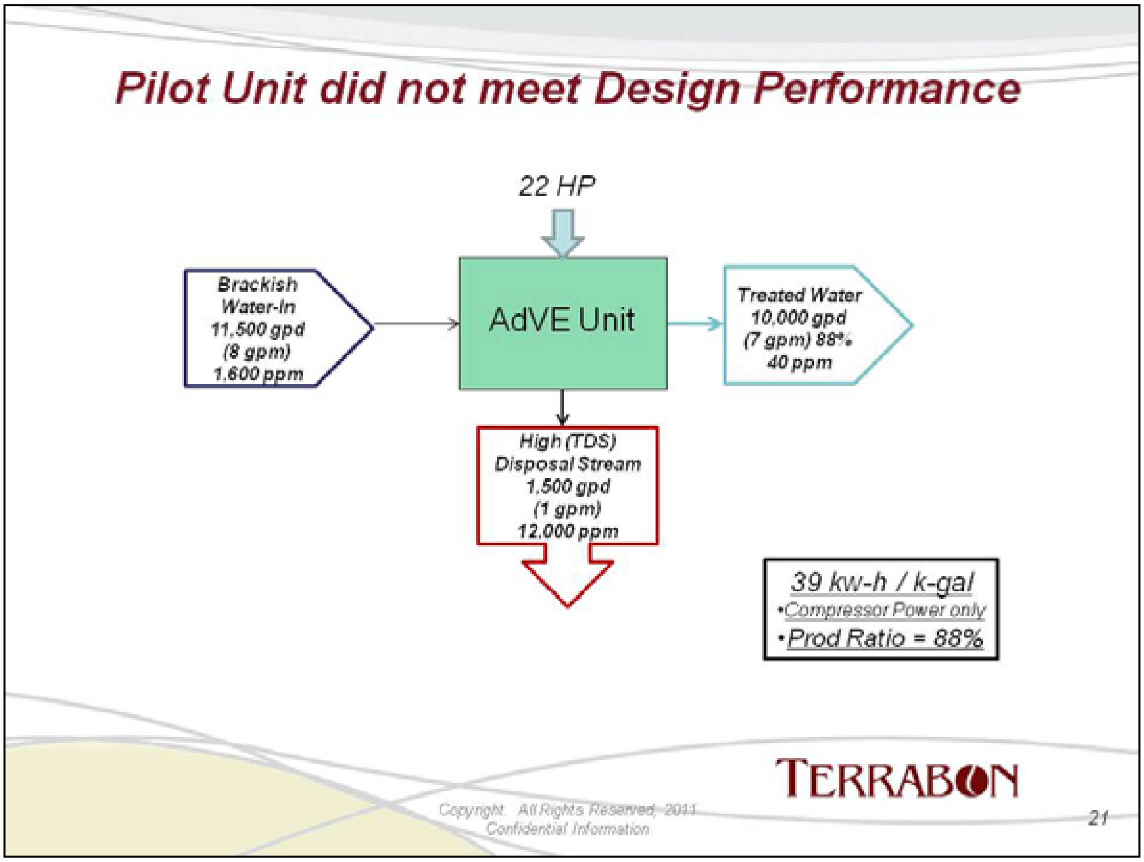

## Pilot Unit did not meet Design Performance

39 kw-h / k-gal
- Compressor Power only
- Prod Ratio = 88%

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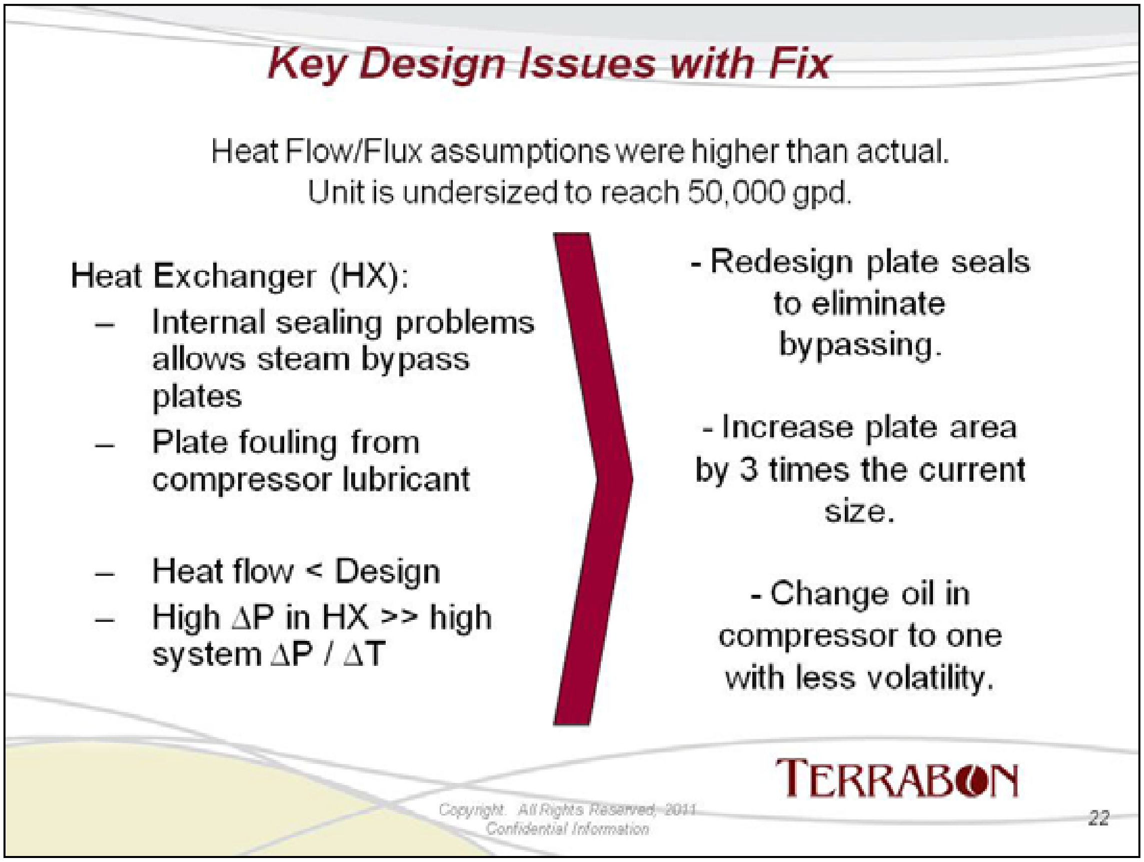

## Key Design Issues with Fix

Heat Flow/Flux assumptions were higher than actual.
Unit is undersized to reach 50,000 gpd.

Heat Exchanger (HX):
- Internal sealing problems allows steam bypass plates
- Plate fouling from compressor lubricant
- Heat flow < Design
- High ΔP in HX >> high system ΔP / ΔT

- Redesign plate seals to eliminate bypassing.
- Increase plate area by 3 times the current size.
- Change oil in compressor to one with less volatility.

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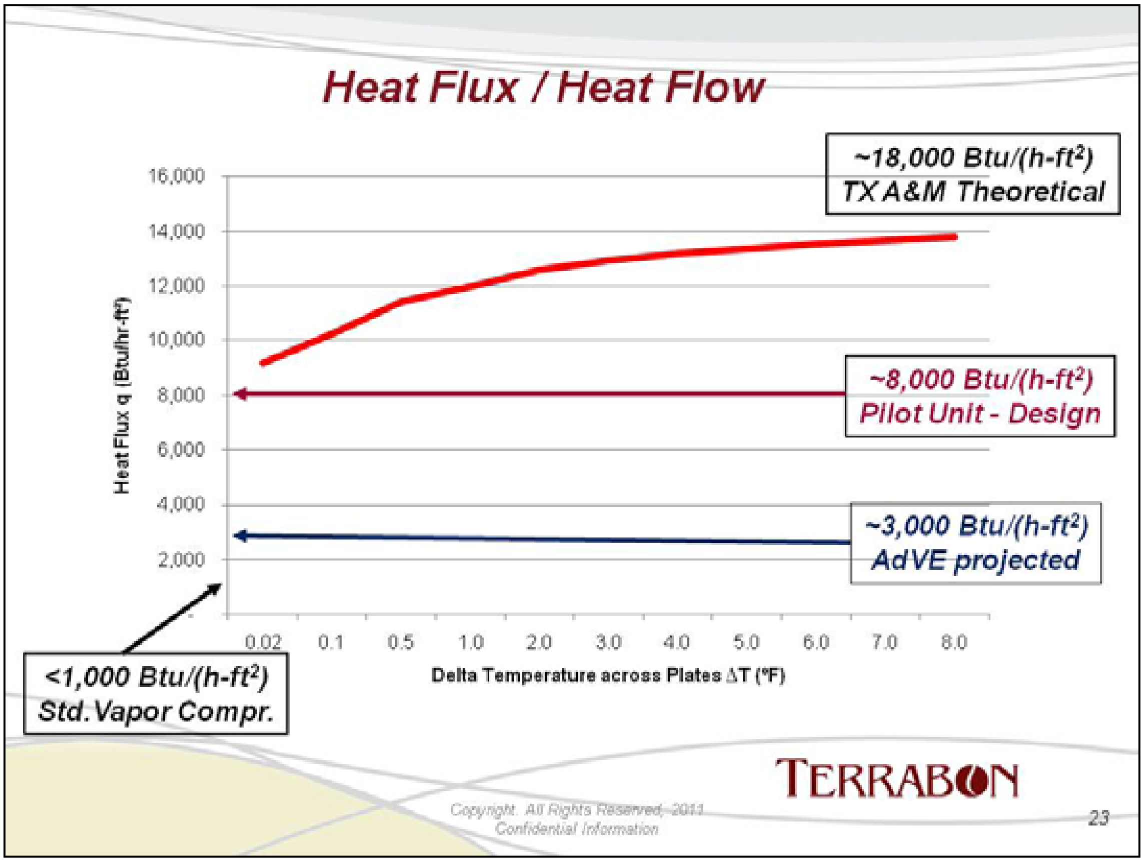

## Heat Flux / Heat Flow

~18,000 Btu/(h-ft²)
TX A&M Theoretical

~8,000 Btu/(h-ft²)
Pilot Unit - Design

~3,000 Btu/(h-ft²)
AdVE projected

<1,000 Btu/(h-ft²)
Std. Vapor Compr.

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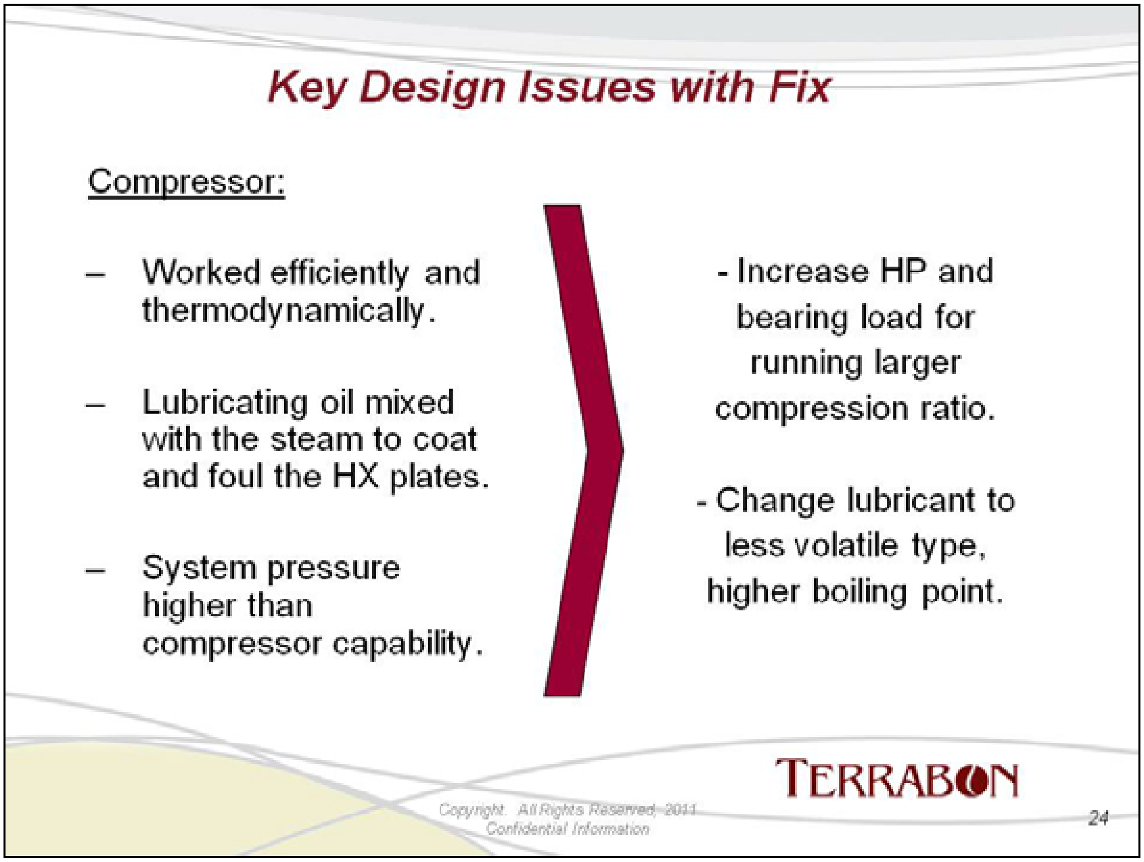

## Key Design Issues with Fix

Compressor:

- Worked efficiently and thermodynamically.
- Lubricating oil mixed with the steam to coat and foul the HX plates.
- System pressure higher than compressor capability.

- Increase HP and bearing load for running larger compression ratio.

- Change lubricant to less volatile type, higher boiling point.

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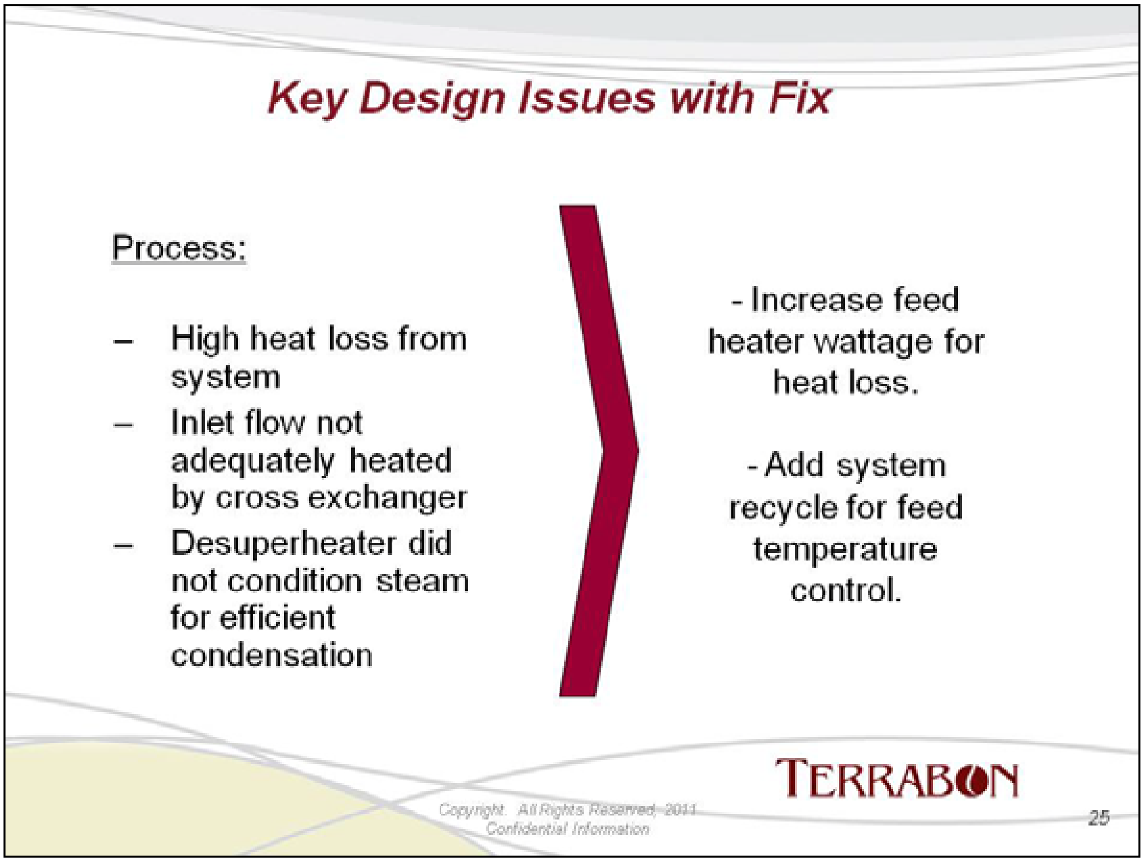

## Key Design Issues with Fix

Process:

- High heat loss from system
- Inlet flow not adequately heated by cross exchanger
- Desuperheater did not condition steam for efficient condensation

- Increase feed heater wattage for heat loss.

- Add system recycle for feed temperature control.

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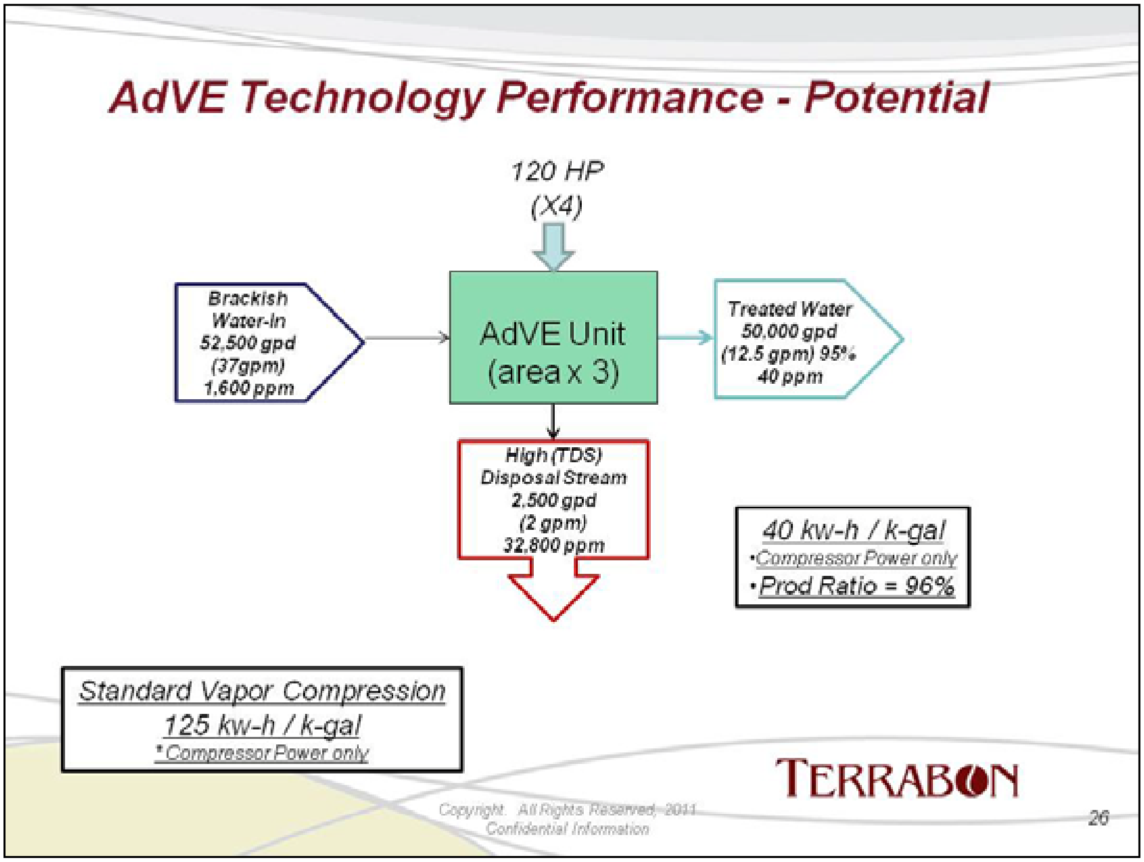

## AdVE Technology Performance - Potential

40 kw-h / k-gal
- Compressor Power only
- Prod Ratio = 96%

Standard Vapor Compression
125 kw-h / k-gal
* Compressor Power only

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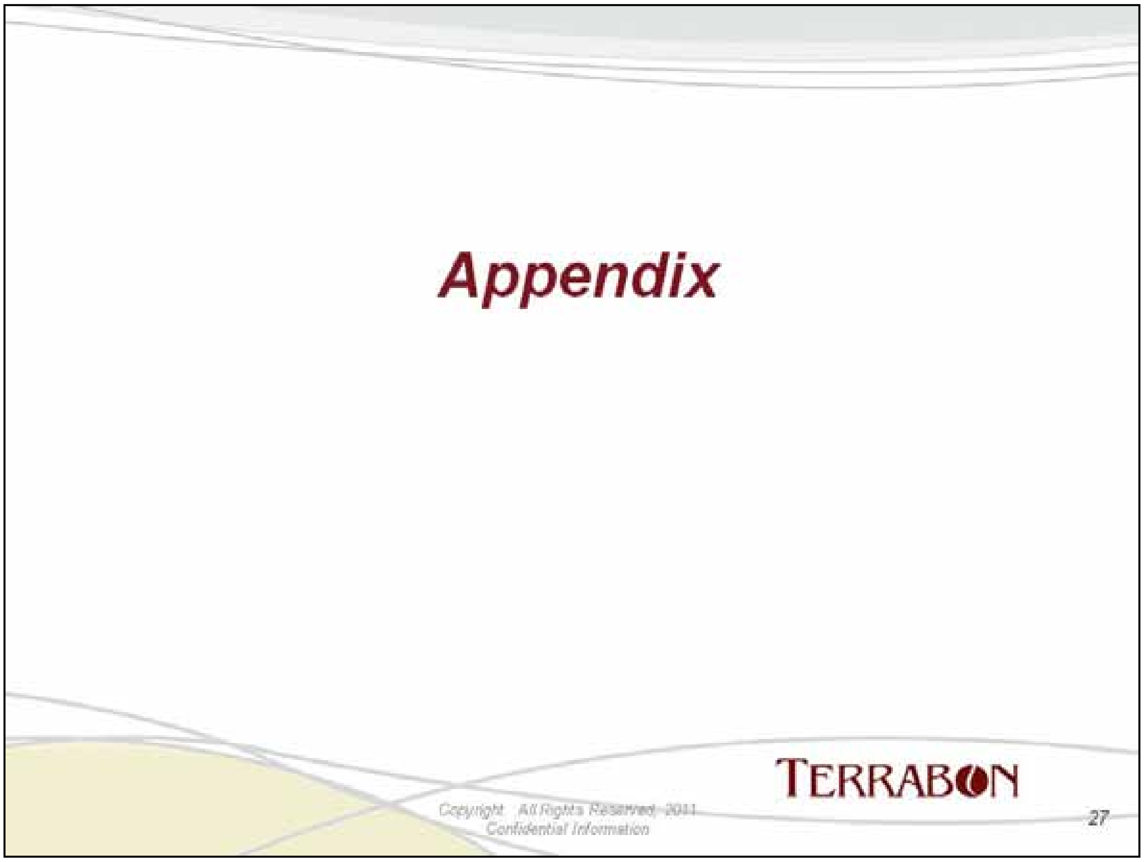

# Appendix

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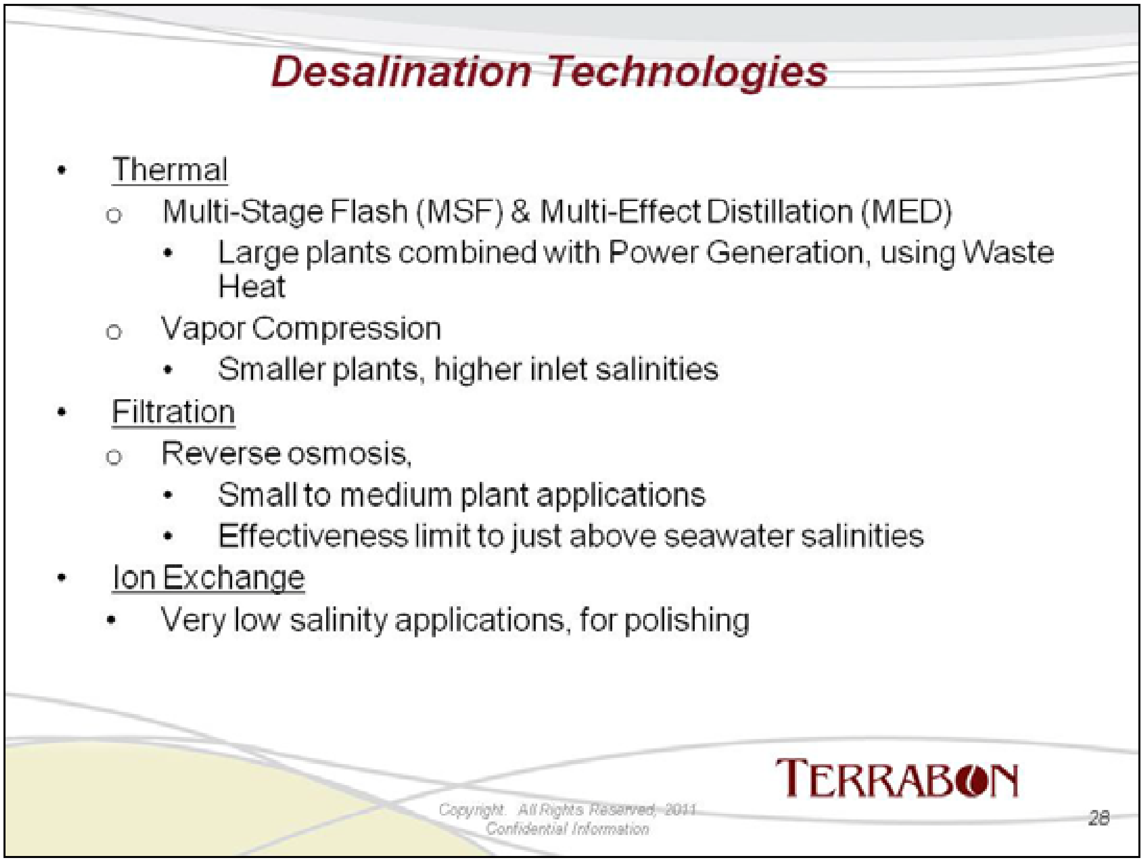

## Desalination Technologies

- Thermal
  - Multi-Stage Flash (MSF) & Multi-Effect Distillation (MED)
    - Large plants combined with Power Generation, using Waste Heat
  - Vapor Compression
    - Smaller plants, higher inlet salinities
- Filtration
  - Reverse osmosis,
    - Small to medium plant applications
    - Effectiveness limit to just above seawater salinities
- Ion Exchange
  - Very low salinity applications, for polishing

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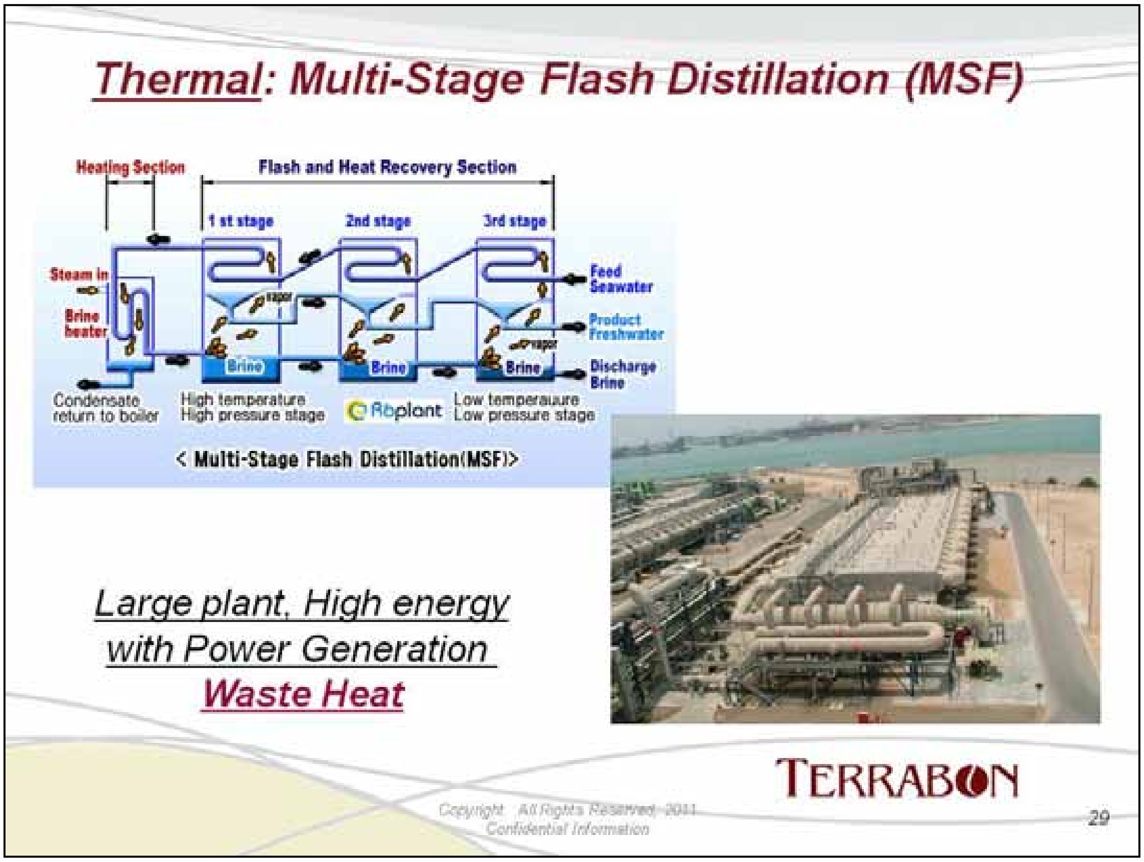

## *Thermal: Multi-Stage Flash Distillation (MSF)*

*Large plant, High energy*
*with Power Generation*
***Waste Heat***

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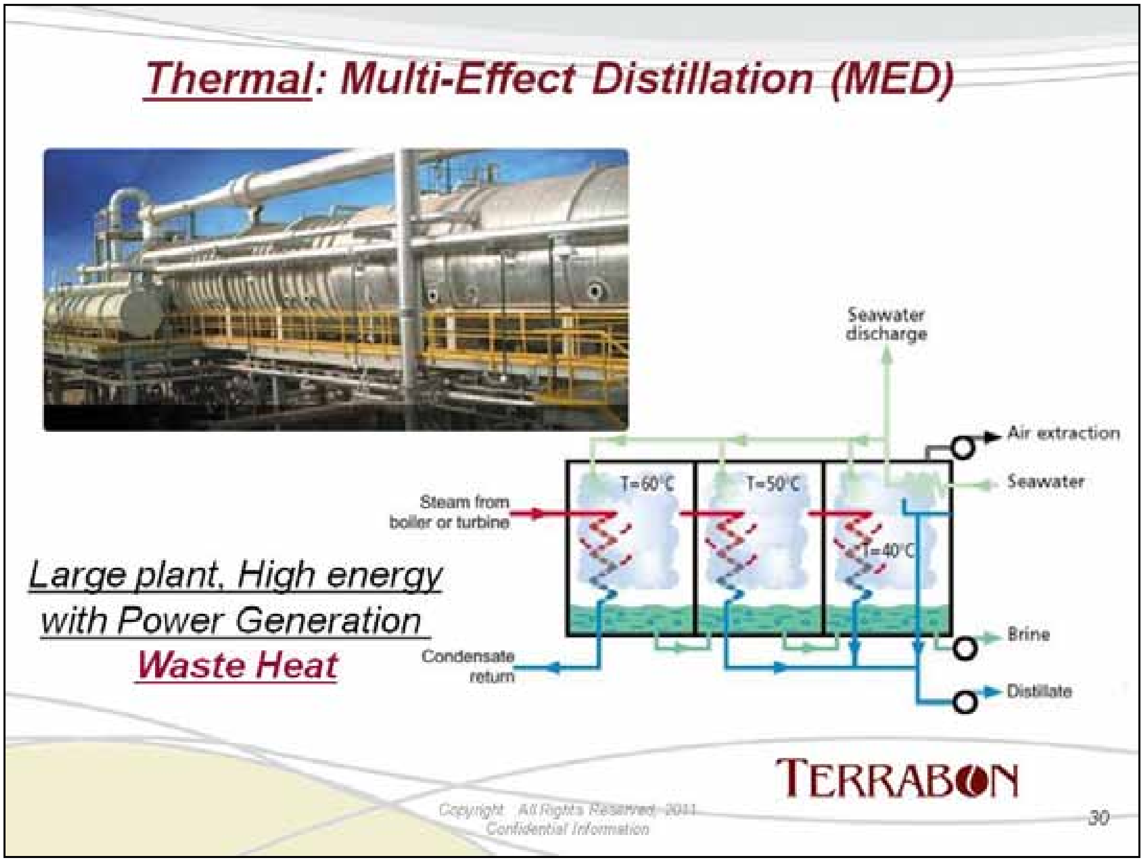

## *Thermal: Multi-Effect Distillation (MED)*

*Large plant, High energy*
*with Power Generation*
***Waste Heat***

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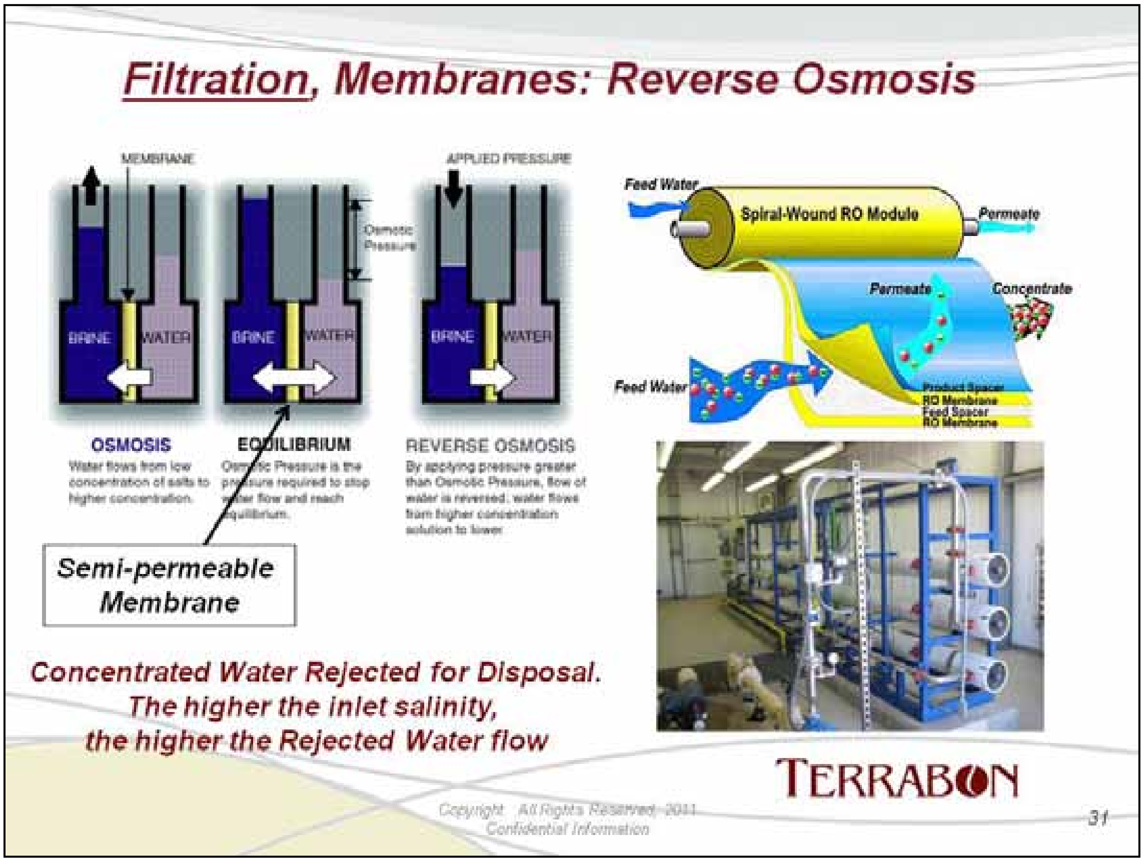


## *Filtration, Membranes: Reverse Osmosis*

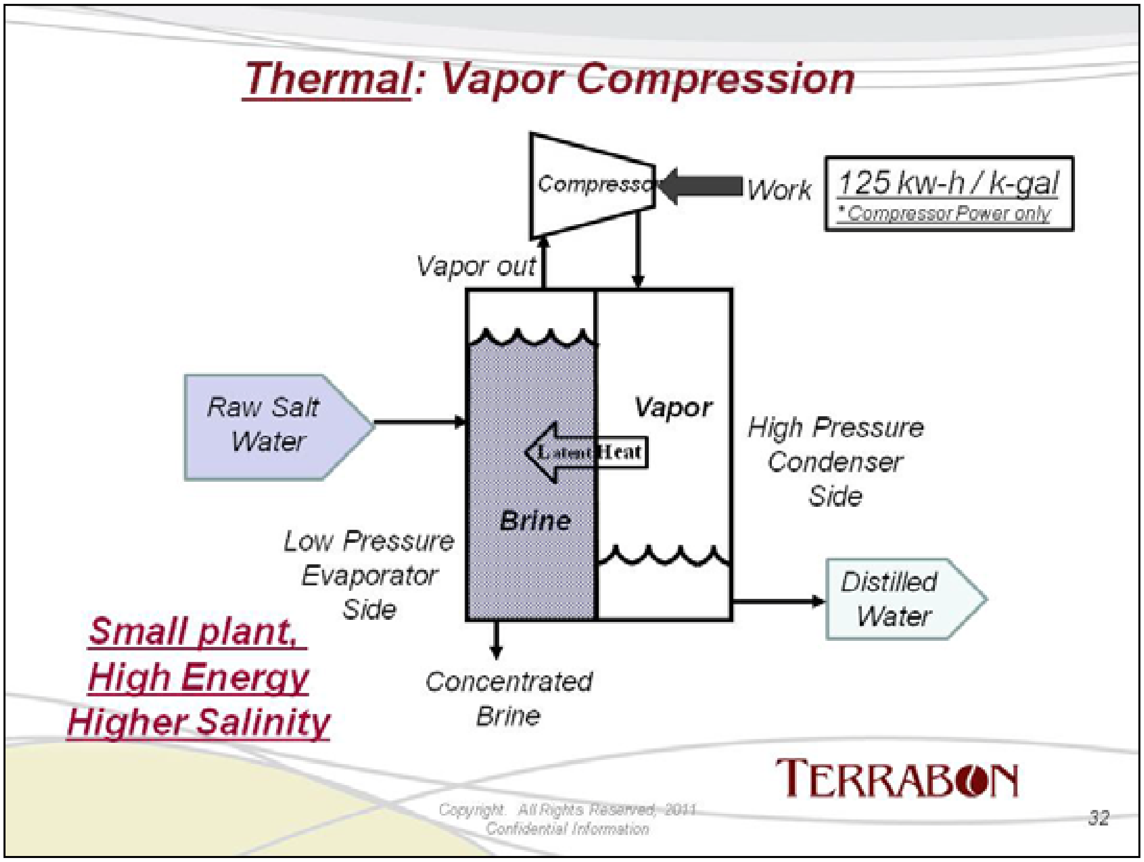
**OSMOSIS**
Water flows from low concentration of salts to higher concentration.

