7-5-2012

Suitability assessment of non-potable water resources in the western United States for future thermoelectric cooling needs

Katie Zemlick

Suitability Assessment of Non-Potable Water Resources in the Western United States for Future Thermoelectric Cooling Needs

Katie Zemlick

Committee

Dr. Bruce Thomson, P.E. (Committee Chair)

Dr. Janie Chermak

Dr. Vincent Tidwell

A Professional Project Report Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Water Resources
Hydroscience Concentration
Water Resources Program
The University of New Mexico
Albuquerque, New Mexico
December, 2011

Committee Approval

The Master of Water Resources Professional Project Report of Katie Zemlick, entitled "Suitability Assessment of Non-Potable Water Resources in the Western United States for Future Thermoelectric Cooling Needs" is approved by the committee:

Bruce Thomson, Ph.D, P.E. Chair	Signature	12/5/11 Date
Janie Chermak, Ph.D	Signature	12/5/11 Date
Vincent Tidwell, Ph.D	Signature	12/8/11 Date

Table of Contents

List of Figures

List of Tables

List of Appendices

List of Acronyms and Abbreviations

AF	Acre-foot
CCS	Carbon Capture and Sequestration or Storage
CWNS	Clean Water Needs Survey
DSS	Decision Support System
EIA	US Energy Information Administration
EPRI	Electric Power Research Institute
ERDAS	Earth Resource Data Analysis System
FIPS	Federal Information Processing Standards
GIS	Geographic Information Systems
IEP	Innovations for Existing Plants
kWh	kilowatt-hour
MGD	Million Gallons per Day
MRLC	Multi-Resolution Land Characteristics
MW	Mega Watt
NAD	North American Datum
NATCARB	National Carbon Sequestration Database
NERC	National Electric Reliability Council
NETL	National Energy Technology Laboratory
NLCD	National Land Cover Database
NPDES	National Pollution Discharge Elimination System
NWIS	National Water Information System
PC	Plant Capacity
PCS	Permit Compliance System
PE	Pump Efficiency
RO	Reverse Osmosis
SIC	Standard Industrial Classification Code
SNL	Sandia National Laboratory
TDS	Total Dissolved Solids
TWDB	Texas Water Development Board
US EPA	US Environmental Protection Agency
USDOE	US Department of Energy
USGS	US Geological Survey
WECC	Western Electric Coordinating Council
WPCF	Water Pollution Control Facility
WRD	Water Reclamation District
WRF	Water Reclamation Facility
WWRP	Wastewater Reclamation Plant
WWTP	Wastewater Treatment Plant

Acknowledgements

Completion of this project would not have been possible without the support and encouragement of a long list of people. I would first like to thank Dr. Vincent Tidwell of Sandia National Laboratories for encouraging me to take on this project in the first place, for providing funding for this research through SNL and the Department of Energy, and for his consistently thoughtful advice and support throughout this process. For a person with very little time to spare, the countless hours of advisement he gave were integral to the success of this study and were very much appreciated. To my committee chair, Dr. Bruce Thomson, for always making time to discuss all aspects of this project and for his overall support in my graduate studies. To Janie Chermak, for the time and energy she gave as a member of my committee and for her excellent suggestions regarding the economic analyses and water rights issues addressed in this project.

The support from numerous Sandia staff members made the scope of this project possible. To Cesar Castillo, whose endless hours of GIS tutorials and data processing expertise provided a foundation for this project's success. His patient guidance, quick response to panicked emails, and willingness to work through this project in its early stages of development elevated the quality of this study. The depth of GIS and statistical analyses contained within this project would not have been possible without the skills, suggestions, and advisement of Dr. Barry Roberts. And to Dr. Jesse Roach and Dr. Peter Kobos whose work with CCS and the NATCARB dataset helped to guide me through the collection and processing of brackish groundwater data. In addition, the economic analysis of wastewater treatment would not have been possible without the data and

expertise provided by Gwendolyn Woods from the University of Arizona and her work with Malcolm Pirnie, Inc.

In the early stages of this project, Scott Anderholm of USGS's assistance with the NWIS database and suggestions regarding well log interpretation was invaluable. In addition, the staff and administrators at the EPA were always helpful with data acquisition from both PCS and CWNS databases. I would also like to thank both my mentor Chuck Hathcock and team leader Dr. Jennifer Nisengard at Los Alamos National Laboratory for their understanding, flexibility, and support during the final stages of this process.

This project required over a year to complete and during that time the thoughtful feedback from my best friend Dr. Elizabeth Zanoni was invaluable and her emotional support kept me sane. My graduate school colleague and friend, Marcos Roybal was always available for GIS questions, theoretical discussions, and overall moral support. To my sisters, Lauren and Jeanne, for listening and encouragement, and for making me laugh through the stress. And to my parents, Mark and Mary Zemlick whose loving support made me the determined perfectionist that I am today.

While I do not, in general know what I would do without him, the endless patience, encouragement and love of my husband, Rand Levitt, made this achievement not only possible, but enjoyable. Thank you for always keeping things in perspective.

Abstract

Thermoelectric power generation relies on the creation of a temperature difference between the heat source and heat sink. Most often the heat sink is water which means that power generation requires significant quantities of water. Inland power plants use fresh water a resource that is becoming increasingly limited in the United States. Thermoelectric plants currently supply nearly 90% of the US demand for electricity. By 2030 thermoelectric consumption is projected to increase by 42 to 63% (NETL 2008) and nearly half of the new 1163 billion kilowatt-hour (kWh) demand will occur in the southern and western regions of the country.(EIA 2011) This anticipated growth in demand for electricity will place further stress on surface- and groundwater resources that in most river basins in the western United States are already fully utilized.

This study identifies non-potable water resources in the form of effluent from wastewater treatment facilities and brackish groundwater sources in a study area comprised of seventeen western states. The suitability of treated wastewater was determined using the volume of effluent available, its quality, and the land characteristics around the treatment plant that would be accessible for a new power plant. Brackish groundwater resources were estimated using USGS well log data in order to understand the general distribution, depth and quality of this resource. After characterization, the estimated costs pertaining to the capture, treatment and distribution of these non-potable sources were calculated and compared.

This assessment is a component of *Energy-Water Decision Support System (DSS)*, a product of the project entitled *Energy and Water in the Western and Texas Interconnects*. This overarching study was implemented by scientists at Sandia National

Laboratories, and funded by the Department of Energy's Office of Electricity. It is intended to perform analyses at the watershed scale to support long-term integrated water and electricity planning in the Western Electric Coordinating Council (WECC) and the Electric Reliability Council of Texas (ERCOT). The water availability and economical assessment generated by this study was compiled in ArcGIS 10 and displayed ArcMap format. It allows users to identify non-potable water resources and costs associated with use and assess their suitability within the larger, multi-dimensional analysis that comprises the DSS.

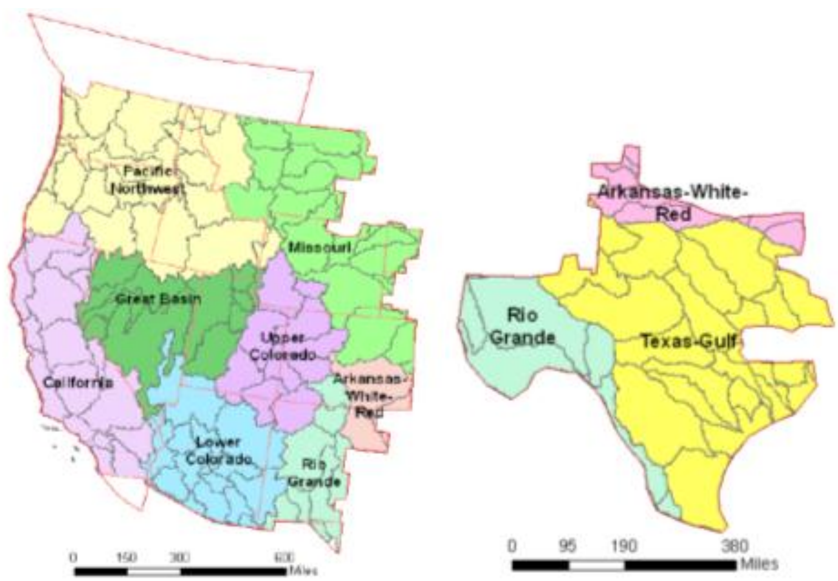
1.0 Introduction

Thermoelectric power generation relies on the creation of a large temperature difference between a heat source and a heat sink. Most often the heat sink is water and may be either sea water for a generating facility on the cost or fresh water if located inland. Power plant cooling for inland facilities requires significant quantities of fresh water, a resource that is becoming increasingly limited in the United States. Currently, electricity provided by plants utilizing thermoelectric cooling supply nearly 90% of the US demand.(Torcellini, Long, & Judkoff, 2003) In addition, thermoelectric consumption is projected to increase by 42 to 63% between 2005 and 2030 (NETL 2008). The Energy Information Administration's (EIA's) *Annual Energy Outlook 2011* forecasts a 31% growth (EIA 2011) in demand by 2035; nearly half of the new 1163 billion kilowatt-hours (kWh)will occur in the southern and western regions of the country.(EIA 2011) 18% of this new demand will come from the residential sector, attributable to population shifts to warmer regions where cooling demands are higher.(EIA 2011) This anticipated growth in demand for electricity will place further demands on surface- and groundwater resources that are already fully utilized in most river basins in the western United States.

The purpose of this study was to identify non-potable water resources, defined as water that is not considered to be suitable for human consumption, in the western United States. This includes quantification of their availability and calculation of the relative cost of utilizing them in future thermoelectric cooling plants. The study described in this report supports a larger program funded by the Department of Energy's Office of Electricity. The *Water-Energy Decision Support System (DSS)* will allow the Western Electric Coordinating Council (WECC) and the Electric Reliability Council of

Texas (ERCOT) (Figure 1) to develop a long-term strategy for electricity production within a framework that integrates transmission planning and water resource availability. This overarching project is the first truly collaborative approach to energy planning in the context of water and will enable planners and policymakers to analyze potential implications of stress on existing water supplies in many western river basins. The information contained in the following study and projected using ArcGIS 10 software will inform the DSS regarding the availability and relative cost of utilizing non-potable resources to support anticipated growth of thermoelectric power generation within the context of the region's long-term energy plans.

Figure 1: Energy and Water in the Western and Texas Interconnects Study Area (Tidwell et al. 2010)

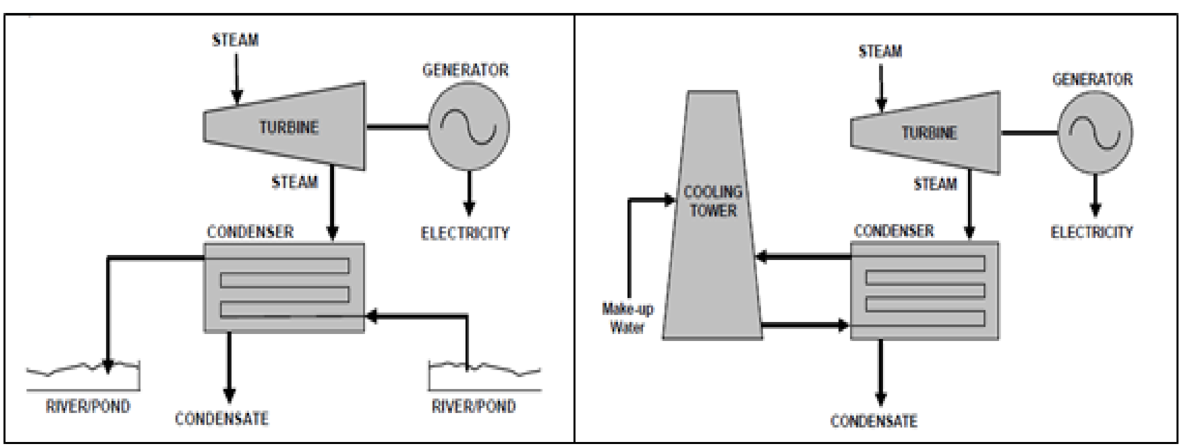


1.1 Background

Thermoelectric power comprises nearly 90% (USGS 2005; EPRI 2002; Feeley et al. 2008; USDOE 2007; EIA 2011) of generating capacity in the US, using a wide variety of fuel types, including coal, oil, natural gas, and nuclear plants (Feeley et al. 2008). In

thermoelectric plants water is used for cooling either in once-through processes or in cooling towers which recycle the cooling water. The schematic in Figure 2 illustrates water use in closed-loop and wet recirculating cooling systems. Using weighted averages, the USGS estimates that 23 gallons of water are withdrawn per kilowatt hour (kWh) of electricity produced (USGS 2005). Collectively, thermoelectric plants account for 49% of total water withdrawals (both fresh and brackish). While this use historically placed second to agriculture in withdrawals of fresh water, as of 2005 thermoelectric power accounted for the majority of all water withdrawals and nearly all water withdrawals for both sectors are supplied by surface water sources.(USGS 2005) Total withdrawals by thermoelectric power plants increased by 3 percent between 2000 and 2005, the largest increase since prior to 1980, an escalation considered a peak 5 year period (USGS 2005). While the type of cooling used is generally regarded as the primary driver of water use and consumption, the Energy Information Administration's (EIA) *Annual Energy Outlook*'s projections for population growth and associated electricity demand project an increase of 30% by 2035 (EIA 2010). Consequently, these competing demands for freshwater are not expected to be easily met with traditional supplies.

Figure 2: Once-through/open-loop (left) and wet-recirculating/closed loop (right) thermoelectric cooling processes (Torcellini, Long and Judkoff 2003, p. 9-10)



The type of cooling applied in thermoelectric power generation (once-through, wet recirculating towers, cooling ponds and dry cooling) is the main determinant of both water use and water consumption (Feeley et al. 2008; USGS 2005). Once-through or open-loop systems withdraw water from a source, circulate it through heat exchangers, and then discharge the water, now warmer, to its source. Recirculating or closed-loop systems reuse water repeatedly in the cooling process, and must supplement water lost to evaporation with additional water. This additional water is referred to as "make-up" water and the amount required varies based upon plant capacity and season.(EPRI 2004) While once-through systems withdraw significantly more water than recirculating systems, their rate of consumption is much less.

The distinction between withdrawal and consumption is important; *withdrawals* refers to the total amount of water taken into a plant for cooling applications while *consumption* refers to the amount of water lost to evaporation as a result of cooling processes. It was calculated that between 0.47 (Torcellini, Long, & Judkoff, 2003) and 0.69 (USGS 2005) gallons of water are consumed per kWh produced. Although only just over 3 percent of the 201,000 million gallons per day (mgd) of the water withdrawn for thermoelectric cooling is consumed or lost as a result of evaporation, blowdown, and drift, on an annual basis this quantity is significant (USGS 2005). Once-through cooling is the prevailing method of cooling (43%), and wet-recirculating cooling is a close second (42%; USGS 2005). Because surface water supplies 99% of the water withdrawn for cooling (USGS 2005), plants in the southwestern United States tend to utilize recirculating cooling systems because of a historical paucity of freshwater supplies, though the consumptive use of this cooling process is greater.

The inextricable connection between water and energy combined with emerging demands for available water resources and for electricity have been subjects of great interest by academics and researchers. Approaches to addressing the problem are varied. In response to a Congressional Directive, the 2006 report entitled *Energy Demands on Water Resources* addressed "energy and water interdependencies, focusing on threats to national energy production that might result from limited water supplies"(USDOE 2006, p.9). It concluded that current trends in energy use and water demand combined with projections of water availability would cause considerable stress on associated frameworks under a 'business-as-usual' approach to energy and water (USDOE 2006). Compounded by a "lack of integrated energy and water planning and management"(USDOE 2006) systems and the significant population growth in traditionally water-stressed regions of the country, the report highlighted the need for combined efforts to innovate within the industry in order to achieve long-term sustainability of water and electricity supplies.(USDOE 2006)

Prior to the 2006 report to Congress, significant investment in water-energy research was instigated by the power industry. In recognition of the water requirements of the power industry and anticipated conflict between dwindling supplies of available freshwater and the demands of a growing population's need for a reliable public supply of both water and electricity, the Electric Power Research Institute (EPRI) instigated numerous investigations into future alternatives. As part of a ten-year research effort, EPRI has published seventeen additional water-energy reports since completion of its 2002 report: *Water and Sustainability* (EPRI 2002). Issues addressed included water use efficiency and conservation, alternate cooling technologies, non-traditional sources of

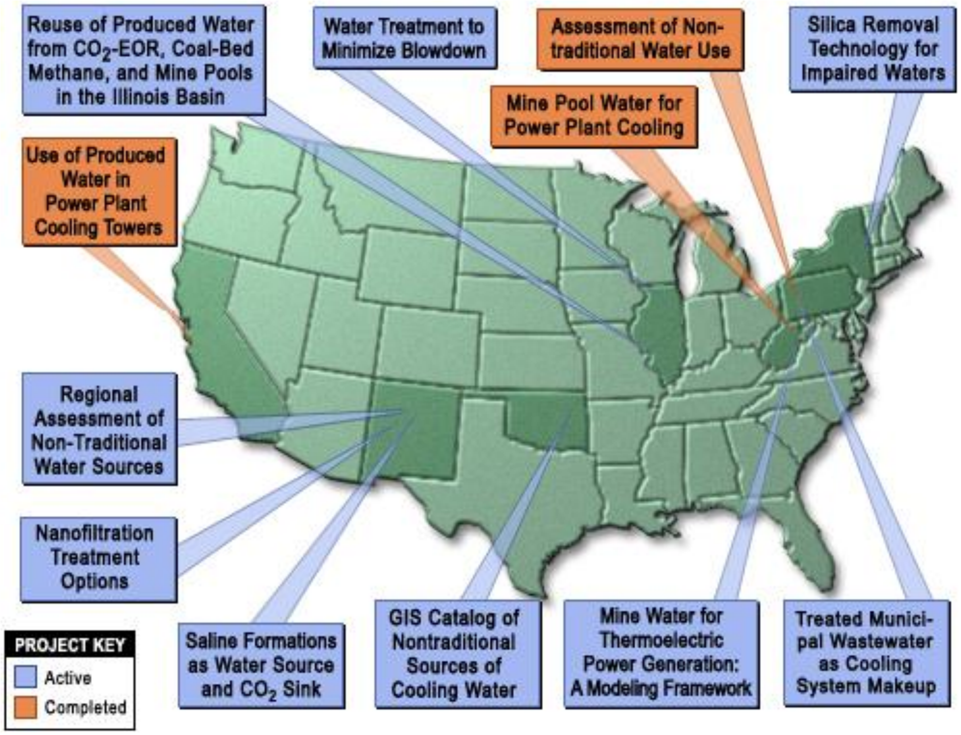
water, and improved management and forecasting techniques (EPRI 2008). Preceded by several technical reports on the interdependence of water and power, their 2008 report *Use of Alternate Water Sources for Power Plant Cooling* focused on the availability and cost of utilizing non-traditional sources of water, including municipal wastewater effluent, agricultural runoff, brackish groundwater, and produced water (EPRI 2008). Their conclusion was that the need to supply existing plants, as well as the ability to site new plants based on the availability of reliable supplies of fresh water that meets the quality required for power plant cooling could considerably alleviate pressure on planners, policymakers, and water users to allocate water supplies effectively.(EPRI 2008)

In 2008, Feeley et al. synthesized the connections between water and power, existing and anticipated future competition for the resource, and overall challenges to sustainability within the energy-water nexus.(Feeley, T.J. III et al., 2008) While the authors emphasized competing demands on water for public, agricultural, and industrial supplies, their conclusion was that planners and officials needed to take more active roles in management of local and regional water resources.(Feeley, T.J. III et al., 2008) They noted that trends in population growth and correlated electricity demand will most likely affect regions in which water resources are traditionally scarce. Lastly, the connection between water management and policy could be significantly impacted by EPA §316(b) ruling, which would eliminate once-through cooling as an option for thermoelectric plants because of the detrimental effects on aquatic life due to the entrainment of fish and larvae in intake systems and markedly warmer effluent discharged into the water source.(Copeland 2010) This would dramatically reduce withdrawal rates but the

necessity to transition to closed-loop or recirculating cooling technologies would increase water consumption in the industry as a whole(Feeley, T.J. III et al., 2008; USGS 2005).

Currently, the Department of Energy's (DOE) "Innovations for Existing Plants: Water-Energy Interface" (IEP) focuses on two main areas of research: water conservation in thermoelectric generation through plant modifications and other water conservation activities, and the investigation into alternative (i.e. non-traditional) sources of water for use in power plant cooling. IEP funded 12 projects (3 of which have been completed) that are investigating alternative sources of water which include, treated municipal waste water, produced water, brackish groundwater, etc.(Figure 3) Of the projects mentioned, the spatial analysis of alternative water sources by ALLConsulting is most similar to this project. Based in Oklahoma, ALLConsulting is currently being funded by the DOE through IEP to create a GIS catalog of non-traditional sources of cooling water for coal fired power plants (USDOE 2010). The project will identify alternate sources of cooling water including produced water, abandoned coal mine water, industrial waste water and low-quality groundwater within a fifteen mile radius of proposed coal-fired power plants (USDOE 2009). Project completion is expected to occur in 2011, and will produce an internet-based catalog that will allow users to assess quality and quantity of sources available near existing and proposed plants based on plant capacity.(USDOE 2009)

Figure 3: Energy-Water IEP Sponsored Research, Non-Traditional Sources (www.netl.doe.gov)



1.2 Study Objectives

Identification of suitable non-potable water resources for cooling of future thermoelectric power plants was the primary driver of this study. For the purposes of this work, suitability is defined by the availability of resources, the cost to treat and transport them, and the relative proximity of the resource to a potential thermoelectric plant. The objectives of this study were to:

1) Identify non-potable resources in the form of wastewater effluent and brackish groundwater in the study area and assess their relative distribution;
2) Determine what role land characteristics play in power plant siting for plants utilizing wastewater effluent in cooling applications and quantify this relationship;
3) Assess the essential economic components of utilizing these resources and calculate a comparative cost for each; and
4) Address the general potential legal and regulatory constraints that may influence application of non-potable resources for thermoelectric cooling processes.

Data collection and analysis formed the foundation for this work and Microsoft Excel and ArcGIS were used to compile and process the data. In addition these two formats can be easily incorporated into the more complex, systems dynamics framework DSS project. The DSS will utilize the data generated in this study along with additional considerations for long-term planning, which include:

1) Access to fuels;
2) Proximity to transmission lines;
3) Projected increase in demand for both water and power;
4) Regional drought vulnerability and its impact on existing freshwater supplies;
5) Evaluate power plant and electric system vulnerabilities due to drought;
6) Political and institutional constraints that will influence the trajectory of water supply and electricity demand decisions in the long-term.

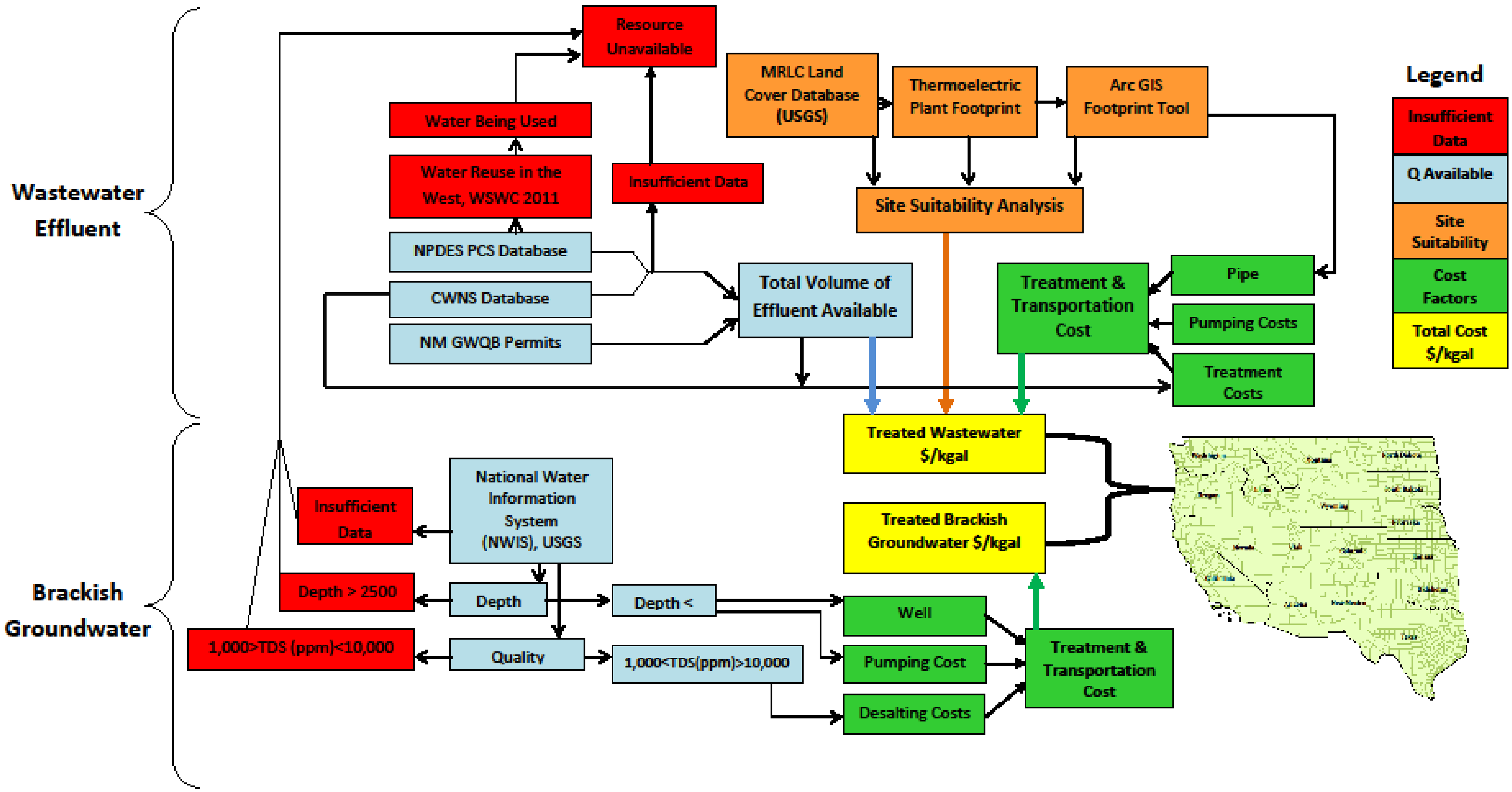
2.0 Methods

Preliminary research for this project involved extensive data collection pertaining to the availability of non-traditional sources of cooling water and its quality; reference costs for extraction, transportation, and treatment of water; and land requirements associated with the construction of a new power plant. In order to create a model of the current system, accurate and up to date data was essential. As a case in point, groundwater levels in the southwest are subject to significant changes as a result of excessive pumping, and linkages between brackish groundwater sources and over used freshwater aquifers could significantly increase drilling and extraction costs.

Non-potable water data was gathered from three primary sources: The Environmental Protection Agency's (EPA) Permit Compliance System (PCS) database and Clean Water Needs Survey (CWNS) databases for municipal wastewater and USGS's NWIS site for brackish groundwater. Wastewater treatment plant effluent outfall locations (latitude and longitude coordinates), discharge volume, level of treatment, and

other characteristics were sorted and plants with flows greater than zero were selected and organized by county in an Excel database. Brackish groundwater resources were estimated by state and compiled in an Excel database that includes well locations and physical characteristics as well water quality. The locations of these sources were then incorporated into ArcGIS and analyzed spatially. A conceptual design of the project methodology including data constraints, amount of water available, undeveloped land availability for new power plants, cost factors, and resulting total cost factors per thousand gallons (kgal) of water are illustrated in Figure 4.

Figure 4: Project Methodology Design



2.1 Municipal Wastewater

Municipal wastewater effluent, while not widely used as a supply for thermoelectric cooling, is subject to increasing reuse in regions where water is a limited resource. It has long been considered a reasonable alternative to withdrawing fresh water for power plant cooling(USEPA 2004; Metcalf and Eddy 2007) as well as a logical alternative to disposing of waste water.(Schmidt, C.J. et al., 1975) In addition, the application of recycled or reclaimed waste water in a variety of applications allows for further conservation of diminishing fresh water resources.(Watson et al. 2004) Of the nearly sixty power plants that utilize treated wastewater for cooling processes, plants in Arizona, California and Texas use significant quantities (USGS 2005; USDOE 2009). Two of the primary criteria of water for thermoelectric cooling, volume and quality of the source water, can be met by treated municipal wastewater.(EPRI 2008; US EPA 2004; Rebhun 1988; Vidic and Dzombak 2009; Veil 2007; Schmidt, C.J. et al. 1975) In addition, while municipal wastewater effluent is widely available, especially in urban areas where demand for electricity is also concentrated, the volume available can be expected to grow in accordance with population.

