TEXAS STATE UNIVERSITY'S SAN MARCOS CAMPUS EDWARDS AQUIFER GROUNDWATER USE TRENDS AND UNTAPPED WATER CONSERVATION OPPORTUNITIES

by

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ABSTRACT:

As climate change intensifies droughts in Central Texas, water scarcity and availability are becoming increasingly urgent issues. Texas State University (TXST) is at the forefront of this challenge. The TXST San Marcos campus relies on the Edwards Aquifer, an environmentally sensitive and economically important water resource, for ~70% of their potable water supply and Spring Lake and the San Marcos River for non-potable water uses. The Edwards Aquifer provides water to over 2 million people regionally and is currently stressed as climate change and demand tests the regulatory flow protection measures established to sustain spring flows through conditions comparable to the drought of record. It is critically important to analyze TXST's water usage and identify opportunities for water conservation to improve campus sustainability and support an ecologically resilient San Marcos springs and river ecosystem. Using descriptive statistics and correlation analyses, I examined relationships among water use and climate, and overall water use temporal trends from 2015 to 2024. The results will contribute to furthering our campus community response toward improving water conservation. This will help TXST maintain regulatory compliance, increase the resiliency of its water supply, protect the San Marcos springs and river, and enable TXST to continue growing and expanding its recognition as an academic leader in Texas.

I. **Introduction**

In response to the pressing need for sustainable water management in Central Texas, this research seeks to conduct an analysis of water usage and examine untapped water conservation efforts tailored specifically for Texas State University (TXST). By seamlessly integrating a historical and contemporary analysis of water usage on campus, the aim is to cultivate a collective stewardship perspective towards responsible water usage and conservation on campus. While the university has made strides in water conservation as a permittee of the Edwards Aquifer Habitat Conservation Plan, the escalating impacts of climate change, characterized by more frequent and severe droughts in Central Texas, emphasize the urgency for enhanced efforts (Zhang et al. 2019). Currently, a significant portion of the student body remains uninformed about the university's water resources and the journey of water from source to faucet and the threatened and endangered species on campus. Consequently, TXST must intensify its water conservation initiatives, concurrently raising awareness among students about environmental issues such as drought. As climate change and drought conditions exacerbate in Central Texas, TXST faces challenges in water availability, particularly impacting Spring Lake, the San Marcos River, and the Edwards Aquifer (Nielsen-Gammon et al. 2021).

This applied directed research project aims to formulate an analysis of water usage and explore untapped water conservation practices the university can implement to better align with current environmental conditions and drought severity. It seeks to identify opportunities for the university to conserve more water and effectively improve environmental awareness among students to foster sustainable water use practices. The significance of this study lies in providing the university and its students with insights into current water usage, conservation efforts, strategies for improvement, and sustainable options for a resilient future water supply.

i. Research Questions:

This research aims to answer the following questions: **RQ1:** What are the water use trends on Texas State University's San Marcos campus from 2015 to 2024 and what factors may be influencing water use? **RQ2:** How do water use trends compare to regulatory withdraw limits designated by the water availability during the regulatory-based Edwards Aquifer Authority Stage I through Stage V Critical Period Management drought restrictions? **RQ3:** What water conservation opportunities can be implemented on the Texas State University's San Marcos campus to reduce withdrawals on Edwards Aquifer groundwater and surface water from Spring Lake and the San Marcos River?

II. <u>Literature Review</u>

Climate change is a growing threat in Texas, affecting the local climates as well as economy. Average annual temperature, precipitation, severe weather, winter weather, sea level rise, wildfire risk, and droughts are all projected to be affected due to climate change. The average annual temperature in Texas has continually increased in the past decade and is only expected to continue increasing. By 2036 the average annual surface temperature in Texas is expected to be 3.0° F higher than the last fifty years of the 20^{th} century averages (Nielsen-Gammon et al. 2021). This will affect many aspects of Texas and its natural resources. An increase in average temperatures and more frequent summer extremes can cause a decrease in soil moisture and fertility, increased risk of wildfires, and a risk to human health.

Climate change also impacts precipitation rates in Texas. Precipitation rates are expected to vary across the state. Variability in precipitation through 2036 present rainfall events that are more intense but less frequent (Nielsen-Gammon et al. 2021). Overall, Texas is expected to shift to a more arid climate through the latter half of the 21^{st} century (Nielsen-Gammon et al. 2020).

This not only shifts local climates but impacts agriculture, surface water and groundwater, and water suppliers (Nielsen-Gammon et al. 2020). Droughts are projected to become more frequent and severe.

Through a probabilistic multivariate drought index, Zhang et al. (2019) project that although there will be an increase in frequency and intensity of extreme precipitation events the droughts will still be amplified. The multivariable assessment within this projection displays the complexities of projecting future droughts, their frequency, duration, and intensity in the future of climate change. When projecting future drought conditions, Zhang et al. includes multiple variables such as average temperature, soil moisture, precipitation averages, precipitation extremes, and temporal variables, thus creating a more accurate projection. Zhang et al. projects droughts in Texas will increase in intensity and be broken up by intense rainfall (Zhang et al. 2019).

Climate change has increased the probability of droughts in Texas, creating challenges for Texas' water supply (Caretta et al. 2022; Nielsen-Gammon et al. 2022). Droughts will affect the water supply of Texas which relies heavily on groundwater. Fifty five percent of the Texas water supply is provided by groundwater (TWDB 2020). Climate projections predict Texas to have drier conditions in the latter half of the 21st century (Nielsen-Gammon et al. 2020). Additionally, the Intergovernmental Panel on Climate Change (IPCC) predicts climate change will cause increased water scarcity problems across the world and Texas (Caretta et al. 2022).

Increased drought and higher temperatures will affect surface water, increasing the reliance on groundwater in Texas, resulting in an increase in the rate of depletion of aquifers (Mace and Wade 2008). Aquifers are becoming increasingly vulnerable due to climate change affecting recharge, storage, and over pumping due to decrease in surface water availability

(Banner et al. 2010). Furthermore, population growth will increase water demand, posing a threat to the water supply of Texas such as the Edwards Aquifer (Cook et al. 2015; Nielsen-Gammon et al. 2020).

It is important that Texas communities adapt to become more resilient to issues of water scarcity. Universities are perfect examples of communities that can lead by example through implementation of water conservation initiatives and sustainable water usage in Texas. Universities are ideal places capable of sustainable water conservation because of their stature, finances, and ability to instill practices among their students and faculty through a developed sense of place, identity, and pride. Universities in Europe have begun to inform students through sustainability policies and practices through the implementation of water conservation practices on their campuses. Barreiros and colleagues (2023) evaluate water conservation practices and consumption on university campuses in Portugal to “improve and promote green and sustainable behaviors, and to calculate water efficiency.” A comparative analysis determined that factors such as university location, campus characteristics such as green areas and irrigation practices, and the age of buildings play a role in water conservation efforts and efficiency (Barreiros et al. 2023). TXST is located on the Edwards Aquifer and is the primary steward of Spring Lake - an environmentally sensitive ecosystem and the perennial headwaters of the San Marcos River that flows through campus. This location is also home to the Meadows Center for Water and the Environment - a nationally recognized educational and research center. These spatial factors of place can play a role in water conservation, encouraging an increase in conservation efforts and efficiency on campus (Barreiros et al. 2023).

Additionally, promoting environmentally friendly behavior on university campuses shows other potential environmental benefits other than conserving water (Parece et al. 2013). A study conducted at ten residence halls at Virginia Tech University analyzed the effectiveness of five different water conservation strategies and prompting strategies to determine which was the most effective at reducing the students' water use. The prompting water conservation strategies included basic information groups, simple feedback groups, comparative feedback groups, coaching groups, and a control group. Each group received different amounts of prompting, feedback, and educational information. However, not one strategy was more effective than the other but overall water consumption decreased (Parece et al. 2013). The decrease in water consumption resulted in a reduction of energy used, reducing the University's carbon footprint (Parece et al. 2013).

With over 30 million residents, Texas is an extremely diverse society lying on an aridity gradient (Nielsen-Gammon et al. 2020), experiencing variation in water stress with a transition from dry to wet conditions moving west to east, with a dry central (Banner et al. 2010). Water availability in Texas is a growing concern as climate change has effects, droughts intensify and become more frequent, and the population grows substantially, increasing the overall water demand. Between 2020 and 2070, the population in Texas is expected to increase by 73% to 51.5 million, with substantial growth expected to occur in the Austin metroplex (TWDB 2022).

In Texas, the six-year drought in the 1950s is considered the state's "drought of record" benchmark—when water supplies were at their lowest, and water demand was at the highest of the time. A drought of record is a pre-determined historic low used in future water planning. The most recent state water plan, the 2022 Texas State Water Plan, examines demands, existing supplies, the needs to address shortages, and the strategies for future supplies. Water demands in Texas are projected to increase by 9% between 2020 and 2070. Other estimates estimate that Texas' population growth is anticipated to create a statewide shortage of 8 million acre-feet in

2060 and 9 million acre-feet by 2070 (Sansom 2013; Cardone and Howe 2018). If appropriate strategies are not put in place, approximately 25% of Texas' population in 2070 will have less than half the municipal water supplies they will require during a drought of record (2022 State Water Plan).

With a population set to nearly double by 2070 (Banner et al. 2010), Texas' water resources need to be gauged and effectively managed to meet future needs (Mace and Wade 2008). Surface water will be dramatically affected, further increasing Texas' reliance on groundwater and depletion rates of aquifers (Mace and Wade 2008). Currently, aquifers play a significant role in Texas' water supply, providing groundwater for about 55% of the state's supply (TWDB 2020). However, aquifers are increasingly vulnerable, as recharge rates, storage capacities, and flow regimes are highly variable as a result of climate change, over pumping, and land cover changes (Banner et al. 2010; Yoon et al. 2018).

Additionally, higher temperatures associated with climate change increase evaporation rates, decreasing surface water supplies, and intensifying the effects of droughts (Banner et al. 2010). Rainfall is expected to occur less frequently but with greater intensity, resulting in flooding events with high runoff and inadequate infiltration impacting groundwater recharge (Banner et al. 2010). While the 1950s are still considered the benchmark for the statewide drought of record, more recent droughts are being referred to regionally as "the drought of record," for example, the 2011 drought in Texas (Combs 2012). As central Texas becomes even more drought prone, it is essential to proactively address water scarcity. Exploring conservation strategies and their implementation on TXST's campus can further its sustainability and resiliency to combat climate change, drought, and water scarcity for a better future.

This directed research examines TXST's water consumption trends and investigates water conservation opportunities for the campus, aimed at promoting sustainability and safeguarding the Edwards Aquifer and the flow of the San Marcos River and Springs. Strengthened conservation efforts on campus will contribute to a more resilient future water supply while preserving these critical natural resources.

III. Background

When examining TXST's water usage and conservation efforts, it is important to understand the context of the university's water portfolio and policy that governs water usage and withdrawals on TXST's campus. The university's main source of water is groundwater from the Edwards Aquifer, which is managed by the Edwards Aquifer Authority and the permittees of the Edwards Aquifer Habitat Conservation Plan.

The Edwards Aquifer is a vast, environmentally sensitive aquifer located through central and south-central Texas. The aquifer extends geographically through parts of ten counties: Kinney, Uvalde, Zavala, Medina, Frio, Atascosa, Bexar, Comal, Guadalupe, and Hays, and is the primary water source for much of the area (EAA n.d). It is one of the most productive aquifers throughout the country (EAA n.d.). The Edwards Aquifer is a karst aquifer characterized by sinkholes, sinking streams, caves, and large springs and highly productive water wells (EAA n.d.). A karst aquifer is formed over soluble rocks such as limestone reacting with mildly acidic water causing the aquifer to be extremely porous and permeable (EAA n.d.) The Edwards Aquifer is highly permeable with water contained in the interconnected rock matrix of caves and conduits, thus accounting for the high yielding wells and springs (EAA n.d.). Additionally, the karst aquifer allows for the fast-moving transmission of large volumes of water, causing groundwater levels to respond quickly to rainfall events or over pumping (EAA n.d.). In addition to its sensitivity to recharge and pumping, the aquifer is home to 40 species, including ten endangered or threatened species, furthering its environmental importance. The federally listed species of concern to the Edwards Aquifer include the Texas blind salamander, fountain darter, San Marcos salamander, Texas wild-rice, Comal Springs riffle beetle, Peck's Cave amphipod, Comal Spring's dryopid beetle, Texas troglobitic water slater, Edwards Aquifer diving beetle, and the Comal Springs salamander (Recon et al. 2022).

Edwards Aquifer groundwater withdrawals are regulated by the Edwards Aquifer Authority (EAA), which is a political subdivision of the state created to protect and preserve the aquifer and its endangered species (EAA n.d.). The EAA was formed by Legislative order of the 1993 Edwards Aquifer Act in response to legal matters regarding the need for improved protection of the endangered species that depend on the sustained quantity and high quality of water in the aquifer and spring ecosystems. The EAA is a groundwater conservation and reclamation district and a regional water management agency, political subdivision of the state to protect and preserve the aquifer and its endangered species (EAA n.d.).

