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PROSPECTIVE COSTS AND CONSEQUENCES OF INSUFFICIENT WATER INFRASTRUCTURE INVESTMENT IN TEXAS

BY GABRIEL COLLINS, J.D.[1]

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EXECUTIVE SUMMARY

Water is one of the four cornerstones of the Texas growth story. The $2.5 trillion Texas economy and a workforce adding six figure numbers of new talent each year need water to grow. The Lone Star state's manufacturing sector now approaches $300 billion in annual economic value generated. Each additional mega-facility Texas attracts or keeps—be it Tesla, Samsung, Texas Instruments, or others—can generate tens or even hundreds of billions of dollars in lifetime economic impacts and support supply chains that incorporate thousands of local small and medium-sized businesses.

But each boardroom making these investment decisions needs confidence that there is enough water for them to operate tomorrow, the next day, and 25 years from now, or they will not locate facilities in Texas. A Texas Legislature that adopts an "invest to grow" approach to water can help materially underwrite water infrastructure investments that bolster confidence.

Water pervades all economic and life activity in Texas. Consider this for perspective: The state consumes about 6.4 million barrels of oil equivalent per day in energy from all sources and for all uses (including chemical and plastics production) but requires nearly 50 times as much water—almost 300 million bpd in 2021.[1]

Accordingly, the direct and opportunity costs of failure to invest are already in the billions per year and could go orders of magnitude higher under the stress of a prolonged drought. **Current costs of water infrastructure underinvestment are already likely on the order of $2 billion annually just for revenue water lost from utility systems. Contingent costs could be far higher, especially if a prolonged drought forces mass scale adoption of more expensive alternative water sources (Exhibit 1).**

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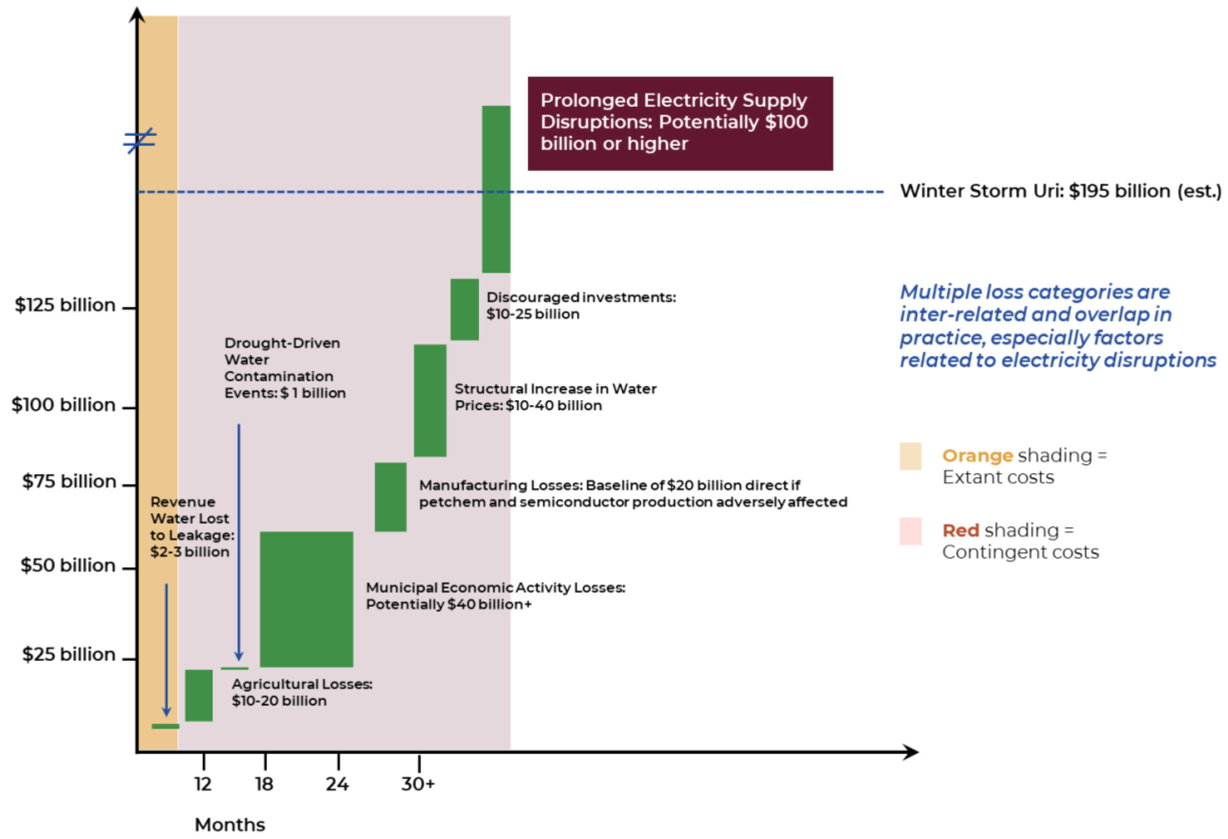
EXHIBIT 1

