Evaluating the energy embedded in Texas' public water supply in a drying climate

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Introduction

Texas is a state that is particularly vulnerable to future water supply shortages. The state's population is expected to nearly double between the years of 2010 and 2060, whereas existing water supplies are projected to decrease by approximately 10% [1]. To date, most of Texas' water delivered by public water supply utilities is extracted by surface water and groundwater supplies, which can be moved and treated at a relatively small energy cost in comparison to alternative water supplies. Drought, however, has strained the water supply in many counties across Texas, and is likely to continue to reduce water availability as the effects of climate change increase [1].

Marginal water sources such as desalinated water, reclaimed water (from treated wastewater effluent), interbasin transfers, and groundwater from deep aquifers will likely be required to meet future demand, but these sources will require more energy than traditional drinking water sources (i.e. surface water reservoirs located near population centers) [2, 3]. New water supply projects, defined in the Texas Water Development Board's (TWDB) State Water Plan, have been proposed to meet future water demand, but these water supply projects will come with an energy cost [1]. The state has already been desalinating brackish water since 2004 and has plans to substantially expand its desalination capacity across the state in the future [5]. Plans to build long pipelines to deliver water from water rich regions to water scarce regions will also drive up the need for energy [2]. In turn, the average energy intensity and cost of Texas' water supply will grow as easily extractable surface and groundwater reservoirs fail to meet demand [4]. These new water supply projects will have energy and environmental implications that have not been assessed at the state level. This analysis aims to fill that data gap and lend insight into the future water requirements of shifting water supplies.

This analysis has 3 main objectives:

(1) To quantify the amount of energy that Texas' public water utilities collectively use to extract, treat, and distribute water to customers;
(2) To evaluate potential increases in energy consumption that follow an increased reliance on desalinated water; and
(3) To compare the energy consumed by public water utilities to the energy consumed for public water supplies at the point-of-use, as well as across other end use sectors.

Background

The United States consumed approximately 12.6% of its 2010 national annual energy use for water-related purposes, yet only 4% of this water-related energy (i.e. 0.5% of annual energy use in 2010) included the energy consumed by public water and wastewater utilities [4]. The majority of water-related energy use at the national scale is for water heating and steam injection. Figure 1 summarizes the distribution of energy for water-related activities at the national scale.

Figure 1. The US consumed 12.3 quadrillion BTUs of primary energy for water-related purposes in 2010, which can be broken down into the categories described here. (Data from [4].)

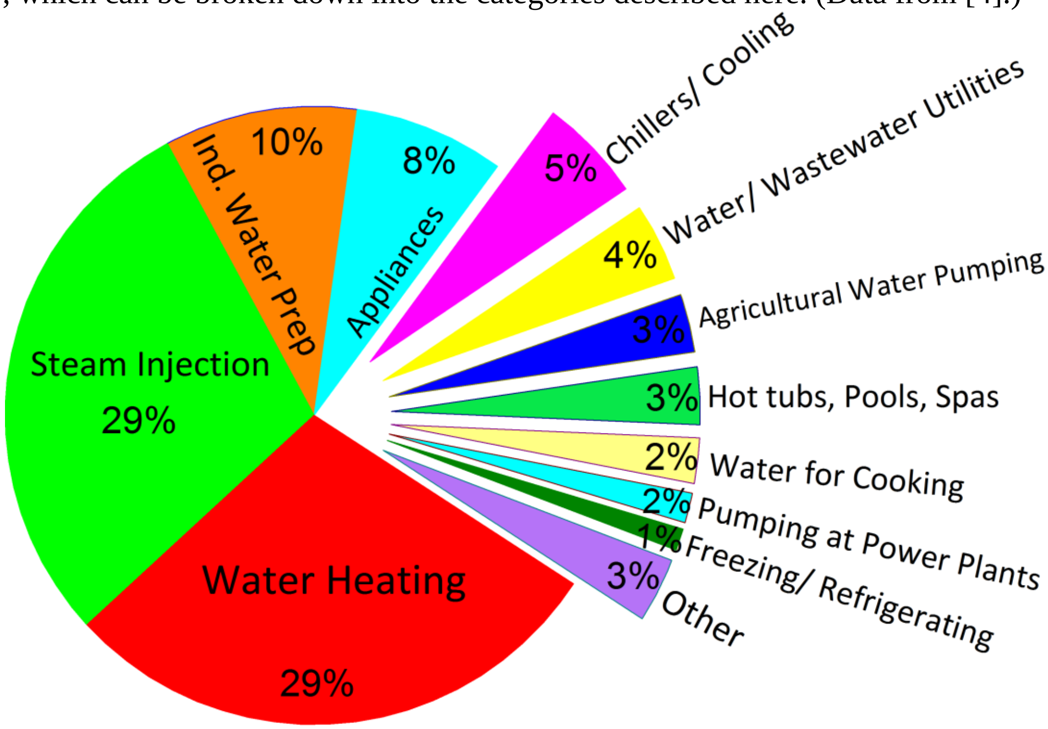


Table 1. Energy is required to treat, move, prepare, and recondition water after use. The energy required for any activity depends on the energy intensity and volume of water considered. (Data from [7-9].)

Water-related Activity	Electricity Consumption (kWh/Mgal)
Water treatment by public water utilities	
Surface Water Treatment	220
Groundwater Treatment	620
Brackish Groundwater Desalination	3,900 – 9,700
Seawater Desalination	9,700-16,500
Raw water pumping and distribution by public water utilities	
Groundwater Well-Pumping (from 120 ft depth)	540
Groundwater Well-Pumping (from average depth)	602
Groundwater Well-Pumping (from 400 ft depth)	2000
Groundwater Distribution to Treatment Facility (Average)	611
Surface Water Pumping to Treatment (Average)	1205
Selected End-use activities	
Dishwashers	83,474
Clothes Washers	35,752
Water Heating	20,562
On-site wastewater treatment	2,455
Water-cooled chillers	207,763

Although the current energy use for public water utilities is relatively small compared to other end-uses of water at the national level (Figure 1), the energy required to treat and move water in water scarce states such as Texas is likely to grow since marginal water sources are more energy consumptive than the baseline water supply. The energy intensity (i.e. the energy consumed for every unit of water treated, moved, or used) of any water system is determined by factors such as source water quality, the water's intended end-use quality, temperature, pressure, and the total distance that the water must be pumped through treatment, end-use, and disposal.

Table 1 highlights the energy intensity of some common modes of water treatment, pumping, distribution, and end-use. Although the energy intensity of some activities such as water-cooled chillers or dishwashers is very high, the overall energy consumed by these activities is lower than some of the less energy intensive activities since only a fraction of water is used for these activities. Since energy requirements for water systems vary significantly by geographical factors, season, and local water quality standards, the energy consumption of regional water systems vary significantly. Current trends suggest that many regions of the US, especially arid states like Texas, are shifting towards more energy consumptive treatment and pumping practices.

Methodology and Results

This study used ArcGIS to evaluate regional shifts in the energy consumed for water supplies in Texas. Texas has large climatic and geographic variations that confound regional analyses, especially in regards to water management, which is particularly sensitive to local characteristics. ArcGIS offers the functionality of considering layers of special data that allow for the methodical consideration of all counties across the state that would be nearly impossible by hand.

