Desalination of Brackish Water & Disposal into Waterflood Injection Wells

Final Report

Submitted to

The Stripper Well Consortium

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DISCLAIMER

ABSTRACT

Management and disposal of produced water is one of the most challenging problems associated with the oil and gas industry. Very large volumes of produced water, or brine, are produced along with the oil and gas resources. At the same time (and many times in the same locations) many communities currently are trying to address long-term water needs while coping with a series of droughts that have significantly altered land-use behavior and impacting both urban and rural communities. There are also many arid regions, such as West Texas, with little fresh water resources, but with many oil, gas production operations. Texas A&M University has shown that Reverse Osmosis (RO) desalination of inland brackish water sources can take advantage of nearby oil field production by using water flooding operations as a place to dispose of saline concentrates.

This project continues an A&M program studying the beneficial re-use of produced water resources from oil and gas operations. The goal of this Stripper Well Consortium project is to show the feasibility of disposal of concentrate brine from a reverse osmosis (RO) desalination facility into an operating oil field waterflood. The specific objectives of this project have been:

To coordinate work from federal and state agencies with private engineering companies, and oil and gas production operations.

To demonstrate that RO concentrate salt water can be mixed with oil field brine being used for water flooding operations.

Desalination testing at A&M and in the field during this project has provided extended run time data on brine disposal operations. This information is being used by operating companies and regulatory agencies when they consider their support for a significant, if unconventional, new methodology to dispose of saline “reject” fluid from inland desalination operations. In the past two years, brackish ground water desalination has become a highly popular topic. Part of the awareness of the cost benefits of the process has come because of the visibility and timeliness of this SWC project.

In addition, the Texas A&M Desalination Program has entered into a licensing agreement with GeoPure Water Technologies, LLC to commercialize the process to be known as **GPRI Designs ™ Desalination technology.**

This report on the new technology of desalination and re-use of oil field brine is only a part of the effort necessary to develop commercial programs. There must be efforts by all to communicate to the users. This involvement with the community is expected to make any proposed projects more likely to be accepted and thus support our efforts to create these new water resources more effectively. A total of 7 of the 9 Regional Water Planning Districts in Texas have brackish ground water desalination in the long range plans. A&M has offered its services to assist the Councils if requested.

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INTRODUCTION

Management and disposal of produced water is one of the most challenging problems associated with the oil and gas industry. Very large volumes of produced water, or brine, are produced along with the oil and gas resources. At the same time (and many times in the same locations) many communities currently are trying to address long-term water needs while coping with a series of droughts that have significantly altered land-use behavior and impacting both urban and rural communities. The Texas Commission on Environmental Quality estimates that by the year 2020, fresh water needs in the state of Texas will increase by more than twenty times. There are also many arid regions, such as West Texas, with little fresh water resources, but with many oil, gas production operations. Texas A&M University has shown that Reverse Osmosis (RO) desalination of inland brackish water sources can take advantage of nearby oil field production by using waterflooding operations as a place to dispose of saline concentrates.

Goals, Objectives & Significance

This project continues an A&M program studying the beneficial re-use of produced water resources from oil and gas operations. The goal of this Stripper Well Consortium project is to show the feasibility of disposal of concentrate brine from a RO desalination facility into an operating oil field waterflood. The specific objectives of this project are:

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This SWC project was designed to be part of a larger City of Andrews/TWRI project demonstration. That larger project was not funded in 2005, thus our project became a two-year program. In the ensuing two years, brackish ground water desalination has become a highly popular topic. Now all but one of the 9 Water Planning Districts in Texas have brackish water desalination (BWDS) in their long range plans. Part of the awareness of the utility of the process has come about because of the visibility and timeliness of this SWC project.

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EXECUTIVE SUMMARY

The specific objectives of this SWC project have been

(1) To coordinate work from federal and state agencies with private engineering companies, oil and gas production operations.

(2) To utilize the mobile desalination unit constructed by A&M to test RO concentrate salt water compatibility. Tests were performed by mixing RO concentrate with oil field brine being used for water flooding operations.

(3) To work with local community leaders who plan pilot municipal desalination facilities.

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With one set of objectives met, the project has taken on a fourth goal, "Water Issues Associated with Unconventional O&G Development," introducing a new issue related to water utilized in the recovery of oil and gas from unconventional resources. This is an emerging industry in Texas requiring large amounts of water resources, most of which cannot be recovered with present technology. This new source of energy from unconventional resources is expected to represent almost 50% of the natural gas produced in the United States in the next 25 years. Texas has the opportunity to be in the forefront of technology developed to achieve this by sustainable economic development. However, this new "face of the O&G industry" is even more dependent on water resources than traditional operations. It also tends to be more intrusive and can negatively impact sensitive environmental areas and local community areas if not integrated into managed processes for change that govern economic development in the state.

The emergence of energy dependence on unconventional gas reserves has not been fully realized by either the public or policy makers. Unconventional gas development represents an important natural resource in Texas that will require significant amounts of water. Technology advancements in gas well fracturing technology in the Barnett Shale has created a drilling "boom" in North Texas To put the issue into perspective, drilling,

completion and fracturing operations in a few Texas counties are using more fresh water daily than a small city. Essentially all of this water is then disposed of in deep wells and removed from the normal, natural water cycle.

METHODOLOGY

Research Coordination with Stakeholders (Objective 1, Tasks 1 & 2))

Stripper Well Control Consortium and NYSERDA Support for Desalination

Research at A&M has been supported in part by the Stripper Well Consortium (SWC). The first project funded at Texas A&M University (2000-2001) was *"Environmental and Regulatory Issues Relating to the Utilization of Produced Water from Oil & Gas Operations*". It identified the agencies and regulatory practices that are encountered when developing a produced water reuse program. The second SWC project (2003), *Establishing Programs to Reimburse Operators for Produced Water Desalination,* was intended to promote the beneficial re-use of produced water resources from oil and gas operations.

This third SWC project has demonstrated that BGW desalination (10,000 ppm dissolved salts) can create fresh water that meets EPA standards for clean drinking water and that the cost of the desalination can be reduced significantly by disposal of RO concentrates into operating oil field water floods. By partnering with industry and community leaders, the technology of desalination and reuse of waste brines can be moved closer to commercialization and become available to independent oil and gas operating companies.

Coordination with City and State Officials (Task 1)

The Texas Water Resources Institute (TWRI) has devoted substantial resources to helping communities address long-term water needs while coping with a series of droughts that have significantly altered land-use behavior and impacted both urban and rural communities. The Texas Commission on Environmental Quality (TCEQ) estimates that by the year 2020, fresh water needs in the state of Texas will increase by more than 100%. The oil and gas (O&G) industry along with Texas A&M University and TWRI have shown that Reverse Osmosis (RO) desalination of inland brackish water sources can take advantage of nearby oil field production by using waterflooding operations as a place to dispose of saline concentrates.

Fresh Water Resources from Desalination of Impaired Waters

Studies of oil field produced brines have found that approximately $^{1}/_{3}$ of the oil field produced water in Texas is brackish, less than 10,000 tds [total dissolved solids). A&M studies have resulted in development of technology to purify this water economically. Coincidently the areas of the state with limited fresh water resources are the oil producing regions that produce a byproduct that can be recovered and used for beneficial purposes.

Along with ample supplies of a byproduct with potential for beneficial use the oil producing regions offer a place to discharge concentrated brines created in desalination. The graphic shown in Figure 1 shows the state wide distribution of oil fields where this technology can be utilized with high probability of success. Figure 1 also indicates "impaired streams" in Texas as classified by the U.S. Army Corp of Engineers.

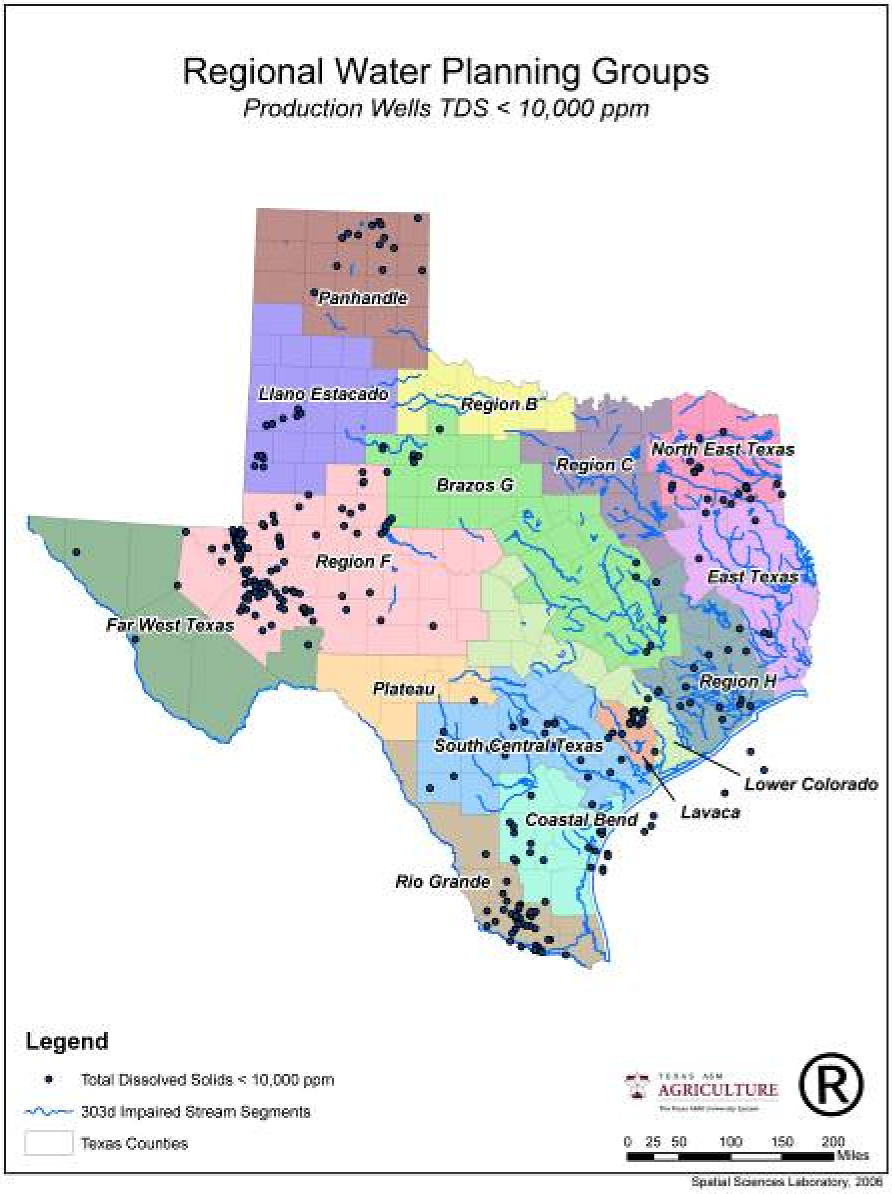

Figure 1. Brackish produced water oil and gas production sites. The sites overlay the Regional Water Planning Districts in Texas, each responsible for its long term water needs. "Impaired streams, as classified by the U.S. Army Corp of Engineers and the EPA are also show in the graphic.