Potential Annual Costs of Severe Drought in Texas, Billion USD

Note: Impacts shown in approximate order they would be expected to manifest



Source: Author's Estimates based on data from US BEA, EIA, ERCOT, SAWS, Texas Municipal League, TWDB. Municipal economic activity loss assessment is based on Wichita Falls' annual GDP loss estimates from 2011-2015. Discouraged investment assumes that two Micron or Samsung-sized firms each year choose to invest somewhere else due to water concerns. Manufacturing losses: assumes $50 million/day of losses sector wide. Value of lost electrical load assumes that 1/8 of dispatchable power base derates by 50% and that it would have run at 40% nameplate utilization, 6-mo timeframe, Value of Lost Load over long-duration assumed to be $13.5k per MWh based on Brattle Study on Value of Lost Load in Texas, 22 August 2024, https://interchange.puc.texas.gov/Documents/55837_12_1421762.PDF; Uri loss estimate: Lee, CC., Maron, M. & Mostafavi, A. Community-scale big data reveals disparate impacts of the Texas winter storm of 2021 and its managed power outage. Humanit Soc Sci Commun 9, 335 (2022). https://doi.org/10.1057/s41599-022-01353-8. To estimate the impacts of structural increases in water prices, the author built a simple model for expenditures on water as a percentage of GDP in Texas (Appendix A) and over the past 20 years, this figure is likely approximately 0.7% of GDP each year—roughly $18 billion. If a prolonged severe drought took out a large portion of surface water supplies—the cheapest option throughout the Triangle and Rio Grande Valley-and they were replaced with a combination of recycled water, imported groundwater, and desalinated brackish groundwater and seawater, water supply costs could rapidly increase by 50% in a baseline case and double from their pre-drought levels in a more extreme, but still plausible one.

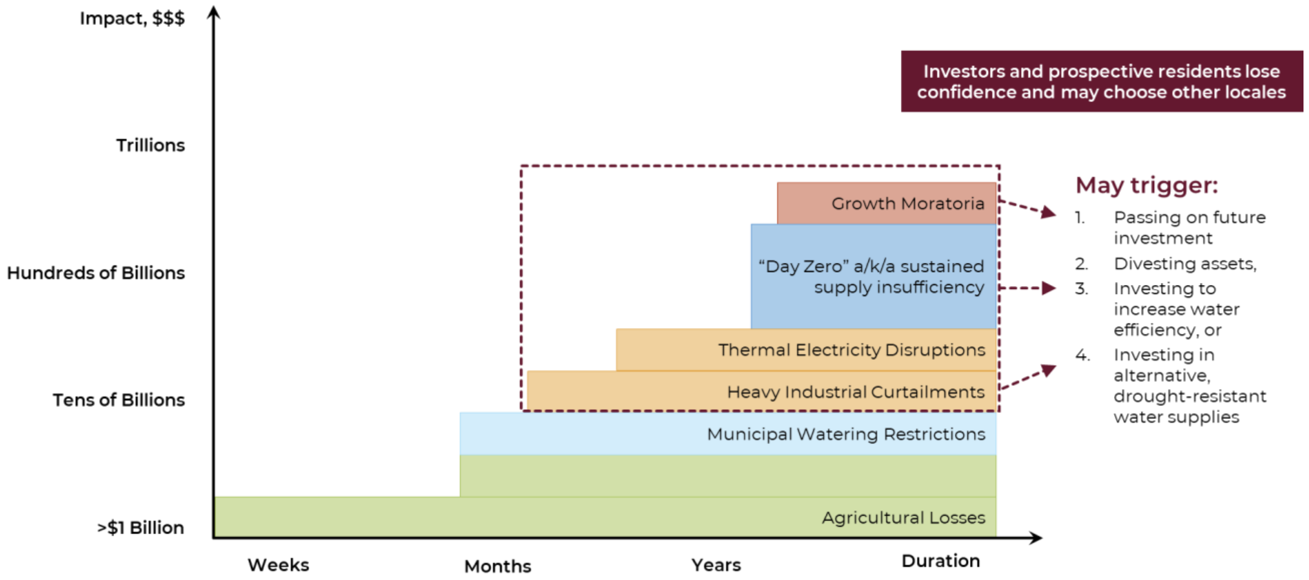
The costs shown in **Exhibit 1** could be significantly higher or lower than what would ultimately manifest, but at a minimum, provide directional guidance as to the severe consequences that could plausibly ensue if Texas is caught underprepared in a future long, severe drought like that of the 1950s. This report augments existing Texas Water Development Board single year snapshot economic loss estimates by taking readers further "under the hood" and explaining potential loss drivers, with special attention paid to electricity generation, manufacturing, and municipalities. Our hope is that this approach helps illuminate additional avenues for policy actions that can mitigate or avoid future drought losses through preemptive infrastructure improvements.

Questions that drive the thinking in this analysis include: Where might we be undercounting the costs? One key area is the multiplier impact of higher water prices on overall economic activity and wellbeing in major municipalities. Would consumers respond to higher water prices in the way they do when gasoline goes up—grouse but move forward, perhaps leaving lawns brown but otherwise acting and spending normally? Or could water costs become a broader and deeper structural tax that slows growth and deters investment?