Numerous research efforts have focused on the current and possible future application of municipal wastewater for thermoelectric cooling.(EPRI 2008; Levine and Asano 2004; Rebhun 1988; Vidic and Dzombak 2009; Veil 2007; Schmidt, C.J. et al. 1975) In a study conducted by Vidic and Dzombak (2009) in which the suitability of wastewater effluent as cooling water supply for existing coal-fired power plants, the amount of cooling water required for proposed coal-fired power plants can be met in all NERC regions, with the percentage of water available for cooling ranging from 0.01-

3.2% of existing wastewater effluent supplies (Vidic and Dzombak 2009). Moreover, their analysis revealed that the water needs of approximately 81% of proposed plants could be met by Publicly Owned Treatment Works (POTWs) within a 10 mile radius and the needs of 97% could be met by POTWs within a 25 mile radius (Vidic and Dzombak 2009). They concluded that, on a nation-wide basis, treated water from POTW's could reliably and economically meet the needs of new thermoelectric coal-fired plants, an analysis that is especially cogent in regions where available supplies of fresh water are scarce (Vidic and Dzombak 2009). However, as noted in their report, there are no federal regulations that govern the reuse of treated wastewater effluent, however the guidelines pertaining to reuse, on the basis of both the quality and the quantity available, do vary by state.(Vidic and Dzombak 2009)

2.1.1 Resource Availability

According to USGS, over 16,000 POTWs discharge wastewater return flow, a number that was confirmed by both state and county in EPRI 2008. The Environmental Protection Agency's (EPA) Permit Compliance System (PCS) is a web-based data source that provides information on National Pollutant Discharge Elimination System (NPDES) permits.(US EPA 2011) The PCS database identifies specific facility information including pipe outflow location coordinates, volume of discharge, and water quality characteristics. In addition, the Clean Water Needs Survey (CWNS) Database, also compiled and administered by the EPA, contains information regarding level of treatment, point of discharge and characterization of discharge location, design capacity vs. actual capacity, and improvement costs.(US EPA 2011) Not all NPDES permits exist in the CWNS database; because CWNS fulfills §205(a) and §516 of the Clean Water Act.

Section §205(a) provides for infrastructure funds for the improvement of water treatment facilities and §516 relates to reporting requirements for facilities receiving those disbursements.(Copeland 2010)

The PCS database identifies point-source discharges by the type of permit issued, and more importantly, the CWNS database provides information regarding the type of treatment used. Although EPRI (2008) notes that municipal effluent that undergoes advanced treatment processes can be used directly in power plant cooling applications, most municipal wastewater effluent is treated to secondary or advanced treatment standards. The level of treatment varies according to quality and designated uses of the receiving water as well as state regulations, and is critically important to system design and treatment cost. In the case of existing plants using low quality water, EPRI noted that retrofitting cooling towers with compatible materials, while a large upfront cost, could prove more cost effective in the long run than constructing a treatment system to improve the water's quality (EPRI 2008). Based on the compatibility between water quality and the materials used to construct thermoelectric cooling systems, it is possible that new thermoelectric plants would opt to alter construction materials to utilize lower quality water, in spite of higher up-front capital costs.(EPRI 2008)

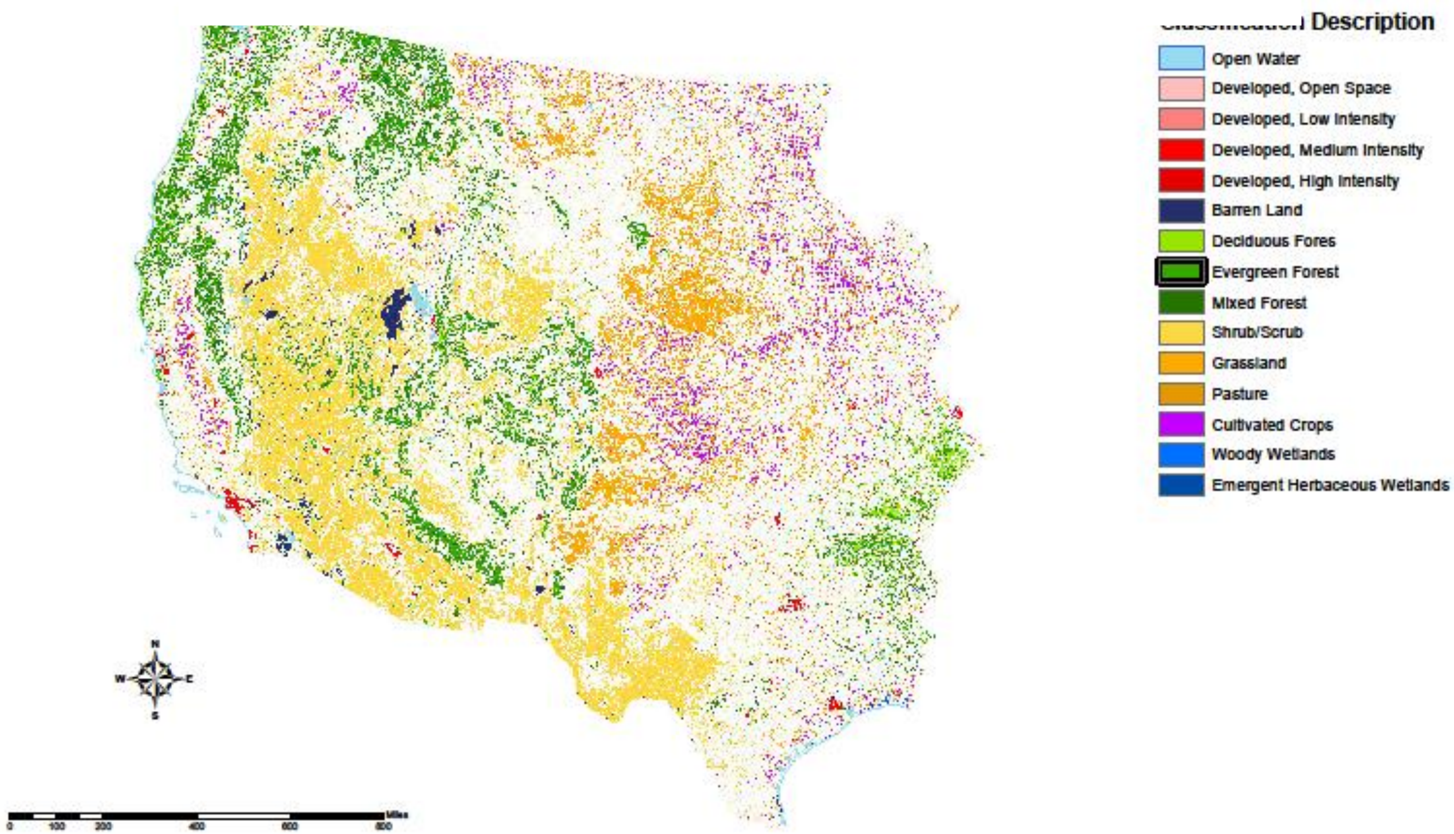
2.1.2 Site Suitability

The economic feasibility of using treated wastewater for thermoelectric cooling water is also dependent upon the presence of available land near the wastewater source, upon which to build a new power plant. The Multi-Resolution Land Characteristics (MRLC) consortium is a group comprised of multiple federal agencies who contribute information for the creation of land cover information on a variety of levels, which

comprise the National Land Cover Database (NLCD).(www.mrlc.gov) This file was created by Cesar Castillo of Sandia National Laboratories and is projected in ERDAS Imagine format with 30 meter grid cell resolution and was used to distinguish developed from undeveloped lands within the study area.(Figure 5) Land classified as "developed" was separated from all other categories, which were classified as "undeveloped".

In order to determine whether or not land development around power plants is an important variable in site selection, Barry Roberts of Sandia National Laboratory created an ArcGIS model to quantify land characteristics around existing plants using the MRLC file. As seen in Figure 6, the proportion of developed land around existing power plants is highly dependent upon fuel type. In addition, it was known that land area requirements for thermoelectric plants also varied based on plant type and capacity, as seen in Table 1. However, it was not known whether land development around an existing plant's footprint was a significant variable in plant site selection. And so, an analysis of developed land around existing plants of varying fuel types and capacities was conducted (Roberts 2011) in order to understand whether or not the proportion of developed land would prove to be a significant factor in site selection for future power plants. This assessment utilized concentric buffers with 1-, 2-, and 3-mile radii. Results indicated that there was a high degree of variability in land development around existing plants, independent of both fuel type and capacity, so only the land requirements for the new plant were considered in the suitability assessment.(Figure 7)

Figure 5: Land Cover Classification of Study Area



Source: Cesar Castillo, lcwest.img from www.mrlc.gov

Figure 6: Comparison of Proportion of Developed Land Within 1 mile of Existing Power Plants by Type (Roberts 2011)

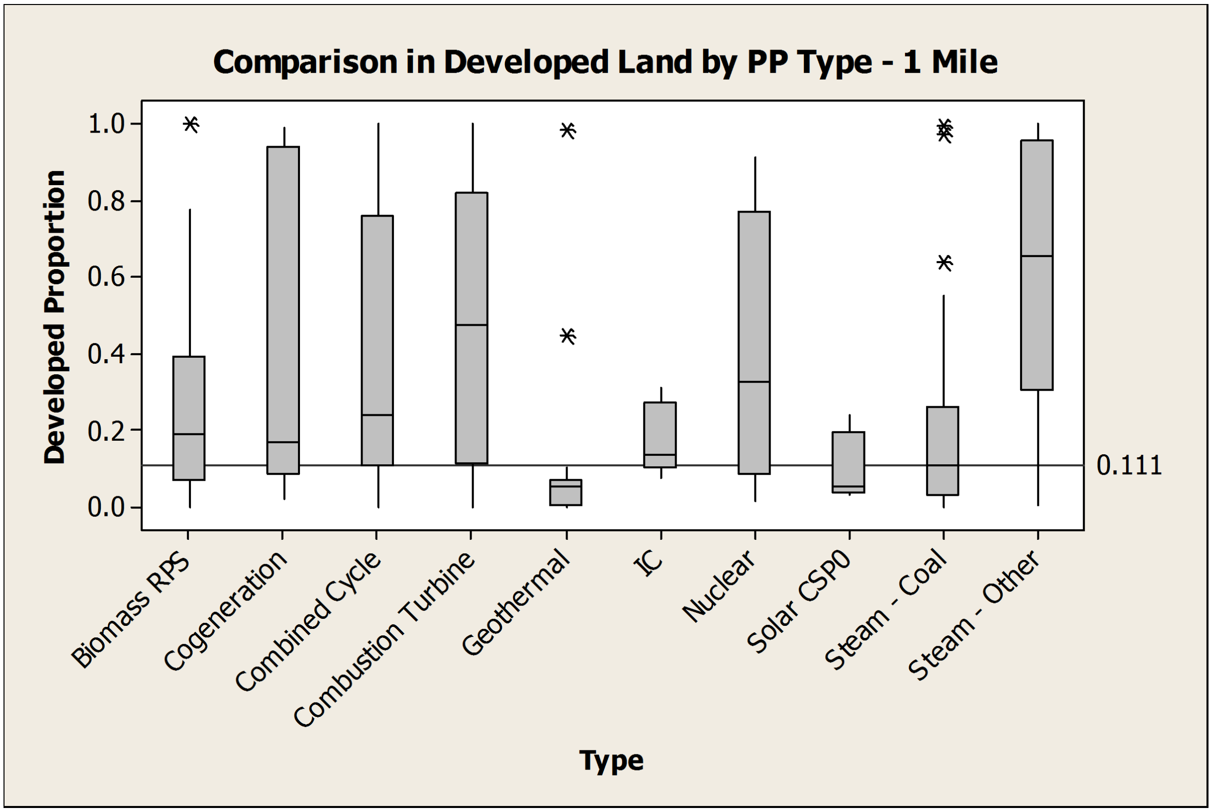
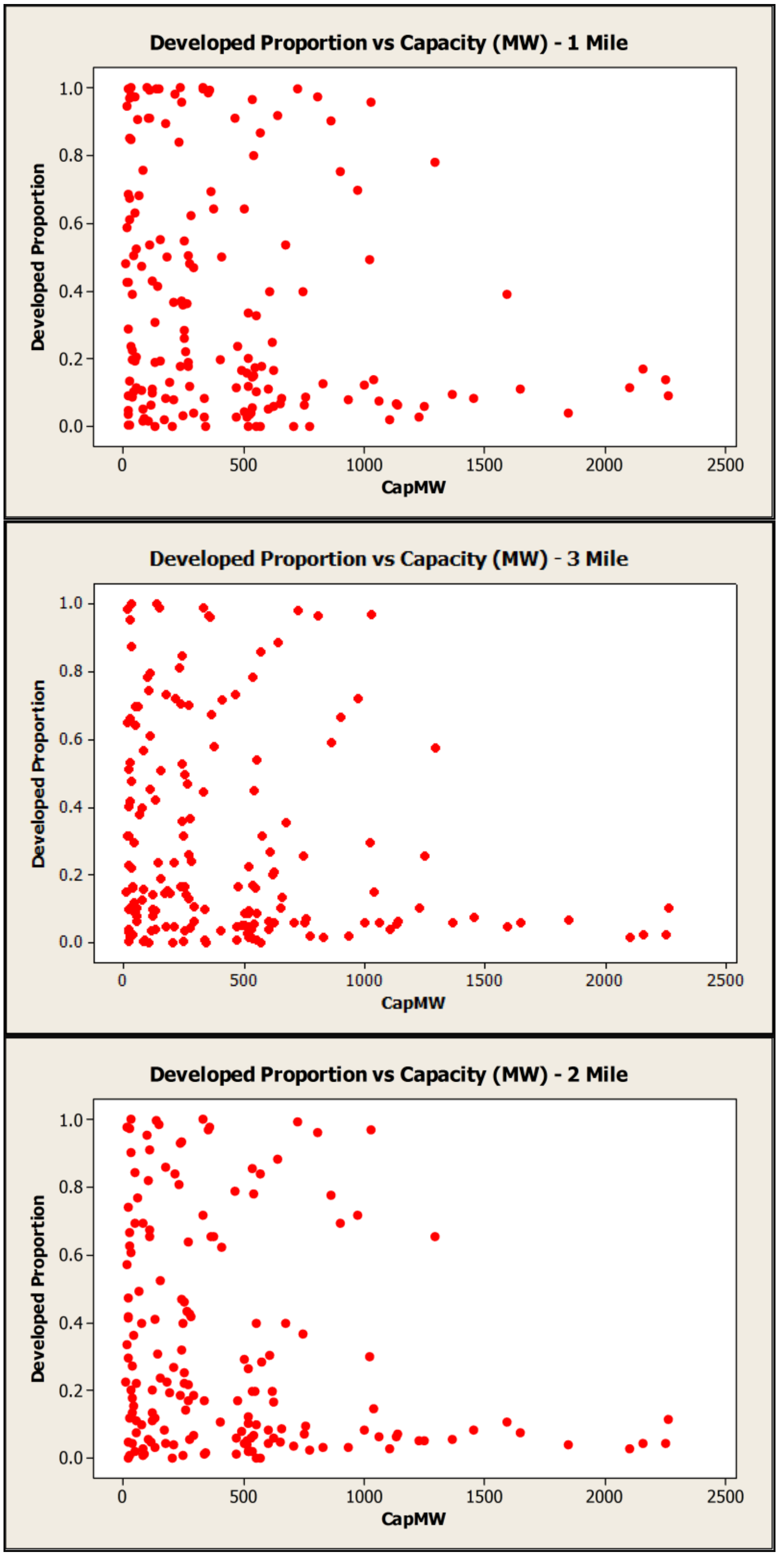


Table 1: Land Requirements for Electric Power Generation (Hightower 2009; B. Roberts, personal communication, August 18, 2011.)

Plant Type	**Plant Size (MW)**	**Land Area (acres)**	**Land Size**	**Footprint (ha)**
Coal/Steam	500-1000	640	1 mi. x 1 mi.	259
Oil/Natural Gas Steam	200-500	320	0.7 mi. x .7 mi.	127
Combined Cycle	200-500	160	0.5 mi. x 0.5 mi.	65

Figure 7: Comparison between proportion of developed land within 1-, 2-, and 3-mile buffers around existing plants and plant size (Roberts 2011)



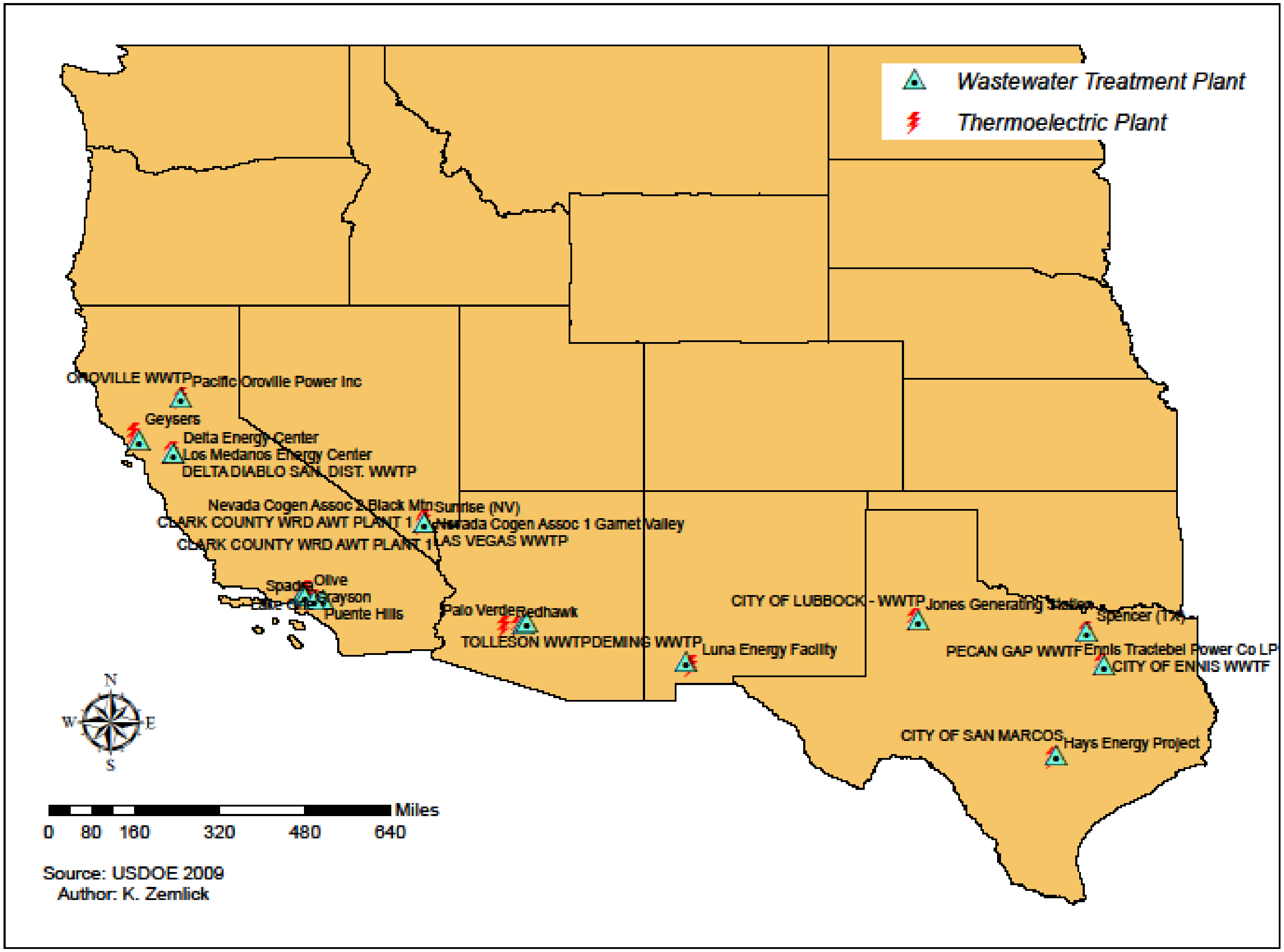
Following spatial relationships between existing plants that are utilizing wastewater effluent for cooling, a five mile buffer was selected to represent a reasonable threshold of proximity between the water source and a new power plant. Twenty-six of the nearly sixty plants that reuse wastewater for cooling are located in the study area and those plants, as well as the wastewater treatment facility providing the cooling water are listed in Table 2. (USDOE 2009) Distance was measured using a NAD 83 projection in ArcGIS using coordinates mapped in Figure 8. After removing the apparent outlier that was the distance between the Redhawk Plant and Tolleson WWTP in Arizona, the average distance between a plant using treated wastewater for cooling and the wastewater plant source was approximately five miles.

Table 2: Existing Thermoelectric Plants Utilizing Wastewater Effluent (USDOE 2009)

Distance (mi.)	**Power Plant**	**Fuel: Prime Mover**	**Use of Water**	**Wastewater Treatment Plant**	**Water Use (mgd)**
14.2	Palo Verde	Nuclear	Cooling tower makeup	91st Ave. WWTP	55
20.1*	Redhawk	Natural Gas	Cooling tower makeup	Tolleson WWTP	3.9
0.98	Olive	Natural Gas	Cooling tower makeup	Burbank WRP	0.1
0.92	Magnolia	Natural Gas	Cooling tower makeup	Burbank WRP	1.0-1.4
11.1	Lake One	Natural Gas	Cooling tower makeup	Burbank WRP	0.1
1	Grayson	Natural Gas	Cooling tower makeup	Glendale WRO	0.3
2.5	Pacific Oroville Power Inc	Solid Renewables	Cooling tower makeup	Oroville WWTP	0.05
13.8	Spadra	Gas Renewables	Cooling tower makeup	Pomona WWRP	0.03
0.56	Puente Hills	Gas Renewables	Cooling tower makeup	San Jose WWRP	0.5
0.14	Delta Energy Center	Gas	Cooling tower makeup	Delta Diablo Sanitation District WWTP	3.85**
1.8	Los Medanos Energy Center	Gas	Cooling tower makeup	Delta Diablo Sanitation District WWTP	3.85**
12.5	Geysers	Geothermal	injected to maintain pressure	Laguna Subregional WPFC	8
1	Sunrise (NV)	Gas	Cooling tower makeup	Las Vegas WWTP	0.09-0.3
7	Hays Energy Project	Gas	Cooling tower makeup	City of San Marcos WWTP	.3
1.3	Spencer (TX)	Gas	Cooling tower makeup	Pecan Gap WWTF	1.0
4.5	Jones Generating Station	Gas	Cooling tower makeup	City of Lubbock WWTP	3-5
2.8	Ennis Tractebel Power Co LP	Gas	Cooling tower makeup	City of Ennis WWTF	1-1.5
12	Luna Energy Facility	Gas	Cooling tower makeup	Deming WWTP	1
n/a	Salt River Project - K7 Plant	Gas	Cooling tower makeup	Tempe Kyrene WRF	3.1
n/a	Northern CA Power Agency - CT2 Project	Gas	Boiler Feed	White Slough WPCF	0.08
n/a	Nevada Power - Clark Station	Gas	Cooling tower makeup	Clark County WRD	0.15-2.7
n/a	Geysers Geothermal Field	Geothermal	injected to maintain pressure	Santa Rosa WRF	11
n/a	Platte River Power - Rawhide Energy Station	Coal	Cooling	Drake WRF	3.8
n/a	Xcel Energy - Harrington Plant	Coal	Cooling tower makeup	Amarillo WWTP	7.5***
n/a	Xcel Energy - Nichols Plant	Gas	Cooling tower makeup	Amarillo WWTP	7.5***
n/a	Geysers Geothermal Field	Geothermal	injected to maintain pressure	Middletown, Southest Regional, Northwest Regional, and Clearlake Oaks	8

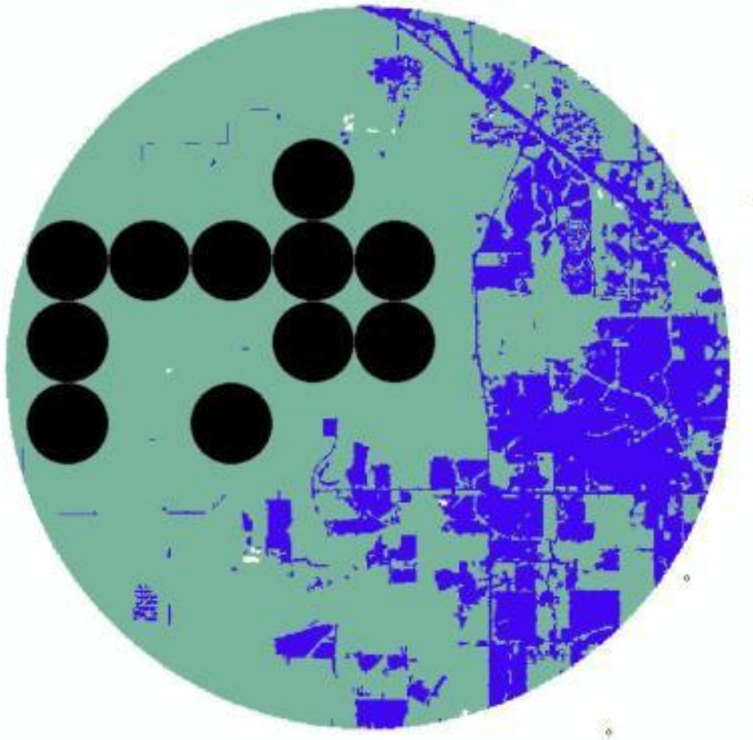
* Water is first piped to Palo Verde then to Redhawk. Distance value computed as miles between plants.
**Delta Energy and Los Medanos Plants water use reported together as 7.7 mgd.
***Harrington and Nichols Plants water use reported together as 15.0 mgd.

Figure 8: Existing Power Plants Utilizing Treated Wastewater for Cooling



Determination of relative suitability of a given power plant based upon undeveloped land availability constituted the final step in this assessment. Once land was characterized based upon the binary qualifier of "developed" vs. "undeveloped", assessing the presence of undeveloped parcels with contiguous areas that met the requirements of different plant types was made possible with an ArcGIS tool created by Barry Roberts.(Roberts 2011) Utilizing the three different footprint sizes referenced in Table1, the tool fit the maximum number of circular footprints in a grid pattern within the five mile buffer surrounding each existing wastewater treatment plant. A graphical description of the tool's function is presented in Figure 9. The purpose of this tool is to produce a count of the number of available parcels of varying sizes, which constitutes a comparable metric for all wastewater treatment plants. Analyzed using a rank percentile function, these plants can be separated into a spectrum ranging from low to high footprint availability.

Figure 9: Example of Arc GIS Tool Results for Modeling Available Land Parcels



2.1.3 Cost

The economics of using treated wastewater in thermoelectric cooling process depends upon a variety of factors including capital, and operation and maintenance costs associated with treatment and transportation, which are assessed here. According to EPRI (2008) and EPA (2004) water from treatment plants using advanced treatment technologies may be directly used for power plant cooling. Advanced treatment processes exceed those of traditional secondary treatment and typically remove excess nutrients when effluent is designated for reuse.(EPA 2004) Figure 10 details the general processes of wastewater treatment based on type. Referencing data gathered from the CWNS

database, plants employing advanced treatment technologies were excluded from treatment cost calculations. Treatment cost data for all other plants was calculated based on data from Malcolm Pirnie Inc. (G. Woods, personal communication, May 5, 2011) Costs considered include capital costs, operation and maintenance costs, as well as treatment-specific costs such as filtration and disinfection. Table 3 details the respective treatment costs based upon plant capacity and treatment type; capacity and cost have an inverse relationship.