More detailed maps derived from graphical information systems (GIS) data are contained in each of the Texas Water Development Board (TWDB) regional water planning regions. The solid circles represent oil or gas leases producing brine with less than 10,000 tds brine. The database containing these locations was derived from the United States Geologic Survey database and updated with additional information from the West Texas Geological Society.

Uncertainties with Regulatory Issues – Failure to Obtain Funding for Municipal Projects (Task 2)

The biggest drawback to utilizing desalination products for beneficial purposes is the environmental and regulatory issues involved. Environmentalists, regulators, industry personnel, and concerned citizens have a basic interest in how to set or negotiate environmental priorities given limited and possibly changing resources. When a new technology or process is being introduced into society, setting these priorities is a problem, especially if the technology has the potential to impact a significant part of the local community. Desalination of brackish ground water, oil field produced brine, or even seawater is one of those technologies. Burnett and Veil address these needs in their paper comparing risks of handling produced water in different manners [1].

Because of the regulatory uncertainties, the targeted project collaboration with the SWC was delayed for a 12 month period, then restructured to include the Region F Water Planning District as the lead agency. A project proposal was submitted to the Texas Water Development Board (TWDB) in October 2006. This proposal was not chosen for funding.

Reasons for Failure to Get Funding (Task 2)

The Agency with responsibility for oversight of fresh water policy issues is the TWDB. Its officials stated that the Texas A&M City of Andrews proposal did not address the regulatory uncertainties in permitting for discharge of brine water into oil and gas fields when the desalination process was treating any brine except oil field brine. The Texas Commission on Environmental Quality (TCEQ) cited a provision in the State of Texas Water Code (1977) for this interpretation.

A meeting was held with the Texas Railroad Commission (TRC) and the TCEQ to resolve the issue. The Texas Commission on Environmental Quality pledged to work with other state agencies to streamline regulations for the permitting process for disposal in deep-underground injection wells of brine produced by desalination operations. Applicants for permits to dispose of brine from desalination in injection wells must meet the current requirements for disposing of hazardous waste in Class I injection wells, including brine from desalination if it is classified as a waste material from "either industrial or municipal facilities". Since injection wells have been used for disposal of salt water associated with oil and gas operations for almost a century, (as Class 2 wells), it is hoped that new cooperative efforts in desalination will allow deep injection wells into oil and gas fields for brine byproduct use in enhanced oil recovery operations. Meetings between TCEQ and the TRC may have removed the roadblock.

In light of the uncertainty in policy, Texas A&M sought other funding sources. First, we have licensed the technology to a commercial vendor to support additional work in this area. Second, representatives of the University have encouraged Federal action in the

U.S. Congress to remedy some of the roadblocks to acceptance of the technology. In January, U.S. Congressman Chet Edwards introduced a bill into the U.S. Congress that he co-authored with Senator Bryant of Colorado to fund $5,000,000 for demonstration projects to. The bill, H.R.902, The More Water and More Energy Act, if enacted into law, would serve to accelerate technology adoption in the oil field and the public arena Appendix 1 contains an announcement from Representative Edwards's office.

Reverse Osmosis Desalination for Oil Field Brine

Membrane technology is the other major method used to desalinate salt water. Like thermal technology, membrane desalination is based on a simple concept: salt water is forced across a membrane, producing potable water on one side of the membrane, and leaving behind briny water on the other side. The two most common types of membrane desalination used today are electrodialysis and reverse osmosis [2]. Electrodialysis is a voltage driven process that uses an electrical current to draw salts and other solids through a membrane, leaving pure water behind. With electrodialysis, ions travel through the electrically charged membrane, which differs from reverse osmosis, where water molecules are forced through the membrane. Electrodialysis is not suited for the removal of dissolved organic constituents and microorganisms, which represents a serious drawback. Instead of using an electrical current, reverse osmosis membrane desalination uses high pressure to pump salt water through a semi-permeable membrane, which acts as a microscopic strainer, filtering out salts, minerals, contaminants, viruses, bacteria, pesticides and other materials. The membrane strains salt and other molecules because they are too large to fit through the microscopic pores.

The technology most adaptable to produced water desalination is RO membrane technology. RO lends itself to scalable systems and is a commercial process. The chief difference for RO design in the oilfield is the care that must be taken with pre-treatment.

RO desalination technology has been chosen by Texas as a preferred option of providing fresh water supplies for the Gulf Coast. Cost of providing water resources have been presented by three different agencies. The TWDB is investigating the potential for similar RO desalination, this time from brackish ground water sources in West Texas, where water supplies are critically low. At present however, the agency has provided no cost estimate for BGW desalination have been reported. This report corrects that omission.

Pre-Treatment of Oil Field Brine

The oil industry refers to water pre-treatment as "water conditioning" and routinely performs this process as a necessary step to water re-injection. Since several billion gallons of water per day are re-injected, the practice of water pre-treatment is well established. A water flood engineer faces the same concerns as those who are designing membrane treatment systems. Such issues as scale removal, biofilm suppression and solids control must be handled in a cost effective manner, otherwise the injection well plugs, necessitating a costly workover.

Comparing the cost of desalinating brackish oil field brine with the costs of desalinating BGW shows that pre-treatment of the oil field brine will be more expensive, but concentrate disposal will be less expensive. Newer desalination technology is also expected to reduce these costs. Pre-treatment to accommodate saline oil field brine desalination is critical. The characteristics of the materials, particularly oily water, make pre-treatment mandatory. Several methods of oil and solids removal have been tested at the A&M facility.

Powered centrifuges are routinely used in offshore oil production operations to remove oil and solids from water before it is discharged into sea. Siddiqui tested the use of a centrifuge to reduce oil concentration from the produced water as a pre-treatment for desalination but found the power requirement to be too high. Hydrocyclone separators have been developed for more efficient oil/brine separation [**2**]. Effective hydrocyclones impart more than 100 g centrifugal force at maximum efficient flow rate. Systems are best for fluids with significant density difference. Hydrocyclones work best over a narrow flow range but have proven to be effective in high pressure and medium pressure oil systems. This technology is now considered to be the most reliable for offshore applications in meeting the required level of oil for discharge. Hydrocyclones have limitations in low-pressure systems. The efficiency of oil removal with a hydrocyclone unit becomes less because there is not enough pressure in the system to drive the water. Consequently, the water has to be pumped, and as a result the produced water becomes more difficult to clean. Small oil droplets and the use of different chemicals make the hydrocyclone option not very effective in a number of gas condensate systems. Also, small density differences between the oil and water phase solid particles present in the feed reduced the efficiency of hydrocyclones.

Doyle [3] studied the use of organoclay for the removal of dispersed oil from water by adsorption and performed limited field tests with this technology. For onshore operation, vaporization of water using large surface area exposure of water on water ponds is another option. Boysen [4] looked into the commercial feasibility of using freeze thaw and evaporation process to treat produced water. This approach may cause environmental impacts relevant to the atmosphere as well as life around the ponds.

<u>Removal of Dissolved Oil from Produced Water:</u> The technology for removing soluble components from produced water has improved in the past decade. The technology for removing soluble components can be based on extraction, precipitation, oxidation process, or by pervaporation systems [5]**.** All these technologies require relatively large facilities to handle the large volume of produced water offshore. Most of these technologies involve the use of other chemicals and solvents, use of additional power, as well as producing a concentrated waste stream. Activated carbon has been used in the chemical industry for a long time for the removal of dissolved organics from waste streams. Some of the new technologies that are available today for the removal of dissolved hydrocarbon components from the produced water are MPPE system from Akzo Nobel (www.akzonobel.com), "Pertraction" technology (www.tno.nl) and surfactant modified zeolite microfiltration.

Table 1 contains data from a test of pre-treatment of an oily water stream with heavy biological contamination using both oil absorbent and a new type of membrane microfilter. This data was collected at Texas A&M University using a specially designed portable unit that monitors power usage as a function of treatment type, water quality, and treatment time. Test results found that contaminants could be removed for less than

$1.00 per 1,000 gallons of raw water processed (power cost only). Power cost is typically the largest expense in membrane plant operations, thus measurement of this cost under field conditions should provide more accurate estimation of a full size facility's cost.

Table 1. Pre-treatment costs: Removing contaminants from waste water

Type of Pre-treatment	Kw Used	Fresh Water Produced	Power per 1,000 gal	Cost* per 1,000 gal
oil + biofilm removal	2.80	199.4	14.04	$0.98
oil removal	0.94	99.4	9.46	$0.66
* = Power cost @ $.07 per Kwh				

Disposal of Materials Removed from Brine during Desalination

Any form of desalination treatment will include some means of handling byproducts and waste removed during the purification process. In addition to brine concentrate, a desalination project may generate solid waste in the form of sand, silt and other debris found in the brine that must be filtered out before it is desalinated by the reverse osmosis membranes. The amount of solid waste generated by a large-scale desalination facility is considerable. At the Tampa facility, the pre-treatment process produces approximately 14 wet tons a day of organic material, suspended solids and metals found in the source water [6]. However, it is also possible to handle slurries produced from the pre-treatment process with the brine discharge directed to re-injection into the oil field. Otherwise, if pre-treatment of raw water creates solid waste, then disposal must be addressed. Quantities could be significant.