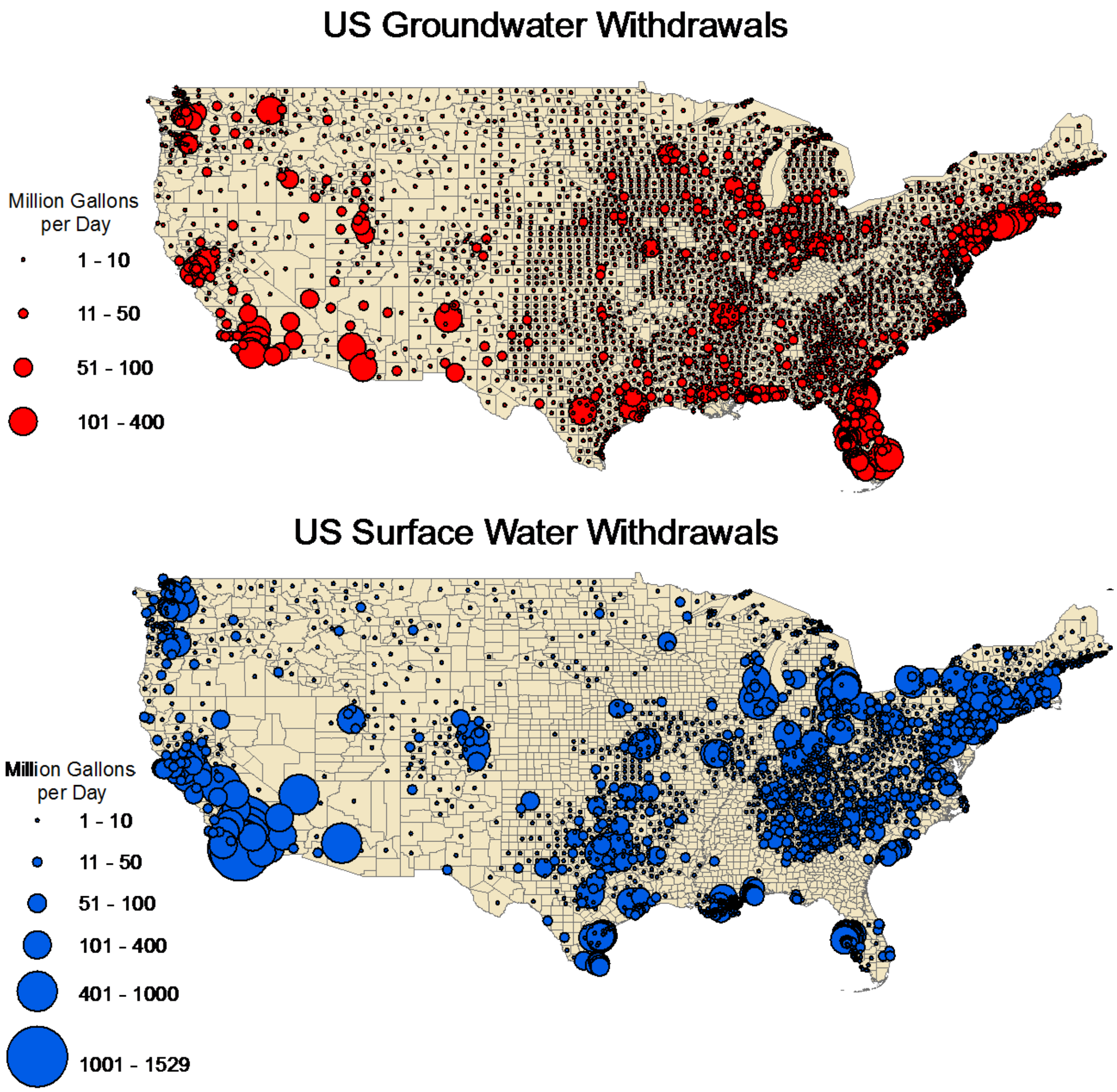
Objective 1: Quantifying the amount of energy that Texas' public water utilities collectively use to extract, treat, and distribute water to customers

To begin this study, I had to estimate the baseline energy consumption for public water supplies in Texas. A national dataset detailing water withdrawal data at the county level from the United States' Geological Society (USGS) was downloaded and joined to a US county shapefile table by FIPS code using the **Join** function. The water withdrawal data summarized 2005 water use, as this was the most recent year that these data were collected. The resulting table included water withdrawal data for every county in the US with feature information so that a US map could be created. Accordingly, I created two US maps that displayed county-level surface water withdrawals and groundwater withdrawals (Figure 2).

Since this analysis was Texas specific, the US county water withdrawal map was clipped using the **Clip (Analysis)** tool, which extracted the state of Texas from each respective dataset using a shapefile of the state. Since the US map and the Texas shapefile were in different coordinate systems, the final output was transformed to a common coordinate system appropriate for Texas:

Geographic Coordinate System: GCS_North_American_1983
Datum: D_North_American_1983
Prime Meridian: Greenwich
Angular Unit: Degree

Figure 2. 2005 US groundwater withdrawals and surface water withdrawals by county (Data from [6].)



The final clipped surface water and groundwater maps of Texas are summarized in Figure 3 and Figure 4, respectively. By changing the **Symbology** of the maps between Figure 2 and Figures 3 and 4, different insights could be derived. In Figure 2, the area of the circles between groundwater and surface water withdrawals correspond to the identical values, and thus, lend themselves to direct comparison. Conversely, in Figures 3 and 4, all values can be viewed in a more orderly grid, but the relative differences between surface water and groundwater withdrawals are harder to visualize.

Figure 3. County-level surface water withdrawal data from USGS indicate that large metropolitan areas are typically served by surface water systems (i.e. Dallas-Fort Worth, Austin, and Houston). (Data from [6].)

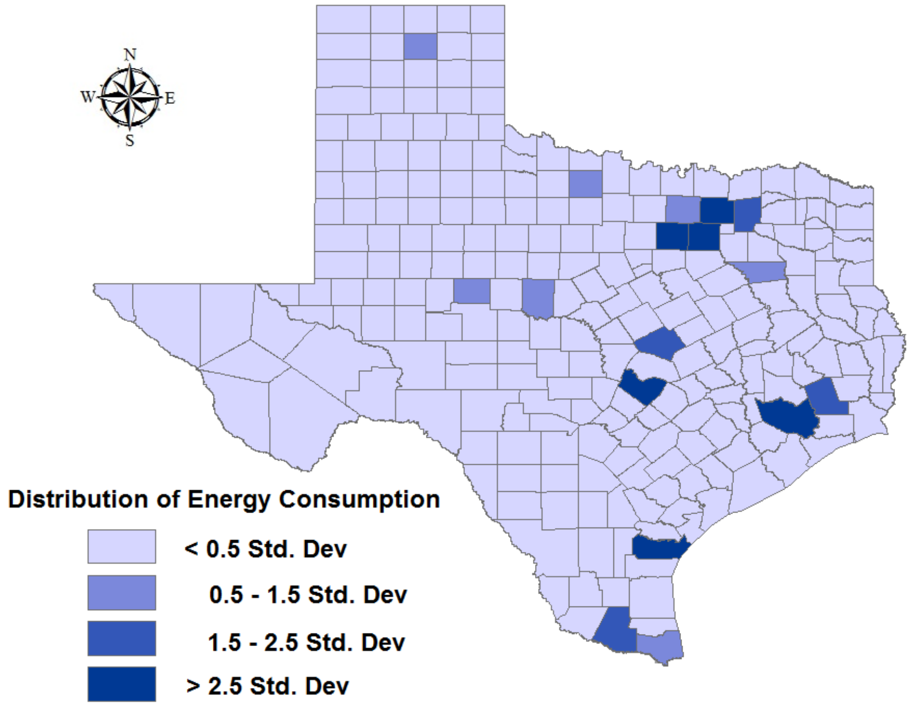
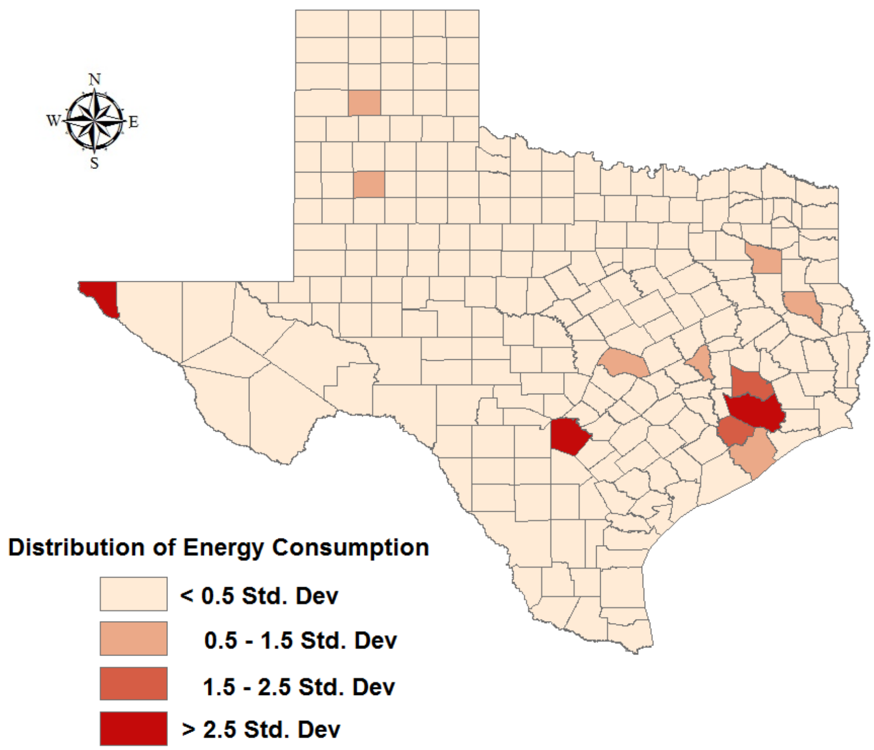
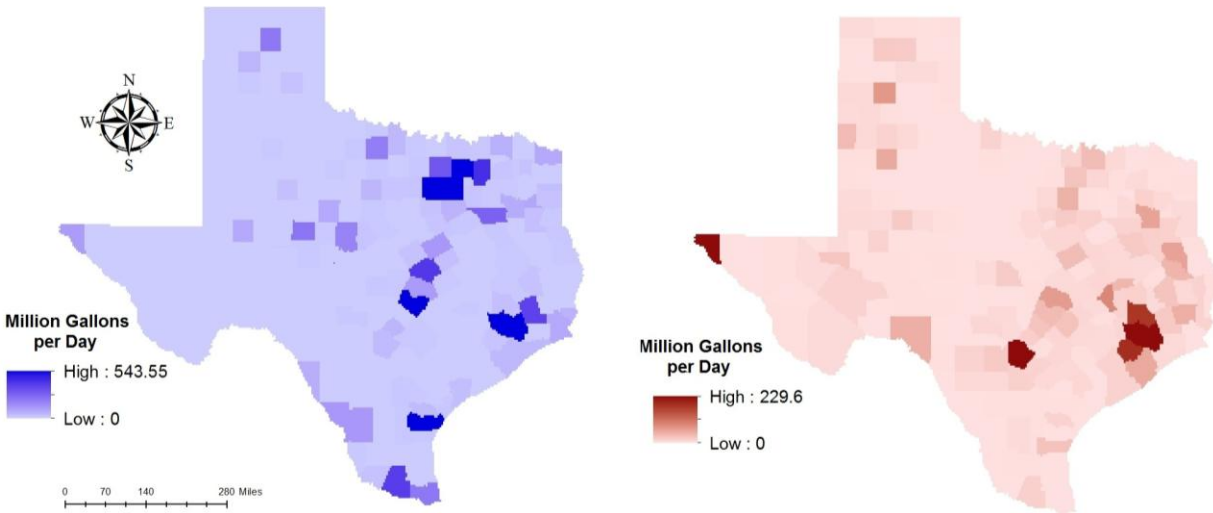


Figure 4. Groundwater data indicate that Harris, Bexar, and El Paso counties extract significantly more volumes of groundwater than other counties in the state. (Data from [6].)