**EQUILIBRIUM**
Osmotic Pressure is the pressure required to stop water flow and reach equilibrium.

REVERSE OSMOSIS
By applying pressure greater than Osmotic Pressure, flow of water is reversed; water flows from higher concentration solution to lower

***Semi-permeable Membrane***

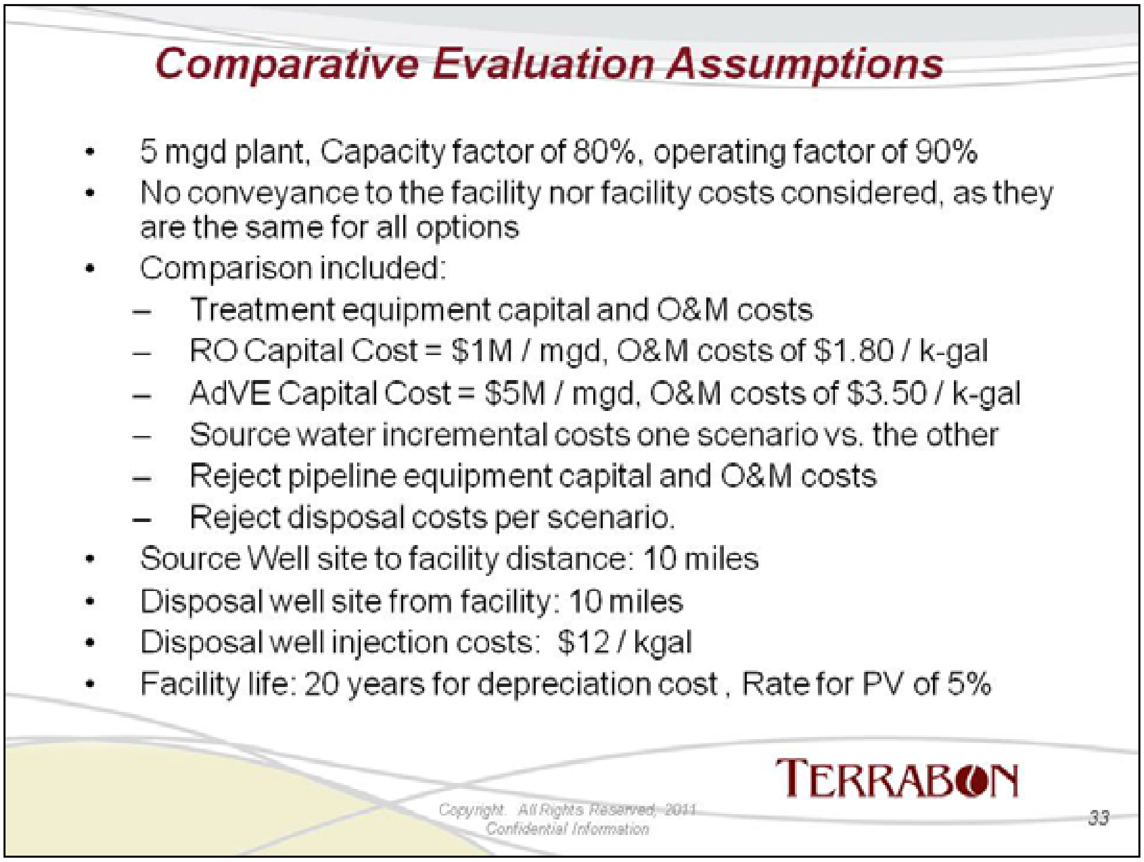
***Concentrated Water Rejected for Disposal.***
***The higher the inlet salinity,***
***the higher the Rejected Water flow***



## *Thermal: Vapor Compression*

125 kw-h / k-gal
*Compressor Power only

***Small plant,***
***High Energy***
***Higher Salinity***



## Comparative Evaluation Assumptions

- 5 mgd plant, Capacity factor of 80%, operating factor of 90%
- No conveyance to the facility nor facility costs considered, as they are the same for all options
- Comparison included:
  - Treatment equipment capital and O&M costs
  - RO Capital Cost = $1M / mgd, O&M costs of $1.80 / k-gal
  - AdVE Capital Cost = $5M / mgd, O&M costs of $3.50 / k-gal
  - Source water incremental costs one scenario vs. the other
  - Reject pipeline equipment capital and O&M costs
  - Reject disposal costs per scenario.
- Source Well site to facility distance: 10 miles
- Disposal well site from facility: 10 miles
- Disposal well injection costs: $12 / kgal
- Facility life: 20 years for depreciation cost , Rate for PV of 5%

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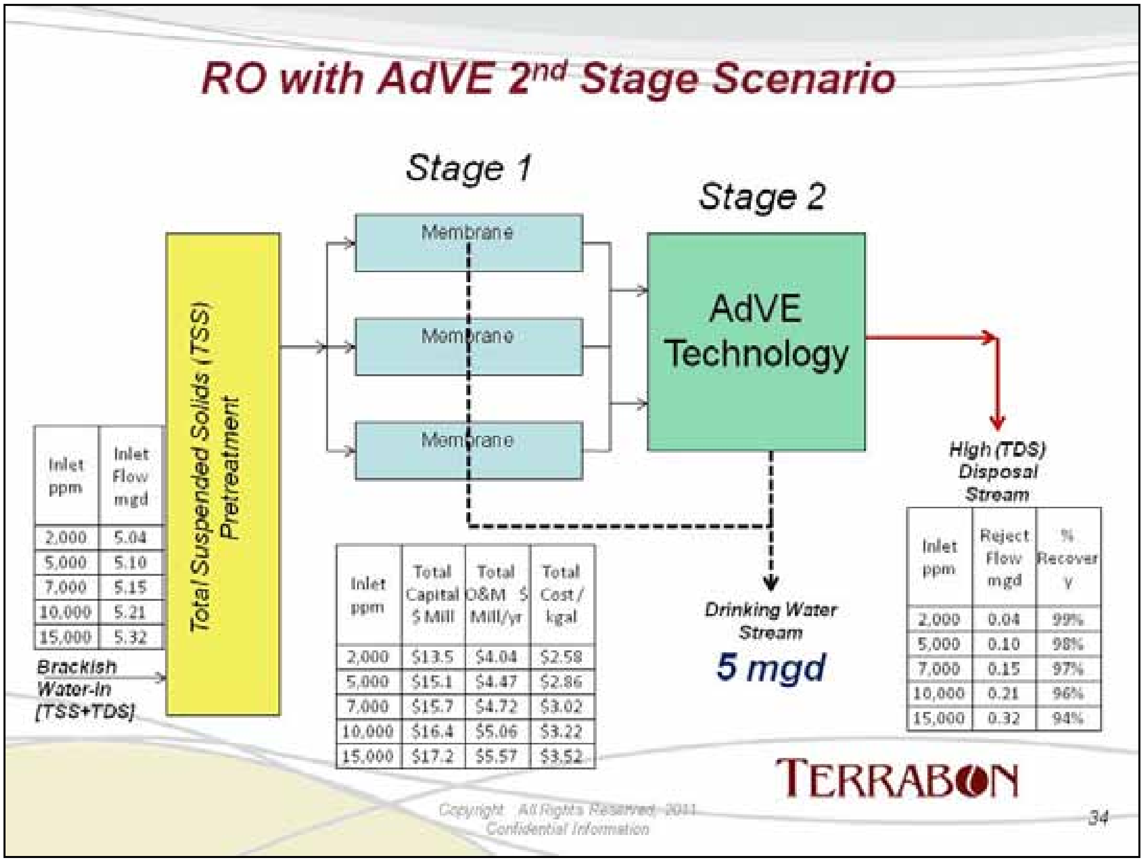

## RO with AdVE 2nd Stage Scenario

Stage 1

Stage 2

Membrane

Membrane

Membrane

AdVE Technology

Total Suspended Solids (TSS) Pretreatment

| Inlet ppm | Inlet Flow mgd |
|---|---|
| 2,000 | 5.04 |
| 5,000 | 5.10 |
| 7,000 | 5.15 |
| 10,000 | 5.21 |
| 15,000 | 5.32 |

*Brackish Water-In [TSS+TDS]*

| Inlet ppm | Total Capital $ Mill | Total O&M $ Mill/yr | Total Cost / kgal |
|---|---|---|---|
| 2,000 | $13.5 | $4.04 | $2.58 |
| 5,000 | $15.1 | $4.47 | $2.86 |
| 7,000 | $15.7 | $4.72 | $3.02 |
| 10,000 | $16.4 | $5.06 | $3.22 |
| 15,000 | $17.2 | $5.57 | $3.52 |

*Drinking Water Stream*

*5 mgd*

*High (TDS) Disposal Stream*

| Inlet ppm | Reject Flow mgd | % Recovery |
|---|---|---|
| 2,000 | 0.04 | 99% |
| 5,000 | 0.10 | 98% |
| 7,000 | 0.15 | 97% |
| 10,000 | 0.21 | 96% |
| 15,000 | 0.32 | 94% |

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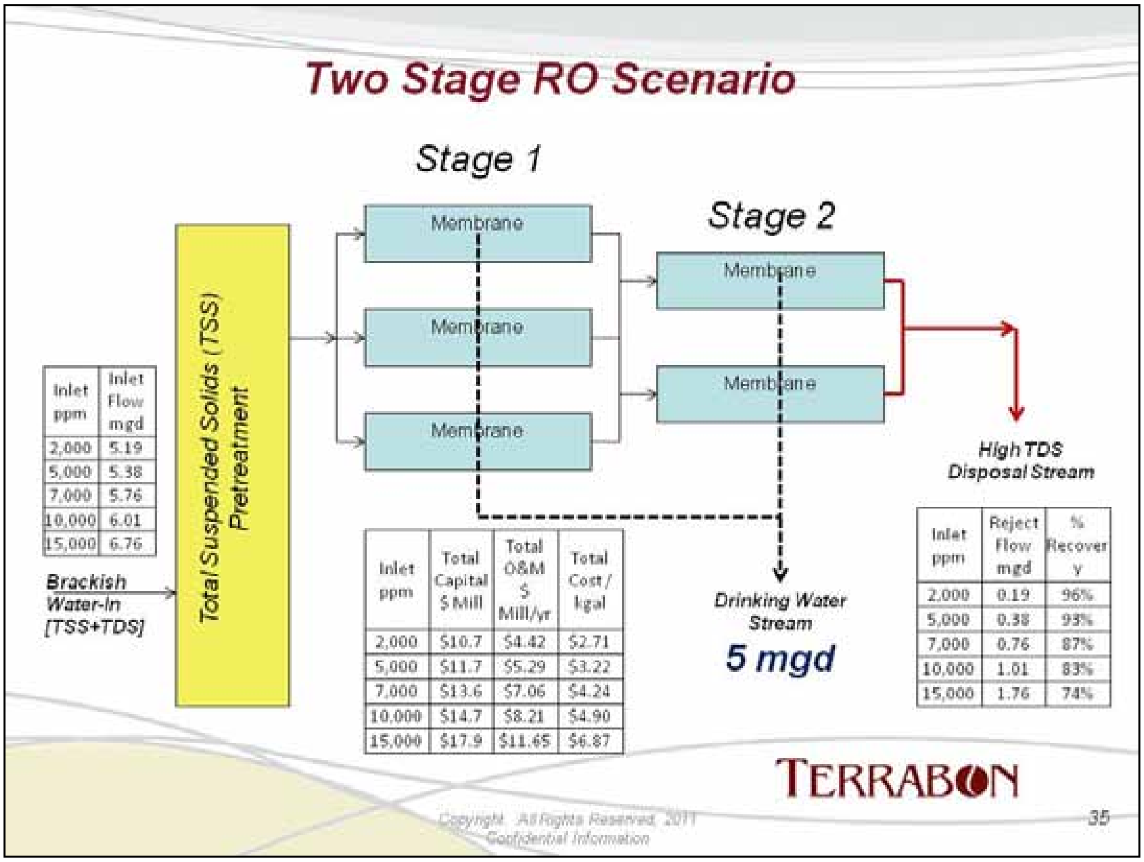

## Two Stage RO Scenario

| Inlet ppm | Inlet Flow mgd |
|---|---|
| 2,000 | 5.19 |
| 5,000 | 5.38 |
| 7,000 | 5.76 |
| 10,000 | 6.01 |
| 15,000 | 6.76 |

| Inlet ppm | Total Capital $ Mill | Total O&M $ Mill/yr | Total Cost / kgal |
|---|---|---|---|
| 2,000 | $10.7 | $4.42 | $2.71 |
| 5,000 | $11.7 | $5.29 | $3.22 |
| 7,000 | $13.6 | $7.06 | $4.24 |
| 10,000 | $14.7 | $8.21 | $4.90 |
| 15,000 | $17.9 | $11.65 | $6.87 |

| Inlet ppm | Reject Flow mgd | % Recovery |
|---|---|---|
| 2,000 | 0.19 | 96% |
| 5,000 | 0.38 | 93% |
| 7,000 | 0.76 | 87% |
| 10,000 | 1.01 | 83% |
| 15,000 | 1.76 | 74% |

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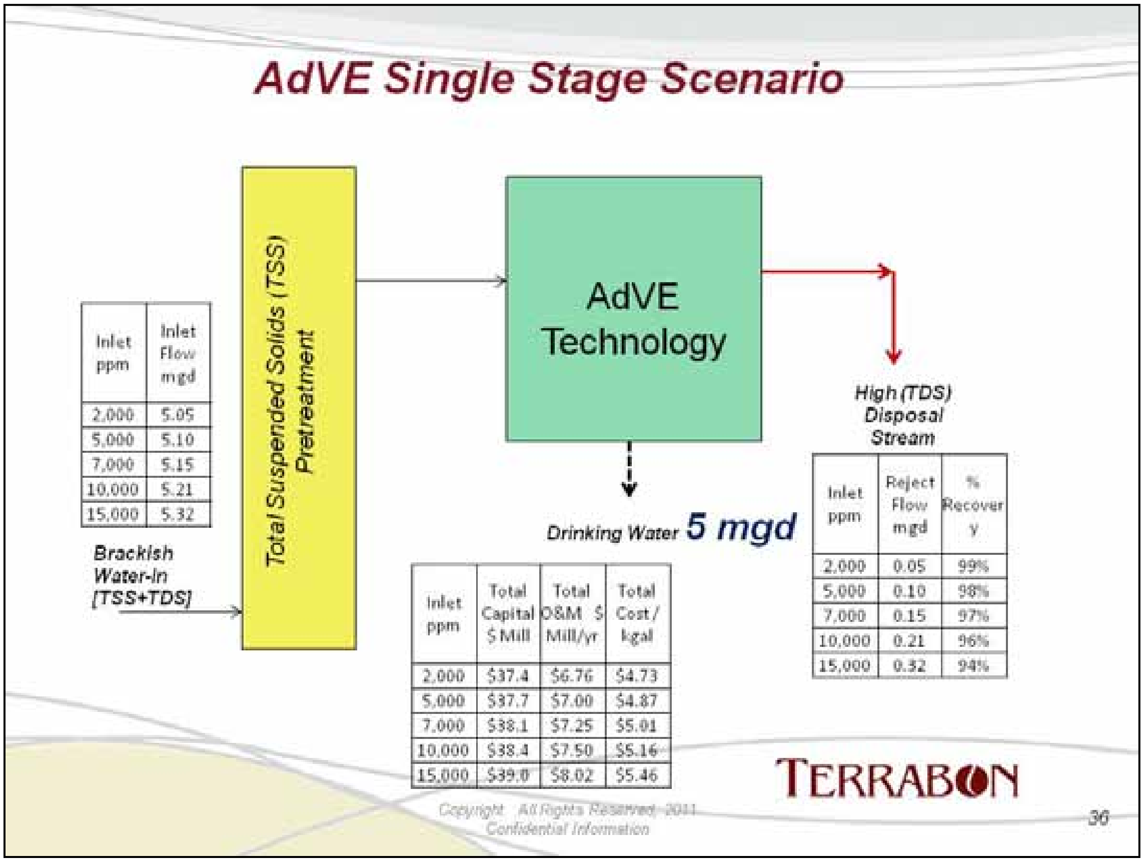

## AdVE Single Stage Scenario

| Inlet ppm | Inlet Flow mgd |
|---|---|
| 2,000 | 5.05 |
| 5,000 | 5.10 |
| 7,000 | 5.15 |
| 10,000 | 5.21 |
| 15,000 | 5.32 |

| Inlet ppm | Total Capital $ Mill | Total O&M $ Mill/yr | Total Cost / kgal |
|---|---|---|---|
| 2,000 | $37.4 | $6.76 | $4.73 |
| 5,000 | $37.7 | $7.00 | $4.87 |
| 7,000 | $38.1 | $7.25 | $5.01 |
| 10,000 | $38.4 | $7.50 | $5.16 |
| 15,000 | $39.0 | $8.02 | $5.46 |

| Inlet ppm | Reject Flow mgd | % Recovery |
|---|---|---|
| 2,000 | 0.05 | 99% |
| 5,000 | 0.10 | 98% |
| 7,000 | 0.15 | 97% |
| 10,000 | 0.21 | 96% |
| 15,000 | 0.32 | 94% |

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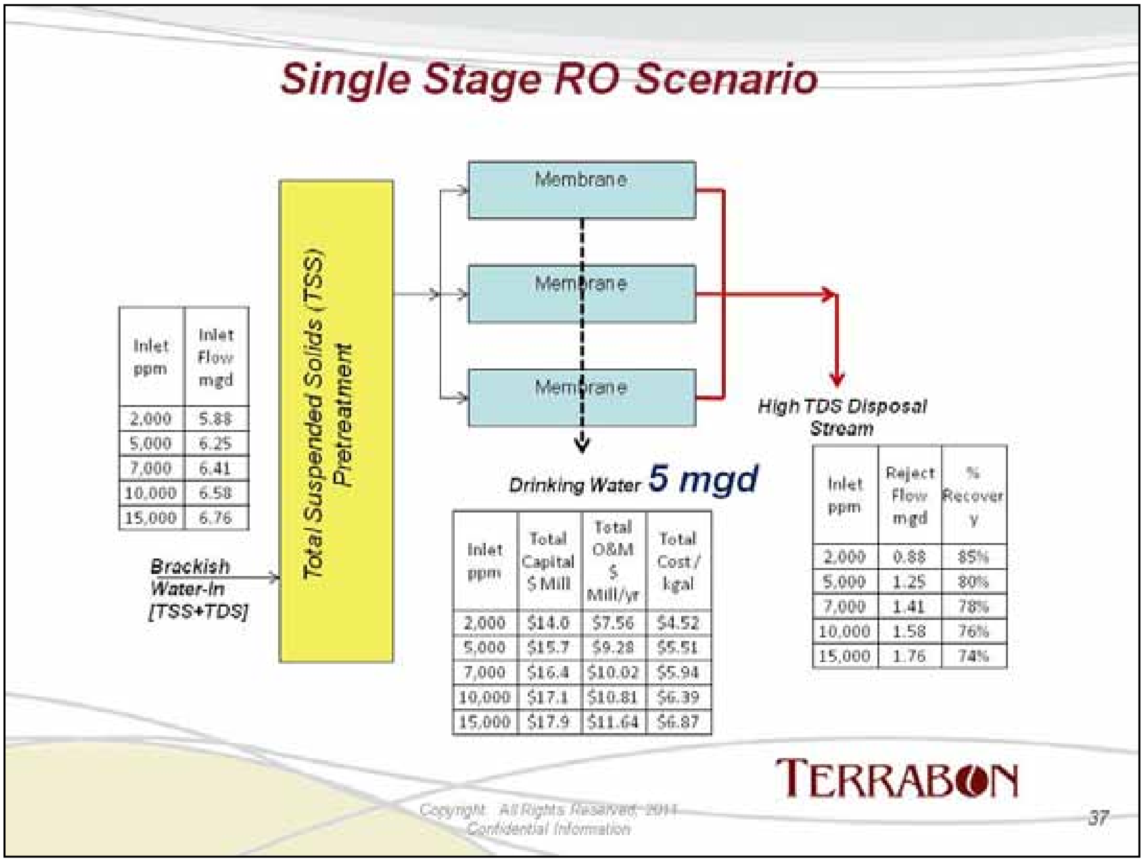

# Single Stage RO Scenario

| Inlet ppm | Inlet Flow mgd |
|---|---|
| 2,000 | 5.88 |
| 5,000 | 6.25 |
| 7,000 | 6.41 |
| 10,000 | 6.58 |
| 15,000 | 6.76 |

| Inlet ppm | Total Capital $ Mill | Total O&M $ Mill/yr | Total Cost / kgal |
|---|---|---|---|
| 2,000 | $14.0 | $7.56 | $4.52 |
| 5,000 | $15.7 | $9.28 | $5.51 |
| 7,000 | $16.4 | $10.02 | $5.94 |
| 10,000 | $17.1 | $10.81 | $6.39 |
| 15,000 | $17.9 | $11.64 | $6.87 |

| Inlet ppm | Reject Flow mgd | % Recovery |
|---|---|---|
| 2,000 | 0.88 | 85% |
| 5,000 | 1.25 | 80% |
| 7,000 | 1.41 | 78% |
| 10,000 | 1.58 | 76% |
| 15,000 | 1.76 | 74% |

# Appendix C

# TDS

**Emailed on**: August 3, 2017

**Sent from**: David Harkins to Philip Bullock, Brian Smith and Jeff Stovall

**Time**: 2:13 p.m.

**Contents**: TDS

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**In detail, the email read as follows**:

Hey Phil,

I just got off the phone with Gary and TDS. He indicated that they will be producing 18 MCF/well/yr at buildout in September 2018. That will include 118 gas wells. This will translate to 2.1 BCF/yr. They have 3 phases of the landfill Phase 1 (original), Phase 2 (current operations) and Phase 3 (future). They will also have a small phase 4 but it has more to do with a floodplain issue. I asked him about declining methane production in the older units and increasing in the existing units (as well as changes in methane %). He is checking into that.

Gary does not want to provide any written documentation as it is not finalized yet. However, he said that he is waiting on some information from AECOM related to the gas collection and chemistry. He is getting that today and will let us know. He also indicated that we could talk to the AECOM folks and will get us connected after he looks at the information he gets today. I will let you know if I hear anything tomorrow. Seems like we are starting to move in the right direction.

David K. Harkins, Ph.D., P.E.

Vice President

Texas Water Resources Lead

Carollo Engineers, Inc.

5316 Hwy 290 West | Suite 330

Austin, TX 78735

P: 512.453.5383 | F: 512.453.0101

C: 512.937.6586

www.carollo.com

**Emailed on**: August 17, 2017

**Sent from**: David Harkins to Philip Bullock and Rudy Kilian

**Time:** 2:49 p.m.

**Contents**: TDS/AECOM

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**In detail, the email read as follows**:

Gary Newton (one of the owners of TDS) finally got me the name of the AECOM folks that have worked for them on the gas production from the TDS site. So, I spoke to Bob Schafer yesterday with AECOM to try to get some additional information related to the gas generation and chemical makeup of the gas. Below is summary of the call yesterday:

We were given some "average" numbers for gas composition by Gary last week (55% methane, 39.4% Carbon Dioxide, and 1.14 Oxygen). These numbers were taken in the field from 13 wells with a Landpec GEM 5000 collection/sampling unit. AECOM says these results are reproducible on all wells and that those numbers seem reasonable for what is coming out of the units. Their first measurements were in 2014 and the later ones were in 2016 and 2017 and the composition was consistent.

Phase I of TDS is complete and producing gas. Phase II has started and will be having garbage deposited into the future. AECOM believes that there is significant gas production and that the gas production will continue to be at the same level and with similar chemistry.

There was an analytical sample taken to determine what additional treatment would be needed to convert the gas to energy. Here are some of the other parameters that the analytical samples identified:

**All units are in Mg/cubic meters**:

Hydrogen sulfide: 260

Trimethylsilanol :21

Hexamethyldisiloxane 4.8

Hexamethylcyclotrisiloxane : 0.35

Octamethylcyclotetrasiloxane : 0.050

Hopefully this will give us additional useful information. Let me know if you have any additional questions and I can pass those on....or Rudy you can call him directly.

# EXECUTIVE SUMMARY

URS Corporation (URS) prepared this report to document the installation and start-up of landfill gas (LFG) extraction wells, header piping, and condensate tanks to conduct a pilot-scale test for the purposes of projecting the potential LFG quantities that can be collected at the Texas Disposal Systems Landfill (TDSL). In 2013, URS designed a LFG collection system (LFGCS) to connect nine new LFG extraction wells to the existing six wells TDS previously installed in April 2005. The previously-existing blower and flare were utilized for the pilot study. The installation of the new system components began in October 2013. Construction was performed by American Environmental Group Ltd. (AEGL) from October 7 through October 30, 2013 under the supervision of URS. The system commissioning and testing program started in November 2013. Additional system modifications were subsequently designed by URS and constructed by AEGL during the week of April 1 through 5, 2014.

In April 2014, once the specified system modifications and pressure tests were completed under the supervision of URS, the system was started up. Vacuum and high flow rates were observed at all of the LFG extraction wells, LFG-1 to LFG-15. The exceptions were at LFG-12S and -12D. LFG-12D is the only LFG extraction well (dual-completion or single) located at an elevation lower than the nearby primary header. There are some condensate blockage issues related to the check valve of this well, resulting in variable static pressures and flow rates in both LFG-12S and -12D. System balancing, and adjustments intended to maximum flow rates from the 'target' evaluation wells, were performed through April 20th, at which point adequate information had been collected to estimate gas production at the TDSL. Based on these observations, the following key conclusions were made:

- LFG generation at study target well LFG-7 averaged nearly 40 standard cubic feet per minute (scfm) during Phase III of the pilot study. Conservatively, it could be assumed that in the long term, between 25 and 40 scfm of LFG could be collected by each well.
- The existing, 15-well system processed a range of approximately 500-550 scfm, with a power-generation capacity of 211,000 kilowatt hours (kWh) of energy produced each day. It is possible that with the blower operating at its maximum capacity (difficulties were noted during the pilot study), greater than 600 cfm could be generated.
- These LFG estimates are similar to those previously estimated by URS (URS, February 2013). URS estimated that the LFG generation across both inactive Cell 1 and the active Cell was about 3,700 cfm in 2013 while in 2028, LFG generation will be approximately 7,200 cfm. LFG generation is predicted to peak at 8,640 cfm in 2047 when the landfill is currently scheduled to close. Up to 576,000 kWh per day of energy could conceivably be generated at that time, though this figure should be considered very approximate and will vary if waste placement rates and composition changes in the future.

URS recommends that TDS consider the power generation capacity of Cell 1, and of the full landfill, and determine if they have potential uses for the energy that would justify the estimated costs. If TDS decides to proceed, URS recommends developing a full-scale design to install approximately 75 LFG wells in Cell 1, and to begin conceptual design work to expand the system to the other landfill cells.

# 1.0 INTRODUCTION

URS Corporation (URS) prepared this report to document the installation of landfill gas (LFG) extraction wells and header piping to conduct a pilot-scale startup test for the purposes of projecting the potential LFG quantities that can be collected at Cell 1, and throughout the landfill, both currently and in the future for the Texas Disposal Systems Landfill (TDSL). To conduct this test, the current LFG collection system (LFGCS) was augmented with the installation of additional LFG wells and header piping. The pre-existing LFGCS was installed in April 2005 for the purpose of mitigating LFG odors from this portion of the landfill. The LFGCS, including the newly installed components, is now composed of a total of 15 LFG extraction wells: six original wells and nine new wells. Of the new wells, five are dual completion wells, allowing LFG to be collected from specific and distinct intervals of the waste mass.

## 1.1 Facility Information

The TDSL is a 341.46-acre, Type I municipal solid waste (MSW) disposal facility located in southeastern Travis County at 3606 Farm-to-Market Road (FM) 1327, Creedmoor, Texas. The site is approximately 3 miles east of the intersection of Interstate 35 and State Highway 45, as shown on Figure 1: Site Location Map. The approximate geographic coordinates of the site entrance gate are N 30.102403, E -97.7604038. The LFGCS was installed in Cell 1 located in the southwestern portion of the landfill property. The general site layout is shown on Figure 2.

## 1.2 Facility Background

### 1.2.1 Facility Description

According to MSW Permit Number 2123, the TDSL has an expected life of 55 years. Based on the year it opened, in 1991, and the then projected annual waste disposal rate the landfill would be expected to close in 2046. TDS describes the characterization of the range and type of solid wastes accepted by the TDSL, to date, as follows:

- Commercial wastes estimated at 83% to 85% of actual tonnage.
- Residential wastes and compostable materials estimated at 5% to 8% of actual tonnage.
- Industrial wastes (Classes II and III) estimated at 8% to 10% of actual tonnage.
- Special wastes estimated at 0% to 1% of actual tonnage.

Operations at the TDSL include the landfill disposal area and ancillary facilities, which include entry control point and scale house, material processing facility, collection and flaring of LFG, surface impoundments for landfill leachate collection and storm water, truck wheel washing station, citizen's drop-off and recycling area, fuel loading and unloading station, a 10,000-gallon steel aboveground storage tank storing diesel fuel for use in non-road equipment, and composting operations. Municipal solid waste is brought to the TDSL via garbage truck, spread in layers, and compacted with heavy equipment. Soil cover is spread over the compacted waste at least weekly to prevent wind-blown trash and to protect the trash from scavengers and vectors.

The landfill bottom liner was constructed of highly recompacted native, high plasticity clay materials to provide an impermeable barrier to leachate and LFG migration from the landfill. Currently the cell is inactive except for occasional placement of asbestos-containing waste, and has an intermediate cover, consisting mainly of compacted high plasticity clay in excess of three feet. Topsoil has been placed on some of the side slopes with natural vegetation growth. Once the landfill cell is closed, it will be covered with an impermeable "cap" or "final cover" expected to be composed of various combinations of compacted native clay a vegetative soil layer, and cover vegetation to control the incursion of precipitation, the erosion of the cover, and the release of LFG and thus odors from the landfill.

Methane ($CH_4$) and carbon dioxide ($CO_2$) are the primary constituents of LFG and are produced by microorganisms within the landfill under anaerobic conditions. Typically, LFG also contains non-methane organic compounds (NMOCs) and volatile organic compounds (VOCs). NMOCs result from either decomposition byproducts or volatilization of biodegradable wastes. This NMOC fraction often contains various organic hazardous air pollutants (HAPs), greenhouse gases (GHGs), compounds associated with stratospheric ozone depletion, and VOCs. Regulations require that Best Demonstrated Technology (BDT) be used to reduce MSW landfill emissions from affected new and existing MSW landfills if the landfill has a design capacity of 2.5 MMg and 2.5 $Mm^3$ or more, and the calculated uncontrolled emissions from the landfill are greater than or equal to 50 Mg/yr of NMOCs. The TDSL capacity is greater than 2.5 MMg and 2.5 $Mm^3$. Based on calculations using actual data through 2013 and future projections through the life of the landfill, the TDSL is expected to produce less than 50 tons of NMOCs per year until 2015. Therefore, additional control technology is not required for the TDSL at the time of this submittal. TDS has, however, voluntarily put a flare in place which is authorized under TCEQ Air Quality Registration No. 75762.

# Appendix D

# NEWGEN

# Summary of Costs

Schedule 1
2.5 MGD

| | Capital | | | | Total | O&M ($/YR) | | | | Total | Power Options ($/YR) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Equipment | Pipeline | Pump Stations | Wells | Capital | Pump Station O&M | Pipeline O&M | Equipment O&M | Full-time Personnel | O&M | Traditional Energy ($.10 per kW-hr) | Renewable Energy ($.11 per kW-hr) | Methane Gas Energy (No Cost)[4] |
| **Desalination System (RO with Boron Removal)[1]** | $41,500,000 | $0 | $0 | $0 | 41,500,000 | $0 | $0 | $2,350,000 | $0 | 2,350,000 | $1,350,000 | $1,485,000 | $0 |
| **Landfill Gas Combined Heat and Power** | N/A | N/A | N/A | N/A | $27,417,713 [2] | N/A | N/A | N/A | N/A | $115,000 [2] | | | |
| **Desalination System + LF Gas Combined Heat & Power[3]** | | | | | $68,917,713 | | | | | $2,465,000 | N/A | N/A | $0 |
| **Wellfield** | 450,000 | 1,230,000 | - | 5,279,560 | 6,959,560 | - | 8,870 | 52,796 | - | 61,666 | $294,336 | $323,770 | $0 |
| **ASR Wells, Wellheads, and Wellfield Piping** | - | - | - | - | 3,687,120 [2] | - | - | 55,307 | - | 55,307 | $32,400 | $35,640 | $0 |
| **Concentrate Disposal Alternatives** | | | | | | | | | | | | | |
| Zero Liquid Discharge | 40,000,000 | - | - | - | 40,000,000 | - | - | 1,200,000 | 150,000 | 1,350,000 | $3,547,800 | $3,902,580 | N/A |
| Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County | - | 26,161,091 | 5,774,420 | - | 31,935,510 | 104,609 | 189,573 | - | - | 294,182 | $176,500 | $194,150 | N/A |
| Trinity Injection Wells on TDS Property | - | 1,189,140 | 4,330,815 | 5,000,000 | 10,519,955 | 78,457 | 8,617 | - | - | 87,074 | $104,500 | $114,950 | $0 |
| Edwards Injection Wells in Caldwell County | - | 7,694,438 | 4,330,815 | 5,000,000 | 17,025,253 | $78,457 | $55,757 | $0 | $0 | 134,214 | $125,000 | $137,500 | N/A |

**Notes:**

1. Costs associated with desalination system not powered by landfill gas CHP.
2. Costs were provided on a total basis.
3. Total projected cost for the desalination system powered by landfill gas CHP.
4. Per Carollo, analysis assumes a zero reimbursement to TDS for methane.

Schedule 2
5.0 MGD

## Summary of Costs

| | Capital | | | | Total | O&M ($/YR) | | | | Total | Power Options ($/YR) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Equipment | Pipeline | Pump Stations | Wells | Capital | Pump Station O&M | Pipeline O&M | Equipment O&M | Full-time Personnel | O&M | Traditional Energy ($.10 per kW-hr) | Renewable Energy ($.11 per kW-hr) | Methane Gas Energy (No Cost)[4] |
| **Desalination System (RO with Boron Removal)**[1] | $60,200,000 | $0 | $0 | $0 | 60,200,000 | $0 | $0 | $3,600,000 | $0 | 3,600,000 | $2,700,000 | $2,970,000 | $0 |
| **Landfill Gas Combined Heat and Power** | N/A | N/A | N/A | N/A | $54,175,427 [2] | N/A | N/A | N/A | N/A | $230,000 [2] | | | |
| **Desalination System + LF Gas Combined Heat & Power**[3] | | | | | $114,375,427 | | | | | $3,830,000 | N/A | N/A | $0 |
| **Wellfield** | 450,000 | 1,230,000 | - | 5,279,560 | 6,959,560 | - | 8,870 | 52,796 | - | 61,666 | $588,672 | $647,539 | $0 |
| **ASR Wells, Wellheads, and Wellfield Piping** | - | - | - | - | 7,076,160 [2] | - | - | 110,000 | - | 110,000 | $97,200 | $106,920 | $0 |
| **Concentrate Disposal Alternatives** | | | | | | | | | | | | | |
| Zero Liquid Discharge | 60,000,000 | - | - | - | 60,000,000 | - | - | 1,800,000 | 150,000 | 1,950,000 | $7,095,600 | $7,805,160 | N/A |
| Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County | - | 26,161,091 | 8,749,121 | - | 34,910,211 | 158,499 | 189,573 | - | - | 348,072 | $353,000 | $388,300 | N/A |
| Trinity Injection Wells on TDS Property | - | 1,189,140 | 6,561,841 | 10,000,000 | 17,750,981 | 118,874 | 8,617 | - | - | 127,491 | $209,000 | $229,900 | $0 |
| Edwards Injection Wells in Caldwell County | - | 7,694,438 | 6,561,841 | 10,000,000 | 24,256,279 | $118,874 | $55,757 | $0 | $0 | 174,631 | $250,000 | $275,000 | N/A |

**Notes:**

1. Costs associated with desalination system not powered by landfill gas CHP.
2. Costs were provided on a total basis.
3. Total projected cost for the desalination system powered by landfill gas CHP.
4. Per Carollo, analysis assumes a zero reimbursement to TDS for methane.

Schedule 3
2.5 MGD

# Cost per 1,000 Gallons in 2017

| Facility: | *Scenario A*<br>**Desalination System without LF Gas CHP Facility** | *Scenario B*<br>**Desalination System without LF Gas CHP Facility** | *Scenario C*<br>**Desalination System without LF Gas CHP Facility** | *Scenario D*<br>**Desalination System with LF Gas CHP Facility** | *Scenario E*<br>**Desalination System with LF Gas CHP Facility** |
|---|---|---|---|---|---|
| Disposal Concentrate: | **Trinity Injection Wells on TDS Property (Alternative 3)** | **Edwards Injection Wells in Caldwell County (Alternative 4)** | **Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County (Alternative 2)** | **Trinity Injection Wells on TDS Property (Alternative 3)** | **Zero Liquid Discharge (Alternative 1)** |
| Power Source: | **Traditional ($.10 per kW-hr)** | **Traditional ($.10 per kW-hr)** | **Renewable ($.11 per kW-hr)** | **Methane** | **Methane/Traditional ($.10 per kW-hr)[1]** |
| <u>**Capital**</u> | | | | | |
| Principal | $1,077,936 | $1,196,830 | $1,469,336 | $1,579,034 | $2,117,825 |
| Interest | 2,254,339 | $2,502,988 | $3,072,894 | $3,302,311 | $4,429,109 |
| **Total P&I** | $3,332,275 | $3,699,817 | $4,542,230 | $4,881,345 | $6,546,934 |
| <u>**Non-Capital Expenses**</u> | | | | | |
| O&M | $2,498,740 | $2,545,880 | $2,705,848 | $2,613,740 | $3,876,666 |
| Power | 1,748,836 | 1,769,336 | 2,002,920 | - | 3,547,800 |
| Total Variable Expenses | $4,247,576 | $4,315,216 | $4,708,768 | $2,613,740 | $7,424,466 |
| **Total** | $7,579,851 | $8,015,033 | $9,250,997 | $7,495,084 | $13,971,400 |
| Total Gallons | 912,500,000 | 912,500,000 | 912,500,000 | 912,500,000 | 912,500,000 |
| $ per 1,000 Gallons in Year 1 | $8.31 | $8.78 | $10.14 | $8.21 | $15.31 |

Notes:

1. Traditional power is assumed for the zero liquid discharge alternative, as it is not able to be powered by the landfill gas combined heat and power facility.

Schedule 4
5.0 MGD

## Cost per 1,000 Gallons in 2017

| | *Scenario A* | *Scenario B* | *Scenario C* | *Scenario D* | *Scenario E* |
|---|---|---|---|---|---|
| Facility: | **Desalination System without LF Gas CHP Facility** | **Desalination System without LF Gas CHP Facility** | **Desalination System without LF Gas CHP Facility** | **Desalination System with LF Gas CHP Facility** | **Desalination System with LF Gas CHP Facility** |
| Disposal Concentrate: | **Trinity Injection Wells on TDS Property (Alternative 3)** | **Edwards Injection Wells in Caldwell County (Alternative 4)** | **Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County (Alternative 2)** | **Trinity Injection Wells on TDS Property (Alternative 3)** | **Zero Liquid Discharge (Alternative 1)** |
| Power Source: | **Traditional ($.10 per kW-hr)** | **Traditional ($.10 per kW-hr)** | **Renewable ($.11 per kW-hr)** | **Methane** | **Methane/Traditional ($.10 per kW-hr)[1]** |
| **Capital** | | | | | |
| Principal | $1,551,863 | $1,670,757 | $1,865,473 | $2,541,997 | $3,314,159 |
| Interest | 3,245,486 | $3,494,134 | $3,901,353 | $5,316,201 | $6,931,061 |
| **Total P&I** | $4,797,349 | $5,164,891 | $5,766,826 | $7,858,198 | $10,245,220 |
| **Non-Capital Expenses** | | | | | |
| O&M | $3,789,157 | $3,836,297 | $4,009,738 | $4,019,157 | $5,841,666 |
| Power | 3,497,672 | 3,538,672 | 4,005,839 | - | 7,095,600 |
| Total Variable Expenses | $7,286,829 | $7,374,969 | $8,015,577 | $4,019,157 | $12,937,266 |
| **Total** | $12,084,177 | $12,539,859 | $13,782,402 | $11,877,355 | $23,182,486 |
| Total Gallons | 1,825,000,000 | 1,825,000,000 | 1,825,000,000 | 1,825,000,000 | 1,825,000,000 |
| $ per 1,000 Gallons in Year 1 | $6.62 | $6.87 | $7.55 | $6.51 | $12.70 |

Notes:

1. Traditional power is assumed for the zero liquid discharge alternative, as it is not able to be powered by the landfill gas combined heat and power facility.

Appendix E

# BSEACD HYDROGEOLOGY REPORT

# Hydrogeology of the Saline Edwards Zone, Southeast Travis County, Central Texas

BSEACD Report of Investigations 2017-1015
October 2017

**Barton Springs/Edwards Aquifer Conservation District**
**1124 Regal Row**
**Austin, Texas**

**Disclaimer**

All of the information provided in this report is believed to be accurate and reliable; however, the Barton Springs/Edwards Aquifer Conservation District and the authors assume no liability for any errors or for the use of the information provided.

*This report documents data collection, evaluation, and interpretation performed by geoscientists licensed by the Texas Board of Professional Geoscientists (TBPG).*

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16-October-2017

*Cover Page: Drilling of saline Edwards multiport well and pond with produced waters. Photograph taken August 2016.*

# Hydrogeology of the Saline Edwards Zone, Southeast Travis County, Central Texas

**Brian A. Smith, Ph.D., P.G., and Brian B. Hunt, P.G.**
Barton Springs/Edwards Aquifer Conservation District

**Bruce Darling, Ph.D., P.G.**
Groundwater & Geochemical Consulting, LLC

BSEACD Report of Investigations 2017-1015
October 2017

**Barton Springs/Edwards Aquifer Conservation District**
**1124 Regal Row**
**Austin, Texas**

# Contents

*Aerial photograph of the multiport well (right side) and the water-holding tanks containing all produced water. Photo taken 11/2/2016.*

# Hydrogeology of the Saline Edwards Zone, Southeast Travis County, Central Texas

**Brian A. Smith, Ph.D., P.G., and Brian B. Hunt, P.G.**
Barton Springs/Edwards Aquifer Conservation District

**Bruce Darling, Ph.D., P.G.**
Groundwater & Geochemical Consulting, LLC

## Summary

Increased demand for water in central Texas is causing water users and providers to look for additional sources of water. The saline portion of the Edwards Aquifer (saline Edwards Aquifer) has often been mentioned as a source of water for desalination or aquifer storage and recovery (ASR). The resource has not previously been considered by large water suppliers because of limitations of data, regulatory framework, and fear of saline encroachment into the freshwater Edwards. Recent legislative efforts combined with hydrogeologic and engineering studies have renewed interest in the saline Edwards Aquifer.

This report documents a hydrogeologic study conducted by the Barton Springs/Edwards Aquifer Conservation District (District) of the saline Edwards Aquifer in southeastern Travis County providing baseline information for an engineering study of desalinization and ASR. This hydrogeologic study is part of an engineering study is conducted by Carollo Engineers, Inc. and is partially funded by a Texas Water Development Board (TWDB) regional facility planning grant and the District.

In August 2016, a multiport monitor well was installed to a depth of 1,100 ft through the entire saline Edwards Aquifer with 18 permanently isolated zones from which head, water chemistry, and permeability data can be collected. Four zones were completed in the units overlying the Edwards Group and 14 zones were completed within the Edwards and associated units. Data collected in the multiport well allow for the detailed hydrogeologic characterization of the various units.

### *Hydrostratigraphy*

Drilling properties, cuttings, geophysical logs, and multiport well data help to describe the hydrostratigraphy of the saline Edwards Aquifer. Data indicate confining units above the saline Edwards Aquifer include the overlying Taylor Clay, Austin Chalk, Eagle Ford (Zone 18), Buda (Zone 17), Del Rio Clay (Zone 16), and the Georgetown Formation (Zone 15). The top of the Edwards Group is at a depth of 564 ft from the surface. The saline Edwards Aquifer is defined in this study to include the Person Formation (Zones 12-14, 111 ft thick), Kainer Formation (Zones 3-11, 340 ft thick), and the top of the Upper Glen Rose (Zones 1 and 2; 75 ft thick). Zone 12 at the base of the Person Formation is the regional dense member (RDM, 22 ft thick) and appears to be an aquitard separating the Person and Kainer Formations. The Walnut Formation (Zone 3, 42 ft thick; aka Basal Nodular Member) has relatively low permeabililty and may also be an aquitard between the Edwards Group and the top of the Upper Glen Rose units.

### *Head values*

Depth to water from land surface in the Edwards zones varied from 36 to 38 ft after conversion to freshwater equivalents. The highest heads within the Edwards are within the Kainer Formation (Zones 4-11) which are about 2 ft higher than the overlying Person Formation (Zones 12-14). This vertical distribution of heads appears to be similar to the data presented in the Kyle transect wells to the south (Thomas et al., 2010). Lateral gradients indicate that heads in the saline zone are generally higher than in the freshwater Edwards, especially during drought conditions. This suggest that the flow potential is from the saline zone in the east to the freshwater zone in the west. During wet periods there is potential for the gradient to reverse. However, there is a time lag in head changes between the saline and freshwater Edwards.

### *Permeability*

Slug testing data indicate transmissivity values range over orders of magnitude between 0.02 and 15,000 ft$^2$/day in the saline Edwards units. Cuttings and thin sections indicate the majority of the Edwards Group from the borehole to be dolomite or dolomitic in composition and contain a high degree of intercrystalline and moldic porosity. Estimates of well yield in this study indicate the Person Formation (Zones 14 and 13; 79 ft thick; 2,470 ft$^2$/d) and Kainer Formation (Zones 4-11; 271 ft thick, 7,140 ft$^2$/d) could have well yields greater than 1,300 gallons per minute (gpm) and 4,300 gpm, respectively.

### *Geochemistry*

Geochemical data compiled for this investigation illustrate that the composition of groundwater from hydrostratigraphic zones 1 to 11, 13 and 14 is a sodium-chloride type water, with variable concentrations of total dissolved solids. TDS increases from 13,000 mg/L in the Upper Glen Rose (Zone 2, -1,025 ft) to 18,500 mg/L in the Kainer formation (Zone 6, -855 ft) and decreases to 13,500 mg/L at the top of the Kainer (Zone 11, -685 ft). Above the Regional Dense Member aquitard (Zone 12), TDS is less than 9,400 mg/L in the Person formation (Zones 13 and 14, -615 ft and -575 ft, respectively). Although the origin of salinity remains unknown, the geochemical data appear to allow for the elimination of at least two potential sources of salinity: seawater (or residual seawater) and halite dissolution.

Results from this hydrogeologic study indicate that the saline Edwards Aquifer can serve as a source of water for a desalination facility and as a reservoir for ASR.

## Introduction

The saline portion of the Edwards Aquifer (saline Edwards Aquifer) has often been mentioned as a source of water for desalination or aquifer storage and recovery (ASR). However, because of limitations of data, the regulatory framework, and potential costs, the resource has not been considered by water suppliers. The Barton Spring/Edwards Aquifer Conservation District (District) has developed rules to encourage desalinization and ASR projects within the saline Edwards. Furthermore, Senate Bill 1532, passed in2013, allowed specific pilot testing for the feasibility of these projects.

In 2015, the District was awarded a regional facility planning grant (TWDB Grant No. 1548321870) to study the feasibility of ASR and desalinization for the saline Edwards Aquifer. A kickoff meeting with stakeholders was held on February 25, 2016. Participants in the study include Texas Disposal Systems, Texas State University, Creedmoor-Maha Water Corporation, cities of Kyle, Buda, and San Marcos, and Hays and Travis Counties. The main subcontractor for the project is Carollo Engineers, Inc., with subcontractors ASR Systems LLC and NewGen LLC.

The District's role was to help provide hydrogeologic characterization for the study. This report documents the installation of a multiport well and hydrogeologic data collected from the well.

## Study Area

The study area is within southern Travis County about 1.5 miles east of the freshwater Edwards Aquifer in the Balcones Fault Zone (BFZ). The freshwater aquifer segment is known as the Barton Springs segment of the Edwards Aquifer (**Figure 1**). The location of the multiport well is on the property of Texas Disposal Systems, Inc.

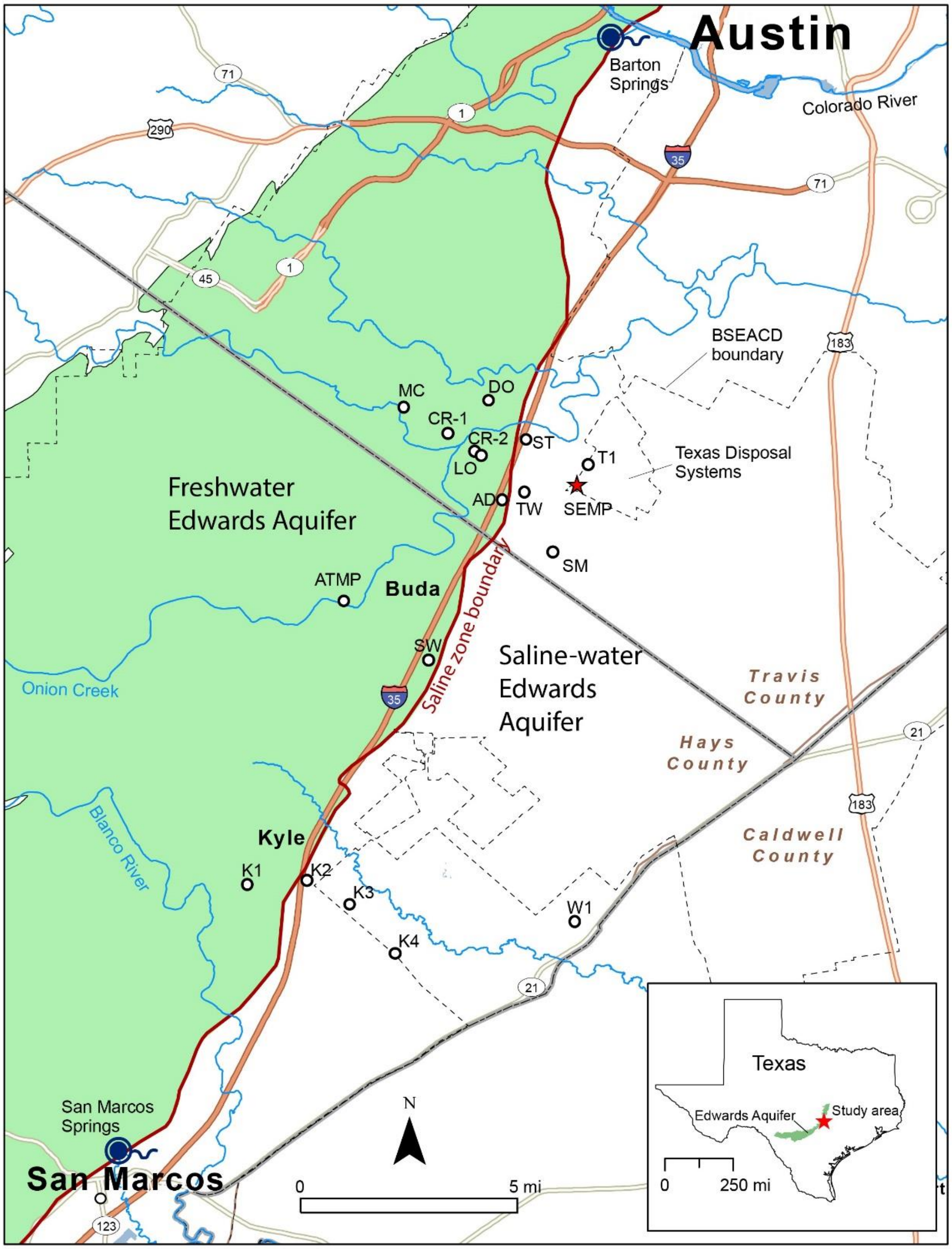
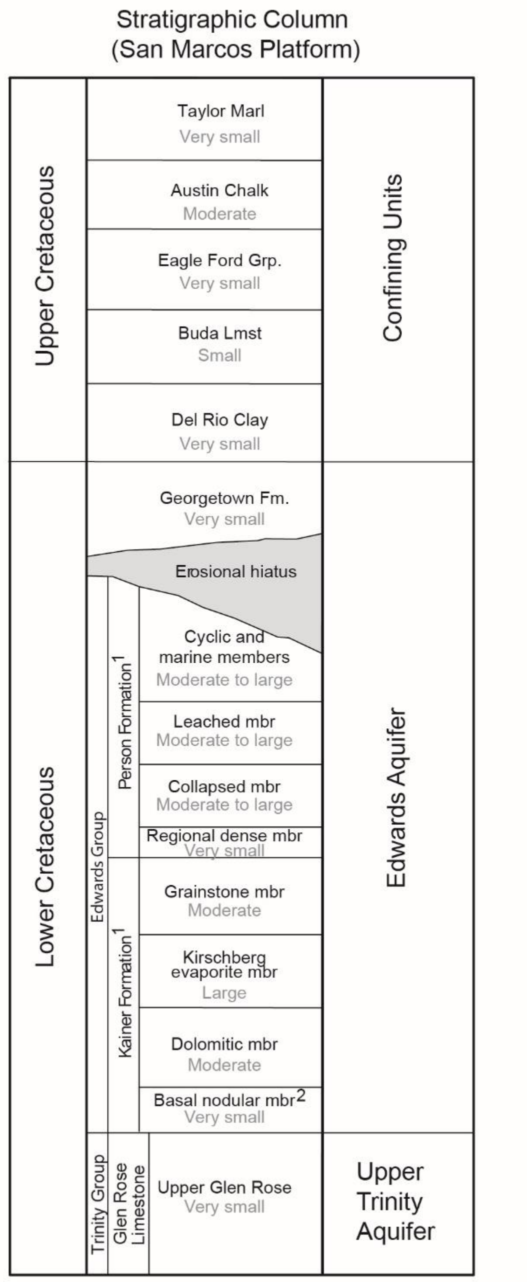


***Figure 1.*** *Location map of the Barton Springs segment of the Edwards Aquifer. The focus of this study is east of the freshwater Edwards Aquifer in Hays and Travis Counties. Saline boundary from Hunt et al., 2014. Wells of interest noted in this study include (from south to north): K1-K4, Kyle transect; W1, Walton test well; SW, Sweeney monitor well; ATMP, Antioch multiport well; SM, Sunfield monitor well; AD, Adkins well; TW, TWDB test well; SEMP, multiport well; T1, TDS test well; ST, St. Albans well; CR, Creedmoor-Maha; MC, McCoys monitor well; and DO, Dowell monitor well.*



Descriptors (small, large etc) indicate relative permeability.