Historically, since one of the major impacts of desalination has been the problem of the disposal of the salts ("concentrate") and other materials removed from the source water, one of the advantages of oil field brine desalination processes is that these materials can be re-introduced back into the petroleum reservoir where it originated. This brine contains concentrated dissolved salts and other materials. However, in the oil and gas industry, high salinity brines are routinely injected into formations for pressure maintenance and secondary recovery by water flooding. Since water from desalination operations may be injected into these oil- and gas-containing formations, the estimated cost savings can be as much as 30% of the cost of operating the desalination unit. This represents a significant cost savings for RO technology that offsets any added pre-treatment needed for the oil field brine. Fresh water is therefore available to communities in need of this valuable resource. This opportunity for the disposal of salts and other materials from water treatment processes is being considered for a number of industries and is the subject of a study by the TWDB [7].

To illustrate the potential for disposal of brine in an oil field, the Spraberry Trend in West Texas was selected for a hypothetical brine disposal project. Spraberry reservoirs originally contained 10 billion bbls of oil in place (more than 2,000,000 M^3). Less than 10% of this oil has been recovered [8]**.** The reservoirs are between 5,000 and 8,000 ft. in depth and extend over portions of Borden, Dawson, Glasscock, Martin, Midland, Reagan, Sterling, Tom Green, and Upton counties**.** (More than 230,000 people live in this area including the cities of Midland, Odessa, and San Angelo.) There are more than 10,000 wells in the Spraberry reservoirs many of them operating in fields which are being waterflooded. A significant number of the injection wells in the Spraberry reservoirs take water on a vacuum (no surface injection pressure). Area rainfall ranges from less than 10" to 18" a year. All three of the major cities in this area are currently under restricted use of municipal water by households and represent potential markets for desalination facilities. There are also several waterways in the area considered "impaired". Figure 2 shows the Colorado River Headwaters watershed (No. 12080002, EPA). There are numerous oil leases producing brackish brine water in this watershed and an extensive infrastructure of pipelines used to carry oil and gas to gathering facilities and pipeline connections.

Another factor favoring alternate sources of potable water in West Texas is that many communities already have infrastructure developed for recycling waste water from municipal water treatment facilities. An example is Andrews, Texas. This city recycled 100% of its discharge from municipal water treatment into landscape irrigation for public parks, golf courses and sports fields. Communities like Andrews have the resources to incorporate an additional source of water into their distribution systems if such a source was available [9].

Desalination of oil field brine has another advantage - that being a means of disposing of the brine concentrate. Brine re-injection into producing formations serves as an example of alternate waste brine disposal for desalination. Byproducts from desalination, regardless of the technique employed, contain concentrated dissolved salts and other materials.

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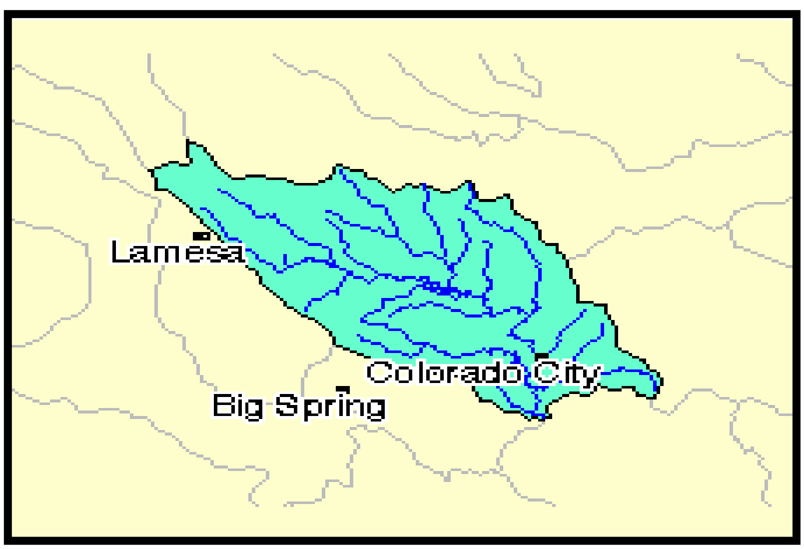

Figure 2. Example of one of the water ways classified by EPA as "impaired". The waterway is in the Colorado River Basin of Texas. One of the proposed uses of fresh water produced from the Spraberry Trend is stream augmentation to reduce chlorides: No. 12080002, EPA.

Disposing of this brine concentrate for traditional desalination processes can represent a significant fraction of the cost of operating the unit to recover fresh water. Since in the oil and gas industry, high salinity brines are routinely injected into formations for pressure maintenance and secondary recovery by water flooding, water from desalination operations could be injected into these oil- and gas-containing formations, and the estimated cost savings are significant.

Costs of Reverse Osmosis Desalination of Oil Field Brine

The two major cost components of oil field brine desalination are (1) removal of suspended solids (pre-treatment) and (2) removal of dissolved solids (desalination). Desalination costs of saline brines are similar to conventional seawater desalination. Estimated costs for several seawater desalination facilities along the California coast range from $2.25 to $3.70 per 1,000 gallons ($711 to $1171 per acre-foot), a substantial decrease from the 1993 cost estimates of $3.17 to $12.70 per 1,000 gallons ($1000 to $4000 per acre-foot). During the same period, the cost of water from other sources in California has steadily increased. In 1991, the Metropolitan Water District of Southern California ("MWD") paid approximately $27 per acre-foot for water delivered from the Colorado River and $195 per acre-foot for water from the California Water Project. Now, MWD pays an average of $460 per acre-foot for delivered water.

In Texas, the three *proposed* desalination facilities on the Gulf Coast have cost estimates ranging from $3.58 to $4.23 per 1,000 gallons ($1,000 to $1,300 per acre-foot). These cost estimates do not include a "transference" cost representing the cost to deliver raw water to the RO facility and to deliver fresh water to existing municipal water lines [10]. The estimates include amortization of the facility (~25 years) and operation and maintenance costs.

The economic justification for desalination of oil field brine is entirely different than the cited examples. O&G production savings would come from the deferred cost of disposal of the excess brine from operating facilities. Enhanced oil recovery processes also require water that must have relatively low salinity. Rather than utilize fresh water from ground water sources, the industry has tried desalination of produced water extensively. One large-scale program to desalinate brackish produced water was in Crockett County Texas [11]. Marathon Oil Company constructed and operated a facility producing 714,000 gallons per day (17,000 barrels per day) to supply feed water for steam flooding operations. The cost of the water treatment (no infrastructure costs) was reportedly less than $4.50 per 1,000 gallons. The steam flood was projected to boost oil production in the Yates Field by more than 100,000 barrels of oil. The facility was deactivated when more advanced oil recovery technology was developed.

More recently, pilot tests of a produced water treatment by membrane technology was performed in the Burgan Field, Oman to test the removal of dispersed oil. Over a five-month period the unit operated at an oil rejection efficiency of 83% to 89% [12].

Experience has shown that membranes can be effective pre-treatment techniques and RO membranes can provide desalination at less cost than the cost of brine disposal. Testing has also shown that desalinating brackish oil field brine is more expensive that desalination of BGW but concentrate disposal will be less expensive. Newer desalination technology is also continuing its advance in the field of industrial, food, and pharmaceutical industries.

The A&M Mobile Desalination Unit was constructed to test both pre-treatment by membranes and RO desalination at field sites. Different types of membranes are tested and RO salt rejection efficiency can be determined directly. It is equipped to run either single stage or multi-stage membrane treatments and can be configured either for parallel or series membrane flows. The unit is shown in Figure 3 in Washington County, Texas in 2006.

Figure 3. The A&M Mobile Desalination Unit.

The unit is shown at a well site in Washington County, Texas in early 2006. The unit took brine from the fiberglass storage tank (shown on the right of the picture) performed pre-treatment by micro-filtration, then desalination by RO. Fresh water was directed to the tank to the left rear of the unit.

In addition to testing the capability of different types of membranes, the unit has power transformers to utilize oil field power and an electrical meter to measure power consumption, one of the highest cost factors in desalination. The cost of desalination is directly related to the power used to pump brine past the filters. As salinity increases, power consumption rises. Data from four different field sites are given for comparison, collected on four types of saline feed brines. Table 2 shows this comparison of electrical power costs.

Table 2. Representative power costs of desalination of oil field brine.

Salinity of Feed Brine, tds (ppm)	Power Costs Kw Hr per 1,000 gal. Permeate			
	Pre-treatment	RO desalination	Operating Cost, $ per 1,000 gal.	Operating Cost, $ per bbl
Contaminated Surface water ~1,500 tds.	$.65	$1.25	$1.90	$0.08

Gas well produced brine ~ 3,600 tds.	$2.50	$2.00	$4.50	$0.19
Oil well produced brine ~50,000 tds	$2.20	$6.00	$8.20	$0.34
Gas well brine ~ 35,000 tds	$2.00 (est.)	$4.20 (est.)	$6.20 (est.)	$0.26

The information in the Table should be used for estimates only. The prime performance monitor should be salt rejection efficiency, then operating cost. Two types of pre-treatment micro-filters were used. In addition, a new low pressure RO filter was employed in the oil well test. Salt rejection efficiency of the low pressure membrane was lower than the filter used earlier.

The energy cost of operating the desalination facility represents roughly one-third of the total operating costs. Using one of the examples given in Table 2, for desalination on-site of brackish produced water from a gas well, the total operating costs would be less than $10 per 1,000 gallons of fresh water produced ($.42 per bbl). For comparison, the operator of the well pays approximately $1.50 per barrel to truck the water to a commercial salt water disposal well. For this example, the field data indicate that a dedicated desalination unit on the site could reduce the water hauling volume by 50% and the total water hauling costs by almost 20%. For this example, the land owner was offered the fresh water for no cost. However in many cases the fresh water should represent a source of income to the operator.

Demonstrating Uses of Desalination (Objective 2, Tasks 3 & 4)

Development of Commercial Size Desalination Unit.