EXHIBIT 2

How Droughts Evolve and Impacts Compound Over Time

Note: Box outlined with dotted red line represents the "inflection zone" in which adverse, long-term shifts begin to manifest



Ecosystem service and environmental value are also not included in this analysis for length and scope reasons but are also vital and valuable. Ensuring sufficient flows in Texas rivers helps maintains the health of our coast and estuaries—critical assets for fisheries, recreation, flood and storm mitigation, natural carbon sequestration, and a reflection of the world we and our children will inhabit. These things are essential and a bit harder to put specific price tags on. Planned flood control and storm mitigation infrastructure helps illustrates the lower end of potential multi-year values, with the proposed "Ike Dike" coastal barrier now estimated to cost nearly $60 billion.[2]

The bottom line is clear: We must invest to grow. The EPA notes that Texas faces $70 billion in unmet drinking water infrastructure needs (2024$) and approximately $20 billion in wastewater transmission and treatment infrastructure needs (2024$) over the next 20 years.[3] The 2022 Texas State Water Plan, with some duplication of the EPA estimate, suggests $80 billion worth of water supply investments needed in the state. In short, Texas could very plausibly require nearly $200 billion in water investments during the coming 50 years, or an

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[2] Douglas, Erin, and Emily Foxhall. "Texas 'Ike Dike' Coastal Barrier Project Could Cost $57 Billion with Inflation, Army Corps Says." The Texas Tribune, September 28, 2023 https://www.texastribune.org/2023/09/28/texas-ike-dike-coastal-barrier-army-corps/

[3] U.S. Environmental Protection Agency. "Clean Water Needs Survey (CWNS): National Needs Assessment." EPA.gov. Accessed November 8, 2024. https://sdwis.epa.gov/ords/sfdw_pub/r/sfdw/cwns_pub/cwns_needs?session=3953482449163

average of $4 billion annually. Rounding up to $5 billion/year in water supply investments against a $2.5 trillion Texas economy suggests an effective “insurance rate” of 0.2%--less than what many private homeowners pay each year as a proportion of underlying home value.

Such investments will be positive contributors to our future. They are a foundational form of “growth insurance” for the most dynamic state in the Union. They also represent a phenomenal job creation opportunity, which this report describes. It’s more than just construction jobs and folks manning facilities—it’s a chance to build a world-class water industry. Israel has built a globally influential water tech and infrastructure sector in a country with only 1/3 the population of Texas and a fraction of the industrial production capabilities.

The coming Texas water infrastructure wave should aspire to more than simply deploying dollars on Project X in Houston or Project Y in Dallas. It is a chance to use investment activities as a lever to deepen water infrastructure firms’ corporate presence, encourage them to site more of their supply chains here, incentivize Texas universities to attack the technological problems that we can solve here while helping others globally[2], and unleash a water tech and entrepreneurial scene befitting our heft as the world’s 11th largest groundwater pumper and a consumer of millions of acre-feet of surface water as well.[4]

[4] Gabriel Collins, J.D., “Overruling The Rule of Capture: What Can Texas Learn From 10 Other States’ Groundwater Law Updates?,” Baker Institute for Public Policy, Rice University, June 2021, https://www.bakerinstitute.org/media/files/files/ccdd8528/ces-pub-groundwater-laws-060321.pdf

METHODOLOGY

To quantify the risks and opportunities ahead, this report engages a wealth of historical evidence from the 1950s and 2011 droughts in Texas and seeks to better quantify their economic impacts as well as derive insights into adaptive responses that Texas will likely need to draw upon in coming years. It also scoured the economics literature in a meta-analysis aimed at supplying a more global context for the economic impacts of past Texas droughts.

The 1950's Drought, also referred to as the Drought of Record, serves as Texas's most frequently cited example of a long, severe drought. But Texas has seen worse and should plan accordingly. Tree rings suggest droughts similar to the 1950s version (and sometimes worse) afflicted Texas at least once per century, with many other dry periods interspersed within.[5] Given the real and present potential for civilization-altering drought in Texas, this report emphasizes a multi-year and decadal perspective.

This study will go beyond a single set of model output numbers and break out a sector-by-sector stack of potential loss components. It will also include a dimension not captured in previous work—the impacts of lost investments and foregone growth opportunities, a key factor for high-growth locales like Texas. To commence that process, we first turn to how water demand and supply have interacted in Texas over the 50 years leading us to where we are now.

The study's core scenario is a protracted drought, rather than single year events such as 2011 (in most of Texas), 2022, or 2023 (Houston area). Several factors underpin this approach. First, while agriculture, thermoelectric power, and some industrial facilities (like chemical plants and refineries) can suffer major effects in a one-year drought, the highest aggregate value sectors—manufacturing and municipalities—typically require multiple years of drought before the direst impacts set in. Several Texas cities' water sourcing decisions in the 1950s, which often saw transitions to alternative water sources only several years into the drought, reflect this reality.[6]

Second, more than 100 years of meteorological data and centuries more of palaeoclimatological data tell us that Texas has repeatedly endured much. Decadal droughts worse than anything experienced in recorded history or living memory are very much

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[5] MK Cleaveland, TH Votteler, DK Stahle, RC Casteel, JL Banner. 2011.Extended chronology of drought in South central, Southeastern, and West Texas. Texas Water Journal. 2(1): 54-96. Available from: https://doi.org/10.21423/twj.v2i1.2049

[6] Manford, Durwood, R. M. Dixon, and O. F. Dent. Historical Ground-Water Uses by Municipalities for the Years 1955 through 1959 for Selected Areas in Texas. Report M293. Texas Water Development Board, 1961. https://www.twdb.texas.gov/publications/reports/historic_groundwater_reports/index.asp.

possible.[7] Third, infrastructure investments and the opportunities they present are also multi-decade propositions. Fourth, a longer timeline reflects both the compounding costs of drought and the potential for adaptations—such as where we source water from—that bring dynamic sets of economic opportunities that in some cases are offset or at least, significantly influenced by, by structurally higher costs.

Because of this dynamism, the study does not seek to produce a single bottom line number. It instead focuses on range and direction, acknowledging the dynamic complexity while also remaining as quantitative as the data permit. Renowned energy analyst Vaclav Smil describes energy production and use as being governed by "…complex interactions of social, economic, technical, and environmental factors" that make accurate forward modelling extremely difficult, if not impossible.[8] Water is very similar.