Modified from Maclay (1995)

[1] Modified from Rose (1972).

[2] Walnut Fm. equivalent

***Figure 2.*** *Regional stratigraphic column and hydrostratigraphy in the study area.*

# Geology

The Edwards Aquifer is composed of about 450 feet of limestone and dolomite of the Cretaceous Edwards Group and Georgetown Formation (**Figures 2 and 3**). The carbonate sediments that make up the Edwards Group accumulated on the Comanche Shelf as shallow marine, intertidal, and supratidal deposits. The Georgetown Formation, disconformably overlying the Edwards Group, was deposited in a more openly circulated, shallow-marine environment (Rose, 1972).

## Structure

The Balcones Fault Zone (BFZ) produces the prominent physiographic feature known as the Balcones Escarpment in central Texas. The BFZ is a dominant structural feature extending in an arcuate pattern from Del Rio along the border with Mexico, toward Dallas in north Texas. The BFZ trends from west to east near San Antonio then changes to a northeast trend near Austin. The BFZ is a fault system consisting of numerous normal faults with hanging walls generally dropping down toward the Gulf of Mexico with displacements ranging from 100 to 800 ft. There are up to 1,200 ft of total displacement across the BFZ. Faults are generally steeply dipping (45-85 degrees) with stratigraphy a fundamental control on the geometries and dips (Ferrill and Morris, 2007). The faults are described as "*en echelon*," which indicates closely-spaced, overlapping and subparallel. Depending on location, the faults can occur at oblique angles to the overall regional structural trend. The faults extend down into the Ouachita rocks (Paleozoic) and may also pass into extensionally reactivated Ouachita faults (Ewing, 1991); but they may also have listric geometries that terminate or sole out into shales at depth (Collins and Hovorka, 1997).

In the study area, faults generally trend to the NE (Figure 3) with steep dips to the southeast (**Figure 4**) (Brune and Duffin, 1983; Collins and Hovorka, 1997). Mapped faults in the study area and proximal to the well include a NE-trending normal fault with about 100 ft of throw down to the southeast (**Figure 3**).

Structure contours of the bottom of the Edwards Aquifer are shown on **Figure 3**. Steep gradients occur within the BFZ and locally where significant faulting has offset the units. In the study area, from the freshwater boundary to about 600 ft east of the multiport well, the contours indicate a structural dip of the Edwards of about 240 ft per mile.

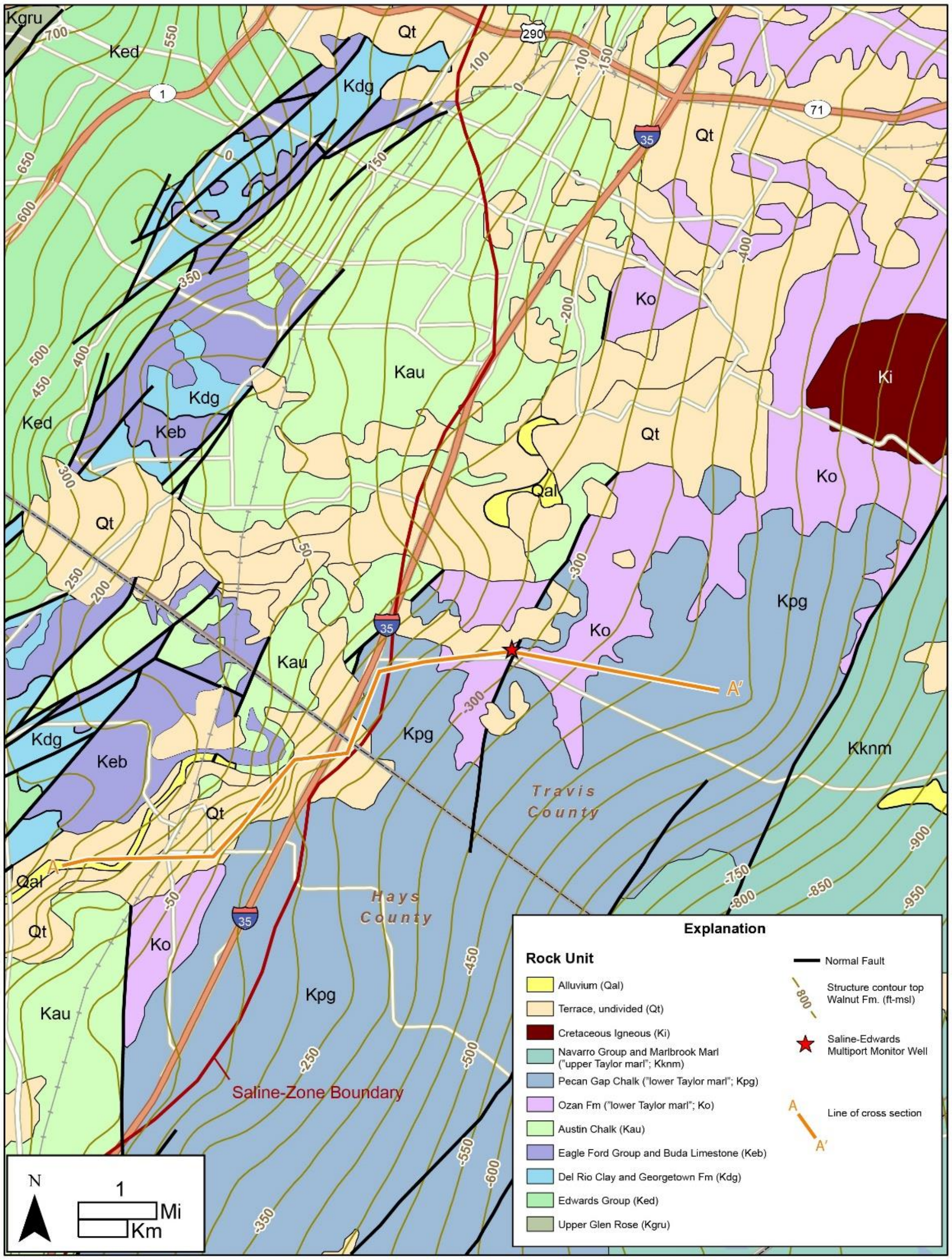
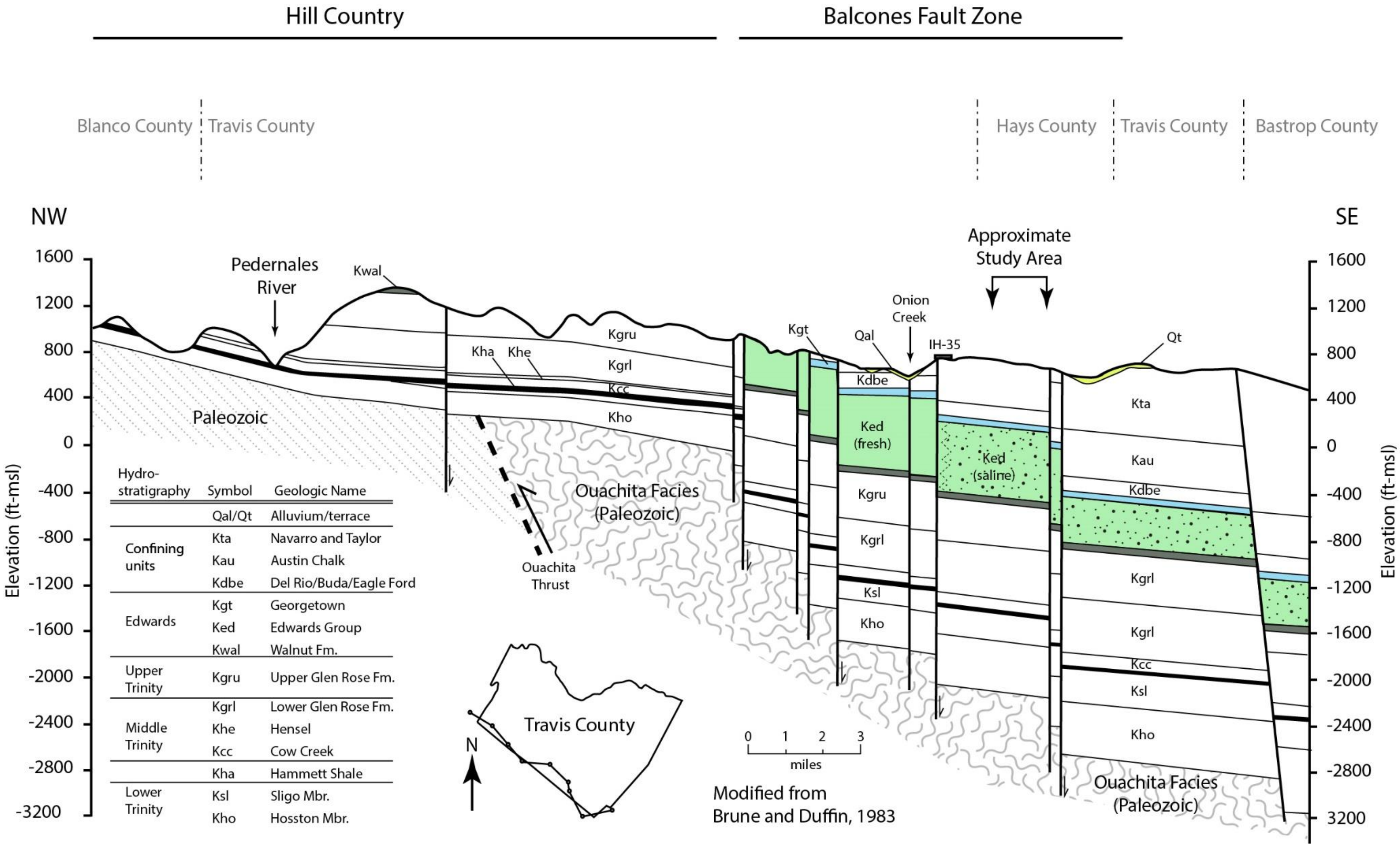


***Figure 3.** Geologic map and structure contour of the Walnut (base of the Edwards). Geologic map from the Geologic Atlas of Texas (GAT). Structure contour units in feet above mean sea level (source: BSEACD unpublished data). Cross section A-A' shown in Figure 14.*



| Hydro-stratigraphy | Symbol | Geologic Name |
|---|---|---|
| | Qal/Qt | Alluvium/terrace |
| Confining units | Kta | Navarro and Taylor |
| | Kau | Austin Chalk |
| | Kdbe | Del Rio/Buda/Eagle Ford |
| Edwards | Kgt | Georgetown |
| | Ked | Edwards Group |
| | Kwal | Walnut Fm. |
| Upper Trinity | Kgru | Upper Glen Rose Fm. |
| Middle Trinity | Kgrl | Lower Glen Rose Fm. |
| | Khe | Hensel |
| | Kcc | Cow Creek |
| | Kha | Hammett Shale |
| Lower Trinity | Ksl | Sligo Mbr. |
| | Kho | Hosston Mbr. |

***Figure 4.*** *Regional cross section modified after Brune and Duffin, 1983.*

## Hydrogeology

The Edwards Aquifer (**Figures 1 and 2**) is a significant water supply for 2 million overall people in central Texas, and its renowned springs, such as Comal, San Marcos, and Barton Springs, provide habitat for a variety of endangered species and recreational opportunities for residents and visitors.

The Edwards and Trinity Aquifers of central Texas are stratigraphically stacked and structurally juxtaposed in the BFZ. Studies have long recognized the importance of faulting for the development of the Edwards Aquifer (Hill and Vaughan, 1898; DeCook, 1963; Abbott, 1975; Sharp, 1990). The freshwater Edwards Aquifer is a karst aquifer developed in faulted and fractured limestones and dolomites (**Figures 3 and 4**). Faulting provided the hydrogeologic architecture (e.g. recharge areas vs. confined aquifers) and the initiation point for karst processes (DeCook, 1963; Slade et al., 1986; Sharp, 1990; Ferrill et al., 2004). Development of the freshwater Edwards Aquifer was influenced significantly by fracturing and faulting and subsequent dissolution of limestone and dolomite units by infiltrating meteoric water (Abbott, 1975; Sharp, 1990; Hovorka et al., 1996; Hovorka et al., 1998; Barker and Ardis, 1996; Small et al., 1996). In addition, development of the aquifer is also thought to have been influenced by deep dissolution processes along the freshwater/saline-water interface, what is known as hypogene speleogenesis (Klimchouk, 2007; Schindel et al., 2008). Permeability is generally enhanced parallel to faults and fractures and decreases perpendicular to faults and fractures in the Edwards Aquifer (Maclay and Small, 1986; Hovorka et al., 1996; Ferrill et al., 2004; Ferrill et al., 2008).

## Saline Edwards Aquifer

The saline Edwards Aquifer is defined as the Edwards Group rock units that contain water with greater than 1,000 mg/L total dissolved solids (**Figures 1 and 4**). The saline Edwards Aquifer occurs east (in the Austin area) and south (in the San Antonio area) of the freshwater Edwards Aquifer. Fluids in the Edwards Group rocks are described as Na-Ca-Cl brines that have increasing salinities (up to 290,000 mg/L) down-dip to the eastern extent of the subsurface Edwards Group equivalent rocks known as the Stuart City Reef (Land and Prezbindownski, 1981). Because of limitations placed on pumping the freshwater Edwards Aquifer, the saline Edwards Aquifer has been viewed as a potential alternative source of water for desalinization or as a reservoir for aquifer storage and recovery (ASR).

Total dissolved solids (TDS) is a measure of water salinity and reflects the amount of dissolved minerals in units of milligrams per liter (mg/L), or parts per million (ppm). Terms used to describe the salinity of water are not consistent. **Table 1** provides a summary of definitions and terms for the area of interest. In this report the term “saline” is used synonymously with the term “brackish”. The term “saline zone” is used to describe the area east of the freshwater zone where groundwater can be produced that contains greater than 1,000 mg/L TDS. Water with less than 1,000 mg/L is considered fresh, generally does not need treatment, and is suitable for most uses. Brackish groundwater generally describes water with 1,000 to 10,000 mg/L TDS (George et al., 2011; NGWA, 2010). Water with greater than 1,500 mg/L TDS may be used for irrigation, depending on the concentrations of certain ions (chloride, sodium etc.). Water with up to 3,000 mg/L TDS can be suitable for livestock (George et al., 2011).

***Table 1.*** *Summary of definitions and terms*

| Term | TDS (mg/L) | Source | Comment |
|---|---|---|---|
| **Freshwater** | < 1,000 | George et al., 2011 | This is also the threshold for secondary drinking water standards set by the TCEQ*. |
| **Brackish water** | 1,000 to 10,000 | NGWA, 2010 | |
| **Slightly saline** | 1,000 to 3,000 | NGWA, 2010 | |
| **Moderately saline** | 3,000 to 10,000 | NGWA, 2010 | |
| **Highly saline** | 10,000 to 35,000 | NGWA, 2010 | |
| **Brine** | >35,000 | | Salinity of seawater is about 35,000 mg/L |

*EPA and the WHO have a secondary standard of 500 mg/L

## Freshwater/saline-water Interface

The freshwater/saline-water interface represents a transition from the rapid-flowing freshwater system to the slow-moving saline fluids down dip of the freshwater Edwards Aquifer. Hydrogeologic characteristics of the freshwater/saline-water interface of the Edwards Aquifer have been studied for some time. In the study area the interface (boundary) between the freshwater and saline-water zones of the Edwards Aquifer were first mapped by Petitt and George (1956). As new data and studies of the boundary have become available, it has been periodically refined (Flores, 1990; Schultz, 1993; Hunt et al., 2014). Maps and cross sections have been generated that indicate the salinity of Edwards groundwater east and west of the freshwater/saline-water interface (**Figures 1 and 4**; Hunt et al., 2014; SWRI, 2003; Flores 1990; LBG-Guyton, 2003; Brune and Duffin, 1983; Baker, et al., 1986).

The freshwater/saline-water interface is often depicted as a two-dimensional (X-Y) boundary. In fact it is a very complex boundary that has three (Z) and four (time) dimensional variability not represented by a simple map boundary (**Figures 1 and 4**). The boundary is likely not vertical because of the heterogeneity of the lithologic units in the Edwards overprinted by diagenesis, structure, and the variable densities of the water.

While faulting has long been known to influence the formation and processes within the freshwater Edwards Aquifer, less is known about the role of structure in the formation or hydrologic functioning of the saline Edwards Aquifer. Petitt and George (1956) first note that faults appear to influence the freshwater/saline-water interface in some locations, but not in others. In Hays and Travis Counties, Baker et al., 1986 reported that faulting appears to have a strong influence on the interface, which parallels mapped faults. However, inspection of **Figure 3** illustrates that this may not be a consistent effect as the interface is mapped northward toward the Colorado River at high angles to mapped faults. Lambert et al. (2010) discuss a well drilled on the freshwater/saline-water interface (**Figure 1; Supplement 1**). The data and conceptualized diagram for this well clearly indicate a wedge of saline water below the freshwater-bearing intervals extending about 1 mile southeast to northwest between two faults.

Studies have established a somewhat muted hydrologic connection between the freshwater and saline zones (Senger and Kreitler, 1984; Slade et al., 1986; Mahler, 2008; Lambert et al., 2010). Increases in salinity at Barton Springs and some wells during drought conditions, when hydraulic gradients from the saline zone are toward the freshwater zone, support that hypothesis (Slade et al., 1986; Garner and Mahler, 2007). However, substantial increases in salinity have not occurred to date despite severe droughts and heavy pumping. This lack of increased salinity supports the ideas of Groschen and Buszka (1997) that substantial flows of saline water into the freshwater zone are unlikely due the compartmentalization (both vertical and horizontal isolation) of the Edwards saline zone.

Hunt et al. (2014) show TDS values in certain wells along the interface vary over time and could be interpreted as indicating saline-water encroachment. However, most of these wells are open well bores that are likely drilled across a complex, non-vertical freshwater/saline-water interface. Accordingly, the boreholes themselves may be pathways for an apparent "encroachment" of salinity as hydrologic conditions vary. This is supported by Lambert et al. (2010) who document intra-aquifer flow within the borehole and flow reversals with changing hydrologic conditions. Competing heads within a borehole drilled across different hydrogeologic units is a likely explanation for the sudden conductivity changes within a monitor well near Barton Springs (Hunt et al., 2014; 58-50-216).

San Antonio Water System (SAWS), in partnership with the U.S. Geological Survey (USGS), has installed about 20 monitor wells in 6 transects across the freshwater/saline-water interface to provide data about possible movement of the interface. The four wells installed along the Kyle transect, about 10 miles south of the study area, are most analogous to this study (**Figure 1; Supplement 1**). The average lateral flow potential (based on heads) in the Kyle transect area (Hays County) is from the saline zone into the freshwater zone (Lambert et al., 2010). However, they conclude that the data for all the wells suggest that the interface is likely to remain stable laterally and vertically over time.

Modeling results of a USGS study (Brakefield et al., 2015) support the idea that the freshwater/saline-water interface is in fact relatively stable and has little potential for movement of significant amounts of saline water into the freshwater zone. Conversely, the risk of movement of freshwater into the saline zone is also assumed to be low. The USGS study simulated the drought of record and high rates of pumping.

## Source of Saline Water

Considering that these lithologic units were deposited on a broad, shallow, carbonate shelf, lithologies of Edwards units are the same on either side of the freshwater/saline-water interface. The rocks experienced the same amount burial, diagenetic, and structural history on either side of the interface. The primary difference between Edwards units on either side of the freshwater/saline-water interface is the degree of (late) diagenesis and dissolution as the rocks on the west side became exposed to the flow of fresh (meteoric) water (Abbott, 1975; Hovorka et al., 1996). Flux of freshwater has been high in the freshwater Edwards Aquifer. This flux of slightly acidic water has dissolved a considerable amount of limestone and dolomite along faults, fractures, bedding planes, and within the matrices. Significant conduits have developed along some of these zones that facilitate flow of even greater quantities of water. In contrast the amount of water flowing through the saline Edwards Aquifer is considerably less and therefore less dissolution takes place. However, there is some dissolution, but the minerals that are dissolved from the rock are not carried away from the zone of dissolution as quickly as the area to the west, and therefore concentrations of dissolved minerals increase. The presence of evaporite minerals in the rocks may also contribute to the high values of total dissolved solids in the water east of the interface. Evaporites were once present in the Edwards units east and west of the interface, but early diagenesis has removed these much of these minerals (Hovorka et al., 1996).

One possible explanation for the high salinity of the saline zone is that the mineral constituents are from the original formation water from the time of deposition. However the chemistry of some parts of the saline Edwards is sodium-chloride water with high sulfate, which indicates that the dissolved constituents are from dissolution of the host rock, including evaporites, rather than just primary formation fluids.

Oetting et al. (1996) looked at geochemical and isotopic parameters for the origin of the saline waters. They found that the saline waters were largely a result of fluid-rock interaction and fluid mixing processes reflecting a diversity of geochemical evolution pathways. For this study area Oetting et al., (1996) describe the area as Na-Cl facies resulting from fluid mixing between meteoric water, Edwards Group brines, and saline groundwaters from the underlying Glen Rose Formation.

Groschen and Buszka (1997) present a detailed study of the hydrogeologic framework and the geochemistry of the saline-water zone. Using hydrogen and oxygen isotopes they identified two hydrological and geochemical regimes in the saline-water zone. The first one, a shallower updip regime of predominantly meteoric water recharged from the freshwater zone; and the second, a deeper downdip regime that is thermally altered, hydrologically stagant, and much older. They further describe the saline zone as hydrologically compartmentalized due (in part) to faults that impede updip and downdip flow. They conclude that substantial amounts of updip flow of saline water toward the freshwater zone is unlikely.

Another theory suggests that saline fluids from deeper in the basin have migrated into this area and have dissolved portions of the rock due to mixing of saline and freshwaters creating highly permeable rocks east of the interface (Hovorka et al., 1996). The source of salinity for the deep basinal brines in the Edwards Group is reported to be the underlying Middle Jurassic evaporites (Land and Prezbindownski, 1981). Zones of caves and karst have developed by this mechanism of dissolution in some parts of the world (Klimchouk, 2007; George Veni, personal communication).

## Saline Edwards Groundwater Availability

The study area is composed of the saline Edwards Aquifer within the northern subdivision of Groundwater Management Area 10. As mandated by Texas Water Code § 36.108, districts are required to submit Desired Future Conditions (DFCs) of the groundwater resources. According to Texas Water Code § 36.108 (d-3), the district representatives shall produce a Desired Future Conditions Explanatory Report for the management area and submit it to the TWDB. A draft report was completed as of the date of this document (SWRI, 2017).

The District and other GCDs regard the saline zone as an alternative water supply that poses little threat to the freshwater Edwards—and in fact can lessen demands placed upon it. The District has rules in place (management zones and buffers) that address potential pumping projects along the interface of the saline zone. To date no permits have been requested for the saline Edwards Aquifer. The estimated modeled available groundwater (MAG) for the saline Edwards Aquifer in the region are listed in **Table 2**. The estimation was done by using a water-budget approach and assuming a closed system (SWRI, 2017).

Texas statute also requires that the total estimated recoverable storage (TERS) of relevant aquifers be determined (Texas Water Code § 36.108) by the TWDB. Total estimated recoverable storage is defined as the estimated amount of groundwater within an aquifer that accounts for recovery scenarios that range between 25 percent and 75 percent of the porosity-adjusted aquifer volume. **Table 3** summarizes the total estimated recoverable storage by groundwater conservation district for the saline Edwards (Balcones Fault Zone) Aquifer within the northern subdivision of Groundwater Management Area 10 (Bradley, 2016). The total estimated recoverable storage for the saline Edwards (Balcones Fault Zone) Aquifer ranges from 365,000 to 1,095,000 acre-feet.

The saline zone of the Edwards Aquifer is generally considered a closed system, especially over the time scale of groundwater availability. Accordingly, the aquifer will be mined over time. The availability numbers generated by the MAG are conservative numbers that reflect a cautious approach due to the (low) potential for negative effects on the freshwater/saline-water interface. It is likely that the DFC expression could be somewhat greater with minimal negative effects. The District requires pilot studies for projects along the interface to demonstrate low risk for negative effects. The TERS numbers represent theoretical values that do not reflect hydrogeologic reality, and are not sustainable, and thus are not useful in planning. Indeed, if those volumes were pumped, and the resulting drawdown occurred, it would likely have significant negative effects on the freshwater Edwards Aquifer.

Given the closed system of the saline Edwards Aquifer, a combination of desalinization and ASR may be a sustainable strategy.

***Table 2.*** *Estimation of Modeled Available Groundwater (MAG; SWRI, 2017)*

| | **Barton Springs/Edwards Aquifer Conservation District** | **Plum Creek Conservation District** | **Non-District Areas** | **Total** |
|---|---|---|---|---|
| **Desired Future Condition** | No more than 75 feet of regional average potentiometric surface drawdown due to pumping when compared to pre-development conditions | | | |
| **Storage Coefficient** | 7.0 x 10-4 | | | |
| **Areal extent (acres)** | 72,363 | 15,478 | 75,270 | 163,111 |
| **Estimated Modeled Available Groundwater (acre-feet per year)** | 3,799 | 813 | 3,952 | 8,564 |

***Table 3.*** *Total estimated recoverable storage (TERS) by groundwater conservation district for the saline Edwards (Balcones Fault Zone) Aquifer within the northern subdivision of Groundwater Management Area 10 (SWRI, 2017).*

| **Groundwater Conservation District** | **Total Storage (acre-feet)** | **25% of Total Storage (acre-feet)** | **75% of Total Storage (acre-feet)** |
|---|---|---|---|
| **Barton Springs/Edwards Aquifer Cons. District** | 690,000 | 172,500 | 517,500 |
| **Plum Creek Conservation District** | 150,000 | 37,500 | 112,500 |
| **Non-district Areas** | 620,000 | 155,000 | 465,000 |
| **Total** | 1,460,000 | 365,000 | 1,095,000 |

## Saline Edwards Multiport Monitor Well

Characterization and monitoring of discrete intervals is needed to provide data that reflect the complexity of the stratigraphic units in the study area. Multiport wells are unique monitoring systems that allow recurrent measurement and sampling of discrete zones. The installation of a multiport monitor well, and the data it provides, is central to the hydrogeologic characterization of the saline Edwards Aquifer and is the focus of this report (**Figure 5**).

***Figure 5.*** *Drilling and development of the borehole for the multiport monitor well. Photo taken on 8/11/2016.*

## Stratigraphy

Geologic characterization is important to the hydrogeologic understanding of an aquifer system. The installation of the multiport well system produced valuable hydrogeologic information. The foundation is the geologic and stratigraphic information described below.

### Previous Work

The Geologic Atlas of Texas (**Figure 3**) and cross sections by Brune and Duffin (1983) (**Figure 4**) provide a general geologic framework for the study area. The study area contains subsurface control shown in **Figure 1**. A test well about 1 mile to the west of the multiport well (TW on **Figure 1**) provided geologic and geophysical control of the area (Flores, 1990). In addition, an abandoned test well (T1 on **Figure 1; Supplement 2;** tracking number 190570) about 0.2 mi north of the multiport well also provided some important geologic data. Studies by the USGS (Lambert et al., 2010; Thomas et al., 2012) from the Kyle transect wells (**Supplement 1**) provided additional geologic and geophysical data.

The classic study by Rose (1972) provides the detailed stratigraphic information of the Edwards Group for the region (**Figure 2**). Subsequent work by Hovorka et al. (1996) provides further detailed information on the stratigraphy and its relationship to the porosity development within the Edwards Aquifer. Hovorka et al. (1996) describe a complex relationship between depositional facies, cyclic stacking patterns, and porosity. The porosity and permeability of the rock units in the saline Edwards Aquifer are strongly influenced by the depositional facies and subsequent early diagenesis (dolomitization, cementation, calcite replacement of evaporites) (Abbott, 1975; Hovorka et al., 1996). For example, the regional dense member (RDM), a subtidal facies is described as having low matrix porosity. Units deposited in shallow water and intertidal environments were subject to more dolomitization, especially on the San Marcos Platform (Rose, 1972; Hovorka et al., 1996). Dolomites potentially have high porosity and permeability. Abbott (1975) noted a greater percentage of dolomite within core taken from a well in the saline zone when compared to core from the freshwater zone.

Because of the depositional cyclicity vertical (unit) porosity is highly variable. High porosity zones ranging from 10-50 ft thick contain 25-35 percent porosity are interbedded with thinner beds of 10-20 percent porosity. Average porosity of the Edwards varies laterally from 16-28 percent, with an interpolated overall average of 18 percent (Hovorka et al., 1996)—however, the saline portion of the Edwards Aquifer is reported to have higher-than average porosity (Maclay and Small, 1986; Schultz, 1993). Stratiform high-porosity units were reported in the middle and upper Kainer, and upper Person. Low-porosity units include the lower Kainer (Walnut Fm), lower Person (RDM), and the Georgetown Formations (Hovorka et al. (1996).

### Results: Stratigraphy

The multiport well systems installed by the District are manufactured by Westbay Instruments of Vancouver, Canada. A borehole was drilled using air-rotary drilling techniques producing boreholes with nominal 5¼ inch diameters (**Figure 5**; **Table 4**). Cuttings were collected, washed, and described (**Figure 6; Supplement 2**).

A geophysical log was run in the borehole by the U.S. Geological Survey (**Figures 9**). All borehole geophysical log data were collected according to the American Society of Testing and Materials (ASTM) borehole geophysical standard procedures. Geophysical tools include caliper, natural gamma, long/short normal resistivity, spontaneous potential, fluid temperature and conductance, EM induction conductivity/resistivity, and neutron.

***Figure 6.*** *Travis White describes cuttings. Photo taken 8/8/2016.*

***Table 4.*** *Basic saline Edwards multiport well Information*

| | |
|---|---|
| **State Well Number** | 58-58-305 |
| **Tracking Number** | 431923 |
| **Ddlat** | 30.1148889 |
| **Ddlong** | -97.7815278 |
| **Land Surface Elevation (ft-msl)** | 658 |
| **Drilling Start Date** | 8/3/2016 |
| **Drilling End Date** | 8/16/2016 |
| **Drilling Method** | Air Rotary |
| **Blowing yield (gpm)** | 500 |
| **Steel Surface Casing Diameter (in)** | 6 |
| **Surface Casing Depth (ft)** | 204 |
| **Borehole diameter (in)** | 5.125 |
| **Well depth (ft)** | 1100 |

The geophysical logs of the borehole are provided in **Supplement 2**. The natural gamma tool was the primary tool used to determine lithologic contacts and regional correlation of the various geologic units (**Table 5**). An attempt was made to isolate the informal members of the Edwards Group defined by Rose (1972) and shown in **Figure 2**. Cuttings and thin sections indicate the majority of the Edwards Group from the borehole to be dolomite or dolomitic in composition and contain a high degree of intercrystalline and moldic porosity (**Supplement 2; Figure 7**). Notable limestone units encountered in the borehole include low porosity units of the overlying Georgetown Formation and also the regional dense member (RDM) of the Person Formation (**Figure 8**). The RDM was identified by the dense argillaceous mudstone cuttings combined with the relatively thick and constant resistivity curve.

On average, the Edwards Group has relatively low resistivity values compared with the more argillaceous limestone units of the RDM, Walnut, and Georgetown Formations. The neutron porosity log indicates the Person has the highest total porosity (average 30 percent) while the Kainer averages a total porosity of 25 percent. The RDM has the lowest at 9 percent. The low RDM value of this study is comparable to the core tests of Hovorka et al., (1996) containing 8.5 percent. The RS curves correlate well with neutron porosity, especially the lateral RS ($R^2$=0.62).

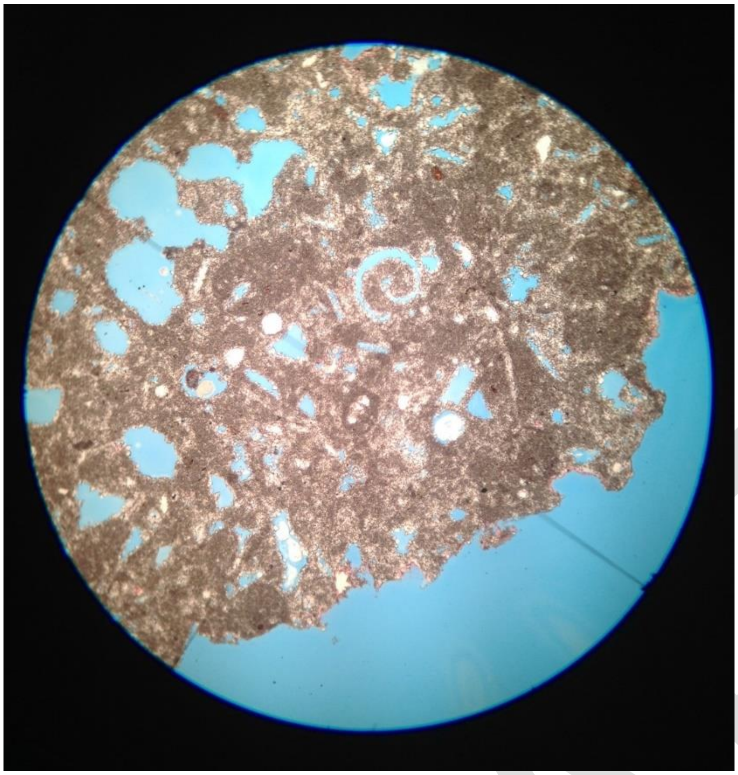


**Figure 7.** Photomicrograph of a dolomite from the Kainer Fm. (727 to 737 ft). This rock is very porous with intercrystalline and skeletal moldic porosity. Photograph in plain light, diameter is 5mm. This sample is comparable to a skeletal modlic porosity with 25 percent porosity reported in Hovorka et al., (1996).

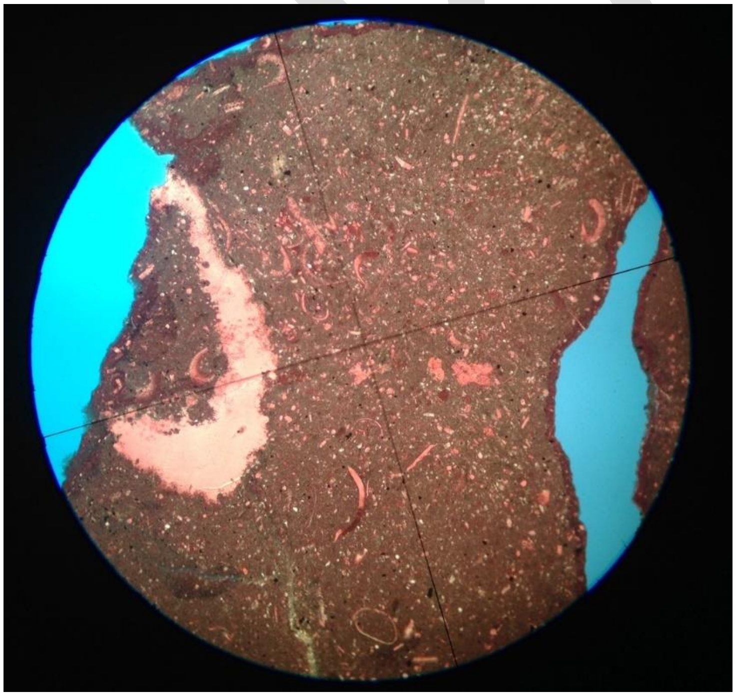


**Figure 8.** Photomicrograph of an argillaceous wakestone from base of the Person Fm. (regional dense member; 627 to 637 ft). This rocks has no observable porosity within the matrix. Photograph in plain light, diameter is 5mm. The geophysical porosity of 9 percent of this study is comparable to the core tests of Hovorka et al., (1996) containing 8.5 percent. Permeability of core plgs are reported to be 0.02 millidarcy (5.48E-5 ft/d) (Hovorka, et al., 1996).

## Results: Multiport Well Design

The multiport well system was designed after reviewing drilling, drill cuttings, geophysical logs and considering the stratigraphy and hydrostratigraphy of the study area. A caliper log was run to measure the diameter of the borehole so that packers could be placed on relatively smooth sections where cavities were not prominent, improving the likelihood that upon inflation the packers would provide effective seals in the annular space. **Table 6** summarizes the multiport well design, stratigraphy, and average geophysical log values.

The casing of the Westbay system consists of multiple segments of 1.9 inch outer-diameter Schedule 80 PVC, which are fitted together with PVC couplings. The multiport components are laid out and numbered in the work area (**Figures 10 and 11**). The components are connected prior to insertion in the borehole and each coupling is hydraulically tested during assembly. Monitor zones are established with permanent inflatable packers (**Figure 12**) placed in the string of casing at the top and bottom of each targeted zone. A special coupling with a spring-loaded valve (sampling port) is installed between the inflatable packers. A pumping port is also installed in each zone. These are short, screened intervals through which slug tests can be conducted and permeability estimated. **Supplement 2** contains the multiport well completion report. After designing the well, its components were assembled and inserted into the well using a 3.5-in diameter steel guide tube (HQ casing). Following insertion of the components, the guide tubing was then pulled out and the packers inflated with water. Inflation of the packers provides a permanent seal of the annular space between the PVC casing and the borehole walls, thus isolating the pumping and sampling ports into discrete zones.

## Discussion: Stratigraphy and Multiport Well Design

The tops of formations were primarily identified with natural gamma logs. However, the identification of the informal members (**Figure 2**) within the Edwards Group was problematic for 6 of the 8 informal members. The two informal members that were readily identified include the RDM and Walnut Fm (basal nodular member)--both of those units were isolated with packers to form zones 12 and 3, respectively. The design of the remaining Edwards zones were determined by adding in relatively numerous zones considering the caliper log and RS log. The average zone thickness is 35 ft. A total of 12 Edwards Group zones were constructed, and the well was constructed with a total of 18 zones.

The Del Rio Clay was unstable during drilling of the borehole and began to collapse and create a cavernous void. Packers were placed conservatively below and above the contact with the Del Rio so as to not inflate the packer into a void.

Key hydrostratigraphic confining, or low permeability, units were isolated with packers and include the Walnut Fm (zone 3), regional dense member (zone 12), and the overlying confining units of the Georgetown Formation and younger units (zones 15 and higher) (**Table 6**).