In order to preserve and protect the aquifer, the Act mandated a capped permitting system that limits the withdrawals while also protecting the threatened and endangered species of the aquifer-fed Comal and San Marcos springs (EAA n.d.). The total amount of withdrawal allowed from the entire aquifer per year is 572,000 acre-feet; this amount was determined to match the annual recharge into the aquifer (EAA n.d.).

This is accompanied by an Incidental Take Permit (ITP) and a Habitat Conservation Plan (HCP). An ITP was issued to the Edwards Aquifer Recovery Implementation Program of the EAA by the U.S. Fish and Wildlife Service, which permittees of the EAA must comply with. The ITP was authorized with an HCP to protect the aquifer and its endangered species. A taking defined by the ESA means “to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct” (ESA § 10(19). An incidental taking is a taking from carrying out an otherwise lawful activity (ESA § 10(a)(1)(B)). Therefore, an ITP allows for the taking of endangered species from lawful activities as long as the permittee is mitigating, minimizing, and avoiding the take as agreed upon through a required HCP. TXST is one of the five permittees of the ITP, the others include the EAA, City of San Marcos, City of New Braunfels, and the City of San Antonio (operating through the San Antonio Water System) that operate through consensus to protect the endangered species from the primary covered activities including groundwater pumping, surface water diversions, and recreation activities.

The EAA’s HCP originated as the Edwards Aquifer Recovery Implementation Program and transitioned to the Edwards Aquifer Habitat Conservation Plan (EAHCP). This regional plan is put in place to protect the endangered species and to ensure that the regional water supply is resilient and stable (EAA 2025). The EAHCP implements conservation measures, carried out by the permittees, that consist of spring flow protection, habitat conservation, and other supporting activities including research and monitoring (EAA 2025). Habitat conservation measures consist of enhancement and restoration of habitat for endangered species as well as recreation management, non-native species reductions, bank stabilization, and water quality protections (EAA n.d.). The spring flow protection measures ensure that wells and springs flow are protected, water levels are stabilized, and that the species have enough flow to survive and have the potential to recover until rainfall recharges the aquifer (EAA 2025). TXST, as a co-permittee of the ITP because of its lawful and permitted withdrawal of the aquifer, must comply with the EAHCP to limit the university's impact on the endangered species, the Edwards Aquifer and its springs, and the San Marcos River, including the flow protection measures.

The EAA has three main flow protection measures: the Voluntary Irrigation Suspension Program Option (VISPO), Aquifer Storage and Recovery (ASR), the regional water conservation program, and Critical Period Management withdrawal reductions. Critical Period Management (CPM) withdrawal reductions directly relate to TXST and are a focus of this research as it pertains to TXST's water usage. The CPM intends to protect the aquifer and spring flows during times of drought and declining groundwater levels (EAA n.d.). CPM is intended to slow the rate of decline of the aquifer groundwater levels and spring discharge by limiting the amount of groundwater that permit holders are allowed to withdraw (EAA n.d.). Triggers, stages, and withdrawal reductions are crucial components of the CPM (EAA n.d.). The total amount of annual water withdrawal from the Edwards Aquifer set by the EAA is 572,000 acre-feet (EAA 2022). This is monitored through permits and meters on wells to ensure withdrawals are not being exceeded (EAA 2022). The EAA permits TXST an allotment of 2,002 acre-feet of groundwater withdrawal from the Edwards Aquifer per year and TXST must adhere the EAA's flow protection measures, specifically CPM.

This plan reduces the authorized groundwater withdrawal from permit holders, like TXST. These withdrawal restrictions are designed to slow the rate of decline in aquifer levels and spring flows until the drought ceases. There are five critical period stages, with five being the most severe. The critical period stages are implemented based on triggers by well levels and spring flows. The drought restriction stages are implemented on stages that are triggered by well levels and spring flows. Each stage implements a percentage of water withdrawal reductions. For TXST, the J-17 well operated by the EAA and the San Marcos Spring flows act as triggers for the critical period drought withdrawal reduction stages. When the J-17 well hits a 10-day average below 660 mean sea level (MSL), it triggers CPM. Stage I is implemented when the J-17 is <660

(20% pumping reduction), Stage II when <650 (30% pumping reduction), Stage III when <640 (35% pumping reduction), Stage IV when <630 (40% pumping reduction), and Stage V when <625 (44% pumping reduction) (EAA n.d.). When a critical period stage is triggered, TXST must reduce its withdrawal by the associated percent reduction according to the stage.

As droughts worsen in central Texas (Banner et al. 2010; Cook et al. 2015; Nielsen-Gammon et al. 2020), it is becoming increasingly more likely that TXST will have to implement withdrawal reduction in order to comply with the EAHCP CPM withdrawal reductions as the drought conditions stay in Stage IV for longer periods and extend into Stage V reductions.

TXST currently has surface water rights to divert Spring Lake water. The max allowed surface water right diversion for Spring Lake is 100 acre-feet per year for irrigation purposes and 534 acre-feet per year for industrial use (Meadows n.d.; EAA 2019; TXST 2021). TXST is allowed a maximum diversion rate of 4.9 cfs from Spring Lake and 3.2 cfs from the San Marcos River under the Texas Commission on Environmental Quality (TCEQ) Certificates 18-3865 and 18-3866. These water rights are used for irrigation and to divert the San Marcos River water to fill the fish ponds on campus and for irrigation. Finding a solution to reduce the reliance on redirecting surface water from Spring Lake and the San Marcos River is a small step in boosting water conservation efforts on campus to protect endangered species habitat.

As previously noted, population growth in Texas is not expected to increase equally, with projections showing that growth will be concentrated primarily around the state's metropolitan areas. Hays County in Central Texas, where TXST is located, is one of the fastest growing counties in the state and in the nation (Hays County 2024). With the expanding population, water demand in Hays County has grown substantially. The 2022 State Water Plan highlights an increase in water consumption and the need for effective management of current surface and groundwater sources to meet future demands. The plan also prompts Texans to invest in water infrastructure development, providing reason to continue exploring and implementing water conservation strategies.

Furthermore, TXST's student body population is growing, and there is a retainment goal to house all incoming freshmen on campus. This year's enrollment of 40,678 surpasses the previous record of 38,849, which was set in 2016. The incoming freshman class of 8,165 first-year students set a record enrollment for the fourth consecutive year. Additionally, new buildings are using water for construction, e.g., new student housing to meet the increase in incoming students living on campus. The increase in student enrollment, more students living on campus, and new buildings on campus all result in the university using more water.

Consequently, TXST must strengthen its water conservation initiatives, concurrently raising awareness among students about environmental issues such as drought. As climate change and drought conditions exacerbate in Central Texas, the university faces challenges in water availability, particularly impacting Spring Lake, the San Marcos River, and the Edwards Aquifer (Nielsen-Gammon et al. 2021). It is important for the university to raise its conservation efforts and water usage practices of this finite resource (Zhang et al. 2023). The university must explore untapped water conservation practices that they are capable of implementing to better align with current environmental conditions and drought severity. With climate change, the increased demand and scarcity of our water resources, there is a clear need for conservation to meet future demands and to protect our aquifer and river.

This research aims to analyze TXST's water usage trends, total annual groundwater usage compared to EAA's flow protection measures CPM withdrawal reduction stages, and address ways TXST can implement additional water conservation strategies on campus to create a more resilient water supply that lessens the impact on the Edwards Aquifer and the San Marcos Springs and River.

IV. <u>Research Design</u>

This study used a quantitative methodology to examine trends in campus water use and explore the relationship between water use and climate data from 2015 to 2024. The analyses included a correlation analysis, a linear regression analysis, and descriptive statistics to assess temporal patterns across climate and groundwater data. Correlation analysis was used to explore associations between climate variables and groundwater use. Linear regression was used to further examine the relationship between groundwater use for irrigation and industrial water and climate data. Descriptive statistics were used to identify water use patterns at TXST over time and to analyze how groundwater withdrawals compare with groundwater allotment under drought conditions.

i. Study Area:

The study area for the analysis focused on TXST's San Marcos campus. Total groundwater withdrawal across campus was assessed annually and monthly through total campus withdrawal, industrial groundwater usage, irrigation groundwater usage, and residential hall building groundwater usage. Additionally, annual surface water diversion totals from Spring Lake and the San Marcos River were analyzed to contextualize overall campus impacts on local surface water. There are two main groundwater wells on TXST San Marcos Campus: the Jackson well, that provides all potable groundwater, and the Freeman Artesian well, that provides groundwater for research purposes. Additionally, there are three secondary back-up wells across campus: the Boiler Plant Well, the Grady Early Well, and the Print Shop Well. Each backup well is required to be pumped and flushed in order to maintain operational status as a backup well.

Irrigation groundwater use data encompasses groundwater withdrawal from campus wells utilized for irrigation throughout campus but excludes irrigation at the intramural fields at Spring Lake, that are irrigated with surface water. Industrial groundwater use data consists of groundwater consumed by five cooling towers and one boiler tower located on campus. The facilities are spread across campus geographically with a central plant, east plant, south plant, southeast plant, and a west campus plant. While the geographical location of each cooling tower is documented in the data, their usage was combined and treated as a single category. Residential hall groundwater use was analyzed for select student dormitories that receive water from campus wells. The following buildings were included due to data availability and size of the hall: San Jacinto, Blanco, Bexar, Freedom Five & O'Shea, Gaillardia and Chautauqua, Lantana, San Marcos, and Mesquite Halls.

ii. Data Sources:

TXST's groundwater usage data (calendar year 2015-2024) was obtained from TXST Utilities Operations. The data entailed groundwater withdrawal on campus and was organized into different categories: domestic water use, water to sewer, and annual withdrawal. Domestic water use had groundwater usage by building. Water to sewer had total water use withdrawn from the main well on campus, the Jackson well, total water withdrawn for irrigation, and total water withdrawn for industrial use by year and monthly totals. From the domestic water use data set, student residential hall building data were extracted by monthly totals for each building and yearly totals. Annual withdrawal provided the total annual withdrawal from the TXST San Marcos campus in acre-feet.

However, some records for 2015 to 2020, total annual water withdrawal were incomplete or unavailable, missing from the Utilities Operations datasets. Nonetheless, these data must be recorded and reported to the EAA for contract compliance reasons. To fill these gaps, annual withdrawal totals for the university were retrieved from the EAA, which requires and tracks TXST's groundwater use for regulatory purposes (EAA 2024).

Climate data were sourced from the National Centers for Environmental Information under the National Oceanic and Atmospheric Administration (NOAA). Average monthly temperature and total monthly precipitation for the years 2015 through 2024 were obtained for Hays County, Texas, where TXST's San Marcos campus is located. Hays County data were used as proxies due to limitations in the available and accessible data for San Marcos. Additionally, the EAA provided daily readings of the J-17 well data and drought stage data, which determines CPM stages.

Some gaps occurred in monthly water use building data, irrigation, and industrial use. These gaps were attributed to metering issues or building inactivity and campus closures due to the COVID-19 pandemic causing data to not be recorded. In these cases, missing data were either omitted from correlation analyses or estimated using multi-year averages.

V. <u>**Methods**</u>

i. Correlation and Regression Analysis:

The correlation and regression analyses were used to address research question 1 (RQ1), which explores the holistic nature of water usage trends on campus and what may be influencing the trends. Pearson correlation tests and linear regression analysis were conducted using Microsoft Excel to analyze how groundwater use for irrigation and industrial purposes relates to monthly average temperature and total precipitation. These analyses between climate data and water usage data on campus will help contextualize various perspectives of understanding water usage trends as climate change increases local temperatures and intensifies droughts (Banner et al. 2010; Cook et al. 2015; Nielsen-Gammon et al. 2020). Both techniques were utilized to validate the results and measure the strength of the relationship with the Pearson correlation test and the linear estimation of the two variables through the regression analysis (Schober et al. 2018).

a. Pearson Correlation Analysis:

A Pearson correlation test was used first to analyze the correlation between the following variables: irrigation and average monthly temperature, irrigation and monthly rainfall, and industrial water usage and average monthly temperature.

The Pearson correlation test measures the significance of the relationship between a dependent variable and an independent variable by quantifying the strength, direction, and significance of each relationship (Faizi and Alvi 2023). Strength indicates the magnitude of the correlation and is measured by the correlation coefficient (r) (Faizi and Alvi 2023). The absolute value of r determines the strength of correlation; r=1 indicates a perfect correlation and r=0 indicates no correlation (O'Brien et al. 2015; Faizi and Alvi 2023). Strength of correlation coefficient was interpreted as follows (Schober et al. 2018):

- 0.00-0.10 indicating a negligible correlation
- 0.10-0.39 indicating a weak correlation
- 0.40-0.69 indicating a moderate correlation
- 0.70-0.89 indicating a strong correlation
- 0.90-1.00 indicating a very strong correlation

Direction indicates the direction in which the correlation is associated, positive or negative (Faizi and Alvi 2023). This predicts whether the independent variable increases or decreases when the dependent variable increases (Faizi and Alvi 2023). Direction is measured through the sign of the correlation coefficient (r), from the range -1 to +1. A negative r value signifies a negative correlation, and a positive r value signifies a positive correlation (Faizi and Alvi 2023).