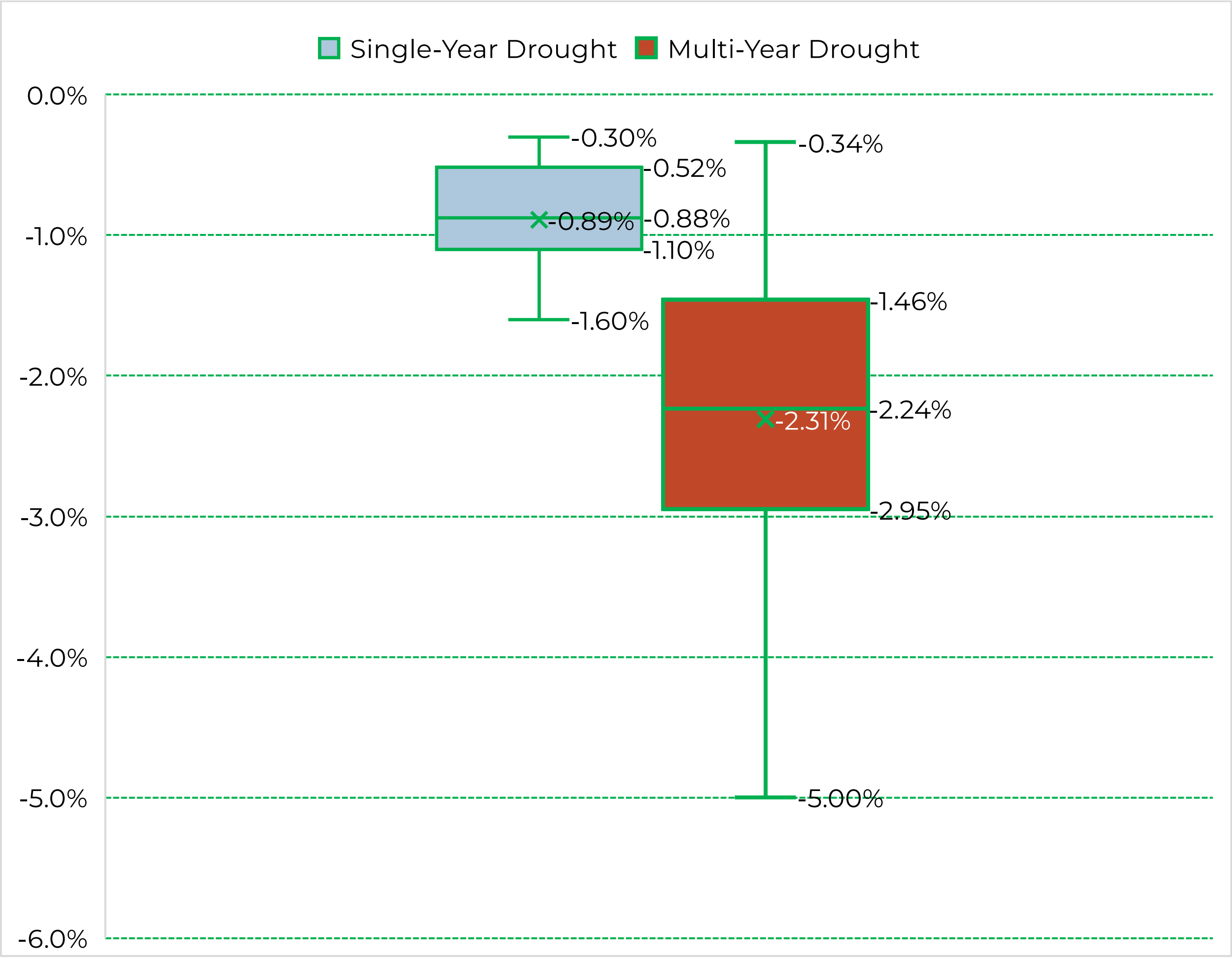
One is dealing with a fundamentally uncontained, but infrastructure-centric system for which broad trends may be ascertained but precise forecasts are often illusory. Given that economic impacts of water insufficiency are tied to a massively complex and dynamic system, this study emphasizes projections anchored as deeply as possible in real world examples. Among others, it engages the saga of Wichita Falls and its adaptation to a severe drought between 2011 and 2015, looks at historical economic activity reports in Texas from the 1950s, draws upon nearly a century of oil & gas production data, and also incorporates insights from more than a dozen studies looking at economic impacts of drought around the world in approximately 100 countries **(Exhibit 3).**

[7] Mazur, Jeremy. "Will Extreme Weather Set the Next Legislative Agenda Again?" Dallas News, August 21, 2024. https://www.dallasnews.com/opinion/commentary/2024/08/21/will-extreme-weather-set-the-next-legislative-agenda-again/ and Mace, Robert. "Forecasting the Unpredictable: Water Planning Under Deep Uncertainty." Jalapeño Blog, Texas State University, July 23, 2024. https://jalapeno.wp.txstate.edu/2024/07/23/forecasting-the-unpredictable-water-planning-under-deep-uncertainty/.