The research program for this project has been completed. The goals of the project have been met. The technology transfer portion of the project will be satisfied through a commercialization partnership with a new oil field service company. The desalination technology developed by our efforts has been licensed to GeoPure Water Technologies, LLC. GeoPure has commissioned a larger scale mobile unit designed for delivery of 20 gallons per minute (18,800 gallons per day) to be used in field operations. A photograph of the unit is shown in Figure 4. It is designed to fit inside a standard cargo container and can be shipped by commercial carrier from site to site.

With the commercialization of the technology handed over to GeoPure, additional field data testing became GeoPure’s responsibility. Information from their testing is being used to commercialize the **GPRI Designs™ Desalination Technology**. Further testing by A&M for the Stripper Well project ceased.

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Figure 4 shows the upgraded portable desalination unit on location in Texas.

The unit both pre-treats the raw brine water and desalinates it in one process step. The unit has been on site in Johnson County Texas for the past two months and has achieved satisfactory results in desalinating fracturing fluid flow back brine recovered from Barnett Shale well completions.

The new portable system is capable of treating wastewater at the rate of 20 gallons per minute, and incorporates cartridge filters, microfiltration membranes, a dedicated hydrocarbon removal system, and reverse osmosis membranes. It is now being used to demonstrate the capabilities of the technology by processing sample batches of water for clients at the GeoPure test laboratory, and by purifying produced water at clients' field sites. In conjunction with the construction of a demonstration system, GeoPure also began a marketing program targeted to the Texas oil and gas industry, as well as groundwater users in west Texas. The marketing program includes papers given in industry conferences, such as the International Petroleum Environmental Conference and International Association of Drilling Contractors, a marketing booth, published articles, and company dedicated marketing presentations.

As a result of this marketing effort, GeoPure is now working with over 30 clients in various stages of feasibility studies. GeoPure has also completed its first commercial oilfield wastewater treatment system in Texas. The system was installed at a location in Benbrook, Texas, and is now processing over 200 gallons per minute of feed water, consisting of a combination of fracturing fluid and mud pit slurry. GeoPure designed, constructed and sold the treatment system to handle feed water where suspended solids have already been removed. The GeoPure system consists of a mechanical filtration step, microfiltration membranes, Mycelex hydrocarbon removal system, and reverse osmosis membranes. It is equipped with monitoring and automatic shutoff controls for maximum performance and safety. While the 200 gpm system was being constructed, GeoPure deployed its 20 gpm demonstration system to serve as an interim fluid handling solution. A Texas A&M microfiltration system was added to increase the interim treatment capacity. Table 3 shows analysis of brine water treated in the field with the 20 gpm unit.

Table 3. Membrane Treatment of Fracture Fluid Return Brine

RO treatment of Barnett Shale Frac Flowback - Test Data				
		(mg/L)		
Analyte	Untreated Water	After Pretreatment	Microfilter Permeate	Final RO Permeate
Alkalinity, Total as CaCO3	160	58	57.4	4.69
Bicarbonate as HCO3	195	70.7	70.1	5.72
Carbonate as CO3	< 1.2	<1.2	<1.2	<1.2
Hydroxide as OH	< 1	<1	<1	<1
pH	6.86	6.82	6.15	6.28
Solids, Total Suspended TSS @ 105 C	4200	54	<4	<4
Potassium	77.4	39.3	39.2	1.13
Magnesium	72	43	40.3	0.094
Calcium	676	472	448	0.662
Sodium	4504	2934	2876	63.6
Boron	9.29	6.5	6.15	3.18
TPH	1.87	0.59	1.2	<1.1
Total Dissolved Solids	14,590	10,429	9,990	191
Chloride	7830	5386	5412	105
Sulfate	396	597	584	1.2
bromide	77	52	55	1.33
phosphorus	56	<1.5		<0.1
iron	173	12.2	0.934	0.017
Manganese	3.7	2.4	2.34	0.0023
Aluminum	106	0.44	0.115	<0.03
Barium	936	0.874	1.08	0.0007

Starting in the Spring of 2007 GeoPure will begin a series of field tests for clients in Canada, Oregon, Wyoming and Oklahoma to prove the capability of the treatment technology. The 20 gpm demonstration unit has been mounted in a travel friendly container, which can be shipped to locations without damaging components. The clients range from service companies to oil and gas operators, including a coal bed methane producer.

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Beneficial Use of Desalinated Oil Field Brine

Many areas of the state have water shortages and would welcome a new source of fresh water that could be used to supplement municipal supplies. TWDB anticipates a significant increase in demand for fresh water resources in the next 20 years. Accordingly, this section summarizes potential uses of water produced from oil field brine and the applicable regulations that such usage must meet.

Areas in West Texas with significant oil and gas production (and brine production) will be the most likely candidates for beneficial use of produced water. As Figure 1 shows, a significant number of produced water facilities are producing brine of less than 10,000 tds. This represents the most affordable potential resource. To consider the feasibility of treating oil field brine, we have concentrated on this less costly opportunity, produced water which represents approximately one-third of the brine produced in Texas.

Affordable desalination and supplemental use by municipalities represents a logical and beneficial use of the resource. Distribution and/or storage of desalinated water, either in surface lakes and ponds or in subsurface aquifers, are significant issues that must be considered when evaluating PWDS economics [13, 14]. Technology is available that allows pre- and post-treatment required to assimilate or blend desalinated water into the local water supply system. For example, Odessa's average daily water use has averaged 12 million gallons/day in winter and 29.5 million gallons/day in summer [15], with a peak of 34.9 million gallons used on June 26, 2002. The difference in water use in the summer is predominately landscape irrigation. Corresponding daily brine disposal in Ector, and neighboring Midland, and Winkler Counties, Texas in 2002 has been slightly more than 4,000,000 gallons of water per day according to county records, or 25% of the water used on landscape irrigation in the city. Most other areas of Texas reflect the same water usage.

Texas A&M has been investigating the potential for rangeland and habitat restoration programs in West Texas. The results of analyses focusing on restoration of rangeland systems may provide a prioritization where habitat enhancement would be most efficient. Of significant interest will be the development of cooperative programs with other environmental agencies and introduction of the technology to determine their opinions on use and acceptance. Hand in hand with this opportunity is the potential to use desalination as a way of enhancing the quality of impaired streams in Texas (Figure 1). These and other uses are influenced by the public's willingness to accept the production of alternative water resources from oil and gas production. The following illustrates some of the significant concerns regarding acceptance of water reuse.

Factors contributing to the degree of public acceptance of water reuse (adapted from Hartley, 2006 [16]. indicate that U.S. public acceptance of water reuse seems to be higher when:

- Human contact is minimal.
- Assurance of public health is clear.
- Protection of the environment is a clear benefit of the reuse.
- Promotion of water conservation is a clear benefit of the reuse.
- Cost of treatment and distribution technologies and systems is reasonable.
- Perception of wastewater as the source of reclaimed water is minimal.
- Awareness of water supply problems in the community is high.
- Role of reclaimed water in overall water supply scheme is clear.
- Perception of the quality of reclaimed water is high.
- Confidence in local management of public utilities and technologies is high.

Potable Uses

The highest level of water treatment is associated with human ingestion. The Texas Commission on Environmental Quality has responsibility for the quality of water discharged into the public sector. Water reuse for non-potable (e.g., irrigation, industrial) or indirect potable (e.g. discharge into drinking water reservoirs or supply) has continued as a topic of discussion in the United States with a focus on dry or drought impacted regions, such as Arizona, California, Colorado, and Texas; or communities experiencing substantial population and economic growth (e.g., Georgia and Florida) .

A significant amount of survey and case study research since the 1970s has found that the public in many of these states support the general concept of using reclaimed water for non-potable reuse initiatives [17]. Generally, constituents favor reuse that promotes water conservation, provides environmental benefits, safeguards human health, and cost effectively treats and distributes a valuable, limited resource. However, as the potential for water reuse becomes more tangible to people with proposed projects in their communities and the increased likelihood of human contact, attitudes change — "the public's support wanes" [18].

In the case of treated brine produced by oil and/or gas wells, there is an increased measure that must be overcome beyond the traditional concerns – both quality and social stigmas. Any potential for the use of treated brine from oil/gas production must meet the same permitting requirements as a municipal drinking water system by the TCEQ (EPA) [19] and overcome social norms.

The applicable TCEQ Rule pertaining to public drinking water systems is Texas Administrative Code (TAC) Chapter 290, Section 42(g). This section states that "other" treatment processes will be considered on an individual basis. Based on input from TCEQ staff, a licensed professional engineer must provide "pilot test data or data collected at similar full-scale operations" of the proposed system demonstrating that the system would meet applicable Drinking Water Standards. The pilot test must be representative of the actual operating conditions that can be expected over the course of a year, meaning the test must be done during the time of the year that would place the most strain on the treatment system. Additionally, proof of a one-year manufacturer's performance warrantee or guarantee assuring the plant will produce treated water that meets minimum state and federal drinking water standards is commonly required by the State as a condition of an operating permit. Therefore, if this water was to be used as an independent potable water source, among other drinking water standards, tds levels must be reduced to the Environmental Protection Agency's secondary standard of 500 mg/L. Permitting for waters with a tds greater than 500 mg/L may be available if this water is the only potential potable resource for a community. However, if the high tds water were to be blended with another public water supply (PWS) and then distributed, the required level of treatment could be less. The caution in this situation would relate to the salt-loading on the primary PWS infrastructure during blending.

The US National Research Council (NRC) [20] released a report, "Issues in Potable Water Reuse", based on an evaluation of several existing reuse projects and the feasibility studies of Tampa and San Diego's projects. The NRC concluded that "reclaimed wastewater can be used to supplement drinking-water sources, but only as a last resort and after a thorough health and safety evaluation”. A point of contention existed in previous years regarding the discharge of RO concentrate from desalination facilities. If the saline concentrate is a waste stream, then the RO facility operator must get a permit from TCEQ for a Class 1 disposal well. However, recently [21] Texas A&M , as part of this SWC project, brokered an agreement between TCEQ and the TRC was made regarding the use of the brine concentrate in oil field brine injection wells for enhanced recovery.