Next, the groundwater and surface water withdrawal maps were converted into raster files using the **Feature to Raster** tool in ArcTools as seen in Figure 5.

Figure 5. Surface water (blue) and groundwater (red) withdrawal raster maps were created by converting shapefiles to rasters to facilitate raster calculations in subsequent steps.



These maps were used in conjunction with the **Raster Calculator (Spatial Analyst)** tool to compute the electricity used for water treatment and pumping by public utilities for each county.

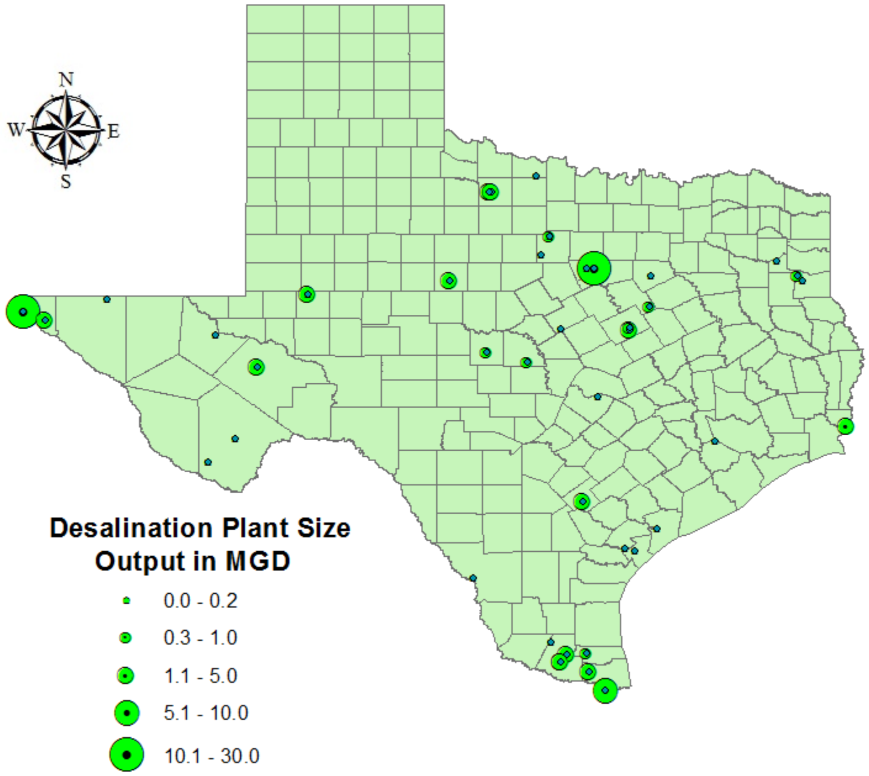
First, the average electricity intensity of surface water supplies (E_{SW}) and ground water supplies (E_{GW}) were computed using data from Table 1. The total electricity intensity of different water supplies was defined as the sum of the electricity intensities well-pumping (i.e. pumping water against gravity), pumping raw water to the treatment facility, and water treatment at the public water utility.

E_{SW} = Total electricity intensity of average surface water supplies
E_{SW} = "Surface Water Treatment" + "Surface Water Pumping to Treatment (Average)"
E_{SW} = 220 kWh/MG + 1205 kWh/MG
E_{SW} = 1400 kWh/ MG (rounded to 2 significant figures)

E_{GW} = Total electricity intensity of average groundwater supplies
E_{GW} = "Groundwater Treatment" + "Groundwater Well-Pumping (from average depth)" + "Groundwater Distribution to Treatment Facility (Average)"
E_{GW} = 620 kWh/MG + 602 kWh/MG + 611 kWh/MG
E_{GW} = 1800 kWh/MG (rounded to 2 significant figures)

In addition to standard surface water and groundwater treatment, Texas currently desalinates about 85 million gallons of brackish groundwater per day, which represents about 2% of total state water withdrawals (or 7% of all groundwater withdrawals). The electricity requirements associated with these withdrawals were calculated by multiplying the average power intensity of brackish water desalination and pumping (assumed to be an average of the range provided in Table 1, E_{BW} = 6800 kWh/MG) by the volume of desalinated brackish water produced in applicable counties (Figure 6). Although Texas only desalinates 2% its municipal water supply, this small proportion of the water supply represents over 9% of the statewide power demand of public water utilities due to the increased energy requirements of brackish desalination water treatment.

Figure 6. Currently operating desalination plants in Texas represent approximately 2% of Texas' water supply (85 million gallons per day total) but 9% of public water utility power demand. (Data from [5].)



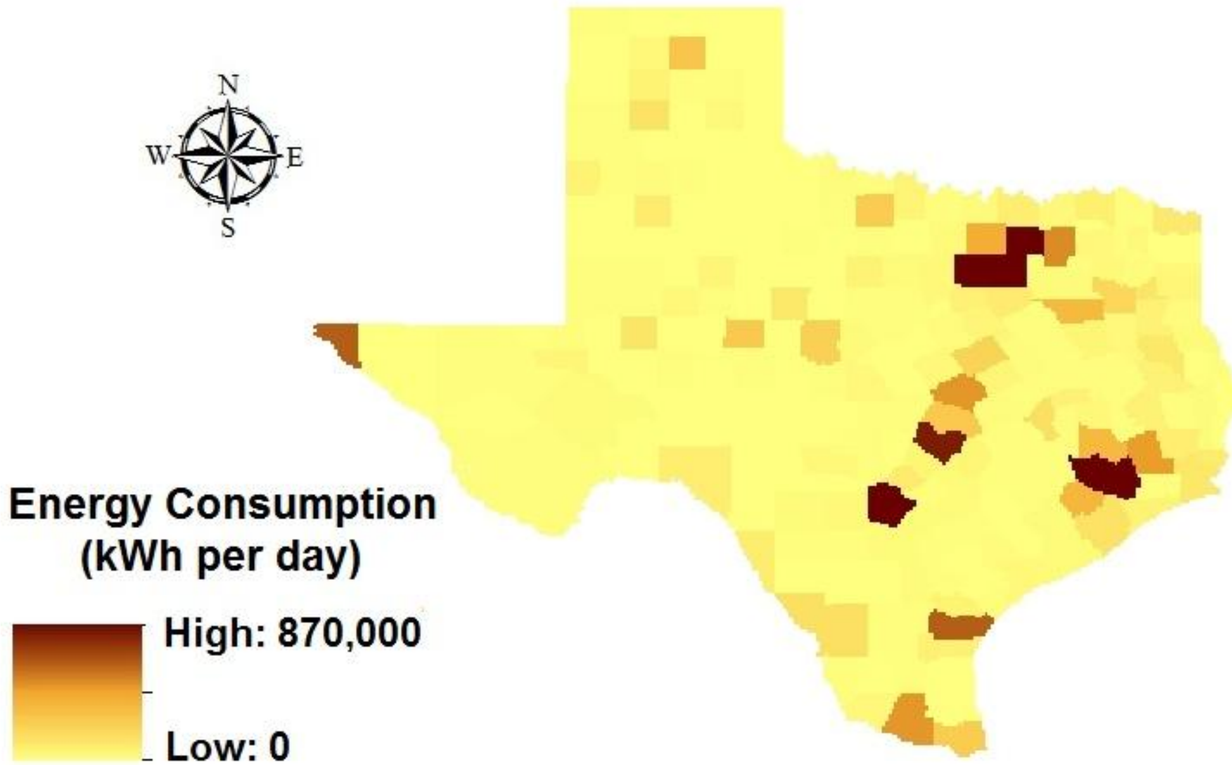
Given electricity intensities E_{SW}, E_{GW}, and E_{BW}, the electricity consumed for each county was calculated by multiplying the total electricity intensity of the given water supply, by the volume of each respective water source delivered by public water utilities within a specific county. For example, if public water utilities delivered 1 million gallons per day (MGD) of surface water in a county, the total electricity consumed for that volume of water would be 1400 kWh per day. This methodology was employed using the following equation within the **Raster Calculator (Spatial Analyst)** tool:

$$\text{Total Electricity} = E_{SW} \times V_{SW} + E_{GW} \times V_{GW} + E_{BW} \times V_{BW}$$

where V_{SW}, V_{GW}, and V_{BW} were the volume of gallons withdrawn for surface water, groundwater, and desalinated brackish water supplies by public water utilities in 2005, respectively.