[8] Smil, Václav. Energy at the Crossroads: Global Perspectives and Uncertainties. Cambridge: MIT Press, 2003. (168)

EXHIBIT 3

Selected Economic Impacts of Droughts Around the World, % Change in GDP



Source: Multiple Academic Studies, Full table listed in Appendix A

For the State of Texas, the most readily available quantification comes from studies of the 2011 Drought and its impacts on the agricultural sector. One brief report from Texas A&M tallied statewide drought-induced losses at $12.5 billion.[9] A paper written by a scholar at the University of Oklahoma tabbed total losses at closer to $17 billion.[10] Those studies help build the sectoral loss stack that will emerge later in this report but are inherently limited to the agricultural sector, as opposed to the manufacturing sector and cities that are less exposed

[9] Guerrero, Bridget. Briefing Paper 09-01-11. Texas A&M AgriLife Extension, 2012. https://agecoext.tamu.edu/wp-content/uploads/2013/07/BriefingPaper09-01-11.pdf

[10] Ziolkowska, Jadwiga R. 2016. "Socio-Economic Implications of Drought in the Agricultural Sector and the State Economy" Economies 4, no. 3: 19. https://doi.org/10.3390/economies4030019

to single-year droughts but could be profoundly impacted by multi-year events with consequences that dwarf agricultural losses.

At a more global macro-level, studies of drought impacts suggest that drought impacts are strongest in lower-income, predominantly agricultural economies and weaker in more developed countries whose water intensities per unit of economic output are generally lower. For instance, a 2023 World Bank study found that in developing countries, moderate single-year drought reduced growth by 0.39% and extreme drought by approximately 0.85%, while in high-income countries only extreme droughts caused adverse impacts, shaving growth by an average of 0.3%.[11]

Another 2023 study by a team of American and Chilean scholars examining the economic impacts of a megadrought in Chile between 2010 and 2020 estimated total economic losses at 0.475% of national GDP during the period of study, approximately tracking the World Bank results.[12] Three studies on drought impacts in Australia, discussed in a 2023 meta-analysis by Fleming-Muñoz et.al, variously estimated the national macroeconomic impact of intense single-year drought at between 0.5% and 1.1% of GDP.[13] For perspective, 1% of 2023 Texas GDP is almost $26 billion.[14]

The Chile-focused study also pointed out two key, interconnected dimensions relevant to the present report: (1) long-duration droughts exact an increasing toll as water stocks are drawn down over time and (2) increased urban water sourcing costs can dramatically amplify a drought's economic impact. The Chilean megadrought deserves special attention in Texas because it has lasted more than a decade.[15] As drought persists, short-run solutions of tapping remaining reservoir water and pumping groundwater can fail as lakes dry up (which happened in West Texas in 2011) and groundwater depletion raises pumping costs and limits withdrawals.

Taken together, these dynamics can yield a tipping point at which adaptive responses become less flexible and more expensive. To that point, the researchers in the Chile drought study noted that while their bottom-line estimate posited a national GDP loss from severe

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[11] Zaveri, Esha, Richard Damania, and Nathan Engle. Droughts and Deficits: Summary Evidence of the Global Impact on Economic Growth. Washington, DC: World Bank, 2023. https://documents1.worldbank.org/curated/en/099640306142317412/pdf/IDU03b9849a60d86404b600bc480bef6082a760a.pdf.

[12] Fernández, Francisco J., Felipe Vásquez-Lavín, Roberto D. Ponce, René Garreaud, Francisco Hernández, Oscar Link, Francisco Zambrano, and Michael Hanemann. "The Economics Impacts of Long-Run Droughts: Challenges, Gaps, and Way Forward." Journal of Environmental Management 344 (2023): 118726. ISSN 0301-4797. https://doi.org/10.1016/j.jenvman.2023.118726

[13] Fleming-Muñoz, D.A., Whitten, S. & Bonnett, G.D. (2023) The economics of drought: A review of impacts and costs. Australian Journal of Agricultural and Resource Economics, 67, 501–523. Available from: https://doi.org/10.1111/1467-8489.12527

[14] U.S. Bureau of Economic Analysis. Gross Domestic Product by State, 1st Quarter 2024. June 2024. https://www.bea.gov/sites/default/files/2024-06/stgdppi1q24.pdf

[15] Reuters. "Chile Announces Unprecedented Water Rationing Plan as Drought Enters 13th Year." Reuters, April 11, 2022. https://www.reuters.com/business/environment/chile-announces-unprecedented-water-rationing-plan-drought-enters-13th-year-2022-04-11/

prolonged drought of -0.475%, a drought that forced urban water restrictions could quadruple that GDP loss, bringing it closer to -2.1% under a 20% rationing scenario.[16]

A 2% GDP loss at the Texas economy's present size would amount to $50 billion annually. Such large stakes reinforce the case for preemptive investment in water infrastructure. Indeed, the Chilean scholars noted that in their assessment "...a dollar invested in drought preparedness can prevent approximately 8.3 dollars in economic losses."[17] The corollary is that investment not only avoid the costs of drought, it also likely opens substantial opportunities for further demographic and economic growth in Texas and doing so in a way that allows our descendants to live better in 2124 than we do today. To arrive there, our past 70 years of history hold lessons for the century to come.