***Figure 9.*** *USGS staff logging the borehole to a total depth of 1,095 ft. Photo taken 8/19/2016.*

***Figure 10.*** *Photograph showing the work area for the installation of the multiport well. Photo taken 8/19/2016.*

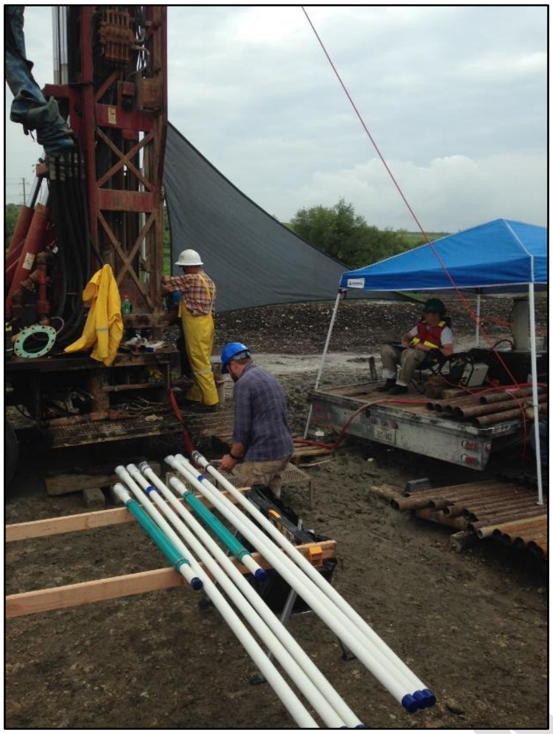


***Figure 11.*** *Multiport well components laid out for installation. Blue items are packers. Photo taken 8/20/2016.*

***Figure 12.*** *Photograph of assembly and testing of multiport coupling component. The coupling that connects the packer (blue, above) and the 10-ft casing section (white, below) is being pressure tested. Photo taken 8/20/2016.*

***Table 5.*** *Depth to geologic units in the saline Edwards multiport well. The deepest geologic unit encountered in the well is the Upper Glen Rose. Older geologic units are estimated based upon other sources as indicated.*

| **Name** | **Unit** | **Depth to Top (ft)** | **Top Elevation (ft-msl)** | **Unit Thickness (ft)** |
|---|---|---|---|---|
| **Taylor Clay** | Kta | 0 | 658 | 107 |
| **Austin Chalk** | Kau | 107 | 551 | 274 |
| **Eagle Ford** | Kef | 381 | 277 | 34 |
| **Buda** | Kbu | 415 | 243 | 40 |
| **Del Rio** | Kdr | 455 | 203 | 60 |
| **Georgetown** | Kgt | 515 | 143 | 49 |
| **Edwards (Person Fm.)** | Kep | 564 | 94 | 111 |
| **Edwards (Kainer Fm.)** | Kek | 675 | -17 | 292 |
| **Walnut Fm** | Kwal | 967 | -309 | 48 |
| **Upper Glen Rose*** | Kgru | 1015 | -357 | 400 |
| ***Lower Glen Rose**** | *Kgrl* | *1415* | *-757* | *250* |
| ***Hensel**** | *Kh* | *1655* | *-997* | *30* |
| ***Cow Creek**** | *Kcc* | *1687* | *-1029* | *90* |
| ***Hammett Shale**** | *Kha* | *1775* | *-1117* | *50* |
| ***Sligo***** | *Ksl* | *1825* | *-1167* | *230* |
| ***Hosston Fm.***** | *Kh* | *2055* | *-1397* | *400* |
| ***Paleozoic***** | *Pz* | *2455* | *-1797* | *unknown* |

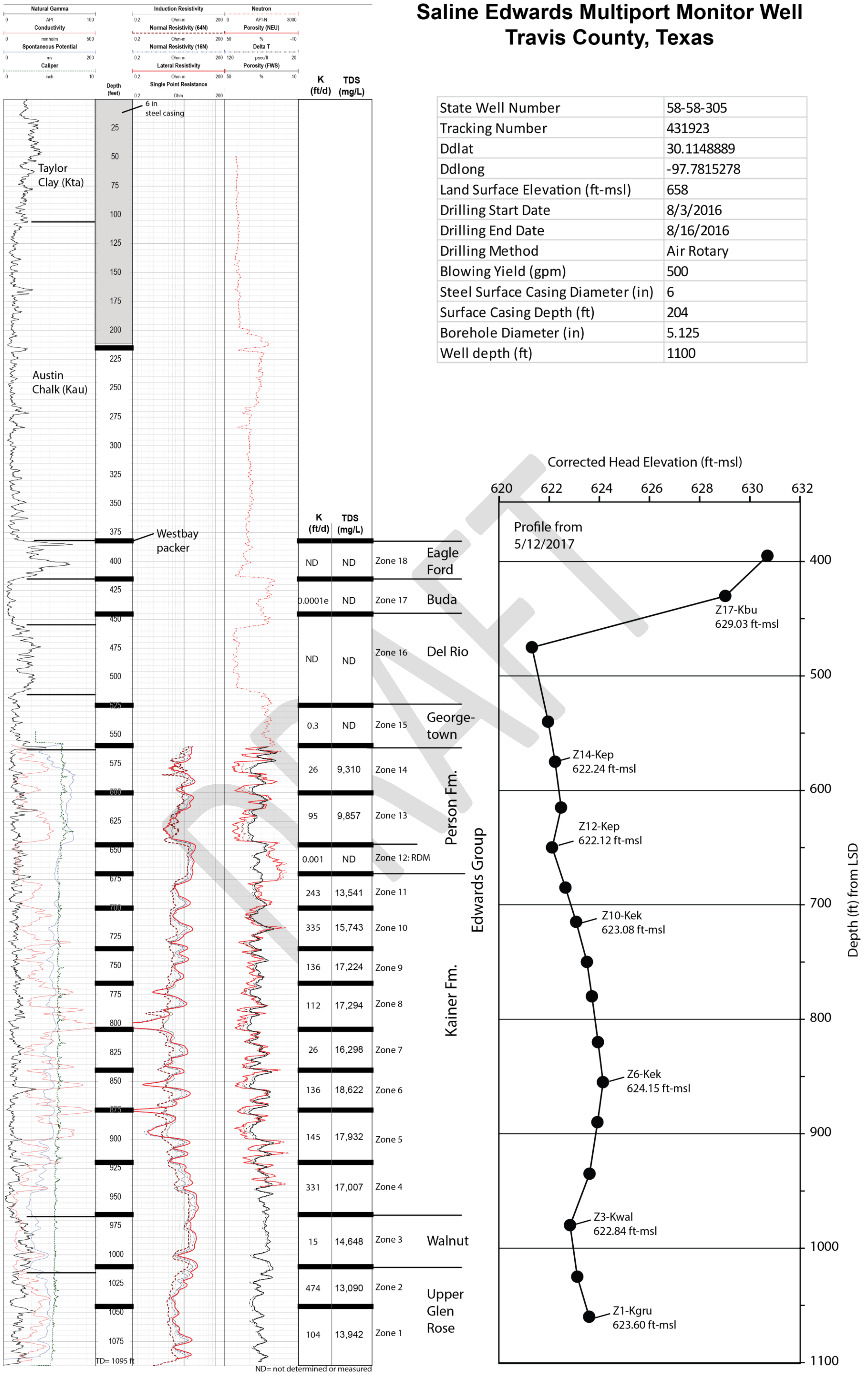
LSD *Thickness estimated from 5858431; **Thickness or depth estimated from Duffin and Brune, 1983

***Table 6.*** *Summary of multiport well design, stratigraphy, and average geophysical values.*

| Well Design | | | | | | | Average Geophysical Log Values | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Zone No.** | **Geologic Unit** | **Top Zone Depth (ft)** | **Bottom Zone Depth (ft)** | **Thickness Zone (ft)** | **Measurement Port Depth (ft)** | **Pumping Port Depth (ft)** | **Nat Gamma (API)** | **Fluid Cond (Ohm-m)** | **Fluid RS (Ohm-m)** | **COND (mmho/m)** | **IND_RES (Ohm-m)** | **RES (16N; Ohm-m)** | **RES (64N; Ohm-m)** | **Lateral RS (Ohm-m)** | **Single Point RS (Ohm)** | **SP (MV)** | **Caliper (in)** | **Fluid Temp (F)** | **Neutron (API-N)** | **Neutron Porosity (%)** | **Sonic Porosity (%)** |
| **n/a** | Taylor Clay | 0 | 107 | 107 | | | 39.5 | | | | | | | | | | | | 500 | | |
| **n/a** | Austin Chalk | 107 | 384.5 | 278 | | | 19.4 | | | | | | | | | | | | 942 | | |
| **18** | Eagle Ford | 385 | 416.5 | 32 | 395 | 405 | 58.3 | | | | | | | | | | | | 900 | | |
| **17** | Buda | 420 | 446.5 | 27 | 430 | 440 | 11.6 | | | | | | | | | | | | 1,611 | | |
| **16** | Del Rio | 450 | 526.4 | 77 | 475 | | 33.5 | 31,981 | | | | | | | | | | | 812 | | |
| **15** | Georgetown | 529 | 561.4 | 32 | 540 | 550 | 25.2 | 31,485 | 0.3178 | 67 | 15.2 | 15.9 | 13.4 | 17.8 | 7.0 | 102.9 | 6.3 | 81.5 | 1,740 | 22 | 16 |
| **14** | Edwards Person Fm. | 564 | 601.4 | 37 | 575 | 585 | 18.2 | 30,532 | 0.3278 | 148 | 8.0 | 10.0 | 8.0 | 11.5 | 5.2 | 127.8 | 6.4 | 81.6 | 1,158 | 29 | 22 |
| **13** | Edwards Person Fm. | 604 | 646.3 | 42 | 615 | 625 | 23.2 | 26,436 | 0.3817 | 182 | 6.8 | 7.1 | 5.8 | 8.4 | 4.7 | 140.6 | 6.4 | 81.9 | 1,095 | 30 | 25 |
| **12** | Edwards Person Fm--RDM | 649 | 671.3 | 22* | 650 | 660 | 24.3 | 31,924 | 0.3136 | 77 | 13.1 | 16.1 | 12.7 | 18.3 | 7.2 | 115.6 | 6.0 | 82.2 | 2,119 | 9 | 23 |
| **11** | Edwards Kainer Fm. | 674 | 701.3 | 27 | 685 | 695 | 21.1 | 31,997 | 0.3128 | 149 | 7.2 | 7.5 | 4.5 | 9.2 | 4.8 | 117.8 | 6.0 | 82.1 | 1,464 | 20 | 22 |
| **10** | Edwards Kainer Fm. | 704 | 736.3 | 32 | 715 | 725 | 19.0 | 31,231 | 0.3205 | 174 | 6.5 | 7.4 | 3.9 | 9.4 | 4.7 | 110.1 | 5.9 | 82.2 | 1,222 | 25 | 23 |
| **9** | Edwards Kainer Fm. | 739 | 766.3 | 27 | 750 | 760 | 23.0 | 31,493 | 0.3179 | 172 | 6.1 | 6.1 | 3.7 | 7.6 | 4.5 | 103.6 | 5.9 | 82.4 | 1,123 | 27 | 22 |
| **8** | Edwards Kainer Fm. | 769 | 806.3 | 37 | 780 | 790 | 21.9 | 32,447 | 0.3085 | 315 | 3.8 | 2.6 | 2.3 | 3.4 | 3.1 | 107.6 | 6.0 | 82.6 | 986 | 32 | 26 |
| **7** | Edwards Kainer Fm. | 809 | 841.3 | 32 | 820 | 830 | 22.1 | 33,083 | 0.3026 | 218 | 5.2 | 5.2 | 2.8 | 6.7 | 4.0 | 98.2 | 6.0 | 82.9 | 1,248 | 25 | 23 |
| **6** | Edwards Kainer Fm. | 844 | 876.3 | 32 | 855 | 865 | 21.6 | 33,379 | 0.2998 | 268 | 4.5 | 4.1 | 2.7 | 5.3 | 3.5 | 100.4 | 5.9 | 83.1 | 1,114 | 29 | 22 |
| **5** | Edwards Kainer Fm. | 879 | 921.3 | 42 | 890 | 900 | 17.6 | 33,587 | 0.2980 | 237 | 4.9 | 4.4 | 2.7 | 5.6 | 3.8 | 98.0 | 5.8 | 83.5 | 1,235 | 26 | 22 |
| **4** | Edwards Kainer Fm.. | 924 | 966.3 | 42 | 935 | 945 | 16.3 | 33,783 | 0.2963 | 99 | 12.3 | 15.6 | 9.3 | 18.6 | 7.0 | 70.2 | 5.6 | 84.0 | 1,710 | 15 | 17 |
| **3** | Walnut Fm. | 969 | 1011.3 | 42 | 980 | 990 | 35.2 | 33,641 | 0.2975 | 93 | 12.4 | 15.8 | 10.8 | 18.5 | 7.2 | 70.6 | 5.6 | 84.7 | | | 16 |
| **2** | Upper Glen Rose | 1014 | 1046.3 | 32 | 1025 | 1,035 | 24.1 | 32,158 | 0.3114 | 165 | 6.6 | 7.1 | 3.9 | 8.8 | 4.7 | 93.1 | 5.6 | 85.5 | | | 22 |
| **1** | Upper Glen Rose | 1049 | 1095 | 46 | 1060 | 1,070 | 25.1 | 29,851 | 0.3386 | 161 | 6.7 | 7.0 | 3.7 | 8.7 | 5.1 | 92.9 | 5.3 | 86.8 | | | 21 |

All depths from land surface. Packers are 3 feet long and not counted in zone thickness or geophysical log values.

*Thickness is consistent with RDM described in Rose (1972).



## Saline Edwards Multiport Monitor Well
## Travis County, Texas

| | |
|---|---|
| State Well Number | 58-58-305 |
| Tracking Number | 431923 |
| Ddlat | 30.1148889 |
| Ddlong | -97.7815278 |
| Land Surface Elevation (ft-msl) | 658 |
| Drilling Start Date | 8/3/2016 |
| Drilling End Date | 8/16/2016 |
| Drilling Method | Air Rotary |
| Blowing Yield (gpm) | 500 |
| Steel Surface Casing Diameter (in) | 6 |
| Surface Casing Depth (ft) | 204 |
| Borehole Diameter (in) | 5.125 |
| Well depth (ft) | 1100 |

| K (ft/d) | TDS (mg/L) | Zone | Formation |
|---|---|---|---|
| ND | ND | Zone 18 | Eagle Ford |
| 0.0001e | ND | Zone 17 | Buda |
| ND | ND | Zone 16 | Del Rio |
| 0.3 | ND | Zone 15 | George-town |
| 26 | 9,310 | Zone 14 | Person Fm. |
| 95 | 9,857 | Zone 13 | |
| 0.001 | ND | Zone 12: RDM | |
| 243 | 13,541 | Zone 11 | Kainer Fm. |
| 335 | 15,743 | Zone 10 | |
| 136 | 17,224 | Zone 9 | |
| 112 | 17,294 | Zone 8 | |
| 26 | 16,298 | Zone 7 | |
| 136 | 18,622 | Zone 6 | |
| 145 | 17,932 | Zone 5 | |
| 331 | 17,007 | Zone 4 | |
| 15 | 14,648 | Zone 3 | Walnut |
| 474 | 13,090 | Zone 2 | Upper Glen Rose |
| 104 | 13,942 | Zone 1 | |

ND= not determined or measured

*Figure 13.* *Geophysical logs, well design, stratigraphy, and hydrogeologic data for multiport monitor well.*

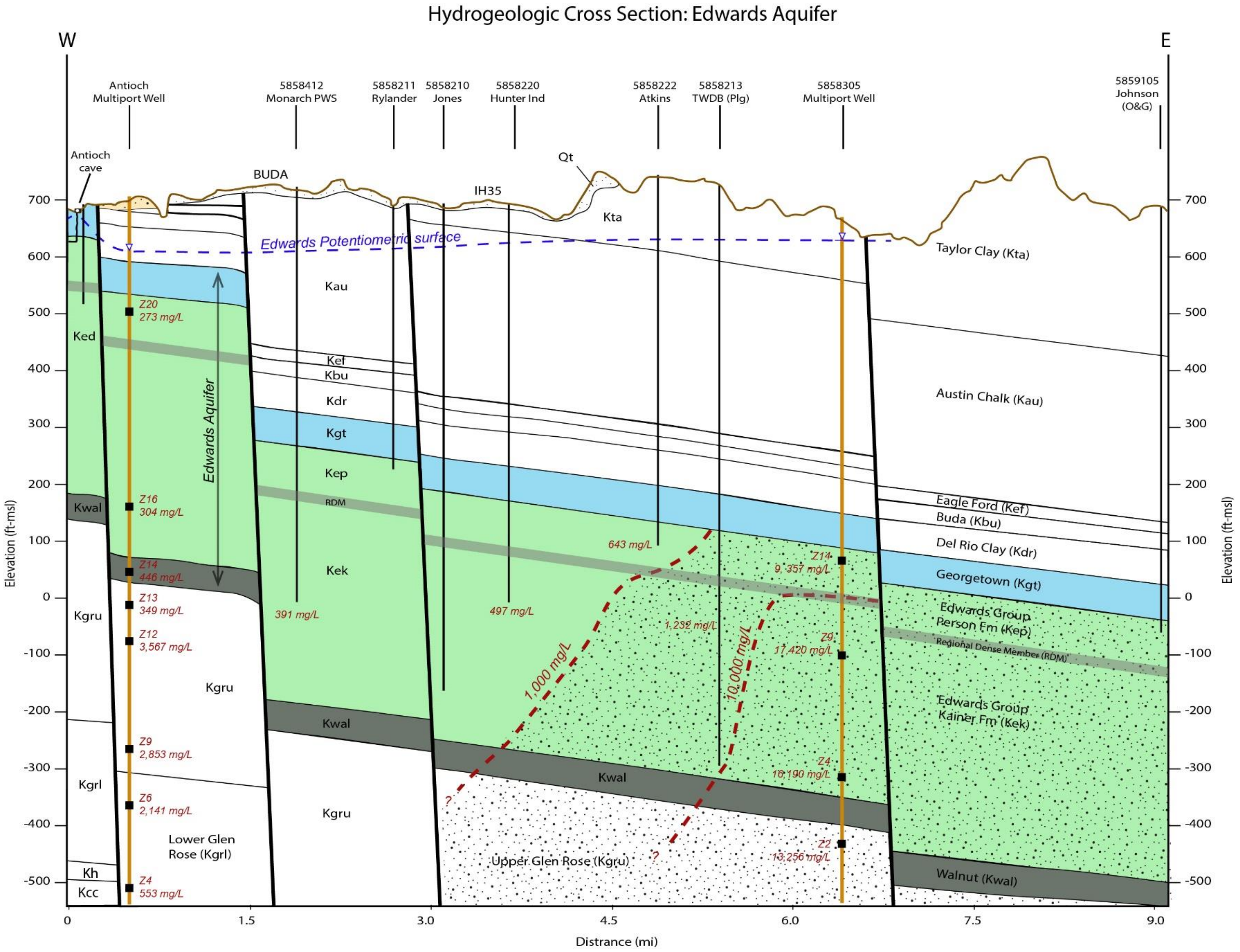


***Figure 14***. *Study area cross section. Line of cross section shown on Figure 3. Pattern indicates saline zone.*

## Water Levels and Hydraulic Gradients

Water level, or head data, were collected from the multiport monitor well (**Figure 15**). This information allows the assessment of the both lateral and vertical hydraulic gradients within the study area. The multiport well is unique for the assessment of hydraulic gradients as the discretely completed zones allow for the measurement of hydraulic heads for each zone.

***Figure 15.*** *Photograph showing equipment during measurement of a profile of water-level data. The trailer contains a winch that lowers the measurement instrument into the well. Photo taken 10/6/2016.*

### Previous work

Water levels in the freshwater portion of the Edwards Aquifer are well characterized with numerous continuous monitor wells and synoptic potentiometric maps (Hunt and Gary, 2014; Hunt and Smith, 2007). Water levels and gradients in the study area were investigated by Thomas et al. (2012) along the Kyle transect about 11 miles SSW of the multiport well (**Figure 1**). Key hydrogeologic data and figures from that study are provided in **Supplement 1**. Lateral-head gradients in the Kyle transect, although varied, were typically from the saline zone into the freshwater zone. In other words, heads were generally higher in the saline transect wells than in the freshwater wells. However, Thomas et al. (2012) used an EM flowmeter to measure flows within the boreholes of the Kyle transect wells. The eastern-most Kyle transect wells 3 and 4 indicated the potential for flow from the middle portion of the Edward to the lower and upper portions of the Edwards, respectively. These data suggest higher heads in the middle portion of the Edwards (**Supplement 1**).

A study by Flores (1990) included a test hole (TW, **Figure 1**) about 1 mile west of the multiport monitor well. Core and lab analyses with water-quality sampling suggest that the regional dense member (RDM) hydraulically separates the Edwards into an upper and lower unit.

## Methods

A head (water-level or potentiometric) profile of a multiport monitor well consists of measuring water pressures (heads) in all of the zones in the well within a short period of time, usually over an hour or two. These values give an accurate indication of the hydraulic potential for vertical flow within the aquifer units. Pressures are measured within each zone using a sampling instrument that includes a pressure transducer. The instrument is lowered into the well using a winch to the sample port for each zone (**Figure 15**). Fluid pressure is measured in one zone at a time. The pressure transducer has a range of 2,000 psi and also measures fluid temperature. Operation of the probe and digital output are sent through a cable to the LCD display on the controller at the surface. Pressures in each zone are recorded on field sheets. Head data and the salinity density corrections are provided in **Supplement 3** and described below.

Measured pressures for each zone are converted to pressure head (Hp) and then depth to water (Dtw) and finally head (Hu) value following the calculations outlined in the equations below. Head (Hu) represents the environmental-water head and is referred to as uncorrected (for freshwater equivalent) head. Note the hydrostatic pressure gradient was calculated independently for each zone based on the fluid density in order for the pressure transducer to measure the correct Dtw. Fluid density was calculated based upon each zone's temperature (measured during profiling) and total dissolved solids (mg/L) (data from sampling) using a spreadsheet calculation derived from Maidment (1993).

$$Hp = (Pz - Patm)/Pgrad$$
$$Dtw = Dp - Hp$$
$$Hu = LSD - Dtw$$

Where:

Hp = pressure head (ft);
Pz = zone pressure (psi);
Patm = atmospheric pressure (psi);
Pgrad = hydrostatic pressure gradient (psi/ft);
Dtw = depth to water (ft)
Dp = depth of port (ft);
Hu = head or water-level elevation (ft-msl) uncorrected;
LSD = land-surface datum (ft-msl).

According to the literature, equivalent freshwater heads define horizontal gradients, while environmental-water heads define vertical gradients (Lusczynski, 1961). However, because of the unique nature of the multiport well, it was determined that equivalent freshwater heads could also define the vertical gradients in this study. Following the methods described in Thomas et al. (2010), we converted uncorrected head (Hu) values into equivalent freshwater heads (Hc). Generally, this follows the equations described below.

$Hc = Hu + (lc - lu)$

Hc = equivalent freshwater head (or corrected head),
Hu = environmental head (uncorrected head);
lu = length of environmental water column (lu = Dp – Dtw);
lc = length of equivalent freshwater column (lc = lu * density ratio);
density ratio = zone fluid density / 0.998

## Results: Water Levels and Hydraulic Gradients

Equivalent freshwater head values are presented in **Table 7**. **Figures 13 and 16** show the vertical distribution of head values compared to the geologic units. Conversions to equivalent freshwater heads increased values from approximately 2 to 11 ft depending on the zone. **Supplement 3** contains the raw and corrected data.

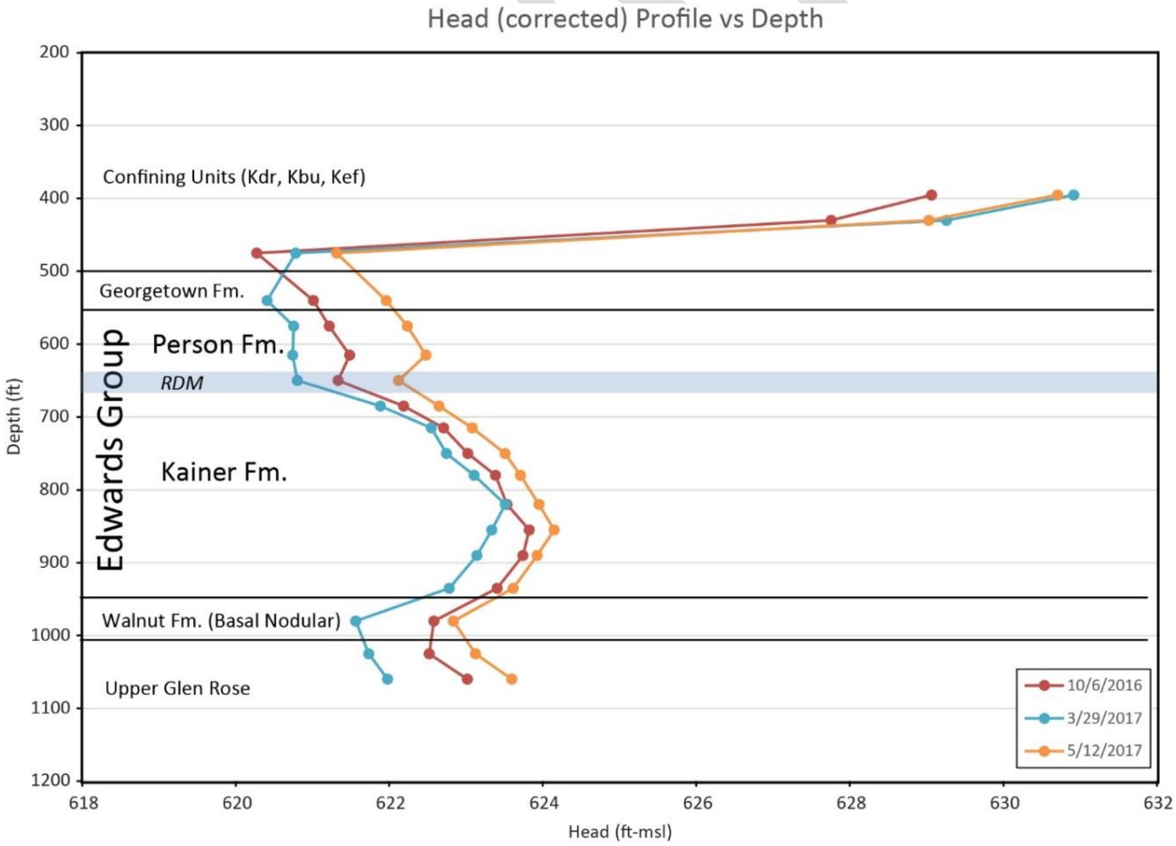


***Figure 16.*** *Hydrograph showing head in each zone versus depth for select profiles.*

**Figures 17 and 18** show the lateral distribution of equivalent freshwater head values in the multiport well compared with other freshwater and brackish water values.

***Table 7.*** *Head profile data collected from the saline Edwards multiport well. Heads are equivalent freshwater head values. Raw data and calculations are presented in* ***Supplement 3****.*

| **Zone** | **Depth Port (ft)** | **8/24/2016** | **10/6/2016** | **11/14/2016** | **1/19/2017** | **3/29/2017** | **5/12/2017** |
|---|---|---|---|---|---|---|---|
| **18-Kef*** | 395.2 | | 629.06 | 629.71 | 630.50 | 630.92 | 630.71 |
| **17-Kbu*** | 430.2 | 619.87 | 627.76 | 628.73 | 628.94 | 629.26 | 629.03 |
| **16-Kdr*** | 475.1 | 618.00 | 620.27 | 619.60 | 619.93 | 620.78 | 621.31 |
| **15-Kgt*** | 540.1 | 618.74 | 621.01 | 620.20 | 618.77 | 620.41 | 621.96 |
| **14-Kep** | 575.1 | 619.11 | 621.22 | 620.52 | 618.97 | 620.76 | 622.24 |
| **13-Kep** | 615.1 | 619.35 | 621.48 | 620.65 | 619.38 | 620.74 | 622.48 |
| **12-Kep**—RDM* | 650 | 618.98 | 621.33 | 620.48 | 618.86 | 620.80 | 622.12 |
| **11-Kek** | 685 | 619.76 | 622.19 | 620.08 | 617.74 | 621.89 | 622.65 |
| **10-Kek** | 715 | 620.30 | 622.71 | 620.49 | 618.10 | 622.55 | 623.08 |
| **9-Kek** | 750 | 620.69 | 623.02 | 620.78 | 618.46 | 622.75 | 623.51 |
| **8-Kek** | 780 | 620.95 | 623.38 | 621.19 | 618.92 | 623.11 | 623.71 |
| **7-Kek** | 820 | 621.03 | 623.53 | 621.31 | 619.21 | 623.51 | 623.95 |
| **6-Kek** | 855 | 621.23 | 623.82 | 621.51 | 619.38 | 623.34 | 624.15 |
| **5-Kek** | 890 | 621.08 | 623.74 | 621.41 | 619.32 | 623.14 | 623.93 |
| **4-Kek** | 935 | 621.11 | 623.41 | 621.39 | 619.43 | 622.78 | 623.61 |
| **3-Kwal** | 980 | 620.48 | 622.58 | 620.92 | 619.02 | 621.56 | 622.84 |
| **2-Kgru** | 1025 | 620.72 | 622.52 | 621.02 | 619.19 | 621.73 | 623.12 |
| **1-Kgru** | 1060 | 621.05 | 623.02 | 621.40 | 619.73 | 621.98 | 623.60 |

**head corrections are estimated based on nearest zone data.*

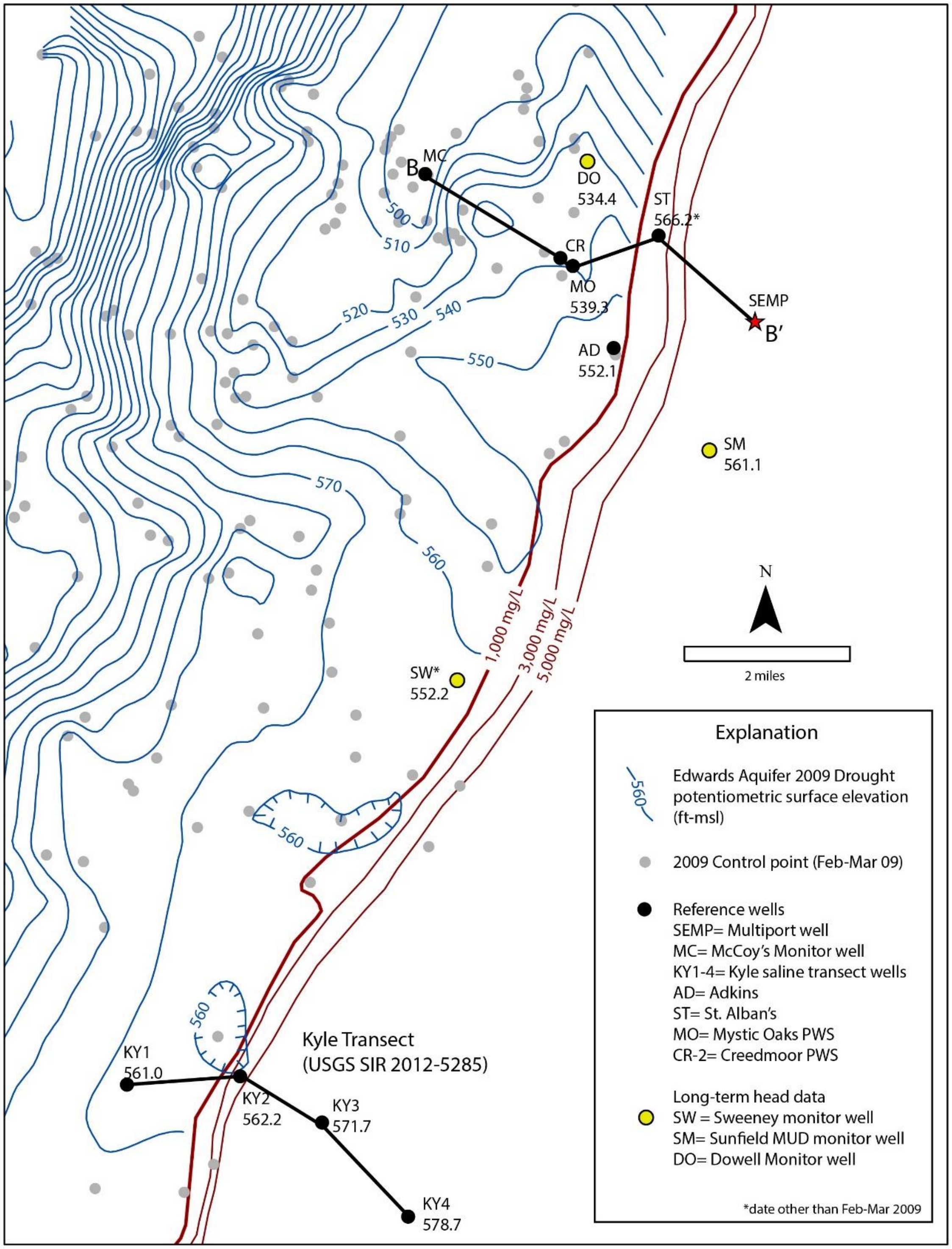


***Figure 17.*** *Map of 2009 drought potentiometric surface and two transects across the freshwater/saline-water interface. The northern transect, B to B', is shown in the profile in Figure 18. The Kyle transect data is shown in profile in Supplement 1.*

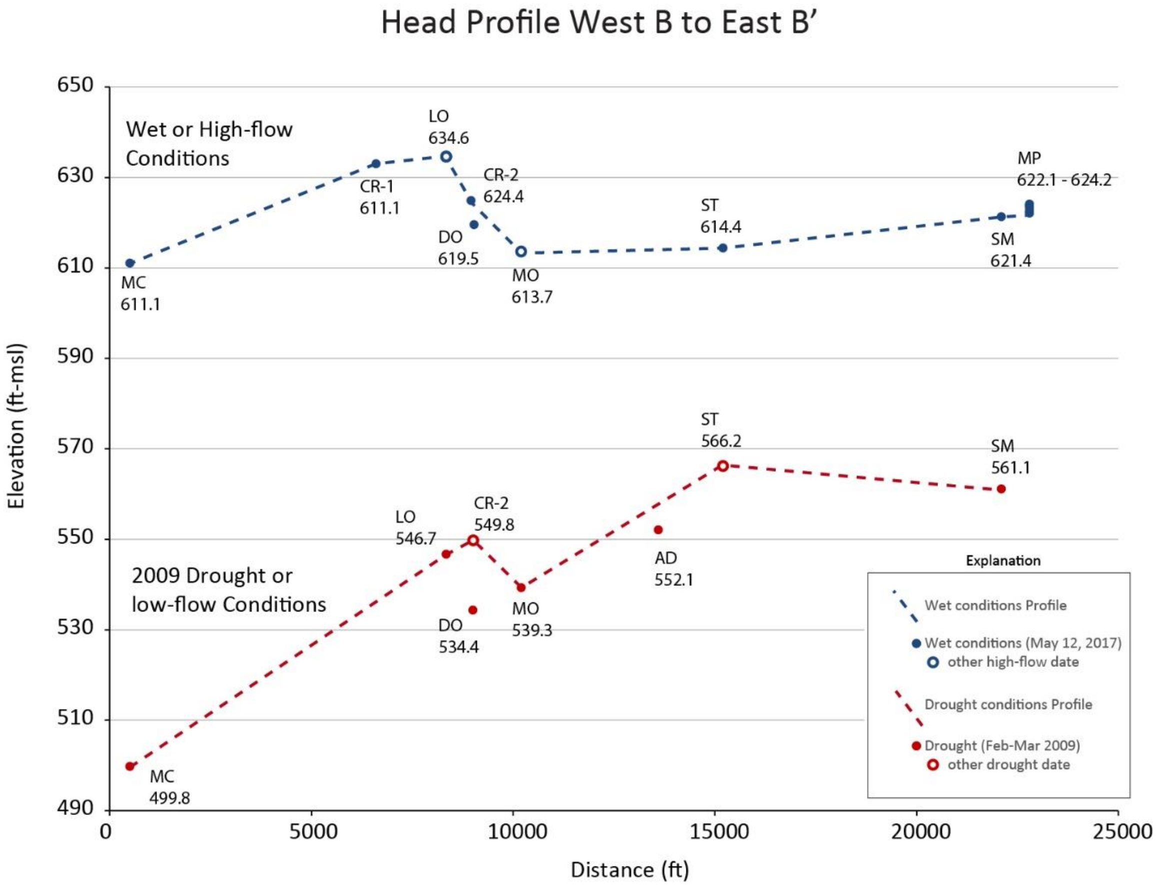


***Figure 18.*** *Transect and profile view across the freshwater/saline-water interface for the study area. Line of section shown in Figure 17. Water-level data provided in Supplement 3.*

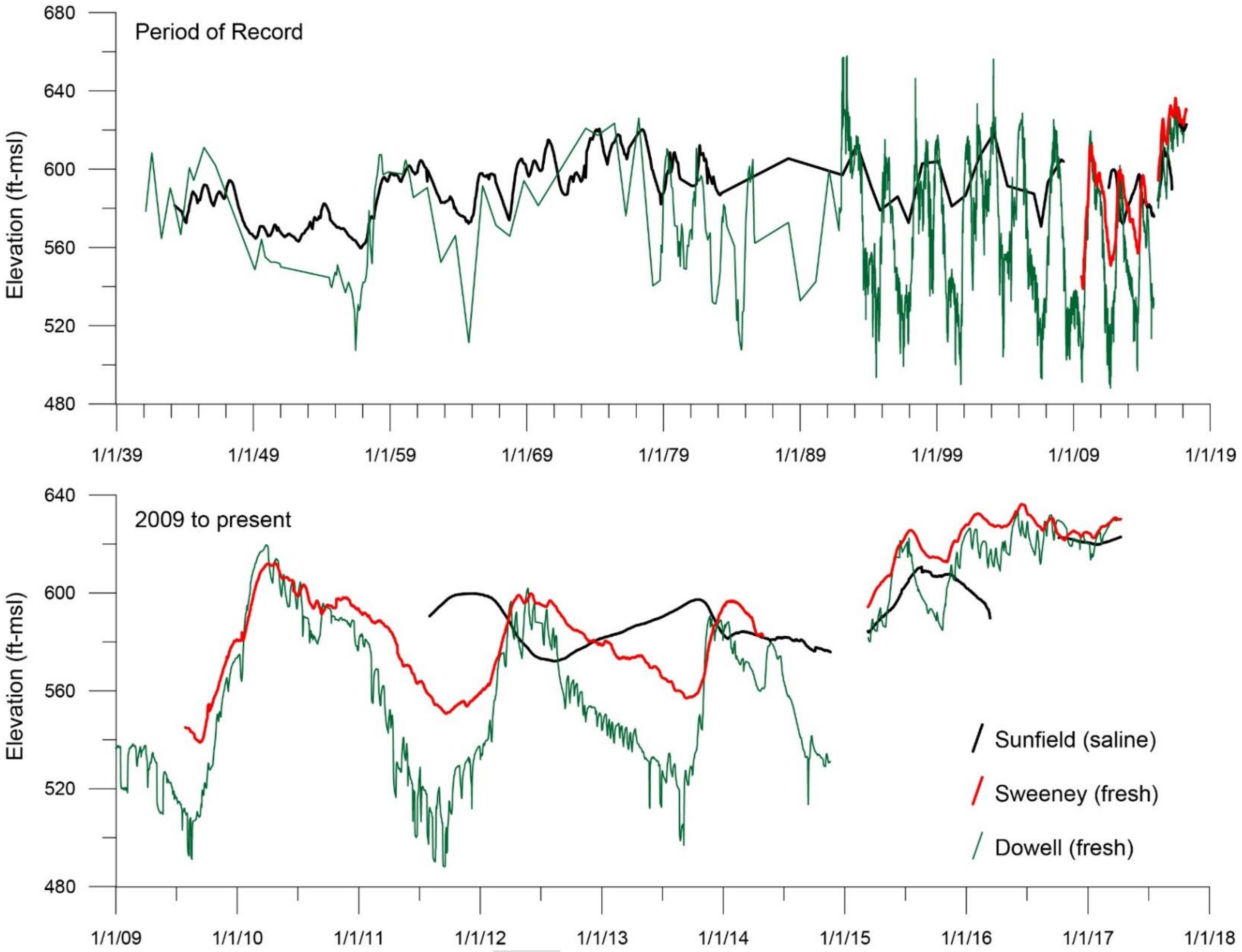


***Figure 19.*** *(Top) Period-of-record hydrograph from three wells in the study area. (Bottom) Same wells, 2009 to present data. Wells located in Figure 17.*

## Discussion: Water-Level and Gradient Data

Head data indicate several potentiometric changes in the profiles that occur where units are thought to be aquitards (**Figures 13 and 16**). Those include the Walnut Fm. (zone 3) at the base of the Edwards Group, the RDM (zone 12) between the Person and Kainer formations, and the overlying confining units of the Georgetown, Del Rio, Buda, and Eagle Ford (zones 15-18).

The highest heads within the Edwards are within the Kainer Formation (Zones 4-11) which are about 2 ft higher than the overlying Person Formation. The Kainer Formation contains the highest salinity and permeable zones. The RDM appears to be an aquitard between the two formations defining a change in heads. This is consistent with the Flores (1990) observations. This vertical distribution of heads appears to be similar to the data presented in the Kyle transect wells (Thomas et al., 2010) that has borehole flow data suggesting higher heads in the middle portion of the Edwards (**Supplement 1**).

Lateral gradients presented in **Figures 17 and 18** indicate that heads in the saline zone are higher than in the freshwater Edwards during drought conditions. This suggest the flow potential is from east (saline) to the west (fresh). However, during wet periods there is potential for the gradient to reverse and indicate a potential for flow from the west (fresh) to the east (saline). The periods of time when the heads are higher in the freshwater Edwards are much less than when heads are lower in the freshwater Edwards.

The Sunfield MUD well (SM, **Figures 18 and 19**) is in a similar setting to the multiport monitor well and is likely a good long-term proxy for heads. Long-term hydrographs (**Figure 19**) indicate that during drought periods the heads are higher in the saline zone, and under the wettest periods the gradients may reverse. However, there is a significant time lag in the saline Edwards well in response to changes in the freshwater Edwards.

# Aquifer Parameters

Permeability and storativity are important variables in determining the feasibility of pumping from, or injecting into, a geologic formation. The focus of this section is on the hydraulic conductivity testing done on zones of the multiport well.

## Previous work

A few studies have directly measured or estimated the permeability (transmissivity) and storativity of the saline Edwards Aquifer (Poteet et al., 1992; Pabalan et al., 2003; Lambert et al., 2010; Thomas et al., 2012). Key hydrogeologic parameters from those studies are summarized in **Table 8.**

## Methods

To measure hydraulic permeability, methods for slug testing in multiport wells were followed as described in Hunt et al., 2016. For this study, slug testing was performed prior to the purging of each zone. The test was performed using a sealed 1-in diameter, 3-ft-long PVC tube as a slug. Water-level changes inside the casing were measured by placing a pressure transducer (In-Situ Level TROLL, 100 psi) below the water level after a zone's pumping port was opened. After heads equilibrated between the zone and the water inside the casing, the slug tests were performed. The slug would be quickly lowered into the water with the pressure transducer recording resulting changes in head. Following removal of the slug and pressure transducer, the pumping port would be closed. Then the procedure would be repeated for each zone. Raw data collected were adjusted to clean up early-time noise, change of sign, and correct the elapsed time to account for when the displacement occurred.

Data were analyzed with AQTESOLV software (**Figure 20**). The program calculates hydraulic conductivity values by fitting solutions to graphical representations of deviation of head (ft) from static level with respect to time (elapsed time in seconds). Data from slug tests can be classified as either overdamped or underdamped (Duffield, 2014). Overdamped slug tests occur in low to moderate hydraulic conductivity aquifers (zone 14, Figure 11). Underdamped slug tests occur in high conductivity aquifers and exhibit oscillatory behavior as shown in zone 2 of **Figures 20**. We selected the commonly-used Bouwer and Rice (1976) straight-line method for overdamped data. AQTESOLV provides suggested head ranges for the straight-line match. For overdamped data, we also selected the Hyder et al. (1994) type-curve method in AQTESOLV (also known as the Kansas Geological Survey or KGS model). For underdamped (oscillatory) data, we selected the Butler (1998) or Butler-Zhan (2004) type-curve method. All methods can be used for confined or unconfined conditions and fully- or partially-penetrating wells. No corrections to the analyses for fluid densities were performed.

**Table 8.** Summary of estimated aquifer parameters and well yields from published sources

| Well | Well ID | Ddlat | Ddlong | Water Type | Well Depth (ft) | Open interval | LSD (ft-msl) | Static Water Depth (ft) | Discharge rate (gpm) | Drawdown (ft) | Specific Capacity (gpm/ft) | Transmissivity (ft^2/d) | Transmissivity (gpd/ft)** | Storativity* | TDS (mg/L) | Potential Well Yield (gpm)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **San Marcos B** | 67-01-812 | 29.890278 | -97.928333 | Saline | 554[a] | 495-545 | 581 | 0 to 7 | n/a | 2.5 | nd | 772 | 5,776 | 0.0002 | 8,810 to 12,267 | 1,450 |
| **San Marcos C--Person** | 67-01-813 | 29.891111 | -97.929444 | Saline | 564[b] | 505-555 | 581 | 2 to 7 | 70 | 15 | nd | 429 | 3,209 | 0.0002 | 8,900 to 11,972 | 860 |
| **San Marcos C--Kainer** | 67-01-830 | 29.891111 | -97.929444 | Saline | 699[c] | 640-690 | 581 | 2 to 7 | 70 | 15 | nd | 429 | 3,209 | 0.0002 | 9,928 to 12,152 | nd |
| **San Marcos D--Person** | 67-01-814 | 29.891945 | -97.930833 | Saline | 582[d] | 506-556 | 576 | -0.40 | nd | nd | nd | 1,026 | 7,672 | nd | 9,160 to 11,952 | nd |
| **San Marcos D--Kainer** | 67-01-831 | 29.891945 | -97.930833 | Saline | 742[d] | 506-556 | 576 | nd | nd | nd | nd | 1,026 | 7,672 | nd | 9,400 to 12,844 | nd |
| **Kyle 2** | 67-02-104 | 29.983055 | -97.871667 | Transitional | 975 | 427-975 | 674 | 76 to 134 | 12 | 5.1 | 2.4 | 472 | 3,530 | nd | nd | nd |
| **Kyle 3** | 67-02-106 | 29.974722 | -97.857223 | Saline | 1100 | 600-1100 | 678 | 89 to 121 | 18 | 8 | 2.3 | 451 | 3,370 | nd | 17,075 | nd |
| **Kyle 4** | 67-02-105 | 29.958334 | -97.842222 | Saline | 970 | 562-970 | 647 | 63 to 76 | 20 | 1.2 | 16.7 | 3,440 | 25,700 | nd | nd | nd |
| **Sunfield MUD #2** | 58-58-301 | 30.092222 | -97.789445 | Saline | 639 | 639-643 | 734 | 119-180 | nd | nd | nd | nd | nd | nd | nd | nd |
| **TWDB Test** | 58-58-213 | 30.112223 | -97.798889 | Transitional | 1010 | 515-985 | 740 | 116 | 8 | nd | nd | nd | nd | nd | 1,232 | nd |
| **TDS Test Well 2008** | 190570 | 30.120833 | -97.777778 | Saline | 800 | 640-763 | 725 | nd | 300 | nd | nd | nd | nd | nd | 13,000 | nd |

TDS= total dissolved solids (mg/L)
LSD= land surface datum (ft-msl)
nd= no data
a-later plugged back from 890 ft
b-later plugged back from 920 ft
c-later plugged back from 920 ft
d-plugged back from 775
*Poteet et al., 1992; Pabalan, et al., 2003
**Lambert et al., 2010; Thomas et al. 2012

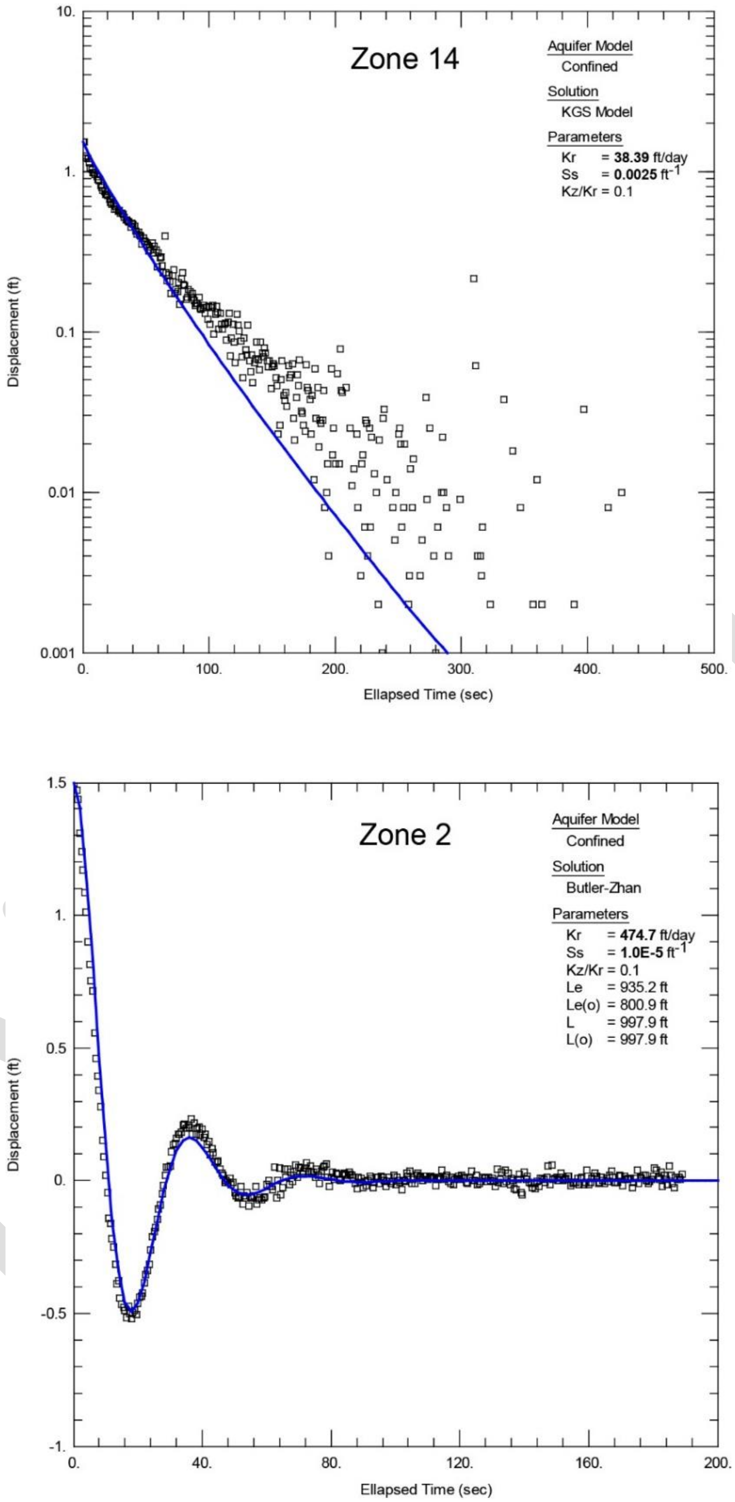


***Figure 20.*** *Example slug test analyses and curves from Aqtesolv. Top figure represents overdamped water-level response and solutions include the KGS and Bouwer-Rice solutions that produced similar values. The lower figure represents underdamped (high permeability) water-level response and the Butler-Zhan solution to estimate permeability.*

## Results: Hydraulic Conductivity

**Table 9** presents the results of estimated hydraulic conductivity from slug testing for each zone tested. **Figure 13** contains hydraulic conductivity data in relation to lithologic, head, and chemistry data. **Supplement 4** contains the raw data and analyses.