Figure 1: Wastewater Treatment Process Types (Based on "Generalized Flow Processes for Wastewater Treatment" EPA 2004 p. 107)

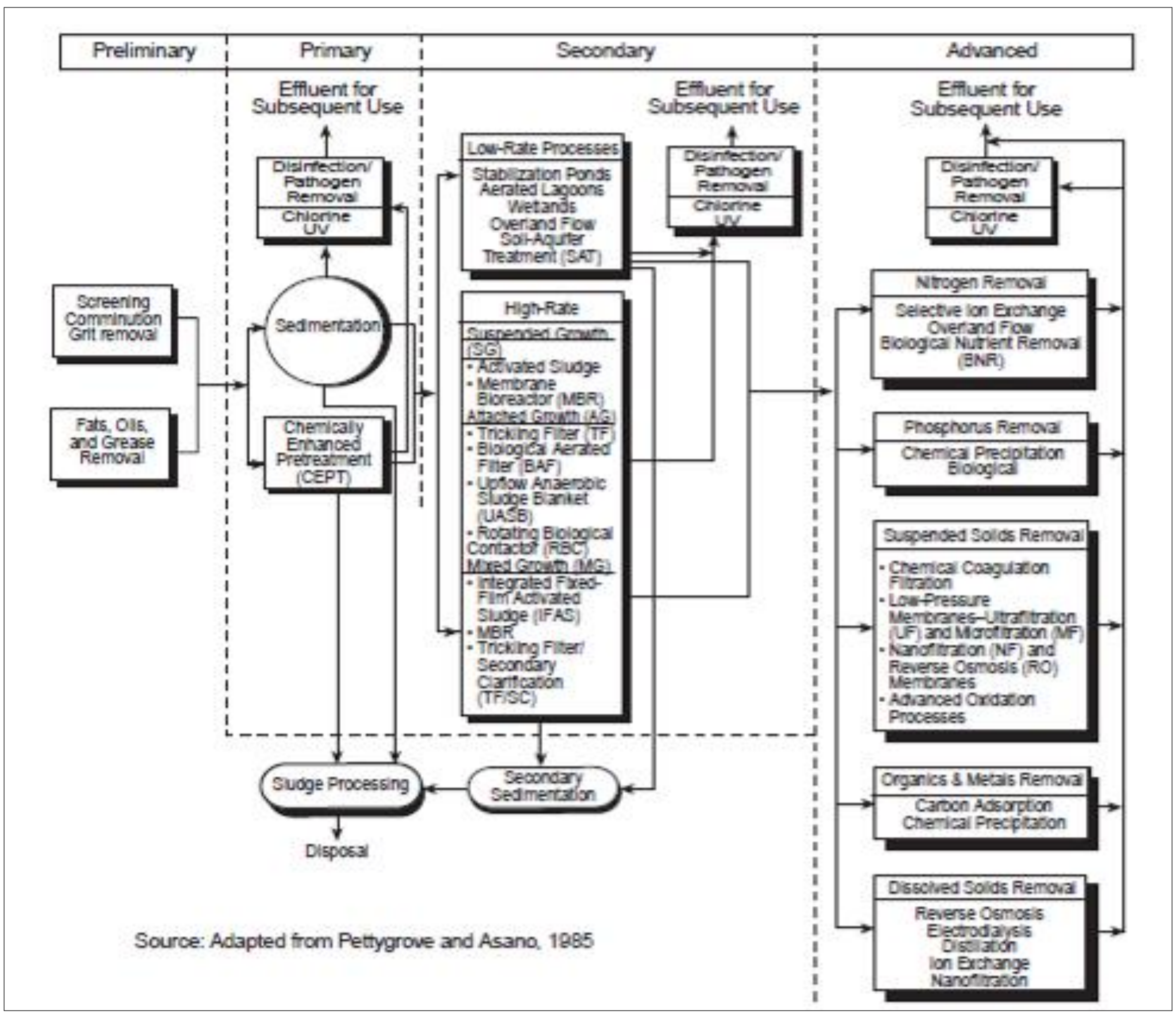


Figure 2: Wastewater Treatment Costs Based on Plant Capacity and Treatment Type

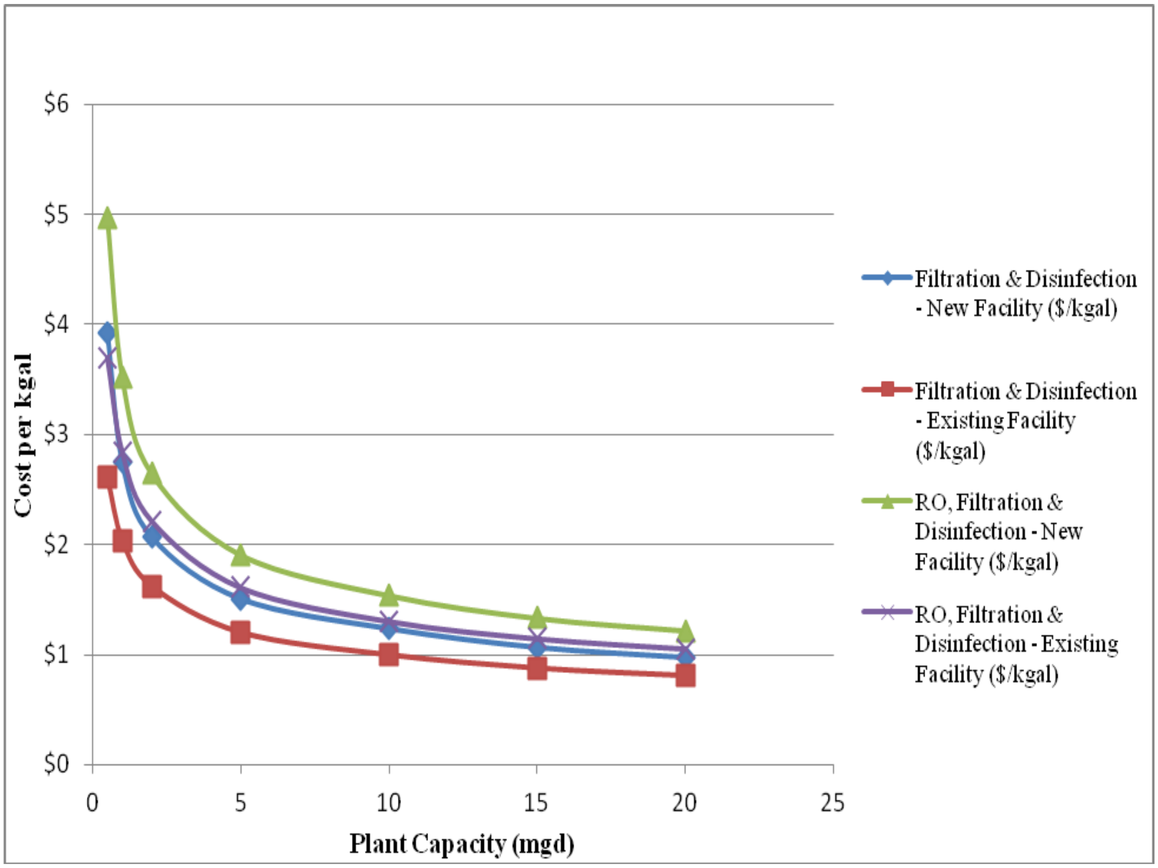


Table 3: Capital and O&M Costs for Water Treatment Based on Capacity and Treatment Type

	Flow (mgd)	**0.5**	**1.0**	**2.0**	**5.0**	**10**	**15**	**20**
Filtration & Disinfection	Capital New Facility ($)	$302,999	$424,649	$638,989	$1,164,873	$1,913,820	$2,476,379	$3,018,673
	Capital Existing Facility ($)	$201,406	$314,872	$499,902	$925,306	$1,535,210	$2,024,866	$2,488,812
	O&M New Facility ($/yr)	$413,180	$579,067	$871,349	$1,588,463	$2,609,754	$3,376,880	$4,116,372
	O&M Existing Facility ($/yr)	$274,644	$429,371	$681,685	$1,261,781	$2,093,469	$2,761,181	$3,393,834
	Filtration & Disinfection - New Facility ($/kgal)	$3.92	$2.75	$2.07	$1.51	$1.24	$1.07	$0.98
	Filtration & Disinfection - Existing Facility ($/kgal)	$2.61	$2.04	$1.62	$1.20	$0.99	$0.87	$0.81
Reverse Osmosis Filtration & Disinfection	Capital New Facility ($)	$356,662	$499,358	$741,235	$1,326,100	$2,108,356	$2,734,641	$3,319,761
	Capital Existing Facility ($)	$255,069	$389,581	$602,148	$1,086,533	$1,729,747	$2,283,128	$2,789,900
	O&M New Facility($/yr)	$551,505	$787,216	$1,189,691	$2,156,216	$3,510,538	$4,569,725	$5,581,674
	O&M Existing Facility ($/yr)	$420,098	$647,553	$1,014,881	$1,855,455	$3,037,273	$4,009,450	$4,924,582
	RO, Filtration & Disinfection - New Facility ($/kgal)	$4.98	$3.52	$2.65	$1.91	$1.54	$1.33	$1.22
	RO, Filtration & Disinfection - Existing Facility ($/kgal)	$3.70	$2.84	$2.22	$1.61	$1.31	$1.15	$1.06

"New Plant" is distinguished from the "Existing Plant" by the inclusion of capital costs for administrative and operating facility, which is not insignificant. Should these sources be utilized by power plants: additional treatment administered at the originating wastewater treatment plant and additional treatment administered by the power plant will be necessary. Should the first option be chosen, O&M costs will be significantly less than if the second option (treatment at the power plant) be employed.

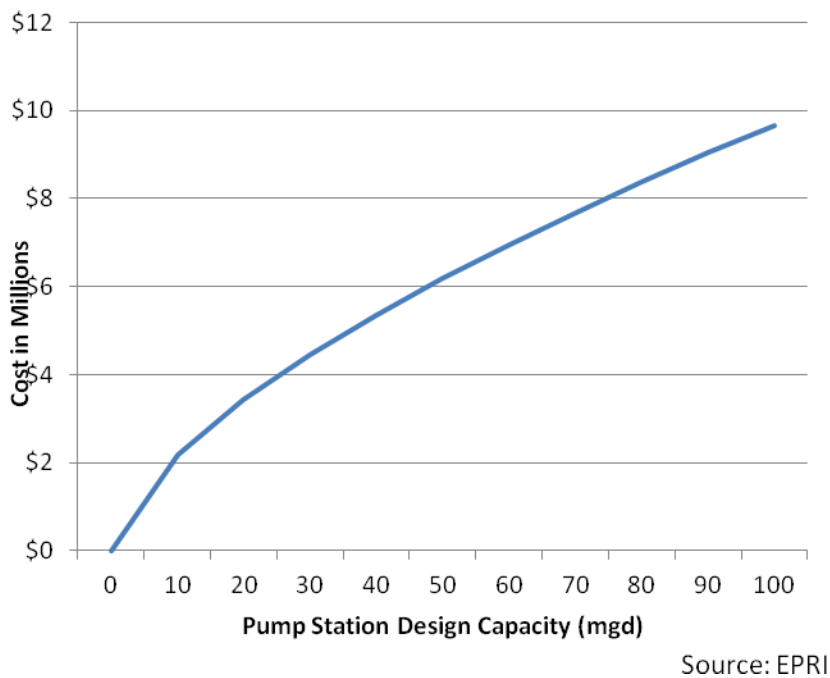
Costs associated with the conveyance and delivery of treated wastewater from its source to a potential new thermoelectric plant are based upon the costs for a pump station (or stations) and the material, labor and equipment associated with laying new pipes to transport the water. The EPA's *2003 Drinking Water Infrastructure Needs Survey--Modeling the Cost of Infrastructure* (USEPA 2005) as cited in EPRI (2008) provides an empirical method for estimating the cost of potable water pump stations, as it is assumed that water supplies will need to be pumped to the power plant site from the source location. Cost for a new pump station where D=design capacity (mgd) is shown in

Equation 1 and represented graphically in Figure 12.

Equation 1: Pump Station Costs

$$\text{Cost (USD)} = e^{12.446+\frac{1.0772^2}{2}} * D^{0.644} * 1.096833$$

Figure 12: Pump Station Cost as a Function of Plant Design Capacity



Pipe size selection is an important factor in choosing what material to construct conveyance pipe with. An engineering rule of thumb suggests a velocity less than 5 ft./s,(B. Thomson, personal communication, November 1, 2010) where velocity = Q/A. For example, a facility discharging 5 mgd (7.75 cfs) needs a pipe area of A=7.75 cfs/5 f/s = 1.55 ft^2. Therefore, appropriate diameter can be calculated using the equation:

A= $\frac{\pi d^2}{4}$. The result is: $d = \left[\frac{4 * 1.55}{\pi}\right]^{\frac{1}{2}}$ = 1.4 ft.*(12in/ft.) = 16.8 in.; a pipe conveying 5 mgd from a wastewater treatment facility to a thermoelectric plant for use in cooling processes would require a pipe approximately 16.8 inches in diameter. Reflected in, a plant would need to discharge and convey 43.6 cfs (28 mgd) in order for concrete pipe to be a more economical choice than steel.

Figure 13: Pipe cost as a function of diameter and material (EPRI 2008)

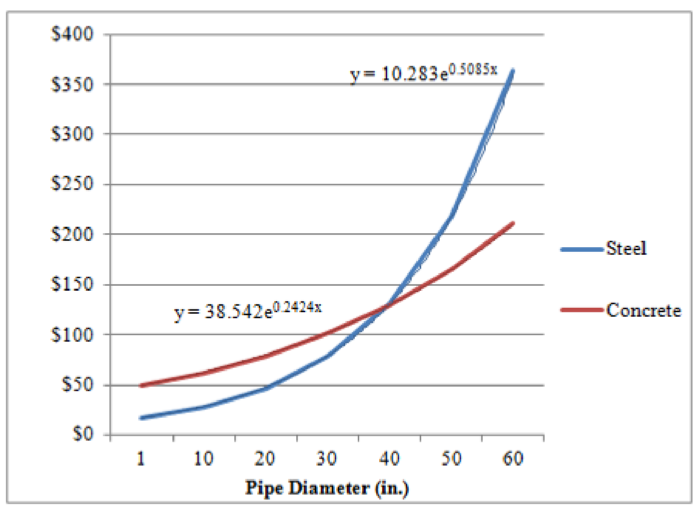
Diameter	Steel	Concrete
1	$17.58	$49.76
10	$27.91	$62.04
20	$46.67	$79.26
30	$78.03	$101.27
40	$130.47	$129.38
50	$218.13	$165.30
60	$364.71	$211.19

Pipe Material Cost Functions

Steel $16.695e^{0.0514x}$

Concrete $48.588e^{0.0245x}$

Source: EPRI 2008



Labor and equipment costs assume trench installation, a commonly used method for pumped systems. (EPRI 2008) Crew and equipment rental was calculated to be approximately $7,000 per day with a daily output of 250 feet per day.(EPRI 2008) Labor and equipment costs were based upon daily output and were calculated by size for concrete and steel pipe. The results from this analysis are displayed in Figure 14: Labor and Equipment Cost as a Function of Material and Diameter.

Figure 14: Labor and Equipment Cost as a Function of Material and Diameter

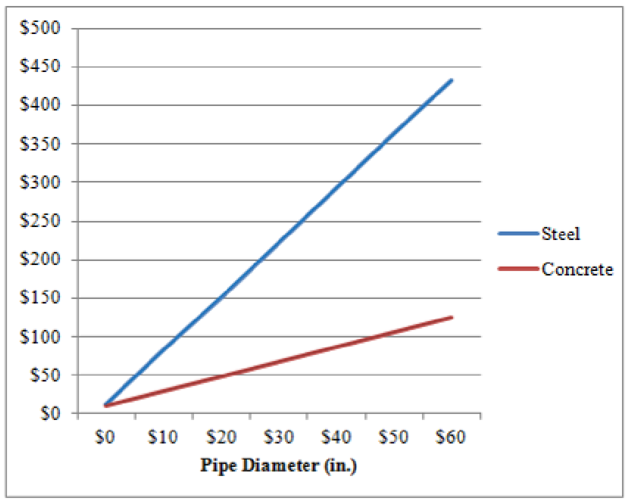
Diameter	Steel	Concrete
0	$11.84	$11.24
10	$82.04	$30.18
20	$152.24	$49.12
30	$222.44	$68.07
40	$292.64	$87.01
50	$362.84	$105.96
60	$433.04	$124.90

Labor & Equipment Cost Functions

Steel $7.0201x + 11.835$

Concrete $1.8944x + 11.235$

Source: EPRI 2008

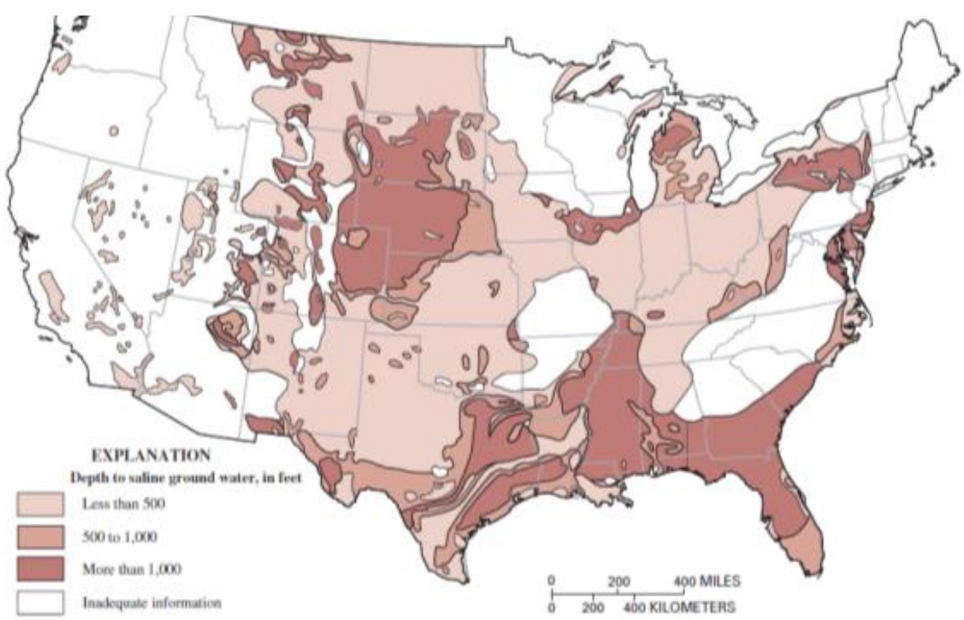


2.2 Brackish Groundwater

Brackish water is characterized by total dissolved solids (TDS) concentrations greater than 1,000 mg/l but less than 10,000 mg/l (Watson et al. 2003) and is widely distributed across the United States. However a precise understanding of the quantity and quality of these deposits has not been exhaustively investigated because until recently it has not been considered a resource of significant value. "Saline" water by contrast is

considered to be of a quality approaching that of seawater (30,000 TDS). Feth et al. (1965) published maps of the distribution and generalized chemical type of brackish groundwater in the country. (Figure 15) The distribution of brackish groundwater in the intermountain west is most notably not included. Historically viewed as a liability rather than a resource, Feth noted that brackish groundwater could represent a cost-effective alternative to treating and transporting the significantly more saline ocean water. (Feth 1970; Watson et al. 2003). In a prophetic statement about the resource in his 1970 paper entitled *Brackish Groundwater Resources of the United States*, J.H. Feth stated "[it's] importance in the national economy will probably grow to major proportions within the next few decades" (Feth, 1970, p. 1454). More than four decades later, brackish groundwater as well as lower quality produced water from oil and gas production have reemerged as a possible alternative to surface water for thermoelectric cooling, especially in states with limited water resources or predisposition to drought. (Dennehey 2004; Veil 2007; EPRI 2008; NRC 2008; DiFilippo 2004)

Figure 15: Distribution and Depth of Brackish Groundwater in the United States
(Feth et al. 1965, reproduced in USGS 2003)

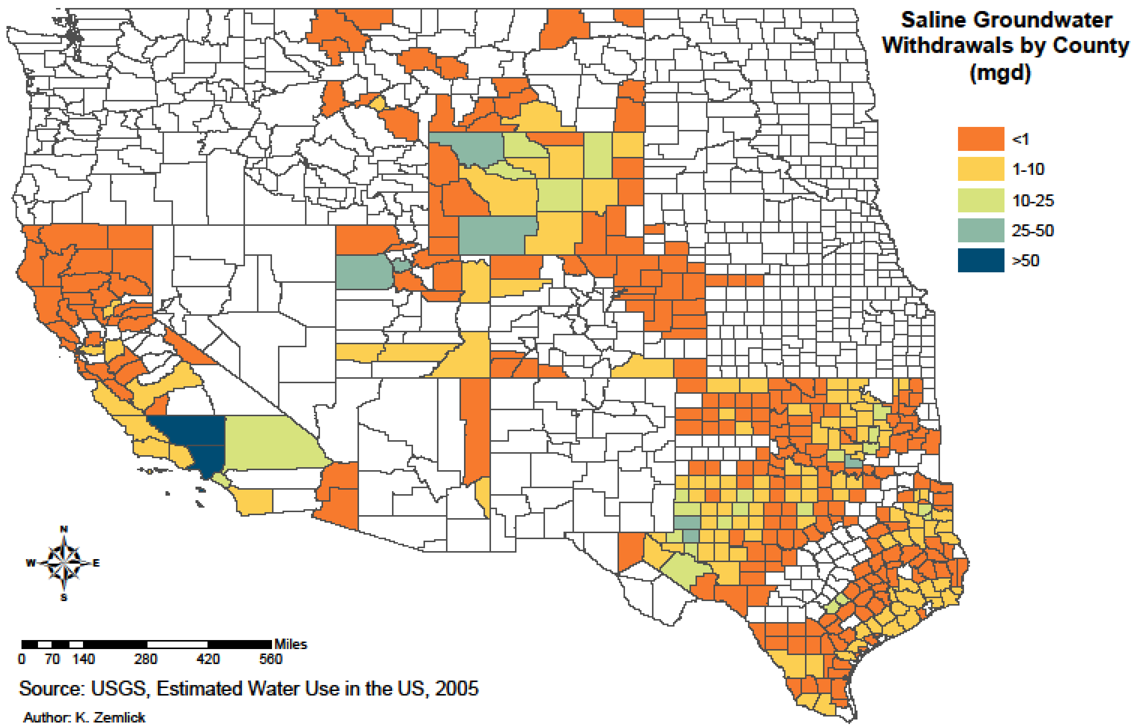


More recently, the National Energy Technology Laboratory (NETL) National Carbon Sequestration Database (NATCARB) has identified deep brackish aquifers as potential storage sites for sequestered carbon and, in addition, has considered the possible reclamation of very brackish water displaced by carbon sequestration. However, many of these sites are characterized by very deep deposits (>2500 ft.) that are considered to be stable storage locations with high TDS concentrations (>15,000 TDS). Both qualities would make these supplies expensive to extract and to treat. , Sandia National Laboratories (SNL) is currently conducting research that will assess the use of brackish groundwater formations as potential storage locations for captured carbon dioxide and displaced water as a source for thermoelectric cooling (USDOE 2010). In anticipation of national legislation that will mandate emissions caps, this project will evaluate the feasibility of using displaced water (rather than disposing of it) in order to meet cooling requirements and to maintain stable pressure within the formation (USDOE 2010). Project completion is scheduled for Fall 2011.

2.2.1 Resource Availability

By far, the majority of brackish water withdrawn (93%) is used in thermoelectric applications (USGS 2005). However, this water typically comes from surface water sources and constitutes 28% of the 99% of surface water withdrawals annually (USGS 2005). Nine of the seventeen states in the study area withdraw brackish groundwater, amounting to 1,265 mgd. (USGS 2005) Figure 16 presents the distribution and volume of brackish groundwater withdrawn by county, as reported in USGS.

Figure 16: Brackish Groundwater Withdrawals by County, 2005



EPRI (2008) noted that New Mexico and Texas have, likely due to their tenuous supplies of freshwater, more exhaustively explored groundwater resources (EPRI 2008). They estimate that Texas overlies 2.7 billion acre feet of brackish groundwater and New Mexico more than 15 billion acre feet (EPRI 2008). Compared to present thermoelectric withdrawals of fresh water, these brackish supplies potentially constitute several hundred years worth of alternate supplies (EPRI 2008).

The USGS maintains a National Water Information System (NWIS) database that contains both historical and real-time data of ground and surface water levels and quality.

In lieu of a comprehensive national dataset, this site provides information on groundwater levels and quality on a state level and will be utilized to assess the presence, quantity, and quality of brackish groundwater in the southern and western states addressed in this report. For the purposes of this study, all wells with a TDS measurement greater than 1,000 mg/l but less than 10,000 mg/l was included in the database. Next, wells with depths in excess of 2500 ft. were discarded. Wells with high TDS and depths greater than 2500 ft. are included in the NATCARB database and hence not included in this database. Lastly, only the most current well measurements were included, leaving one entry per well number in the database. Approximately 22,500 wells with records meeting the study criteria were included in the database.

2.2.2 Cost

While wastewater treatment plant effluent may be widely distributed, available in consistent and appropriate volumes, and be of high quality, its use may be constrained by hydrologic, political and legal factors.(Watson et al. 2003; Alley 2003; Cooley et al. 2006) Brackish groundwater however, may be independent of these same limitations.(Watson et al. 2003) The *Desalting Handbook for Planners* (Watson et al. 2003) addresses desalting cost constraints for both seawater (TDS>30,000 mg/l) as well as lower TDS groundwater. It was the primary source for calculating the costs of extraction and treatment of brackish groundwater.

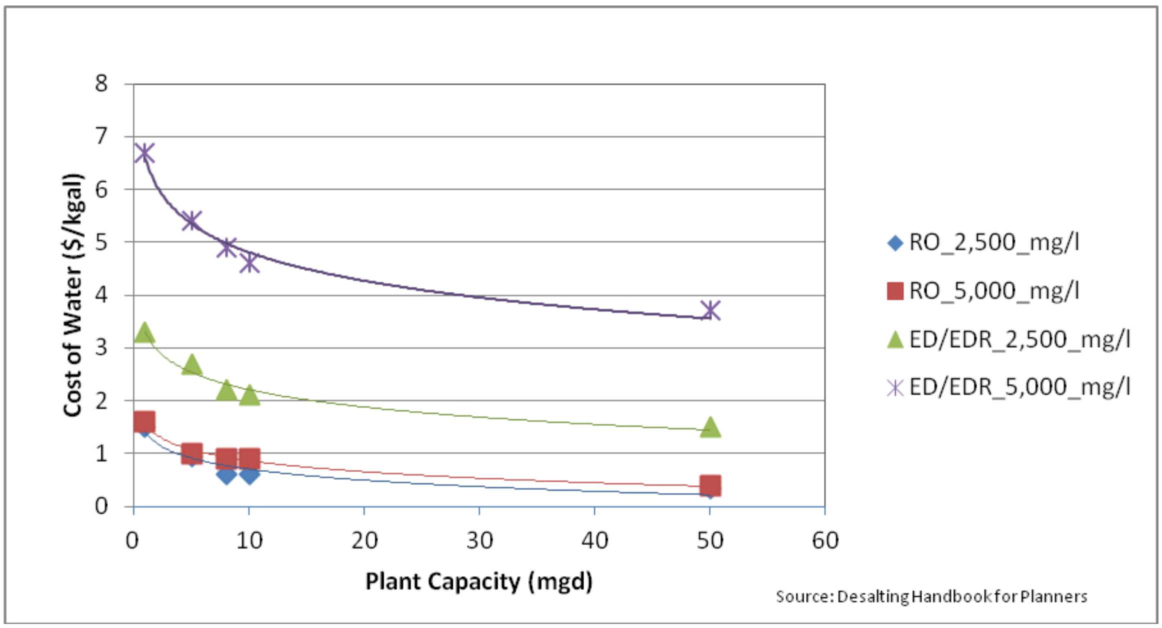
Desalination refers to treatment processes in which salts are removed from water. Desalination technologies are used throughout the world and consist of two different processes: thermal and membrane technologies.(Watson et al. 2003; Alley 2003) Thermal

processes use heat to evaporate then condense water, separating salts from pure water while membrane technologies use high pressures to pass demineralized water through semipermeable membranes leaving the salts behind in a concentrated solution for subsequent disposal.(Watson et al. 2003) Because thermal technologies require heating of the feed water, they are not considered to be cost-effective on water with less than 10,000 mg/L TDS and are typically employed in regions where sea water and fuel are plentiful.(Watson et al. 2003) Membrane processes include reverse osmosis (RO) which requires a large pressures for desalination, and electrodialysis reversal (EDR) which use electrical charges to separate ionic constituents (i.e. salts) from water. As of 1999, nearly seven billion gallons of water was desalinated per day, distributed evenly among thermal and membrane desalination technologies. (Watson et al. 2003)

Costs associated with desalination are expensive and include: capital costs of facilities, electricity, labor, membrane replacement, chemicals, and concentrate disposal. According to cost estimates for membrane technologies calculated by Watson et al. (2003), annual operation and maintenance costs amount to roughly 15% of overall capital cost, 56% of which is due to electrical power requirements, followed by the annual costs for chemicals and repairs (~15%), remaining costs include labor and insurance.(Watson et al. 2003, D-20) For the purposes of this study, RO and EDR were evaluated as economically viable desalination technologies and cost data was obtained from the *Desalting Book for Planners* (Watson et al. 2003) based on the quality of the feed water.(Figure 17) Because desalination facilities require large amounts of energy on a continuing basis, the location of these facilities in close proximity to power plants has

recently been recognized as a cost-effective and beneficial arrangement for both parties.(Watson et al. 2003). In Middle Eastern countries bordering the Arabian Gulf for example, distillation plants co-located with power plants to take advantage of waste heat from power generation to improve the overall efficiency of the desalination process. (Watson et al. 2003)

Figure 17: Desalting Costs Based on Capacity, Quality and Treatment Type



Extracting brackish water for treatment requires construction of wells into the brackish groundwater aquifer. Well completion costs depend on the depth and size of the well and were calculated using general economic data available in the *Desalting Handbook for Planners* (USDOE 2003). (Table 4) A comparison of these costs is shown

in Figure 18 and reveals that well depth has an inverse relationship with cost per foot and production capacity when capacity is less than 30 mgd. The point at which these three costs meet is at a capacity of approximately 27 mgd, where cost/foot/mgd is equal to $400. This measure was used to calculate the cost of well construction at the wells inventoried in the study area.