Figure 7 shows the resulting raster map of electricity consumption by each county for surface, groundwater, and brackish groundwater treatment at public water utilities. Counties containing large cities (i.e. Dallas, Austin, San Antonio, and Houston) consumed the greatest amount of electricity for public water supplies, which is consistent with the fact that they withdraw the greatest volumes of water for the public supply across the state (Figure 5). Five counties consumed no electricity through public water utilities indicating that people in these counties are served primarily by private groundwater wells.

Figure 7. County-level public water withdrawal data from the USGS were used to create a raster map of electricity consumption for surface water, groundwater, and desalinated brackish water treatment and pumping by public water utilities. County-wide electricity consumption by public water utilities ranged from 0 to 870 MWh per day.



Overall, the water currently supplied by Texas' public water utilities via surface water, groundwater, and brackish water desalination was found to consume approximately 7 GWh per day or about 2.6 TWh per year. On average, each county consumed approximately 28 MWh per day or 10 GWh per year. However, as seen in the histogram in Figure 9, a few counties skew the average upward.

Figure 8. The majority of Texas' 254 counties consumed between 100 and 200 MWh per day for surface water and groundwater treatment via public water utilities. Dallas county and Harris county were outliers, consuming 760 and 860 MWh/day, respectively.

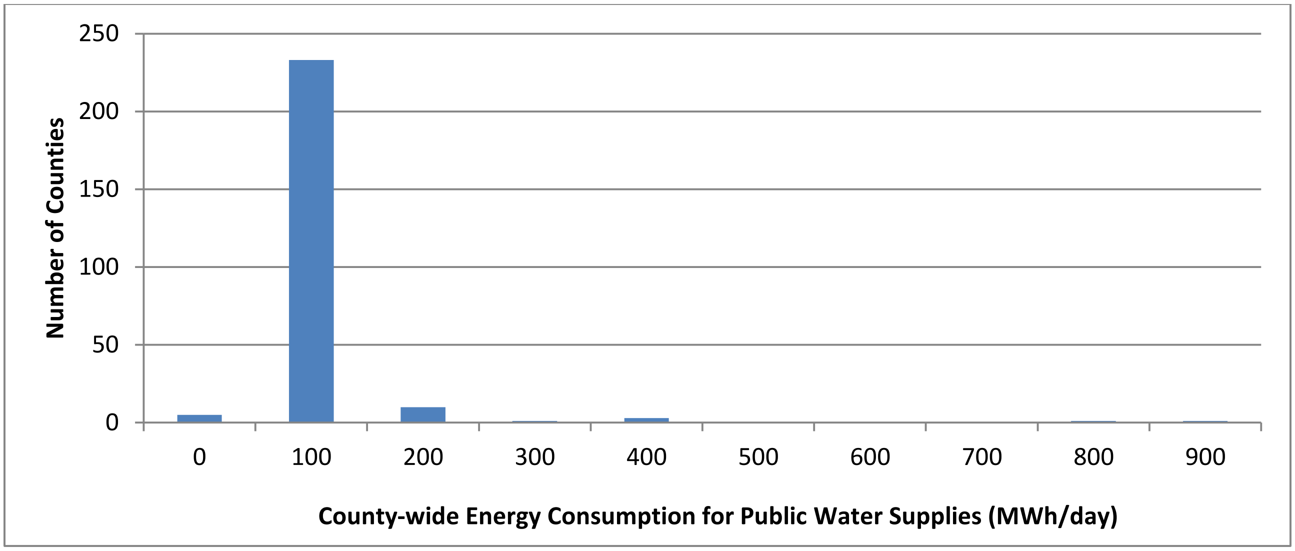
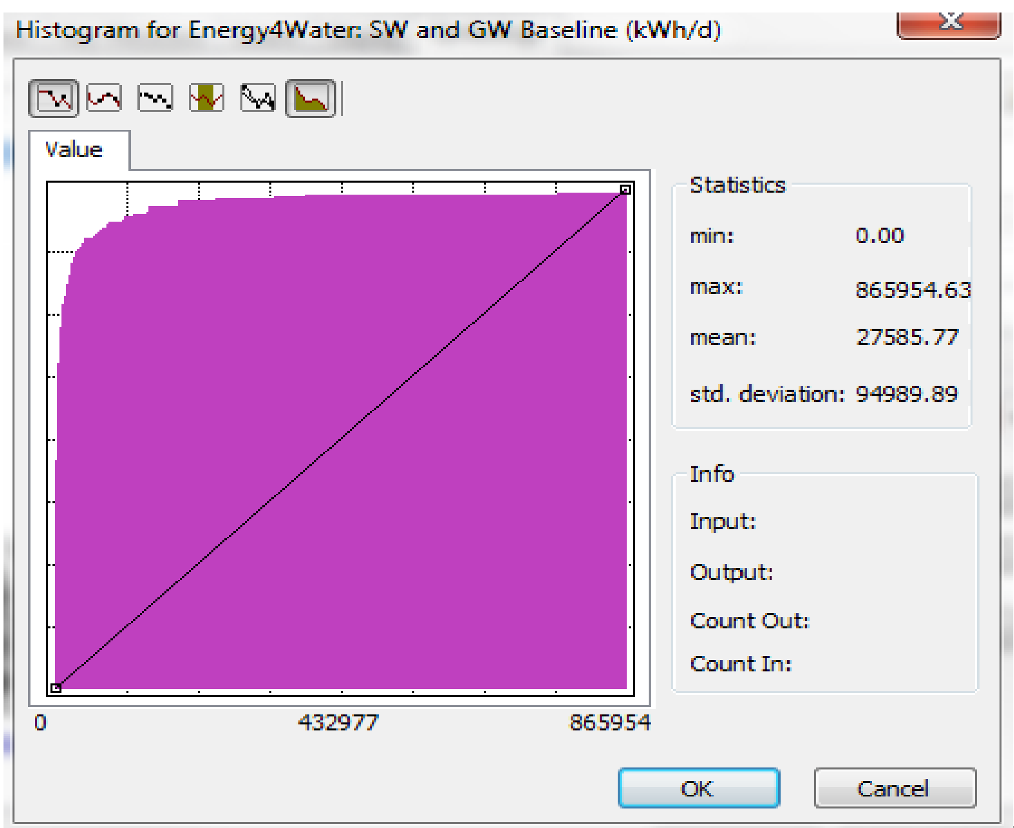


Figure 9. Public water utilities consumed an average of 27.6 MWh per day in Texas counties, but the standard deviation of these data indicates that the spread is quite large.



Objective 2: Evaluating potential increases in energy consumption, by public water utilities, that follow an increased reliance on desalinated water

Next, shifts in power consumption based on shifts in water supplies were evaluated based on several different water extraction scenarios. Although the overall water demanded by the state of Texas is projected to increase in the future, these increases for the public supply will not be uniform across Texas' counties and will be impacted non-uniformly by a number of factors such as population growth, industry growth, energy prices, end-use technology efficiency, leakage rates, etc. Thus, this initial analysis does not anticipate future increases in water demand and only evaluates the substitution of supplies to compare against changes from the baseline described above (i.e. the total water delivered by public water utilities to each county is held constant, while the treatment technology/water source shifts).

Two different changes to the water supply were considered in this study. The first considered increases in desalinated brackish water supplies in counties on the interior of Texas (i.e. a specified distance from the coast) and the second considered increases in desalinated seawater supplies in counties adjacent to the Gulf of Mexico.

To date, desalination projects in Texas have been limited to brackish water desalination, typically in facilities less than 5 million gallons per day. To quantify the change in power demand upon significant shifts from baseline water treatment towards desalinated water treatment, a shapefile was created that isolated counties a prescribed distance from the coast. Counties sufficiently far from the coast were clipped from 14 coastal counties, as these interior counties are more likely to desalinate brackish groundwater in the future than seawater. (See Figure 10.) A shapefile containing the volume of total public water supplies demanded across each of these interior counties from the USGS 2005 data was created and then converted to a raster using the **Raster Calculator (Spatial Analyst)** tool. Based on the associated raster map, the **Raster Calculator (Spatial Analyst)** tool could be used to consider a number of other scenarios.

Four scenarios were modeled in addition to the baseline scenario to evaluate how shifts in water treatment towards brackish water desalination might increase the electricity required by public water supplies in the future. Since the area of interest was so vast for these scenarios, modest shifts, as well as large shifts, in the volume of desalinated brackish water treated for each county were evaluated. Specifically, the electricity increase following a 2%, 5%, 10%, or 20% (i.e. "p" in equation below) shift from baseline water supplies to brackish desalination was quantified for each scenario. Since no increase in water demand was considered, the first scenario considered a scenario in which 2% of current water supplies in the interior counties were shifted to brackish water desalination in place of baseline treatment practices. The resulting increases in power demand for these interior counties are summarized in Figure 11. The power demand resulting from each scenario was calculated with the **Raster Calculator** by the following equation:

$$\text{Total Electricity} = (E_{SW} \times V_{SW} + E_{GW} \times V_{GW}) \times (1-p) + E_{BW} \times V_{BW} \times p$$

Figure 10. Counties a prescribed distance from the coast were clipped to create a new shapefile that only includes interior counties shown here.