***Table 9.*** *Summary of permeability data from slug test analyses. Neutron log data from Table 6.*

| Zone | Zone Thickness (ft) | Pumping Port Depth (ft) | Formation | Date | DTW (ft)* | K (ft/d)** | Transmissivity (Ft^2/d) | Transmissivity (gpd/ft) | Neutron Porosity (%) |
|---|---|---|---|---|---|---|---|---|---|
| **18** | 32 | 405 | Kef | ND | | ND | ND | ND | 22 |
| **17** | 27 | 440 | Kbu | 11/10/2016 | 45.95 | 0.00001*** | 0.00 | 0.00 | 29 |
| **16** | 76.9 | NA | Kdr | ND | | ND | ND | ND | 30 |
| **15** | 32 | 550 | Kgt | 11/9/2016 | 45.4 | 0.34 | 11 | 81 | 9 |
| **14** | 37 | 585 | Ked | 10/14/2016 | 43.11 | 26.3 | 973 | 7,279 | 20 |
| **13** | 41.9 | 625 | Ked | 10/25/2016 | 45.81 | 95.02 | 3,981 | 29,783 | 25 |
| **12** | 22 | 660 | Ked_RDM | 10/24/2016 | 53.51 | 0.001 | 0.02 | 0.16 | 27 |
| **11** | 27 | 695 | Ked | 10/19/2016 | 45.51 | 243 | 6,561 | 49,080 | 32 |
| **10** | 32 | 725 | Ked | 11/8/2016 | 47.53 | 334.5 | 10,704 | 80,072 | 25 |
| **9** | 27 | 760 | Ked | 10/20/2016 | 45.63 | 136 | 3,672 | 27,469 | 29 |
| **8** | 37 | 790 | Ked | 11/7/2016 | 48.02 | 112 | 4,144 | 30,999 | 26 |
| **7** | 32 | 830 | Ked | 10/17/2016 | 40.8 | 240 | 7,680 | 57,450 | 15 |
| **6** | 32 | 865 | Ked | 11/4/2016 | 48.59 | 136.3 | 4,362 | 32,627 | 22 |
| **5** | 42 | 900 | Ked | 11/3/2016 | 46.86 | 145.3 | 6,103 | 45,651 | 29 |
| **4** | 42 | 945 | Ked | 10/21/2016 | 47.81 | 331 | 13,902 | 103,994 | 30 |
| **3** | 42 | 990 | Kwal | 10/31/2016 | 48.35 | 15 | 630 | 4,713 | |
| **2** | 32 | 1035 | Kgru | 10/18/2016 | 47.73 | 474 | 15,168 | 113,465 | |
| **1** | 45.7 | 1070 | Kgru | 10/26/2016 | 46.44 | 104.1 | 4,757 | 35,588 | |

NA = not applicable or no data; Zone 16 Kdr has no pumping port; Zones 12, 15, 17, 18 were not purged or sampled due to very low K; *DTW- depth to water, prior to purging zone; **average or select value; ***estimated

## Well Yield Estimates

Estimates for potential well yields (Q, gpm) are important for an evaluation of the saline Edwards Aquifer as a potential water supply and injection target. **Table 10** provides transmissivity values for each Edwards zone and an upper and lower estimate of yield (Q) for a production well given the permeability data collected in this study, published storativity values, and certain assumptions. Transmissivities were averaged over two aquifer units—an upper Edwards Aquifer unit (zones 13 and 14), and a lower Edwards Aquifer unit (zones 4-11). Drawdowns were limited to ½ and 2/3 of the water column as outlined in Pabalan, et al. (2003). Using these parameters and assumptions, the yield was obtained using the Theis equation in AQTESOLV.

**Table 10.** *Estimated well yield for a potential production well.*

| Zone | Pumping Port Depth (ft) | Formation | Date | DTW (ft) | K (ft/d) | Flag | Zone Thickness (ft) | Transmissivity (Ft^2/d) | TDS (mg/L) | Aquifer Interval | Combined thickness (ft) | Tavg (ft^2/d) | Storativity* | Average TDS (mg/L) | Max Drawdown (ft)** | Min Drawdown (ft)*** | Qmax (gpm) | Qmin (gpm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **14** | 585 | Ked--Person Fm | 10/14/2016 | 43.11 | 26.3 | | 37 | 973 | 9,310 | Upper Edwards Zone | 79 | 2,477 | 0.000198 | 9,094 | 363 | 179 | 2,750 | 1,300 |
| **13** | 625 | Ked--Person Fm | 10/25/2016 | 45.81 | 95.02 | | 42 | 3,981 | 8,877 | | | | | | | | | |
| **12** | 660 | Ked (RDM) | 10/24/2016 | 53.51 | 0.001 | e | 22 | 0.02 | nd | | | | | | | | | |
| **11** | 695 | Ked--Kainer Fm. | 10/19/2016 | 45.51 | 243 | | 27 | 6,561 | 13,541 | Lower Edwards Zone | 271 | 7,141 | 0.000198 | 16,707 | 435 | 214 | 9,000 | 4,300 |
| **10** | 725 | Ked--Kainer Fm. | 11/8/2016 | 47.53 | 334.5 | | 32 | 10,704 | 15,743 | | | | | | | | | |
| **9** | 760 | Ked--Kainer Fm. | 10/20/2016 | 45.63 | 136 | | 27 | 3,672 | 17,224 | | | | | | | | | |
| **8** | 790 | Ked--Kainer Fm. | 11/7/2016 | 48.02 | 112 | | 37 | 4,144 | 17,294 | | | | | | | | | |
| **7** | 830 | Ked--Kainer Fm. | 10/17/2016 | 40.8 | 240 | | 32 | 7,680 | 16,298 | | | | | | | | | |
| **6** | 865 | Ked--Kainer Fm. | 11/4/2016 | 48.59 | 136.3 | | 32 | 4,362 | 18,622 | | | | | | | | | |
| **5** | 900 | Ked--Kainer Fm. | 11/3/2016 | 46.86 | 145.3 | | 42 | 6,103 | 17,932 | | | | | | | | | |
| **4** | 945 | Ked--Kainer Fm. | 10/21/2016 | 47.81 | 331 | | 42 | 13,902 | 17,007 | | | | | | | | | |

e= estimated

Pumping well construction: rc= 6 in, rw= 12 inches

Q = well yield (gpm)

*from Poteet et al., 1992

**drawdown is 33% of difference of static level to port depth of shallowest zone

***drawdown is 67% of difference of static level to port depth of shallowest zone

### Discussion of Permeability

Porosity data in **Table 6** do not correlate with the direct measurements of permeability in **Table 9**. The transmissivity data of this study (**Table 9**) are similar to the data from the Kyle transect (**Table 8; Supplement 1**). Collectively, these data suggest relatively high-yielding wells are possible in the saline Edwards Aquifer (**Table 10**). Estimates of well yield (Q) in **Table 10** are relatively insensitive to order of magnitude changes in storativity. However, well yield (Q) is sensitive to changes in transmissivity. This study provides the most detailed measurements of transmissivity for the saline Edwards Aquifer.

## Geochemistry

Geochemical data for each zone is an important variable in determining the feasibility for desalinization and also for understanding mixing or other geochemical processes with a desalinization and ASR system.

***Figure 21.*** *Photograph of inertial pump during purging of a zone. Photo taken 10/14/2016.*

### Previous work

Numerous studies have focused on the geochemistry of the saline Edwards to map and characterize the geochemical facies and TDS concentrations as they relate to the freshwater interface (Flores, 1990;

Schultz, 1993; Lambert et al., 2010). The most recent delineation of the freshwater/saline-water interface in the study area was completed by Hunt et al., 2014 (**Figure 1**). Other studies have focused on the origin of the saline water (section titled Saline Edwards Aquifer).

Recent geochemical studies include Mahler (2008) who presents statistical analyses of major ion and trace element geochemical data from wells that transect the freshwater/saline-water interface in the San Antonio area. Data were collected for more than 21 years from these wells. Mahler (2008) concludes that the transition zone wells (wells 1,000 to 10,000 mg/L) have relatively constant geochemistry and are not as connected to the surface hydrological conditions as the freshwater wells. Despite being less influenced by surface hydrological conditions, these wells do show some geochemical response to varying hydrologic (drought versus non-drought) conditions, although more slowly than the freshwater wells. Most of the data from these studies are derived from wells with long open-hole intervals.

## Methods

After completion of the multiport well and isolation of the zones through packer inflation, each zone was individually purged. Purging of a zone was done by opening the pumping port and then using an inertial pump inside the PVC casing. Target purge volumes were calculated as four times the zone volume plus one PVC volume. Target purge volumes ranged from 215 to 320 gallons per zone. Purge rates varied based on the permeability of the zone and ranged from 0.5 to 3.5 gpm. Actual purge volumes varied from 110%-190% of the target volume. During the course of purging, a Horiba UM-50 measured field parameters and confirmed stability of values. After purging a zone, the pumping port was closed.

Westbay multiport systems offer the ability to collect discrete fluid samples. Four 250-ml stainless steel bottles are attached to the sampling instrument. Prior to insertion in the well, a vacuum is placed on the stainless steel sample bottles. The sampling instrument and sample bottles are lowered to the desired port depth. Because of the design of the multiport components, the sampling instrument can be placed at the exact port to be sampled. The instrument contains a valve through which water samples (up to 1 L) can be collected. When the instrument is in place, the valve is opened and water from the formation passes through the instrument and into the stainless steel bottles. The instrument and sample bottles are then retrieved to the surface.

Sampling, preservation, decontamination, and chain of custody procedures were generally followed as described by the Texas Water Development Board's guidelines UM 51 (Boghici, 2003). All samples were filtered in the field with disposable polyethersulfone membrane filters (QuickFilter) with 0.45 micron membranes and delivered to Environmental Laboratory Services (ELS).

All samples were analyzed for major anions and cations, deuterium, oxygen 18, and strontium 86/87. Two samples for carbon-14 analysis were collected from zones 10 and 13.

## Results: Geochemistry

Samples of groundwater from 13 hydrostratigraphic zones were collected in October and November 2016. Two zones were resampled in March 2017 for confirmation of ion geochemistry and analysis of carbon 14. Results of laboratory analyses are summarized in **Table 11**. Detailed lab reports are in **Supplement 5**.

All geochemical analyses were funded by the Texas Water Development Board and data are available online (http://www2.twdb.texas.gov/apps/waterdatainteractive/groundwaterdataviewer).

**Figure 22**, a Durov diagram, is a graphical representation of the multiport well geochemistry compared with other waters. The basis of the Durov diagram is percentage plotting, in separate trilinear diagrams, of the major cations (calcium, magnesium, and sodium + potassium) and the major anions (bicarbonate, sulfate, and chloride) in units of millequivalents per liter (meq/L). Lines from each pair of points in the cation (left) and anion (top) trilinear fields are projected into the central square to form a common point, which represents the composition of a sample with respect to cations and anions. The points from the square field are also projected into TDS (right) and pH (bottom) fields. Similar in concept to Piper diagrams, Durov diagrams allow for more detailed comparison of samples based not only on major-ion chemistry, but also TDS and pH. The latter variables add two dimensions for interpretation that are not included with Piper diagrams.

The locations of symbols representing the multiport well in the trilinear and the square fields indicate that the overall hydrochemical signature is sodium-chloride. The points lie near symbols that represent waters of similar composition: seawater and the St. Alban's saline boundary well. Accounting for variations in the ratios of sodium-to-magnesium and chloride-to-sulfate, differences in TDS further differentiate the multiport samples from seawater and the transition-zone well.

Within the trilinear and square fields, symbols representing the multiport well form an overlapping cluster. The spread of multiport symbols in the TDS field illustrates that the concentration of dissolved solids is not uniform in the Upper Glen Rose and Walnut formations (Zones 1 – 3) and the Kainer and Person formations (Zones 4 - 14).

Edwards springs and wells, Middle Trinity springs, and Onion Creek surface water are clearly differentiated from multiport samples by the cluster of green symbols near the upper right corner of the square. The compositions are all calcium-bicarbonate (Ca-HCO3), with TDS typically less than 400 mg/L. Middle Trinity wells are distinguished from the above by the dominance of sulfate and magnesium and TDS as high as 1000 mg/L.

The variation in geochemical composition in the 13 hydrostratigraphic zones described in this report is further illustrated by depth profiles of major cations, anions.

In **Figure 23**, TDS increases from 13000 mg/L in the Upper Glen Rose (Zone 2, -1025 ft) to 18500 mg/L in the Kainer formation (Zone 6, -855 ft) and decreases to 13500 mg/L at the top of the Kainer (Zone 12, -685 ft). Above the Regional Dense Member aquitard (Zone 12), TDS is less than 9400 mg/L in the Person formation (Zones 13 and 14, -615 ft and -575 ft, respectively). The chloride depth profile mimics that of TDS, an indication that chloride is a primary component of dissolved solids.

In **Figure 24**, the profile of sulfate does not follow that of chloride. The lowest concentrations are in the Upper Glen Rose, Walnut and lower Kainer formations (Zones 1 -7), and the highest are in the Upper Kainer (Zone 9) and Upper Person (Zone 14) formations.

There is also marked conformance between the depth profiles of the concentrations of sodium and chloride (**Figure 25**), and calcium + magnesium and bicarbonate (**Figure 26**). **Figures 24** - **26** underscore that the hydrochemical profile, although relatively uniform with respect to overall composition, varies with regard to stratigraphy, with the highest TDS occurring in the Kainer formation. A more detailed assessment of geochemical factors accounting for hydrochemical signatures will be developed in a separate report on the inorganic and isotope geochemistry of the Edwards and Trinity Aquifer systems.

## Equilibrium Chemistry

### *Effect of Mixing Injectate with Groundwater of the Edwards Aquifer (Person Formation)*

Groundwater mixing models were developed with Geochemist's Workbench© v. 11 to illustrate the effect of mixing groundwater of the Person formation (14-Kep and 13-Kep) with two potential sources of injected water: (1) desalinated groundwater of the Kainer formation (11-Kep – 4-Kep), and (2) fresh groundwater from the Creedmoor Water Supply Corporation. Such models are a means of assessing the compatibility of injectate and native groundwater and to ascertain whether groundwater in the mixing zone is oversaturated or undersaturated with respect to key mineral species. This is especially important if arsenic-bearing minerals are disseminated within the matrix of the receiving formation. In situations in which there are marked differences between the hydrochemical compositions of injectate and groundwater, mixing models also illustrate the degree to which higher-TDS water of the storage zone will dominate the composition of water in the mixing zone.

The ratios of the Person-Kainer and the Person-Creedmoor models were 1:99, 2:98, 5:95, 25:75, and 50:50. The composition of Person groundwater was modeled as a 50:50 mixture of groundwater from zones 14-Kep and 13-Kep. The composition of desalinated Kainer groundwater was based on Carollo's estimated concentration of dissolved solids, and the composition of Creedmoor groundwater was taken from data on the Creedmoor WSC well as found in the groundwater data base of the Texas Water Development Board. Dissolved oxygen (DO) concentrations for Person and treated Kainer were set to 0.1 mg/L, and to 2.1 mg/L for Creedmoor. The Creedmoor estimate was based on data from a BSEACD study of DO concentrations in groundwater (Lazo-Herenca et al., 2011). The compositions of Person, treated Kainer, Creedmoor, and the modeled mixtures are listed in **Table 12**. The results of the mixing models are illustrated by two Schoeller diagrams (**Figure 27**). The Schoeller format was selected because it better illustrates changes in composition based on the mixing ratios used in this assessment.

Carollo's estimated composition of treated Kainer water required adjustment to eliminate a large negative charge imbalance (-54 percent) and to force electroneutrality, a fundamental requirement of geochemical modeling of aqueous systems. The adjustment was made by specifying charge balance on sodium. This increased the estimated TDS from 7 mg/L to 16 mg/L.

The compositions of the endmembers are: Person (Na-Cl-SO4), treated Kainer (Na-OH), and Creedmoor (Ca-HCO3). There are also large differences in TDS (Person, 9487 mg/L; treated Kainer, 16 mg/L; and Creedmoor, 484 mg/L) and in ionic strength (Person, 0.1744 mol/L; treated Kainer, 0.0004 mol/L; and Creedmoor, 0.0087 mol/L).

The models illustrate that the saline groundwater of the Person formation strongly dominates the composition of all mixtures with treated Kainer groundwater and four of the five mixtures with Creedmoor groundwater. The dominance of Person groundwater in the mixtures is clearly illustrated by the Schoeller diagrams of **Figure 27**. All Person-Kainer mixtures are Na-Cl, and the TDS of the mixtures ranges from 110 at a 1:99 Person-Kainer ratio to 4823 at 50:50. The TDS of mixtures with Creedmoor groundwater ranges from 574 at 1:99 to 4984 at 50:50. Mixtures consisting of 5 percent or more Person groundwater are Na-Cl. At lower percentages of Person groundwater, the mixtures are Ca-HCO3.

Selected saturation indices are listed in columns below the table of concentrations (**Table 12**). Positive values indicate oversaturation with respect to a mineral species, and negative values are interpreted to indicate undersaturation. It is important to note that oversaturation does not signify that a mineral will precipitate, only that it has the potential to form. Negative indices indicate the potential for dissolution.

The negative indices for pyrite indicate the potential for dissolution of the mineral. At this time, the presence of pyrite in the matrix of the Person formation has not been verified. Pyrite is a mineral with which arsenic is often associated. Concentrations of arsenic in zones 14 and 13 are 3.68 μg/L and 3.79 μg/L, respectively. The occurrence of arsenic in the samples indicates that arsenic is available within the formation. The mineralogical association, however, is not known.

It is important to note that DO of Creedmoor groundwater might drive the oxidation of any pyrite in the Person formation. Oxygenated waters injected at early ASR sites in Florida were the key factors that led to the release of arsenic in concentrations greater than the 10-μg/L MCL (Arthur et al., 2002; Price and Pichler 2006; Jones and Pichler 2007), primarily from pyrite ($FeS_2$) and arsenopyrite (FeAsS). The occurrence of arsenic in groundwater at ASR sites in Florida was not observed until the early stages of cycle testing, and the mineral associations were discovered only after investigators examined cores and cuttings from the storage zone (Suwannee Limestone).

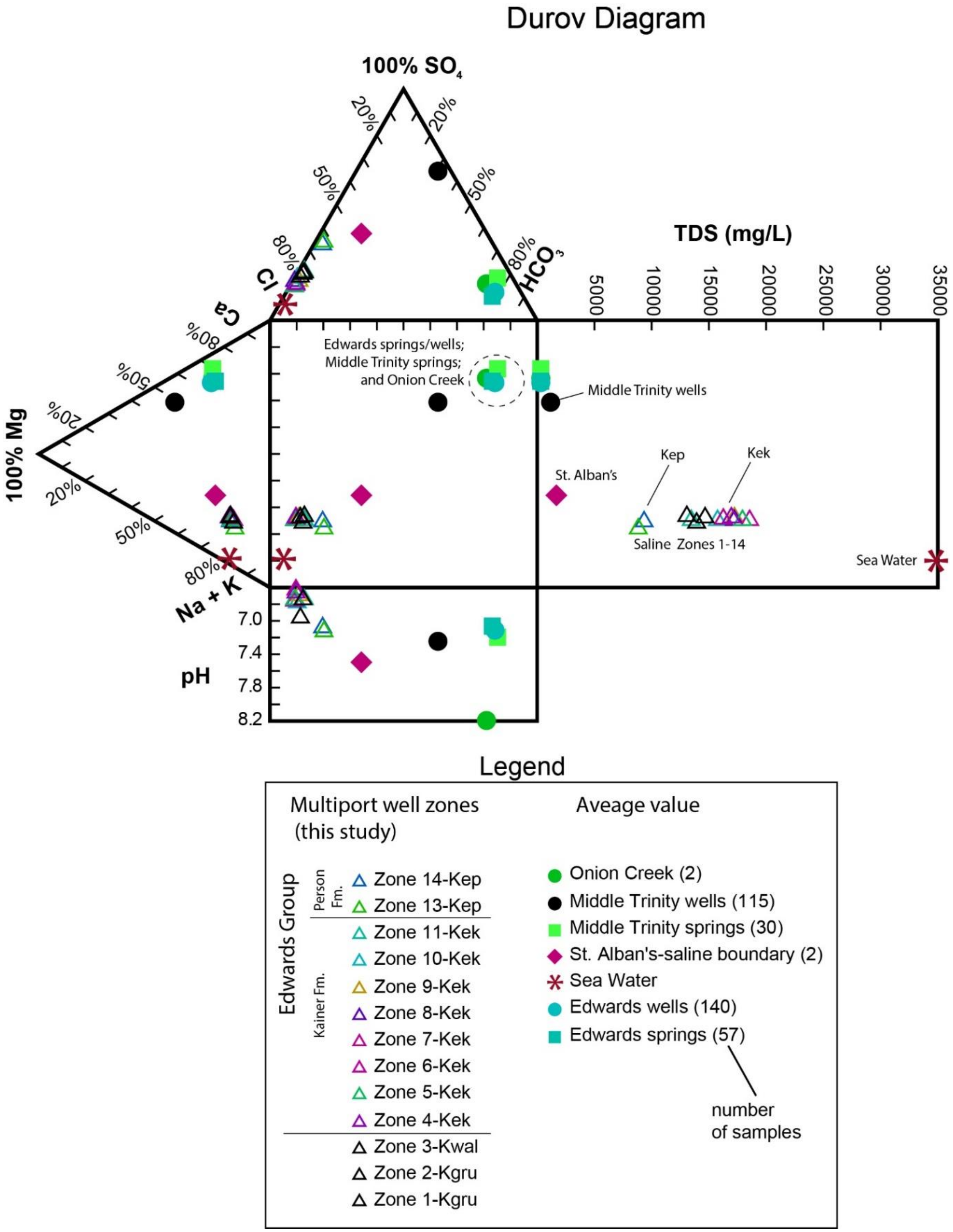


***Figure 22.*** *Durov diagram showing geochemistry of the multiport zones compared to other source waters. Results indicate all the multiport zones have a sodium-chloride water type.*

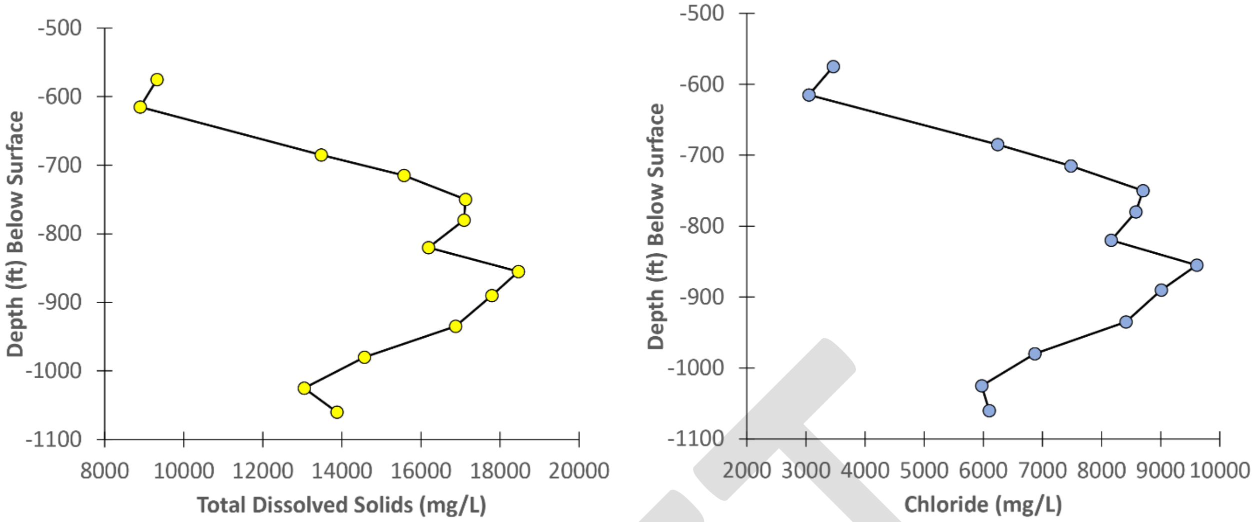


***Figure 23.*** *Depth profile of total dissolved solids (mg/L) and chloride (mg/L).*

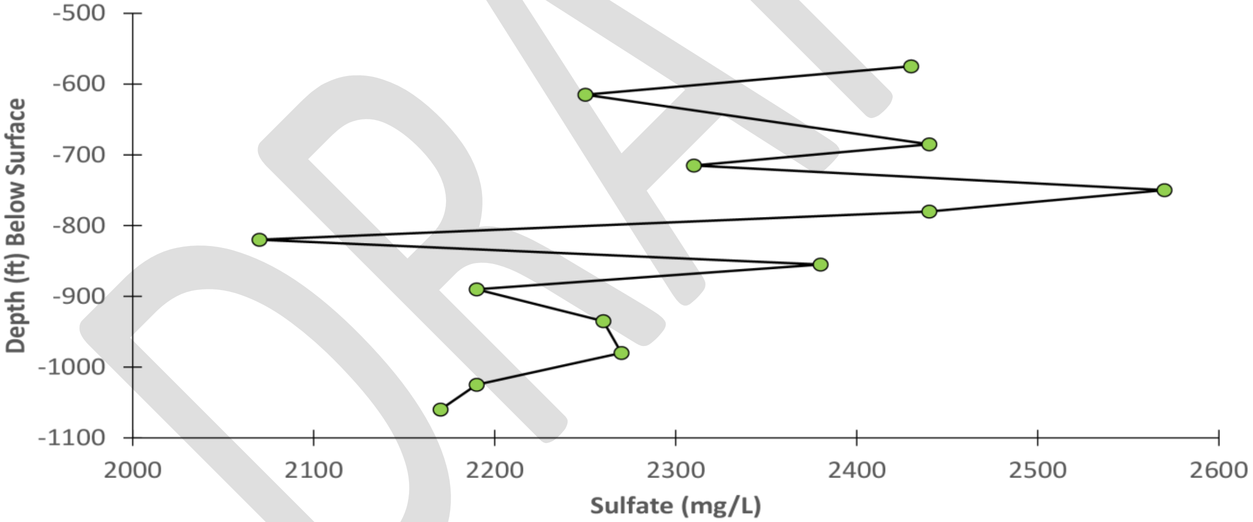


***Figure 24.*** *Depth profile of sulfate (mg/L).*

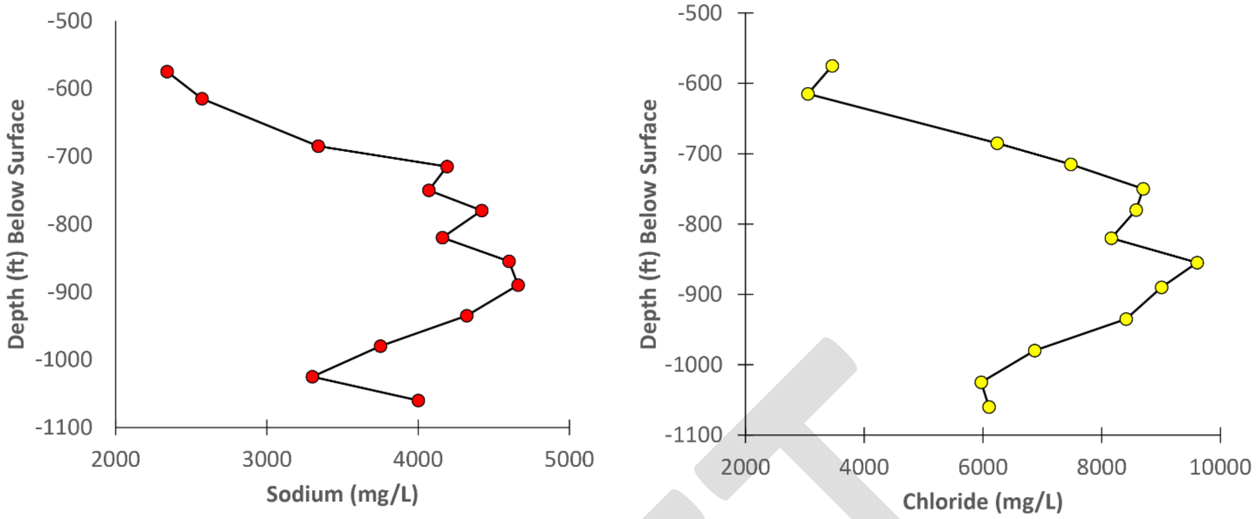


**Figure 25.** *Depth profile of sodium (mg/L) and chloride (mg/L).*

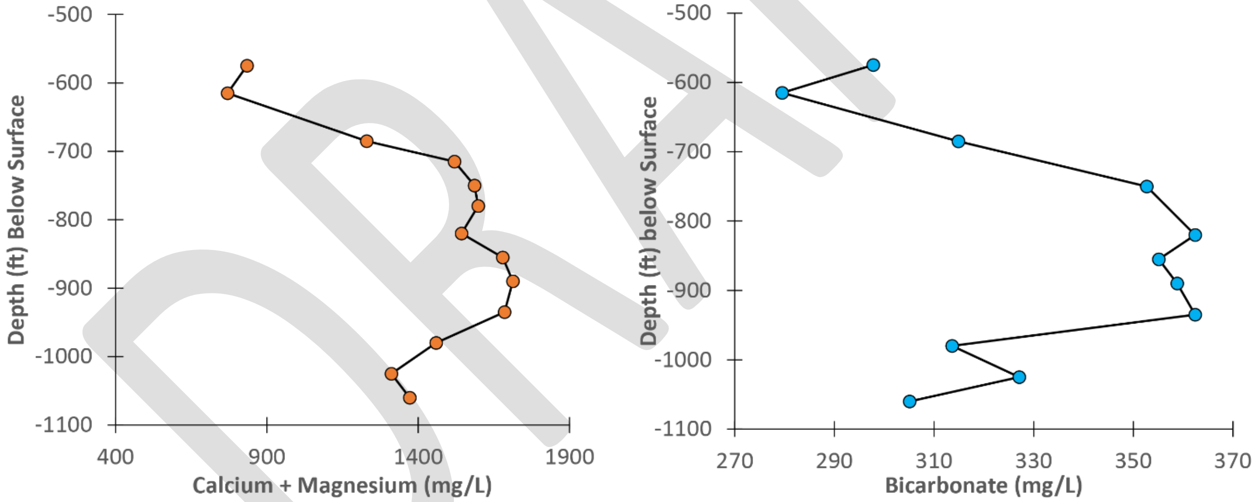


***Figure 26.*** *Depth profile of Calcium + Magnesium (mg/L) and Bicarbonate (mg/L).*

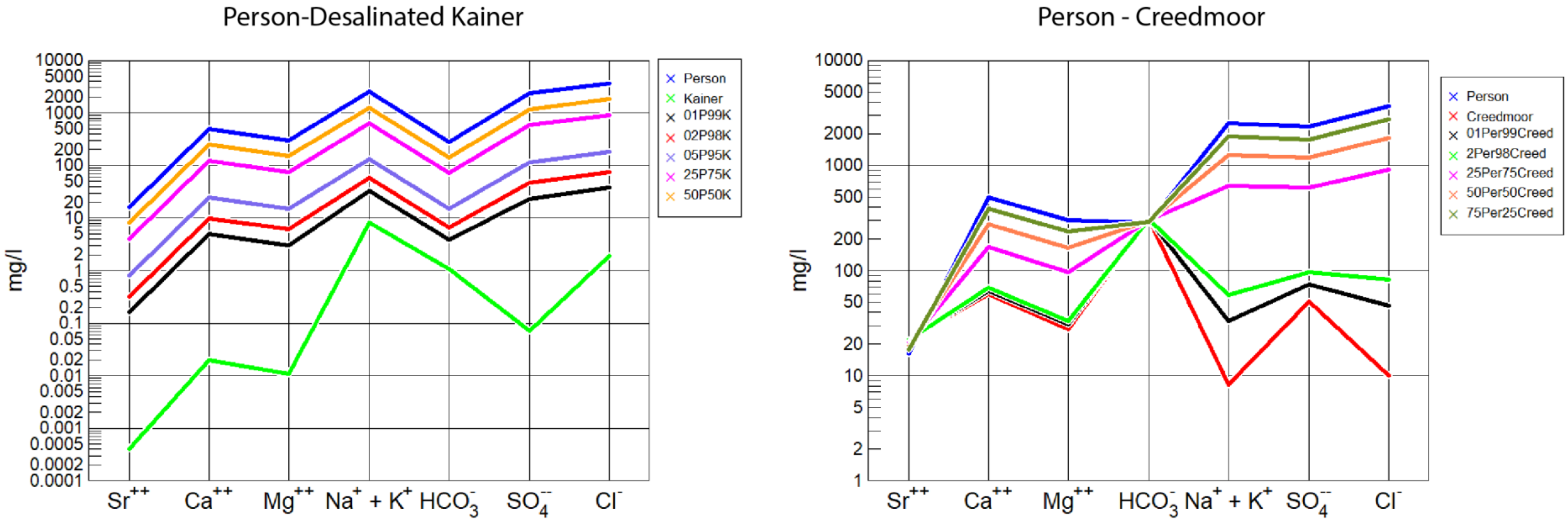


***Figure 27.*** *Schoeller diagrams illustrating results of mixing groundwater of Person formation with desalinated injectate and with fresh groundwater from Creedmoor WSC. Person:Injectate and Person:Creedmoor mixing ratios are 1:99, 2:98, 5:95, 25:75,and 50:50.*

***Table 11.*** *Summary of geochemistry data.*

| Zone | Geologic Unit | Sample Port Depth (ft) | Purge Volume* | Sample Date | Purge Water Conductivity (uS/cm) | Temp C | TDS (mg/L) | An/Cat Charge Balance (%) | Ca (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | SO4 (mg/L) | HCO3 (mg/L) | Cl (mg/L) | AS (ug/L) | Fl (mg/L) | Sr (mg/L) | Si (mg/L) | Br (mg/L) | B (ug/L) | Mn (ug/L) | Fe (ug/L) | Nitrite/Nitrate (mg/L as N) | pH | Deut (PERMIL VSMOW) | O-18 (PERMIL VSMOW) | Sr-86/87 | Delta Carbon 13 C13/C12 per mil | PMC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 18 | Eagle Ford | 395 | NA | NS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 17 | Buda | 430 | NA | NS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 16 | Del rio | 475 | NA | NS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 15 | Georgetown | 540 | NA | NS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 14 | Edwards-- Person Fm | 575 | 122% | 10/14/2016 | 14,200 | 24.22 | 9,310 | -0.82 | 518 | 316 | 2,340 | 69 | 2,430 | 298 | 3,460 | 3.68 | 3.1 | 15.90 | 11.6 | 32.40 | 4,840 | 44.90 | 221 | <0.02 | 7.1 | -28.1 | -4.73 | 0.7086722 | | |
| 13 | Edwards-- Person Fm | 615 | 140% | 10/25/2016 | 14,300 | 24.78 | 8,877 | -8.15 | 478 | 292 | 2,570 | 70 | 2,250 | 279 | 3,050 | 3.79 | 5 | 16.60 | 13.1 | 33.60 | 4,170 | 30.60 | 99 | <0.04 | 7.1 | -30.0 | -4.57 | 0.7086857 | | |
| 13 | Edwards-- Person Fm | 615 | n/a | 3/29/2017 | | 24.12 | 9,857 | -4.85 | 569 | 322 | 2,660 | 70 | 2,590 | 256 | 3,460 | 3.97 | 3.12 | 17.20 | 12.5 | 30.10 | 4,290 | 11.40 | <50 | <0.02 | nd | nd | nd | nd | 0.0 | < 0.0044 |
| 12 | Edwards-- Person (RDM) | 650 | | NS | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | Edwards-- Kainer Fm | 685 | 190% | 10/19/2016 | 22,200 | 2440 | 13,541 | 1.69 | 773 | 457 | 3,340 | 98 | 2,440 | 315 | 6,240 | 7.7 | 2.88 | 18.90 | 16.2 | 51.55 | 6,750 | 140.00 | 1,020 | <0.02 | 6.7 | -28.7 | -4.27 | 0.7087400 | | |
| 10 | Edwards-- Kainer Fm | 715 | 140% | 11/8/2016 | 23,200 | 24.23 | 15,743 | -3.23 | 972 | 548 | 4,190 | 120 | 2,310 | 175 | 7,480 | 8.81 | <10 | 22.00 | 14.8 | 53.30 | 7,870 | <2.00 | 60 | <0.1 | 6.8 | -27.4 | -3.88 | 0.7088100 | | |
| 10 | Edwards-- Kainer Fm | 715 | n/a | 3/29/2017 | | 24.75 | 15,642 | 1.64 | 970 | 520 | 3,820 | 116 | 2,480 | 283 | 7,520 | 10.3 | 2.75 | 22.20 | 21.4 | 59.20 | 7,210 | 1.67 | <50 | <0.08 | nd | nd | nd | nd | 0.1 | < 0.0044 |
| 9 | Edwards-- Kainer Fm | 750 | 166% | 10/20/2016 | 23,800 | 25.4 | 17,224 | 4.46 | 1,010 | 576 | 4,070 | 115 | 2,570 | 353 | 8,700 | 9.84 | 2.8 | 20.80 | 15.8 | 69.20 | 7,530 | <2.00 | <1000 | <0.1 | 6.7 | -28.0 | -4.08 | 0.7088310 | | |
| 8 | Edwards-- Kainer Fm | 780 | 120% | 11/7/2016 | 25,200 | 24.06 | 17,294 | 0.26 | 1,030 | 568 | 4,420 | 129 | 2,440 | 179 | 8,580 | 9.62 | <10 | 22.70 | 15.9 | 63.00 | 8,430 | <2.00 | <50 | <0.1 | 6.8 | -27.5 | -3.83 | 0.7088495 | | |
| 7 | Edwards-- Kainer Fm | 820 | 154% | 10/17/2016 | 25,500 | 26.12 | 16,298 | 0.00 | 1,000 | 543 | 4,160 | 133 | 2,070 | 362 | 8,160 | 10.4 | 3.79 | 22.30 | 27.8 | 61.80 | 7,910 | 4.81 | 183 | <0.04 | 6.6 | -27.4 | -3.99 | 0.7088500 | | |
| 6 | Edwards-- Kainer Fm | 855 | 122% | 11/4/2016 | 25,400 | 24.65 | 18,622 | 3.08 | 1,090 | 589 | 4,600 | 134 | 2,380 | 355 | 9,610 | 9.76 | <5 | 24.10 | 19.9 | 72.20 | 8,850 | 2.92 | <50 | <0.1 | 6.8 | -27.7 | -3.89 | 0.7088755 | | |
| 5 | Edwards-- Kainer Fm | 890 | 117% | 11/3/2016 | 26,200 | 25.45 | 17,932 | -1.00 | 1,110 | 603 | 4,660 | 137 | 2,190 | 359 | 9,010 | 9.66 | <5 | 24.80 | 20.3 | 68.30 | 8,780 | 2.58 | <50 | <0.1 | 6.7 | -27.3 | -3.79 | 0.7088816 | | |
| 4 | Edwards-- Kainer Fm | 935 | 163% | 10/21/2016 | 24,600 | 25.95 | 17,007 | -0.86 | 1,070 | 615 | 4,320 | 117 | 2,260 | 362 | 8,410 | 11.10 | 2.90 | 22.30 | 11.2 | 58.20 | 5,130 | 5.06 | <2500 | <0.1 | 6.7 | -27.4 | -3.93 | 0.7088526 | | |
| 3 | Walnut Fm | 980 | 110% | 11/2/2016 | 21,300 | 24.86 | 14,648 | -1.97 | 936 | 523 | 3,750 | 105 | 2,270 | 314 | 6,870 | 7.03 | <5 | 22.80 | 16.8 | 56.60 | 6,300 | 9.19 | <50 | <0.1 | 7.0 | -27.8 | -4.07 | 0.7087874 | | |
| 2 | Upper Glen Rose Mbr | 1025 | 132% | 10/18/2016 | 20,300 | 26.82 | 13,090 | -1.69 | 848 | 463 | 3,300 | 107 | 2,190 | 327 | 5,970 | 6.29 | 3.90 | 18.40 | 28.6 | 49.20 | 6,730 | 14.60 | 68 | <0.04 | nd | -29.8 | -4.26 | 0.7088380 | | |
| 1 | Upper Glen Rose Mbr | 1060 | 147% | 10/28/2016 | 21,900 | 26.29 | 13,942 | -8.16 | 881 | 491 | 4,000 | 114 | 2,170 | 305 | 6,100 | 6.68 | <10 | 20.90 | 15.2 | 55.60 | 6,760 | 8.14 | <50 | <0.04 | 6.7 | -28.2 | -4.07 | 0.7088300 | | |

*100%=4 x zone volume and 1 x pipe volume.

*Table 12. Modeled results of mixing groundwater from Person formation with desalinated injectate and with groundwater from Creedmoor WSC. Person:Injectate and Person:Creedmoor mixing ratios are 1:99, 2:98, 25:75, 50:50, and 75:25*

| SAMPLE ID | UNIT | PERSON | KAINER | 01P99K | 02P98K | 05P95K | 25P75K | 50P50K | CREEDMOOR | 1P-99C | 2P-98C | 5P-95C | 25P-75C | 50P-50C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **TEMPERATURE** | C | 24.5 | 25 | 25 | 24.99 | 24.98 | 24.88 | 24.75 | 24 | 24 | 24.01 | 24.02 | 24.13 | 24.25 |
| **PH** | pH | 7.093 | 10.41 | 10.32 | 10.26 | 9.989 | 8.615 | 7.483 | 7.1 | 7.097 | 7.095 | 7.087 | 7.07 | 7.068 |
| **SIO2(AQ)** | mg/l | 12.35 | 0.0013 | 0.1242 | 0.2471 | 0.6159 | 3.077 | 6.161 | 10.9 | 10.92 | 10.93 | 10.97 | 11.26 | 11.63 |
| **O2(AQ)** | mg/l | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 2.1 | 2.079 | 2.059 | 1.998 | 1.589 | 1.077 |
| **CA++** | mg/l | 498 | 0.0195 | 4.976 | 9.933 | 24.81 | 124.1 | 248.4 | 60 | 64.36 | 68.72 | 81.82 | 169.2 | 278.6 |
| **MG++** | mg/l | 304 | 0.011 | 3.037 | 6.062 | 15.14 | 75.74 | 151.6 | 27.9 | 30.65 | 33.4 | 41.65 | 96.73 | 165.7 |
| **SR++** | mg/l | 16.25 | 4.00E-04 | 0.1621 | 0.3239 | 0.8092 | 4.048 | 8.106 | 22 | 21.94 | 21.88 | 21.71 | 20.57 | 19.13 |
| **NA+** | mg/l | 2448 | 8.264 | 32.55 | 56.83 | 129.7 | 616 | 1225 | 7 | 31.32 | 55.64 | 128.6 | 615.5 | 1225 |
| **K+** | mg/l | 69.75 | 0.0343 | 0.7282 | 1.422 | 3.504 | 17.4 | 34.81 | 1.2 | 1.883 | 2.566 | 4.615 | 18.29 | 35.41 |
| **HCO3-** | mg/l | 283.9 | 1.065 | 3.879 | 6.695 | 15.14 | 71.52 | 142.1 | 309.6 | 309.3 | 309.1 | 308.3 | 303.2 | 296.8 |
| **SO4--** | mg/l | 2340 | 0.0713 | 23.36 | 46.65 | 116.5 | 583 | 1167 | 51 | 73.8 | 96.61 | 165 | 621.6 | 1193 |
| **CL-** | mg/l | 3650 | 1.904 | 38.21 | 74.53 | 183.5 | 910.7 | 1822 | 10 | 46.26 | 82.53 | 191.3 | 917.4 | 1826 |
| **BR-** | mg/l | 33 | 0.0155 | 0.3438 | 0.6721 | 1.657 | 8.232 | 16.47 | 0.01 | 0.3387 | 0.6673 | 1.653 | 8.234 | 16.47 |
| **F-** | mg/l | 2.8 | 0.0023 | 0.03015 | 0.05799 | 0.1416 | 0.6992 | 1.398 | 0.9 | 0.9189 | 0.9378 | 0.9946 | 1.374 | 1.848 |
| **B** | mg/l | 4.505 | 0.0849 | 0.1289 | 0.1729 | 0.3049 | 1.186 | 2.29 | 0.1 | 0.1439 | 0.1877 | 0.3194 | 1.198 | 2.298 |
| **FE** | mg/l | 0.1600 | | 0.0016 | 0.0032 | 0.0080 | 0.0399 | 0.0798 | 0.1000 | 0.1006 | 0.1012 | 0.1030 | 0.1150 | 0.1299 |
| **MN** | mg/l | 0.0378 | | 0.0004 | 0.0008 | 0.0019 | 0.0094 | 0.0188 | 0.1000 | 0.0994 | 0.0988 | 0.0969 | 0.0845 | 0.0689 |
| **AS** | mg/l (as As) | 0.0037 | | 0.0000 | 0.0001 | 0.0002 | 0.0009 | 0.0019 | 0.0000 | 0.0000 | 0.0001 | 0.0002 | 0.0009 | 0.0019 |
| **TDS** | mg/l | 9487 | 16.06 | 110.1 | 207.2 | 494.2 | 2416 | 4823 | 483.7 | 573.7 | 663.8 | 946.8 | 2735 | 4984 |
| **WATER TYPE** | | Na-Cl | Na-OH | Na-Cl | Na-Cl | | Na-Cl | Na-Cl | Ca-HCO3 | Ca-HCO3 | Ca-HCO3 | Na-Cl | Na-Cl | Na-Cl |
| | | | | | | | | | | | | | | |
| **IONIC STRENGTH** | mol/l | 1.74E-01 | 3.73E-04 | 2.39E-03 | 4.36E-03 | 1.01E-02 | 4.65E-02 | 9.01E-02 | 8.71E-03 | 1.05E-02 | 1.22E-02 | 1.75E-02 | 5.17E-02 | 9.33E-02 |
| **QUARTZ** | log Q/K | 0.3446 | -4.3840 | -2.3770 | -2.0590 | -1.4900 | -0.3218 | 0.0262 | 0.2800 | 0.2809 | 0.2814 | 0.2834 | 0.2969 | 0.3135 |
| **CALCITE** | log Q/K | 0.2430 | -2.7900 | -0.0042 | 0.4153 | 0.8812 | 0.8923 | 0.2237 | -0.0742 | -0.0705 | -0.0651 | -0.0505 | 0.0468 | 0.1279 |
| **DOLOMITE** | log Q/K | 1.4950 | -4.7160 | 0.9013 | 1.7490 | 2.6960 | 2.7480 | 1.4310 | 0.6527 | 0.6734 | 0.6958 | 0.7521 | 1.0260 | 1.2260 |
| **GYPSUM** | log Q/K | -0.4380 | -8.0950 | -3.3080 | -2.7900 | -2.1490 | -1.1530 | -0.7812 | -2.1190 | -1.9630 | -1.8490 | -1.6200 | -1.0350 | -0.7402 |
| **FLUORITE** | log Q/K | 0.2730 | -9.2690 | -4.7270 | -3.9210 | -2.8670 | -1.1000 | -0.3951 | -0.8432 | -0.8237 | -0.8038 | -0.7435 | -0.4077 | -0.1150 |
| **GOETHITE** | log Q/K | 5.8900 | | 3.1870 | 3.5360 | 4.1300 | 5.3220 | 5.6340 | 5.7120 | 5.7140 | 5.7150 | 5.7200 | 5.7570 | 5.8030 |
| **HALITE** | log Q/K | -3.8510 | -9.3370 | -7.4660 | -6.9500 | -6.2300 | -4.9430 | -4.3950 | -8.7560 | -7.4480 | -6.9530 | -6.2420 | -4.9480 | -4.3970 |
| **PYRITE** | log Q/K | -230 | | -249 | -248 | -246 | -238 | -233 | -240 | -240 | -240 | -239 | -238 | -237 |

## Origin of Salinity

The origin of salinity in the eastern reaches of the Edwards Aquifer has been a subject of research for many years. The results of several prominent investigations are summarized in an earlier section of this report. There is not universal agreement among researchers, and the matter of salinity sources remains one of great interest. This section of the report considers key major ions and ionic ratios, as wells as oxygen and hydrogen isotope ratios as indicators of source(s) of salinity.