The coefficient of determination (R^2) was also calculated to indicate the amount of variance accounted for between the two variables (Schober et al. 2018). This interprets the percentage of variance that can be explained by the climate variable (Schober et al. 2018). Significance determines whether the two variables have a statistically significant correlation, indicating the probability that the correlation is due to random chance (Faizi and Alvi 2023). Significance is measured through the probability value (p-value). A p-value is measurement between 0 and 1, with a p-value <0.05 showing a significant correlation (O'Brien et al. 2015). To calculate the p-value for a Pearson correlation test in Excel, a t statistic (t) must be calculated (Cohen 1988). The t-statistic tests the significance of the r value. A higher t value indicates a more significant observed relationship.

The t-statistic was determined using the equation (Cohen 1988):

$$t = \frac{r \times \sqrt{n-2}}{\sqrt{1-r^2}}$$

Equation 1: t-Statistic Equation

Where 'r' is the coefficient correlation and 'n' is the number of pairs in the relationship (Cohen 1988). A 't' distribution test is then used to calculate the p-value for the Pearson correlation test (Biau et al. 2010). The results of the t statistic and the degrees of freedom ($df = n - 2$) were used in Excel's TDIST function to derive the p-value. The null hypothesis states that there is no correlation between the water usage data and the climate data, while the alternative hypothesis states that there is a statistically significant relationship between the variables.

b. *Linear Regression Analysis:*

The Linear Regression analysis was conducted to further examine the relationship between the groundwater usage data and the climate data: irrigation and average monthly temperature, irrigation and monthly rainfall, and industrial water usage and average monthly temperature. The linear regression analysis shows the change in one variable corresponding to the change in another variable, the independent and dependent variables (Faizi and Alvi 2023). The independent variable is the explanatory variable, and the dependent variable is the response variable. Linear regression predicts the value of the dependent variable with respect to the changes in the independent variable, which is plotted on a scatter plot with a trendline (Faizi and Alvi 2023). This analysis is a measurement of the relationship between the two variables.

A linear regression analysis calculates a Multiple R (correlation coefficient (r)), a coefficient of determination (R^2), a significance F (p-value), and a t value. Additionally, the data are plotted on a scatterplot, and a linear trend line is calculated and plotted representing the predicted outcome of the dependent variable between the changes in the independent variable (Faizi and Alvi 2023).

The regression analysis in the Excel data analysis package outputs a regression statistics table containing the Multiple R (correlation coefficient (r)) and the Coefficient of determination (R^2). Multiple R (correlation coefficient (r)), similar to the Pearson correlation test, measures the strength and direction of the correlation and is measured from -1 to +1 (Faizi and Alvi 2023). This is measured on the same scale as the Pearson correlation test for magnitude of correlation coefficient (Faizi and Alvi 2023). Coefficient of determination (R^2) is also calculated with the regression analysis further validating the amount of variance between the two (Schober et al. 2018). The significance 'F' value (p-value) is output by the regression analysis. Equivalent to a p-value in the Pearson correlation test, this measures the significance of the correlation and is a measurement between the values 0 and 1 where a value of <0.05 shows a significant correlation (O'Brien et al. 2015). The regression analysis plots the data on a scatterplot, which outputs a trendline estimating correlational change as the independent variable changes (Schober et al. 2018). The groundwater usage data, irrigation and industrial facilities usage, are plotted on the Y axis, and the climate data, average monthly temperature and monthly precipitation totals, are plotted on the X axis. These regression models help identify directional trends, assess how well climate variables predict monthly water use, and predict trends as temperatures increase and precipitation decreases.

ii. Descriptive Statistics:

Descriptive statistics were used to address Research Questions 1 and 2 (RQ1 & RQ2) to examine patterns in groundwater use trends over time and how groundwater use compares to regulatory withdraw limits during the EAA CPM withdrawal reduction stages. Line and bar graphs were produced to visualize results and help illustrate temporal patterns and how the university's usage aligns with regulatory restrictions under various drought stages.

Days and percentage of the year in each CPM drought withdrawal stage were calculated for the study years using the daily J-17 well level data. Monthly J-17 well high-water Level Elevation averages were calculated. Additionally, daily high-water level for the J-17 well was plotted on a line graph with the associated levels for each CPM drought withdrawal stages.

Student residential halls groundwater usage monthly totals for the buildings San Jacinto, Blanco, Bexar, Freedom Five & O'Shea, Gaillardia and Chautauqua, Lantana, San Marcos, and Mesquite Halls were plotted to highlight usage trends over time. Monthly irrigation groundwater usage and industrial groundwater usage totals were plotted on two separate line graphs to show trends over time.

Total annual groundwater withdrawal by the university was plotted on a line graph to visualize trends in total usage for the duration of the study. Additionally, total annual groundwater withdrawal by the university was plotted on a bar graph to analyze trends over time and how they compare to the EAA CPM stages. Average annual total groundwater withdrawal per year was also calculated.

Research Question 3 (RQ3) focused on water conservation opportunities for the university to implement to cut withdrawals. Water reuse is a conservation strategy examined through descriptive statistics to address research question 3 and quantify potential reductions in groundwater withdrawals. TXST has access to treated reuse water via the City of San Marcos, which could offset groundwater withdrawals. This study estimated the volume of groundwater that could have been conserved annually from 2015 to 2024 by substituting reuse water for irrigation and industrial purposes. The total amount of groundwater that could be reduced by using reuse water was displayed on a bar graph.

iii. Study Limitations:

Some study limitations are important to be acknowledged. Climate data were selected that only represent the county level, which may not fully reflect conditions in San Marcos. Missing groundwater use data for random months accounts for small limitations in the analysis. Although the missing data was either omitted or calculated through averages, it does not accurately represent the definite water usage data. Monthly residential hall building groundwater usage data availability was arbitrary. Missing values may result from construction, facility closure, metering issues, or data reporting errors. Extended absences may indicate the building was inactive or not metered, while brief gaps likely reflect meter failure or errors. It can be especially difficult to determine outliers from true usage anomalies, which may have affected the analysis.

VI. Results

The results will contribute to TXST furthering our understanding of groundwater usage and to comprehending water conservation needs on campus. This will help TXST maintain regulatory compliance, increase the resiliency of its water supply, protect the San Marcos springs and river, and enable TXST to continue growing and expanding its national recognition.

i. Pearson Correlation Test Results:

a. Irrigation and Average Monthly Temperature:

The results for the Pearson Correlation Test for irrigation groundwater usage and average monthly temperature display a strong positive correlation (Table 1). The correlation coefficient (r) is 0.75, indicating a strong correlation with a positive direction between irrigation groundwater usage and average monthly temperature (Schober et al. 2018). The coefficient of determination (R^2) is 0.56. This indicates that 56% of the variance in the irrigation data can be explained by the variation in average monthly temperature (Puth et al. 2014). The other 44% could be explained by random variables such as precipitation. A T statistic value of 11.74 indicates that the correlation coefficient is significant, which states that the observed relationship between the two variables is not due to random chance (Cohen 1988; Bevans 2020). The number of pairs (N) is 109 and the degree of freedom (df) is 107, which is consistent throughout the Irrigation data Pearson tests. The p-value is <0.01, indicating a significant correlation (O'Brien et al. 2015; Faizi and Alvi 2023). A p-value of <0.05 indicates that the probability of the correlation being due to chance alone is very low (Faizi and Alvi 2023).

Table 1: Irrigation & Average Monthly Temperature Pearson Correlation Test

Irrigation & Average Monthly Temperature	
Pearson Correlation Test	
Coefficient (r):	0.75

R^2	0.56
N:	109
T Statistic	11.74
DF	107
p-value	5.89×10^{-21}

b. Irrigation and Total Monthly Precipitation:

The results for the Pearson Correlation Test for irrigation groundwater usage and monthly precipitation totals displayed a weak negative correlation (Table 2). The correlation coefficient (r) is -0.25, indicating a weak correlation with a negative direction (Schober et al. 2018). The coefficient of determination (R^2) is 0.064. This is a low coefficient of determination. Thus, only 6% of the variability in the dependent variable, monthly total precipitation, is explained by the independent variable, irrigation groundwater usage. A T statistic value of absolute value 2.69 shows a significant relationship (Cohen 1988). A T statistic value over 2 is considered significant (Cohen 1988). The p-value is 0.008. This p-value is <0.05 indicating that the correlation analysis is significant and the probability of the correlation happening by chance is low (Faizi and Alvi 2023). A negative correlation between irrigation and precipitation is to be expected, however the extremely low coefficient of determination and the weak correlation were not expected. The low p-value proves the correlation is statistically significant, but the low correlation coefficient and coefficient of determination indicate the relationship between irrigation and precipitation is weak. This indicates that irrigation is not determined or impacted by the amount of precipitation; rather the amount of irrigation is determined by other factors such as a time-based irrigation schedule.

Table 2: Irrigation and Total Monthly Precipitation Pearson Correlation Test

Irrigation & Total Monthly Precipitation
Pearson Correlation Test

Coefficient (r):	-0.25
R^2	0.06
N:	109
T Statistic	-2.70
DF	107
p-value	0.0081

c. *Industrial Groundwater Use and Average Monthly Temperature:*

The results for the Pearson Correlation Test for cooling tower plant groundwater usage and average monthly temperature display a very strong positive correlation (Table 3). The correlation coefficient (r) is 0.94, indicating a very strong correlation with a positive direction between cooling tower plant groundwater usage and average monthly temperature (Schober et al. 2018). The coefficient of determination (R^2) is 0.88. Therefore, 88% of the variance in the cooling tower plant groundwater usage data can be explained by the variation in average monthly temperature (Puth et al. 2014). The number of pairs (N) is 106 and the degree of freedom (df) is 104.A T statistic value of 28.13, indicating a significant observed relationship between the two variables (Cohen 1988). The p-value is <0.01, which indicates the correlation is significant (O'Brien et al. 2015; Faizi and Alvi 2023). The probability of this correlation happening by random chance is low (Faizi and Alvi 2023).

Table 3: Industrial Groundwater Use and Average Monthly Temperature Pearson Correlation Test

Industrial Groundwater Use & Average Monthly Temperature Pearson Correlation Test	
Coefficient (r):	0.94
R^2	0.88
N:	106
T Statistic	28.13
DF	104
p-value	2.02×10^{-50}

ii. Linear Regression Analysis:

The results of the regression prove to be the same for the correlation coefficient (r), the coefficient of determination (R^2), the significance F value (p-value), and the t-statistic value. This indicates accuracy and validity across the Pearson Correlation Test and the Regression Analysis. However, the regression analysis adds to the correlation test by providing a scatterplot with a trendline that estimates the predicted y values, irrigation and cooling tower facilities groundwater usage, with the change in the x value, average monthly temperature, and monthly precipitation totals.

a. Irrigation and Average Monthly Temperature:

The results for the regression analysis of irrigation groundwater usage and average monthly temperature display a strong positive relationship (Table 4; Figure 1). Irrigation and average monthly temperature have a positive strong correlation ($r = 0.75$), indicating that average monthly temperature explained 56% ($R^2 = 0.56$) of the variance in monthly irrigation totals (Schober et al. 2018; Puth et al. 2014). The overall regression was statistically significant with a p-value of <0.01 (Puth et al. 2014). The scatterplot's trend line significantly predicts monthly irrigation totals based on the average monthly temperature.

Table 4: Irrigation and Average Monthly Temperature Regression Statistics

Irrigation and Average Monthly Temperature	
Regression Statistics	
Multiple R (r)	0.75
R Square (R^2)	0.56
Significance F (p-value)	5.89×10^{-21}
t-Statistic	11.74

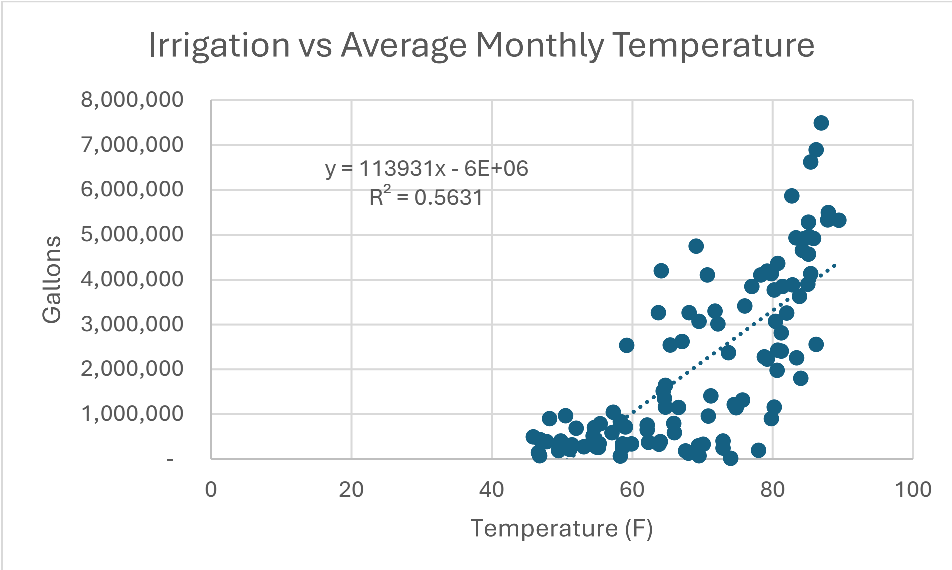

Figure 1: Irrigation vs Average Monthly Temperature

b. *Irrigation and Total Monthly Precipitation:*

The results for the regression analysis of irrigation groundwater usage and monthly precipitation totals display a weak negative relationship (Table 5, Figure 2). Irrigation and monthly precipitation have a negative weak correlation (r = 0.25), indicating that average monthly temperature explained 6% (R^2 = 0.06) of the variance in monthly irrigation totals (Schober et al. 2018; Puth et al. 2014). The overall regression was statistically significant with a p-value of <0.01 (Puth et al. 2014). Although the regression is statistically significant, the scatterplot's trend line does not accurately predict monthly irrigation totals based on monthly precipitation totals.