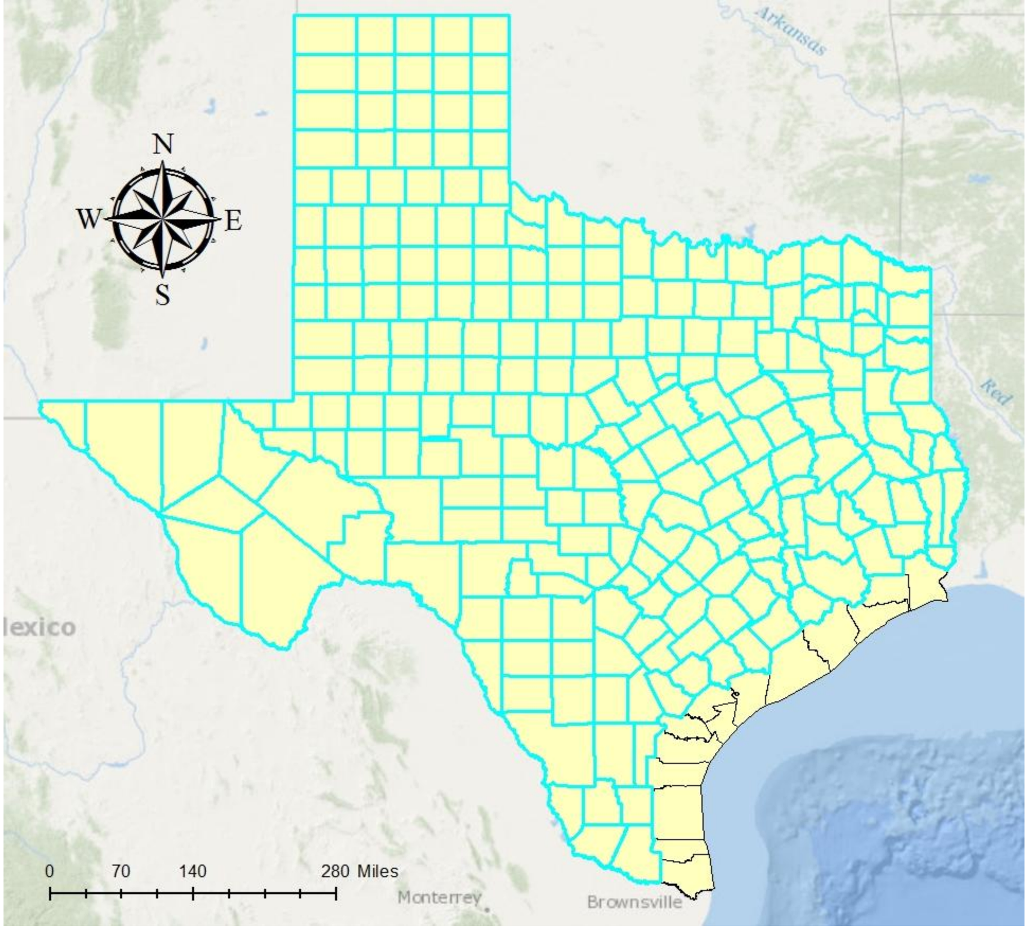
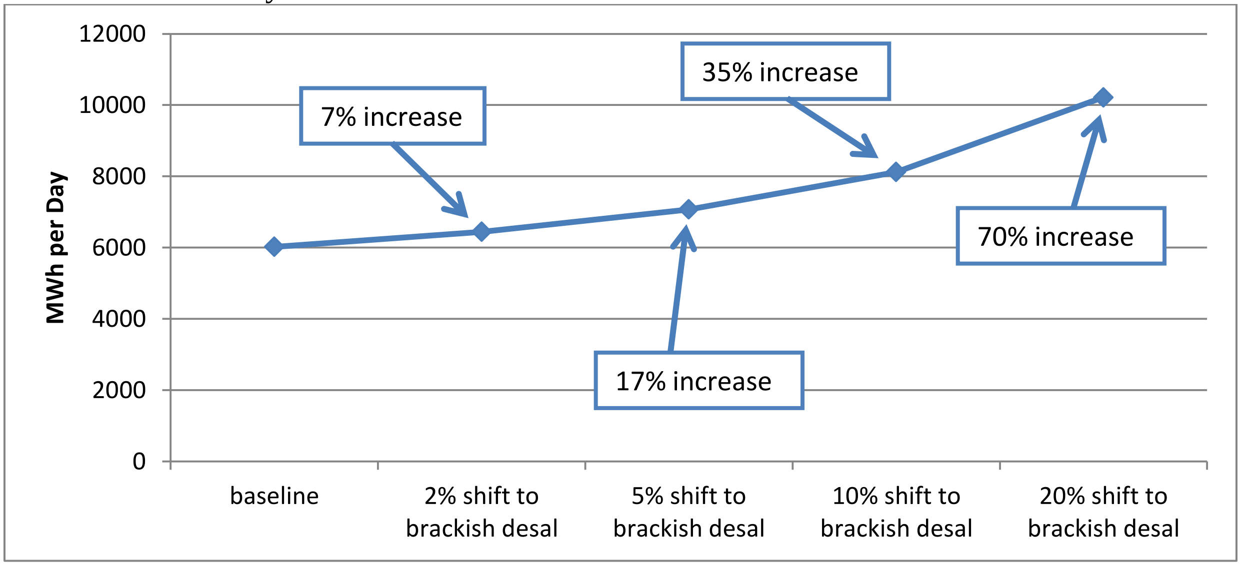


Figure 11. Shifts from baseline water treatment practices in Texas' interior counties (n = 240) to brackish desalination could increase the electricity demanded by public water utilities in these counties substantially.

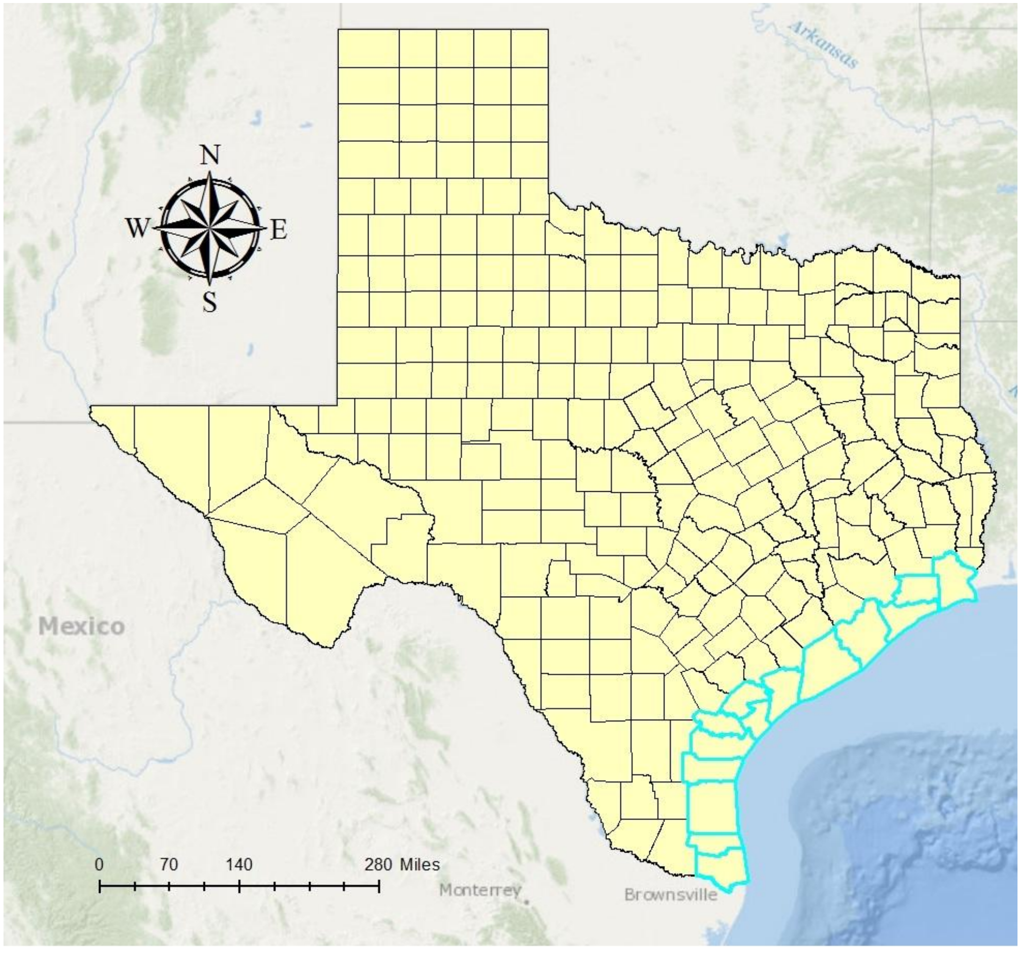


Next, a similar methodology was assumed to consider increases in seawater desalination. In these scenarios considered above, the 14 coastal counties excluded in the interior analysis were isolated from the interior counties. Six coastal county scenarios were modeled in GIS by assigning varying levels of seawater desalination to replace existing water supplies. An average energy intensity of E_{SeaW} = 13,100 kWh per million gallons of treated water was assumed for desalinated energy supplies from seawater. A 10% supply shift represented all 14 coastal counties shifting 10% of their existing water supplies to seawater desalination, while keeping 90% the same as the baseline scenario. Water demand was held constant. The county-level power demand resulting from each sea water desalination scenario was calculated with the **Raster Calculator** by the following equation:

$$\text{Total Electricity} = (E_{SW} \text{ x } V_{SW} + E_{GW} \text{ x } V_{GW)} \text{ x } (1\text{-p}) + E_{SeaW} \text{ x } V_{SeaW} \text{ x p}$$