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[16] Fernández, Francisco J., Felipe Vásquez-Lavín, Roberto D. Ponce, René Garreaud, Francisco Hernández, Oscar Link, Francisco Zambrano, and Michael Hanemann. "The Economics Impacts of Long-Run Droughts: Challenges, Gaps, and Way Forward." Journal of Environmental Management 344 (2023): 118726. ISSN 0301-4797. https://doi.org/10.1016/j.jenvman.2023.118726

[17] Ibid. (7)

The 1950s Drought

This author attempted to locate studies quantifying the economic impacts of the 1950s Drought in Texas upon sectors other than agriculture but was unsuccessful. He did locate nine annual economic activity reports from the Federal Reserve Bank of Dallas, whose district covers all of Texas as well as northern Louisiana and southern New Mexico.[18]

Some of the reports mentioned drought and localized impacts on agricultural activities but did not indicate structural downturns in manufacturing or industrial activity caused specifically by water shortages. In fact, drought was overwhelmed by exogenous macroeconomic forces such as elevated defense spending during the Korean War and oil price gyrations triggered by instability in the Middle East and the 1956 Suez Crisis.[19]

It is also noteworthy that the Texas population grew through the entire 1950s drought at a rate higher than that of the past decade **(Exhibit 4).** While not probative, if the non-agricultural economy were wracked by water shortage-induced disruptions, one would expect net outflows from a region whose agricultural sector was adversely affected by drought. Indeed, Texas cities were a magnet for rural migration as nearly 100,000 farms and ranches failed during the 1950s.[20] The water crisis of the 1950s thus continued the urbanization that World War II had jump-started. The war had already irreversibly transformed Texas from a rural agrarian state into a more industrial one where locals moved into cities alongside arrivals from outside Texas as population grew by 20% between 1940 and 1950.[21] The “shock absorber” of being able to move from farm to city does not exist in nearly the same degree today. A massive future drought would leave nowhere for people to go but out of Texas—an outcome we distinctly seek to avoid.

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[18] Federal Reserve Bank of Dallas. Annual Report of the Federal Reserve Bank of Dallas. 1915-2018. https://fraser.stlouisfed.org/title/475, accessed on August 1, 2024.

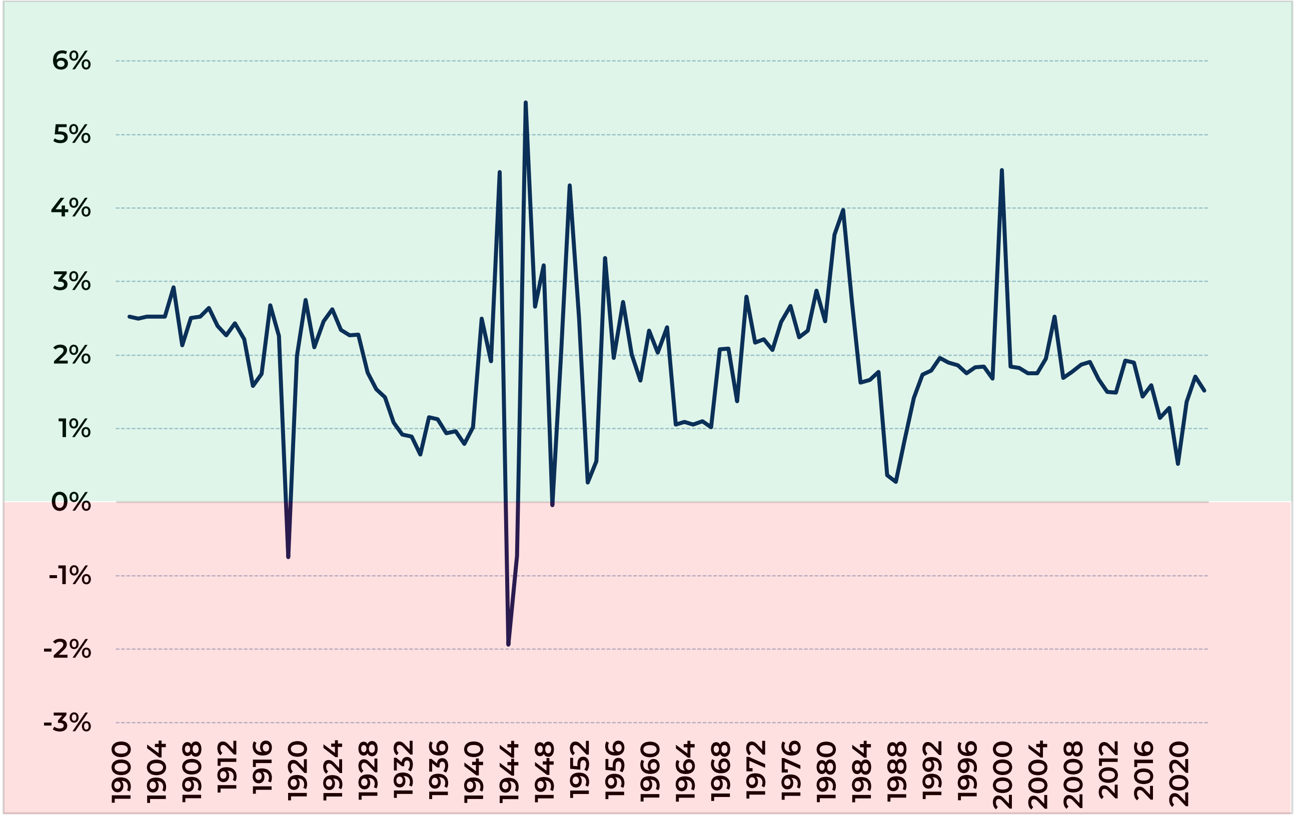
[19] See 1956 Annual Report of the Federal Reserve Bank of Dallas, Page 4

[20] Genoways, Ted. "The Shape of Droughts to Come." Texas Monthly, July 2018. Accessed August 4, 2024. https://www.texasmonthly.com/arts-entertainment/drought-to-come-agriculture-water-crisis/