Table 5: Irrigation and Total Monthly Precipitation Regression Statistics

Irrigation and Total Monthly Precipitation	
Regression Statistics	
Multiple R (r)	0.25
R Square (R^2)	0.06
Significance F (p-value)	0.0081

t-Statistic	-2.70

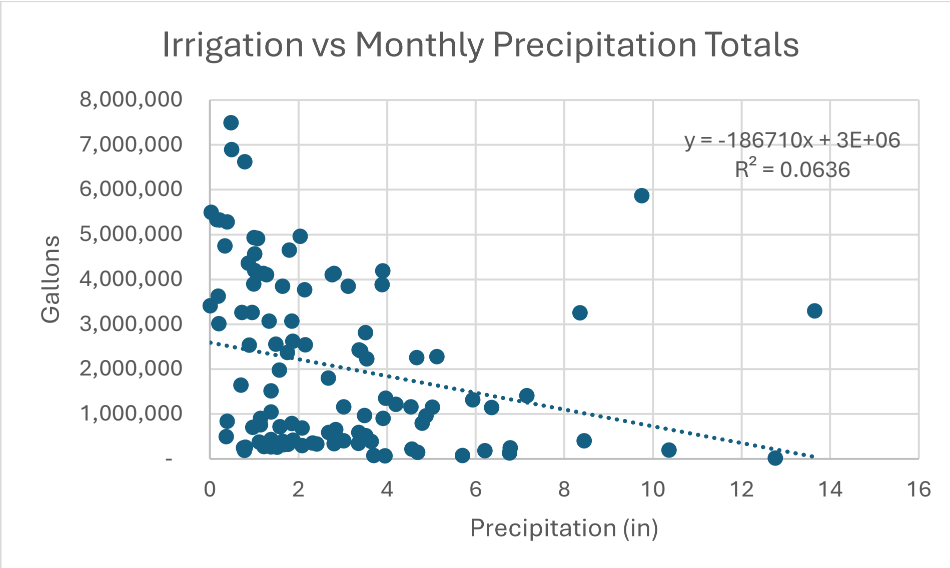

Figure 2: Irrigation vs Monthly Precipitation Totals

c. Industrial Groundwater Use and Average Monthly Temperature:

The results for the regression analysis of irrigation groundwater usage and average monthly temperature display a very strong positive relationship (Table 6, Figure 3). Industrial monthly groundwater totals and average monthly temperature have a positive very strong correlation (r = 0.94), indicating that average monthly temperature explained 56% (R^2 = 0.56) of the variance in monthly cooling tower facility groundwater totals (Schober et al. 2018; Puth et al. 2014). The linear regression was statistically significant with a p value of <0.01 (Puth et al. 2014). The scatterplot's trend line significantly predicts monthly cooling tower facilities' groundwater totals based on the average monthly temperature.

Table 6: Industrial Groundwater Use and Average Monthly Temperature Regression Statistics

Industrial Groundwater Use and Average Monthly Temperature
Regression Statistics

Multiple R (r)	0.94
R Square (R^2)	0.88
Significance F (p-value)	2.02E-50
t-Statistic	28.13

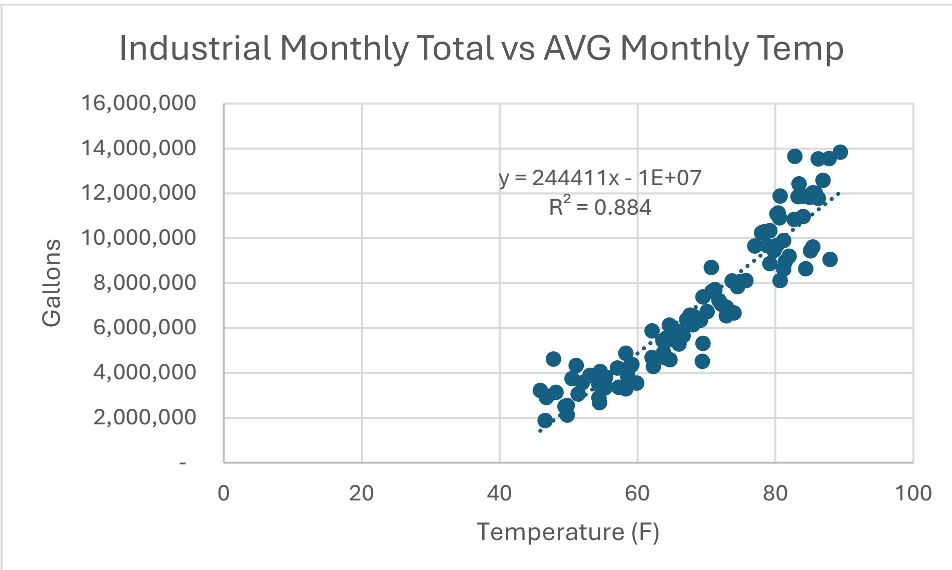

Figure 3: Industrial Monthly Total vs Average Monthly Temperature

iii. Descriptive Statistics Results:

a. *Drought Statistics:*

Table 7: J-17 Well Monthly Daily High Water Elevation Average by Year (2015-2024)

J-17 Well Monthly Daily High Water Elevation Average by Year (2015-2024)										
Months	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**
Jan	640.04	667.15	684.75	664.39	686.65	672.08	664.76	662.87	636.58	641.07
Feb	645.09	663.62	684.88	664.94	685.24	673.11	661.23	664.50	637.70	644.69
Mar	645.96	664.89	685.34	664.82	683.48	671.73	660.01	657.13	635.38	640.79
Apr	647.47	665.53	680.83	664.93	680.18	671.44	651.41	648.41	637.49	638.54
May	654.14	673.79	672.65	659.30	682.70	664.87	665.87	648.41	644.26	635.67
Jun	667.67	681.24	668.93	646.81	681.04	665.44	666.84	637.46	642.07	630.65

Jul	664.39	667.66	658.16	649.07	679.05	656.77	667.84	634.04	630.77	631.32
Aug	649.47	667.97	659.01	643.44	667.94	656.41	663.61	633.21	627.57	630.99
Sep	646.36	675.17	660.19	664.62	665.99	661.68	659.02	634.66	629.08	631.12
Oct	646.38	675.90	664.24	679.27	668.61	660.18	663.09	631.69	632.80	627.29
Nov	661.24	679.02	662.34	684.88	673.59	659.36	665.97	636.01	636.29	628.51
Dec	666.01	685.55	664.83	685.42	672.29	661.95	664.07	637.20	638.37	627.04

Table 8: Days of Year in EAA Critical Period Management Stage I - Stage V Drought Restrictions

Days of Year in EAA Critical Period Management Stage I - Stage V Drought Restrictions						
Years	**Stage I**	**Stage II**	**Stage III**	**Stage IV**	**Stage V**	**No Restrictions**
2015	46	181	18	0	0	120
2016	0	0	0	0	0	365
2017	58	0	0	0	0	307
2018	39	78	0	0	0	248
2019	0	0	0	0	0	365
2020	103	0	0	0	0	263
2021	80	15	0	0	0	270
2022	34	62	207	0	0	62
2023	0	50	239	76	0	0
2024	0	67	157	142	0	0

Table 9: Percent of Year in EAA Critical Period Management Stage I - Stage V Drought Restrictions

Percent of Year in EAA Critical Period Management Stage I - Stage V Drought Restrictions						
Years	**Stage I**	**Stage II**	**Stage III**	**Stage IV**	**Stage V**	**No Restrictions**
2015	13%	50%	5%	0%	0%	33%
2016	0%	0%	0%	0%	0%	100%
2017	16%	0%	0%	0%	0%	84%
2018	11%	21%	0%	0%	0%	68%
2019	0%	0%	0%	0%	0%	100%
2020	28%	0%	0%	0%	0%	72%
2021	22%	4%	0%	0%	0%	74%
2022	9%	17%	57%	0%	0%	17%
2023	0%	14%	65%	21%	0%	0%
2024	0%	18%	43%	39%	0%	0%

The line graph for the J-17 well daily high-water level shows that although there are periods of peaks in water level height with no Critical Period Management drought restrictions, the years 2020 to 2024 have shown a dramatic decrease in daily high-water levels (Figure 4). For 2023 and 2024, TXST was under a stage of Critical Period Management drought withdrawal reduction for the whole year (Tables 8 and 9). Furthermore, for the years 2022, 2023, and 2024 TXST spent a majority of the year in Stage III (2022=57%,2023=65%,2024=43%) (Table 9). The most recent years (2023 and 2024) proved to be the most drought-intensive years of the study, reaching Stage IV Critical Period Management drought withdrawal reductions (2023=21%,2024=39%) (Table 9). If enacted for the duration of the year TXST's total allowed allotment under the CPM withdrawal reductions stages are displayed in table 10.

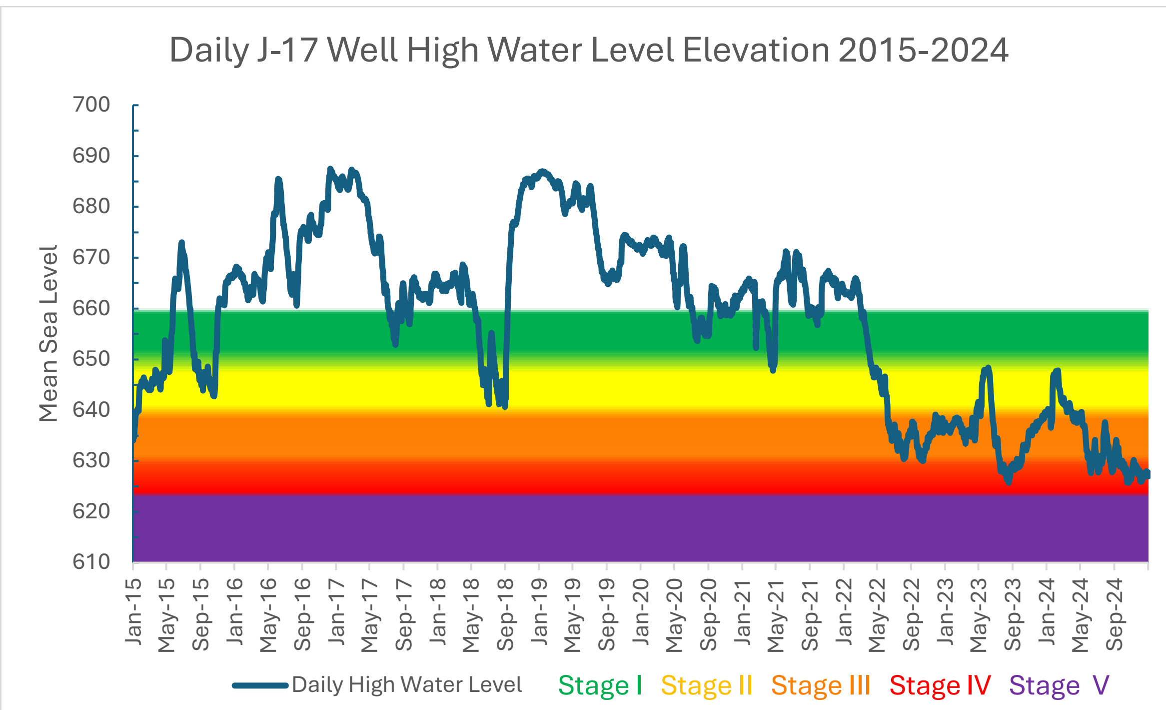

Figure 4: Daily J-17 Well High-Water Level Elevation 2015-2024

Table 10: EAA Critical Period Management Withdrawal Reduction Stages and TXST's Reduced Total Allotment

EAA Critical Period Management Withdrawal Reduction Stages and TXST's Reduced Total Allotment

Stage I	20% reduction (<660 ft MSL J-17 well)	1601 acre-feet per year
Stage II	30% reduction (<650 ft MSL J-17 well)	1401 acre-feet per year
Stage III	35% reduction (<640 ft MSL J-17 well)	1301 acre-feet per year
Stage IV	40% reduction (<630 ft MSL J-17 well)	1201 acre-feet per year
Stage V	44% reduction (<625 ft MSL J-17 well)	1121 acre-feet per year

b. Student Residential Halls Groundwater Use Monthly Totals Trends Over Time:

Student Residential Halls results show varied results as certain buildings dealt with construction, metering errors, or unavailable data. Gaillardia and Chautauqua, Lantana, and Mesquite Halls show a steady trend in groundwater usage. San Jacinto, Freedom Five & O'Shea, Blanco, and San Marcos show a slight increasing trend (Figures 5, 6, and 8-12). However, Bexar Hall groundwater usage shows a sharp increase followed by a sharp decrease in use that steadied out to normal levels (Figure 7). This could be interpreted as a metering error, but it is uncertain.