Saline groundwaters are derived from many sources: seawater, evaporated seawater, residual brines derived from the precipitation of halite, evaporated fresh waters, oil field waters, dissolution of halite and gypsum, and interaction between water and rocks other than evaporites. The concentrations of dissolved solids are affected by each source, and ratios of selected ions are often used as indicators of a source or sources of salinity.

The ratio of sodium to chloride in seawater is approximately 0.86, and in freshwater that has dissolved halite (NaCl), the ratio is 1.0 – a reflection of the equimolar ratio of sodium to chloride in the halite lattice. In addition to Na/Cl molar ratios, the ratio of chloride to bromide (Cl/Br) is often considered to be an indicator of source (Davis et al., 1997; Acala' and Custodio, 2008), and the stable isotope ratios $\delta^{18}O$ and $\delta^{2}H$ are indicators of processes such as evaporation and rock-water interaction (Sharp, 2007, p. 88 - 91).

The concentrations of sodium and chloride are strongly correlated in groundwater samples from the 13 hydrostratigraphic zones, as illustrated by **Figure 28**. The coefficient of determination ($R^2$) of the regression equation is 0.92, a measurement of the degree to which the variability of the concentration of sodium is explained by the association with the predictor variable, chloride. Molar ratios of sodium-to-chloride, however, are neither consistent with halite dissolution nor a seawater-only source (**Figure 29**), as most of the ratios and all of the chloride concentrations are below those of seawater.

Chloride-bromide ratios do not support a halite source or a seawater source (**Figure 30**). Chloride and bromide are conservative ions, and few processes other than dissolution or precipitation of halite, interaction with other lithic sources, or mixing of groundwaters significantly affect their concentrations (Hem, 1985). The magnitude of the chloride-bromide ratio is sensitive to the origin of water as marine, as a second-cycle solution of marine salt, or as a residual brine from the precipitation of halite. In seawater the weight ratio of chloride to bromide is 290, and the molar ratio is 650 (Davis et al., 1998; Alcala' and Custodio, 2008). During evaporation, the ratio remains constant up to the point at which halite begins to precipitate. Because of its larger radius, the bromide ion is excluded from the halite lattice, so that the residual brine is enriched in bromide relative to chloride. This causes the chloride-bromide ratio to decrease in the residual brine. Because halite is deficient in bromide, the ratio increases substantially as halite is later dissolved by other waters.

**Figure 30** illustrates that the weight ratios are much lower than the seawater ratio of 290 (or 650 molar). This could be an indication that the waters are derived from residual brine, or that higher bromide concentrations are related to very long-term interaction with unidentified lithic sources of bromide. The water-rock interaction hypothesis is supported by at least one other line of data, abundances of the stable isotopes oxygen-18 ($^{18}O$) and deuterium ($^{2}H$).

Oxygen-18 and deuterium are incorporated into the water molecule. Although naturally occurring, they are much less abundant than the more common stable isotopes oxygen-16 ($^{16}O$) and protium ($^{1}H$). The abundances are reported in per mil units as $\delta^{18}O$ and $\delta^{2}H$. Waters derived from precipitation will characteristically have $\delta^{18}O$ and $\delta^{2}H$ values that lie along or subparallel to the global meteoric water line (GMWL). The GMWL describes the association between $\delta^{18}O$ and $\delta^{2}H$, measured from samples of precipitation collected from locations around the planet. The equation of the GMWL is (Craig, 1961):

$\delta 2H = 8\delta^{18}O + 10$

**Figure 31** shows the GMWL along with $\delta^{18}O$ and $\delta^{2}H$ measurements from samples of water from springs discharging from the Edwards Aquifer in southern Travis, Hays, and Comal counties. The data are found in the groundwater chemistry data base of the Texas Water Development Board (http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp). Also plotted on the figure are the $\delta^{18}O$ and $\delta^{2}H$ measurements from the groundwater samples listed in Table 11 of this report.

The spring water samples generally lie on or slightly subparallel to the GMWL. The variability in the measurements is related to factors such as season of recharge and evaporation. Accounting for that variability, the measurements are consistent with water derived entirely from precipitation in the central Texas region.

The samples from **Table 11** (listed as Saline Edwards on the figure) form a distinct linear pattern extending to the right of the GMWL. Such patterns are characteristic of waters that have become enriched in $^{18}O$ through contact with carbonates and silicates, rocks with heavier $\delta^{18}O$ values than unevaporated surface waters. This is a common feature of thermal waters (Faure, 1986, p. 451) as well as basinal brines and saline formation waters (Clayton et al., 1966). It is apparent that the 13 samples collected from the multiport well display the plotting pattern common to waters that have been in contact with $^{18}O$-enriched rocks. Such enrichment typically occurs under higher temperature environments than is the case with respect to this area of the Edwards Aquifer. If the enrichment occurred in a higher-temperature environment, then a reasonable hypothesis might be that the saline waters of the Glen Rose, Walnut, Kainer, and Person formations might have originated as deep-basin brines and then migrated in a high geopressured system to shallower formations of the Gulf Coast Basin. That hypothesis has been proposed by Hoff and Dutton (2017) in their evaluation of brackish Edwards Group water and measurements of geopressured in oil and gas wells of south-central Texas:

> *Brackish water in the Edwards Aquifer in south-central Texas is hypothesized to occur in a zone of convergent flow with hydrodynamic and transient mixing mainly between hydropressured freshwater moving downdip by gravity and saline water migrating updip from depth by a geopressure drive. Another source of water and dissolved mass is upward-directed cross-formational flow into the Edwards Group.*
>
> *And*

> *The presence of geopressure conditions in the deep Edwards Group is indicated by fluid-pressure data from oil and gas wells, but has not been verified using field information. Geopressure in the superjacent Cenozoic section might have induced high fluid pressure in the Edwards Group. A regime of geopressure or 'subgeopressure' within the Edwards Group, however, seems required to drive saltwater updip toward the freshwater zone and to account for high hydraulic head in fault-bounded saline rocks adjacent to the freshwater aquifer.*

The geochemical data considered in this report do not support halite dissolution as a source of salinity in the Glen Rose – Person formations. This inference is based, first, on sodium-chloride ratios and chloride-bromide ratios that are inconsistent with ratios that would have been derived from the dissolution of halite. Furthermore, the prominent horizontal trajectory of $\delta^{18}O$ values to the right of the GMWL is strongly indicative of groundwater that has been enriched in $^{18}O$ under higher temperatures. All considered, the data support the hypothesis that the salinity is derived from long-term rock-water interaction in deeper formation of the central Texas Gulf Coast Basin.

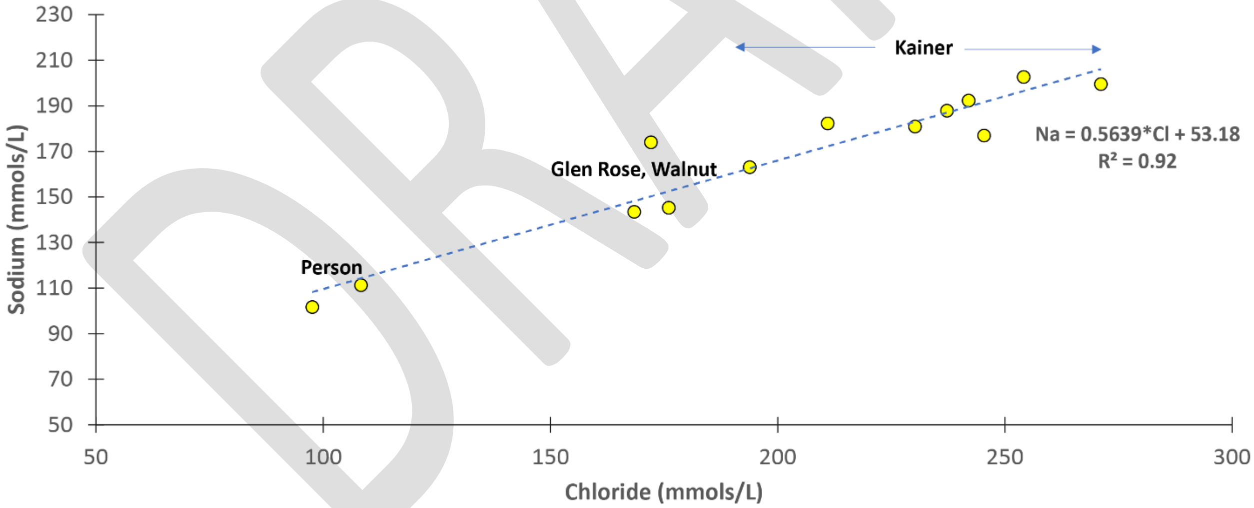


***Figure 28.*** *Graph of sodium and chloride concentrations in groundwater from the Glen Rose, Walnut, Kainer, and Person formation. The regression model illustrates a high degree of correlation between the ions, on the basis of the R2 statistic, which is interpreted to mean that 92 percent of the variability of sodium concentrations is accounted for by the association with chloride.*

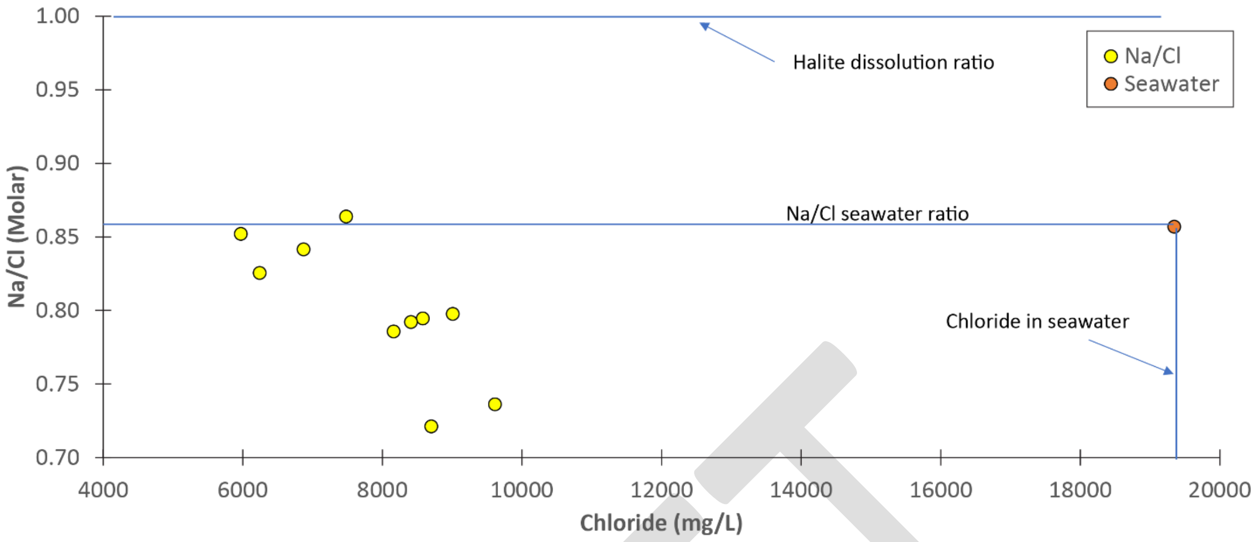


***Figure 29**. Sodium-chloride molar ratios in samples of groundwater from the Glen Rose, Walnut, Kainer, and Person formations. Ratios derived entirely from the dissolution of halite should fall on or very near to the halite line. Seawater-derived ratios should cluster around a ratio of approximately 0.86.*

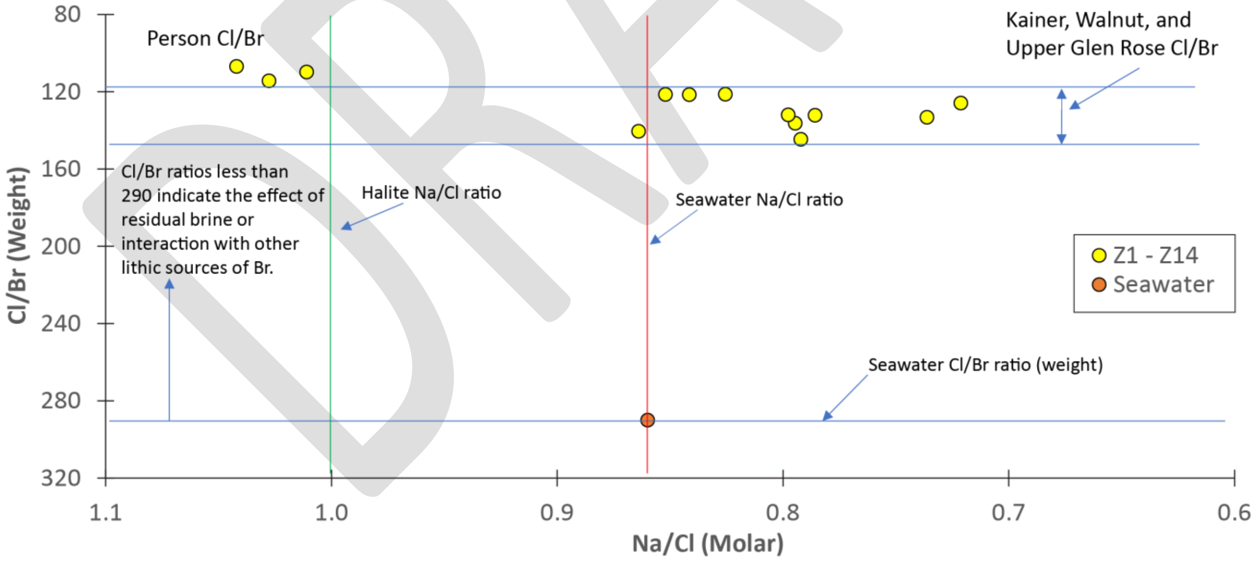


***Figure 30.** Plot of chloride-bromide weight ratios and sodium-chloride molar ratios. The ratios are significantly lower than the seawater ratio, 290. This indicate that the waters are derived either from residual brines or from contact with lithic sources enriched in bromide.*

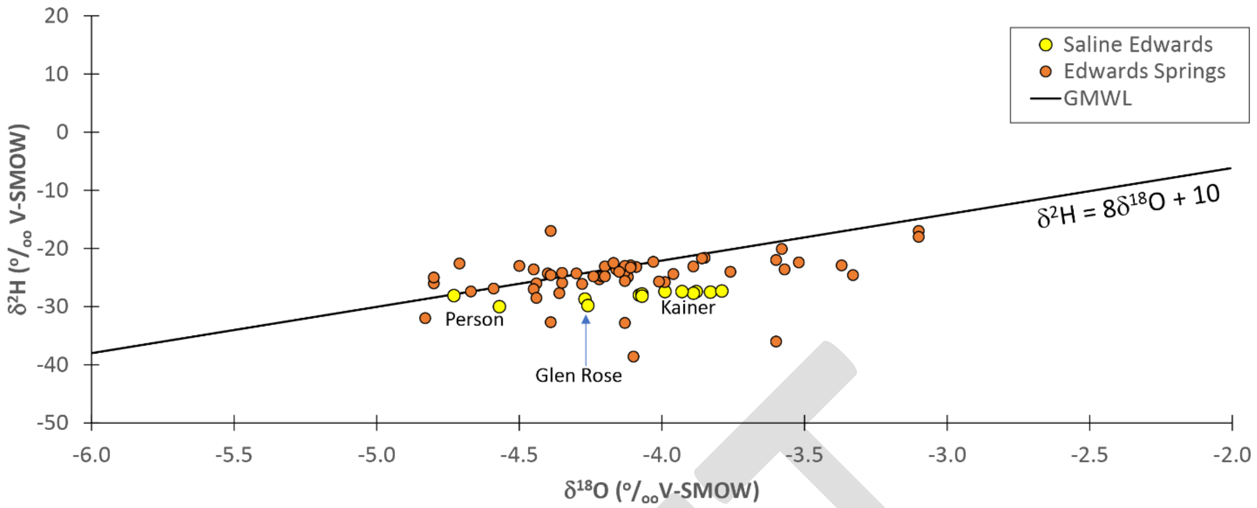


***Figure 31**. Global Meteoric Water Line along with d18O and d2H values from Edwards springs and zones 1 – 14. The horizontal deflection to the right of the GNWL formed by the Glen Rose, Walnut, and Kainer samples is a pattern consistent with enrichment of water in 18O in thermal systems and in basinal brines and formation waters.*

## Discussion of Geochemistry Data

Geochemical data compiled for this investigation illustrate that the composition of groundwater from hydrostratigraphic zones 1 – 11, 13 and 14 is sodium-chloride, with variable concentrations of total dissolved solids. TDS increases from 13000 mg/L in the Upper Glen Rose (Zone 2, -1025 ft) to 18500 mg/L in the Kainer formation (Zone 6, -855 ft) and decreases to 13500 mg/L at the top of the Kainer (Zone 11, -685 ft). Above the Regional Dense Member aquitard (Zone 12), TDS is less than 9400 mg/L in the Person formation (Zones 13 and 14, -615 ft and -575 ft, respectively). Although the origin of salinity remains unknown, the geochemical data appear to allow for the elimination of at least two potential sources of salinity: seawater (or residual seawater), and halite dissolution.

Ratios of sodium to chloride are not consistent with ratios derived from a seawater-only source or from the dissolution of halite. Most sodium-chloride ratios are less than that of seawater, 0.86. The sodium-chloride ratio of halite-dissolution brines is 1.0 or very close to that because of the equimolar concentrations of sodium and chloride in the halite lattice. Chloride-bromide ratios are not close to that of seawater (290) but are low enough (150) to be consistent with that expected for residual brines. The samples are enriched in bromide, compared with the concentration of bromide in seawater, but the greatest TDS of the 13 samples is far below that of residual brines, and less than the TDS of seawater, 35,000 mg/L.

An alternative hypothesis to explain the low chloride-bromide ratios is the interaction of groundwater and unidentified lithic sources of bromide, perhaps in deeper formations of the Gulf Coast. An indication of such interaction is the plotting pattern of $\delta^{18}O$ and $\delta^2H$ values along a horizontal trajectory to the right of the global meteoric water line. Such patterns are characteristic of groundwaters that have become enriched in $^{18}$O through interaction with carbonates or silicates in high-temperature environments. A recent study of the occurrence of saline water in the Edwards Group of south-central Texas posits migration of deep formation brines to shallower formations of the Gulf Coast by geopressured systems that drive brine upward along pathways along fault-bounded blocks. This is a reasonable hypothesis to account for the occurrence of saline water along the saline and freshwater boundary and more concentrated brines in deeper formations to the east.

Mixtures of desalinated groundwater from the Kainer formation or of fresh Edwards groundwater from the Creedmoor WSC will be strongly dominated by the sodium-chloride receiving water of the Person formation. All mixtures of treated Kainer and Person will be sodium-chloride in composition, and mixtures of freshwater Edwards and Person will be sodium-chloride at Person-Edwards mixtures of 5:95. There is potential for the release of arsenic within the storage zone. The occurrence of arsenic in samples from zones 13 and 14 indicates that arsenic is available and mobile. The mineralogical associations of arsenic in the matrix of the Person formation are unknown; but there remains a probable association with ferrous iron, perhaps in the form of pyrite. Injection of Edwards water with measurable concentrations of dissolved oxygen could drive the dissolution of pyrite and to the release of arsenic. If freshwater Edwards is the injectate, it will be advisable to monitor arsenic concentrations in recovery water, especially over long periods of storage.

## Conclusions

The multiport well provides detailed hydrogeologic data that are critical for characterizing the saline Edwards Aquifer in the study area. Some conclusions from this study include:

- Heads are generally higher in the saline Edwards than the freshwater Edwards Aquifer, with a potential for flow toward the freshwater/saline-water interface.
- Vertical flow potential is variable. There is downward flow potential from the upper Edwards (Person) to the lower Edwards (Kainer Fm), and there is upward flow potential from the Upper Glen Rose to the lower Edwards (Kainer Fm).
- The overlying geologic units (Georgetown, Del Rio, Buda, Eagle Ford) confine the underlying saline Edwards Aquifer.
- The Person (111 ft thick) and Kainer Formations (292 ft thick) of the Edwards Group appear to be hydrologically isolated from each other due to the regional dense member (22 ft thick), as determined by this study and as noted in other publications. The regional dense member is likely to provide confinement between the Person and Kainer Formations over a large area.
- The upper Edwards (Person Fm) has an average transmissivity of 2,400 ft2/d. The Kainer has an average of 7,100 ft2/d.
- Estimates indicate relatively high-yielding wells are possible in the saline Edwards, with yields greater than 1,000 gpm. This is consistent with other studies.
  Saline waters are sodium-chloride waters with a range in TDS of 9,000 to 17,900 mg/L. The Kainer Formation had the highest TDS, followed by the Upper Glen Rose and then the Person Formation.
- Although the origin of salinity remains unknown, the geochemical data appear to allow for the elimination of at least two potential sources of salinity: seawater (or residual seawater), and halite dissolution. Isotope data suggest a potential source of the saline water is from interaction with

carbonates or silicates in high-temperature environments, such as deeper formations of the Gulf Coast.

- Mixtures of the injectate with receiving groundwaters of the Person formation will be dominated by the sodium-chloride groundwater. There is potential for the release of arsenic within the storage zone. The occurrence of arsenic in samples from zones 13 and 14 indicates that arsenic is available and mobile. It will be advisable to monitor arsenic concentrations in recovery water.
- Results from this hydrogeologic study suggest that the saline Edwards Aquifer can serve as a source of water for a desalination facility and potentially a reservoir for ASR.

## Future Studies

A test well for production of the saline Edwards Aquifer that is relatively close to the multiport well is needed for additional evaluations. Data from the production well and observations from the multiport well will help provide storativity and transmissivity values representative of a larger area. In addition, the data would help confirm the confining characteristics of the RDM.

## Acknowledgements

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*Photograph of the installation of the last Westbay casing piece in the multiport well. Photograph taken on 8/20/2016.*

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*Photograph of completed Multiport well on 9/13/2016.*

## Supplemental Information Available Upon Request

**Supplement 1. Kyle Transect: Excerpted Figures from Lambert et al., 2010.**

**Supplement 2. Drilling and well completion reports**

- Drilling notes, cuttings, and thin section descriptions;
- Geophysical log
- Westbay completion report
- State of Texas Well Reports

**Supplement 3. Water Levels**

- Digital spreadsheet of data

**Supplement 4. Permeability Testing**

- Digital slug data
- Aqtesolve solutions

**Supplement 5. Sampling and Chemistry results**

- Table 11 in spreadsheet
- PDF files of laboratory results

Appendix F

# BIG 6 INFORMATION

# Drought Analysis Report

| Owner - System | Permitted Pumpage | Aug 2014 Pumpage | Aug 2014 Target | Aug 2014 % | Sep 2014 Pumpage | Sep 2014 Target | Sep 2014 % | Oct 2014 Pumpage | Oct 2014 Target | Oct 2014 % | Nov 2014 Pumpage | Nov 2014 Target | Nov 2014 % | Dec 2014 Pumpage | Dec 2014 Target | Dec 2014 % | Jan 2015 Pumpage | Jan 2015 Target | Jan 2015 % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Tier 1 (<12M gallons/year)** | | | | | | | | | | | | | | | | | | | |
| Benjamin Rosas | 1,000,000 | 128,100 | 120,000 | 7% | 97,900 | 80,000 | 22% | 92,700 | 66,400 | 40% | 70,300 | 56,000 | 26% | 71,300 | 50,400 | 41% | 66,800 | 63,000 | 6% |
| Lougheed Scott - Crestview R.v. | 2,000,000 | 128,900 | 240,000 | -46% | 126,200 | 160,000 | -21% | 141,200 | 132,800 | 6% | 146,600 | 112,000 | 31% | 106,300 | 100,800 | 5% | 122,300 | 126,000 | -3% |
| Malone Addition Water Supply | 2,000,000 | 313,000 | 240,000 | 30% | 127,000 | 160,000 | -21% | 128,000 | 132,800 | -4% | 82,500 | 112,000 | -26% | 121,900 | 100,800 | 21% | 121,500 | 126,000 | -4% |
| Mision Cristiana Maranatha | 500,000 | 34,110 | 60,000 | -43% | 48,520 | 40,000 | 21% | 27,570 | 33,200 | -17% | 19,930 | 28,000 | -29% | 42,410 | 25,200 | 68% | 30,050 | 31,500 | -5% |
| Stripe-susser Corp - Stripe-susser Corp (pws Store) | 150,000 | 10,570 | 16,650 | -37% | 7,750 | 11,280 | -31% | 8,360 | 10,320 | -19% | 9,690 | 9,720 | 0% | 5,820 | 9,120 | -36% | 9,000 | 10,800 | -17% |
| Glen Schuknecht | 480,000 | 51,243 | 57,600 | -11% | 36,472 | 38,400 | -5% | 31,178 | 31,872 | -2% | 26,880 | 26,880 | 0% | 21,752 | 24,192 | -10% | 24,390 | 30,240 | -19% |
| Comal Tackle Company | 843,750 | 67,380 | 84,375 | -20% | 52,590 | 52,650 | 0% | 49,250 | 49,275 | 0% | 47,200 | 47,250 | 0% | 52,560 | 52,650 | 0% | 52,500 | 65,813 | -20% |
| Hays County Youth Athletic Association | 4,820,550 | 452,600 | 636,313 | -29% | 415,900 | 424,208 | -2% | 374,100 | 404,926 | -8% | 120,600 | 377,931 | -68% | 152,300 | 154,258 | -1% | 60,200 | 77,129 | -22% |
| Park Hills Baptist Church | 420,000 | 9,500 | 46,620 | -80% | 13,400 | 31,584 | -58% | 21,900 | 28,896 | -24% | 31,400 | 27,216 | 15% | 14,500 | 25,536 | -43% | 23,400 | 30,240 | -23% |
| St. Albans Episcopal Church | 562,500 | 45,550 | 62,438 | -27% | 23,520 | 42,300 | -44% | 29,340 | 38,700 | -24% | 22,920 | 36,450 | -37% | 23,420 | 34,200 | -32% | 27,750 | 40,500 | -31% |
| Twin Oaks Ranch Church Camp | 1,000,000 | 54,680 | 111,000 | -51% | 52,640 | 75,200 | -30% | 24,850 | 68,800 | -64% | 19,000 | 64,800 | -71% | 6,500 | 60,800 | -89% | 48,030 | 72,000 | -33% |
| Texanna Properties, Inc. | 1,649,250 | 75,100 | 197,910 | -62% | 67,900 | 131,940 | -49% | 71,000 | 109,510 | -35% | 82,600 | 92,358 | -11% | 65,944 | 83,122 | -21% | 68,966 | 103,903 | -34% |
| Michael Thames Custom Homes | 100,000 | 7,180 | 11,100 | -35% | 4,570 | 7,520 | -39% | 5,740 | 6,880 | -17% | 4,000 | 6,480 | -38% | 4,340 | 6,080 | -29% | 4,520 | 7,200 | -37% |
| Aqua Texas, Inc. - Mooreland | 6,000,000 | 302,000 | 720,000 | -58% | 251,000 | 480,000 | -48% | 262,000 | 398,400 | -34% | 245,000 | 336,000 | -27% | 236,000 | 302,400 | -22% | 234,000 | 378,000 | -38% |
| The Inn Above Onion Creek | 1,300,000 | 132,840 | 144,300 | -8% | 73,360 | 97,760 | -25% | 78,910 | 89,440 | -12% | 50,290 | 84,240 | -40% | 48,450 | 79,040 | -39% | 56,550 | 93,600 | -40% |
| Cornerstone Htj, Llc. | 980,000 | 66,100 | 129,360 | -49% | 61,900 | 86,240 | -28% | 88,200 | 82,320 | 7% | 32,700 | 76,832 | -57% | 40,110 | 31,360 | 28% | 9,040 | 15,680 | -42% |
| Mccoy Corporation | 120,000 | 5,100 | 13,320 | -62% | 1,810 | 9,024 | -80% | 3,570 | 8,256 | -57% | 5,750 | 7,776 | -26% | 2,890 | 7,296 | -60% | 4,630 | 8,640 | -46% |
| Mystic Oak Water Co-op | 7,700,000 | 327,500 | 924,000 | -65% | 185,000 | 616,000 | -70% | 219,600 | 511,280 | -57% | 195,500 | 431,200 | -55% | 185,100 | 388,080 | -52% | 234,360 | 485,100 | -52% |
| Hays Hills Baptist Church | 600,000 | 31,880 | 43,800 | -27% | 22,300 | 40,800 | -45% | 38,620 | 42,240 | -9% | 21,690 | 36,000 | -40% | 18,540 | 32,160 | -42% | 22,520 | 51,600 | -56% |
| Sosebee E.y. | 517,500 | 11,840 | 62,100 | -81% | 9,110 | 41,400 | -78% | 9,960 | 34,362 | -71% | 7,280 | 28,980 | -75% | 8,880 | 26,082 | -66% | 13,500 | 32,603 | -59% |
| Uplifting Properties, Lp | 1,000,000 | 26,750 | 111,000 | -76% | 25,950 | 75,200 | -65% | 38,030 | 68,800 | -45% | 19,340 | 64,800 | -70% | 23,470 | 60,800 | -61% | 29,240 | 72,000 | -59% |
| Manchaca Baptist Church | 600,000 | 42,300 | 66,600 | -36% | 32,500 | 45,120 | -28% | 17,100 | 41,280 | -59% | 27,600 | 38,880 | -29% | 18,400 | 36,480 | -50% | 16,200 | 43,200 | -63% |
| Church Of Christ At Buda/kyle | 200,119 | 6,000 | 22,213 | -73% | 4,050 | 15,049 | -73% | 2,320 | 13,768 | -83% | 4,820 | 12,968 | -63% | 2,580 | 12,167 | -79% | 4,760 | 14,409 | -67% |
| Bear Creek Office Park | 750,000 | 10,530 | 83,250 | -87% | 10,420 | 56,400 | -82% | 13,290 | 51,600 | -74% | 11,430 | 48,600 | -76% | 9,010 | 45,600 | -80% | 15,580 | 54,000 | -71% |
| Onion Creek Kennels | 850,000 | 51,300 | 94,350 | -46% | 28,940 | 63,920 | -55% | 27,130 | 58,480 | -54% | 19,150 | 55,080 | -65% | 19,310 | 51,680 | -63% | 17,460 | 61,200 | -71% |
| Randolph Austin Company | 585,000 | 31,100 | 64,935 | -52% | 45,700 | 43,992 | 4% | 43,700 | 40,248 | 9% | 19,400 | 37,908 | -49% | 13,300 | 35,568 | -63% | 11,900 | 42,120 | -72% |
| Byron Benoit And Company - Bryon Benoit And Compan | 2,000,000 | 32,500 | 222,000 | -85% | 28,500 | 150,400 | -81% | 22,300 | 137,600 | -84% | 21,600 | 129,600 | -83% | 17,500 | 121,600 | -86% | 40,100 | 144,000 | -72% |
| Southern Hills Church Of Christ | 400,000 | 12,070 | 48,000 | -75% | 5,470 | 32,000 | -83% | 5,370 | 26,560 | -80% | 10,430 | 22,400 | -53% | 11,630 | 20,160 | -42% | 6,910 | 25,200 | -73% |
| Texas-lehigh Cement Company - Howe | 1,500,000 | 46,664 | 210,000 | -78% | 38,080 | 144,000 | -74% | 20,262 | 108,000 | -81% | 12,388 | 72,000 | -83% | 20,486 | 54,000 | -62% | 16,018 | 60,000 | -73% |
| Gilbert C Johnson | 9,500,000 | 775,700 | 1,152,000 | -33% | 515,100 | 760,000 | -32% | 480,300 | 706,800 | -32% | 360,000 | 532,000 | -32% | 164,000 | 342,000 | -52% | 112,800 | 427,500 | -74% |
| Lady Bird Johnson Wildflower Center - Wildflower Center | 6,700,000 | | 884,400 | | | 589,600 | | 0 | 562,800 | -100% | 0 | 525,280 | -100% | 2,250 | 214,400 | -99% | 25,940 | 107,200 | -76% |
| V.f.w. Post No. 3377 | 500,000 | 19,120 | 60,000 | -68% | 14,000 | 40,000 | -65% | 8,460 | 33,200 | -75% | 5,370 | 28,000 | -81% | 9,680 | 25,200 | -62% | 7,090 | 31,500 | -77% |
| Pcsi - Pcsi Water System | 1,331,000 | 12,500 | 147,741 | -92% | 13,500 | 100,091 | -87% | 16,900 | 91,573 | -82% | 14,900 | 86,249 | -83% | 21,000 | 80,925 | -74% | 20,100 | 95,832 | -79% |
| St. John's Presbyterian Church | 100,000 | 7,920 | 12,000 | -34% | 3,440 | 8,000 | -57% | 3,720 | 6,640 | -44% | 1,020 | 5,600 | -82% | 13,040 | 5,040 | 159% | 1,260 | 6,300 | -80% |
| Lockaway Storage | 100,000 | 5,160 | 11,100 | -54% | 1,680 | 7,520 | -78% | 1,950 | 6,880 | -72% | 1,360 | 6,480 | -79% | 1,290 | 6,080 | -79% | 1,380 | 7,200 | -81% |
| Manchaca Bible Fellowship Baptist Church | 100,000 | 330 | 11,100 | -97% | 660 | 7,520 | -91% | 600 | 6,880 | -91% | 570 | 6,480 | -91% | 670 | 6,080 | -89% | 880 | 7,200 | -88% |
| The Porter Co. Mechanical Contractors | 500,000 | 4,390 | 55,500 | -92% | 4,370 | 37,600 | -88% | 6,100 | 34,400 | -82% | 3,910 | 32,400 | -88% | 4,580 | 30,400 | -85% | 4,040 | 36,000 | -89% |
| Manchaca Optimist Youth Sports Complex | 4,232,000 | 497,133 | 558,624 | -11% | 246,233 | 372,416 | -34% | 221,541 | 355,488 | -38% | 421,882 | 331,789 | 27% | 95,601 | 135,424 | -29% | 7,087 | 67,712 | -90% |
| Whittington, Keith And Kelly | 500,000 | 8,090 | 55,500 | -85% | 3,730 | 37,600 | -90% | 3,410 | 34,400 | -90% | 2,500 | 32,400 | -92% | 2,600 | 30,400 | -91% | 3,600 | 36,000 | -90% |
| Texas-lehigh Cement Company - Spectrum | 825,000 | 23,647 | 70,125 | -66% | 21,704 | 54,780 | -60% | 22,170 | 54,780 | -60% | 15,495 | 54,780 | -72% | 13,897 | 54,780 | -75% | 5,516 | 68,475 | -92% |
| Barton Properties | 800,000 | 3,380 | 88,800 | -96% | 3,290 | 60,160 | -95% | 3,470 | 55,040 | -94% | 3,210 | 51,840 | -94% | 4,270 | 48,640 | -91% | 3,370 | 57,600 | -94% |
| Rudy's Country Store | 1,875,000 | 54,300 | 208,125 | -74% | 46,800 | 141,000 | -67% | 37,600 | 129,000 | -71% | 6,200 | 121,500 | -95% | 9,300 | 114,000 | -92% | 7,500 | 135,000 | -94% |
| Lowden Bob - Painted Horse Pavilion | 1,000,000 | 610 | 111,000 | -99% | 1,260 | 75,200 | -98% | 970 | 68,800 | -99% | 1,770 | 64,800 | -97% | 1,210 | 60,800 | -98% | 2,652 | 72,000 | -96% |
| Hunt Enterprises | 600,000 | 21,660 | 72,000 | -70% | 12,170 | 52,800 | -77% | 11,940 | 50,400 | -76% | 9,720 | 47,040 | -79% | 5,100 | 19,200 | -73% | 300 | 15,000 | -98% |
| Oak Forest Water Supply Corporation - (edwards) | 9,000,000 | 17,600 | 1,080,000 | -98% | 19,300 | 720,000 | -97% | 15,200 | 597,600 | -97% | 16,300 | 504,000 | -97% | 11,300 | 453,600 | -98% | 11,100 | 567,000 | -98% |
| Travis County - Travis County Pct #3 | 1,500,000 | 2,150 | 166,500 | -99% | 740 | 112,800 | -99% | 240 | 103,200 | -100% | 1,410 | 97,200 | -99% | 120 | 91,200 | -100% | 530 | 108,000 | -100% |
| Cook-walden/forest Oaks | 5,000,000 | 211,750 | 660,000 | -68% | 93,334 | 440,000 | -79% | 182,213 | 420,000 | -57% | 37,479 | 392,000 | -90% | 455 | 160,000 | -100% | 0 | 80,000 | -100% |
| Ddc Creekside Villas, Ltd. - Ddc Creekside | 1,998,200 | 0 | 263,762 | -100% | 0 | 0 | 0% | 0 | 0 | 0% | 0 | 0 | 0% | 0 | 0 | 0% | 0 | 31,971 | -100% |
| Hays Consolidated I.s.d. - Beacon Hill | 421,875 | 0 | 50,625 | -100% | 0 | 33,750 | -100% | 0 | 28,013 | -100% | 0 | 23,625 | -100% | 0 | 21,262 | -100% | 0 | 26,578 | -100% |