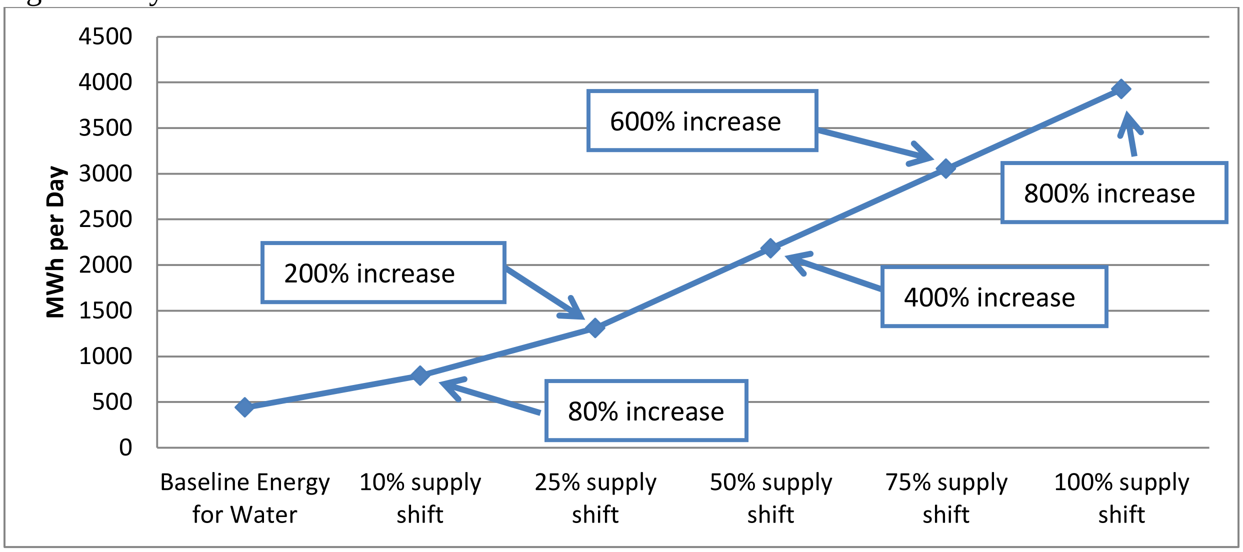
Where V_{SeaW} represented the volume of sea water assumed to replace baseline water supplies in each scenario.

Figure 12. Counties along the coast were clipped into a separate layer as these are the counties that are conducive to seawater desalination facilities in the future, as well as groundwater contamination via saltwater intrusion.



Depending on the level of seawater desalination in these counties, the energy required for water treatment and pumping across these 14 counties could increase substantially from the baseline. Shifting the current supply of water for these 14 counties to 10%, 25%, 50%, 75%, and 100%, increased the energy for public water supplies by 80%, 200%, 400%, 600%, and 800%, respectively. However, when considered in the context of total public water utility energy use across all 254 counties in Texas, shifting the water supply to desalinated water in these 14 counties will only increase total statewide energy for the public water supply by 0.05% as these counties only represent 7% of total Texas' water withdrawals. Thus, even though seawater desalination is more energy intensive than other types of water treatment, the power demand will be dependent on the volume of water provided by this technology. Results are summarized in Figure 13.

Figure 13. Significant shifts in coastal Texas counties from surface water and groundwater supplies to seawater desalination would increase the local energy intensity of water supplies significantly.

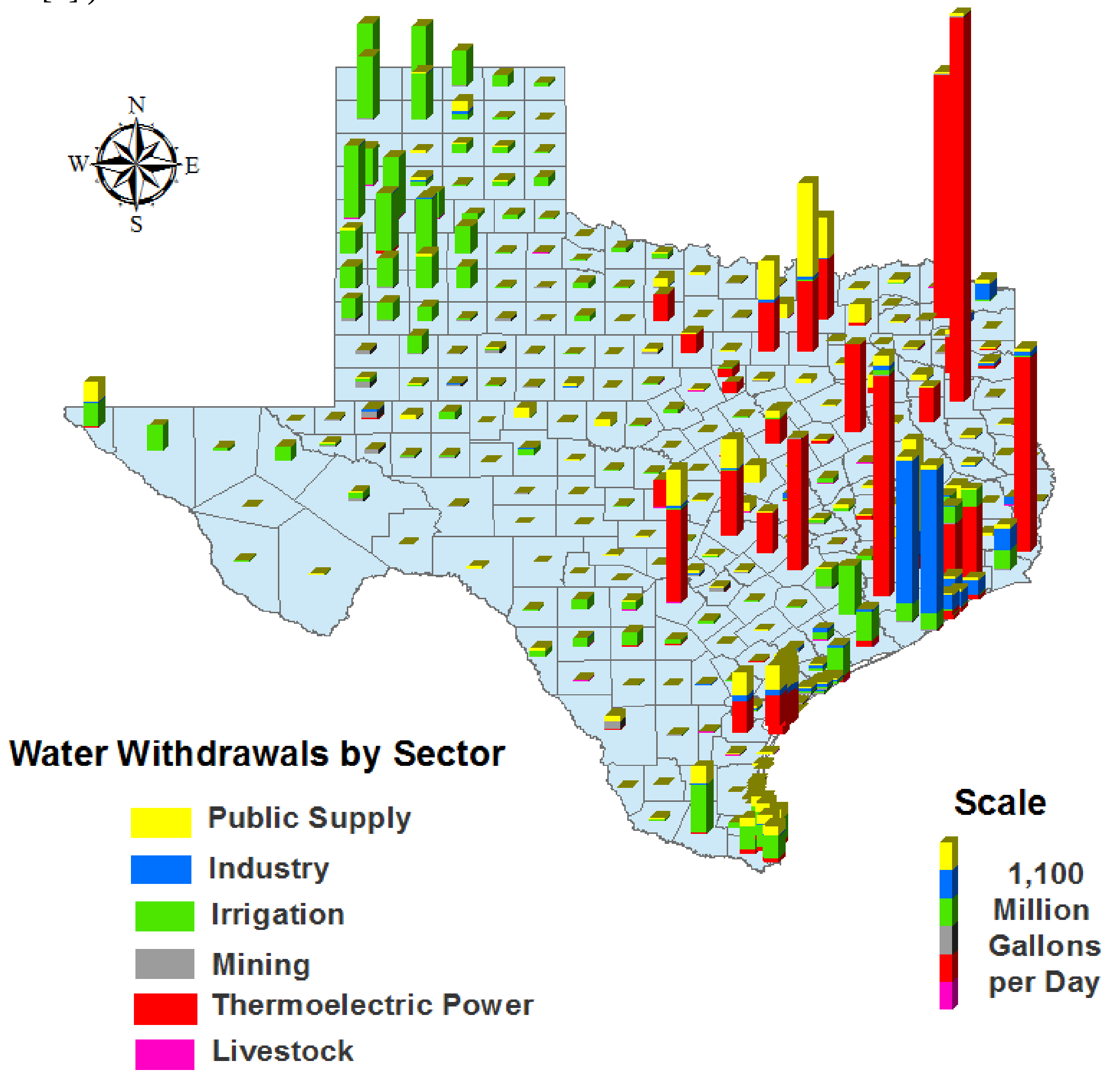


Objective 3: Comparing the energy consumed by public water utilities to the energy consumed for public water supplies at the point-of-use, as well as across other end use sectors.

Next the energy consumed throughout the entire water cycle water calculated to estimate the energy required for all of Texas' water supplies across all sectors. Figure 14 describes the volume of water withdrawn for each sector considered in this stage of the analysis. Thermoelectric power demand or irrigation required the most water by volume for most counties.

Based on these county-level water withdrawal data, an energy intensity was assigned to each sector so that the primary associated with any pumping, treatment, or end-use could be described. These energy intensities were derived from the national analysis of the energy for water in the US described previously and national water withdrawal data from the USGS [4].

Figure 14. Water withdrawal data by county and sector collected by the USGS. (Based on data from [6].)