Table 4: Well Completion Costs as a Function of Well Depth and Capacity

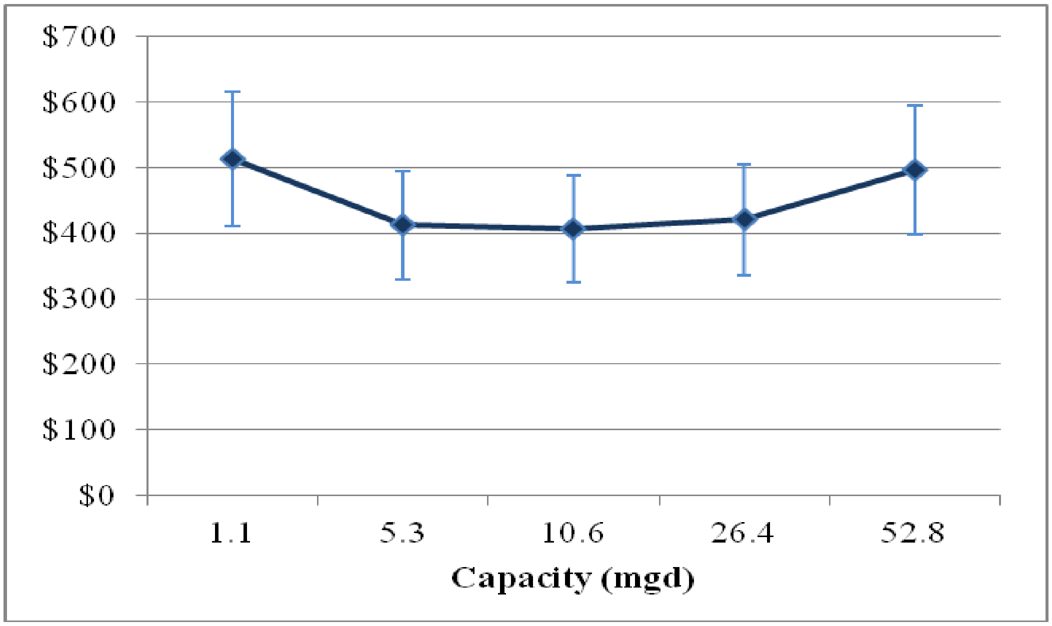
m^3	gallons	mgal	400 ft.	400 ft. ($)	600 ft.	600 ft. ($)	800 ft.	800 ft. ($)
4,000.0	1,056,688.0	1.1	0.3	$250,000	0.3	$300,000	0.4	$400,000
20,000.0	5,283,440.0	5.3	0.9	$900,000	1.3	$1,300,000	1.7	$1,700,000
40,000.0	10,566,880.0	10.6	2.0	$2,000,000	2.5	$2,500,000	3.0	$3,000,000
100,000.0	26,417,200.0	26.4	5.0	$5,000,000	6.5	$6,500,000	8.0	$8,000,000
200,000.0	52,834,400.0	52.8	13.0	$13,000,000	15.0	$15,000,000	17.0	$17,000,000

Depth	mgal	400 ft. ($)	$/ft. depth/mgd	
400	1.1	$250,000	$591	
400	5.3	$900,000	$426	AVERAGE
400	10.6	$2,000,000	$473	$516
400	26.4	$5,000,000	$473	
400	52.8	$13,000,000	$615	

Depth	mgal	600 ft. ($)	$/ft. depth/mgd	
600	1.1	$300,000	$473	
600	5.3	$1,300,000	$410	AVERAGE
600	10.6	$2,500,000	$394	$432
600	26.4	$6,500,000	$410	
600	52.8	$15,000,000	$473	

Depth	mgal	800 ft. ($)	$/ft. depth/mgd	
800	1.1	$400,000	$473	
800	5.3	$1,700,000	$402	AVERAGE
800	10.6	$3,000,000	$355	$402
800	26.4	$8,000,000	$379	
800	52.8	$17,000,000	$402	

Figure 18: Well Completion Costs (USDOE 2003). Cost curve based on average depth completion costs with 20% error bars.



Pumping costs were calculated using the following Equation where ρ = density [M/L^3], g = gravity [L/T^2], Q = flow [L^3/T], d = dynamic head [L], PE= Pump Efficiency (70%), and Power= Watts [$M*L^2/T^3$].

Equation 2: Energy Required for the Extraction of Brackish Groundwater

$$\text{Power (watts)} = \frac{\rho g Q}{PE * 1.356}$$

Table 5: Brackish Groundwater Treatment Cost as a Function of Capacity, Quality and Treatment Type

Plant Capacity (mgd)	RO 2,500 mg/l	RO 5,000 mg/l	ED/EDR 2,500 mg/l	ED/EDR 5,000 mg/l
1	$1.50	$1.60	$3.30	$6.70
5	$0.95	$1.00	$2.70	$5.40
8	$0.60	$0.90	$2.2	$4.90
10	$0.60	$0.90	$2.1	$4.60
50	$0.35	$0.40	$1.5	$3.70

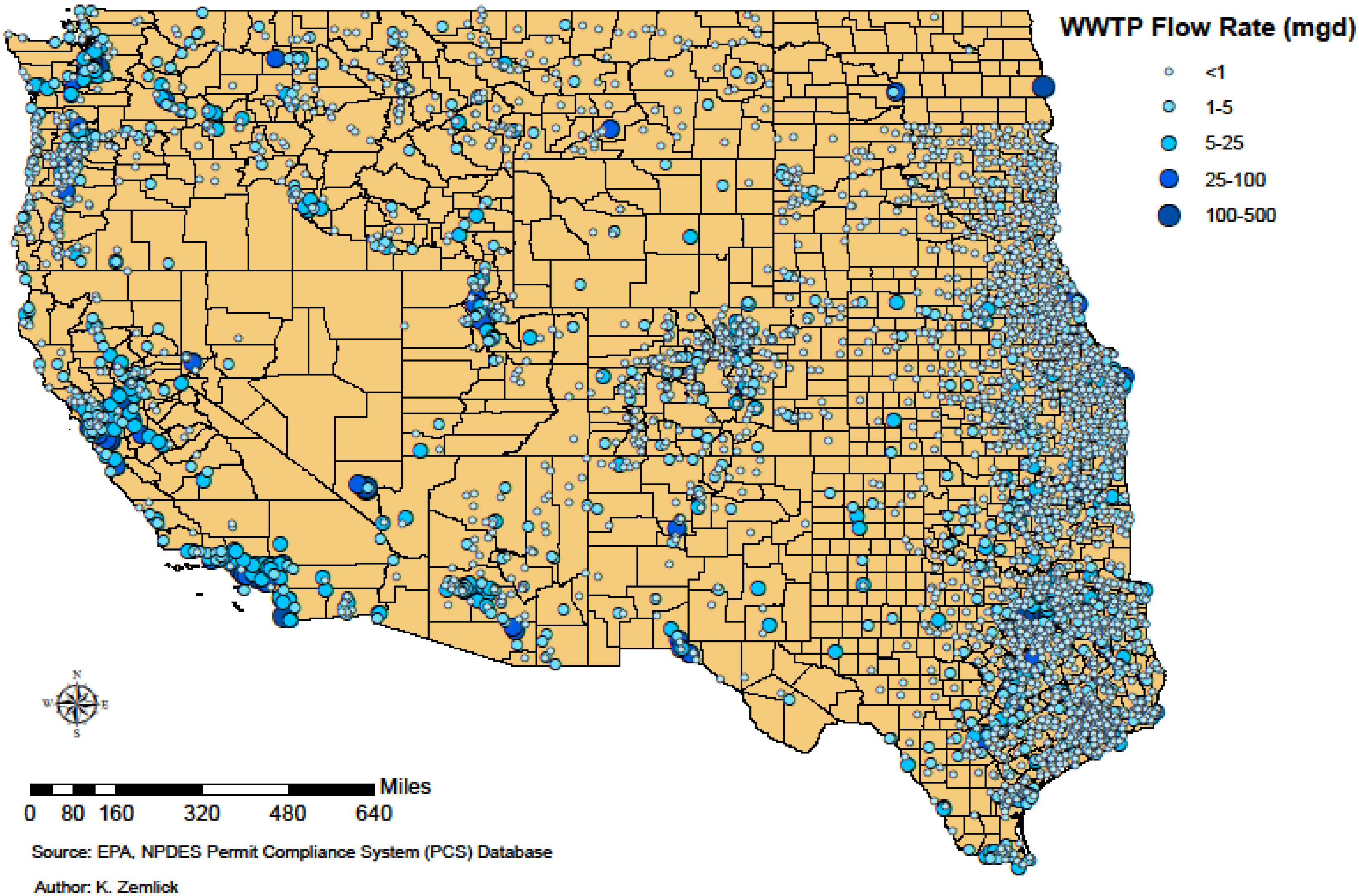
3.0 Results

3.1 Municipal Wastewater

3.1.1 Resource Availability

Nearly four thousand wastewater treatment plants with daily flow data were identified using the EPA PCS database, shown in Figure 19. All plants are rated under the Standard Industrial Classification (SIC) as 'Sewerage' facilities, code 4952 and are represented by blue circles. The occurrence is an important factor in determining availability of wastewater effluent as a potential source of cooling water for future thermoelectric plants as both volume and quality of effluent are important factors in assessing the suitability of the source. In addition to the geographic location of wastewater treatment plants, Figure 19 represents the relative size of existing plants based on flow as reported in the EPA PCS database. It is apparent that plant flows are dominated by smaller plants discharging less than 5 mgd, with larger capacity plants located near large communities. Table 6 summarizes total wastewater treatment effluent by state and a detailed summary of effluent by county is summarized in Appendix 1.

Figure 19: Wastewater Treatment Plants by Capacity in the Study Area

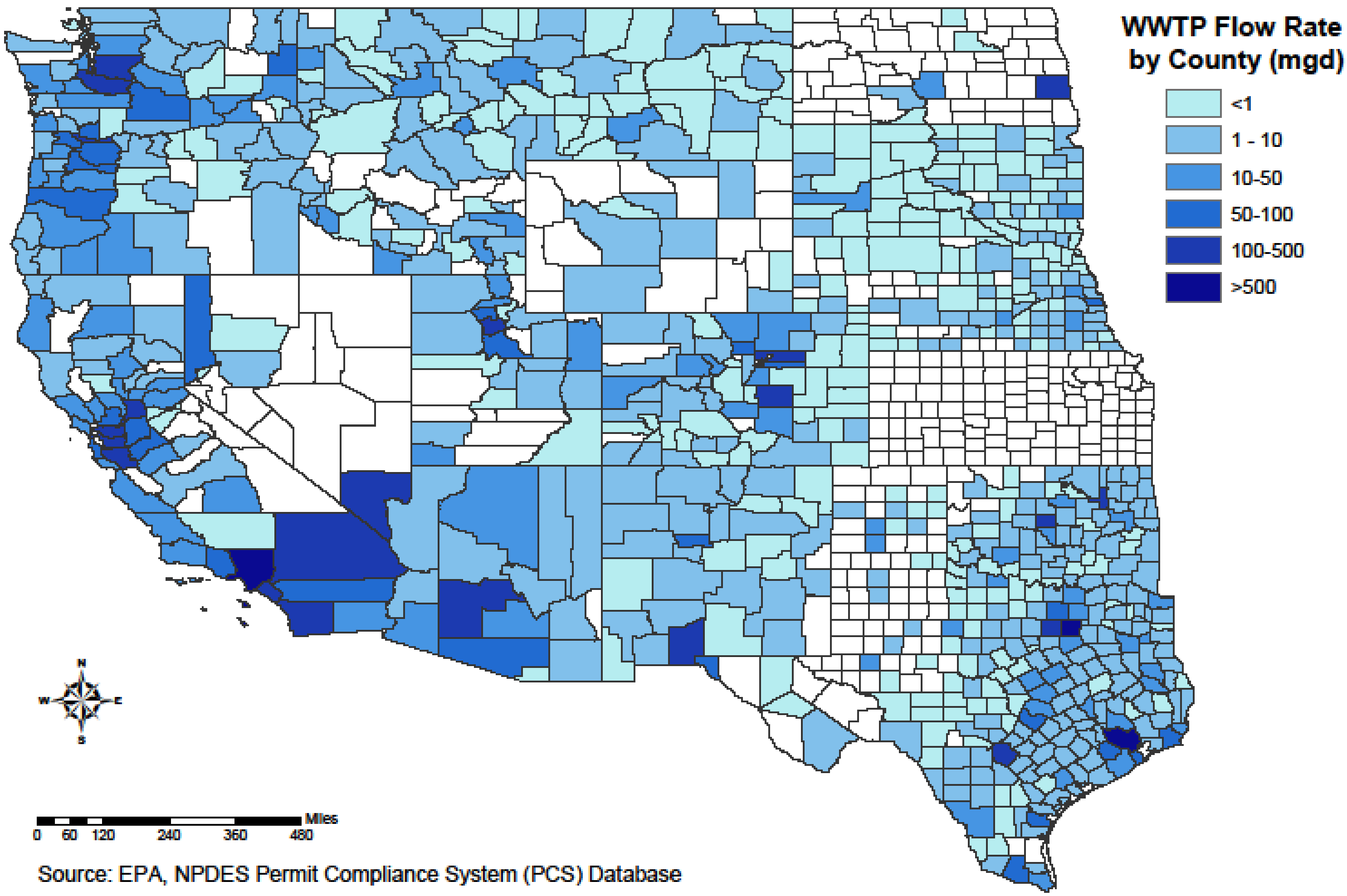


Although wastewater is discharged in every state in the study area, a high degree of variability exists on a county level. This variability is represented in Figure 20. However, if wastewater is to be used for cooling processes, low (300 gal/kWh) and high (600 gal/kWh) (EPRI 2008) withdrawal-conservative closed-loop cooling facilities have the potential supplement the projected increase in demand of 1162 billion kWh by 2035. These figures do not take into account an increase in wastewater discharge due to population growth in larger metropolitan areas. In addition, it is assumed that areas of low development will continue to employ septic and gray-water systems which do not result in a wastewater discharge.

Table 1: Wastewater Treatment Plant Effluent By State

State	Number of Plants	Total Flow (mgd)	State	Number of Plants	Total Flow (mgd)
AZ	109	571	NV	12	328
CA	233	4038	OK	252	457
CO	315	785	OR	180	549
ID	62	169	SD	277	130
KS	398	377	TX	1306	3171
MT	175	165	UT	68	420
ND	11	187	WA	116	991
NE	261	247	WY	13	37
NM	61	235	Total	3849	12857

Figure 20: Wastewater Effluent by County



Source: EPA, NPDES Permit Compliance System (PCS) Database

Author: K. Zemlick

Figure 21: Potential New Generating Capacity Based on Plant Type and Cooling Water Requirements (EPRI 2008)

	Cooling Type	Once-Through	Once-Through	Closed - Loop	Closed - Loop
	Withdrawal Level	Low	High	Low	High
gal/kWh		20,000	50,000	300	600
State	Total WWTP Flow (mgd)	Amount of Electricity Produced in Billions of Kilowatt-hours			
AZ	571.50	1.43	0.57	95.25	47.62
CA	4,037.57	10.09	4.04	672.93	336.46
CO	785.19	1.96	0.79	130.86	65.43
ID	169.02	0.42	0.17	28.17	14.08
KS	377.27	0.94	0.38	62.88	31.44
MT	164.99	0.41	0.16	27.50	13.75
ND	186.95	0.47	0.19	31.16	15.58
NE	247.23	0.62	0.25	41.20	20.60
NM	234.91	0.59	0.23	39.15	19.58
NV	328.08	0.82	0.33	54.68	27.34
OK	456.68	1.14	0.46	76.11	38.06
OR	548.88	1.37	0.55	91.48	45.74
SD	129.50	0.32	0.13	21.58	10.79
TX	3,170.34	7.93	3.17	528.39	264.20
UT	420.43	1.05	0.42	70.07	35.04
WA	991.29	2.48	0.99	165.22	82.61
WY	37.08	0.09	0.04	6.18	3.09
Total	**12,857**	**32**	**13**	**2,143**	**1,071**

3.1.2 Site Suitability

Land availability near a cooling water source is a significant variable and worthy of both spatial and economic consideration in the determination of whether a wastewater treatment plant could be considered a reasonable future source for thermoelectric cooling processes.

Figure 22, Figure 23, and Figure 24 display the results of this analysis and show that as relative plant footprint size decreases, more undeveloped land within the wastewater treatment plants becomes available for new power plant construction. Aggregate availability by state and fuel type can be seen in Figure 25.

Pipe construction costs depend upon the distance between the wastewater treatment plant and receiving thermoelectric power plant. Given that the five-mile buffer analysis determined the number of undeveloped land parcels for generic coal, natural gas/oil, and combined cycle plants (259 ha, 127 ha, 65 ha respectively) it was important to determine what relationship these available parcels may have on potential pipeline construction costs.

It was assumed that wastewater treatment plants near undeveloped land would likely have widely distributed potential locations for new power plants. For this reason, all footprint sizes were averaged in order to produce a single footprint value for each wastewater treatment plant, assuming that many available footprints would allow for the siting of a future power plant of intermediate size. It was also assumed that numerous potential sites would enable planners to site a new power plant at a closer distance to an existing wastewater treatment plant, thus requiring a reduced piping distance and lower construction and conveyance costs. The overarching assumption is that within the range of footprints available, it is more likely that a treatment plant with many footprints would require less piping distance, and consequently more economical, than a plant with very few footprints available.

The numbers of locations around individual wastewater treatments were ranked in percentiles with 20% increments in order to reflect intervals of whole miles within the five mile radius that might be suitable for a power plant. Treatment plants with very few suitable locations within their buffer were grouped into the lowest bin and assigned the highest mileage value of 5, while those plants with the greatest number of possible locations were assigned to the highest bin with a value of 1. The bin values are representative of the mileage value used to calculate pipeline costs for a new plant. The rank distribution of undeveloped footprints are displayed in Figure 26 the average number of footprints for all plant sizes determines the likelihood of approximate siting distance for a new plant (large number of plants correlates with closer distance and small number of plants correlates with farther distance). The figure reveals that approximately 37% of existing wastewater treatment plants likely has undeveloped possible locations within a distance of 1 mile. (Figure 26)

Figure 22: Number of Undeveloped Footprints around Existing Wastewater Treatment Plants by County for New Coal Steam Plants

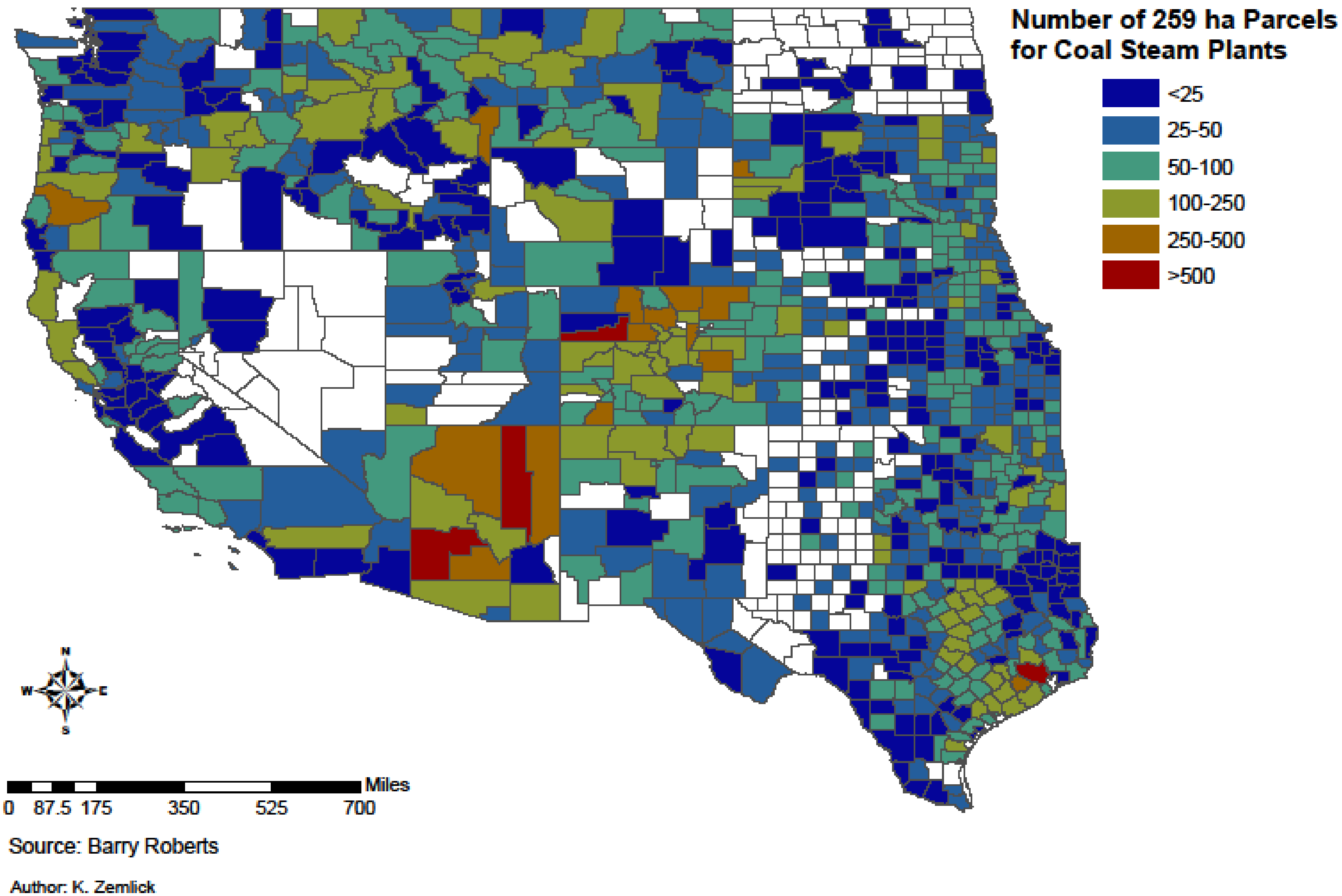


Figure 23: Number of Undeveloped Footprints around Existing Wastewater Treatment Plants By County for New Oil/Natural Gas Plants

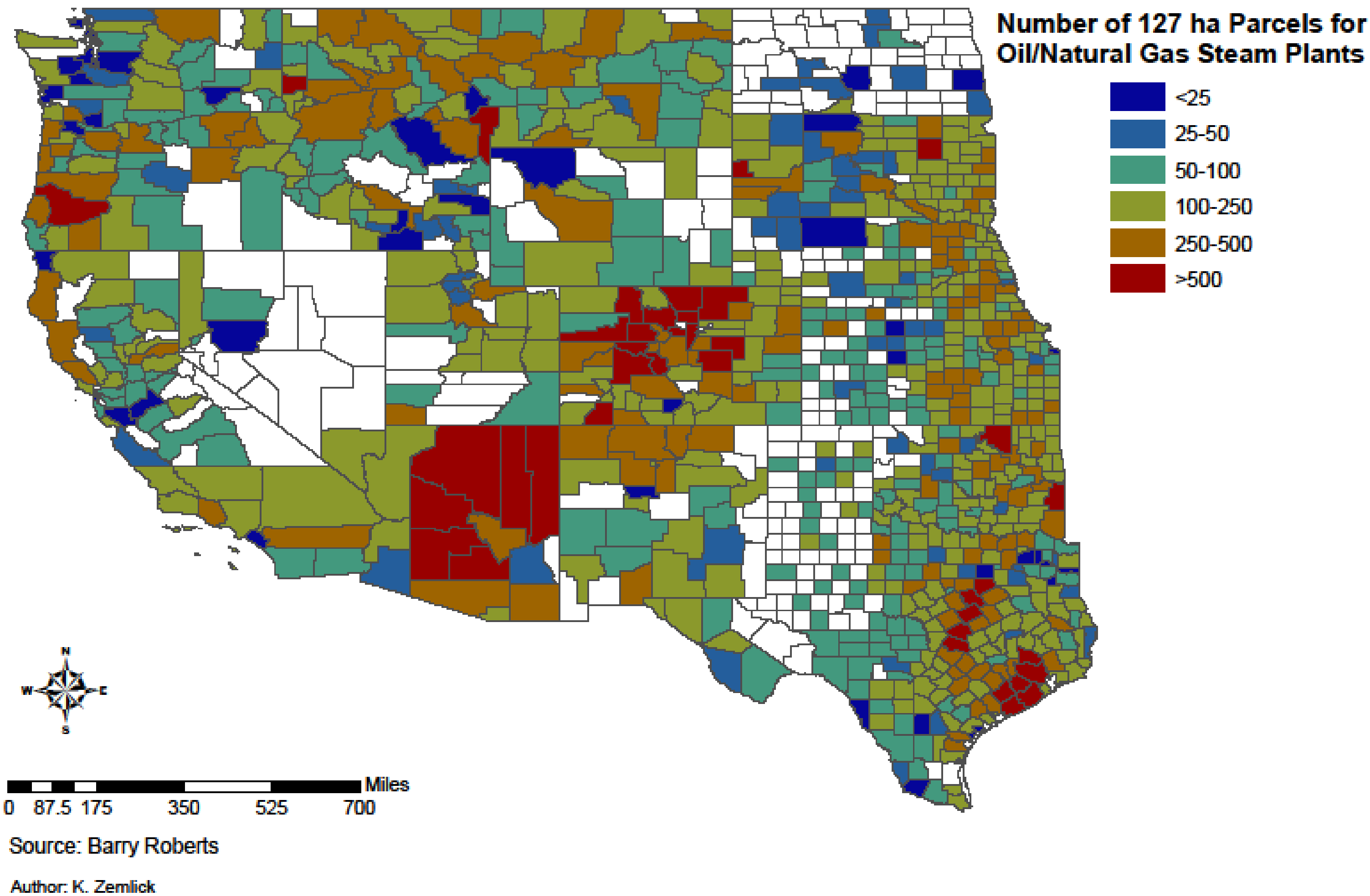


Figure 24: Number of Undeveloped Footprints around Existing Wastewater Treatment Plants for New Combined Cycle Plants

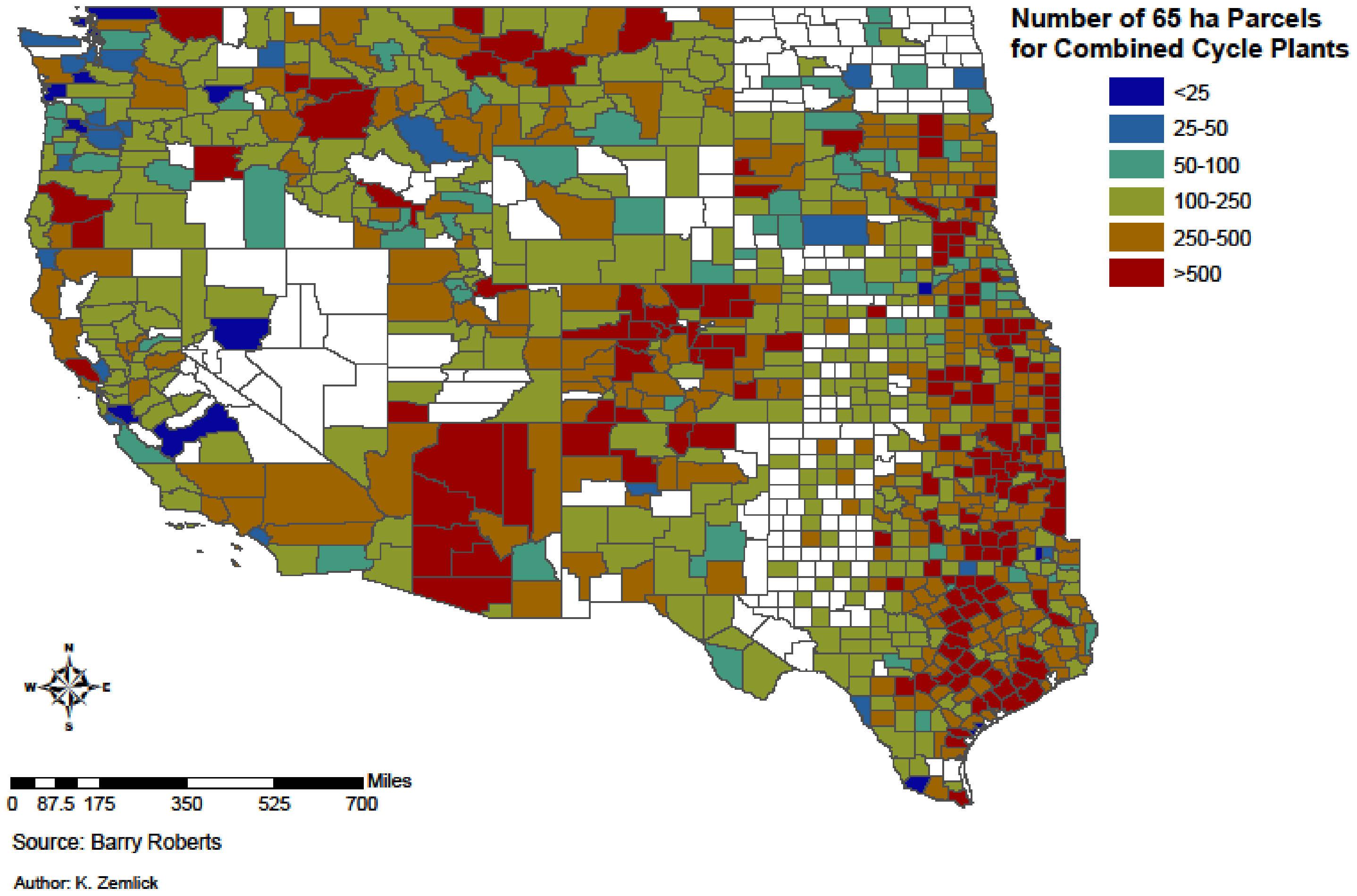


Figure 25: Number of Undeveloped Land Footprints by State and Power Plant Type

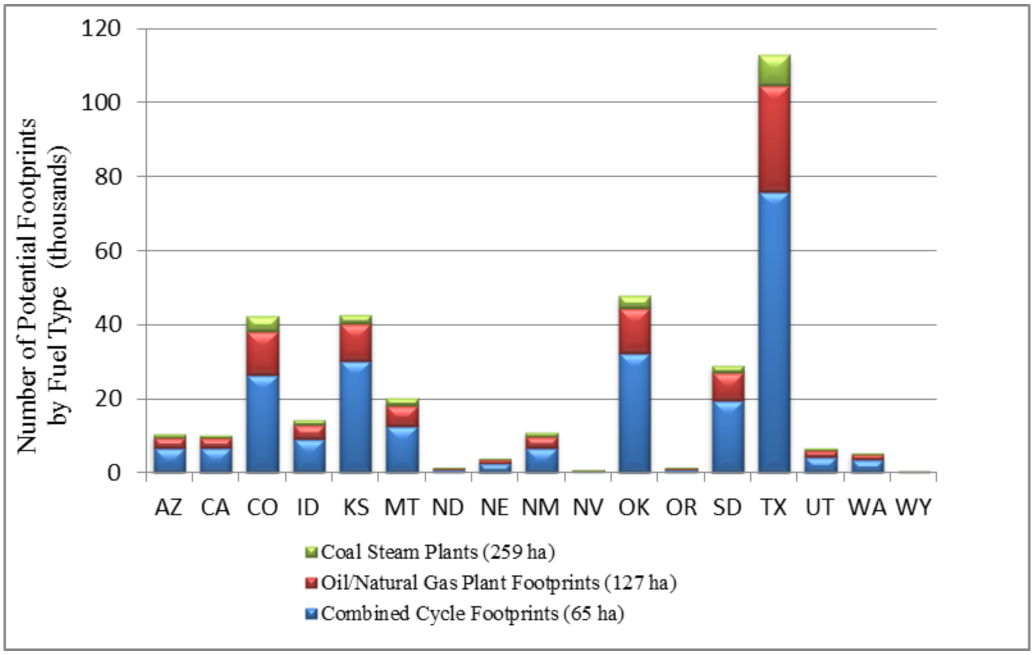
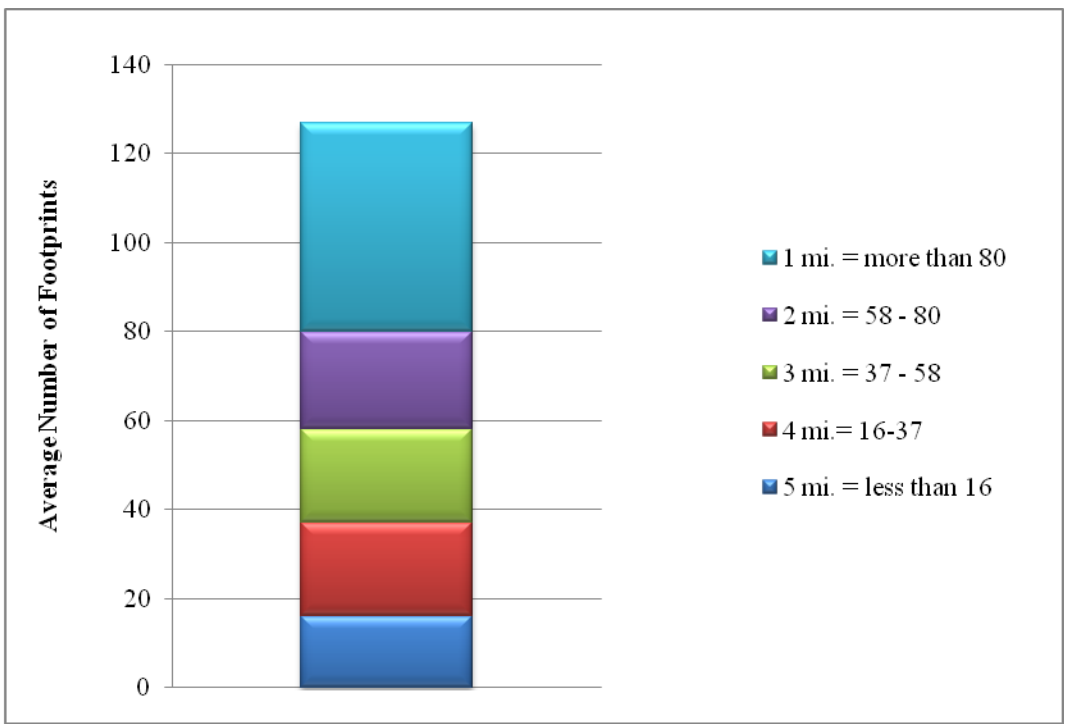