# Drought Analysis Report

| Owner - System | Permitted Pumpage | Aug 2014 Pumpage | Aug 2014 Target | Aug 2014 % | Sep 2014 Pumpage | Sep 2014 Target | Sep 2014 % | Oct 2014 Pumpage | Oct 2014 Target | Oct 2014 % | Nov 2014 Pumpage | Nov 2014 Target | Nov 2014 % | Dec 2014 Pumpage | Dec 2014 Target | Dec 2014 % | Jan 2015 Pumpage | Jan 2015 Target | Jan 2015 % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Independence Park Condominum Community, Inc. - Inde | 3,700,000 | 115,900 | 488,400 | -76% | 0 | 203,500 | -100% | 0 | 194,250 | -100% | 0 | 181,300 | -100% | 0 | 74,000 | -100% | 0 | 59,200 | -100% |
| Industrial Asphalt, Lp - Hays Quarry | 2,000,000 | 0 | 200,000 | -100% | 0 | 124,800 | -100% | 28,415 | 116,800 | -76% | 0 | 112,000 | -100% | 0 | 124,800 | -100% | 0 | 156,000 | -100% |
| Ladybird Montessori Llc - Ladybird Montessori School | 150,000 |  | 19,800 |  |  | 0 | 0% | 0 | 0 | 0% | 0 | 0 | 0% | 0 | 0 | 0% | 0 | 2,400 | -100% |
| Neuro Institute Of Austin, L.p. | 5,625,000 | 98,800 | 624,375 | -84% | 0 | 423,000 | -100% | 0 | 387,000 | -100% | 0 | 364,500 | -100% | 0 | 342,000 | -100% | 0 | 405,000 | -100% |
| Onion Creek Memorial Park, Inc. | 590,625 | 0 | 77,962 | -100% | 0 | 51,975 | -100% | 0 | 49,613 | -100% | 0 | 46,305 | -100% | 0 | 18,900 | -100% | 0 | 9,450 | -100% |
| Robert Kretchmar & Helen Cutler - Fm 1626 Commercial | 330,000 | 0 | 36,630 | -100% | 0 | 24,816 | -100% | 0 | 22,704 | -100% | 0 | 21,384 | -100% | 0 | 20,064 | -100% | 0 | 23,760 | -100% |
| Robert Kretchmar & Helen Cutler - Fm 1626 Agricultural | 100,000 | 0 | 13,200 | -100% | 0 | 8,800 | -100% | 0 | 8,400 | -100% | 0 | 7,840 | -100% | 0 | 3,200 | -100% | 0 | 1,600 | -100% |
| Shoal Creek Properties | 500,000 | 0 | 55,500 | -100% | 0 | 37,600 | -100% | 0 | 34,400 | -100% | 0 | 32,400 | -100% | 0 | 30,400 | -100% | 0 | 36,000 | -100% |
| Thomas Weatherford | 5,000,000 | 0 | 500,000 | -100% | 0 | 312,000 | -100% | 0 | 292,000 | -100% | 0 | 280,000 | -100% | 0 | 312,000 | -100% | 0 | 390,000 | -100% |
| **Tier 2 (>=12M and <120M gallons/year)** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Aqua Texas, Inc. - Bliss Spillar (edwards) | 12,875,000 | 1,968,000 | 1,545,000 | 27% | 742,000 | 1,030,000 | -28% | 850,000 | 854,900 | -1% | 698,000 | 721,000 | -3% | 704,000 | 648,900 | 8% | 782,000 | 811,125 | -4% |
| Onion Creek Country Club | 95,166,500 | 9,116,000 | 11,419,980 | -20% | 7,170,400 | 7,613,320 | -6% | 7,258,600 | 7,613,320 | -5% | 2,089,000 | 2,283,996 | -9% | 2,234,000 | 2,283,996 | -2% | 4,222,000 | 4,758,325 | -11% |
| Aqua Texas, Inc. - Onion Creek Meadows | 36,300,000 | 2,593,000 | 4,356,000 | -40% | 1,723,000 | 2,904,000 | -41% | 1,659,000 | 2,410,320 | -31% | 1,711,000 | 2,032,800 | -16% | 1,486,000 | 1,829,520 | -19% | 1,913,000 | 2,286,900 | -16% |
| Huntington Utility Company, L.l.c. | 18,000,000 | 1,200,000 | 2,268,000 | -47% | 850,000 | 1,353,600 | -37% | 817,000 | 720,000 | 13% | 867,000 | 1,008,000 | -14% | 816,000 | 907,200 | -10% | 770,000 | 1,080,000 | -29% |
| City Of Austin - Nature Center | 16,000,000 | 538,009 | 2,112,000 | -75% | 248,189 | 1,408,000 | -82% | 406,885 | 1,344,000 | -70% | 216,135 | 1,254,400 | -83% | 349,282 | 512,000 | -32% | 180,481 | 256,000 | -29% |
| Aqua Texas, Inc. - Bear Creek Park | 12,098,000 | 955,000 | 1,451,760 | -34% | 621,000 | 967,840 | -36% | 509,000 | 803,307 | -37% | 484,000 | 677,488 | -29% | 447,000 | 609,739 | -27% | 504,000 | 762,174 | -34% |
| Texas-lehigh Cement Company - Plant | 54,750,000 | 4,694,900 | 5,475,000 | -14% | 2,987,025 | 4,161,000 | -28% | 3,323,600 | 3,942,000 | -16% | 3,397,775 | 3,723,000 | -9% | 3,399,000 | 3,504,000 | -3% | 2,514,750 | 3,832,500 | -34% |
| Oak Forest Water Supply Corporation - (trinity) | 16,500,000 | 1,087,712 | 1,980,000 | -45% | 1,312,172 | 1,320,000 | -1% | 713,756 | 1,095,600 | -35% | 748,732 | 924,000 | -19% | 586,600 | 831,600 | -29% | 673,284 | 1,039,500 | -35% |
| Twin Creek Park Water Supply Co. | 12,000,000 | 628,600 | 1,440,000 | -56% | 502,800 | 960,000 | -48% | 383,100 | 796,800 | -52% | 408,500 | 672,000 | -39% | 372,100 | 604,800 | -38% | 430,000 | 756,000 | -43% |
| Slaughter Creek Acres Water Supply | 14,000,000 | 869,500 | 1,414,000 | -39% | 542,200 | 985,600 | -45% | 525,900 | 918,400 | -43% | 485,600 | 828,800 | -41% | 514,900 | 828,800 | -38% | 534,200 | 1,036,000 | -48% |
| Ruby Ranch Water Supply Corporation - (edwards) | 32,000,000 | 2,093,500 | 3,840,000 | -45% | 3,405,400 | 2,560,000 | 33% | 2,107,700 | 2,124,800 | -1% | 1,765,100 | 1,792,000 | -2% | 1,396,700 | 1,612,800 | -13% | 1,019,500 | 2,016,000 | -49% |
| City Of Hays Water Department | 15,400,000 | 970,000 | 1,848,000 | -48% | 850,941 | 1,232,000 | -31% | 455,059 | 1,022,560 | -55% | 517,296 | 862,400 | -40% | 389,176 | 776,160 | -50% | 480,000 | 970,200 | -51% |
| Mountain City Oaks Water System | 43,164,000 | 2,855,200 | 5,179,680 | -45% | 2,158,100 | 3,453,120 | -38% | 1,623,800 | 2,866,090 | -43% | 1,577,900 | 2,417,184 | -35% | 1,385,000 | 2,175,466 | -36% | 1,311,800 | 2,719,332 | -52% |
| Cimarron Park Water Company, Inc. | 118,000,000 | 8,408,400 | 11,800,000 | -29% | 5,294,600 | 7,552,000 | -30% | 5,289,700 | 7,835,200 | -32% | 4,110,500 | 8,024,000 | -49% | 4,064,100 | 7,552,000 | -46% | 3,913,100 | 8,614,000 | -55% |
| Marbridge Foundation | 26,730,000 | 1,530,200 | 3,207,600 | -52% | 1,327,650 | 2,138,400 | -38% | 1,431,010 | 1,774,872 | -19% | 924,300 | 1,496,880 | -38% | 1,071,520 | 1,347,192 | -20% | 756,020 | 1,683,990 | -55% |
| Aqua Texas, Inc. - Bliss Spillar (trinity) | 38,625,000 | 2,937,000 | 4,635,000 | -37% | 1,697,000 | 3,090,000 | -45% | 1,795,000 | 2,564,700 | -30% | 1,827,000 | 2,163,000 | -16% | 1,256,000 | 1,946,700 | -35% | 1,090,000 | 2,433,375 | -55% |
| City Of Hays Water Department - Elliott Ranch | 54,450,000 | 4,120,100 | 6,534,000 | -37% | 3,278,600 | 4,356,000 | -25% | 1,991,000 | 3,615,480 | -45% | 2,238,300 | 3,049,200 | -27% | 1,590,000 | 2,744,280 | -42% | 1,495,000 | 3,430,350 | -56% |
| Aqua Texas, Inc. - Leisurewoods Water Company | 88,764,000 | 7,015,000 | 10,651,680 | -34% | 3,979,000 | 7,101,120 | -44% | 3,579,000 | 5,893,930 | -39% | 2,466,000 | 4,970,784 | -50% | 2,349,000 | 4,473,706 | -47% | 2,334,000 | 5,592,132 | -58% |
| Arroyo Doble Water System | 52,800,000 | 2,900,700 | 5,808,000 | -50% | 1,920,900 | 3,801,600 | -49% | 1,724,900 | 3,505,920 | -51% | 1,498,600 | 2,956,800 | -49% | 1,694,200 | 3,294,720 | -49% | 1,578,600 | 4,118,400 | -62% |
| Hays Consolidated I.s.d. - Hays High School | 30,000,000 | 2,617,300 | 3,600,000 | -27% | 2,126,000 | 2,400,000 | -11% | 1,691,700 | 1,992,000 | -15% | 1,208,500 | 1,680,000 | -28% | 986,000 | 1,512,000 | -35% | 695,200 | 1,890,000 | -63% |
| Aqua Texas, Inc. - Shady Hollow Estates Water Compan | 80,000,000 | 7,021,000 | 9,600,000 | -27% | 4,033,000 | 6,400,000 | -37% | 2,830,000 | 5,312,000 | -47% | 3,075,000 | 4,480,000 | -31% | 2,169,000 | 4,032,000 | -46% | 1,853,000 | 5,040,000 | -63% |
| Village Of San Leanna | 31,651,200 | 1,643,300 | 3,798,144 | -57% | 867,000 | 2,532,096 | -66% | 871,300 | 2,101,640 | -59% | 755,600 | 1,772,468 | -57% | 616,300 | 1,595,221 | -61% | 590,100 | 1,994,026 | -70% |
| Ruby Ranch Water Supply Corporation - (trinity) | 20,300,000 | 937,400 | 2,436,000 | -62% | 37,200 | 1,624,000 | -98% | 0 | 1,347,920 | -100% | 2,100 | 1,136,800 | -100% | 238,700 | 1,023,120 | -77% | 311,600 | 1,278,900 | -76% |
| St. Andrews School | 16,000,000 | 1,408,600 | 2,080,000 | -32% | 447,200 | 1,536,000 | -71% | 870,300 | 1,280,000 | -32% | 513,200 | 1,024,000 | -50% | 726,600 | 768,000 | -5% | 93,400 | 800,000 | -88% |
| City Of Sunset Valley | 18,590,000 | 15,900 | 2,230,800 | -99% | 24,700 | 1,487,200 | -98% | 2,600 | 1,234,376 | -100% | 7,900 | 1,041,040 | -99% | 6,000 | 936,936 | -99% | 4,600 | 1,171,170 | -100% |
| Grey Rock Golf Club - Grey Rock | 35,000,000 | 3,967,000 | 4,620,000 | -14% | 892,500 | 3,080,000 | -71% | 968,900 | 2,940,000 | -67% | 0 | 2,744,000 | -100% | 0 | 1,120,000 | -100% | 0 | 560,000 | -100% |
| Soccerfield Development Llc - Austin United Capital Socc | 12,000,000 | 0 | 1,584,000 | -100% | 0 | 1,056,000 | -100% | 0 | 1,008,000 | -100% | 0 | 940,800 | -100% | 0 | 384,000 | -100% |  | 192,000 |  |
| **Tier 3 (>=120M gallons/year)** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Creedmoor-maha Water Supply Corporation | 235,065,600 | 15,620,800 | 28,207,871 | -45% | 13,132,400 | 18,805,248 | -30% | 13,434,400 | 15,608,356 | -14% | 13,778,000 | 13,163,674 | 5% | 13,108,800 | 11,847,306 | 11% | 11,750,100 | 14,809,133 | -21% |
| City Of Buda | 275,000,000 | 24,162,300 | 32,999,999 | -27% | 17,308,900 | 22,000,000 | -21% | 16,548,600 | 18,259,999 | -9% | 13,769,200 | 15,400,000 | -11% | 11,762,400 | 13,860,000 | -15% | 12,480,600 | 17,325,000 | -28% |
| Goforth Special Utility District | 350,900,000 | 22,327,000 | 54,038,600 | -59% | 17,517,000 | 37,616,480 | -53% | 17,586,000 | 23,299,760 | -25% | 10,609,000 | 14,036,000 | -24% | 5,871,000 | 8,140,880 | -28% | 6,100,000 | 10,176,100 | -40% |
| City Of Kyle | 350,000,000 | 21,476,707 | 42,000,000 | -49% | 19,648,253 | 22,450,000 | -12% | 18,156,777 | 18,633,499 | -3% | 11,857,300 | 15,715,000 | -25% | 13,130,241 | 14,143,500 | -7% | 13,144,450 | 22,050,000 | -40% |
| Centex Materials, Lp. | 214,291,000 | 11,135,200 | 21,429,100 | -48% | 11,831,600 | 13,371,758 | -12% | 11,748,400 | 12,514,594 | -6% | 7,236,200 | 12,000,296 | -40% | 8,829,000 | 13,371,758 | -34% | 8,345,700 | 16,714,698 | -50% |
| Monarch Utilities, Inc. | 324,400,000 | 12,456,000 | 41,847,600 | -70% | 10,137,000 | 21,540,160 | -53% | 7,415,000 | 20,761,600 | -64% | 6,587,000 | 17,906,880 | -63% | 6,878,000 | 14,273,600 | -52% | 5,860,000 | 16,220,000 | -64% |
|  |  | 185,663,855 | 350,015,817 | -47% | 141,513,493 | 221,976,257 | -36% | 131,508,736 | 185,274,017 | -29% | 99,720,822 | 151,368,231 | -34% | 92,151,684 | 130,348,326 | -29% | 89,337,804 | 163,850,485 | -45% |

## Appendix G

# PUBLIC PRESENTATIONS

**Barton Springs/Edwards Aquifer Conservation District**

# Project Overview

## Regional Desalination and Aquifer Storage Recovery Plan

February 25, 2016

# Objective

The purpose of this study is to assess the feasibility of the development of two water management strategies in conjunction with the development of waste-to-energy to supply power to offset the electrical demands of these strategies in an effort to address potential future water shortages within the Barton Springs segment of the Edwards Aquifer.

# Background Information

- Sustainable yield studies have demonstrated the need to reduce pumpage from the Barton Springs segment of the Edwards Aquifer during periods of extreme drought.
- Studies for the Habitat Conservation Plan (HCP) grant have further demonstrated the need for alternative sources of water.
- Large amounts of water will be needed for expected growth in the District, particularly in the southeastern portion.
- Sources other than the freshwater Edwards will be needed to supply these developments.

# Background Information

- This study will make BSEACD the first public agency to examine the feasibility of using ASR in conjunction with desalination of water from the saline Edwards Aquifer.
- It is also the first to evaluate the use of biogas to offset the power demands of desalination and pumping.
- If desalination of saline Edwards water and/or ASR is shown to be a feasible water supply alternative, then the probability of meeting the DFC for Barton Springs could be increased by offering permitted users a significant new water supply strategy.

# Scope of Work

- Task 1 Kickoff Meeting
- Task 2 Installation of Saline Multiport Monitoring Well in the Edwards and Trinity Aquifers
- Task 3 Data Collection and Analysis
- Task 4 Assessment of Available Supplies and Demands
- Task 5 Evaluation of Water Management Strategies
  - a Desalination with Green Energy Offset
  - b Aquifer Storage Recovery
- Task 6 Documentation and Reporting
- Task 7 Meetings and Stakeholder Involvement

# Kickoff Meeting Agenda
# TWDB Regional Facility Plan
# Brackish Desalination Study of the Edwards Aquifer
## Barton Springs/Edwards Aquifer Conservation District

**Date:** February 25, 2016 **Project No.:**
**Time:** 10:00 A.M.
**Location:** BSEACD Offices–1124 Regal Row, Austin, TX 78748

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Introductions: BSEACD Staff and Directors, Texas Water Development Board Staff, Carollo Team (Carollo Engineers, ASR Systems, and NewGen Strategies & Solutions)

Project Overview and Objectives: Dr. Brian Smith, BSEACD

Overview of Desalination: Dr. Justin Sutherland, Carollo

Introduction to ASR: Dr. David Pyne, ASR Systems

Discussion of Participant Goals and Objectives for the Feasibility Study: Moderated by Dr. David Harkins, Carollo

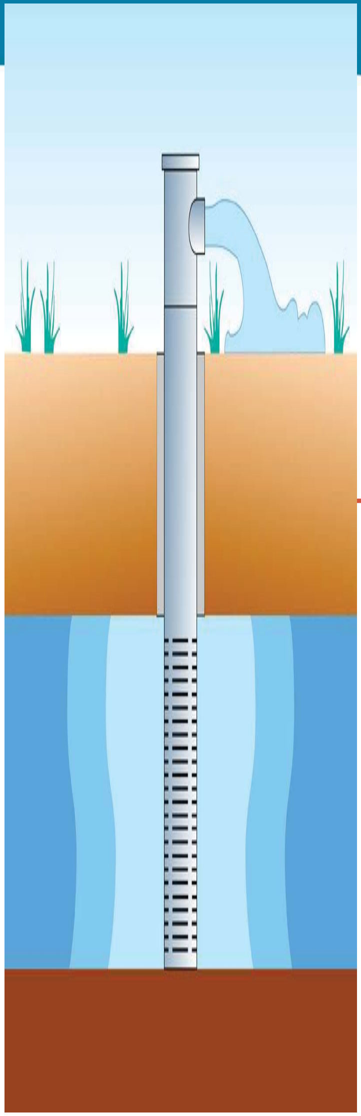
Project Schedule: Dr. Jeff Stovall, Carollo

TWDB Input: ??, TWDB

Lunch and Field Trip

Adjourn

# BARTON SPRINGS EDWARDS AQUIFER CONSERVATION DISTRICT



# AQUIFER STORAGE RECOVERY (ASR) AND REVERSE OSMOSIS DESALINATION: AN INTEGRATED WATER SUPPLY SOLUTION

---

Austin, Texas
February 25, 2016

R. David G. Pyne, P.E.
ASR Systems LLC
Gainesville, Florida

# ASR Operating Ranges

- Well depths
  - 140 to 3,000 feet
- Storage interval thickness
  - 10 to 400 feet
- Storage zone Total Dissolved Solids
  - 30 mg/L to 35,000 mg/L
- Storage Volumes
  - 100 AF to 270,000 AF
  - (30 MG to 80 BG)
- Bubble radius typically less than 1000 ft
- Individual wells up to 8 MGD capacity
- Wellfield capacity up to 157 MGD

Calleguas MWD, California

ASR Well

# Potential ASR Objectives for BSEACD (1/2)

Select and Prioritize One or More Pertinent ASR Applications for each ASR wellfield:

1. **Seasonal storage**
2. **Long-term storage (“water banking”)**
3. Emergency storage (“strategic water reserve”)
4. Diurnal storage
5. **Disinfection byproduct reduction**
6. Restore groundwater levels
7. Control subsidence
8. **Maintain distribution system pressures**
9. **Maintain distribution system flow**
10. Aquifer thermal energy storage (ATES)
11. **Stabilize aggressive water**

*Kiawah Island, South Carolina*

*Denver, Colorado*

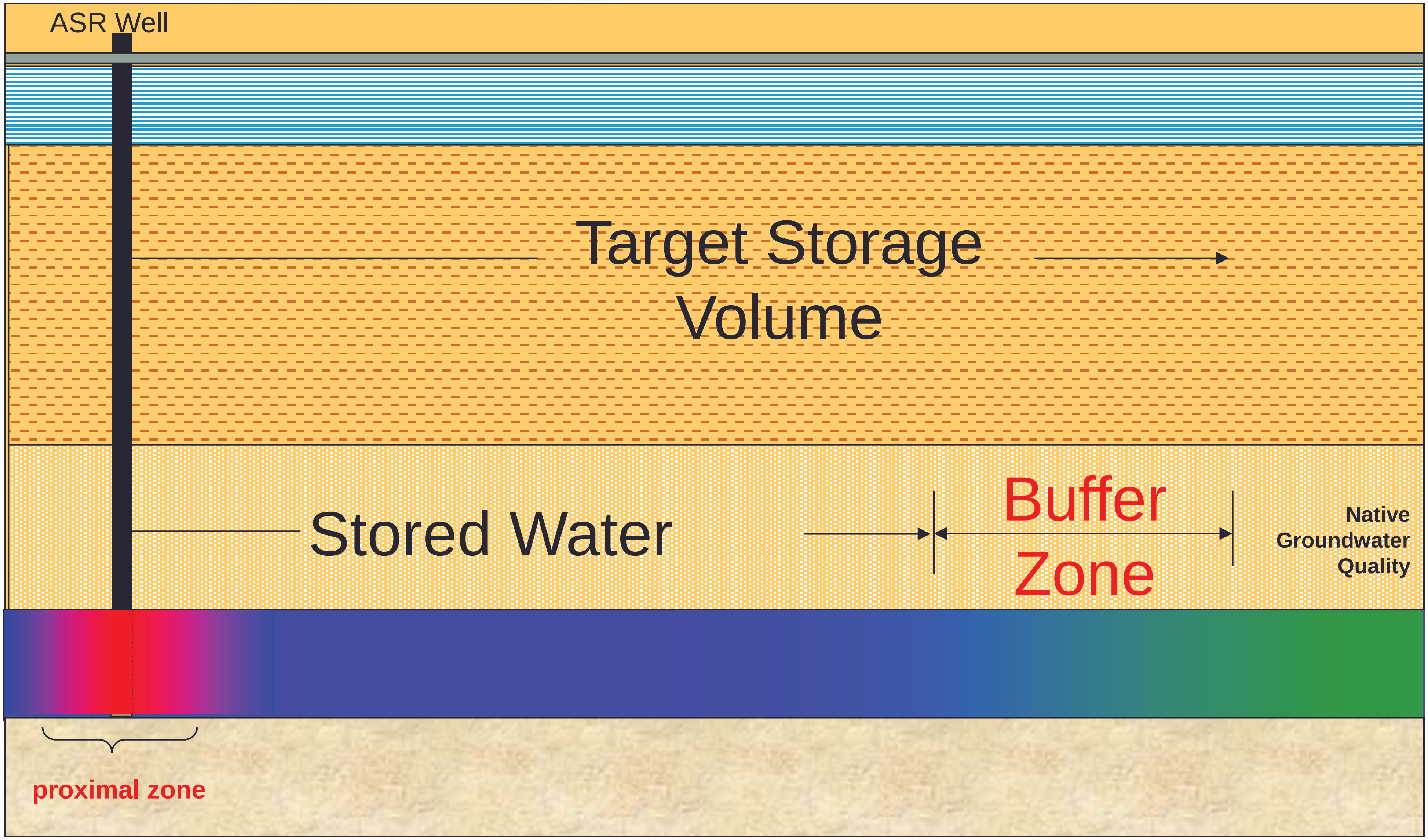
# Potential ASR Objectives (2/2)

12. **Reduce environmental effects of streamflow and/or reservoir diversions**
13. Agricultural water supply
14. Nutrient reduction in agricultural runoff
15. Enhance wellfield production
16. **Downsize and/or defer expansion of water facilities**
17. Reclaimed water storage for reuse
18. Hydraulic control of contaminant plumes (ie: “bad water” line)
19. **Maintenance or restoration of aquatic ecosystems (ie: Barton Springs)**
20. **Achieve water supply reliability**

***Manatee County, Florida***
***ASR Well, 1983***

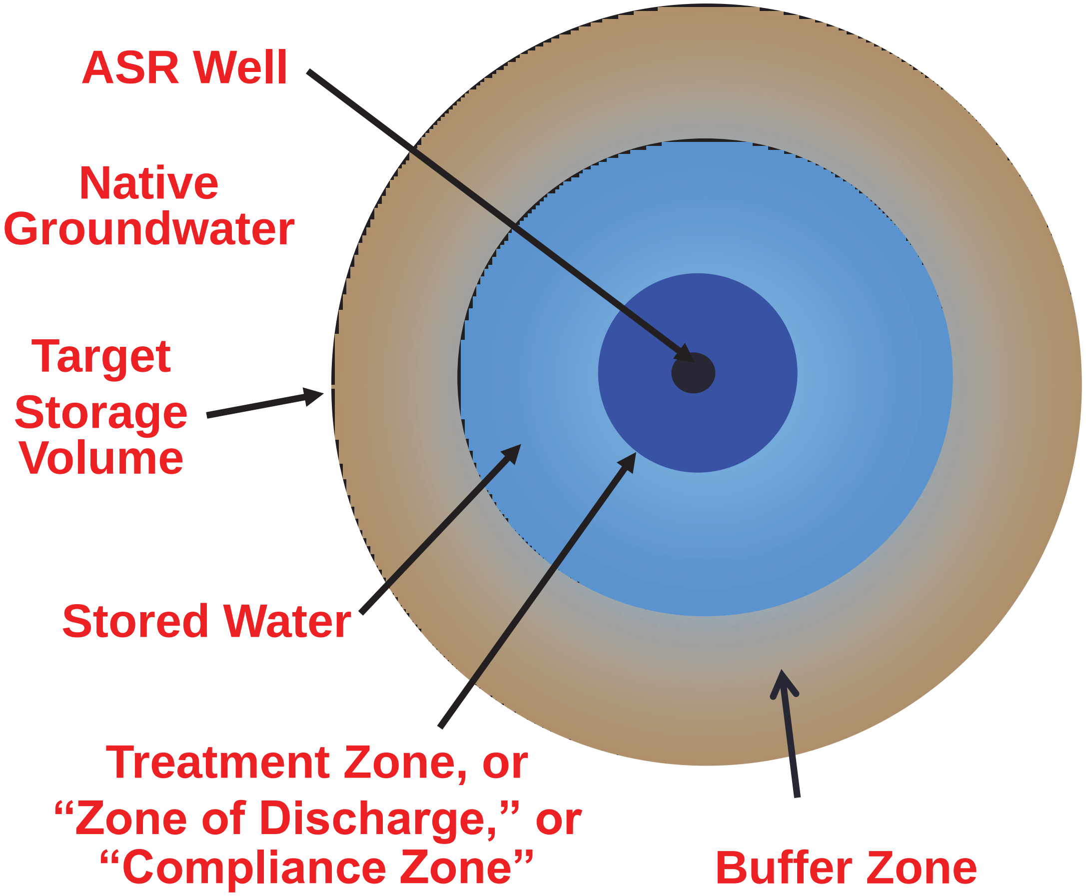
***ACEC Grand Award, 1984***

Target Storage Volume (TSV) is sum of stored water volume plus buffer zone volume.  It is often expressed in MG/MGD of recovery capacity, or “days”



# Treatment occurs in an aquifer due to natural physical, geochemical and microbial processes.

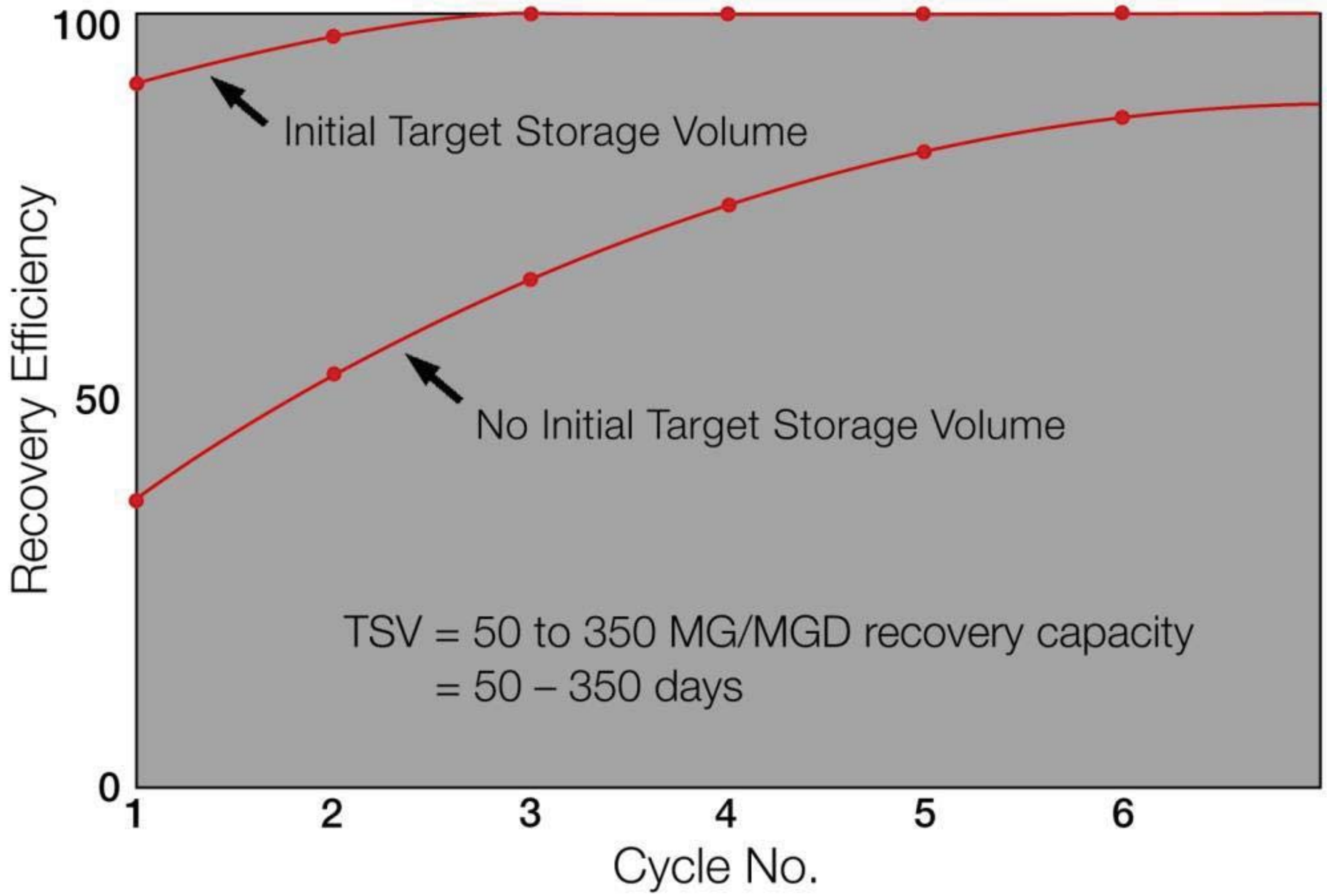
**ASR Bubble (Top View)**



**Improvements in Water Quality**

- $NO_3$, $NH_3$, P
- THMs
- HAAs
- $H_2S$
- Fe, Mn
- Ra
- Gross Alpha Rad.
- Bacteria
- Protozoa
- Viruses

# Initial development of the TSV facilitates achieving high recovery efficiency



# South Island Public Service District
# Hilton Head, SC

- Carollo and ASR Systems
- RO Treatment of Brackish Groundwater
- ASR Storage of Treated Drinking Water in a Different Brackish Aquifer

- LONG COVE ASR FACILITIES

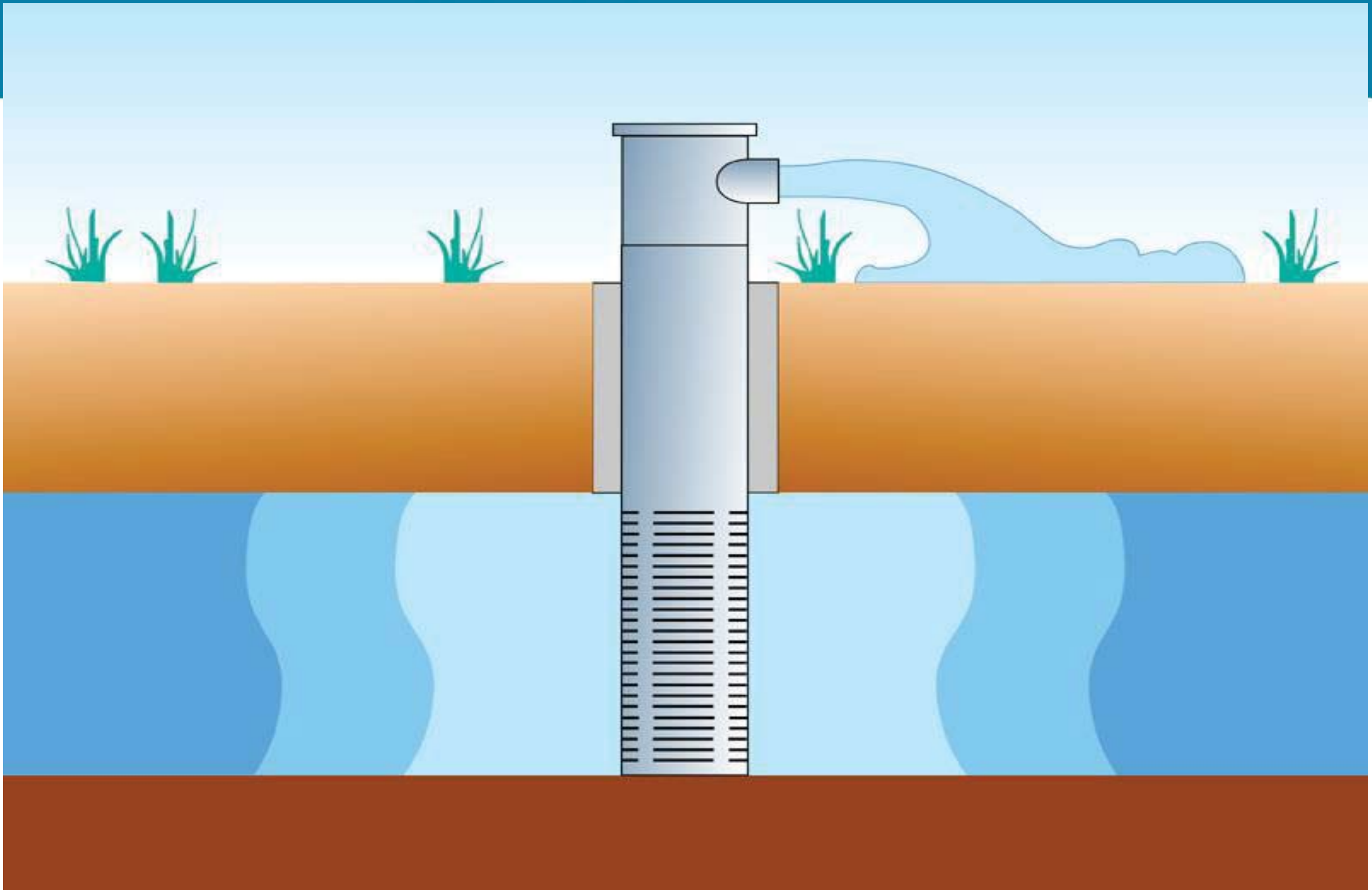
- 2.0 MGD ASR Wells
- Depth about 600 ft
- Semi-confined limestone artesian aquifer
- Native Groundwater TDS about 2,500 mg/l
- 100% Recovery Efficiency

- PALMETTO BAY ASR FACILITIES

# ASR well design and WTP process design need to be integrated

- Conventional surface water treatment processes with alum and lime to reduce color and meet drinking standards in product water can produce recharge water that is highly aggressive to aquifers, producing Fe and Mn through dissolution of pyrite, siderite and feldspars. Increasing the alkalinity and pH of the product water can probably resolve this issue. Phosphate addition for corrosion control in the distribution system may not be effective in the aquifer due to microbial activity and geochemistry.
- Ozone and other WTP processes can accelerate oxidation processes in the aquifer, potentially mobilizing metals and creating clays.
- Other strong oxidation processes such as hydrogen peroxide, often utilized for reclaimed water treatment, are probably aggressive to clastic aquifer geochemistry.
- Meeting peak demands from ASR storage can greatly reduce WTP capital and operating costs, and overall unit costs for water supply.

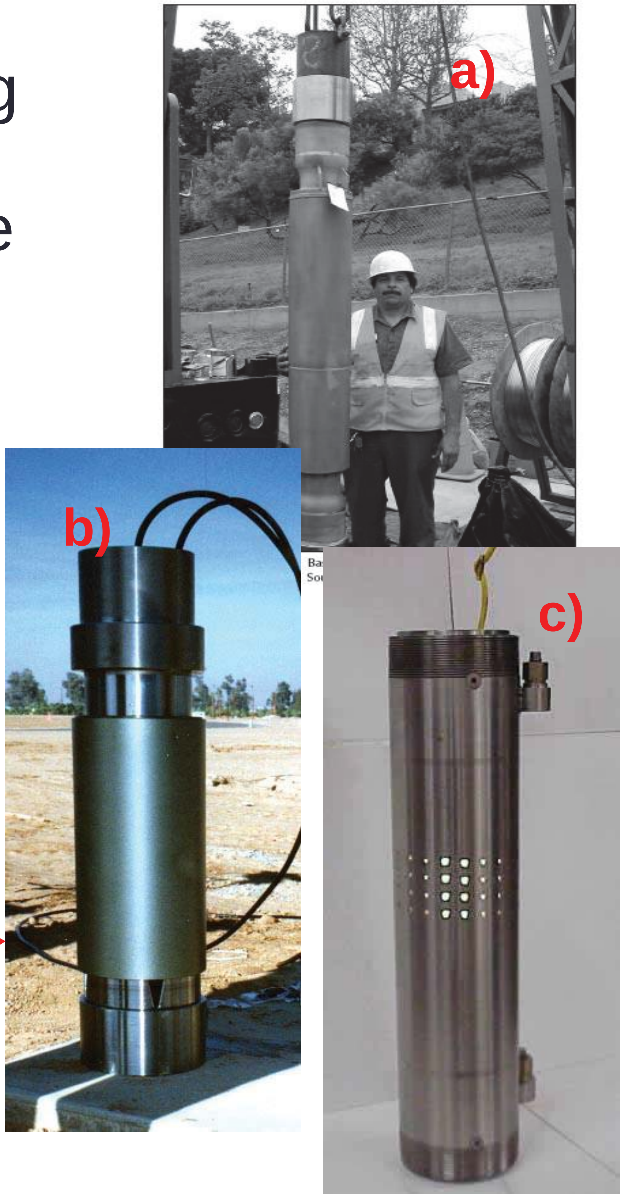
# ASR IS A STORAGE AND TREATMENT PROCESS



…and also a proven and cost-effective technology

# ASR Physical Treatment Processes

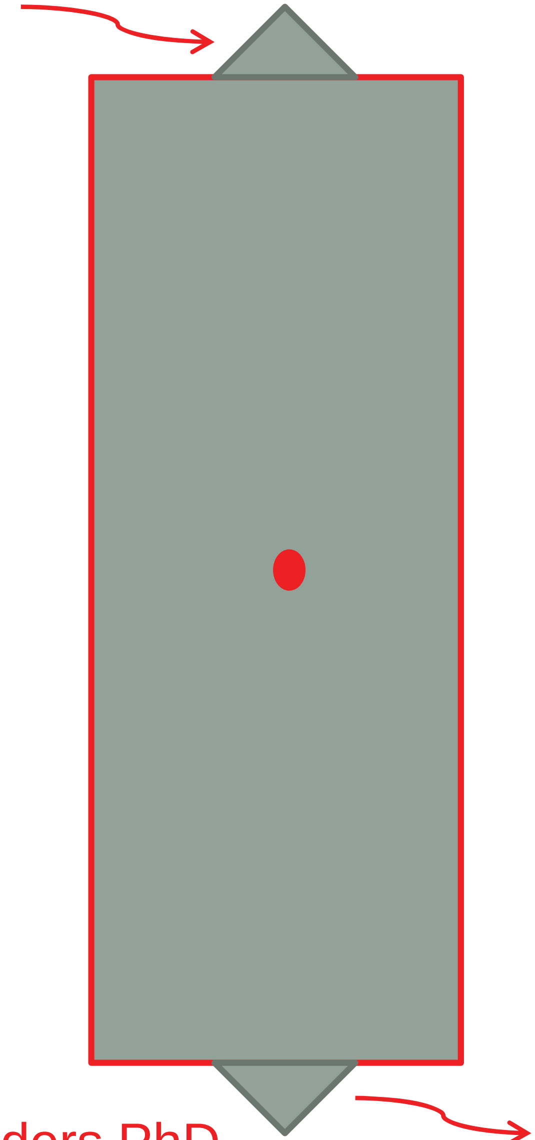
- Change from turbulent flow to laminar flow as water moves radially away from the well during recharge.
- Displacement, dispersion and advection as the stored water bubble expands during recharge, contracts during recovery, and moves downgradient in the aquifer.
- Pros: Precipitation and filtration of any particulates or flocs in intergranular spaces and other flow conduits.
- Cons: Well clogging and redevelopment.
- Cons: Air entrainment and cascading, if not controlled.
- Dissolved air solution and release.
- Subsidence and raising of ground surface elevations.



Downhole Flow Control Valves
a) Baski, b) V-Smart, c) 3-R

# ASR Microbial Treatment Processes

- Aquifers may be envisioned as a seething, frothing mass of bacteria that haven't had anything to eat for a long long time and are waiting to be fed.
- It is complicated and expensive to characterize and investigate subsurface microbial reactions in wells, and to reverse microbial clogging mechanisms.
- Dissolved oxygen uptake by microbial activity can be rapid (hours to days), generating $CO_2$.
- Ammonia reduction and denitrification occurs more slowly (days to weeks).
- Pros: DOC, N, P, Disinfection Byproduct (DBP), bacteria, virus, protozoa reduction occurs during ASR storage due to microbial activity.
- Cons: Well clogging also occurs due to microbial activity.

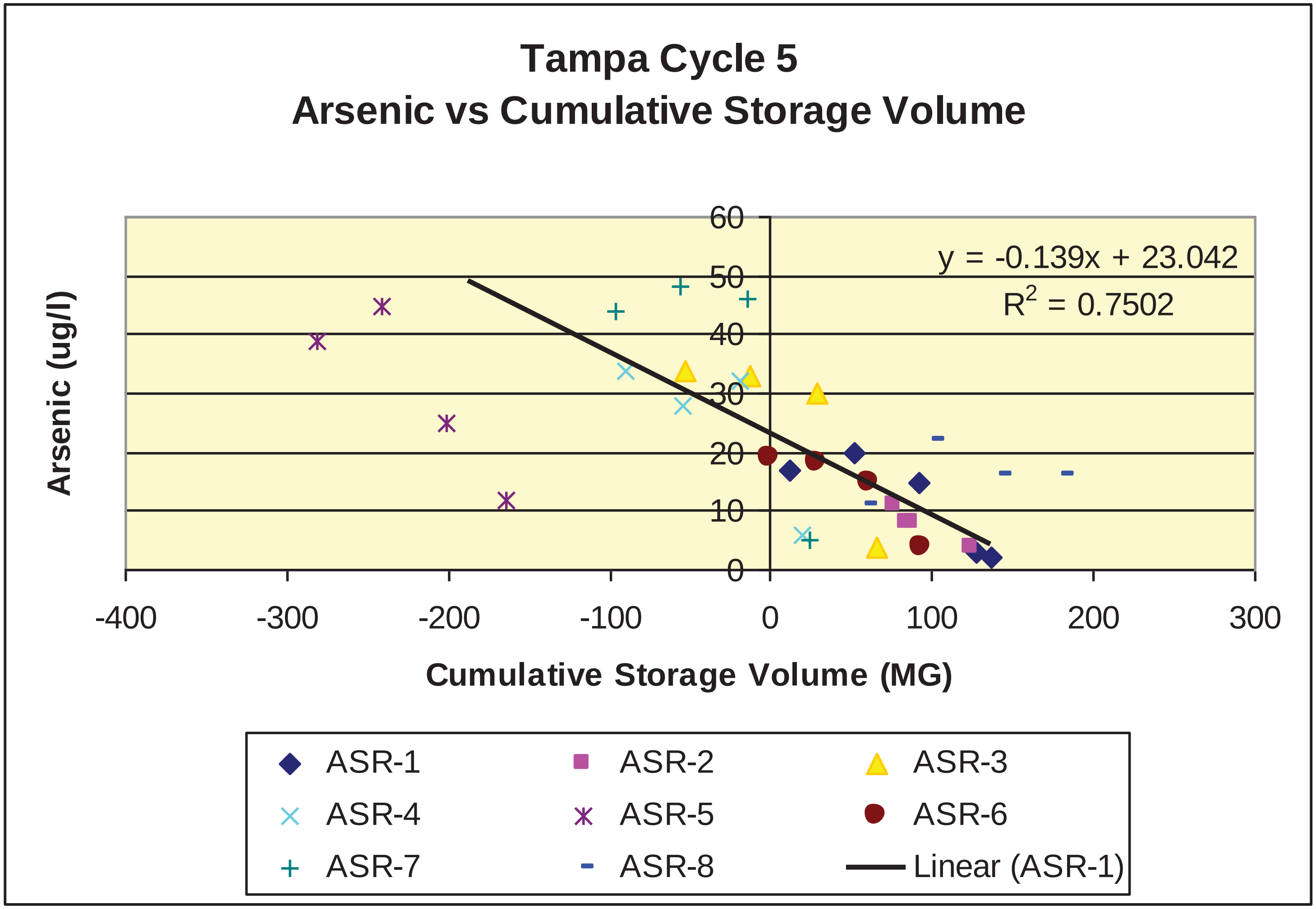


Well clogging "picture" courtesy: John H. Schnieders PhD

# ASR Geochemical Treatment Processes

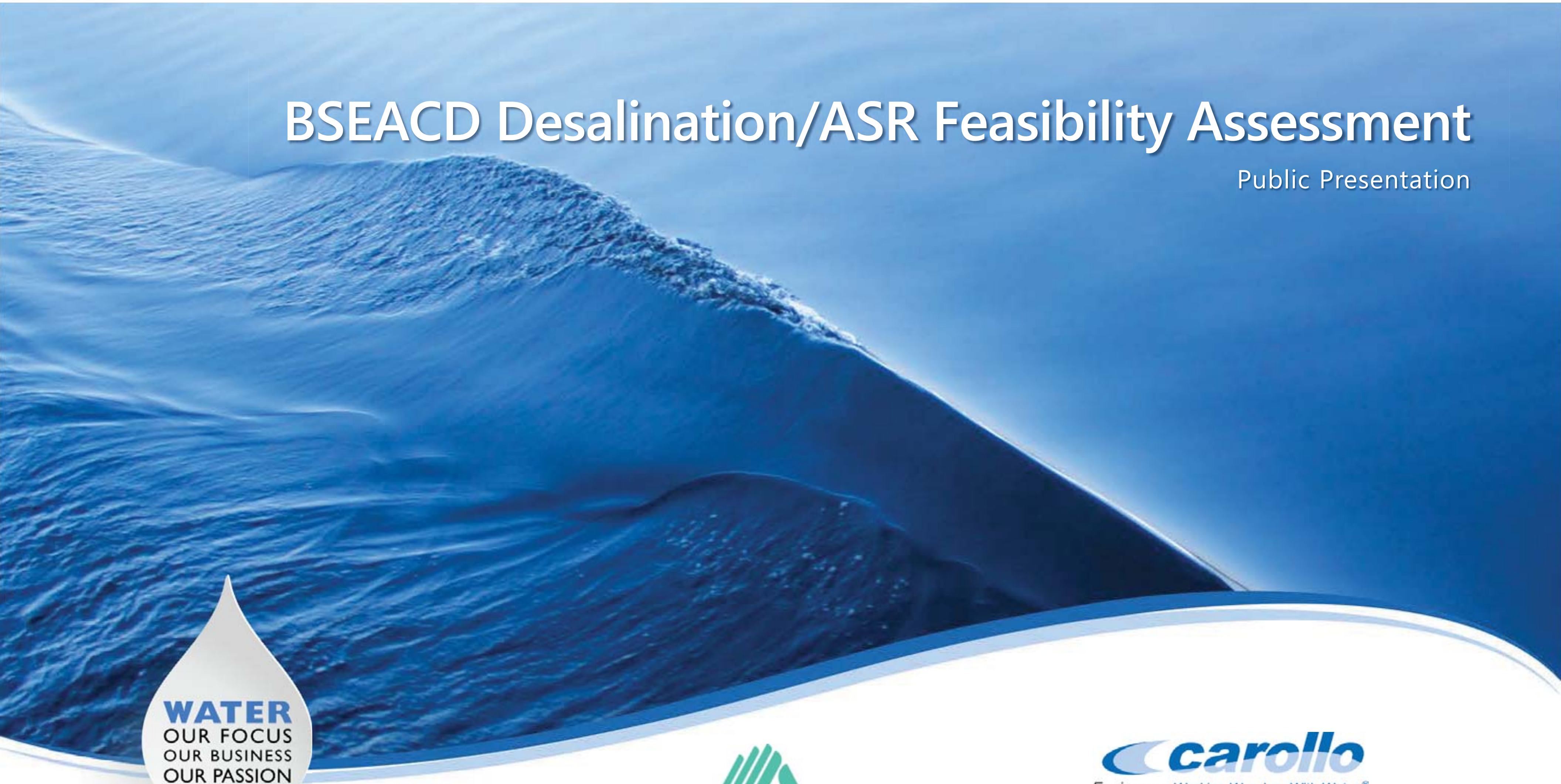
- Importance for successful ASR generally underestimated.
- Investigations expensive but necessary, particularly for finer-grained lithologic settings for ASR wells.
- Microbiological and geochemical treatment processes underground are two sides of the same coin, but the geochemical processes are relatively easier to investigate, given accurate input data.
- Processes include (but not limited to) oxidation, reduction, ion exchange, adsorption, diagenesis (weathering), leaching, dissolution, precipitation.
- Investigation tools include continuous wireline coring, core lab analysis, geochemical modeling, field and bench testing.
- Pros: Reactions can usually be controlled at low to acceptable cost (buffer zone, pH & alkalinity adjustment, deoxygenation).
- Cons: metals mobilization (Fe, Mn, As, U), formation of kaolinite clay, turbidity increase, well clogging, need for pre- or post-treatment.