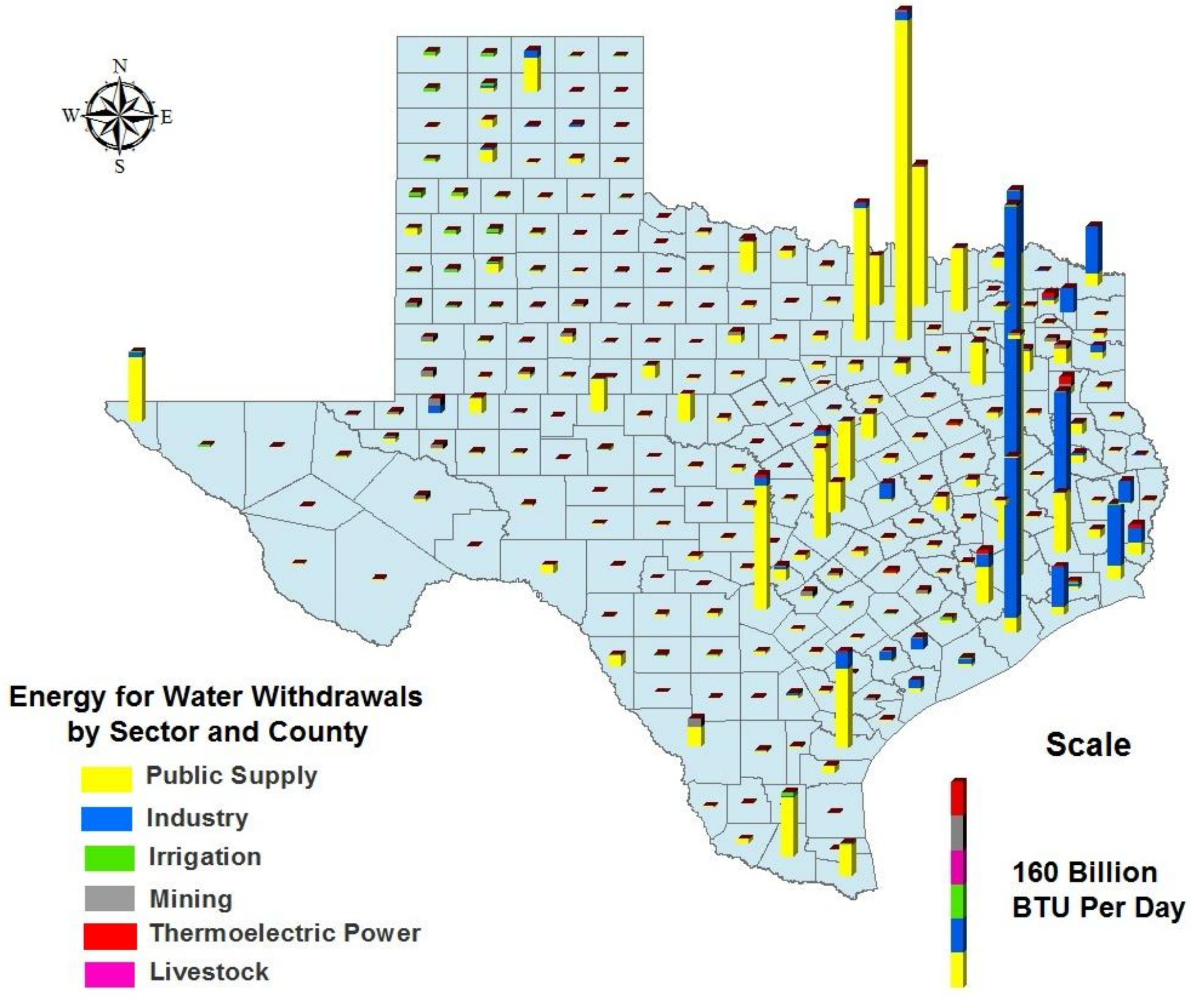


The energy intensity of public water supplies was derived from the baseline scenario described in Objective 1 of this paper, which concluded that 7 GWh per day or about 2.6 TWh per year of electricity was consumed across the state for the public water supply. Since this conclusion is in terms of power consumption, a secondary form of energy, a heat rate was required to convert it into units of primary energy. (A heat rate describes the primary energy consumed in a power plant to produce a unit of electric output. Thus, an average, weighted heat rate considers the characteristics of each power plant in the Electricity Reliability Council or Texas (ERCOT) grid to derive an average based on actual operational constraints.) Accordingly, the weighted average heat rate across all power plants in the ERCOT had to be multiplied by this electricity consumption to derive a metric in units of BTU. Once the primary energy for public water supplies was derived and divided by the entire volume of water delivered by public water supply utilities across the state, an average energy intensity of 0.47 billion BTU per MG was calculated. Table 2 summarizes the energy intensity calculation for each sector based on state or national data.

Table 2 summarizes how these energy intensities were computed by sector.

Sector	Energy Consumed for Water by Sector Nationally from [4] (billion BTU per day)	Water Withdrawals from [6] (MGD)	Energy Intensity (billion BTU per MG)
Public Supply (TX)	1750	3272	0.47
Industrial (USA)	12000	37000	0.32
Irrigation (USA)	1000	127000	0.0079
Livestock (USA)	1000	4000	0
Mining (USA)	1000	4000	0.25
Thermoelectric (USA)	21000	201000	0.0050

Figure 15. The energy consumed for water-related purposes (i.e. pumping, treating, heating, pressurizing, cooling, and evaporating) in the public supply sector was larger than other sectors in most counties of Texas.



Next, the volume of water supplied to each county for each respective sector in Texas was multiplied by each corresponding energy intensity metric listed in Table 2. The result indicated the primary energy that was consumed for each sector within each county for its water supplies. Results are summarized in Figure 15.

Comparing Figure 14 and Figure 15, we see that the volume of water withdrawn within each sector does not necessarily correspond to the energy consumed to prepare that volume of water. For example, if the goal is to conserve water, Figure 14 would suggest that implementing more efficient irrigation systems or dry-cooling systems to power plants would provide large savings in water in these sectors. However, if the goal is to conserve energy, reducing water use in the Public Supply would be advantageous. The main reason for these trends is that the irrigation and thermoelectric power sectors, for example, withdraw large amounts of water, but they do very little to it. Treatment and pumping are typically very minimal in these sectors, and the water is typically not heated or pressurized, meaning that the volumes are large, but the energy intensities are not. Water delivered in the pubic supply, however, is typically treated to a standard designated as safe for drinking by the US Environmental Protection Agency and might be pumped long distances from its point of extraction to its point of treatment. Once the water reaches its point of use, municipal customers will often heat, pressurize, cool, or waste (via leaks) their water, all of which have important energy implications. Therefore, the volumes of water within the public supply are relatively low in comparison to other sectors, but the energy intensity of the water is very high.

Discussion

This project carried out a first-order analysis of the energy used for Texas' water supplies, with special attention to the role of increasing desalination in the future. The next steps of this analysis will be to create a more refined estimate of the amount of desalinated water supplies that each county might exploit in the future by considering projected population growth and projected water scarcity.

One means of doing this might be to try and anticipate increases in marginal water supplies by corroborating withdrawal data with a water scarcity metric, such as the one created by the NDRC in Figure 6. This metric consider future water demand, available precipitation, changes in available precipitation, the ratio of groundwater withdrawals to total withdrawals, surface storage, and changes in summer deficits in 2050 to project 5 criterions: available renewable water, groundwater use, and susceptibility to drought, the increased need for storage, and the growth and water demand in 2050 within a climate change scenario. If the criterion falls above or below a certain threshold that indicates susceptibility to water stress, it is assigned a value of one; if the criterion does not indicate water stress it is given a value of 0. The sums of these 5 values are mapped in Figure 16, with 5 indicating the most severe water scarcity scenario. Areas of high water scarcity are likely to require more energy intensive water supplies as time proceeds [10].

It should not be understated, the complexity of modeling increases and decreases in water demand as it does not relate linearly to population growth. According to the State Water Plan conservation will also play a major role in achieving anticipated water demand in the future, which will affect both the quantity of water extracted across Texas, as well as, the energy for those water withdrawals. However, mapping the conservation goals in GIS lends some insight into the feasibility of these conservation plans. Figure 17 shows the conservation goals by all of the TWDB's regional planning districts for 2020, 2030, 2040, 2050, and 2060 (left) , as well as how these conservation goals are proportioned as a fraction of total water supply in 2060. Many planning regions rely quite heavily on conservation schemes (A, B, O, E, M, and K) to supplement a significant volume of their demand in 2030. Most of these conservation goals are anticipated to come from irrigation water savings. Comparing these goals to the map of withdrawals by sector (Figure 14), it is evident that some of these counties do withdraw large volumes of water for irrigation, and therefore, might be able to realize their conservation goals, but some counties (e.g. K) withdraw relatively little irrigation water, and thus should do studies to evaluate the feasibility of their anticipated goals. I also wanted to map per capita water demand from the public water supply alone to see how much water from the public water supply Texans currently use. Figure 18 shows per capita water use. Counties shaded in green indicate counties where residents are already falling at or below the recommended conservation goal set by the TWDB of 140 gallons per capita per day [1]. Thus, many counties might have trouble achieving aggressive conservation goals since they are already relatively water lean. These trends are also important to consider when evaluating future water demand.