Figure 26: Footprint Rank Distribution for Pipeline Mileage



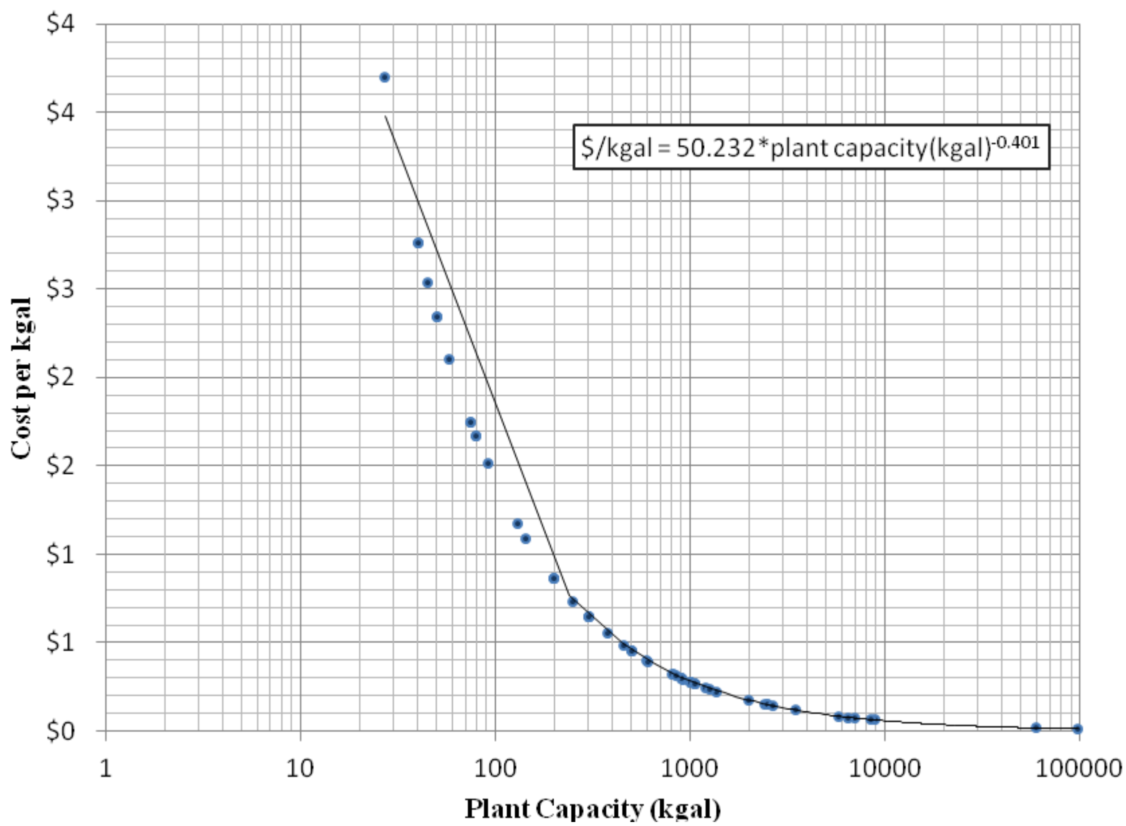
3.1.3 Cost

The costs associated with the treatment and transportation of effluent from existing wastewater treatment facilities to a new thermoelectric plant are represented in Figure 27. Initial capital costs for pump station and piping have a positive relationship with plant capacity, but this initial expense is offset by the inverse relationship between plant capacity and treatment cost. This correlation is represented by the following equation, derived from the data table in Figure 27.

Equation 3: Cost per thousand gallons (kgal) of treated wastewater

$$\frac{\text{Cost}(\$)}{\text{kgal}} = 50.232 * PC^{-0.401}$$

Figure 27: Total Cost of Treated Wastewater as a Function of Plant Capacity



3.2 Brackish Groundwater

3.2.1 Resource Availability

The distribution, depth and quality of brackish groundwater in the western United States were generalized by Feth et. al 1965, but a more detailed analysis of these factors was analyzed using USGS well logs, available in the National Water Information System (NWIS) database. Figure 28 represents the presence of USGS wells with brackish (1,000 mg/l<TDS>10,000 mg/l) measurements, obtained from the NWIS online database. In addition, number of brackish wells (Figure 29), quality of well water (Figure 30), and average well depth (Figure 31) vary greatly on both state and county levels. While water quality is not generally highly variable over short time periods, wells referenced in the NWIS database include measurements from the entire period of record, which extends back nearly 100 years. The decision to use salinity data from the most recent measurement was based upon the LBG-Guyton 2003 assessment of brackish water in Texas for the Texas Water Development Board. Based upon the data presented in these figures, brackish groundwater is present in every state in the study region, although its distribution varies. 138 counties in the study area reported saline groundwater use but did not have brackish well logs in the NWIS database. It was assumed that well characteristics for surrounding counties were comparable; depth and quality data from these counties was extended to counties with no well data but reported brackish water use.

Figure 28: Locations of Brackish Wells in the NWIS database

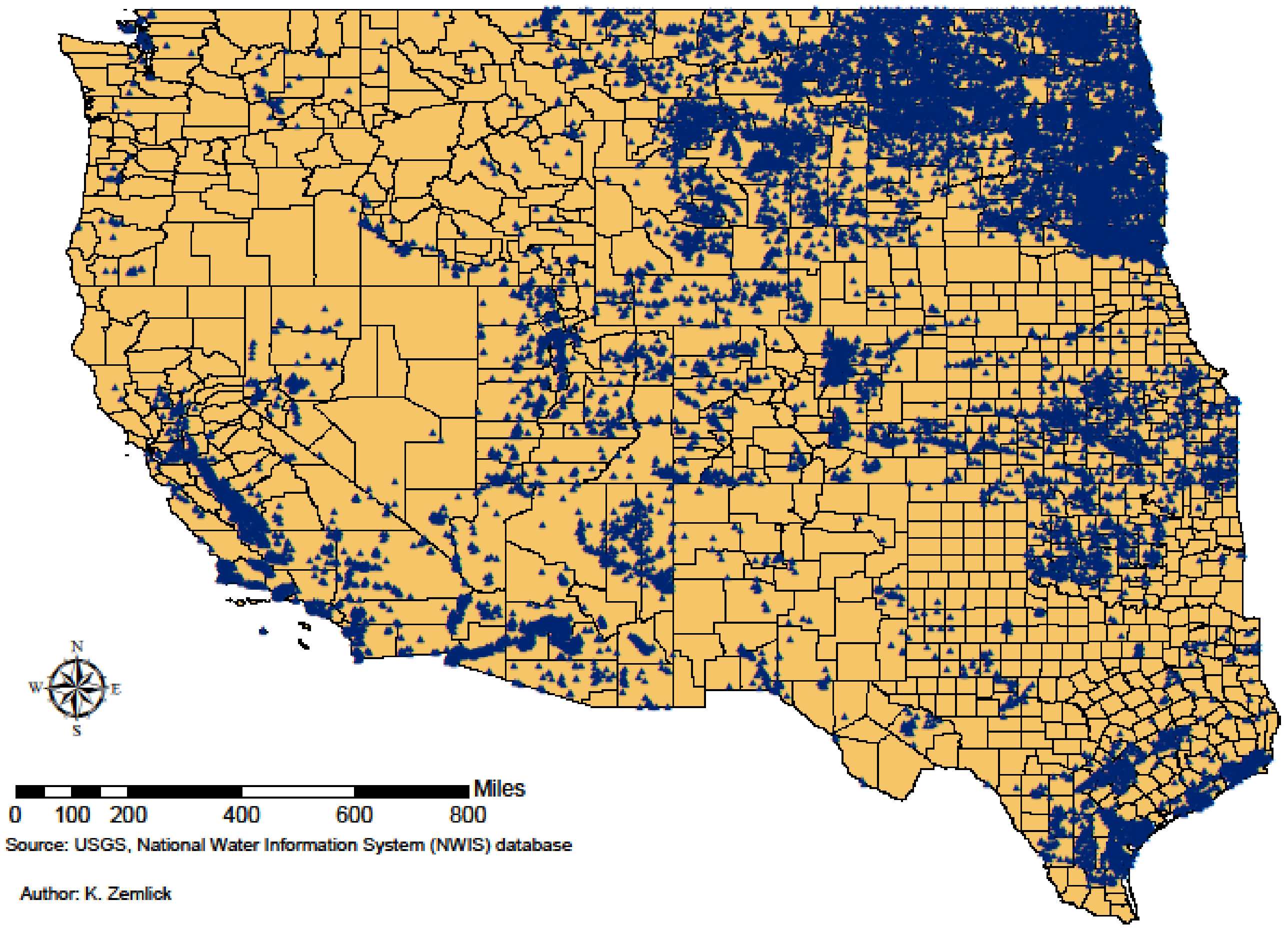


Figure 29: Number of Brackish Wells by County from the NWIS database

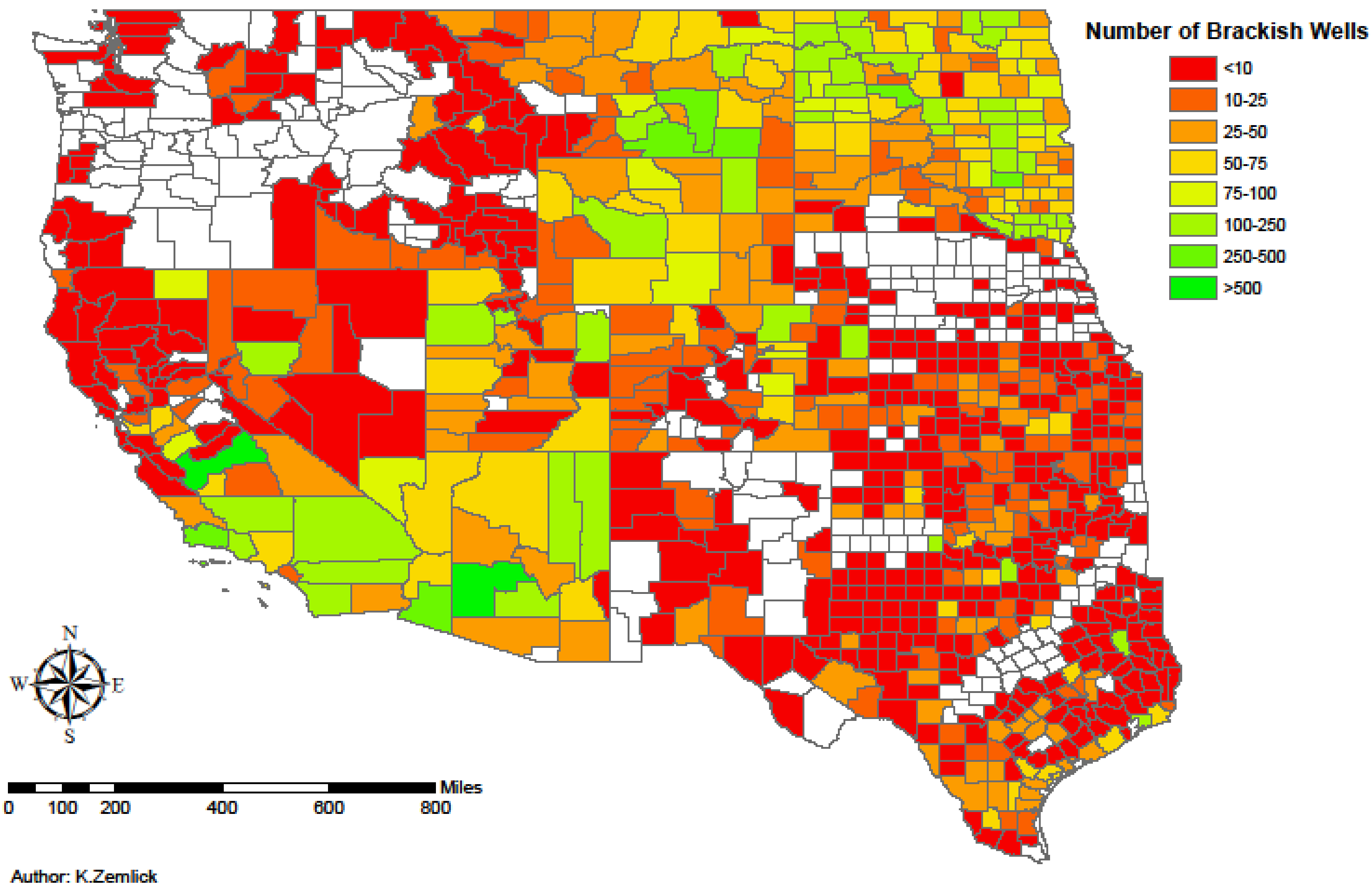


Figure 30: Average TDS of NWIS Brackish Wells by County

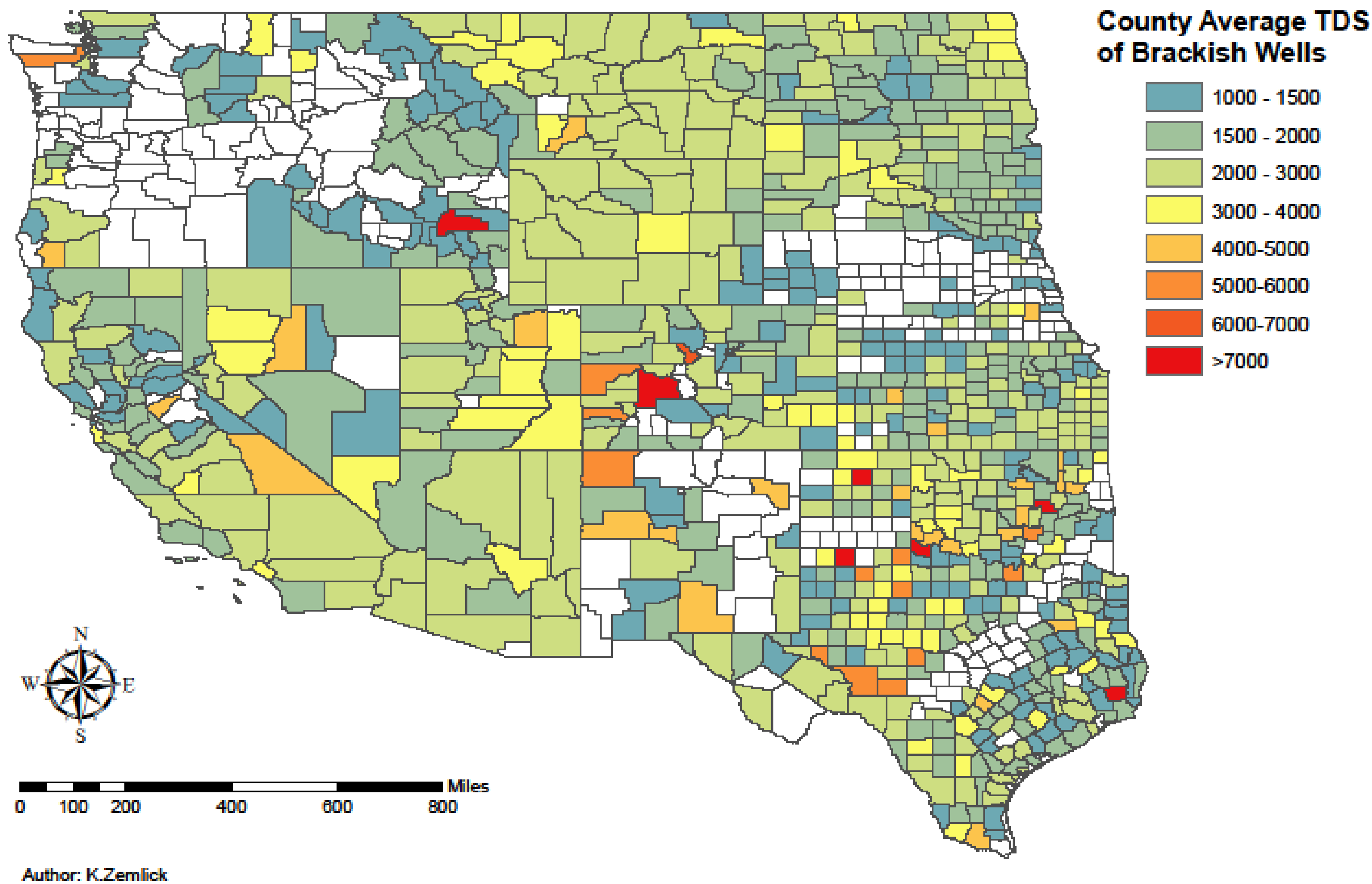
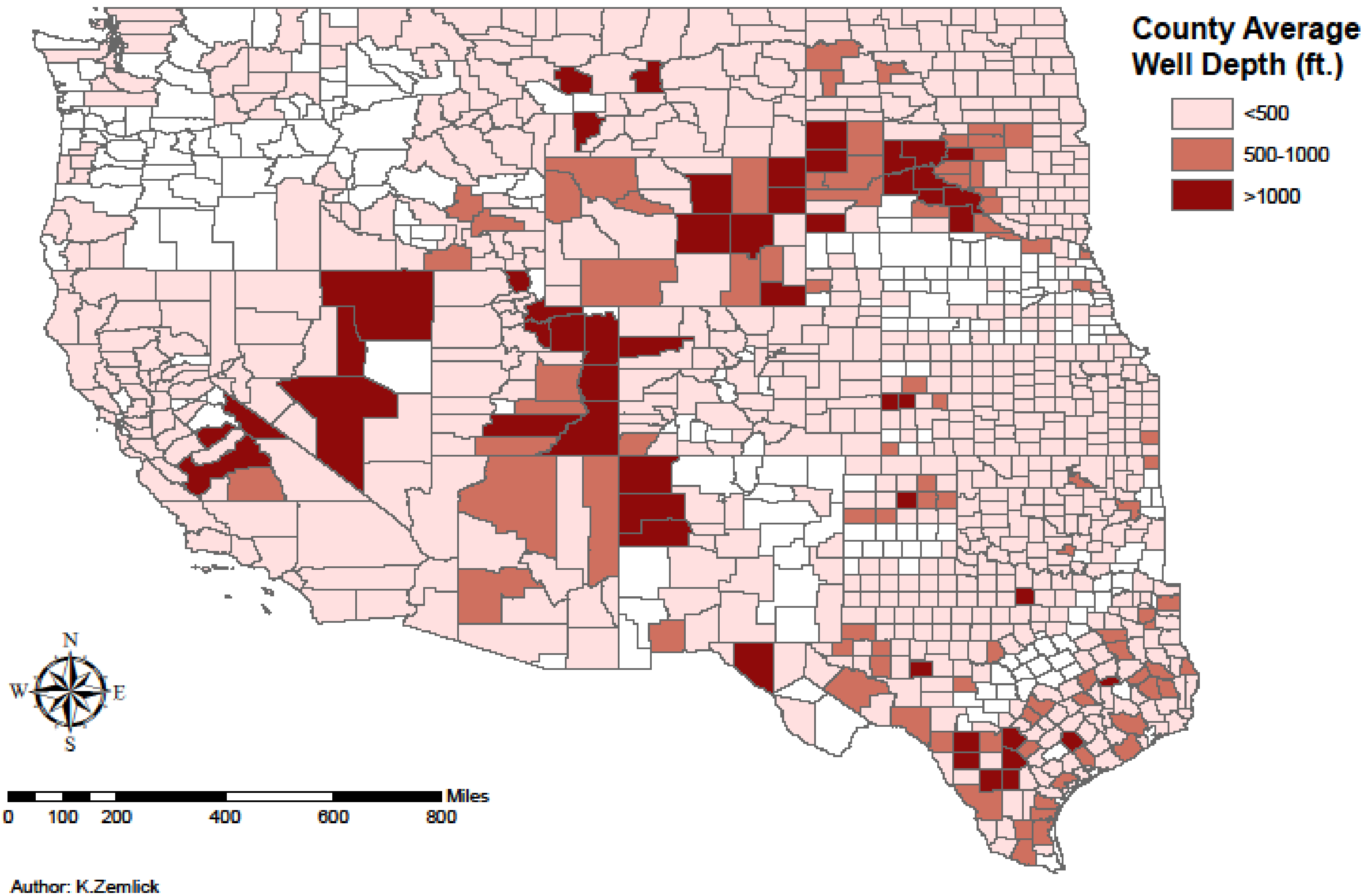


Figure 31: Average Depth of NWIS Brackish Wells by County



The quantity of brackish groundwater present in the study region is integral to determining suitability of the resource for use in thermoelectric cooling applications. Texas is the only state that has conducted an inventory of its brackish groundwater resources. (LBG-Guyton 2003) Figure 32 represents the distribution of brackish groundwater by aquifer and volume and Figure 33 represents brackish groundwater availability by water management region. The LBG-Guyton Associates report further characterized brackish groundwater presence by salinity, creating two classes of brackish groundwater: 1,000-3,000 TDS and 3,000-10,000 TDS.

In an effort to uncover significant relationships between USGS well characteristics and brackish groundwater volume, the data from the LBG-Guyton Associates (2008) study were compared to the NWIS database. Because the USGS well data was generalized by county, in the Texas data was further separated using county area to determine volume. (Appendix 1) Figure 34 compares the predicted volume calculated in the multi-variate regression to the actual volume reported in LBG-Guyton Associates (2003). These results indicate that the variability of the volume of brackish groundwater present as reported in LBG-Guyton Associates 2003 cannot be explained or predicted based upon the variability of dependent variables defined by well data.

Only counties that had NWIS well data were included in this evaluation. Well statistics for USGS wells were calculated. This summary is available in Appendix 3: USGS Brackish Well Statistics by County, Texas. In order to establish whether well characteristics, brackish groundwater withdrawals, population, or area had any significant relationship with volume of brackish groundwater in Texas, a statistical correlation analysis was processed. This data (Table 7) shows no significant relationship between

volume of groundwater availably by county and USGS well statistics, although the correlation between volume and both 'Number of Wells' and 'Maximum Depth' is roughly 50%.(Table 7) In addition, a multi-variate analysis was conducted, utilizing the same data set. This confirmed the results of the correlation analysis, producing an adjusted R-Square value of 0.395. (Figure 34) Because the p-value for 'Maximum Depth' was less than 0.05, this value was regressed with volume of groundwater values, which produced an R-Square value of 0.269. These results indicate that perhaps the greatest uncertainty in this analysis is the quantification of brackish groundwater available. None of the NWIS well characteristic variables can predict with certainty a reliable estimate of brackish groundwater present.