# Arsenic declines due to geochemical processes as the cumulative storage volume increases



ARSENIC ALSO DECLINES WITH DISTANCE , WITH TIME, AND WITH INCREASING NUMBERS OF OPERATING CYCLES AT ABOUT THE SAME VOLUME

DISTANCE USUALLY LESS THAN 200 FT



# BSEACD Desalination/ASR Feasibility Assessment

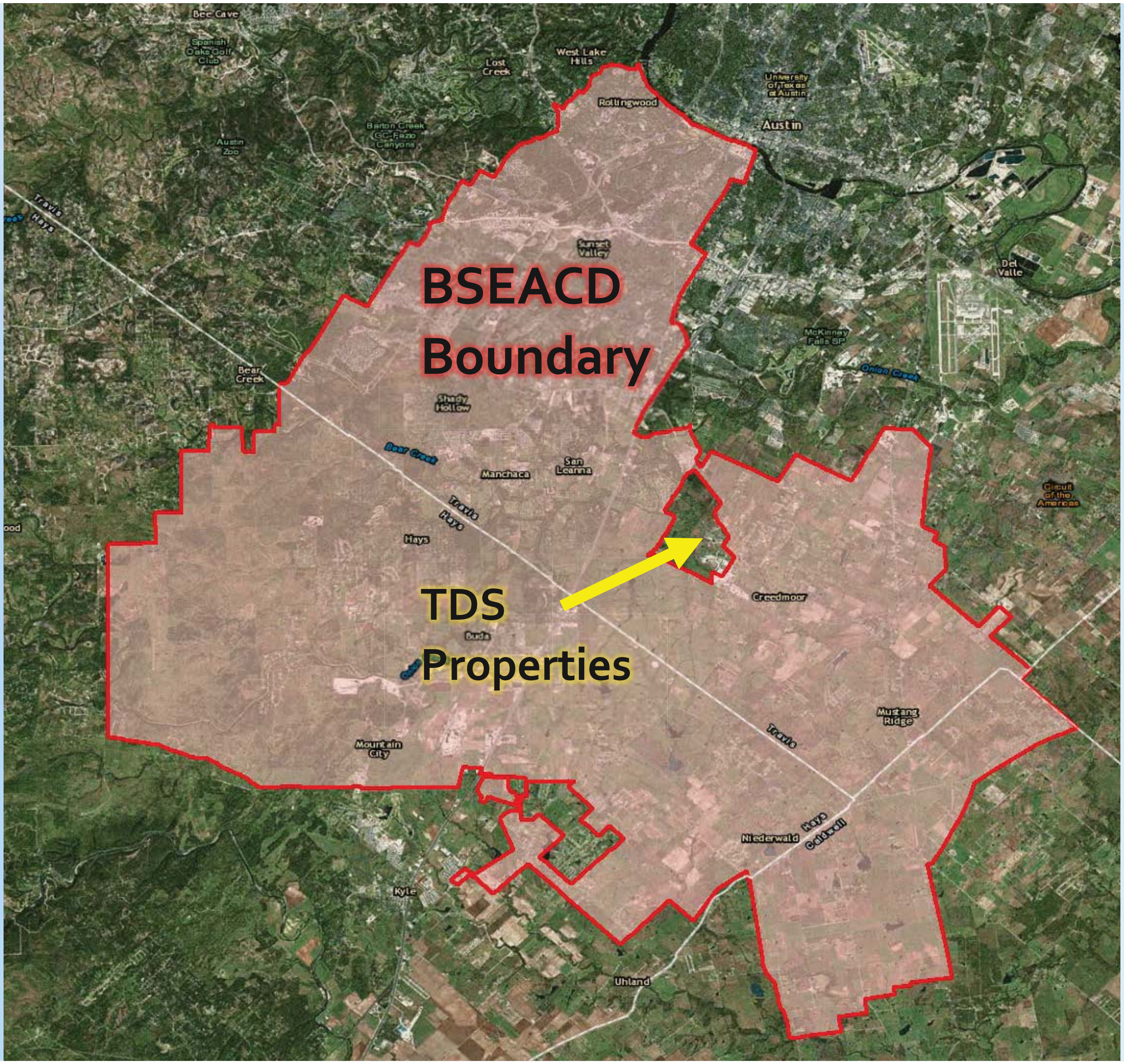
Public Presentation

**WATER**
OUR FOCUS
OUR BUSINESS
OUR PASSION

Barton Springs
Edwards Aquifer
CONSERVATION DISTRICT

carollo
Engineers...Working Wonders With Water®

# BSEACD


BSEACD Boundary
TDS Properties
Bee Cave
Spanish Oaks Golf Club
Austin Zoo
Barton Creek GC-Fazio Canyons
Lost Creek
West Lake Hills
Rollingwood
University of Texas at Austin
Austin
Travis
Hays
Sunset Valley
Del Valle
McKinney Falls SP
Onion Creek
Bear Creek
Shady Hollow
Bear Creek
Manchaca
San Leanna
Circuit of the Americas
Travis
Hays
Hays
Creedmoor
Buda
Mustang Ridge
Travis
Mountain City
Hays
Caldwell
Niederwald
Kyle
Uhland

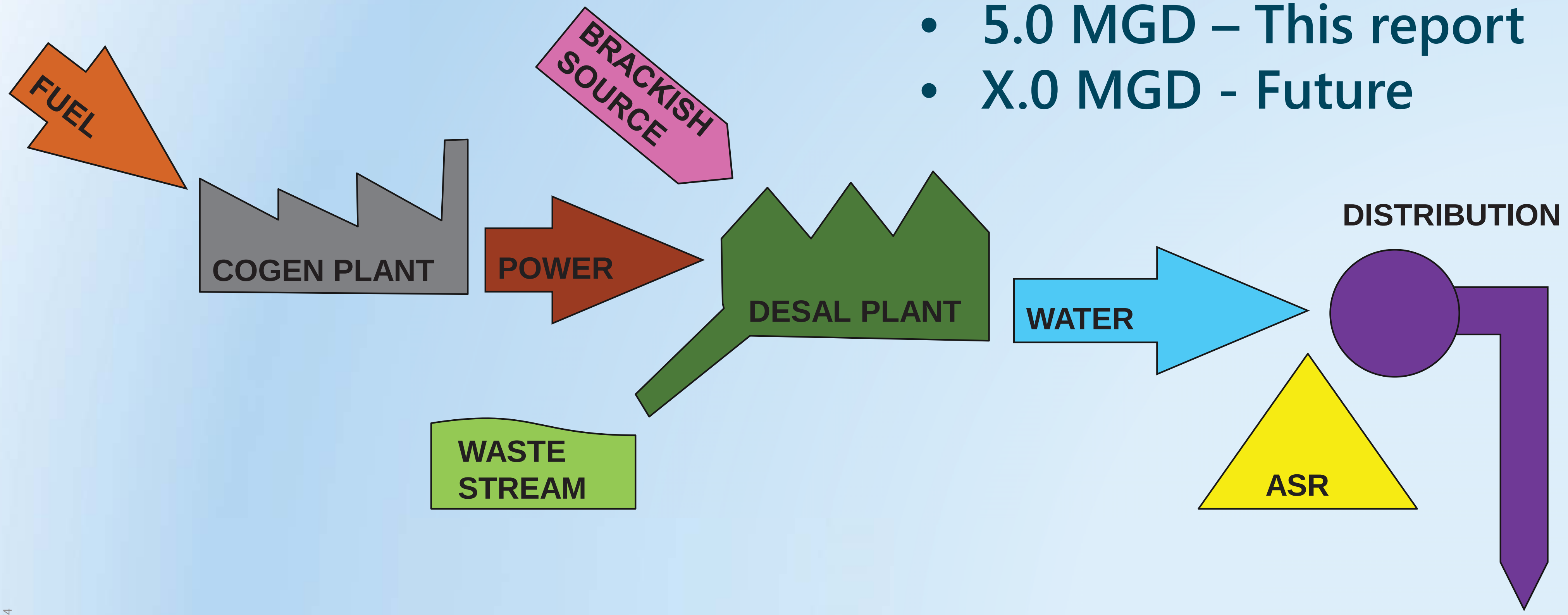
# Purpose

- The purpose of this study was to assess the feasibility of implementing two water management strategies using waste-to-energy power to offset the electrical demands of these strategies.

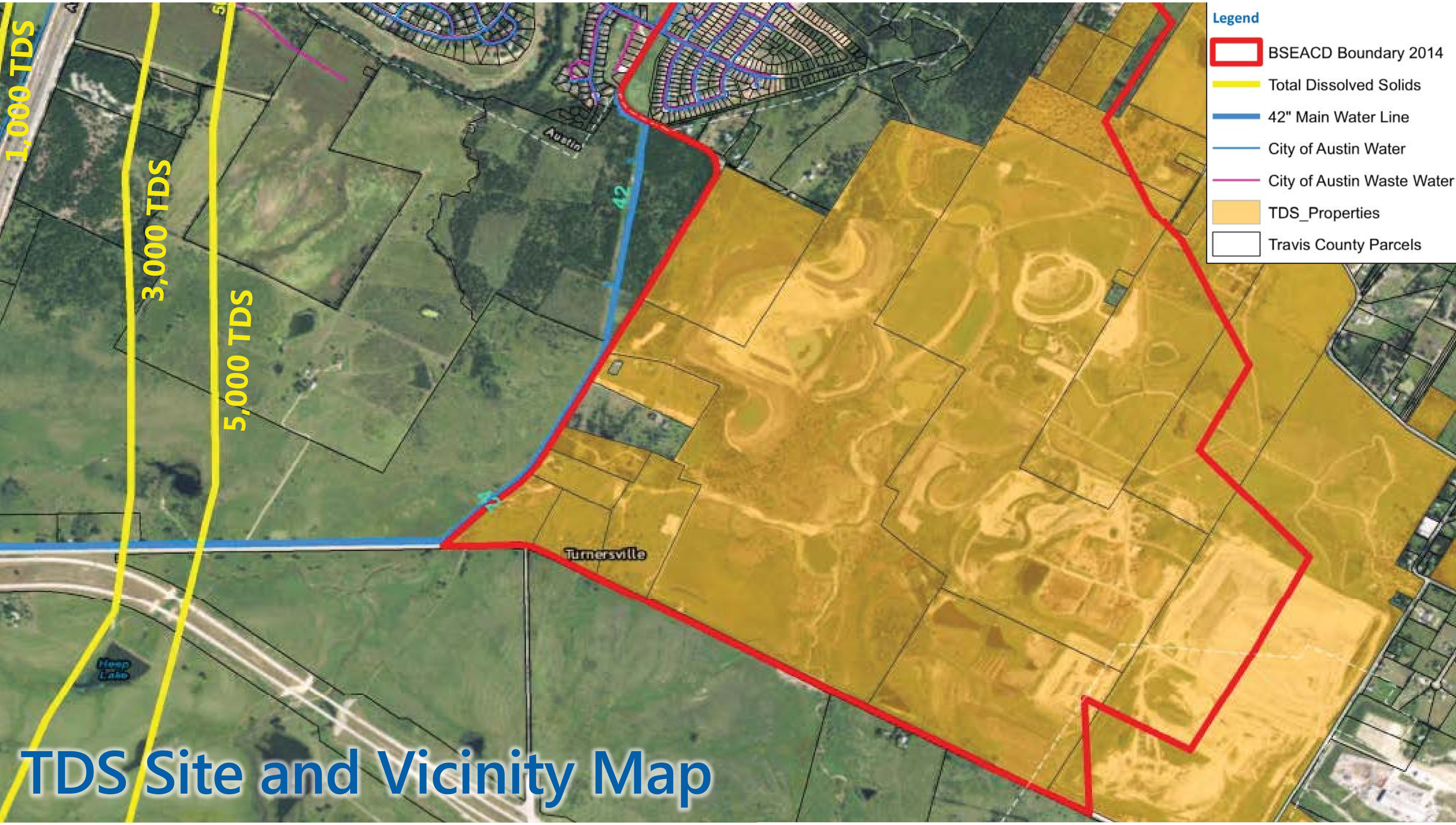
- The Feasibility Assessment is an effort to address potential future water shortages within the Barton Springs segment of the Edwards Aquifer.

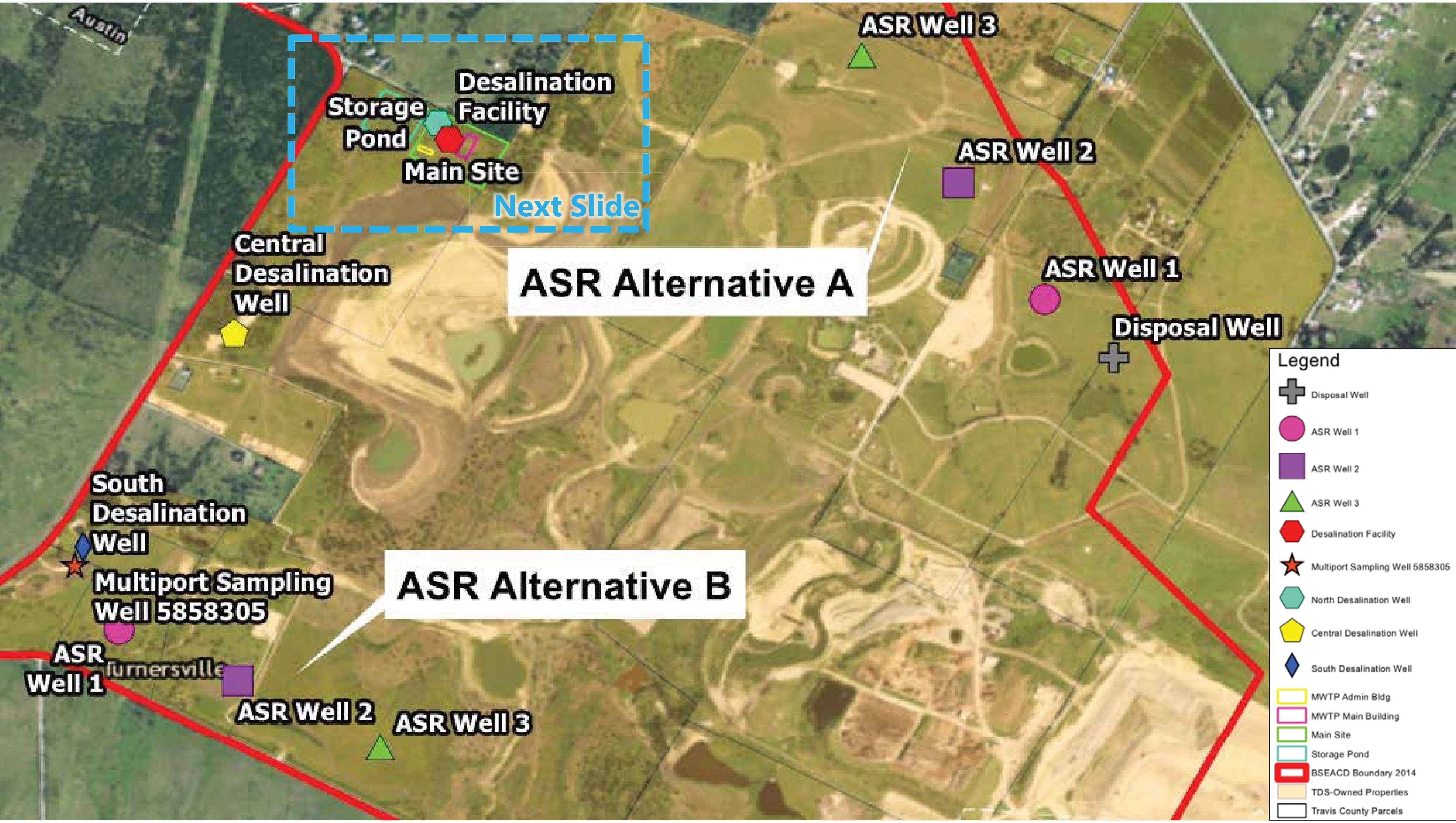
# Major Project Components

- 2.5 MGD – This report
- 5.0 MGD – This report
- X.0 MGD - Future



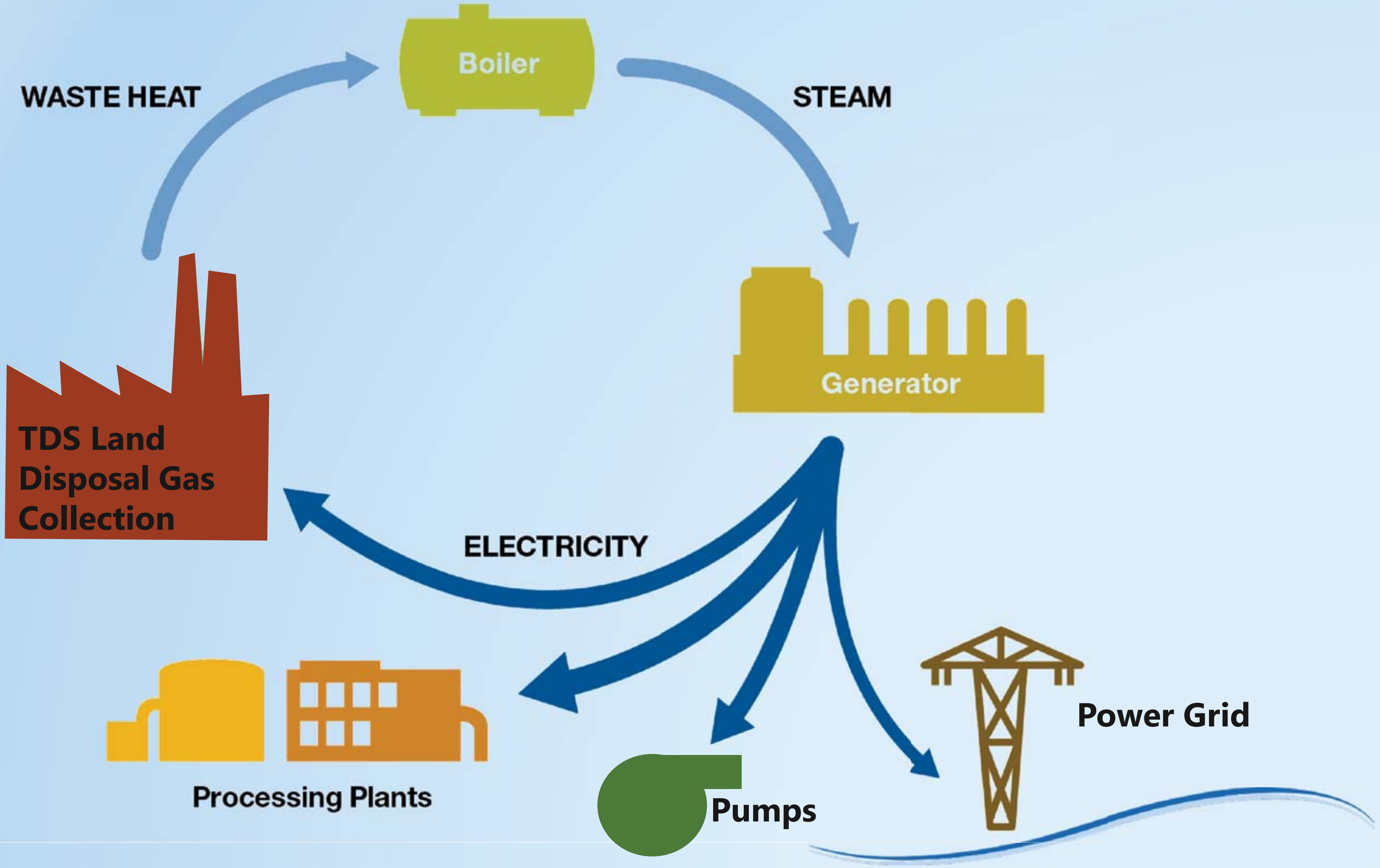
# TDS Site and Vicinity Map



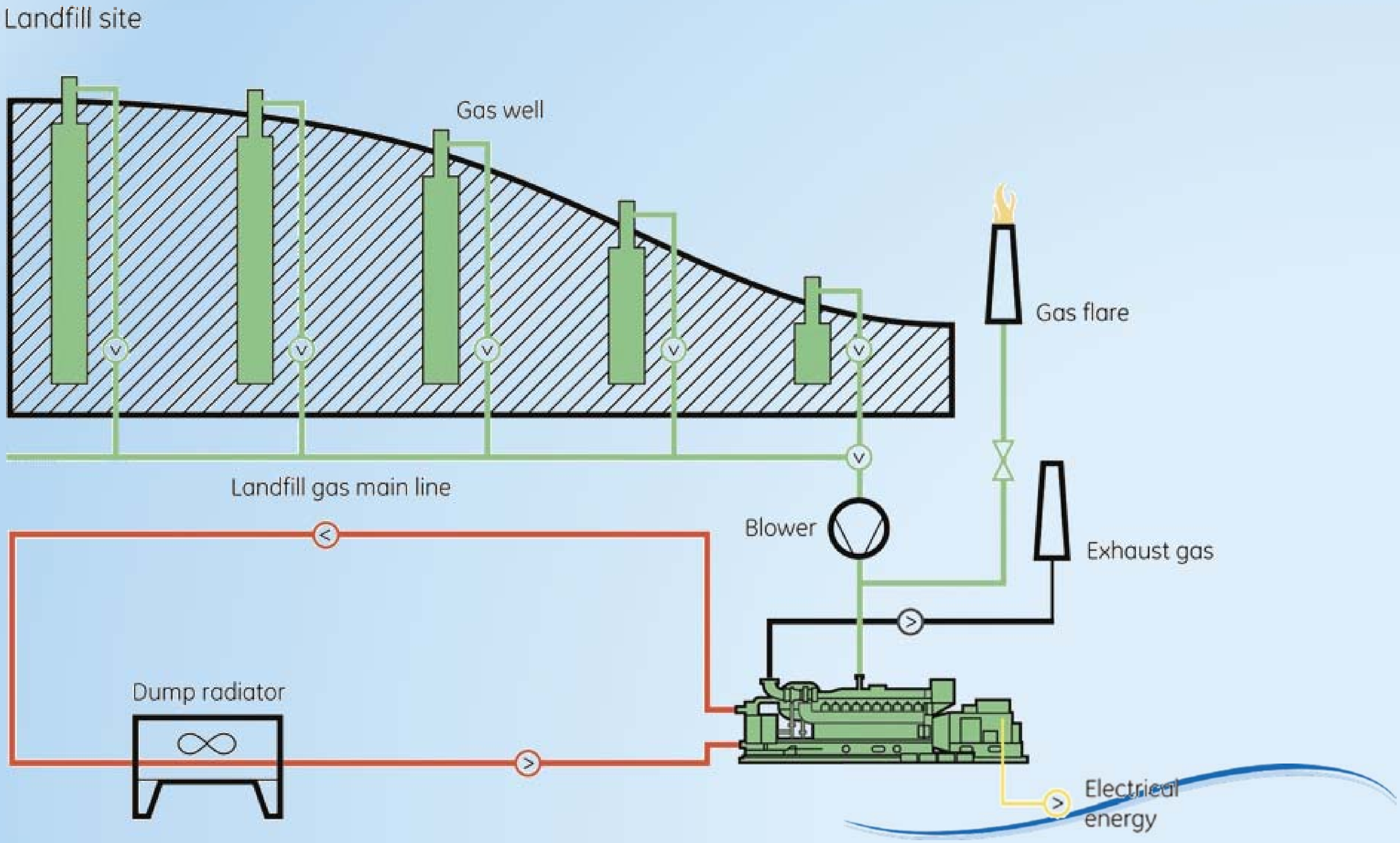

Austin
ASR Well 3
Desalination Facility
Storage Pond
Main Site
Next Slide
ASR Well 2
Central Desalination Well
ASR Alternative A
ASR Well 1
Disposal Well
South Desalination Well
Multiport Sampling Well 5858305
ASR Alternative B
ASR Well 1
Turnersville
ASR Well 2
ASR Well 3
Legend
Disposal Well
ASR Well 1
ASR Well 2
ASR Well 3
Desalination Facility
Multiport Sampling Well 5858305
North Desalination Well
Central Desalination Well
South Desalination Well
MWTP Admin Bldg
MWTP Main Building
Main Site
Storage Pond
BSEACD Boundary 2014
TDS-Owned Properties
Travis County Parcels


North
Desalination
Well
Storage Pond
Desalination Facility
Main Site
MWTP Admin
Bldg
MWTP
Main
Building

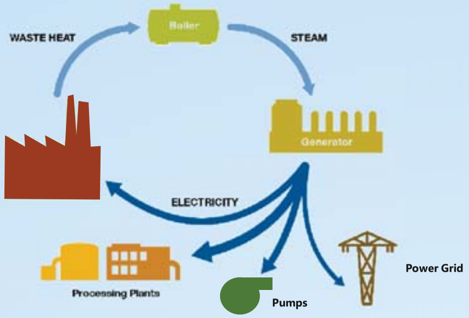
# Cogeneration



# Cogeneration



# Cogeneration

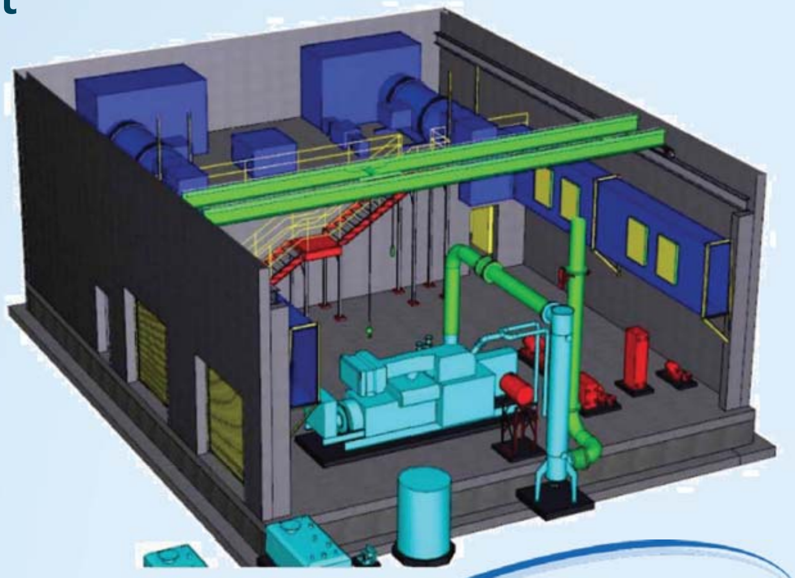


- Utilize the landfill gas to generate electricity to power the desalinization equipment as well as other loads required for the project.

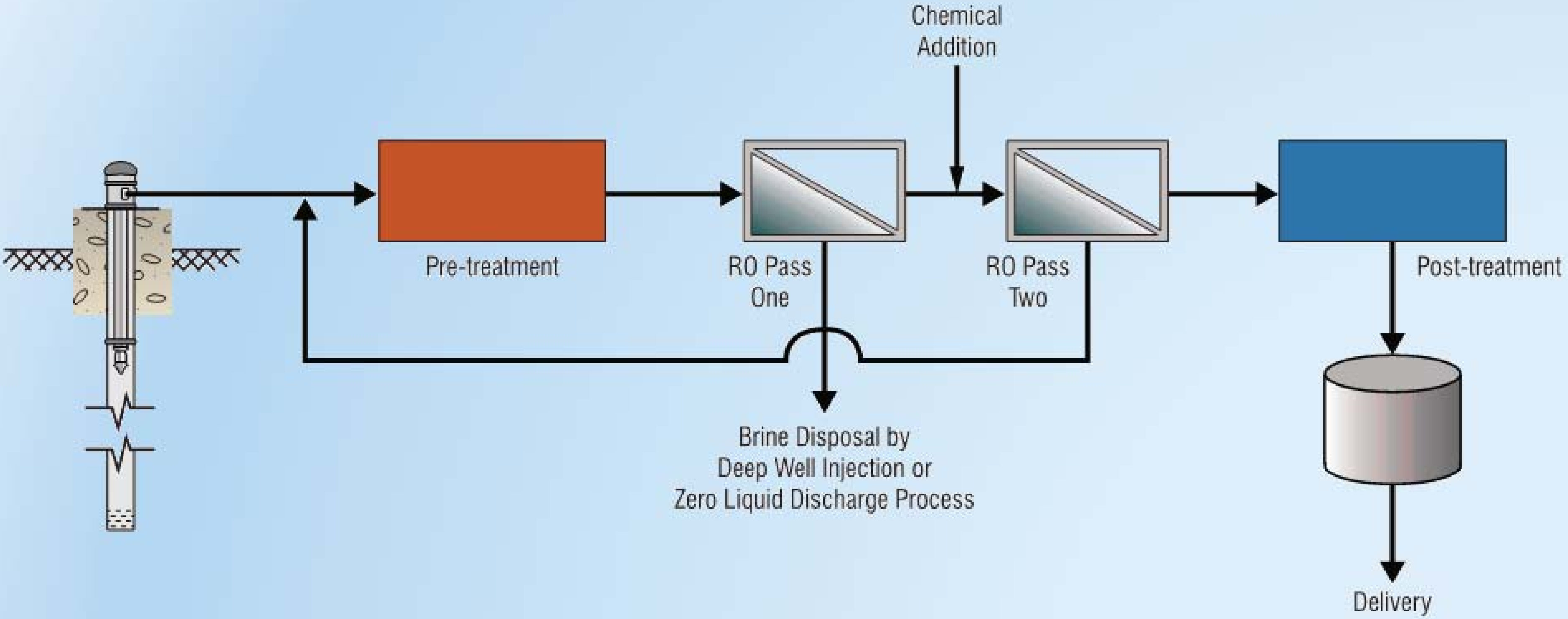
- Gas production can be estimated at 58.2 Million cubic feet per day or 40,410 standard cubic feet per minute

- Cogeneration engine size selection is normally based on available biogas, volatility, and average plant power demand.

- Based on the selected desalinization and injection alternatives, the total process connected load will be approximately 2.3 MW.



# Desalination



Chemical Addition

Pre-treatment

RO Pass One

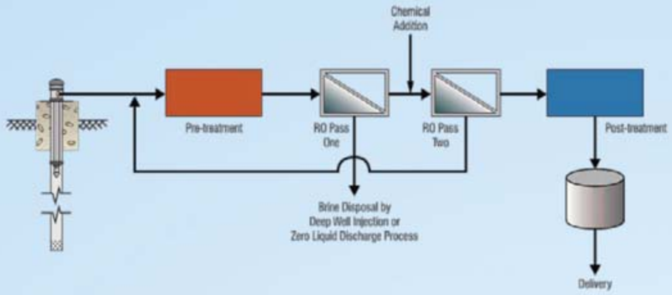
RO Pass Two

Post-treatment

Brine Disposal by
Deep Well Injection or
Zero Liquid Discharge Process

Delivery

# Desalination

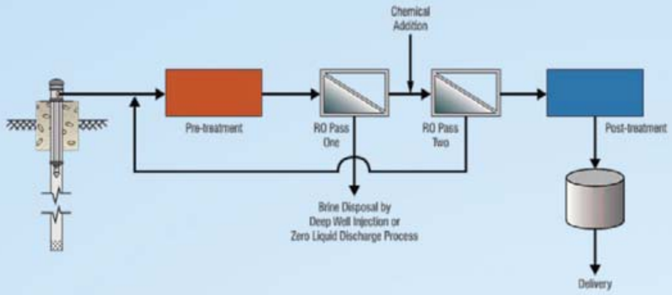


- Desalination of saline groundwater from the Edwards Aquifer.

- The 3 proposed desalination wells will be sized to pump 1,500 gpm each.

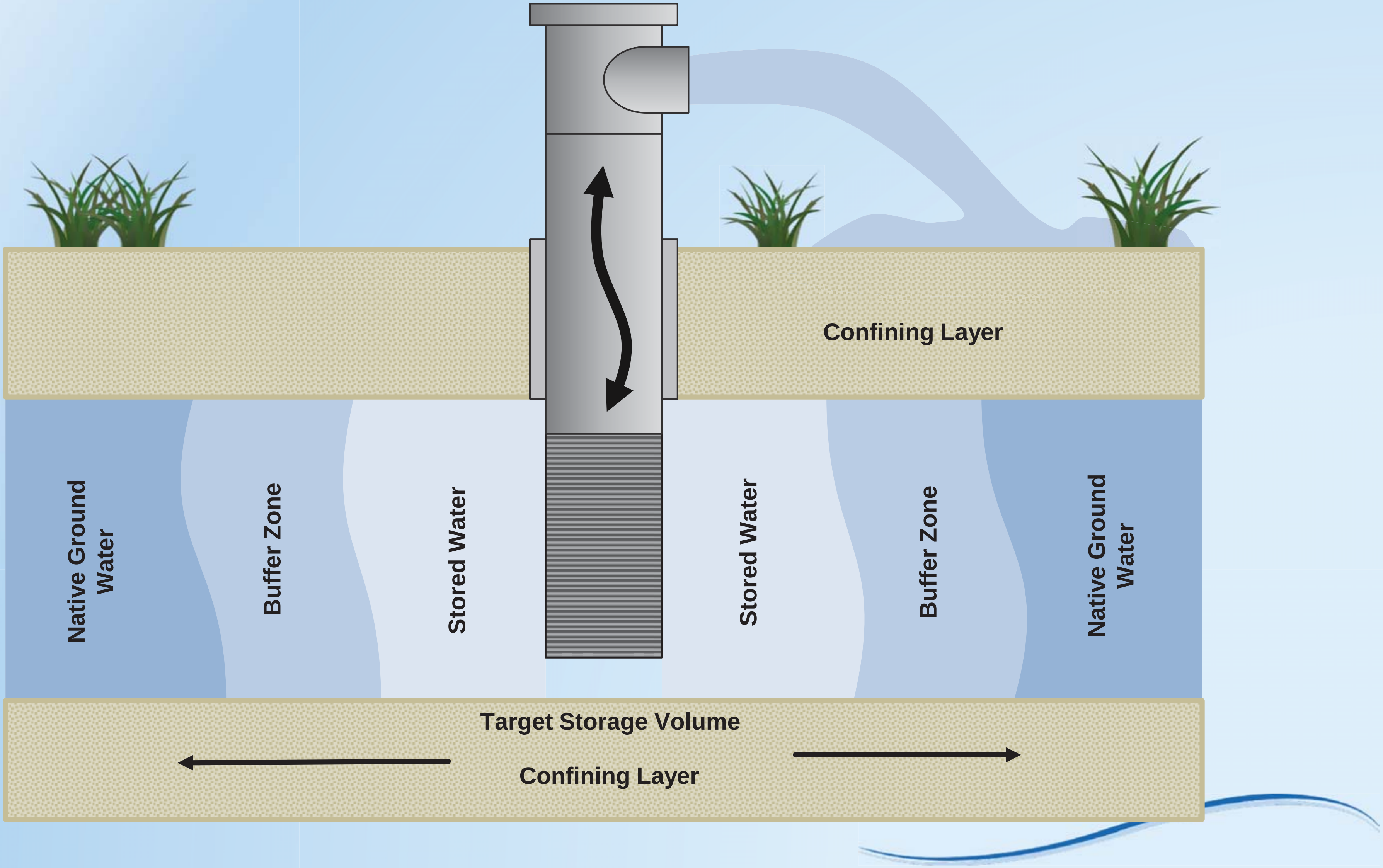
- Types: desalination technologies may be defined as pressure-driven, electrically-driven, and thermal.
  - ➢ Reverse osmosis (RO),
  - ➢ electrodialysis reversal (EDR),
  - ➢ and multi-effect distillation (MED)

# Concentrate Disposal

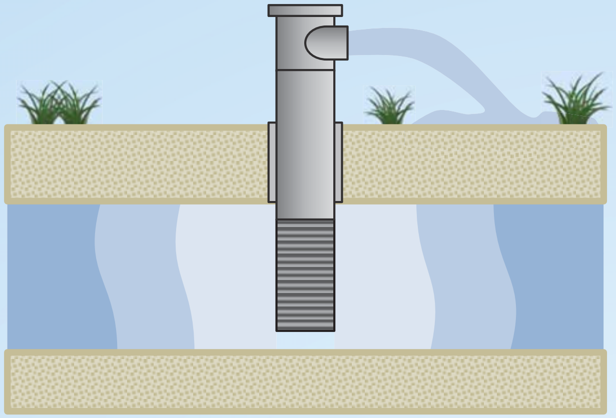


- Deep Well Injection
  - Existing Salt Flat (Edwards) Field Injection Wells in Caldwell County
  - Trinity Injection Wells on TDS Property
  - Edwards Injection Wells in Caldwell County
- Zero Liquid Discharge

# ASR


Confining Layer
Native Ground Water
Buffer Zone
Stored Water
Stored Water
Buffer Zone
Native Ground Water
Target Storage Volume
Confining Layer

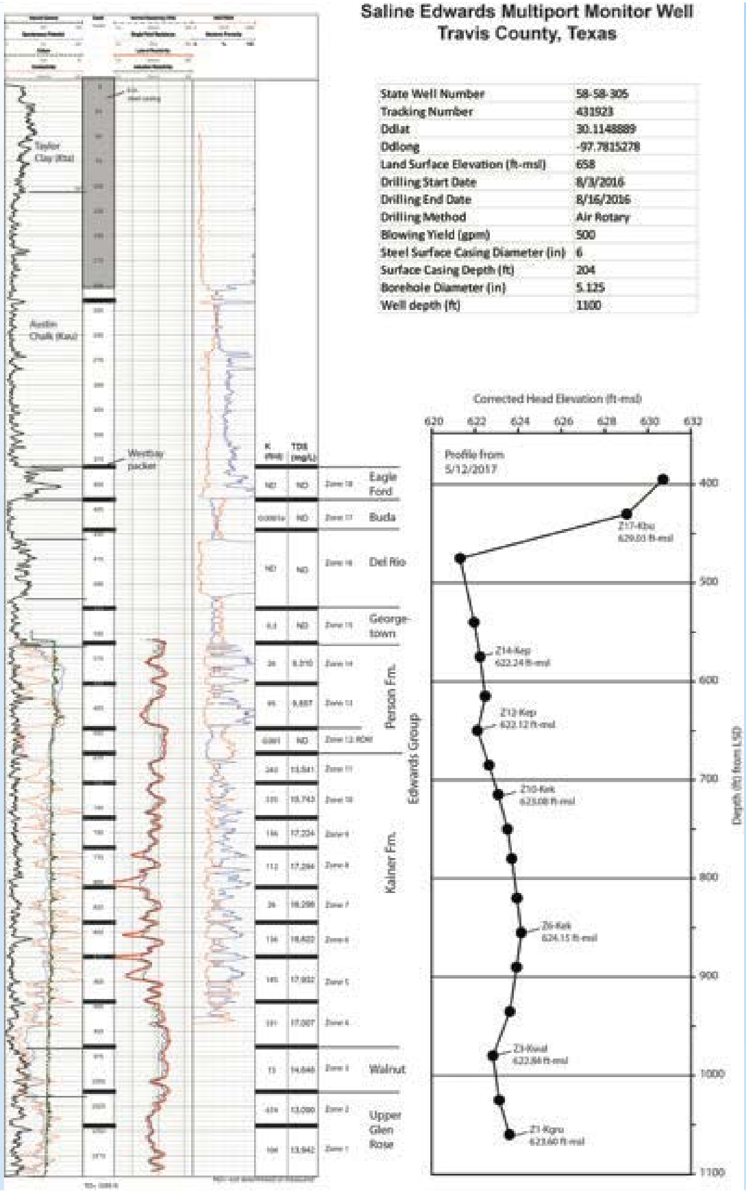
# ASR



- Three ASR wells are assumed to be needed, each designed to produce 500 gpm.
- Installed capacity will total 1,500 gpm (2.2 mgd).
- Firm ASR recovery capacity with the largest well out of service would be 1,000 gpm, or 1.5 mgd.

# Multiport Monitor Well

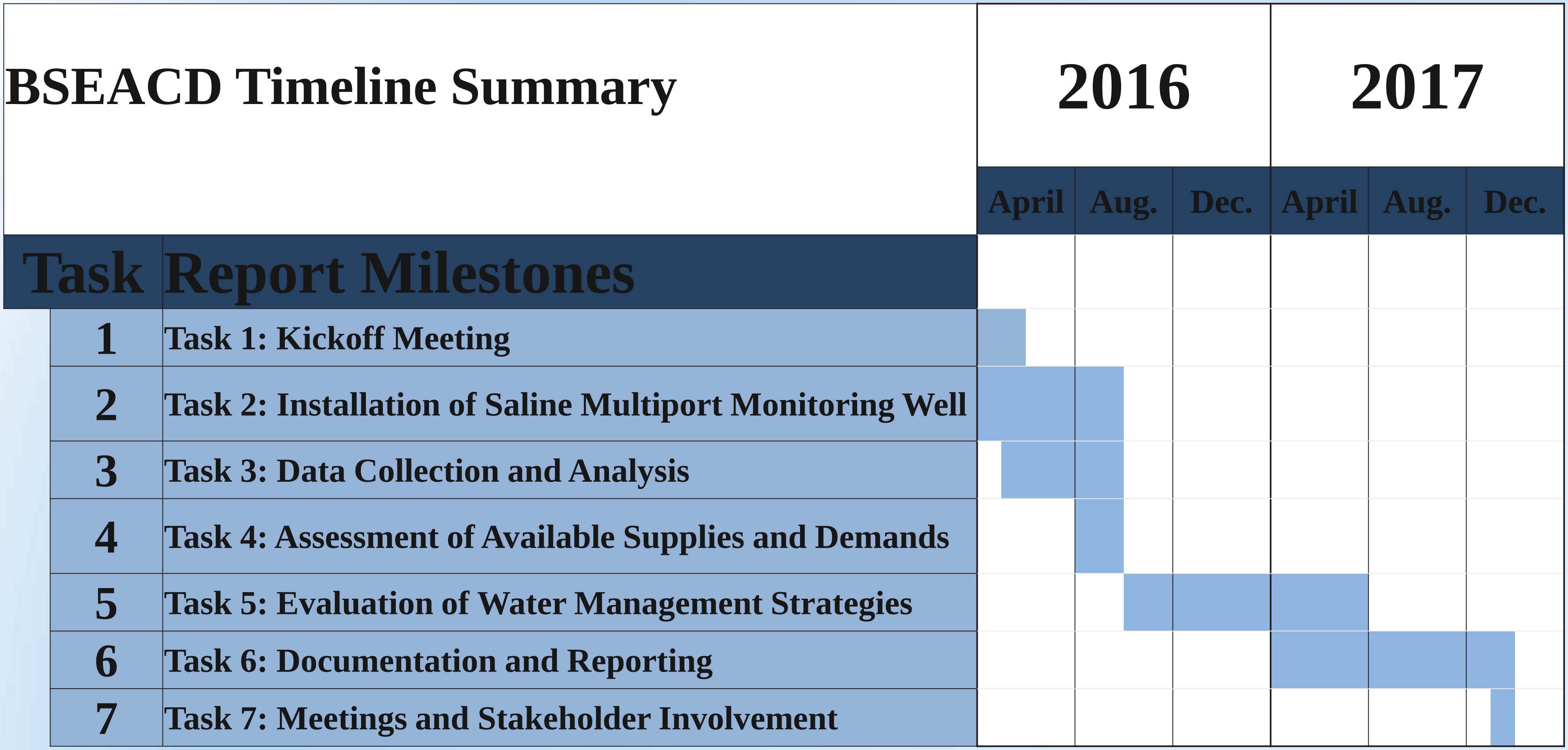
- Total of 18 monitor zones; 11 Edwards zones
- Total depth of well 1,095 ft
- Very high TDS values in all Edwards zones (up to 18,622 mg/L)
- Confining unit between upper two Edwards zones and lower zones
- Upper two Edwards zones could be used for ASR
- Lower Edwards zones could be used as source for water desalination



**Saline Edwards Multiport Monitor Well**
**Travis County, Texas**

| | |
|---|---|
| State Well Number | 58-58-305 |
| Tracking Number | 431923 |
| Ddlat | 30.1148889 |
| Ddlong | -97.7815278 |
| Land Surface Elevation (ft-msl) | 658 |
| Drilling Start Date | 8/3/2016 |
| Drilling End Date | 8/16/2016 |
| Drilling Method | Air Rotary |
| Blowing Yield (gpm) | 500 |
| Steel Surface Casing Diameter (in) | 6 |
| Surface Casing Depth (ft) | 204 |
| Borehole Diameter (in) | 5.125 |
| Well depth (ft) | 1100 |

# BSEACD Timeline Summary



| Task | Report Milestones | 2016 April | 2016 Aug. | 2016 Dec. | 2017 April | 2017 Aug. | 2017 Dec. |
|---|---|---|---|---|---|---|---|
| 1 | Task 1: Kickoff Meeting | ▨ | | | | | |
| 2 | Task 2: Installation of Saline Multiport Monitoring Well | ▨ | ▨ | | | | |
| 3 | Task 3: Data Collection and Analysis | ▨ | ▨ | | | | |
| 4 | Task 4: Assessment of Available Supplies and Demands | | ▨ | | | | |
| 5 | Task 5: Evaluation of Water Management Strategies | | ▨ | ▨ | ▨ | | |
| 6 | Task 6: Documentation and Reporting | | | | ▨ | ▨ | ▨ |
| 7 | Task 7: Meetings and Stakeholder Involvement | | | | | | ▨ |

## Finalization: October 31st, 2017

# Questions?

# Appendix H

# ASRS

## Barton Springs EACD ASR Construction Cost Estimate
**25-Sep-17**

| Item | Unit | Number | Unit Cost, $ | Total Cost, $ |
|---|---|---|---|---|
| **PHASE ONE** | | | | |
| ASR Demonstration Well Constr. | each | 1 | 250,000 | 250,000 |
| | | | | - |
| Monitor well constr. | each | 2 | 85,000 | 170,000 |
| | | | | - |
| Coring, lab analysis, geochem analysis | each | 1 | 150,000 | 150,000 |
| | | | | - |
| Test well to Sligo Fm | each | 1 | 150,000 | 150,000 |
| | | | | - |
| Plug & abandon 2009 test well | each | 1 | 50,000 | 50,000 |
| | | | | - |
| Equip ASR well | each | 1 | 225,000 | 225,000 |
| | | | | - |
| Equip monitor well | each | 2 | 25,000 | 50,000 |
| | | | | - |
| ASR Wellhead facilities | each | 1 | 250,000 | 250,000 |
| | | | | - |
| Tap 42-inch pipeline | each | 1 | 40,000 | 40,000 |
| | | | | - |
| 12-in transmission pipeline | feet | 6,000 | 80 | 480,000 |
| | | | | - |
| Geophysical logging | each | 4,000 | 6 | 24,000 |
| | | | | - |
| Well development | hrs | 32 | 1,000 | 32,000 |
| | | | | - |
| Interim recharge | lump sum | 1 | 50,000 | 50,000 |
| | | | | - |
| Pump tests (3) | lump sum | 1 | 25,000 | 25,000 |
| | | | | - |
| Standby time | hrs | 8 | 300 | 2,400 |
| | | | | - |
| Owners Allowance | lump sum | 1 | 100,000 | 100,000 |
| **Total Construction Cost, Phase 1** | | | | **2,048,400** |
| **Consultant Services** | | | | **1,024,200** |
| **Contingencies (30%)** | | | | **614,520** |
| **Total Capital Cost Estimate** | | | | **3,687,120** |

**Barton Springs EACD ASR Construction Cost Estimate**
**25-Sep-17**

| **Item** | **Unit** | **Number** | **Unit Cost, $** | **Total Cost, $** |
|---|---|---|---|---|
| **PHASE TWO** | | | | |
| Construct ASR Well | each | 2 | 250,000 | 500,000 |
| Geophysical logging | each | 4,000 | 4 | 16,000 |
| | | | | - |
| Well development | hrs | 32 | 1,000 | 32,000 |
| | | | | - |
| Equip ASR well | each | 2 | 225,000 | 450,000 |
| | | | | - |
| ASR Wellhead facilities | each | 2 | 300,000 | 600,000 |
| | | | | - |
| 12-in transmission pipeline | feet | 1,600 | 50 | 80,000 |
| | | | | - |
| Interim recharge | lump sum | 2 | 25,000 | 50,000 |
| | | | | - |
| Pump tests (3) | lump sum | 2 | 25,000 | 50,000 |
| Standby time | hrs | 16 | 300 | 4,800 |
| | | | | - |
| Owners Allowance | lump sum | 1 | 100,000 | 100,000 |
| **Total Construction Cost, Phase 2** | | | | **1,882,800** |
| **Consultant Services** | | | | **941,400** |
| **Contingencies (30%)** | | | | **564,840** |
| | | | | **3,389,040** |
| **TOTAL, PHASES 1 AND 2** | | | | **7,076,160** |

Note: The above costs do not include construction, testing, equipping three brackish water production wells and associated transmission piping.