Discharge to Supplement In-Stream Flow or Rangeland Habitat Enhancement

The TCEQ monitors the condition of the state surface waters, assesses the status of water quality every two years, and submits their assessment to the U.S. EPA. The report is published on the TCEQ Web site as the *Texas Water Quality Inventory and 303(d) List* (Inventory and List). Requirements for the Inventory and List are codified in the federal Clean Water Act, Sections 305(b) and 303(d) [22]. Further requirements are set out in state law in Title 30 of the Texas Administrative Code (30 TAC), and in rules and guidance established by the TCEQ.

Discharges to surface water designated as Waters of the State must meet Texas Surface Water Quality Standards (TSWQS) as contained in TAC Chapter 307. Without a specific stream or amount of discharge set, it is difficult to outline all necessary regulations one must follow. Figure 1 shows the location of impaired streams with O&G sites nearby. With proper treatment and regulatory approval, one of the uses of fresh water from desalination would be to augment stream flow.

The permitting process, done through the TCEQ Water Quality Division, is conditional on two key variables, the receiving stream ambient quality and the volume of the discharge. The TSWQS identify individual water quality standards for each stream in the State, and these standards are based on the use category a particular stream is assigned. A discharge, once dilution has occurred, must not hinder the water quality standards set for the receiving stream.

Most notable for brine, TCEQ Guidance Document RG-194, Procedures to Implement the Texas Water Quality Standards, provides a section entitled, “Screening Procedures and Permit Limits for Total Dissolved Solids”. This document states, “Concentrations and relative ratios of dissolved minerals such as chloride and sulfate that compose total dissolved solids (tds) will be maintained to protect existing and attainable uses” [24]. The screening procedure is applied to all domestic dischargers with an average permitted flow of 1 million gallons per day (MGD), all industrial majors, and all industrial minors that discharge process water. The screening procedure is divided into categories based on the type of receiving stream: intermittent stream, perennial stream, intermittent stream within three miles of a perennial stream or intermittent stream with perennial pools, lake, and bay or wide tidal river. The equations used take the following into consideration:

- TDS criterion of the receiving stream (as defined in the TSWQS)
- Harmonic mean flow of the receiving stream

- Effluent flow volume
- Effluent tds concentration
- Effluent concentration at the edge of the human health mixing zone

For discharges to freshwater, a screening procedure is used to determine whether a total dissolved solids permit limit or further study of the receiving water is required. If screening demonstrates elevated levels of tds, then appropriate permit limits are calculated.

One of the potentially beneficial ways to use desalinated brine from oil field operations is to add the water to nearby streams. Waterways in Texas often fail to meet EPA standards on clean water. In the West, salinity is a problem. In the central part of the state, runoff from agricultural operations impair quality while in the Eastern part of the state, in forested watersheds, channel gradients and stream velocities are so low and water temperatures so high that low DO concentrations should not be surprising [24]. Addition of ultra-low salinity oxygenated fresh water into waterways with low flow can result in perceptible betterment in water quality and attendant fishery and wildlife habitat improvement.

Restoring Rangeland Habitat

Rangeland functions and processes are centered around three main variables, soils, water, and biodiversity. The successful restoration of degraded rangeland systems requires a system that, combined, addresses each of these critical characteristics and integrates management to improve the sustainability of each. The restoration of thousands of acres of degraded rangelands in the western United States will require a major effort from all who benefit from them. One of the major constraints to effectively restoring arid and semi-arid rangelands is the lack of water for establishment of vegetation. Treatment of produced water from oil and gas production could significantly benefit efforts to develop restoration strategies for arid and semi-arid rangelands throughout the western United States.

It is estimated that 4 MM barrels of water (150,000,000 gal) is produced daily in Texas, equivalent to 10% of the water usage in the state, at this time little or none of it available for re-cycling. However, water alone will not provide the ‘utopia’ for rangeland restoration.

Degraded rangelands have undergone change due to environmental or human forces and have generally transitioned over a threshold [25] of ecological health into a state that is usually less productive, both ecologically and in terms of human benefits. To restore such degraded lands requires significant inputs outside of normal ecological succession. The use of treated produced water for the purpose of restoration in semi-arid regions provides a resource that otherwise would not be available to provide the inputs required to transition the system back across the threshold into a more productive site.

Livestock Uses

Another potential use of the brine-produced water is livestock agriculture purposes. There are very little, if any, regulations to follow; however, specific guidelines have been suggested for salinity and livestock uses (Table 4). If the owner of the livestock is amenable to using a water supply, he is allowed to do so. A typical rule of thumb, though, is a tds limit of 6,000 mg/L for this purpose. This is the concentration TCEQ employees use when gauging if a particular stream is suitable for livestock use. One specific managerial consideration is that livestock consuming high moisture forage (green grass) can tolerate higher levels of salinity in drinking water [26].

Table 4. Guide to the use of saline waters for livestock and poultry [26].

Total soluble salts content of waters	Uses
Less than 1,000 mg/L (EC < 1.5 mmhhos/cm)	Relatively low level of salinity. Excellent for all classes of livestock and poultry.
1,000-3,000 mg/L (EC = 1.5-5 mmhos/cm)	Very satisfactory for all classes of livestock and poultry. May cause temporary and mild diarrhea in livestock not accustomed to them; may cause watery droppings in poultry.
3,000-5,000 mg/L (EC = 5-8 mmhos/cm)	Satisfactory for livestock, but may cause temporary diarrhea or be refused at first by animals not accustomed to them. Poor waters for poultry, often causing watery feces, increased mortality, and decreased growth, especially in turkeys.
5,000-7,000 mg/L (EC = 8-11 mmhos/cm)	Can be used with reasonable safety for dairy and beef cattle, sheep, swine, and horses. Avoid use for pregnant or lactating animals. Not acceptable for poultry.
7,000-10,000 mg/L (EC = 11-16 mmhos/cm)	Unfit for poultry and probably for swine. Considerable risk in using for pregnant or lactating cows, horses or sheep, or for the young of these species. In general, use should be avoided although older ruminants, horses, poultry, and swine may subsist on them under certain conditions.
Over 10,000 mg/L (EC > 11-16 mmhos/cm)	Risks with these highly saline waters are so great that they cannot be recommended for use under any condition.

The damage of high saline water depends more on the total amount of minerals present rather than on any specific one. The ions most commonly involved in high saline waters are calcium, magnesium, sodium, bicarbonate, chloride, and sulfate. Usually chlorides are less harmful than sulfates. Magnesium chloride appears to be more injurious than calcium or sodium salts [27].

Illustrations for use of desalination of oil and gas produced water as potential livestock water shortage mitigation are discussed here for Regions A, F and O as a potential strategy to meet anticipated shortages in those regions. (Regions are shown in Figure 1.)

Region A expects the largest shortages for the future to be associated with irrigation use, followed by livestock and municipal [28]. In Region A livestock water shortages were identified for Carson, Dallas, Hartley, Hutchinson, Moore, Randall, and Sherman counties primarily associated with confined animal feeding operations. The total water demand for livestock use within the region is expected to increase to 89,000 acre-feet by 2060, and CAFOs (confined animal feeding operations) are expected to require roughly 82 percent of this total water use by 2060.

Regional water planning groups indicate that projected livestock water shortages will be met in a similar manner as what has been observed over the last forty years as the CAFO industry has expanded in the region; either new wells are drilled or nearby irrigated cropland is purchased (or water rights bought or leased) for its water and waste disposal. It is also possible that water allocated for irrigation use be transferred to livestock water users [28].

Currently, only precipitation enhancement has been addressed as a strategy for meeting potential livestock shortages. The addition of desalination of produced water may provide additional resources for water planning in Region A where logistics (social, political & economic) and volumes are consistent with development of oilfield desalination programs.

Anticipated livestock requirements for Region O contain similar predictions as those of Region A. Total livestock water demand projections for the Llano Estacado Region are the sum of water demand projections for beef cattle feedlots, swine feedlots, dairies, horses, range beef cows/bulls, range beef stocker cattle, sheep, and poultry. Total livestock water use in 2000 was estimated at 37,724 ac ft [29]. Total livestock water demand for the region is projected to be 70,457 ac ft/yr in 2060.

The Region F RWPG increased the TWDB projections for the region by 32 percent to account for revised water use for different livestock categories and water use for wildlife associated with the hunting industry in the region. Livestock demand in Region F is expected to remain constant at 23,060 acre-feet per year throughout the planning period [30].

Most of the livestock demand in Region F is for free-range livestock. In addition, Region F has added water to account for wildlife that relies on the same water sources as commercial livestock. Region F encourages individual ranchers to adopt practices that prevent the waste of water for livestock. However, the savings from these practices will be small and difficult to quantify. Therefore, livestock water conservation will not be considered in the planning process.

The use of treated produced water for livestock or rangeland habitat enhancement will, by nature, be localized due to the logistics of the water source. However, for those areas in or around producing oil and gas fields or saltwater disposal sites, desalinated oil/gas field water could be a significant input of water resources. If employed, the practice could reduce local stresses for livestock and wildlife; thus, freeing traditional resources for other uses.

Irrigation

Desalination of oil field brine (or any other impaired water) is generally too expensive to be used for irrigation of crops. An exception to this guideline would be either hydroponics irrigation of greenhouse crops or for drip irrigation of a high value crop.

If irrigation is being used, then necessary treatment levels of water to be used for crop irrigation are driven by the salt tolerance of the crop or landscape. TCEQ Rules, TAC Chapter 309, Subchapter C (Land Disposal of Sewage Effluent) provides the following table regarding crops. Information received from the Texas A&M Soil and Crop Sciences Department provided the following information on salinity tolerance of turf grass: Additionally, when irrigating with something considered reclaimed water, care must be taken regarding the potential for runoff to waters of the state. This can be avoided with the use of modern management practices**.**

Aquifer Recharge

ASR (aquifer storage and recharge) facilities have been used in the United States for over 30 years, those in Florida becoming operational in 1983. Currently, there are seven ASR facilities operating in Florida and at least twelve undergoing operational testing. The facilities are being used to inject and recover treated and untreated groundwater, partially treated surface water, and reclaimed wastewater. Some of the issues these pilots are trying to resolve include are source water quality, regional changes in aquifer flow and pressure, target storage volume (TSV) efficiency, and water quality changes.