[21] Texas State Historical Association. "Texas Post-World War II." Handbook of Texas Online. Accessed November 8, 2024. https://www.tshaonline.org/handbook/entries/texas-post-world-war-ii

EXHIBIT 4

Annual Percentage Change in Texas Population, 1900-2023



Source: Texas Demographic Center, US Census Bureau, Author's Analysis

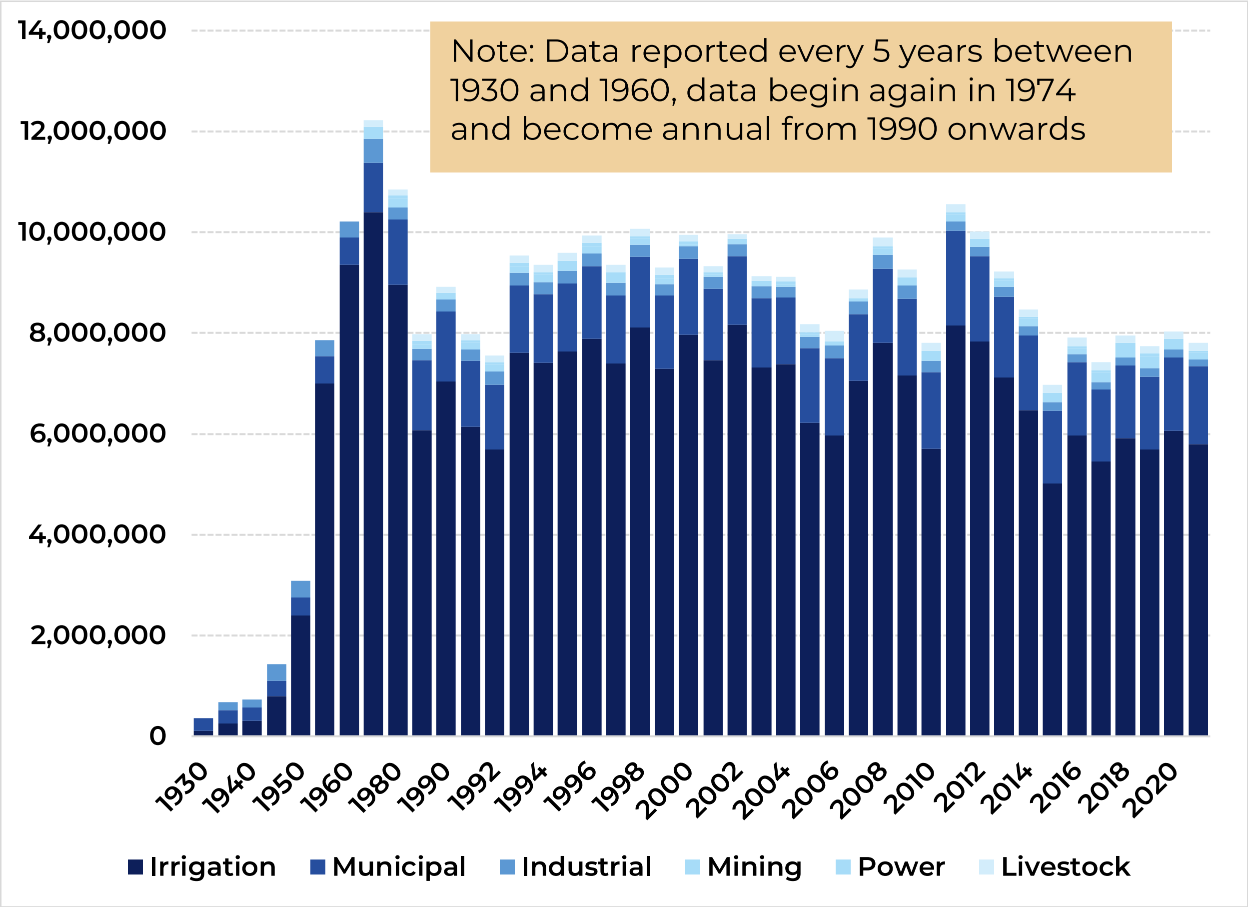
The 2020s and Beyond Do Not Enjoy the 1950s' Drought Shock Absorbers.

In the 1950s, Texas absorbed the drought shock through two key channels. First, people moved from farms and ranches into town to take up work amidst a broader industrial and economic boom. Second, development of more advanced drilling equipment, better pumps, and rural electrification to power them (along with some piston-engine motors) allowed parched farms and cities alike to more than double their use of groundwater resources between 1950 and 1960 **(Exhibit 5).**

Such a rapid and sustained scale-up of groundwater abstraction today would almost certainly be hydrologically infeasible. In many areas, there is not sufficient water to expand groundwater production by millions of acre-feet per year. Furthermore, to the extent groundwater production expansions are undertaken, they can induce substantial secondary consequences, ranging from destruction of habitat in the Edwards Aquifer hydro shed to subsidence and permanent impairment of aquifer storage capacity in the Greater Houston Area as pore spaces collapse.