Table 7: Correlation of Brackish Groundwater Volume and USGS Well Variables

	Thousands of acre-feet per square mile	#Wells	Minimum Depth	Maximum Depth	Average Depth	STDEV Depth	Minimum TDS	Maximum TDS	Average TDS	STDEV TDS	Total Brackish Withdrawals	County Population
Thousands of acre-feet per square mile	1.000											
#Wells	0.499	1.000										
Minimum Depth	-0.068	-0.323	1.000									
Maximum Depth	0.526	0.482	0.029	1.000								
Average Depth	0.325	0.179	0.487	0.778	1.000							
STDEV Depth	0.391	0.358	-0.108	0.924	0.738	1.000						
Minimum TDS	-0.262	-0.232	0.219	-0.232	-0.116	-0.262	1.000					
Maximum TDS	0.314	0.455	-0.295	0.417	0.162	0.365	0.084	1.000				
Average TDS	-0.059	-0.015	0.017	0.060	0.055	0.045	0.694	0.675	1.000			
STDEV TDS	0.164	0.220	-0.270	0.285	0.123	0.312	-0.174	0.846	0.558	1.000		
Total Brackish Withdrawals	-0.119	0.073	-0.160	-0.105	-0.175	-0.099	-0.115	0.110	-0.017	0.130	1.000	
County Population	-0.025	0.024	-0.004	0.255	0.291	0.321	-0.078	0.197	0.100	0.228	-0.025	1.000

Table 8: Results from Multi-Variate Regression Analysis

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.677
R Square	0.459
Adjusted R Square	0.395
Standard Error	6.773
Observations	105.000

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	11.000	3616.394	328.763	7.167	0.000
Residual	93.000	4265.845	45.869		
Total	104.000	7882.239			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	10.480	1.942	5.396	0.000	6.623	14.336	6.623	14.336
#Wells	0.041	0.048	0.846	0.400	-0.055	0.136	-0.055	0.136
Min_Depth	-0.004	0.010	-0.371	0.711	-0.023	0.016	-0.023	0.016
Max_Depth	0.010	0.004	2.535	0.013	0.002	0.017	0.002	0.017
Avg_Depth	0.002	0.007	0.298	0.766	-0.012	0.017	-0.012	0.017
StdDev_Depth	-0.022	0.013	-1.672	0.098	-0.048	0.004	-0.048	0.004
Min_TDS	-0.005	0.003	-1.453	0.150	-0.011	0.002	-0.011	0.002
Max_TDS	0.001	0.001	1.795	0.076	0.000	0.003	0.000	0.003
Avg_TDS	0.002	0.003	0.593	0.555	-0.004	0.008	-0.004	0.008
StdDev_TDS	-0.005	0.003	-1.452	0.150	-0.011	0.002	-0.011	0.002
Total Brackish GW Withdrawals (MGD)	-0.251	0.143	-1.761	0.082	-0.535	0.032	-0.535	0.032
Population	0.000	0.000	-1.374	0.173	0.000	0.000	0.000	0.000

Figure 32: Distribution of Brackish Groundwater Aquifers in Texas (Kasalawad et. al 2004, modified from LBG-Guyton Associates 2003)

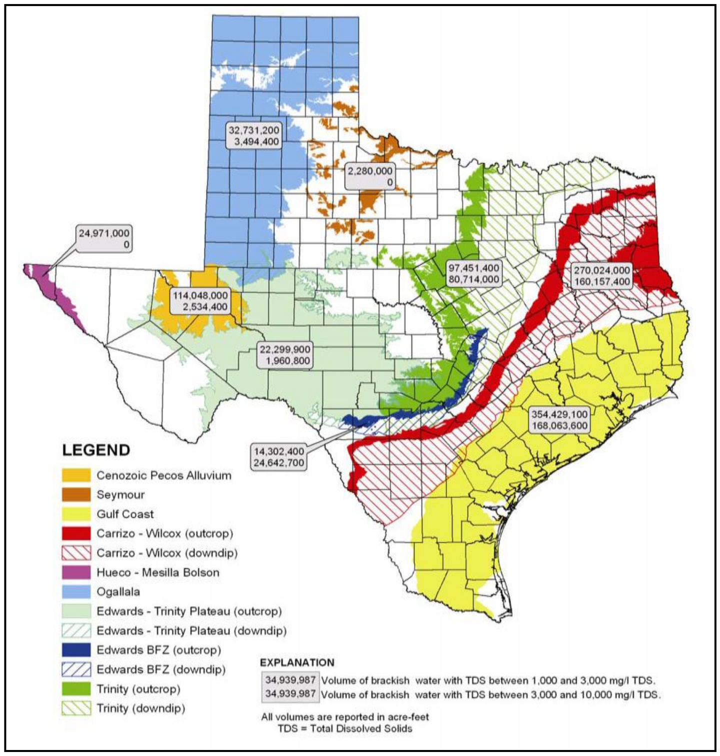


Figure 33: Distribution of Brackish Groundwater by Water Management Region in Texas (Kasalawad et. al 2004, modified from LBG-Guyton Associates 2003)

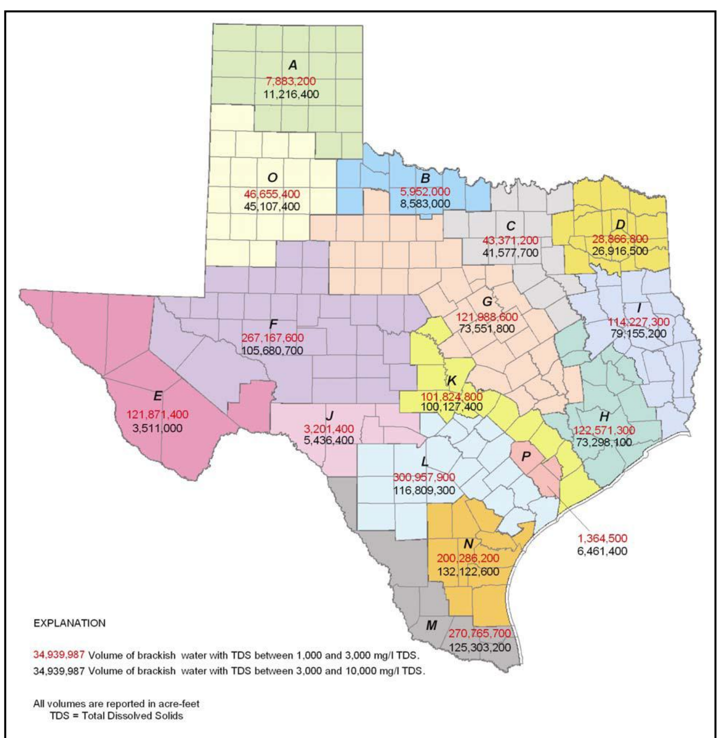
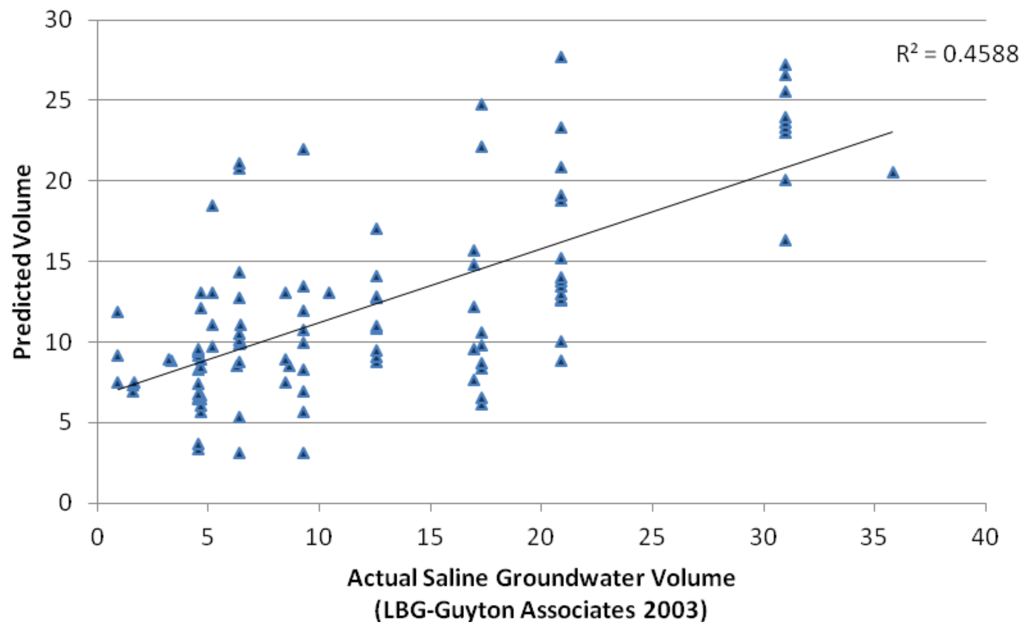


Figure 34: Actual vs. Predicted Brackish Groundwater Volume in Millions of Acre-Feet Based on Multi-variate Regression



However, because the goal of this analysis was to determine whether or not certain counties could be identified as being more likely than others to have brackish groundwater present, actual and predicted values were ranked: Low<5,000 AF; Medium 5,000 AF to 20,000 AF; High>20,000 AF. These rankings were then correlated, resulting in a value of 0.446.

With the data available, no general ranking of brackish groundwater availability can be conducted at this time. Figure 35 and Figure 36 represent the disparity in number of USGS well records as compared to state and municipal well records for Texas and Arizona respectively. Multiple hydrologic factors such as areal extent and thickness of the aquifer, storage coefficient, hydraulic conductivity, that may vary widely on spatial and temporal scales cannot be assessed using data currently available. Regional studies, similar to that completed by LBG-Guyton and Associates (2003) are needed in states where brackish groundwater is present but not as widely distributed as Texas, in order to

but not as widely distributed as Texas, in order to further evaluate a correlation between well records and volume of brackish groundwater present.

Figure 35: Comparison of TWDB Brackish Wells (Kasalawad et. al 2004, modified from LBG-Guyton Associates 2003)(left) and USGS Brackish Wells (right) in Texas

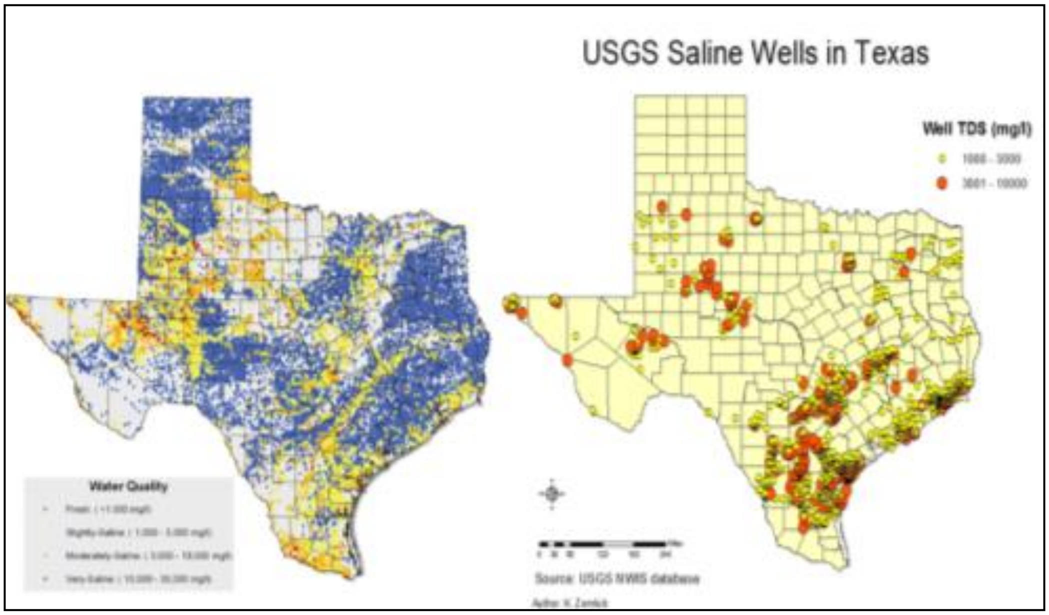
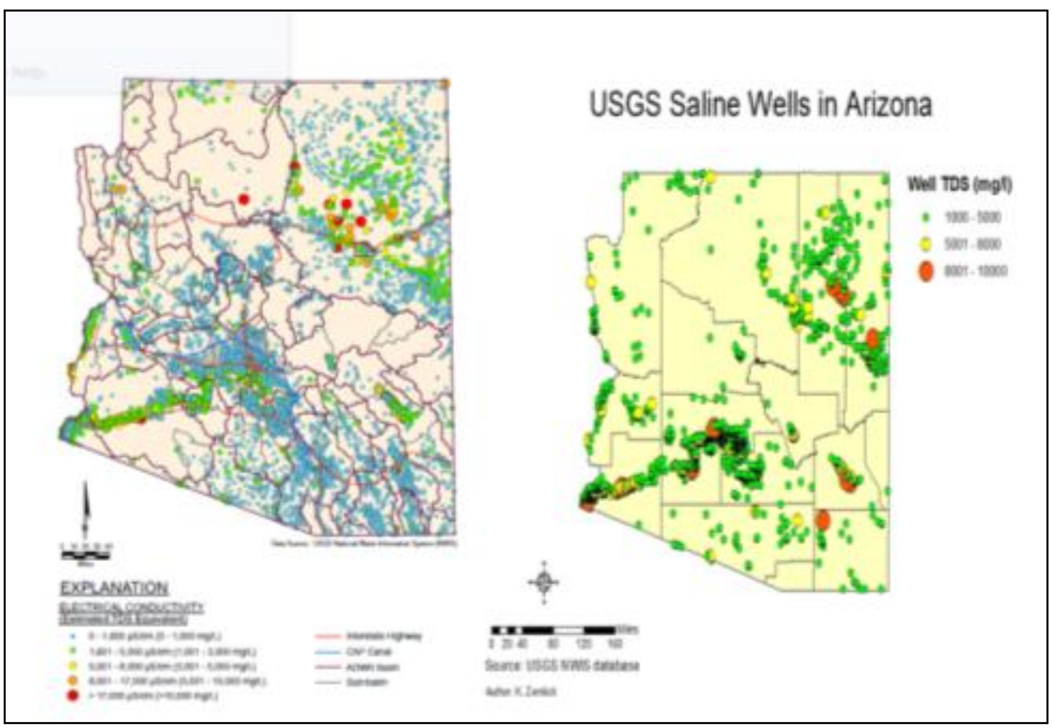


Figure 36: Comparison of Brackish Wells (EL Montgomery & Associates 2003) (left) and USGS Brackish Wells (right)



3.2.2 Cost

The cost to use brackish groundwater in thermoelectric cooling processes depends upon both depth of the brackish formation and quality of the water within it. Figure 37 represents the distribution of relative costs for well completion in the study area. Because volume of water available was not considered to be a limiting factor in using this resource, treatment costs were calculated based on extraction of 1 mgd. These results are displayed in Table 8, which gives the cost to treat one thousand gallons of brackish water.

Desalination cost figures obtained from the *Desalting Handbook for Planners* were applied to the data and included capital and operation and maintenance cost as well as disposal and equipment costs and therefore were not subject to amortization analysis as was done for wastewater. In addition, these values assume brackish groundwater quality and depth is evenly distributed and consistent at a county level. Unlike treated wastewater, these calculations presume that plant site selection is less dependent upon land development characteristics and that, given a brackish source, a plant could be located in close proximity to it and the wells that extract it. Also, it is assumed that the costs of brackish water treatment will be borne by the power plant alone rather than shared, as may be the case with a wastewater utility. Therefore, the significant cost that pipe construction distance imposed on wastewater treatment plants as sources for cooling water were not considered specifically in the cost of desalinated brackish water.

Figure 37: Well Completion Cost as a Function of Depth by County

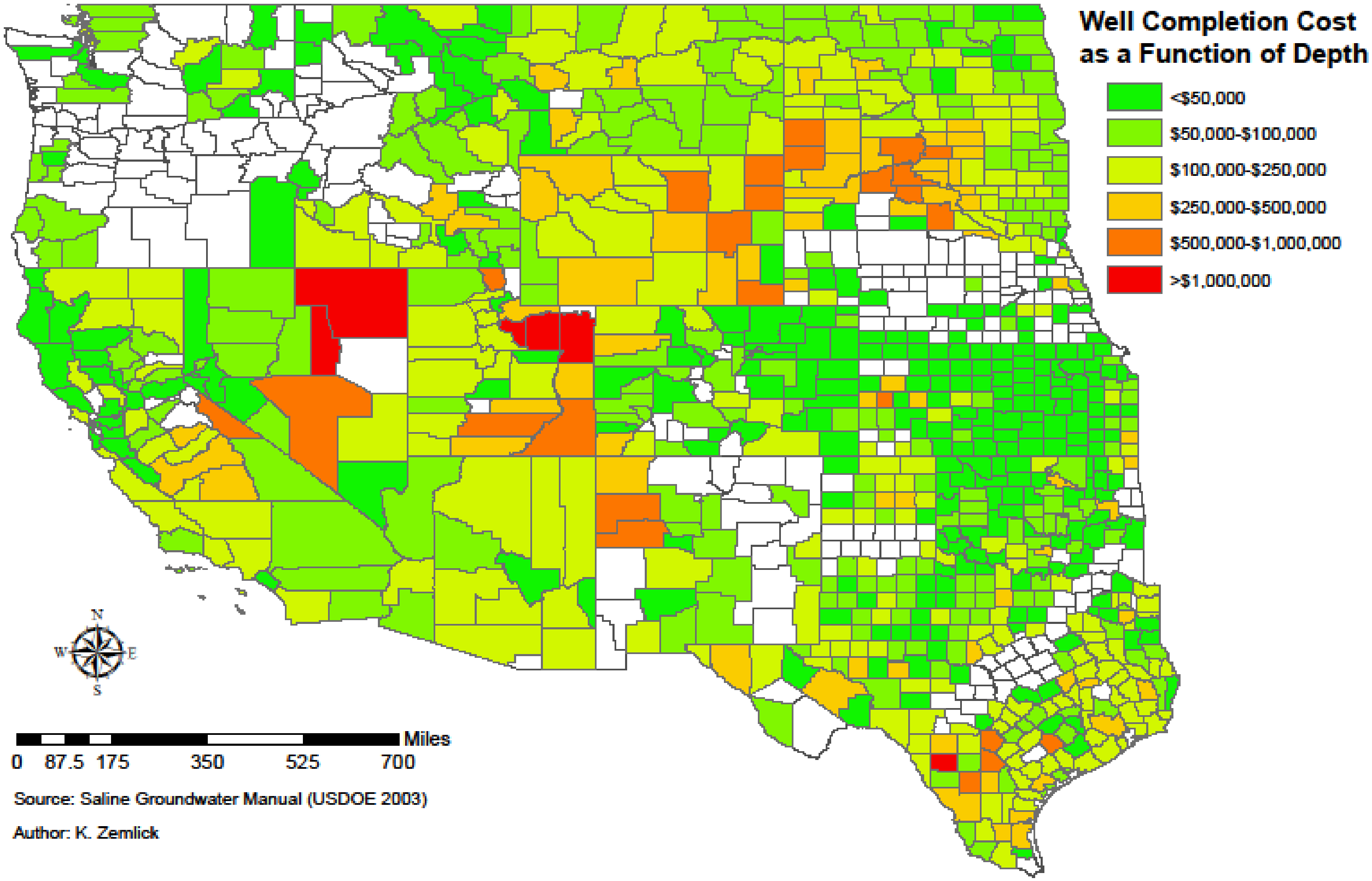


Table 8: Cost Calculations for Brackish Groundwater Extraction and Treatment

County	FIPS	Well Count	Average Depth	Average TDS	Total Cost/kgal
Bernalillo	35001	14	133	1194	$4.30
Cibola	35006	3	980	3038	$4.22
Curry	35009	1	304	1000	$4.48
Dona Ana	35013	45	150	1842	$4.31
Harding	35021	2	145	4920	$3.31
Lea	35025	4	470	3575	$3.66
Lincoln	35027	3	209	1907	$4.38
Luna	35029	1	529	1060	$4.73
McKinley	35031	6	568	1673	$4.77
Otero	35035	12	189	4479	$3.36
Roosevelt	35041	20	136	2512	$3.30
San Juan	35045	4	657	6419	$3.87
Santa Fe	35049	1	183	1720	$4.35
Sierra	35051	8	20	1244	$4.17
Socorro	35053	8	287	2851	$3.46
Torrance	35057	3	219	1837	$4.39
Valencia	35061	1	77	4140	$3.23

3.3 Traditional Water Resources

Water used in power plant cooling has traditionally been supplied by fresh water, from both surface and groundwater sources. While these supplies are largely understood to be diminishing, purchase of water rights transfers within many river basins in the study area is still a possibility. Whether these sources will continue to be available and economical to purchase is a will vary over time, regionally, and will depend upon new and competing demands.

The Bren School of Environmental Science and Management at the University of California, Santa Barbara maintains the "Water Transfer Database," which catalogs water trading in 12 western states between 1987 and 2008. The primary goal of the database is to understand how competing demands for freshwater and how best to manage them in a

changing climate. Based on the information in this database, Figure 38 illustrates a rapid increase in Price between 2004 and 2007. In addition, while the transfer of water steadily increased, it peaked in 2008 with 203 transfers. The rapid decline exhibited in Figure 38, could be explained by an incomplete dataset on the part of the Brun School, who stopped collecting in 2008. While the cost does vary by state, the weighted average based on the number of transfers, the price for a kgal of transferred water is $0.33/kgal.

Figure 38: Average Price of Water Transfer per kgal of Water (Based on UCSB 2010)

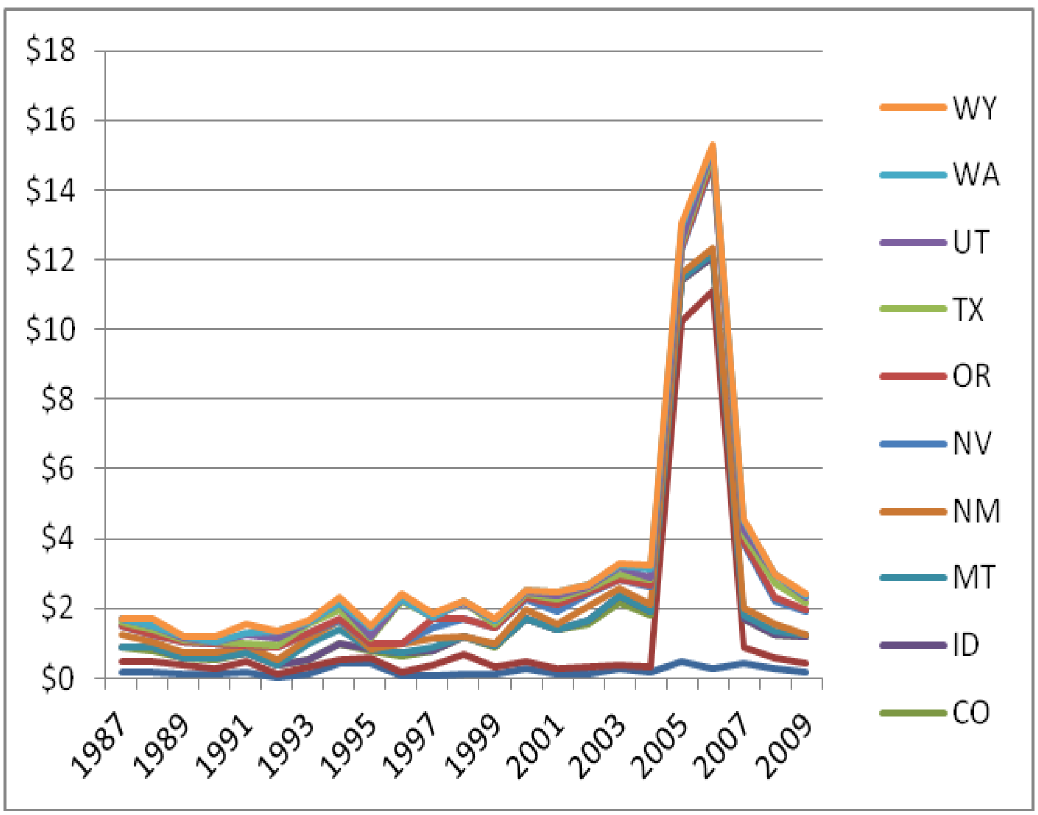


Figure 39: Water Right Transfer Cost per kgal of Traditional Fresh Water. From *Water Transfer Level Data Summary* (UCSB 2010)

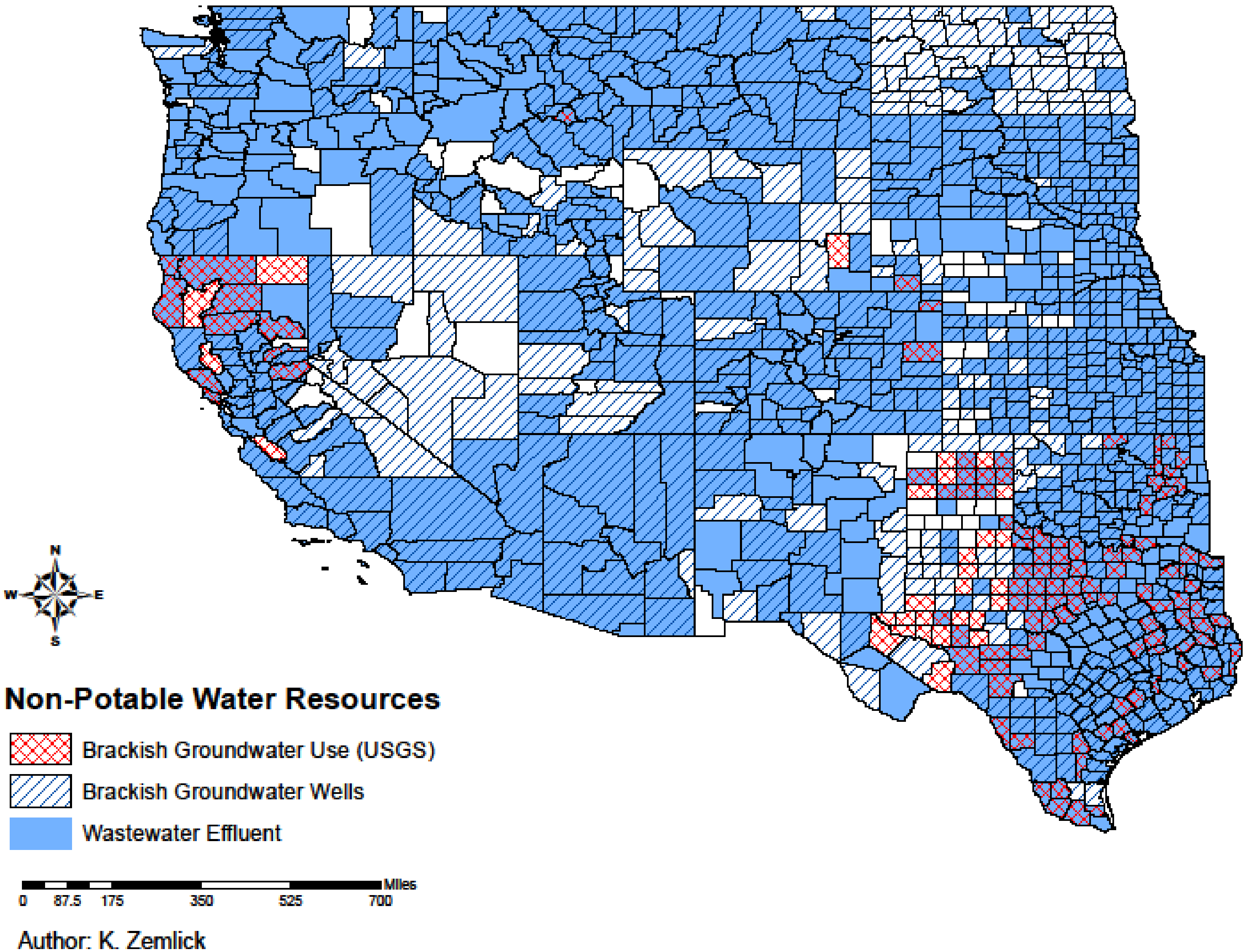
Year	Number of Sales	AZ	CA	CO	ID	MT	NM	NV	OR	TX	UT	WA	WY
1987	66	$0.16	$0.34	$0.39		$0.01	$0.35	$0.24		$0.10	$0.12		
1988	75	$0.18	$0.32	$0.30	$0.07		$0.16	$0.21		$0.17	$0.08		$0.22
1989	68	$0.14	$0.23	$0.22	$0.01		$0.15	$0.29		$0.07	$0.04	$0.03	
1990	118	$0.10	$0.18	$0.25	$0.05		$0.17	$0.22		$0.05	$0.01	$0.03	$0.11
1991	111	$0.16	$0.31	$0.27	$0.01		$0.20			$0.05	$0.23	$0.03	$0.26
1992	118		$0.13	$0.24	$0.01		$0.16	$0.36		$0.03	$0.21	$0.23	
1993	113	$0.13	$0.21	$0.19	$0.01	$0.47	$0.13	$0.14		$0.27	$0.08		$0.02
1994	158	$0.41	$0.15	$0.41	$0.01	$0.43	$0.23		$0.06	$0.28	$0.21		$0.11
1995	116	$0.41	$0.16	$0.24	$0.01		$0.04	$0.13		$0.16	$0.04	$0.28	$0.06
1996	94	$0.06	$0.13	$0.45	$0.08		$0.27		$0.02	$1.19	$0.09		$0.13
1997	100	$0.08	$0.28	$0.42	$0.01	$0.08	$0.27	$0.31	$0.22	$0.06	$0.02		$0.12
1998	127	$0.14	$0.54	$0.50	$0.03	$0.00	$0.01	$0.49	$0.01	$0.44		$0.06	$0.02
1999	194	$0.12	$0.23	$0.54	$0.03	$0.01	$0.06	$0.44	$0.01	$0.09	$0.11		$0.08
2000	126	$0.26	$0.24	$1.21	$0.01		$0.26	$0.30	$0.05	$0.08	$0.07	$0.05	
2001	104	$0.13	$0.16	$1.08			$0.19	$0.35	$0.19	$0.18	$0.10	$0.08	
2002	108	$0.13	$0.19	$1.24	$0.07		$0.41	$0.37	$0.07	$0.12	$0.05	$0.04	
2003	114	$0.27	$0.14	$1.75	$0.24		$0.18	$0.24	$0.04	$0.13	$0.19	$0.08	$0.04
2004	135	$0.18	$0.16	$1.49	$0.07	$0.02	$0.20	$0.52	$0.07	$0.12	$0.07	$0.27	$0.07
2005	169	$0.48	$9.75	$1.19	$0.02	$0.04	$0.16	$0.67	$0.03	$0.12	$0.11	$0.40	$0.07
2006	174	$0.25	$10.84	$1.00	$0.01	$0.06	$0.19	$2.42	$0.05	$0.25	$0.14	$0.05	$0.04
2007	164	$0.43	$0.45	$0.83	$0.01	$0.09	$0.19	$1.85	$0.07	$0.19	$0.15	$0.23	$0.05
2008	203	$0.26	$0.31	$0.66	$0.02	$0.11	$0.21	$0.67	$0.06	$0.43	$0.24		$0.00
2009	150	$0.15	$0.29	$0.77		$0.02		$0.67	$0.05	$0.23	$0.13	$0.07	$0.02

3.4 Comparison of Non Potable Resources

3.4.1 Availability

Non-potable water resources, in the form of reclaimed wastewater and brackish groundwater are present in wide throughout the western United States. Figure 40 shows the presence of wastewater discharges (blue), brackish groundwater wells (blue diagonal lines), and reported brackish groundwater use (USGS 2005) but no brackish wells. The majority of the study area has both resources present. When incorporated into the DSS, additional variables that will influence the overall suitability of these sources such as access to fuel (rail lines), existing electric power transmission infrastructure, as well as modeled water availability scenarios will be comparable within these ArcGIS map layers.

Figure 40: Presence of Non-Potable Water Resources in the Western US



3.4.2 Cost

While low quality water resources may be present in the majority of the study area, treatment costs differ greatly. The economic analysis of wastewater effluent included the capital and operation and maintenance costs for treatment and transportation. Those results determined that the cost of additional treatment for use as cooling water at a thermoelectric facility would be on average, $1.16/kgal. For the same volume of treated brackish groundwater, which was calculated using extraction and an average cost value of available technologies and quality, the cost was an average of $3.77/kgal weighted by plant capacity. Wastewater treatment costs were inversely related to treatment capacity as there are economies of scale for large plants; however, regular treatment costs decrease with increasing capacity. Costs for brackish water treatment inversely depend on quality; higher TDS water is more expensive to treat al than is lower TDS water.