ASR can be used to store any type of water where water can be used later on and can be re-injected. Examples include**, a**dapted from Almulla [31]:

> 1) Potable water systems. In this case water can be stored at certain periods of the year where the demand of water is not high or there is no need to use the stored water. At high demands or in emergency, this water can be pumped out and used.
> 2) Reclaimed wastewater systems. In countries like United Arab Emirates, treated wastewater is used for irrigation purposes. However, in the winter there is a huge surplus in treated wastewater where in the summer there is a great shortage in irrigation water. This suggests that treated wastewater can be stored in the winter and reclaimed and used in the summer.
> 3) Surface-water or storm water systems. Due to rain, this runoff water can be collected in dams and directed to water storage facilities. This is an advantage in water management since currently most storm water runoff is uncontrolled and serves little more than a pollutant for waterways and surface water sources.

The combination of Aquifer Storage and Recharge in coordination with desalination facilities, referred to as DASR, is increasingly recognized as a cost-effective combination, taking advantage of the economies associated with steady operation of membrane desalination facilities, plus the large volume water storage capabilities available in ASR wells to meet seasonal variations in water demand, storing excess water in winter months when demand is low and recovering the stored water in summer months when demand is high [32].

Public confidence in water reuse projects is seemingly higher when the water is put back into natural systems such as streams and aquifers before recovery for reuse. Societal perceptions view natural systems as beneficial with respect to removal of human pathogens, the most significant concern to human health. Putting reclaimed water into the natural environment increases the cycle time of recycling and allows more time for biodegradation of contaminants that degrade more slowly [33].

A second major advantage is the capacity for inter-seasonal and inter-year storage that natural systems provide. This is where aquifers have major advantages over surface impoundments. The capacity is very large so that matching supply and demand for recycled water, particularly for agricultural use, is not the dilemma it can be where finite active surface storage capacity is bounded by spill or running dry. Aquifers have more blurry bounds that may provide a softer landing when the system is pushed to its limits.

Finally, aquifers offer storage where there is no room for surface storage, such as in urban areas; they do not consume prime valley floors, do not harbor mosquitoes or algal blooms, including toxic cyanobacteria, and there are no evaporation losses that also increase the salinity of the remnant water**.** One potential attraction for aquifer recharge is that it could be used for water rights transfer from party to party. Such offsets are accepted in the Columbia River Basin where a one-to-one replacement of fresh water is required for permits to be issued for new fresh water usage [34].

The major disadvantages to ASR are (1) the cost of injection of the fresh water into the underground formation and (2) the uncertainty of monitoring of water quality. Hydrologic models of water flow often do not have the precision needed to track salinity gradients or other potential contaminant contents. O&G reservoir engineering models offer possible solutions for the latter but a cost effective ASR program is still tied to injection costs of the desalination stream.

Barriers to Adoption

The barriers to adoption of desalination of waste water, brackish ground water and oil field produced brine include political issues, community perception issues, and technical issues. The Governor and the TWDB have provided leadership for the State in developing desalination programs in Texas. However, lack of public funding, environmental, and regulatory issues related to desalination of produced water (and other inland saline waters) inhibit technology advancement of this resource. Public perception and acceptance of the advantages of RO desalination is unclear. Cost reduction advancements in technology are slowed by a lack of a clear “path to market” of new products and processes. Supplemental state government funding for demonstration projects (both sea water desalination and inland BGW desalination) is lacking. With these issues affecting the market for commercial development, it is clear that a more concerted effort is needed to develop new water resources from desalination, address conveyance issues associated with water transfer, and be prepared to meet the demand for the new resource if it were to be made available. Some selected issues are discussed below.

The Texas Commission on Environmental Quality has been working with other state agencies to streamline regulations for the permitting process for disposal in deep-underground injection wells of brine produced by desalination operations. Applicants for permits to dispose of brine from desalination in injection wells must meet the current requirements for disposing of hazardous waste in Class I injection wells, including brine from desalination if it is classified as a waste material from "either industrial or municipal facilities". Since injection wells have been used for disposal of salt water associated with oil and gas operations for almost a century, (as Class 2 wells), it is hoped that new cooperative efforts in desalination will allow deep injection wells into oil and gas fields for brine byproduct use in enhanced oil recovery operations. Recent private meetings between TCEQ and the Texas Railroad Commission may have removed the roadblock.

Local issues that communities would identify as barriers include the perception that desalinated produced water is not pure enough for consumption by humans or livestock and that there might be environmental drawbacks to its use for plants, range, and habitat sustainability. It is suggested however, that advanced technology and an improved regulatory climate will increase the likelihood of adoption of PWDS by water use groups in the state.

General Regulatory Requirements

Desalination of sea water and brackish ground water and subsequent use by municipalities would be regulated through NPDES (national pollution discharge environmental statements) permitting through TCEQ (EPA). Ramirez and Lee described the TPDES (Texas pollution discharge environmental statements) permitting process, including the Clean Water Act requiring every industrial or municipal facility that directly discharges pollutants into streams, lakes or the ocean to have a wastewater discharge permit. In the context of a seawater desalination facility, the TPDES permit application process would serve to ensure that discharges of brine concentrate will not have significant adverse effects on the receiving waters.

Despite the delegation of NPDES permitting authority to the State of Texas, EPA continues to exert influence over coastal activities. The Submerged Lands Act of 1953 gave coastal states title to "lands beneath navigable waters," and granted state jurisdiction over coastal waters for the "territorial sea." However, the federal government, in the Submerged Lands Act, also retained "all its navigational servitude and rights in and power of regulation and control of said lands and navigable waters for the constitutional purposes of commerce, navigation, national defense, and international affairs." Because of this, the federal government still has the ultimate authority to regulate activities involving discharges into coastal areas. The United States Supreme Court has consistently upheld the federal government's right to regulate coastal activities. Because of this and provisions of the Clean Water Act, TCEQ must provide EPA with a copy of each TPDES permit it issues, and EPA may object to any such permit issued by TCEQ. EPA also continues to have the authority to enforce any permit violations against any discharger. Moreover, a TPDES permit only lasts for a maximum of five years (although it could be less), and EPA has the right to review each permit renewal application at the end of its term. There are numerous other agencies that may be provided a draft TPDES permit for review depending on the nature and location of the discharge [22].

A TPDES permit incorporates the general requirements of the Clean Water Act, Code of Federal Regulations, Various state's Water Code, and Administrative Codes are permit conditions specific to a particular facility's operations. When the state's Wastewater Permits Section drafts a particular facility's permit, the most influential source of regulations are the Surface Water Quality Standards. An example is the ("TSWQS") contained in Chapter 307 of Title 30 of the Texas Administrative Code [24] The specific TSWQS that would be most relevant to the permitting of a seawater desalination facility would be aesthetics, temperature, salinity and toxicity. A TPDES permit will typically contain limitations on the amount of pollutants that can be discharged, with those limitations based on technology-based standards or water quality based standards. Technology-based standards are traditionally organized by EPA-classified categories of industries. However, EPA has not yet created an industrial category for desalination, so there are no industry-wide technology-based standards. Therefore, effluent limits in a TPDES permit for a seawater desalination facility will be subject to separate issues [22].

The Ground Water Protection Council (http://www.gwpc.org) and its advisors are addressing this issue. After discussions with several state underground injection control (UIC) agencies and EPA's UIC program staff, four possible injection scenarios have been identified, and scenarios offered on how injected concentrate might be regulated (Table 5). The scenarios include two types of source water (brackish ground water and produced water) and two injection strategies (inject for enhanced oil recovery or inject for disposal).

Table 5 Injection well class for concentrate injection under different scenarios [1]

Source of Raw Water	Injected for Enhanced Recovery	Injected for Disposal
Produced Water	Class II	Class II
Brackish/Saline Ground Water	Class II	Not determined – regulators need additional data

If the source water is produced water, then disposal of the resulting concentrate could be made to a Class II well regardless of the injection strategy. They also noted that if brackish water concentrate is injected for enhanced oil recovery, the resulting well will also be a Class II well. Another scenario is brackish ground water as source water and disposal of the concentrate via injection. Some regulators suggest that they would need to know the chemical constituents present in the concentrate and their levels. Alternately the concentrate may be considered as a byproduct, and if used for beneficial purposes (such as enhanced recovery), could be injected into a Class II well. Circumstances will dictate whether concentrate injection will require Class I, Class II or Class V wells.

Source water quality is of great concern, particularly when the end use will be potable. Any system providing drinking water to more than 25 people must meet restrictions on the amount of pollutants allowed in the drinking water system. Due to the concern regarding contaminants that exist in the source water, as well as potential precipitation, fouling, and scaling of the membranes, a study conducted for the Nueces River Authority suggested source waters high in salt content be tested for 27 different parameters prior to the planning of a treatment facility.

Because the rules regarding this type of water source are not clearly defined, clarification is needed. Regulatory staff has suggested that, once a project is defined, an official letter be sent to the State to inquire about all relevant regulations and permits necessary.

RESULTS AND DISCUSSION

Desalination Becoming a Commercial Market

In recent months, brackish ground water desalination has become a highly popular topic. Now all but one of the 9 Water Planning Districts in Texas have BWDS in their long range plans. Part of the awareness of the utility of the process has come about because of the visibility and timeliness of this SWC project.

In addition, the Desalination Program has entered into a licensing agreement with GeoPure Water Technologies, LLC to commercialize the process to be known as **GPRI Designs ™ Desalination technology.** In early 2007, GeoPure had 30 project client sites staked out for placement of mobile units 300,000 gallon per day unit operating in North Texas.

New Opportunities for Desalination and O&G Operations

The success of the desalination program at A&M has created a strong interest in the technology for treating produced water from conventional sources (such as the Permian Basin) and for water associated with development of unconventional resources such as coal bed methane (CBM) and Barnett Shale fracturing flow back brine. In Texas the most active drilling area is in the Barnett shale where more than 20 rigs are running at any one time developing this oil shale resource.