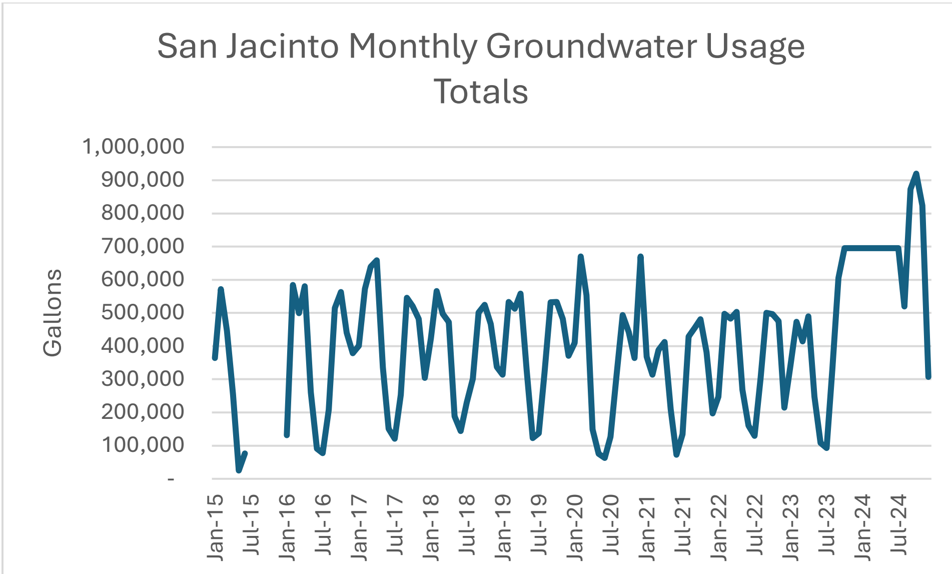

Figure 5: San Jacinto Hall Monthly Groundwater Usage Totals

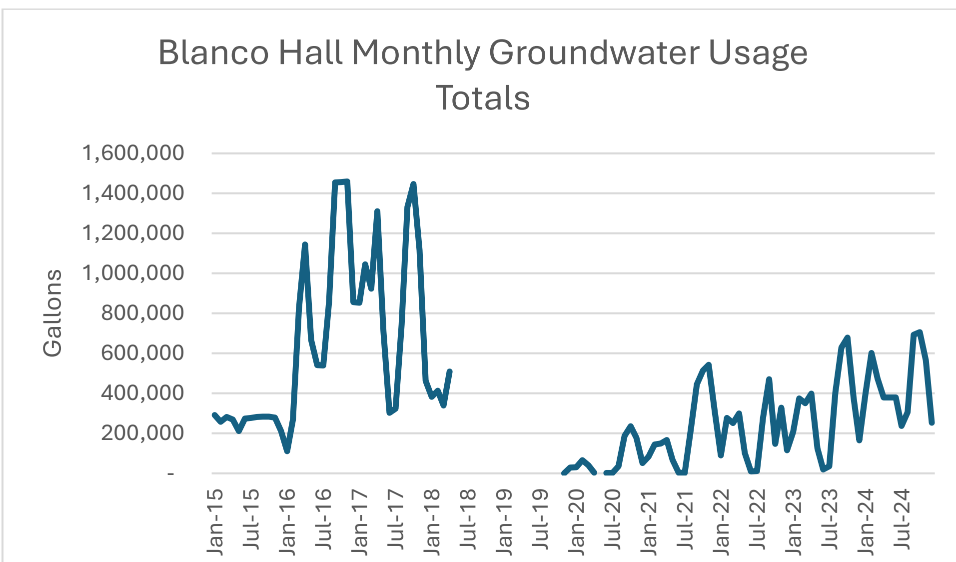

Figure 6: Blanco Hall Monthly Groundwater Usage Totals

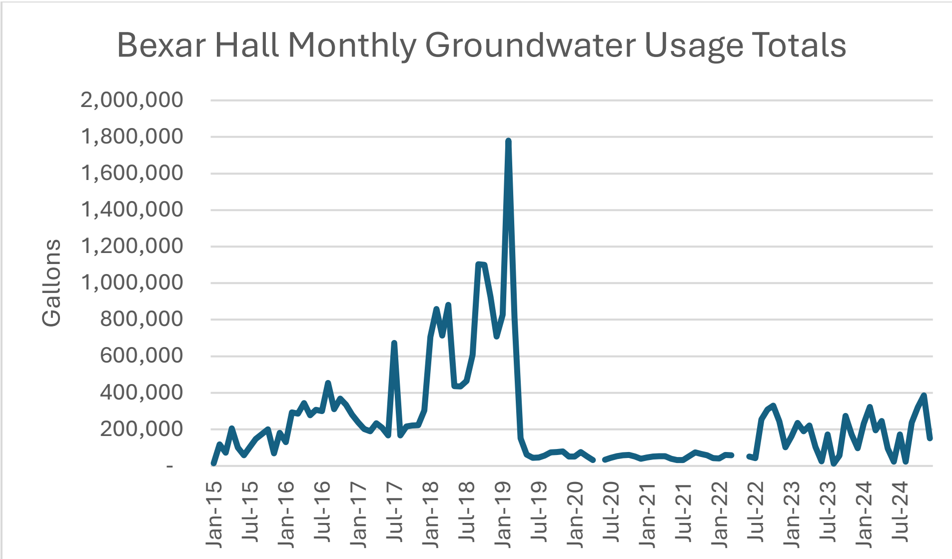

Figure 7: Bexar Hall Monthly Groundwater Usage Totals

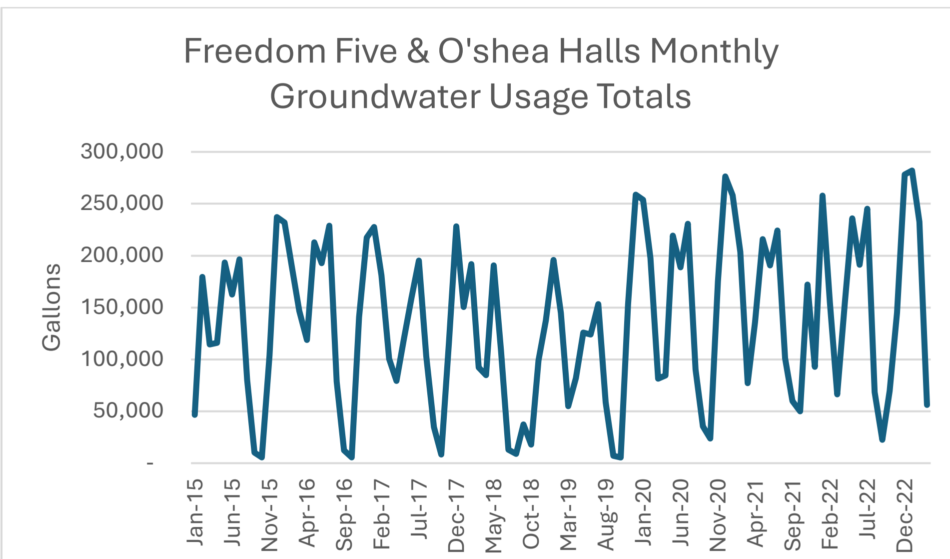

Figure 8: Freedom Five & O'Shea Hall Monthly Groundwater Usage Totals

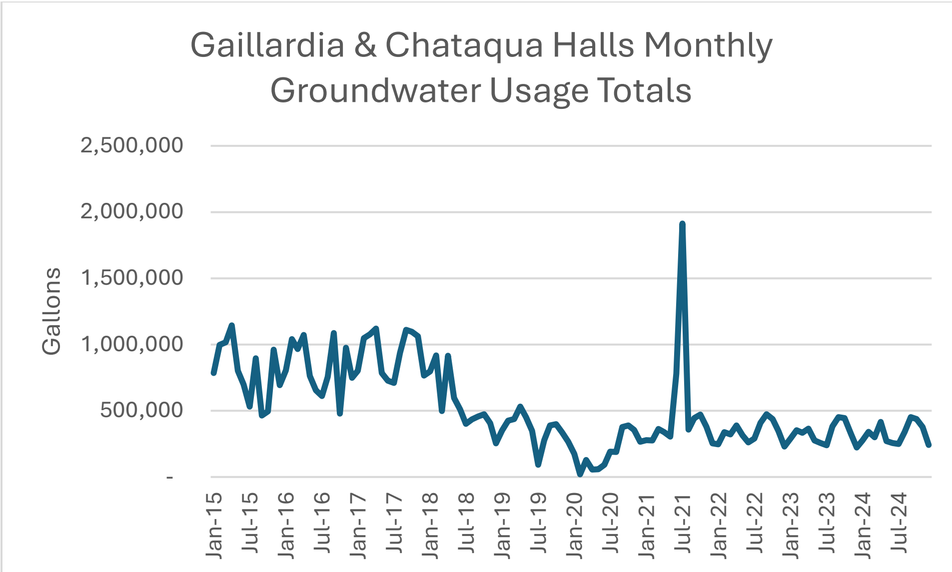

Figure 9: Gaillardia and Chautauqua Hall Monthly Groundwater Usage Totals

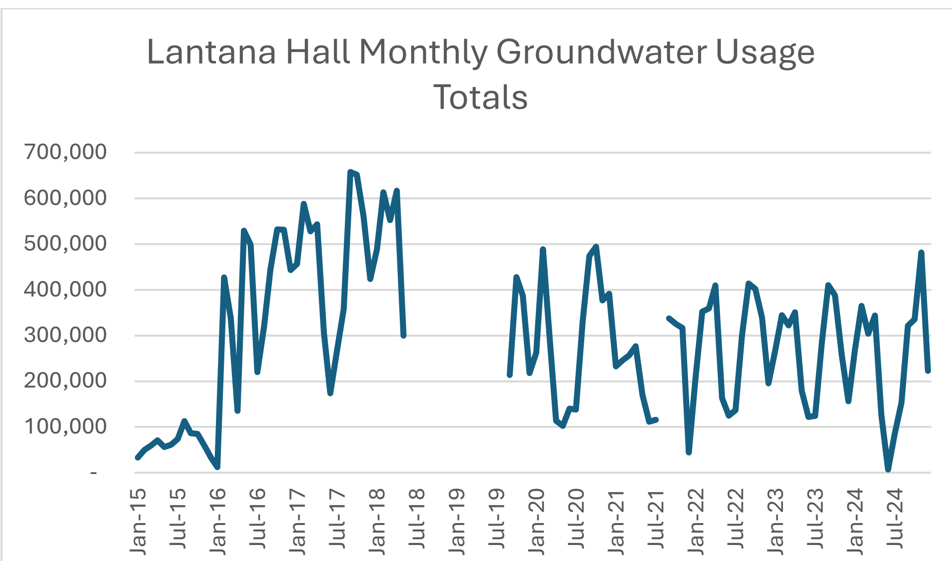

Figure 10: Lantana Hall Monthly Groundwater Usage Totals

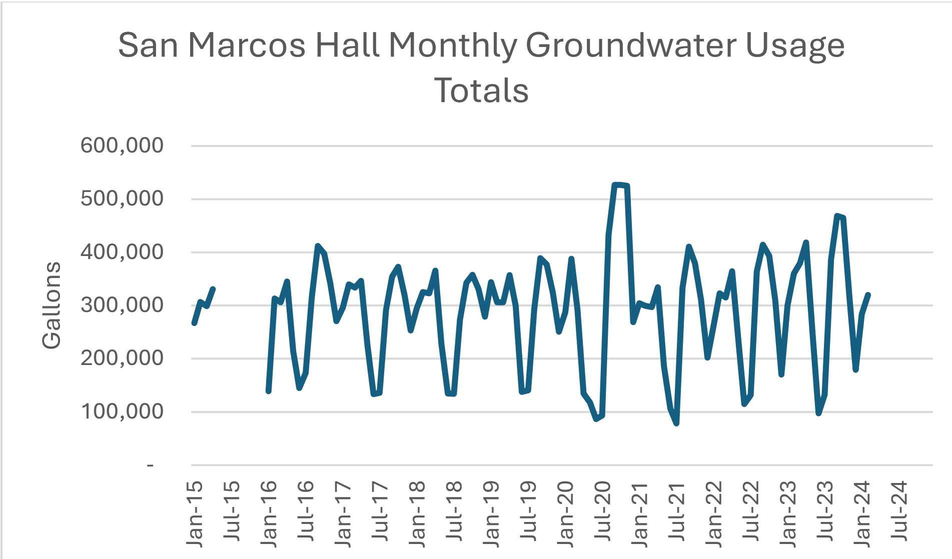

Figure 11: Sam Marcos Hall Monthly Groundwater Usage Totals

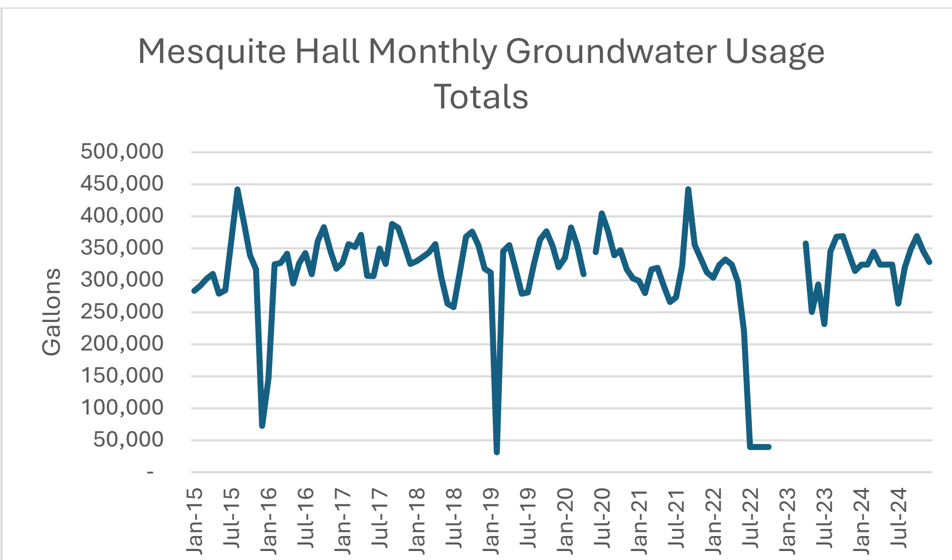

Figure 12: Mesquite Hall Monthly Groundwater Usage Totals

c. *Industrial Groundwater Use Trends Over Time:*

Plotting monthly industrial groundwater totals for the duration of the study shows an increasing trend in monthly totals (Figure 13). Industrial water on average accounts for 23% of total annual groundwater withdrawals by TXST.