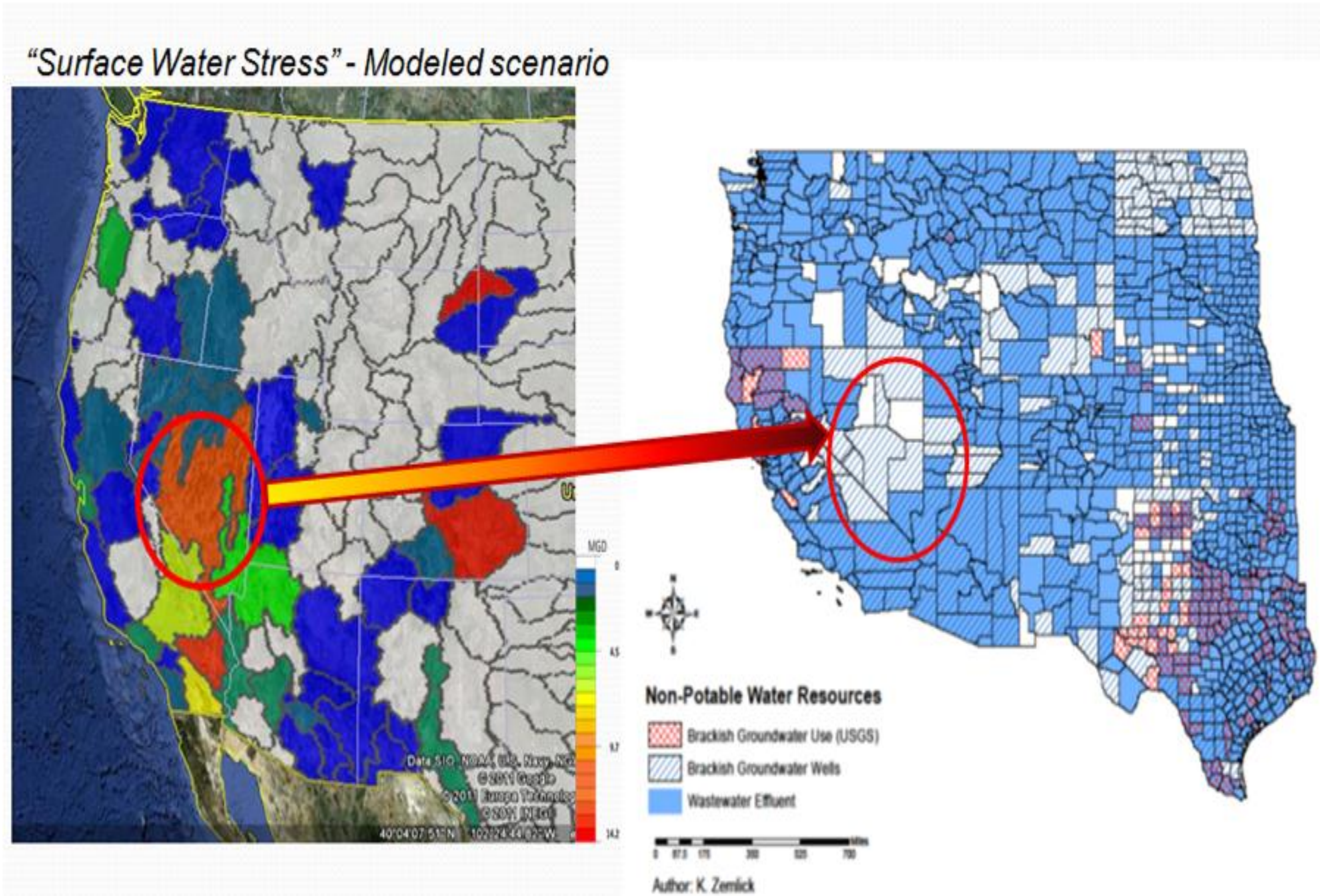
3.4.3 Suitability

The overall suitability of non-potable water resources must be determined based on the presence or availability of the water and the costs associated with treating it. Both factors can vary on a local and regional scale and are dependent upon the water requirements of a potential plant. Generally, treated wastewater, when available, is of a consistent volume and is considerably lower than brackish water in terms of treatment costs. However, in regions constrained by a lack of undeveloped land or where historic water scarcity has resulted in use of wastewater for other purposes, treated brackish water may prove to be a more appropriate source for cooling water. For example, in North Dakota and Nevada where wastewater is not evenly distributed but brackish water is, the

tradeoff between economic cost and non-potable water availability may make brackish water a more attractive resource.(Figure 40)

The purpose of the DSS is to allow stakeholders to assess tradeoffs between water and power under modeled scenarios. The image on the left in Figure 41 is an example of a scenario in which low flows, compromised water availability, and increases in demand lead to surface water stress in basins within the study area. (personal communication, V.C. Tidwell, October 11, 2011) The image to the right of the modeled scenario shows the distribution of non-potable water resources in water-stressed areas and reveals possible constraints to their application in cooling processes for prospective thermoelectric power plants.

Figure 41: Identification of Regions of Low Non-Potable Water Availability Under Modeled Scenarios



Aside from general low quality water availability, the costs associated with these sources might prove to be a determining factor when deciding which to utilize for thermoelectric cooling. Figure 42 Figure 43 and Figure 44 reveal the comparative costs for brackish and wastewater sources in Clark County, Nevada. Figure 42 shows the gross volume available in the county as well as average treatment costs based on the plants present. Figure 43 is an example of a more detailed analysis in which a potential user could identify the total flow and estimated treatment costs, as well as the number of undeveloped land footprints around a given plant. Figure 44 shows the relative cost for brackish water desalination in the county, a value that is readily comparable to treated wastewater options. The results of this study will provide planners and policy makers with the spatial and economic data necessary to weigh water and energy tradeoffs given changing future scenarios.

Figure 42: Treated Wastewater Options in Clark County, NV

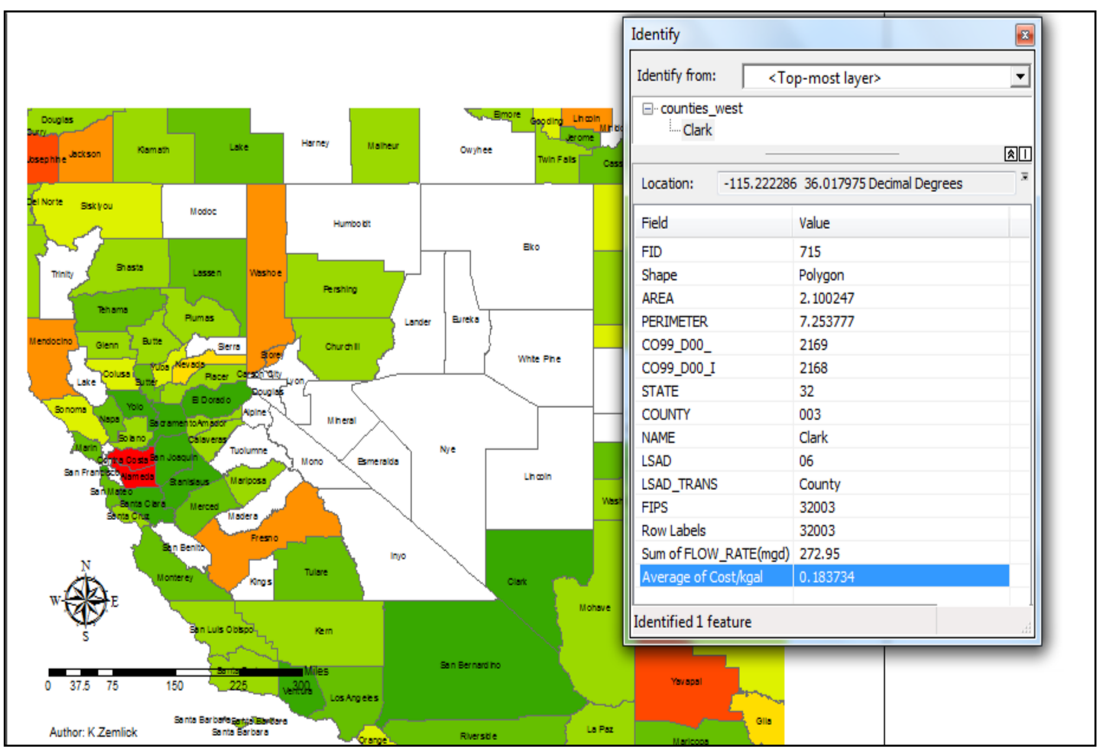


Figure 43: Wastewater Cost for Plants in Clark County, NV

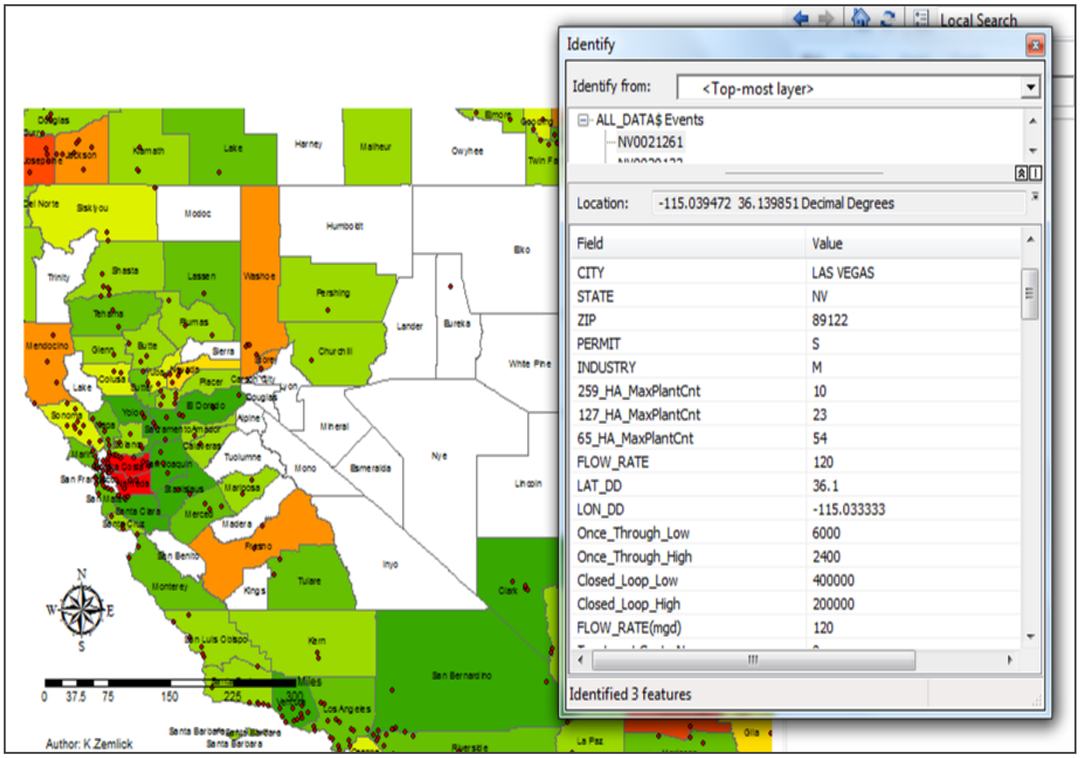
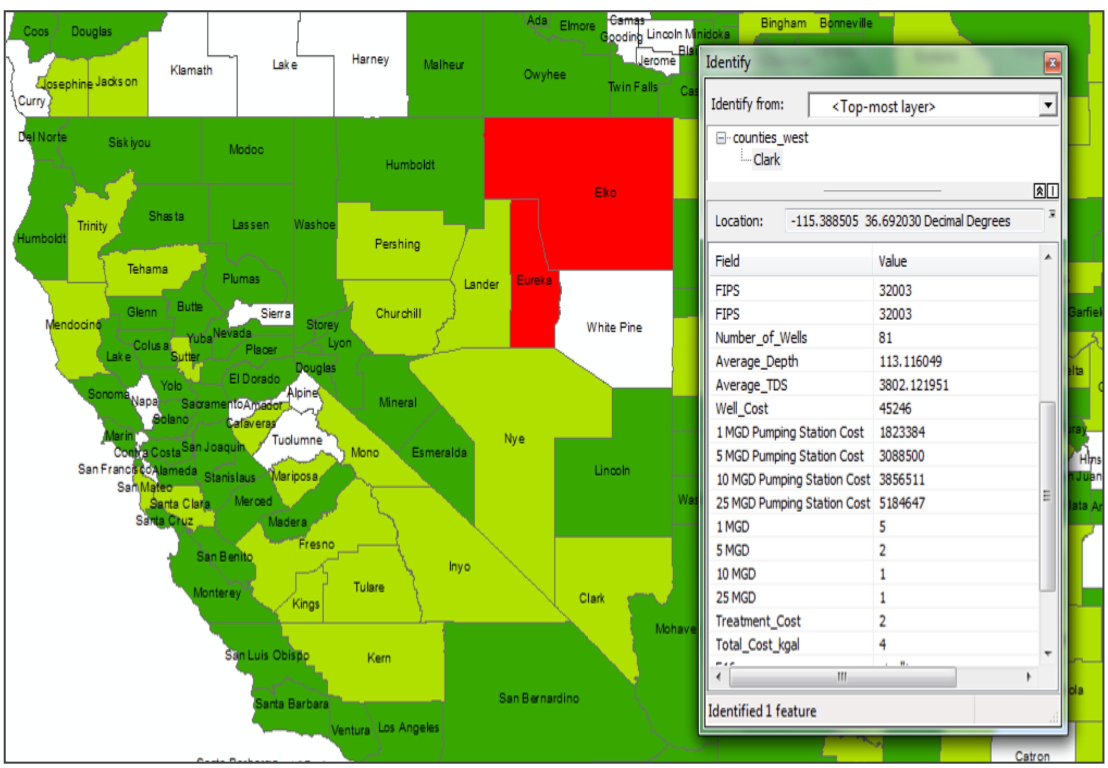


Figure 44: Brackish Groundwater Cost in Clark County, NV



4.0 Discussion

The results of the analyses conducted during the course of this project can be incorporated both spatially through ArcGIS and mathematically with the Excel calculations tabulated. While this analysis will eventually be incorporated into the *Energy and Water in the Western and Texas Interconnects* Decision Support System model designed by Sandia National Laboratories, this project has identified additional factors that will require consideration as brought to light the importance of incorporating institutional factors into non-potable water as a potential source for thermoelectric cooling processes. However, certain assumptions were made during the course of this study that may, if modified, change the way the data is presented.

Numerous assumptions were made in the analysis of wastewater as a potential non-potable source for cooling. The volume of wastewater treatment effluent as assessed based upon the design capacity of the plant, as reported in the PCS database. This value could easily change based on design modification and water-conserving measures on the part of clients served by the plant, both of which could increase or decrease the volume of effluent available. In addition, information pertaining to the level of treatment used at each facility was obtained from the CWNS database, of which not all PCS facilities were present. Therefore, treatment information for many facilities is not available, and for the purposes of this project were considered to be secondary when no information was present. This too would have a marked impact on the cost per thousand gallon value calculated. The last assumption that could influence the overall cost of the proposed water source refers to the landcover classification and percentile rank function, from which the *likely* distance the water would need to be transported was calculated. The

landcover model assumes a direct correlation between footprint availability and proximity to the treatment plant. This could potentially be problematic if, for example, the footprints were not evenly distributed across the buffer zone and were concentrated outside of the buffer, in which case, a plant with a bin value of 1 would, in fact, be best represented by a bin value of 5. Based upon the interval rankings for distance classification, this discrepancy would, in reality, increase the cost for pipe construction by a factor of five.

Assessment of the volume of brackish groundwater resources available in the study area proved to be a difficult undertaking. Groundwater is highly variable in both quantity and quality and both of these factors are dependent upon the complex geologic environment in which these aquifers are located. Factors such as the storativity, saturated thickness, porosity and general hydraulic conductivity would have a great impact on the amount of water that could be made available for use and whether, based upon these depth estimates, would be sustainable. In addition, the connectedness of brackish aquifers to freshwater aquifers could be exacerbated by increased pumping and could, depending upon their spatial and geologic relationships, compromise the quality and quantity of water in these increasingly valuable groundwater resources. While the data obtained in this study did not reveal any significant variables with which to estimate the volume of water present when compared to the much more detailed LBG-Guyton Assoc.(2003) work in Texas, it did reaffirm the need for more research regarding brackish groundwater presence and general quality in the region. However, the general distribution of brackish groundwater appears to be represented, though faintly, in the data presented in Figure 31.

This figure is, at least visually comparable to Feth 1965 (Figure 15) and comparisons between Arizona and Texas well data (Figure 35 &
Figure 36) do suggest that with more detailed well data, further, more accurate characterizations of brackish groundwater volume may be calculated.

4.1 Institutional Constraints

Institutional constraints likely represent a significant factor in whether non-potable water resources are available for use. Twenty-six thermoelectric plants in California, Arizona, New Mexico, Colorado and Texas currently use wastewater effluent in their cooling processes. However, only Texas and California have designated funds at a state level reserved for these types of water reuse applications.(Bracken 2011)

State laws, and more specifically the legal framework as it pertains to water rights will likely be the main determinant as to whether wastewater effluent could be considered "new" water and whether its use in thermoelectric applications is encouraged or constrained. The cornerstone of the prior appropriation doctrine, which governs water rights in the west is that water must be put to "beneficial use" in order for a right to be valid and retained. All states within the study area, with the exception of Colorado, Montana, Nevada, Oklahoma and Utah explicitly designate water reuse as a "beneficial use."(Bracken 2011) If reuse is deemed beneficial, both the treatment plant and potential power plant could obtain valid rights to the water, if it is not already being put to use by another party.

Depending upon individual state laws, both wastewater treatment plant effluent and brackish groundwater might not be considered "new" sources of water, in which case, additional costs would likely be incurred in their application in thermoelectric cooling.

For example, the state of Arizona considers all groundwater, regardless of quality, to be "potable", and the surface waters of Colorado are considered fully appropriated or accounted for. In both cases, institutional constraints at the state level may be prohibitive when non-potable water resources assessed here are claimed to be either new or truly alternative.

5.0 Conclusions

The objectives of this study were addressed in the classification of non-potable resources in the form of wastewater effluent and brackish groundwater and the assessment of their relative distribution; the role land characteristics play in power plant siting and the relative costs associated with the presence of undeveloped land was quantified, the essential economic components associated with both sources were calculated and compared, and potential legal constraints were addressed. The results of this study indicate that non-potable water resources in the form of treated wastewater effluent and brackish groundwater are present in the study area, and are relatively accessible and economically viable. While the quality of detail in the data differed between brackish groundwater and wastewater, information regarding their general distribution and relative costs on a local and regional level will provide planners with the tools to assess their options in terms of non-potable water resources.

Availability of water in the west has long been a concern for policymakers, planners, industry and agriculture and it is unlikely that the magnitude of these competing demands will lessen in the future. Population growth, climate change, and a multitude of factors that influence the scarcity of fresh water will likely cause users to look at sources that have not traditionally been applied. While non-potable resources should not be

considered a "magic bullet" or a replacement for thoughtful, comprehensive and cooperative planning efforts, this study shows that it is a resource that merits further investigation and consideration.

6.0 Future Work

Whether or not wastewater effluent is available for reuse and is not otherwise spoken for is the focus of additional work, currently being explored by Barry Roberts of SNL. As a comprehensive dataset does not exist wherein wastewater treatment facilities document return flow credits or indicate that they are the end user, a more detailed assessment of the true availability of this water is required. This assessment will employ a combination of ArcGIS tools and data obtained from the National Hydrology Dataset Plus (NHDPlus). It will identify points of discharge from individual facilities and, using ArcGIS to calculate the closest water body, compare the outflow from the wastewater treatment plant with that of the water body as it is available in NHDPlus. The results of this analysis will include receiving water body information and a ratio of water body flow: effluent flow; a large ratio indicates that the receiving body is large and, depending upon state water laws, is likely appropriated. The results of this analysis will be compared to the data available in the NPDES PCS Database and CWNS database in order to determine whether the water can be considered available for use.

7.0 Works Cited

Alley, W. M. (n.d.). *Desalination of ground water: Earth science perspectives.* Retrieved from U.S. Geological Survey Fact Sheet 075-03: http://water.usgs.gov/pubs/fs/fs075-03/

Cohen, R. et al. (2004). *Energy Down the Drain: the Hidden Costs of California's Water Supply*. Oakland: National Resources Defense Council.

Copeland, C. (April 23, 2010) *Clean Water Act: A Summary of the Law. National Council for Science and the Environment*. http://www.cnie.org/nle/crsreports/10May/RL30030.pdf Accessed 12 October 2011.

Committee on Advancing Desalination Technology, National Research Council. (2008). *Desalination : A National Perspective.* Washington, D.C.: The National Academies Press.

Cooley, H. et al. (2006). *Desalination, with a Grain of Salt.* Oakland: Pacific Institute for Studies in Delvelopment, Environment and Security.

Dennehey, K. F. (2004). Water Desalination and Reuse Strategies for New Mexico. *New Mexico Groundwater Reserch Institute* (pp. 11-15). Albuquerque: Ne.

DiFillipo, M. (2004). *Use of Produced Water in Recirculating Cooling Systems at Power Generating Facilities.* Department of Energy.

EIA, Energy Information Administration. (2011). *Annual Energy Outlook : With Projections to 2035*. EIA.

EPRI, Electric Power Research Institute. (2008) *Use of Alternate Water Sources for Power Plant Cooling.* Final Report 1014935.

EPRI, Electric Power Research Institute. (2003). *A Survey of Water Use and Sustainability in the United States with a Focus on Power Generation.* Topical Report 1005474.

EPRI, Electric Power Research Institute. (2004). *Comparison of Alternate Cooling Technologies for U.S. Power Plants: Economic, Environmental, and Other Tradeoffs.* Final Report 1005358.

EPRI, Electric Power Research Institute. (2006). *Use of Degraded Water Sources as Cooling Water in Power Plants.* California Energy Commission.

EPRI, Electric Power Research Institute. (2002). *Water & Sustainability (Volume 3): U.S. Water Consumption for Power Production - The Next Half Century.* Topical Report 1006786.

EPRI, Electric Power Research Institute. (2002). *Water & Sustainability (Volume 4): U.S. Electricity Consumption for Water Supply & Treatment-The Next Half Century.* Topical Report 1006787.

Feeley, T.J. III et al. (2008). Water: A Critical Resource in the Thermoelectric Power Industry. *Energy* , 1-11.

Feth, J. (1970). Saline Groundwater Resources of the Conterminous United States. *Water Resources Research* , 1454-1457.

LBG-Guyton Associates. (2003). *Brackish groundwater manual for Texas regional water planning groups: Report prepared for the Texas Water Development Board, Austin, Texas.* Retrieved from http://www.twdb.state.tx.us/RWPG/rpgm_rpts/2001483395.pdf. Accessed 3 January 2011.

Levine, A. (2004). Recovering Sustainable Water from Wastewater. *Environmental Science and Technology* , 201A-208A.

New Mexico Water Resources Research Institute. (2004). *New Mexico Brackish Groundwater Assessment Program Workshop: Report of Findings and Recommendations.* Albuquerque: WRRI (Water Resources Research Institute).

Rebhun, M. a. (1988). Reuse of Wastewater for Industrial Cooling Systems. *Journal of the Water Pollution Control Federation* , 237-241.

Schmidt, C.J. et al. (1975). Municipal Wastewater Reuse in the U.S. *Journal of the Water Pollution Control Federation* , 2229-2245.

Stillwell, A. (2009). *Energy-Water Nexus in Texas.* University of Texas Austin.

Torcellini, P., Long, N., & Judkoff, R. (2003). *Consumptive Water Use for U.S. Power Production.* Golden: National Renewable Energy Laboratory (NREL).

UCSB, Bren School of Environmental Science and Management. (2010, July 16) *Water Transfer Level Data Summary*. Accessed on 16 November 2011. http://www.bren.ucsb.edu/news/water_transfers.htm

US EPA. (2011, October 7) *PCS Search.* Accessed on 1 November 2010. From EPA Envirofacts: http://www.epa.gov/enviro/facts/pcs/search.html.

US EPA, ORD, National Risk Management Research Laboratory. (2004). *Guidelines for Water Reuse.* Washington D.C.

USDOE, U.S. Department of Energy. (2006). *Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water.*

USDOE, U.S. Department of Energy. (2007). *Estimating Freshwater Needs to Meet Future Thermoelectric Generation Requirements.* National Energy Technology Laboratory.

USDOE, U.S. Department of Energy. (2009). *Use of Non-Traditional Water for Power Plant Applications: An Overview of DOE/NETL R&D Efforts.* National Energy Technology Laboratory.

USDOE, United States Department of Energy. (2008, Rev. 2009). *Water Requirements for Existing and Emerging Thermoelectric Technologies.* National Energy Technology Laboratory.

USGS, U.S. Geological Survey (2010, October 23) *National Water Information System*. Accessed on 2010, October 23. From USGS Groundwater Information: http://water.usgs.gov/ogw/

USGS, U.S. Geological Survey. (2005). *Estimated Use of Water in the United States 2005.* USGS Circular 1344.

Veil, J. (2007). *Use of Reclaimed Water for Power Plant Cooling.* Argonne National Laboratory.

Vidic, R. a. (2009). *Reuse of Treated Internal or External Wastewaters in the Cooling Systems of Coal-Based Thermoelectric Power Plants.* USDOE/NETL.

Watson, I. C., Morin, O., & Henthorne, L. (2003). *Desalting Handbook for Planners, 3rd Edition.* Denver: U.S. Bureau of Reclamation.

Appendix 1: Treatment and Transportation Costs for Wastewater Based on Flow

NPDES	Flow Rate (mgd)	Flow Rate (kgal/d)	Pipe Diameter	Pipe Cost per Foot	Pipe Material	Pipe Cost per Mile	Pump Station Cost	Construction Time (Days)	Labor & Equipment * Days	TOTAL CAPITAL COST (1 MI PIPELINE)	Treatment cost/mgd capacity/year	Capital cost/kgal	Treatment cost/kgal	Total Cost
NM0020010	0.3	300	4.13	$21	Steel	$108,993	$1,241,549	53	$64,020	$1,414,562	$48,071	$0.65	$0.44	$1.09
NM0020109	2	2000	10.66	$29	Steel	$152,483	$2,286,981	53	$66,441	$2,505,905	$160,600	$0.17	$0.22	$0.39
NM0020133	0.82	820	6.83	$24	Steel	$125,203	$1,716,244	53	$65,020	$1,906,467	$90,987	$0.32	$0.30	$0.62
NM0020141	1.37	1370	8.82	$26	Steel	$138,740	$2,024,673	53	$65,760	$2,229,173	$126,013	$0.22	$0.25	$0.47
NM0020150	1.2	1200	8.26	$26	Steel	$134,765	$1,940,114	53	$65,550	$2,140,429	$116,070	$0.24	$0.27	$0.51
NM0020168	1	1000	7.54	$25	Steel	$129,871	$1,829,494	53	$65,284	$2,024,649	$103,295	$0.28	$0.28	$0.56
NM0020231	0.6	600	5.84	$23	Steel	$119,009	$1,552,014	53	$64,654	$1,735,677	$74,679	$0.40	$0.34	$0.74
NM0020273	0.9	900	7.15	$24	Steel	$127,314	$1,768,467	53	$65,140	$1,960,921	$96,579	$0.30	$0.29	$0.59
NM0020303	0.9	900	7.15	$24	Steel	$127,314	$1,768,467	53	$65,140	$1,960,921	$96,579	$0.30	$0.29	$0.59
NM0020311	7	7000	19.95	$47	Steel	$245,743	$3,423,359	53	$69,883	$3,738,985	$355,145	$0.07	$0.14	$0.21
NM0020583	5.8	5800	18.16	$42	Steel	$224,142	$3,222,217	53	$69,220	$3,515,579	$315,433	$0.08	$0.15	$0.23
NM0020672	3.5	3500	14.1	$34	Steel	$181,998	$2,738,551	53	$67,717	$2,988,266	$228,673	$0.12	$0.18	$0.30
NM0020681	1.06	1060	7.76	$25	Steel	$131,368	$1,864,144	53	$65,366	$2,060,878	$107,171	$0.27	$0.28	$0.55
NM0020711	0.92	920	7.23	$24	Steel	$127,832	$1,781,027	53	$65,169	$1,974,028	$98,054	$0.29	$0.29	$0.58
NM0020770	0.9	900	7.15	$24	Steel	$127,314	$1,768,467	53	$65,140	$1,960,921	$96,579	$0.30	$0.29	$0.59
NM0022101	0.13	130	2.72	$19	Steel	$101,368	$948,464	53	$63,496	$1,113,328	$28,280	$1.17	$0.60	$1.77
NM0022250	60	60000	58.4	$203	Concrete	$1,072,811	$6,837,473	26	$62,241	$7,972,525	$1,401,600	$0.02	$0.06	$0.08