With the development of technology to horizontally drill the Barnett Shale, and perform multi-stage fracture treatments, the volume of fresh water has grown to more than 5 million gallons of water per well completion. In Johnson County, Texas the O&G industry is actually using more fresh water than the city of Cleburne Texas. As this water is produced, it contains saline materials, suspended solids and hydrocarbons. As Figure 5 reveals, only a part of the flow back brine can be treated at the present time to recover any water for subsequent fracturing operations. We have been working to adapt membrane pre-treatment measures to solving this problem.

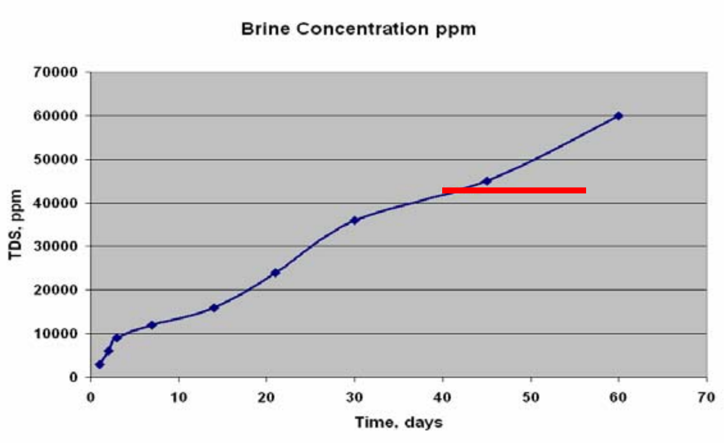

Figure 5. Salinity of Flow Back Brine. The horizontal line represents the practical limit for "normal" desalination measures.

Preliminary experimental results with a new type of low fouling membrane show even highly saline brines can be treated for re-injection. Further work is planned to follow up on this phenomenon.

With one set of objectives met, the project has taken on a fourth goal, "Water Issues Associated with Unconventional O&G Development," introducing a new issue related to water utilized in the recovery of oil and gas from unconventional resources. This is an emerging industry in Texas requiring large amounts of water resources, most of which cannot be recovered with present technology. This new source of energy from unconventional resources is expected to represent almost 50% of the natural gas produced in the United States in the next 25 years. Texas has the opportunity to be in the forefront of technology developed to achieve this by sustainable economic development. However, this new "face of the O&G industry" is even more dependent on water resources than traditional operations. It also tends to be more intrusive and can negatively impact sensitive environmental areas and local community areas if not integrated into managed processes for change that govern economic development in the state.

Water Resources Associated with Unconventional O&G Development

Oil and gas exploration and production has been one of the major industries in Texas for more than 100 years. The fields that were discovered during this time are nearing their economic limit. One reason that O&G operators are interested in desalination of produced water is that it has the chance of reducing operating costs of their wells and extending their lifetimes. Within the last 10 years however, unconventional reservoirs are being brought on production as new technology makes their development economical. Most of the attention to unconventional resources has been focused on Coal Bed Natural Gas (CBNG). Figure 6 shows unconventional energy trends, soon to represent more than 50% of our natural gas supply.

The increase in importance of CBNG and other unconventional resources is the result of a combination of factors - tax breaks for exploration, research funding that triggered new technology in imaging, horizontal wells, and hydraulic fracturing and high gas prices. As the figure shows, much of the energy play is in environmentally sensitive areas, in the

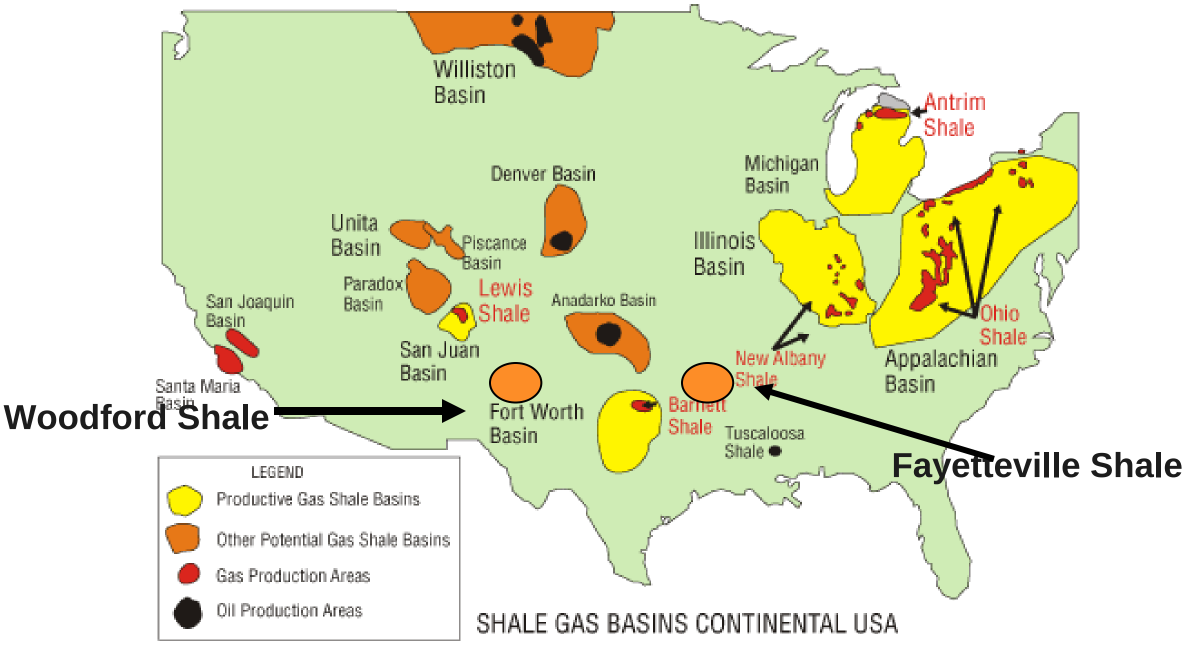

Figure 6. Unconventional Shale Gas Resources in the U.S.

West public lands, and in the East, in populated areas that have not experienced oil and gas “booms”. Despite the issues related to the impact of drilling in environmentally sensitive areas, and despite the needs for technology advances, most industry specialists believe that this source of energy for the U.S. is destined to become more and more important. Figure 7 shows a chart resulting from a study by the Petroleum Technology Council, PTTC. The contribution of unconventional resources increases steadily over the next 50 years until it represents more than 50% of the U.S, natural gas needs [35].

In Texas, the most activity is in the Barnett Shale play in the North Central part of the state. In the past three years, the drilling boom in the Barnett Shale has become the most active area in the U.S. The field, the largest active gas field in Texas, now produces more than 220 BCF (billion cubic feet) of natural gas per year.

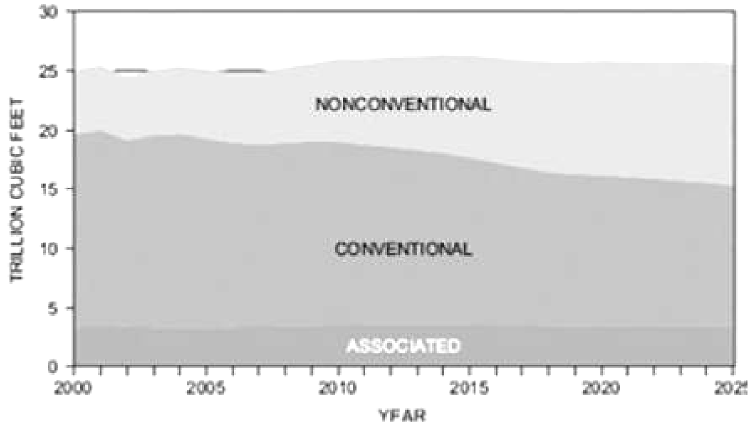

Figure 7 Gas production forecasts for the lower 48 states and Canadian Fields. The period is for the next 20 years. Source PTTC [36].

Drilling activity isn't limited to Texas however. Unconventional energy resources in Oklahoma include Hunton de-watering and coal bed natural gas (CBNG activity in the Arkoma and Cherokee basins). CBNG active in Oklahoma's Arkoma Basin produced about 70 BCF of gas cumulatively through mid-2003. About two-thirds of this production is from vertical wells, but horizontal production is rapidly overtaking that from vertical. Cherokee Basin CBNG cumulative production is about 45 BCF, all from vertical wells. CBNG wells in southeast Kansas are now producing about 10 BCF per year, and activity is strong. Arkansas CBNG production is just now beginning to increase.

Water Resources Used in Energy Production

The connection between unconventional energy resources and water resources is typified by the photograph in Figure 8. It shows a well fracturing operation in the Barnett Shale using fresh water from the municipality of Cleburne, Johnson County Texas. Cleburne sells water to operators at retail rates to stimulate Barnett Shale wells. A horizontal well fracturing operation uses on average 5 million gallons of water to create vertical fractures that intersect natural fissures in the shale. Flow back of the water, now containing mineral salts from the underground formation, occurs over a period of several days to months.

Flow back water must be captured in lined pits and transported to off site disposal. Salinity characteristics of this brine vary greatly, depending on the amount of flow back water, the zone that has been discharging the water, and the formation water content as a component of the fracturing water. Table 6 shows typical analytical data from water transport trucks carrying brine to off-site disposal. Total dissolved salts are in excess of 100,000 ppm. Total suspended solids (tss) are likewise quite high averaging almost 200 ppm for transport samples and more than 15,000 for the pit sample.

Figure 8. Photograph of a fracturing operation in the Barnett Shale.

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The issue is that all of the fresh water must be transported in to the site, then all of the flow back brine stored, re-loaded in transports and trucked to disposal wells that are dozens of miles away. The brine water is then injected and lost permanently from the environmental natural water.

The Social Cost of Energy Production

The issue of supplying adequate water resources for communities intersects with the need for water resources for energy production for those communities. Efforts by Texas A&M and others to reduce the use of water in energy production and to make fresh water available for those communities is part of the process of sustainable natural resource development.

Texas, in the 21st century is becoming a different society than most adults recall growing up. In almost every county in Texas, the population is shrinking. The urban centers and the counties near the urban areas are absorbing practically 100% of the state's population growth. On the other hand, almost 100% of the population would rather live in a small community. Fewer job opportunities and inadequate socio-economic infrastructure most likely prevent even greater migration to the country.