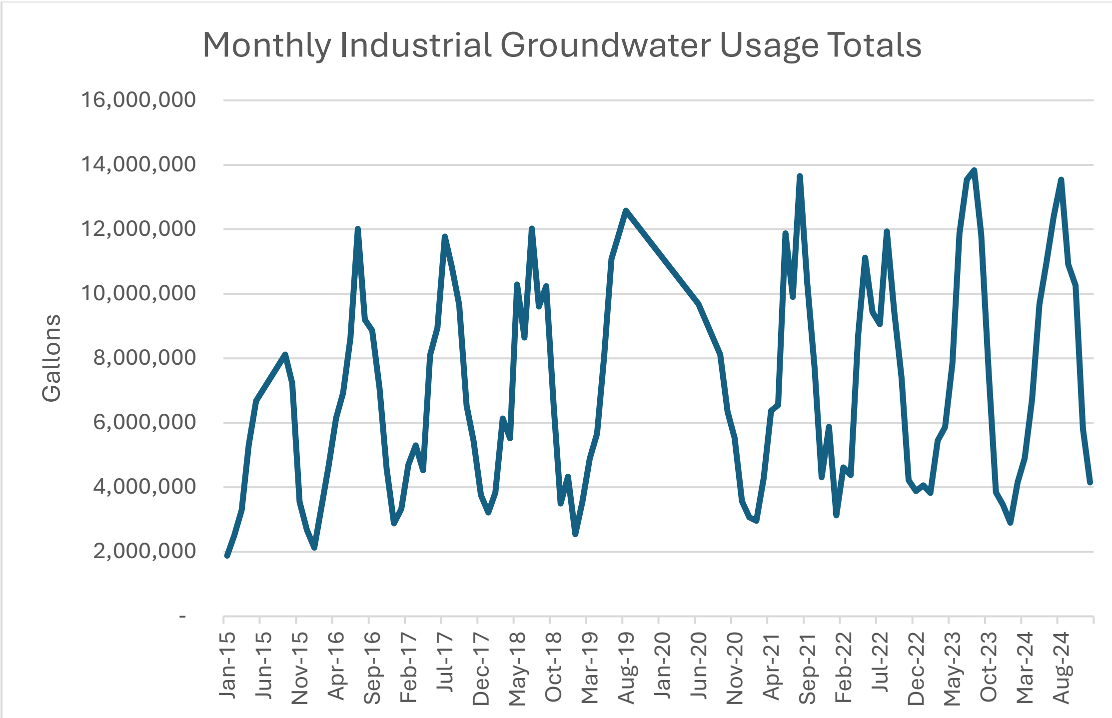

Figure 13: Monthly Industrial Groundwater Usage Totals

d. *Irrigation Groundwater Use Trends Over Time:*

Plotting monthly irrigation groundwater usage totals for the duration of the study shows that there is an increasing trend until 2020, which is followed by a decrease in irrigation totals (Figure 14). Irrigation on average accounts for 6% of total annual groundwater withdrawals by TXST.

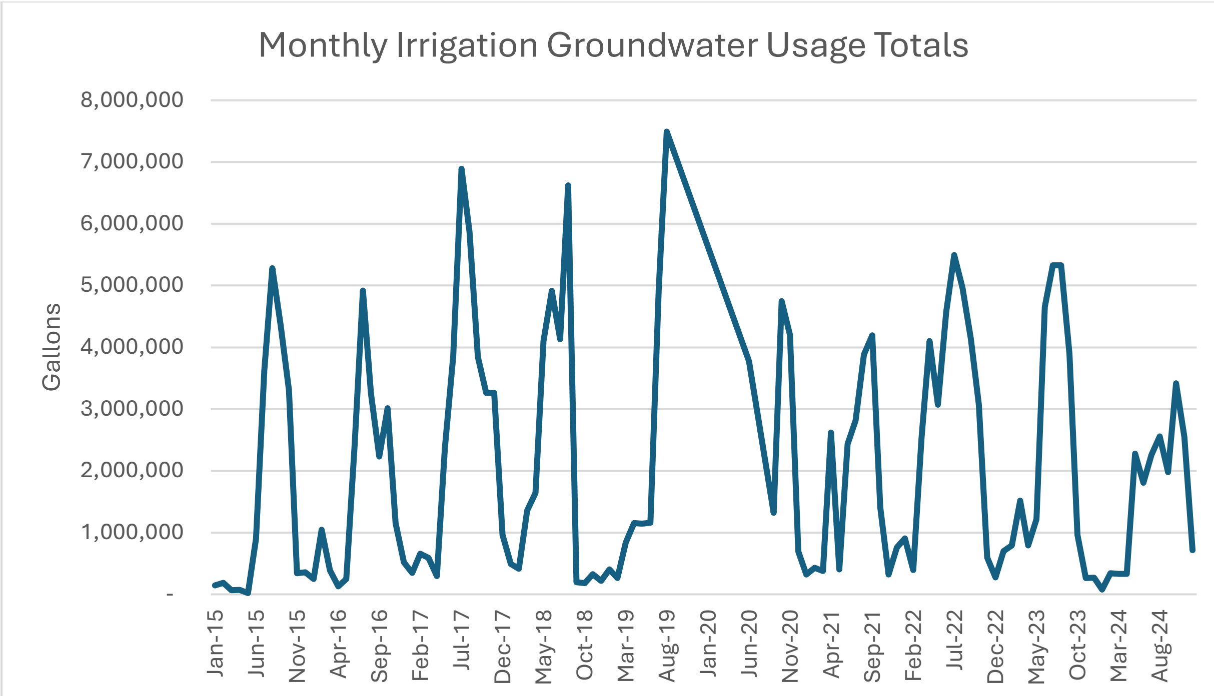

Figure 14: Monthly Irrigation Groundwater Usage Totals

e. *Overall Usage Trends and How Do They Relate to Drought Restrictions:*

The total annual groundwater withdrawal trends from 2015-2024 show a slight decrease in total usage with a decrease for the years 2020 through 2022, followed by an increase for 2023 and 2024 (Figure 15). The total annual groundwater withdrawal average for the duration of the study is 1186.48 acre-feet. Furthermore, seven out of ten years would have been impacted by Critical Period Management Critical Stage Reductions if activated by the EAA and sustained drought (Figure 16).

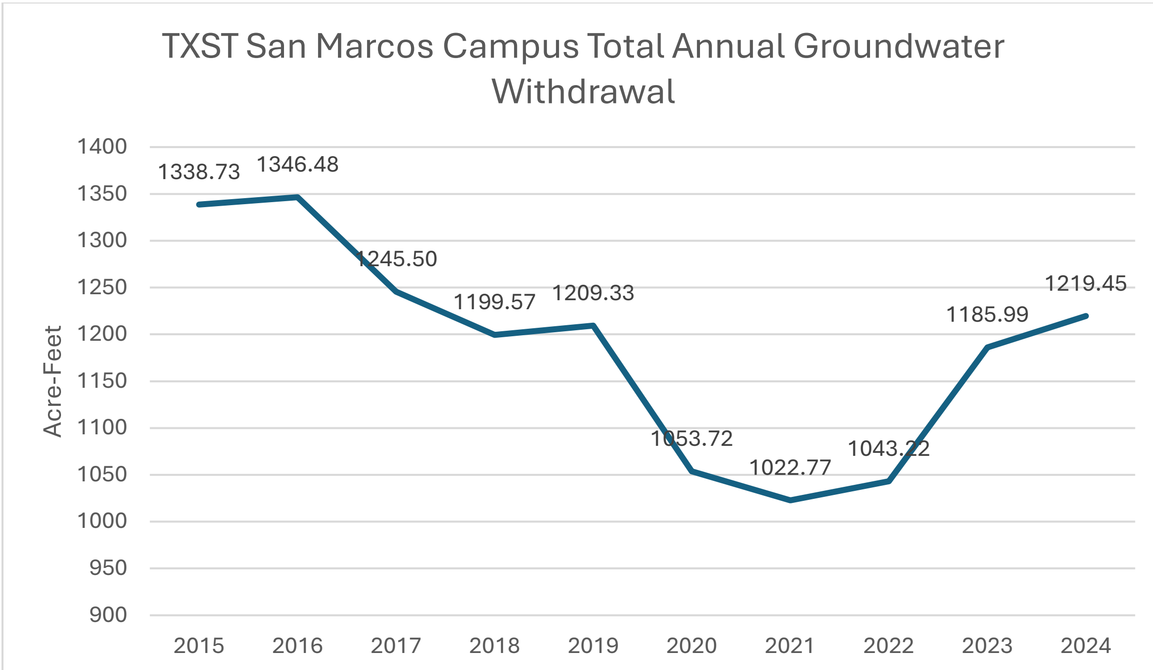

Figure 15: Texas State University San Marcos Campus Total Annual Groundwater Withdrawal

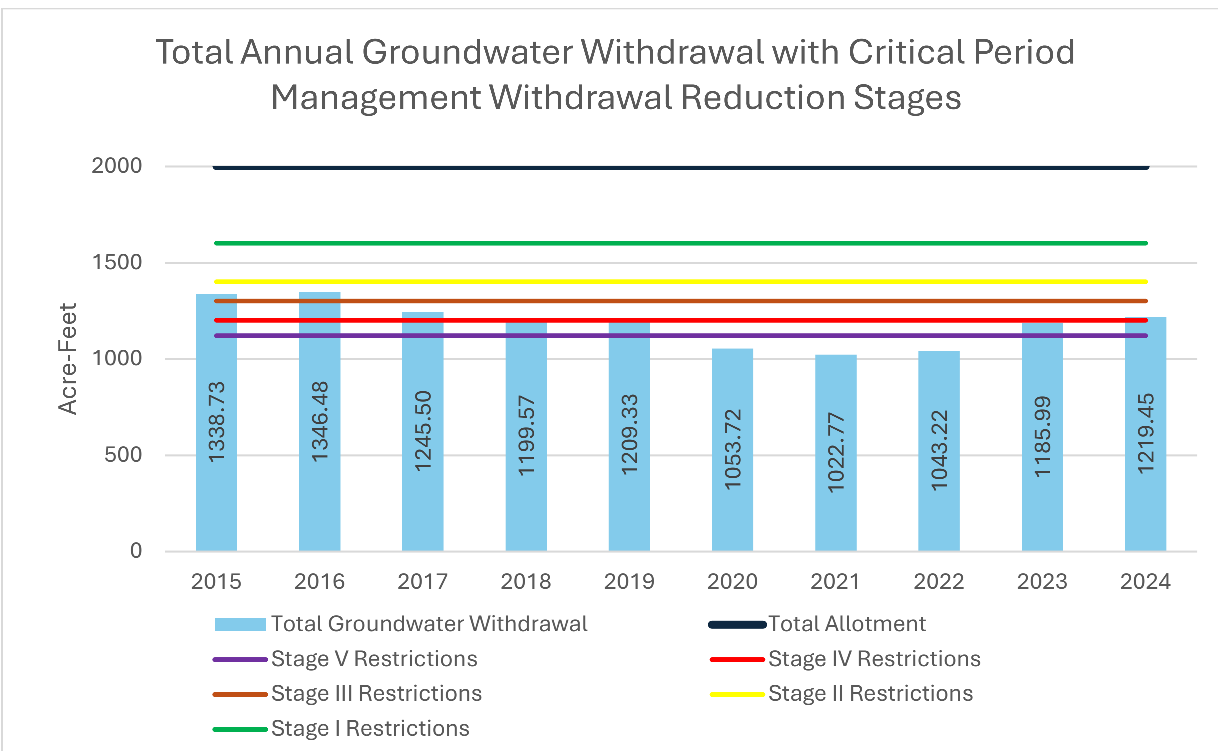

Figure 16: Total Annual Groundwater Withdrawal with Critical Period Management Drought Restriction Stages

f. *Total Surface Water Diversion:*

On average, total annual surface water diversion are 41.94 acre-feet, with a majority being from Spring Lake for irrigation of the Spring Lake Intramural Fields (Table 11).