Figure 16. Projected water scarcity susceptibility for Texas Counties in the year 2050 under a climate change scenario. (Data from [10].)

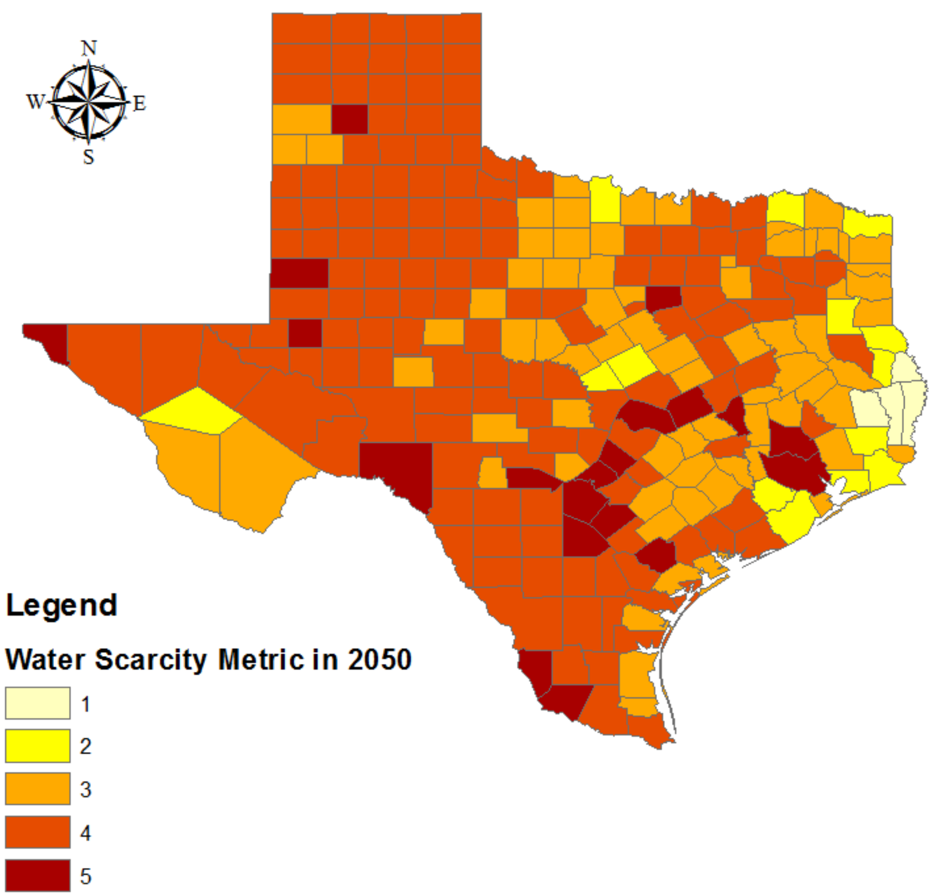


Figure 17. Water conservation will play an increasing role in achieving future water demand for many TWDB planning regions. The diagram on the left shows conservation goals by year in units of acre-ft per year. The diagram on the right, shows the proportion that these conservation strategies represent in context of total anticipated 2060 water demand. (Data from [1].)

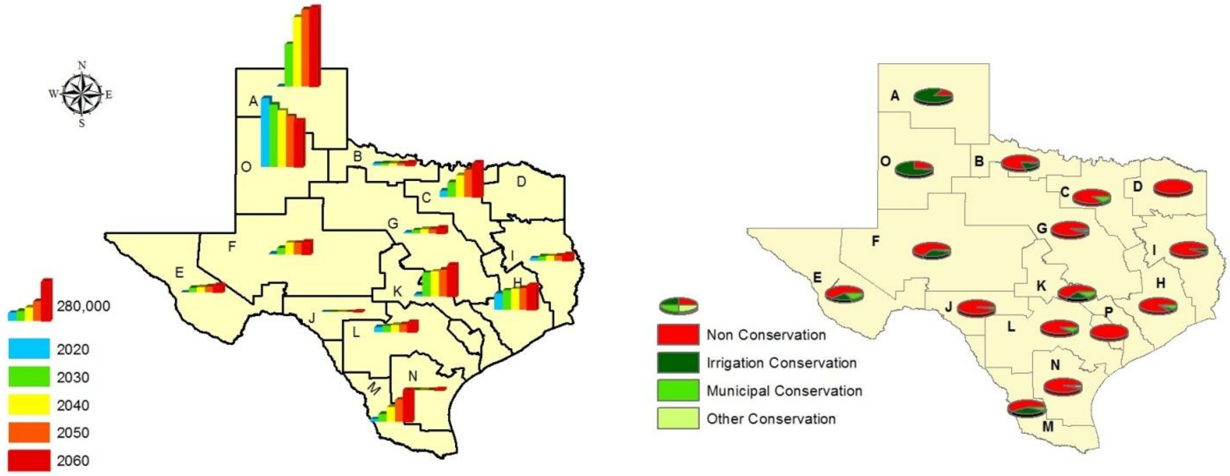
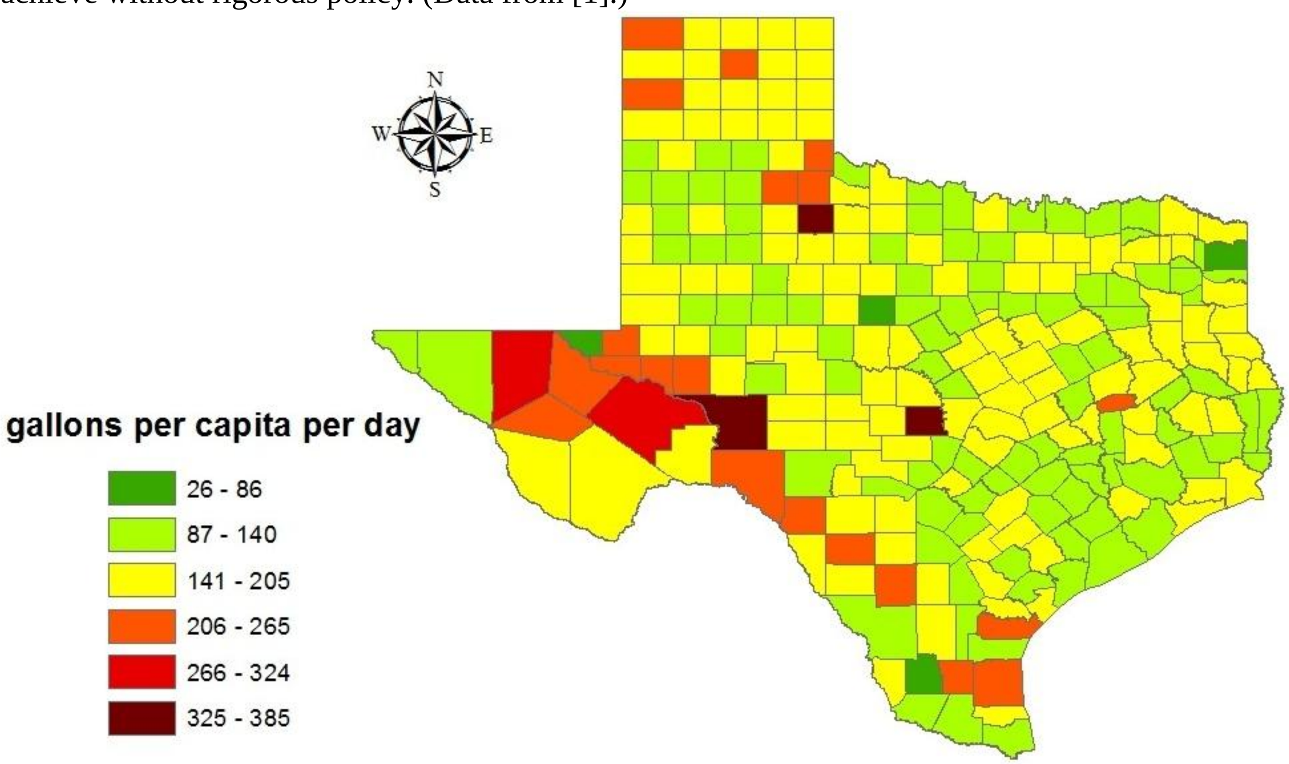


Figure 18. Municipal water demand data from 2010 suggest that many counties have already achieved the per capita water use suggested by the TWDB (i.e. under140 gallons per capita per day – shown in shades of green) so some municipal conservation goals might be difficult to achieve without rigorous policy. (Data from [1].)



Conclusion

Overall, the results of this analysis indicate that Texas consumes approximately 15% of its annual energy consumption on its water supplies. Approximately one third of this energy use was for water heating and another third was for direct steam injection, based on the results of my recent national analysis. Only 0.2% of Texas' total primary energy consumption was for water pumping and treatment by public water utilities; rather, the majority of energy use was consumed once that water was delivered to the residential and commercial sectors at end use. If we only consider electricity consumption, public water utilities consumed nearly 1% (2.6 TWh) of Texas' annual electricity generation on water treatment and pumping. Depending on the increase in marginal water supplies, such as desalination, the electricity consumed by public water utilities might increase substantially.

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