When economic booms come to local communities, many times its leaders are unable to cope with the change. The role of state and federal government in local communities is diminishing as funds for economic development are stretched. It is becoming the responsibility of the communities themselves to take the lead in their own survival and development. Unconventional energy development brings both good and bad changes to these cities. The ability to recover water resources from energy development helps to accommodate the changes it brings.

Table 6. Composition of Typical Flow Back Water from Barnett Shale [36]

	Flowb-1	Prod H2O-2	Truck 920	Flowb-4	TruckL080	DoubW#2	Pit Sample
Conductivity	224600	240600	283000	225000	254600	271000	1410
Chloride	69296	75254	87660	69379	79891	83781	150
Sulfate	395	363	510	359	< 40	480	182
Bromide	580	603	597	572	559	570	1.1
Potassium	326	411	825	301	357.4	832	743
Magnesium	1060	1164	1550	1070	999.4	1550	296
Silicon	15.91	13	7.84	12.64	6.42	8.68	
Calcium	8970	9982	13480	8950	11700	13460	287
Sodium	31920	33480	36900	31600	35760	36760	505
Boron	47.82	45	31	47	30.02	31.52	3.4
Silica	34	27	17	27	13.7	18.6	
pH	6.55	6	6.51	6.52	6.11	6.42	10.01
TDS	118600	127800	152100	121000	140600	151400	1243
TSS	352	162	164	450	274	178	15650
TPH	136	74	27	1234	6.4	293	2.04

CONCLUSIONS

Desalination testing at A&M and in the field during this project has provided extended run time data on brine disposal operations. This information, developed by GeoPure Water Technologies, LLP is being used in their marketing efforts to commercialize the A&M process. Operating companies and regulatory agencies have accepted oil field brine disposal as the most cost effective methodology to dispose of saline “reject” fluid from inland desalination operations. In the past two years, brackish ground water desalination has become a highly popular topic. Part of the awareness of the cost benefits of the process has come because of the visibility and timeliness of this SWC project.

In addition, the Texas A&M Desalination Program has entered into a licensing agreement with GeoPure Water Technologies, LLC to commercialize the process to be known as **GPRI Designs ™ Desalination technology.** More than 100 field projects are being considered for mobile desalination unit installations.

This report on the new technology of desalination and re-use of oil field brine is only a part of the effort necessary to develop commercial programs. There must be efforts by all to communicate to the users. This involvement with the community is expected to make any proposed projects more likely to be accepted and thus support our efforts to create these new water resources more effectively. A total of 7 of the 9 Regional Water Planning Districts in Texas have brackish ground water desalination in the long range plans. A&M has offered its services to assist the Councils if requested.

Because of the promise of desalination, the new partnership with GeoPure Water Technologies LLC will aggressively market the technology for commercial application. In the meantime, plans are being made to test the new type of brine treatment solids removal with brine from operating oil and gas leases.

Advancement of Desalination

Our feasibility study recommends a number of steps to help advance desalination technology. Technology demonstrations or "road shows" could bring new concepts of pure water to communities in need. The TWDB should continue to lead by example and should encourage other State Agencies to address water needs in a comprehensive fashion and to communicate, remove paperwork barriers, and advance worthy projects.

Coordination with Stakeholders

Collaboration should not be limited to just state organizations. The Rio Grande Basin Initiative is one example of economic development programs that seeks new approaches to solving problems [37] common to the states of New Mexico and to Texas. The annual meeting of the Association is set for May 14, 17 2007 (Continue to visit the conference Web site at http://riogrande-conference.tamu.edu.

In the summer of 2005, Congress approved money for the U.S. Bureau of Reclamation to build a national inland desalination research center near Alamogordo A research alliance was established that includes these two states, plus Arizona, named CHIWAWA (Consortium for Hi-Technology Investigations in Water and Wastewater) [38]. The purpose of this initiative is to create sustainable urban and rural water supplies and protect environmental quality by conducting innovative, collaborative research, education and training programs in inland desalination technology, concentrate disposal and water resources management. The consortium is pooling advanced expertise and experience in arid environment water resource management to address pressing technological, management and training issues related to inland desalination, source water characterization, and concentrate and water resources management (http://www.nmsu.edu/~ucomm/Releases/2006/january/desalination.htm)

Finally, the efforts to address the needs of local communities at the local level is paramount, especially in the regions of the State where fresh water resources are insufficient for current or future needs. This report on the new technology of desalination and re-use of oil field brine is only a part of the effort necessary to develop commercial programs. There must be efforts by all to communicate to the users. This involvement with the community is expected to make any proposed projects more likely to be accepted and thus support our efforts to create these new water resources more effectively.

Led by the Texas Water Resources Institute at Texas A&M, personnel from the Dwight Look College of Engineering and the Global Petroleum Research Institute (GPRI) have worked with the Texas Railroad Commission, Texas Water Development Board, and the Texas Commission on Environmental Quality to further the cause of desalination in Texas. Among a number of activities, the group has participated in the following;

- Desalination Research Workshop, Austin Texas 2002, volunteer activity
- Collaboration with TWDB USBR research project "Pass the Salt", volunteer activity

- Collaboration with the South Central Desalination Association Workshops, 2005, San Antonio, College Station
- Development of the "Future of Desalination" A&M Workshop, August 2005,
- Hosting the "Future of Desalination" A&M Workshop August 2006
- Proposed Brackish Ground Water Desalination with Concentrate Injection into Oil Fields, BLM Proposal 2005 (funding denied)
- Proposed Brackish Ground Water Desalination with Concentrate Injection into Andrews, Texas Oil Fields, (TWDB funding denied)
- "Use of RO Concentrate in Oil Fields for Beneficial Use", (Stripper Well Consortium Project, 2006).
- Desalination of Oil Field Brine with Concentrate Injection into the Darst Field. Meeting with TCEQ and TRRC to Resolve Regulatory Issues, January 2006
- Technology License for the GPRI Designs TM Desalination Process negotiated with GeoPure Water Technologies LLC
- Brackish Ground Water Desalination Demonstration Project Solicitations. TWDB August, 2006.

The meeting with TCEQ and the TRRC resolved a regulatory barrier to desalination of brackish ground water or oil field brine with re-injection of brine concentrate into an operating oil field.

Demonstrating that RO Desalination is Commercially Viable Technology

There is new technology for developing new sources of fresh water for the community. Two examples are the desalination of brackish water from underground aquifers to make it potable, and the treatment and desalination of oil field produced water to make it usable for livestock, agriculture and industrial uses.

Studies have shown that it is extremely important that the user (defined as local community who might have a use for the water) be included in the change process that comes from adoption of this new technology. The user's interest in anyone's recommended systems is very important because these interests are the basis for the system's acceptance and adoption.

ACKNOWLEDGEMENTS

This engineering study was performed with assistance from members of the Texas Water Resources Institute (TWRI) who provided both guidance and information relating to GIS data.

Several consultations were conducted with members of the Texas Water Development Board and with members of the petroleum engineering faculty at Texas A&M University. Thanks also go to the staff of Texas Railroad Commissioner Michael Williams who provided information for this study while Texas Water Resources Institute provided reference material on fresh water issues in Texas.

Special thanks go to Mr. John Veil of Argonne National Laboratory who provided the information on water policy issues in Texas and across the U.S. Thanks go also to Ms. Connie Conaway who assisted with bot the project and the preparation of the report.

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Appendix 1

February 9, 2007 **202-225-6105**

Edwards Co-Authors Bill To Help Recycle Water in Barnett Shale Operations

Local Leaders, Industry, Voice Support for Legislation

(Washington, DC) - U.S. Rep. Chet Edwards announced that he has co-authored a bill, H.R.902, The More Water and More Energy Act, that will spur research and development of ways that water from natural gas and oil production could be used for agricultural purposes and to reduce water costs for business.

"Finding ways to filter and reuse water used in drilling of natural gas wells will help preserve long term water supply for North Central Texas families and businesses while allowing natural gas operations to continue," said Rep. Edwards, the second ranking Democrat on the Energy and Water Appropriations Subcommittee.

H.R. 902 directs the Interior Secretary to carry out a study to identify the obstacles to increasing the ways in which produced water can be used. It authorizes $5 million in federal grants to assist in developing three pilot plants to demonstrate the feasibility, effectiveness and safety of processes in which produced water can be recovered and made suitable for use. Edwards worked with the author of the bill, U.S. Rep. Mark Udall of Colorado, to add language to include Texas specifically so that industry working in the Barnett Shale could apply for the grants. As a result, one of the pilot plants would be built in Texas, another in Colorado, one would be in Arizona or Nevada and the other would be built in California.

"Natural gas production has been an economic boon for many areas in North Central Texas, including Johnson County," said Johnson County Commissioner RC McFall. "At the same time, our water supply is precious and we have to look for new ways to conserve water in order to support our growing population. I have spoken personally with Congressman Edwards about this issue, and I thank him for taking a leadership role in looking for ways to protect the water supply for families in this area."

Officials from the oil and gas industry support Edwards' bill. Bill Whitsitt of the Domestic Petroleum Council, a national trade association representing 24 of the largest United States independent natural gas and crude oil exploration and production companies, supports the bill and said, "Beneficial use of water in these environments should be a win-win for the energy industry and water consumers, but the costs of water treatment and inconsistent water quality regulations among states make that process extremely difficult. The ability to carry out meaningful projects with real potential benefits will be crucial."

Produced water is the water generated during oil and gas production. The U.S. generates over five million gallons of produced water per day. While this water can be and is used for agricultural purposes, most often it is handled as a waste and reinjected. Given the increasing demand for fresh water supplies in the Barnett Shale and throughout Texas and the American West, Edwards said it makes sense to consider how recycled water could supplement our water resources.

"Conserving our water resources and reducing demand on the water supply will prove vital in the years ahead, as population growth increases demand for available water resources," said Edwards. "By being good stewards of our water supply, we will not only help protect the availability of fresh water for families in North Central Texas, we can reduce water costs for businesses, save Texas taxpayers millions of dollars and encourage economic growth in our area."

Edwards represents District 17 and is a senior member of the Appropriations Committee.