Table 11: Texas State University San Marcos Campus Surface Water Diversions

TXST San Marcos Campus Surface Water Diversions			
Surface Water Diversion	**San Marcos River (gal)**	**Spring Lake (gal)**	**Total Surface Water Diversion (ac-ft)**
2015	3,891,100	6,373,000	31.5
2016	104,100	6,702,000	20.89
2017	18,700	14,675,000	45.09
2018	100	10,945,000	33.59
2019	-	13,040,000	40.02
2020	10,603,080	13,779,000	74.83
2021	2,442,640	8,537,000	33.7
2022	4,147,356	14,797,000	58.14
2023	2,708,520	13,102,000	48.52
2024	2,756,310	8,036,000	33.12

g. *Reuse Implementation:*

Implementation of reuse water for irrigation and industrial use would cut TXST's total annual groundwater withdrawal by 29% on average accounting for 344.41 acre-feet per year (Figure 17). Utilizing reuse would cause TXST to stay out of CPM withdrawal reduction stages causing water withdrawal reduction percentages that would have affected seven out of the last ten years.

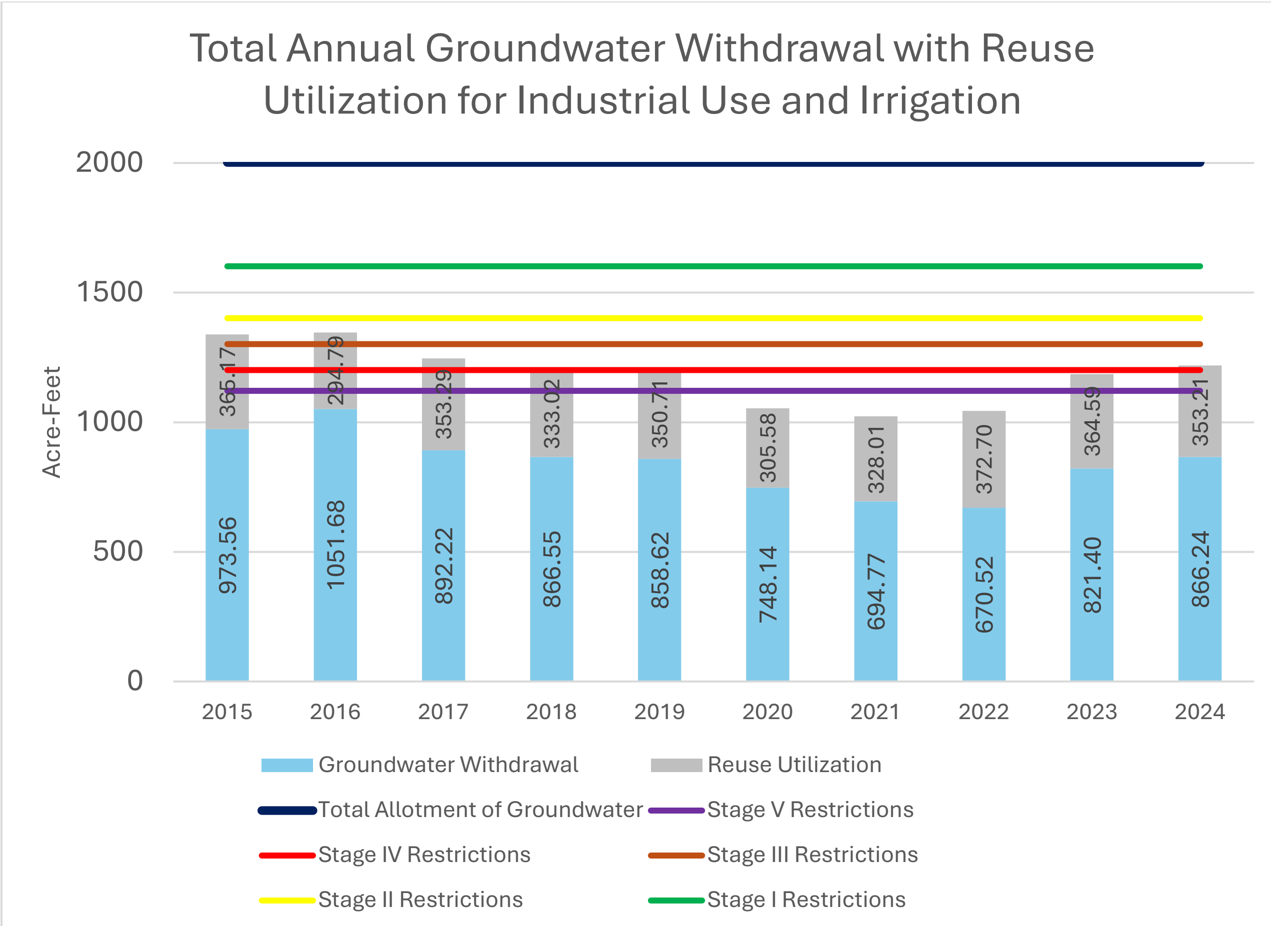

Figure 17: Total Annual Groundwater Withdrawal with Reuse Utilization for Industrial Use and Irrigation

VII. <u>Discussion</u>

The results of the Pearson correlation test and the linear regression for irrigation groundwater usage and temperature further emphasize the needs for improved conservation in irrigation practices as average temperatures in Central Texas are projected to increase due to climate change (Tables 1-6) (Nielsen-Gammon et al. 2021). The regression analysis indicates that as temperatures increase, irrigation and industrial use is likely to also increase, worsening existing water usage concerns (Figures 1 and 3). This trend is especially concerning in the context of the projected intensification of droughts, potentially triggering CPM withdrawal reduction stages that TXST must comply with.

Total monthly irrigation levels reveal a downward trend post 2020 (Figure 14). Despite the decline from existing conservation measures put in place, the correlation and regression analysis show a clear relationship between rising temperatures and increasing irrigation, which would challenge the existing conservation measures if not addressed proactively. A statistically significant but weak negative correlation between irrigation and precipitation suggests that rainfall does not influence irrigation levels on campus. This finding highlights an opportunity for TXST to improve irrigation on campus by implementing smart irrigation systems that more effectively utilize precipitation as natural irrigation.

Additionally, Industrial groundwater usage trends indicate a steady increase throughout the study period (Figure 13). The correlation and regression results for industrial groundwater usage and average monthly temperature also indicate as temperatures increase industrial groundwater usage will increase. The demand for industrial groundwater use can therefore be expected to rise as temperatures increase from ongoing climate change and as campus expands. The total annual groundwater withdrawal analysis shows a decrease in total use for the years 2020 through 2022 (Figure 15). However, this decline can be explained by the COVID-19 causing TXST's campus operations to be significantly reduced and students to be off campus. Therefore, these years represent outliers and do not accurately represent the university's total annual groundwater withdrawals on campus under normal, fully operational conditions. Overall campus groundwater use has since rebounded, increasing to normal levels around 1200 acre-feet per year. This resurgence places TXST at risk of having to implement groundwater withdrawal reductions under the EAA CPM stages, especially if Stage 5 is triggered. Residential Hall trends were impacted by arbitrary data due to metering errors, lack of data, or construction, making it extremely difficult to determine if outliers represent data errors or actual usage.

Moreover, the J-17 Well data show the intensifying drought conditions, a trend projected to worsen as with ongoing climate change (Figure 4) (Zhang et al. 2019). It is important for TXST to keep groundwater withdrawal levels down to protect the finite groundwater resources it has as climate change makes them more vulnerable (Zhang et al. 2019; Nielsen-Gammon et al. 2021). Implementing conservation strategies is critical to maintain campus water resources for a resilient future.

VIII. <u>Conservation Opportunities</u>

To address the need for conservation and prevent TXST from exceeding EAA CPM withdrawal reductions, as well as sustaining a resilient water supply for future growth of TXST, untapped water conservation strategies and opportunities must be implemented across the campus. Water conservation strategies and opportunities are addressed to analyze research question three (RQ3).

i. Water *Reuse*:

Utilizing water reuse on campus is a key conservation measure that could drastically decrease TXST's groundwater withdrawals. TXST has access to roughly 1100 acre-feet per year of City of San Marcos (COSM) recycled water that is readily available. This reuse water, already treated to non-potable standards, could substantially lower TXST's demand on the Edwards Aquifer, the San Marcos River, and Spring Lake. Reuse water or recycled water is previous wastewater that has been filtered and treated for non-potable or potable use (Cardone and Howe 2018; Hanes 2024). Utilizing reuse water combats water scarcity challenges faced by increasing populations while preserving existing water resources and supplies (Cardone and Howe 2018). Implementation of reuse water combats water scarcity, protects groundwater levels and availability, and protects water quality by decreasing drawdown of groundwater and diverting wastewater effluent into local waterways (Hanes 2024).

The Texas Water Development Board (TWDB) has recommended the adoption of reuse to limit the amount of groundwater withdrawals to protect aquifers and spring flows while highlighting the benefits and cost effectiveness of using reuse for outdoor irrigations (Hanes 2024). Regulatory agencies also support the use of reuse water. In 2015, TCEQ approved the use of direct and indirect reuse water (Puig-Williams & Mace 2019). Additionally, the EAA supports the utilization of reuse water to protect aquifer levels (EAA n.d.).

As the results of this study show, if TXST was to implement reuse water for irrigation and industrial water, groundwater withdrawals could be cut by an average of 29% per year. Irrigation accounts for 6% of groundwater use on average and industrial use accounts for 23% on average. If reuse was just piped for cooling tower facilities utilization, TXST's groundwater withdrawals would be cut by 23% on average and cut down on the energy used to treat the cooling water twice.

The regression analysis shows a direct relationship between increasing temperatures and higher industrial groundwater use. Additionally, industrial groundwater use has increased annually from 2015 to 2024. As climate change continues to increase average temperatures, the results predict that industrial groundwater use will continue to increase placing more demand on the aquifer and increasing groundwater withdrawals. However, utilizing reuse water for industrial water would eliminate this demand and reduce groundwater withdrawals.

Using reuse water for irrigation has benefits of its own. Reuse water has nutrient value (Rahman et al. 2016). This can help reduce the needs for fertilizers and increase the health of the irrigated landscape, plants, and soils (Rahman et al. 2016). Reducing the need for fertilizers through the use of reclaimed water for irrigation can help protect the local water quality by preventing the runoff and infiltration of the harsh fertilizers (Calsense 2016). The use of reclaimed water on TXST's campus will decrease overall groundwater withdrawal, create healthier landscapes, while also providing the opportunity to cut down surface water diversions as well.

The roughly 1100 acre-feet of COSM reuse water would easily account for all of TXST's irrigation and cooling tower facilities water demands with over 70% of COSM reuse water left available for other use. The excess COSM reuse water could be used to further TXST's water conservation efforts by eliminating our need to divert surface water from Spring Lake and the San Marcos River, or be used for indoor non-potable use like toilets and urinals. Current surface water diversions from Spring Lake are being used for irrigations of the Spring Lake Intramural Fields. However, this could be prevented by utilizing the additional 70% of COSM reuse water. It is essential to keep water in Spring Lake to inform the public through the education and research center and proactively manage the environmentally sensitive habitat as lake levels fall due to increased drought causing decreased spring flows (Zhang et al. 2019).

The additional reuse water could be piped to buildings for non-potable use. As TXST expands by building new housing and buildings on campus, it can offset the new demand by utilizing indoor non-potable reuse. Replacing the need for potable water for toilet and urinal flushing with non-potable reuse water can decrease total potable water usage in residential buildings by 25% and 75% in commercial buildings (Puig-Williams & Mace 2019).

Furthermore, researchers at TXST's Ingram School for Engineering are pioneering direct potable reclaimed water research. With support from faculty, staff, and students, reuse water is an effective way to cut down TXST's total annual groundwater withdrawals.

ii. Improved Irrigation Strategies:

TXST can further conserve water through efficient irrigation technologies. The results of the correlation and regression analysis show that as temperatures rise, irrigation increases. A simple solution to solve the demand for water for irrigation would be to implement reclaimed water or the use of captured rainwater to meet the irrigation needs. However, there are additionally efficient irrigation strategies that TXST can implement to increase the efficiency of its irrigation while lowering the demand for water.

Improving irrigation strategies and technologies can increase water conservation by increasing irrigation efficiency. Implementing smart irrigation systems can adjust irrigation schedules based on local weather (Calsesne 2016). The results of this study show a weak negative correlation between irrigation and precipitation. Improving irrigation systems can increase efficiency by incorporating weather data, such as rainfall, and the needs of the plants through smart monitors (Calsense 2016). Additionally, improving sprinkler heads with check valves can increase irrigation efficiency by regulating pressure to prevent wasted water and ensure an evenly distributed flow to achieve maximum cover, preventing unnecessary overwatering (Calsense 2016).