NM0022268	1	1000	7.54	$25	Steel	$129,871	$1,829,494	53	$65,284	$2,024,649	$103,295	$0.28	$0.28	$0.56
NM0022292	6.5	6500	19.22	$45	Steel	$236,747	$3,342,636	53	$69,614	$3,648,997	$339,268	$0.08	$0.14	$0.22
NM0023311	8.9	8900	22.49	$53	Steel	$280,082	$3,698,576	53	$70,826	$4,049,484	$412,560	$0.06	$0.13	$0.19
NM0023370	0.5	500	5.33	$22	Steel	$115,937	$1,463,522	53	$64,465	$1,643,924	$66,613	$0.45	$0.37	$0.82
NM0023396	0.058	58	1.82	$18	Steel	$96,772	$731,400	53	$63,162	$891,334	$16,936	$2.11	$0.80	$2.91
NM0023477	0.25	250	3.77	$20	Steel	$106,996	$1,170,759	53	$63,886	$1,341,641	$42,888	$0.74	$0.47	$1.21
NM0023485	0.8	800	6.74	$24	Steel	$124,665	$1,702,652	53	$64,989	$1,892,306	$89,644	$0.32	$0.31	$0.63
NM0024066	1.25	1250	8.43	$26	Steel	$135,949	$1,965,785	53	$65,613	$2,167,347	$119,081	$0.24	$0.26	$0.50
NM0024163	0.075	75	2.06	$19	Steel	$98,019	$794,512	53	$63,254	$955,785	$19,956	$1.75	$0.73	$2.48
NM0024830	0.04	40	1.51	$18	Steel	$95,253	$648,925	53	$63,048	$807,226	$13,388	$2.76	$0.92	$3.68
NM0024848	0.144	144	2.86	$19	Steel	$102,113	$980,220	53	$63,549	$1,145,882	$30,169	$1.09	$0.57	$1.66
NM0024899	2.5	2500	11.92	$31	Steel	$162,673	$2,457,353	53	$66,908	$2,686,934	$185,238	$0.15	$0.20	$0.35
NM0024988	0.454	454	5.08	$22	Steel	$114,450	$1,418,740	53	$64,372	$1,597,562	$62,638	$0.48	$0.38	$0.86
NM0024996	0.05	50	1.69	$18	Steel	$96,128	$697,267	53	$63,114	$856,509	$15,421	$2.35	$0.84	$3.19
NM0026395	8.5	8500	21.98	$52	Steel	$272,818	$3,644,214	53	$70,637	$3,987,669	$403,325	$0.06	$0.13	$0.19
NM0027731	0.3	300	4.13	$21	Steel	$108,993	$1,241,549	53	$64,020	$1,414,562	$48,071	$0.65	$0.44	$1.09
NM0027987	2.4	2400	11.68	$30	Steel	$160,671	$2,425,264	53	$66,818	$2,652,753	$180,456	$0.15	$0.21	$0.36
NM0028011	0.075	75	2.06	$19	Steel	$98,019	$794,512	53	$63,254	$955,785	$19,956	$1.75	$0.73	$2.48
NM0028827	2.5	2500	11.92	$31	Steel	$162,673	$2,457,353	53	$66,908	$2,686,934	$185,238	$0.15	$0.20	$0.35
NM0028835	1	1000	7.54	$25	Steel	$129,871	$1,829,494	53	$65,284	$2,024,649	$103,295	$0.28	$0.28	$0.56
NM0029041	0.091	91	2.27	$19	Steel	$99,080	$845,556	53	$63,332	$1,007,968	$22,553	$1.52	$0.68	$2.20
NM0029149	0.027	27	1.24	$18	Steel	$93,945	$571,781	53	$62,948	$728,674	$10,427	$3.70	$1.06	$4.76
NM0029165	2.64	2640	12.25	$31	Steel	$165,449	$2,500,849	53	$67,030	$2,733,328	$191,756	$0.14	$0.20	$0.34
NM0029238	0.04	40	1.51	$18	Steel	$95,253	$648,925	53	$63,048	$807,226	$13,388	$2.76	$0.92	$3.68
NM0029351	1.01	1010	7.58	$25	Steel	$130,122	$1,835,365	53	$65,298	$2,030,785	$103,959	$0.28	$0.28	$0.56
NM0029483	0.605	605	5.86	$23	Steel	$119,157	$1,556,167	53	$64,663	$1,739,987	$75,081	$0.39	$0.34	$0.73
NM0029602	0.85	850	6.95	$24	Steel	$126,002	$1,736,216	53	$65,065	$1,927,283	$93,075	$0.31	$0.30	$0.61
NM0029629	98	98000	74.63	$302	Concrete	$1,596,883	$8,007,662	26	$63,053	$9,667,598	$1,895,810	$0.01	$0.05	$0.06
NM0030279	0.5	500	5.33	$22	Steel	$115,937	$1,463,522	53	$64,465	$1,643,924	$66,613	$0.45	$0.37	$0.82
NM0030295	0.3	300	4.13	$21	Steel	$108,993	$1,241,549	53	$64,020	$1,414,562	$48,071	$0.65	$0.44	$1.09

NM0030317	0.045	45	1.6	$18	Steel	$95,702	$674,008	53	$63,082	$832,792	$14,421	$2.54	$0.88	$3.42
NM0030368	0.08	80	2.13	$19	Steel	$98,360	$811,196	53	$63,279	$972,835	$20,790	$1.67	$0.71	$2.38
NM0030414	0.3	300	4.13	$21	Steel	$108,993	$1,241,549	53	$64,020	$1,414,562	$48,071	$0.65	$0.44	$1.09
NM0030457	0.2	200	3.37	$20	Steel	$104,829	$1,089,589	53	$63,739	$1,258,157	$37,157	$0.86	$0.51	$1.37
NM0030473	0.05	50	1.69	$18	Steel	$96,128	$697,267	53	$63,114	$856,509	$15,421	$2.35	$0.84	$3.19
NM0030490	1.05	1050	7.73	$25	Steel	$131,120	$1,858,463	53	$65,353	$2,054,936	$106,544	$0.27	$0.28	$0.55
NM0030503	0.5	500	5.33	$22	Steel	$115,937	$1,463,522	53	$64,465	$1,643,924	$66,613	$0.45	$0.37	$0.82
NM0030520	1.05	1050	7.73	$25	Steel	$131,120	$1,858,463	53	$65,353	$2,054,936	$106,544	$0.27	$0.28	$0.55
NM0030601	0.2	200	3.37	$20	Steel	$104,829	$1,089,589	53	$63,739	$1,258,157	$37,157	$0.86	$0.51	$1.37
NM0030619	0.375	375	4.62	$21	Steel	$111,758	$1,334,040	53	$64,200	$1,509,998	$55,434	$0.55	$0.40	$0.95
NM0030694	0.08	80	2.13	$19	Steel	$98,360	$811,196	53	$63,279	$972,835	$20,790	$1.67	$0.71	$2.38
NM0030864	0.2	200	3.37	$20	Steel	$104,829	$1,089,589	53	$63,739	$1,258,157	$37,157	$0.86	$0.51	$1.37

Appendix 2: Brackish Groundwater Availability by Quality and County in Texas (based on LBG-Guyton Associates 2003)

County	FIPS	WMR_Area (sq.mi)	Area (sq_mi)	WMR	Percent_ Area	1000-3000 TDS Vol.	3000-10000 TDS Vol.	Total Brackish Volume	Duplicates (*0.5)	County Volume 1000-3000 TDS	County Volume 3000-10000 TDS	Total Brackish Volume in County
King County	48269	9085	912	B	10.04%	5952000	8583000	14535000	1	597493	861607	1459100
Montague County	48337	9085	931	B	10.25%	5952000	8583000	14535000	1	609941	879557	1489498
Tarrant County	48439	13154	864	C	6.57%	43371200	41577700	84948900	1	2848770	2730966	5579736
Wise County	48497	13154	905	C	6.88%	43371200	41577700	84948900	1	2983954	2860561	5844515
Navarro County	48349	13154	1071	C	8.14%	43371200	41577700	84948900	1	3531287	3385261	6916548
Rains County	48379	12012	232	D	1.93%	28866800	26916500	55783300	1	557534	519866	1077400
Gregg County	48183	12012	274	D	2.28%	28866800	26916500	55783300	1	658467	613979	1272446
Marion County	48315	12012	381	D	3.17%	28866800	26916500	55783300	1	915605	853745	1769350
Titus County	48449	12012	411	D	3.42%	28866800	26916500	55783300	1	987700	920969	1908669
Wood County	48499	12012	650	D	5.41%	28866800	26916500	55783300	1	1562056	1456521	3018577
Van Zandt County	48467	12012	849	D	7.07%	28866800	26916500	55783300	1	2040286	1902440	3942726
Cass County	48067	12012	938	D	7.81%	28866800	26916500	55783300	1	2254167	2101871	4356039
Harris County	48201	12012	1729	D	14.39%	28866800	26916500	55783300	1	4155070	3874345	8029414
El Paso County	48141	24069	1013	E	4.21%	121871400	3511000	125382400	1	5129242	147769	5277011
Culberson County	48109	24069	3813	E	15.84%	121871400	3511000	125382400	1	19306812	556211	19863023
Presidio County	48377	24069	3856	E	16.02%	121871400	3511000	125382400	1	19524539	562484	20087022
Hudspeth County	48229	24069	4571	E	18.99%	121871400	3511000	125382400	1	23144882	666782	23811664
Coke County	48081	40072	899	F	2.24%	267167600	105680700	372848300	1	5993803	2370906	8364709
Scurry County	48415	40072	903	F	2.25%	267167600	105680700	372848300	1	6020472	2381455	8401927
Howard County	48227	40072	903	F	2.25%	267167600	105680700	372848300	1	6020472	2381455	8401927
Mitchell County	48335	40072	910	F	2.27%	267167600	105680700	372848300	1	6067142	2399916	8467058

Martin County	48317	40072	915	F	2.28%	267167600	105680700	372848300	1	6100478	2413102	8513580
Concho County	48095	40072	992	F	2.48%	267167600	105680700	372848300	1	6613852	2616172	9230024
Runnels County	48399	40072	1054	F	2.63%	267167600	105680700	372848300	1	7027217	2779683	9806900
Tom Green County	48451	40072	1522	F	3.80%	267167600	105680700	372848300	1	10147462	4013926	14161387
Pecos County	48371	40072	4764	F	11.89%	267167600	105680700	372848300	1	31762489	12563956	44326445
Williamson County	48491	30608	562	G	1.84%	121988600	73551800	195540400	0.5	1119929	675250	1795179
Brazos County	48041	30608	586	G	1.91%	121988600	73551800	195540400	1	2335511	1408173	3743684
Washington County	48477	30608	609	G	1.99%	121988600	73551800	195540400	1	2427178	1463442	3890620
Lee County	48287	30608	629	G	2.06%	121988600	73551800	195540400	1	2506888	1511503	4018391
Burleson County	48051	30608	666	G	2.18%	121988600	73551800	195540400	1	2654352	1600415	4254767
Grimes County	48185	30608	794	G	2.59%	121988600	73551800	195540400	1	3164498	1908002	5072500
Knox County	48275	30608	854	G	2.79%	121988600	73551800	195540400	1	3403629	2052184	5455812
Kent County	48263	30608	902	G	2.95%	121988600	73551800	195540400	1	3594933	2167529	5762462
Limestone County	48293	30608	909	G	2.97%	121988600	73551800	195540400	1	3622832	2184350	5807182
Stonewall County	48433	30608	919	G	3.00%	121988600	73551800	195540400	1	3662687	2208380	5871067
Milam County	48331	30608	1017	G	3.32%	121988600	73551800	195540400	1	4053267	2443877	6497144
Polk County	48373	11306	528.5	H	4.67%	122571300	73298100	195869400	0.5	2864803	1713163	4577966
Galveston County	48167	11306	399	H	3.53%	122571300	73298100	195869400	1	4325663	2586763	6912426
Chambers County	48071	11306	599	H	5.30%	122571300	73298100	195869400	1	6493916	3883386	10377301
Austin County	48015	11306	653	H	5.78%	122571300	73298100	195869400	1	7079344	4233474	11312818
Fort Bend County	48157	11306	875	H	7.74%	122571300	73298100	195869400	1	9486104	5672726	15158829
Harrison County	48203	11306	899	H	7.95%	122571300	73298100	195869400	1	9746294	5828321	15574614
Montgomery County	48339	11306	1044	H	9.23%	122571300	73298100	195869400	1	11318277	6768372	18086649
Liberty County	48291	11306	1160	H	10.26%	122571300	73298100	195869400	1	12575863	7520414	20096277
Brazoria County	48039	11306	1387	H	12.27%	122571300	73298100	195869400	1	15036829	8992081	24028910
Polk County	48373	15364	528.5	I	3.44%	114227300	79155200	193382500	0.5	1964629	1361414	3326043
Orange County	48361	15364	356	I	2.32%	114227300	79155200	193382500	1	2646766	1834109	4480875
Sabine County	48403	15364	490	I	3.19%	114227300	79155200	193382500	1	3643021	2524476	6167497
San Augustine County	48405	15364	528	I	3.44%	114227300	79155200	193382500	1	3925541	2720252	6645793
Panola County	48365	15364	801	I	5.21%	114227300	79155200	193382500	1	5955224	4126745	10081970

Jefferson County	48245	15364	904	I	5.88%	114227300	79155200	193382500	1	6721002	4657400	11378403
Tyler County	48457	15364	923	I	6.01%	114227300	79155200	193382500	1	6862262	4755288	11617551
Jasper County	48241	15364	938	I	6.11%	114227300	79155200	193382500	1	6973783	4832568	11806352
Anderson County	48001	15364	1071	I	6.97%	114227300	79155200	193382500	1	7962603	5517783	13480386
Houston County	48225	15364	1231	I	8.01%	114227300	79155200	193382500	1	9152161	6342102	15494263
Bandera County	48019	9253	792	J	8.56%	3201400	5436400	8637800	1	274020	465322	739343
Kinney County	48271	9253	1364	J	14.74%	3201400	5436400	8637800	1	471924	801389	1273312
Val Verde County	48465	9253	3171	J	34.27%	3201400	5436400	8637800	1	1097119	1863052	2960171
Hays County	48209	11934	339	K	2.84%	101824800	100127400	201952200	0.5	1446230	1422121	2868351
Wharton County	48481	11934	545	K	4.57%	101824800	100127400	201952200	0.5	2325059	2286301	4611360
Williamson County	48491	11934	562	K	4.71%	101824800	100127400	201952200	0.5	2397584	2357617	4755201
Blanco County	48031	11934	711	K	5.96%	101824800	100127400	201952200	1	6066485	5965358	12031843
Bastrop County	48021	11934	888	K	7.44%	101824800	100127400	201952200	1	7576707	7450405	15027112
Fayette County	48149	11934	950	K	7.96%	101824800	100127400	201952200	1	8105711	7970591	16076302
Travis County	48453	11934	989	K	8.29%	101824800	100127400	201952200	1	8438472	8297804	16736277
Matagorda County	48321	11934	1114	K	9.33%	101824800	100127400	201952200	1	9505013	9346566	18851580
Hays County	48209	19989	339	L	1.70%	300957900	116809300	417767200	0.5	2552022	990504	3542525
Caldwell County	48055	19989	546	L	2.73%	300957900	116809300	417767200	1	8220672	3190649	11411321
Comal County	48091	19989	562	L	2.81%	300957900	116809300	417767200	1	8461571	3284148	11745718
Kendall County	48259	19989	662	L	3.31%	300957900	116809300	417767200	1	9967188	3868516	13835704
Guadalupe County	48187	19989	711	L	3.56%	300957900	116809300	417767200	1	10704941	4154856	14859797
Karnes County	48255	19989	750	L	3.75%	300957900	116809300	417767200	1	11292132	4382759	15674891
Refugio County	48391	19989	770	L	3.85%	300957900	116809300	417767200	1	11593255	4499633	16092888
Wilson County	48493	19989	807	L	4.04%	300957900	116809300	417767200	1	12150334	4715849	16866183
Gonzales County	48177	19989	1068	L	5.34%	300957900	116809300	417767200	1	16079996	6241049	22321045
Frio County	48163	19989	1133	L	5.67%	300957900	116809300	417767200	1	17058647	6620888	23679536
Atascosa County	48013	19989	1232	L	6.16%	300957900	116809300	417767200	1	18549209	7199413	25748621
Bexar County	48029	19989	1247	L	6.24%	300957900	116809300	417767200	1	18775051	7287068	26062119
Medina County	48325	19989	1328	L	6.64%	300957900	116809300	417767200	1	19994602	7760406	27755007
La Salle County	48283	19989	1489	L	7.45%	300957900	116809300	417767200	1	22418646	8701238	31119884

Uvalde County	48463	19989	1557	L	7.79%	300957900	116809300	417767200	1	23442466	9098608	32541074
Webb County	48479	11065	3357	M	30.34%	270765700	125303200	396068900	1	82147352	38015621	120162973
Aransas County	48007	10738	252	N	2.35%	200286200	132122600	332408800	1	4700328	3100661	7800989
San Patricio County	48409	10738	692	N	6.44%	200286200	132122600	332408800	1	12907250	8514513	21421763
Nueces County	48355	10738	836	N	7.79%	200286200	132122600	332408800	1	15593152	10286319	25879471
Kleberg County	48273	10738	871	N	8.11%	200286200	132122600	332408800	1	16245975	10716966	26962941
Bee County	48025	10738	880	N	8.20%	200286200	132122600	332408800	1	16413844	10827704	27241548
Brooks County	48047	10738	943	N	8.78%	200286200	132122600	332408800	1	17588926	11602869	29191795
McMullen County	48311	10738	1113	N	10.37%	200286200	132122600	332408800	1	20759782	13694585	34454367
Kenedy County	48261	10738	1457	N	13.57%	200286200	132122600	332408800	1	27176103	17927233	45103336
Duval County	48131	10738	1793	N	16.70%	200286200	132122600	332408800	1	33443207	22061447	55504654
Cochran County	48079	20175	775	O	3.84%	46655400	45107400	91762800	1	1792215	1732750	3524965
Yoakum County	48501	20175	800	O	3.97%	46655400	45107400	91762800	1	1850028	1788645	3638674
Terry County	48445	20175	890	O	4.41%	46655400	45107400	91762800	1	2058156	1989868	4048024
Lynn County	48305	20175	892	O	4.42%	46655400	45107400	91762800	1	2062782	1994340	4057121
Lubbock County	48303	20175	900	O	4.46%	46655400	45107400	91762800	1	2081282	2012226	4093508
Dawson County	48115	20175	902	O	4.47%	46655400	45107400	91762800	1	2085907	2016698	4102604
Dickens County	48125	20175	904	O	4.48%	46655400	45107400	91762800	1	2090532	2021169	4111701
Hockley County	48219	20175	908	O	4.50%	46655400	45107400	91762800	1	2099782	2030112	4129895
Hale County	48189	20175	1005	O	4.98%	46655400	45107400	91762800	1	2324098	2246986	4571084
Lamb County	48279	20175	1016	O	5.04%	46655400	45107400	91762800	1	2349536	2271580	4621115
Gaines County	48165	20175	1502	O	7.44%	46655400	45107400	91762800	1	3473428	3358182	6831610
Wharton County	48481	2345	545	P	23.24%	1364500	6461400	7825900	0.5	158561	750845	909406
Jackson County	48239	2345	830	P	35.39%	1364500	6461400	7825900	1	482957	2286977	2769935

Appendix 3: USGS Brackish Well Statistics by County, Texas

County	Area (sq_mi)	1000_AF/mi^2	Percentile Rank	#Wells	Min_Depth	Max_Depth	Avg_Depth	StdDev_Depth	Min_TDS	Max_TDS	Avg_TDS	StdDev_TDS	Total Brackish GW Withdrawals (MGD), from USGS 2005	County Population (US Census 2010)
King County	912	1.60	0.05	2	55	95	75	28	2080	2410	2245	233	2.59	286
Montague County	931	1.60	0.06	2	110	140	125	21	1305	2585	1945	905	3.90	19568
Tarrant County	864	6.46	0.37	22	14	100	38	26	1010	8920	2493	2133	0.00	1789900
Wise County	905	6.46	0.39	1	238	238	238	0	1405	1405	1405	0	1.71	59415
Navarro County	1071	6.46	0.46	10	24	61	42	14	1220	2725	1713	517	0.58	49440
Rains County	232	4.64	0.02	3	25	60	43	18	1205	1902	1486	368	0.00	11287
Gregg County	274	4.64	0.03	3	500	540	515	22	1030	1390	1158	202	17.23	119637
Marion County	381	4.64	0.07	5	158	832	466	247	1079	1415	1193	135	0.27	10306
Titus County	411	4.64	0.08	2	163	700	432	380	1170	1220	1195	35	2.96	30206
Wood County	650	4.64	0.12	3	24	97	71	41	1030	3900	2217	1498	8.67	43136
Van Zandt County	849	4.64	0.19	3	34	723	289	378	1145	4050	2187	1617	4.15	52005
Cass County	938	4.64	0.28	4	438	708	591	116	1020	1175	1082	67	0.13	29203
Harris County	1729	4.64	0.48	6	60	2358	929	845	1280	6030	2732	1834	4.44	4070989
El Paso County	1013	5.21	0.35	24	20	870	427	254	1010	3930	1766	998	0.00	751296
Culberson County	3813	5.21	0.80	1	410	410	410	0	1960	1960	1960	0	0.22	2300
Presidio County	3856	5.21	0.81	4	83	204	157	59	1200	3240	2155	1013	0.00	7470
Hudspeth County	4571	5.21	0.86	9	285	1583	1031	474	1160	4710	2612	970	0.00	3115
Coke County	899	9.30	0.49	10	30	265	125	81	1550	7130	3731	1715	1.70	3311
Scurry County	903	9.30	0.50	5	140	258	205	47	1820	3780	2924	758	20.66	16222
Howard County	903	9.30	0.50	8	14	170	66	51	1150	9930	3679	2892	12.78	32940
Mitchell County	910	9.30	0.52	5	65	100	83	18	1640	4230	3338	1037	4.34	9347
Martin County	915	9.30	0.53	1	175	175	175	0	2040	2040	2040	0	2.97	4581
Concho County	992	9.30	0.54	1	141	141	141	0	5970	5970	5970	0	0.49	3579
Runnels County	1054	9.30	0.56	4	30	115	64	42	2700	5430	3740	1269	0.70	10170
Tom Green County	1522	9.30	0.67	14	28	270	106	76	1260	4810	2271	1080	0.88	108378
Pecos County	4764	9.30	0.97	31	100	1975	516	438	1020	10000	2559	2163	16.96	16248
Williamson County	562	3.19	0.15	1	72	72	72	0	1260	1260	1260	0	0.00	205343
Brazos County	586	6.39	0.17	23	60	1297	477	430	1010	3030	1582	612	0.71	179992
Washington County	609	6.39	0.18	7	27	450	192	181	1069	5050	1860	1419	0.25	32893
Lee County	629	6.39	0.20	2	205	335	270	92	1140	1175	1158	25	0.23	16231
Burleson County	666	6.39	0.27	23	51	2202	616	620	1020	4040	1666	667	0.93	16570
Grimes County	794	6.39	0.34	29	14	1415	427	250	1001	3505	1864	707	0.20	26011
Knox County	854	6.39	0.36	19	20	69	42	12	1030	5930	2436	1549	0.36	3322
Kent County	902	6.39	0.38	3	65	254	156	95	1170	6770	3597	2874	14.08	703

Limestone County	909	6.39	0.38	5	60	306	138	101	1040	3740	1834	1097	1.00	22287
Stonewall County	919	6.39	0.40	3	30	157	82	67	2330	9960	5000	4300	2.64	1354
Milam County	1017	6.39	0.42	1	46	46	46	0	1445	1445	1445	0	0.08	24628
Polk County	529	8.66	0.31	2	326	689	508	257	1575	2140	1858	400	0.50	23265
Galveston County	399	17.32	0.45	5	270	1018	499	306	1770	3740	2460	872	0.85	286814
Chambers County	599	17.32	0.58	148	11	1050	278	200	1010	5350	1852	764	3.23	31431
Austin County	653	17.32	0.59	1	112	112	112	0	1018	1018	1018	0	0.56	27248
Fort Bend County	875	17.32	0.70	4	30	665	361	349	1006	2100	1437	466	4.45	556870
Harrison County	899	17.32	0.72	1	37	37	37	0	1200	1200	1200	0	1.10	64795
Montgomery County	1044	17.32	0.78	3	39	195	127	80	1240	3420	2040	1200	4.70	447718
Liberty County	1160	17.32	0.82	3	68	834	464	384	1140	1430	1257	153	2.50	75779
Brazoria County	1387	17.32	0.87	75	20	1300	544	317	1000	8230	1780	1224	8.85	309208
Polk County	529	6.29	0.13	2	326	689	508	257	1575	2140	1858	400	0.50	23265
Orange County	356	12.59	0.29	15	17	900	498	254	1020	2500	1315	377	1.53	81816
Sabine County	490	12.59	0.41	2	500	565	533	46	1037	1077	1057	28	0.00	10208
San Augustine County	528	12.59	0.43	1	285	285	285	0	1315	1315	1315	0	0.01	8574
Panola County	801	12.59	0.57	1	79	79	79	0	1040	1040	1040	0	3.45	23310
Jefferson County	904	12.59	0.60	60	10	681	226	200	1000	5570	1808	860	2.73	243237
Tyler County	923	12.59	0.62	2	450	1013	732	398	1365	1650	1508	202	0.38	20556
Jasper County	938	12.59	0.63	1	250	250	250	0	1085	1085	1085	0	0.34	34370
Anderson County	1071	12.59	0.65	1	573	573	573	0	1046	1046	1046	0	3.42	57001
Houston County	1231	12.59	0.71	2	287	600	444	221	1051	1265	1158	151	0.57	22363
Bandera County	792	0.93	0.00	2	400	525	463	88	2680	2930	2805	177	0.00	20560
Kinney County	1364	0.93	0.04	1	514	514	514	0	2020	2020	2020	0	0.00	3274
Val Verde County	3171	0.93	0.11	2	306	753	530	316	2300	2320	2310	14	0.01	48165
Hays County	339	8.46	0.10	6	200	1030	623	326	1060	9570	4630	3992	0.00	77773
Wharton County	545	8.46	0.32	1	32	32	32	0	1500	1500	1500	0	4.38	20500
Williamson County	562	8.46	0.55	1	72	72	72	0	1260	1260	1260	0	0.00	205343
Blanco County	711	16.92	0.64	2	227	360	294	94	2215	3325	2770	785	0.00	9198
Bastrop County	888	16.92	0.69	28	16	809	241	224	1000	4020	1955	1008	0.01	74876
Fayette County	950	16.92	0.74	1	125	125	125	0	1255	1255	1255	0	0.49	22891
Travis County	989	16.92	0.76	5	431	600	534	70	1120	8240	3518	2918	0.00	1026158
Matagorda County	1114	16.92	0.79	33	38	802	376	234	1001	3980	1571	648	1.07	36978
Hays County	339	10.45	0.14	6	200	1030	623	326	1060	9570	4630	3992	0.00	77773
Caldwell County	546	20.90	0.61	47	15	580	181	150	1021	4265	1610	610	11.89	37810
Comal County	562	20.90	0.63	8	330	743	497	132	1420	2865	2118	449	0.00	114525
Kendall County	662	20.90	0.66	2	85	152	119	47	1060	1630	1345	403	0.00	34053
Guadalupe County	711	20.90	0.68	32	11	565	155	135	1001	6770	1943	1073	21.50	121432
Karnes County	750	20.90	0.73	2	212	316	264	74	1010	1230	1120	156	0.32	15029
Refugio County	770	20.90	0.75	66	55	1150	753	309	1000	5210	1668	796	9.23	7225
Wilson County	807	20.90	0.77	1	600	600	600	0	1070	1070	1070	0	0.34	40749

Gonzales County	1068	20.90	0.84	45	25	2175	414	510	1030	9240	2251	1672	0.05	19610
Frio County	1133	20.90	0.85	11	110	370	241	74	1155	3120	1646	527	0.35	16156
Atascosa County	1232	20.90	0.88	11	175	2185	860	686	1088	5525	2440	1310	0.57	44633
Bexar County	1247	20.90	0.89	27	518	2274	1453	559	1060	5400	3279	1512	0.00	1651448
Medina County	1328	20.90	0.92	7	180	740	529	226	1130	2440	1799	399	0.00	44728
La Salle County	1489	20.90	0.94	35	145	2483	815	689	1010	4915	1967	941	0.12	5810
Uvalde County	1557	20.90	0.95	13	64	1668	1013	599	1030	3070	1849	763	0.00	26811
Webb County	3357	35.79	1.00	24	235	1991	673	500	1030	4025	1916	730	1.12	241438
Aransas County	252	30.96	0.47	57	13	1201	220	245	1000	9010	2597	1845	0.07	24826
San Patricio County	692	30.96	0.83	34	60	901	314	207	1050	4560	2073	1077	2.09	68223
Nueces County	836	30.96	0.88	39	10	1173	506	306	1020	9580	2276	1468	0.79	323046
Kleberg County	871	30.96	0.90	40	27	1650	745	416	1000	9950	2379	1892	0.32	30647
Bee County	880	30.96	0.91	67	47	1539	268	282	1010	4030	1586	641	0.60	32487
Brooks County	943	30.96	0.93	21	70	2312	627	541	1000	4580	1826	924	0.25	7377
McMullen County	1113	30.96	0.96	35	64	2105	396	536	1165	9595	3421	1934	0.70	810
Kenedy County	1457	30.96	0.98	23	490	1360	911	197	1000	2700	1393	426	0.28	369
Duval County	1793	30.96	0.99	50	42	2300	405	451	1004	7125	2271	1531	3.59	12010
Cochran County	775	4.55	0.13	3	159	216	190	29	1080	1420	1237	172	3.03	2927
Yoakum County	800	4.55	0.16	1	158	158	158	0	1070	1070	1070	0	15.30	7698
Terry County	890	4.55	0.21	2	144	208	176	45	1150	1550	1350	283	4.42	12142
Lynn County	892	4.55	0.22	1	124	124	124	0	1570	1570	1570	0	0.43	5674
Lubbock County	900	4.55	0.23	1	175	175	175	0	1170	1170	1170	0	1.26	270550
Dawson County	902	4.55	0.24	1	190	190	190	0	1220	1220	1220	0	3.80	13657
Dickens County	904	4.55	0.25	1	144	144	144	0	2930	2930	2930	0	0.38	2439
Hockley County	908	4.55	0.26	1	115	115	115	0	1830	1830	1830	0	8.17	22272
Hale County	1005	4.55	0.30	1	495	495	495	0	7560	7560	7560	0	0.37	35408
Lamb County	1016	4.55	0.33	1	149	149	149	0	3580	3580	3580	0	0.44	13162
Gaines County	1502	4.55	0.44	2	100	128	114	20	1005	2540	1773	1085	20.43	15382
Wharton County	545	1.67	0.01	1	32	32	32	0	1500	1500	1500	0	4.38	20500
Jackson County	830	3.34	0.09	4	82	1234	503	504	1016	1630	1203	287	6.96	14274