Another strategy for irrigation conservation is xeriscaping. Xeriscaping is a specific type of landscaping that protects water resources by reducing or eliminating the need for irrigation (Ismaeil et al. 2022). This water efficient landscaping practice can significantly save local water resources (Sovocool et al. 2006). Xeriscaping can reduce irrigation water usage by 30 to 50 percent (Sovocool et al. 2006; Ismaeil et al. 2022). Implementing xeriscaping on TXST's campus can conserve water by lessening the need for irrigation.

Furthermore, the addition of native vegetation on campus can also help decrease irrigation and increase water conservation on campus. Native regional plants that are adapted to the climate can decrease the need for conservation. Drought-tolerant native plants can decrease the need for irrigation while also creating functional, beautiful, water wise landscapes (Andrews and Kratsch 2015). Native plants also help slow evapotranspiration by increasing soil health, increasing water retention in turn making irrigation more efficient and preventing excess runoff (Schuster et al. 1996).

iii. One Water Strategies:

One Water is an emerging water management and conservation strategy in Texas and the nation. One Water is a holistic water management strategy that views all water, including potable drinking water, wastewater, stormwater as a single water resource that must be managed sustainably (Cardone and Howe 2018; Puig-Williams & Mace 2019). One Water projects and strategies utilize reuse, green infrastructure, and rainwater harvesting (Puig-Williams & Mace 2019). Implementing One Water at TXST would build long-term resilience while ethically managing and protecting campus's finite water resources. One Water provides numerous benefits including improved water security, optimized local infrastructure and sustainable development, and increased education and awareness of water conservation on campus (Cardone & Howe 2018). Areas where freshwater sources are plenishing, but the demand is growing, such as TXST San Marcos campus, are best suited for One Water Projects (Puig-Williams & Mace 2019). The Meadows Center for Water and the Environment at TXST is leading research initiatives for One Water implementation and integration, assisting communities create a resilient water supply. Given One Water research happening on campus, TXST is well positioned to integrate One Water practices into new campus buildings.

Furthermore, the local region around TXST's campus includes great examples of One Water in practice. A nearby example of One Water in action is the Blue Hole One Water Primary School (Blue Hole Primary) in Wimberly, which is the first One Water school in Texas. Located within twenty miles from TXST's campus, Blue Hole Primary understood the value of its limited water resources and the susceptibility to frequent droughts (Gary et al. 2023). Dealing with population growth and a decline in spring flow and groundwater levels due to demand and droughts, Blue Hole Primary, with the help of the Meadows Center, incorporated One Water to protect its local water supply and water quality (Gary et al. 2023). The One Water design lowered the water consumption footprint by approximately 90% (Gary et al. 2023). Blue Hole Primary utilizes a bio-infiltration wastewater treatment system, green infrastructure, and alternative water sources such as rainwater harvesting and A/C condensate capture. Harvested rainwater and A/C condensate is captured and used for indoor non potable water demands through toilets and urinals (Gary et al. 2023). Green stormwater infrastructure was used to protect surface water flows and provide infiltration; the bio-infiltration system removes the need for a connection to the city's wastewater treatment system while also providing infiltration (Gary et al. 2023). TXST can learn from this local model and the expertise from the Meadows Center to implement similar strategies in new campus developments.

Utilizing One Water alternative water sources across campus for various reasons could effectively reduce groundwater withdrawals. A/C condensate capture is another reliable source of water to be used for non-potable reuse (Jurga et al. 2023). A/C condensate consists of capturing vapor and water condensate from air conditioning systems (Diaz et al. 2014; Jurga et al. 2023). The water conservation strategy can increase water security by alleviating the need for potable water in non-potable applications. Efficient applications for condensate reuse are for toilet flushing, irrigation, cooling towers and boilers, and decorative fountains and water features (Diaz et al. 2014). A/C condensate can be efficiently used for cooling tower water because of its ideal quality, with minimal dissolved solids, and its natural properties require less chemical treatment (Diaz et al. 2014). A/C condensate capture for cooling towers does not require storage because it can be directly applied to the cooling towers (Diaz et al. 2014).

The city of San Antonio designated A/C condensate capture as a requirement for all new commercial buildings to encourage reuse to alleviate the demand for the city's limited water resources (Jurga et al. 2023). Blue Hole Primary and San Antonio are local examples of efficient use of A/C condensate capture to conserve local water resources (Gary et al. 2023; Jurga et al. 2023). The implementation of A/C condensate capture should be implemented in all new buildings on campus and retrofitted into old buildings to provide a sustainable water resource to reduce groundwater withdrawals on campus.

Rainwater harvesting (RWH) is another One Water strategy that can be utilized at TXST to limit groundwater withdrawals. Rainwater harvesting captures rainwater from rooftops systems to meet the needs for outdoor or indoor demands (Briones & Mace 2023). RWH can help combat water scarcity by using rainwater to help meet demands. Even in drier climates, RWH is a sufficient practice to meet demands, however requires lower levels of daily use (Briones & Mace 2023). Like Blue Hole Primary, TXST can utilize RWH in new buildings for all non-potable needs (Gary et al. 2023). RWH can be an effective water conservation strategy on university campuses (Korkmaz 2022). Although climate change is expected to bring variability to precipitation in central Texas (Nielsen-Gammon et al. 2020), RWH systems on rooftops at university campuses can effectively contribute to the water supply of the university while reducing the need for groundwater withdrawals (Korkmaz 2022).

New buildings on campus provide large catchment areas. The addition of large rainwater tanks and capacity can make RWH a reliable source of water even through intense droughts (Briones & Mace 2023). Rainwater capture cisterns can also be piped to capture A/C condensate to further increase the efficiency of the system (Gary et al. 2023). Promoting water conscious and conservation behavior on campus through One Water education can increase the reliability of RWH for potable and non-potable use on campus (Briones & Mace 2023).

Another alternative water source and water conservation strategy that TXST can implement to lower irrigation is capturing water that is flushed by the backup wells, the Boiler Plant Well, the Grady Early Well, and the Print Shop Well. The backup groundwater wells are required to be flushed in order to maintain operational status. This results in over 10,000 gallons on average annually. Capturing and storing the 10,000 gallons that is flushed can be used for supplemental needs across campus, such as irrigation or construction.

iv. Conservation Awareness and Conservation Efficiency:

Additionally, promoting water conservation and awareness behavior on university campuses yields other potential environmental benefits other than conserving water (Parece et al. 2013). Promoting water-conscious habits can significantly reduce campus water consumption. Parece and colleague's (2013) study of ten residence halls at Virginia Tech University explored five different water conservation strategies and prompting strategies to determine the most effective at decreasing water use by students. The results showed that not one strategy was more effective than the other but "overall water consumption was reduced by 11.6%" (Parece et al. 2013). Moreover, the reduction of water consumption results in a "reduction of energy used to treat and transport the water," ultimately reducing the University's carbon footprint by reducing 4,097 kg of carbon emissions (Parece et al. 2013). Encouraging TXST students to reduce their water consumption as the student body continues to rise, not only lowers their groundwater withdrawal but can also reduce TXST's carbon footprint, furthering the argument for the implementation of conservation messaging on campus.

Looking at TXST's residential hall groundwater usage, the results of this study show that monthly building water metering data is arbitrary with some months having data and others having no data or inaccurate data. The addition of improved water usage metering on buildings can be a helpful tool for improving water usage monitoring and water conservation on campus. Having precise water usage measurements can provide a better analysis on water usage trends while providing real time monitoring, leak detection, and usage threshold alerts. Improved metering can establish water consumption thresholds for conservation objectives (Calsense 2016). This can provide awareness on consumption exceeding thresholds in certain builds and alert the possibility of leaks or the need to implement improved conservation strategies through messaging or the addition of efficient appliances and fixtures (Calsesne 2016).

Additionally, efficient appliances and fixtures can increase water conservation in buildings on campus. Low flow plumbing fixtures and appliances are an efficient water conservation strategy for buildings (Sheth 2017). Efficient appliances and fixtures consist of low flow toilets and urinals, sinks, faucets, and appliances like washing machines (Lee and Tansel 2013; Sheth 2017). Water efficient appliances and fixtures can reduce indoor water use by 30 to 35 percent (Lee and Tansel 2013; Sheth 2017). Additionally, efficient appliances and fixtures can save up to 40% energy compared to older, inefficient appliances (Sheth 2017).

v. Conservation in Action on Universities' Campuses:

Other universities in Texas are improving their water conservation by implementing strategies that lessen their use of potable water, creating a more sustainable campus. The

University of Texas at Austin (UT) is a national leader in water conservation on a university campus. UT is revolutionizing its water conservation with the creation of a reclaimed and recovered water processing facility on campus, enhancing their sustainability (Pruitt 2025). The on campus wastewater reclamation and reuse system, called the UT WaterHub, will have the capacity to produce 1 million gallons per day of non-potable reuse water (The University of Texas at Austin Utilities and Energy Management 2025). The non potable reuse water provides a new resilient water source for UT's campus and will be utilized for efficient heating and cooling operations in cooling towers and boilers on campus (The University of Texas at Austin Utilities and Energy Management 2025). This new water source proactively combats water scarcity on UT's campus while enhancing the resilience of campus (Pruitt 2025). The UT WaterHub is projected to conserve water by reducing potable water usage by 40% (Pruitt 2025). This 28 million dollar project shows UT's commitment to water conservation on campus, providing the gold standard for other universities across the nation (The University of Texas at Austin Utilities and Energy Management 2025). Prior to the WaterHub, UT used reclaimed water on two of its cooling tower facilities (Calsense 2016). The reclaimed water comes from the City of Austin's municipal reclaimed water system. Using the reclaimed water for the cooling towers offset 130 million gallons of potable use per year (Calsense 2016).

UT has integrated smart irrigation systems that adjust irrigation based on local weather conditions and plant's needs (Calsense 2016). Improved sprinkler heads have been implemented across UT's campus to increase water conservation through regulating pressure and efficient irrigation (Calsense 2016). Additionally, across campus reclaimed water is used for irrigation, cutting down the demand for potable water on non-potable actions (Calsense 2016). Landscapes around the new Moody Center are irrigated with reuse water and multiple landscapes across the campus also utilize reuse water (Calsense 2016).

Another water conservation strategy UT is implementing is improved metering on buildings. Improved metering has been applied to buildings across UT's campus, allowing for efficient monitoring for excessive usage or leaks (Calsense 2016). UT is leading the way for water conservation on university campuses in Texas and across the nation and is a nearby resource and example of ways TXST can enhance its water conservation.

University of Texas at San Antonio (UTSA) is moving towards implementing water conservation strategies as they face intensifying droughts causing water scarcity. UTSA has set out to reduce their total water usage by 20% by 2030. In order to accomplish this goal, UTSA is implementing conservation strategies such as A/C condensate capture and reuse, rainwater harvesting for irrigation, reducing irrigation practices, and improved water metering on buildings to track progress. A/C condensate capture is being utilized in new buildings for reuse. The captured condensate water is being stored and used for irrigation and being used to fill and operate decorative outdoor fountains. To reduce potable water usage for irrigation, UTSA is implementing rainwater harvesting on new buildings for irrigation. New buildings have rainwater capture cisterns that also capture A/C condensate. The rainwater and A/C condensate captured is used for irrigation, helping to reduce their potable water used for irrigation.

UT and UTSA are examples of water conservation strategies on university campuses nearby that TXST can be implementing to improve water conservation and protect its water availability and resilience for the future.

IX. Conclusion

This study examined water use trends at Texas State University's San Marcos campus from 2015 to 2024 and explored water conservation opportunities the university can implement to proactively conserve water and be water stewards for the Edwards Aquifer, Spring Lake, and the San Marcos River.

The results show overall water use has returned to average after a decline due to the COVID-19 pandemic, causing campus operations to halt. Irrigation usage has declined due to the implementation of conservation strategies but has the opportunity to be enhanced as demand is expected to rise. Industrial groundwater use has steadily increased and is projected to continue as temperatures rise and campus further expands. Residential Halls predominantly showed steady trends with some slightly increasing, however metering errors and issues proved difficult to determine accurate trends and outliers.

TXST has a significant opportunity to enhance its water conservation efforts by adopting conservation strategies, reusing water, improving irrigation efficiency, utilizing alternative water sources, and implementing behavioral and technological conservation measures. Utilizing reuse proves to be the most effective strategy to decrease groundwater withdrawals with potentially cutting withdrawals by 29% annually if implemented for industrial water use and irrigation. Groundwater conservation is essential to protect the spring flows of the San Marcos Springs and the San Marcos River, the lifeblood of the community and habitat for endangered species. It is essential for TXST to proactively conserve water not only for the aquifer, river, and springs, but to create a resilient water supply for the future.

Improved monitoring, analyzing water use trends, and implementing conservation opportunities can help TXST facility operators develop a comprehensive, resilient approach to campus water management. By proactively being water stewards and conserving water, TXST can be a leader in university sustainability and water conservation while reinforcing its water supply for the future and protect the Edwards Aquifer, Spring Lake, and the San Marcos River.

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