EXHIBIT 5

Annual Groundwater Use in Texas, Acre-Feet, 1930-2021



Source: Texas Water Development Board, Author's Analysis

Texas now has more than 30 million residents and a Canada-sized economy and multiple sectors of national and global consequence could be exposed to water scarcity in a future drought of record. Five counties in the Texas Triangle alone (Bexar, Dallas, Harris, Tarrant, and Travis) account for nearly half of the state's economic output.[22] Texas has a $300 billion/year manufacturing sector, producing items including semiconductors, F-35 stealth fighters, cars & trucks, oilfield equipment, and many other vital goods.[23]

Texas is also one of the United States' most important agricultural states, with an agricultural economic base that, depending on farm commodity prices, can exceed that of Iowa, a state

[22] U.S. Bureau of Economic Analysis. "Local Area Gross Domestic Product, 2022." Last modified December 12, 2023. https://www.bea.gov/sites/default/files/2023-12/lagdp1223.pdf

[23] U.S. Bureau of Economic Analysis, Gross Domestic Product: Manufacturing (31-33) in Texas [TXMANNGSP], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/TXMANNGSP, August 4, 2024

as synonymous with farming as Texas is with oil.[24] The state by itself produces more oil than any OPEC+ members aside from Russia and Saudi Arabia and about twice as much gas as Qatar.[25] It also has a globally-competitive services sector staffed by a diverse and dynamic urban population, human capital that is mobile and could be repelled by disruptions and degradation of living conditions caused by a lack of water.

As we assess these sectors and their degree of exposure to a severe drought, their respective responses to the 2011 Drought—the most significant for which we have detailed water usage data—can help us better understand the foundation for potential economic consequences. Agriculture had the most dramatic response, with water usage increasing by about 3-million-acre feet between 2010 and 2011, 80% of which came from a surge in groundwater production **(Exhibit 6)**. Municipal usage followed, increasing by about 760 thousand acre-feet, roughly split between groundwater and surface water. Manufacturing water use rose by about 200 thousand acre-feet. Water usage in the thermoelectric power sector actually declined by 124 thousand acre-feet.

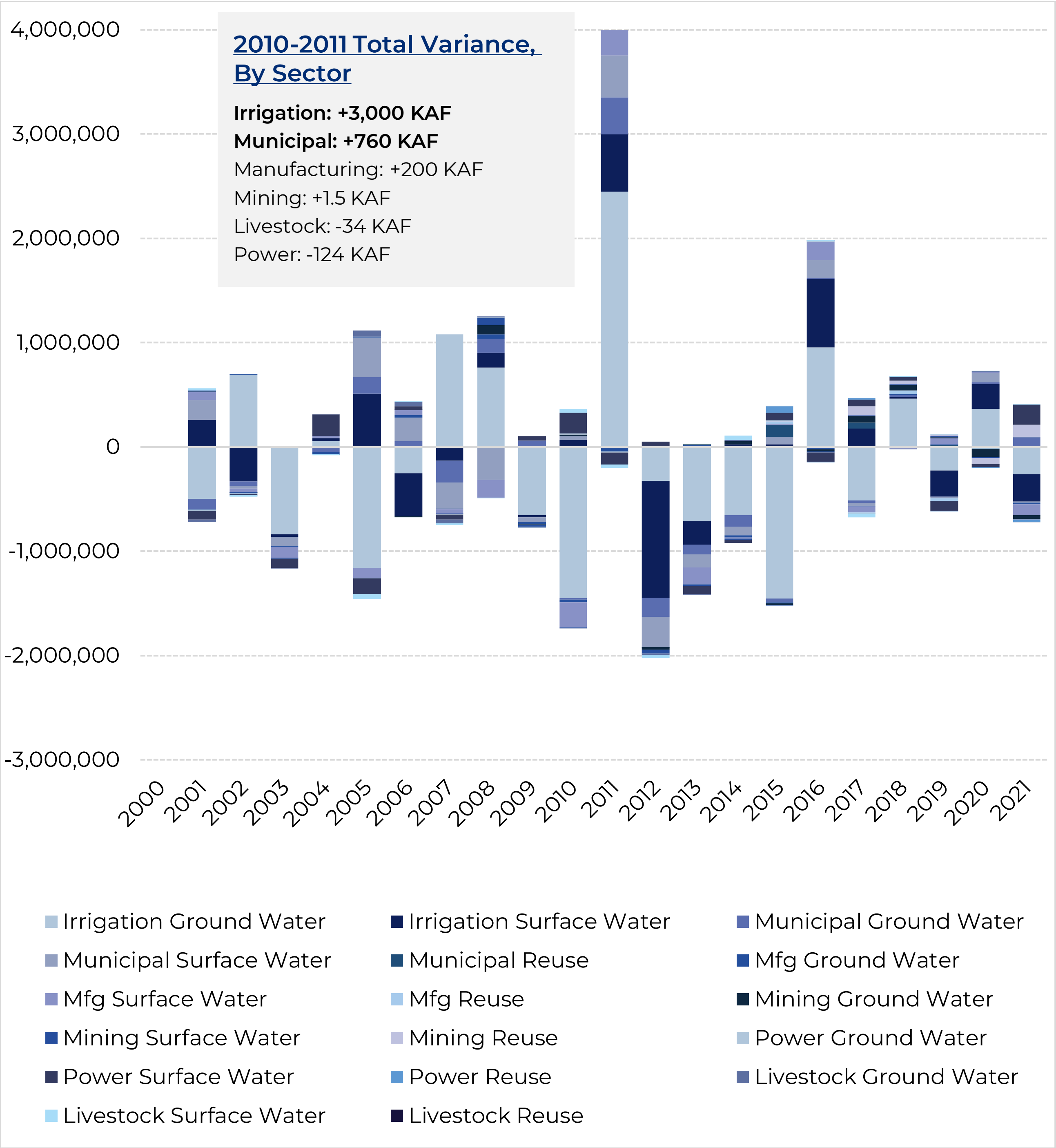
A key point to note is that underneath the macro use change numbers lies a significant geospatial dislocation: most of the shift in agricultural water use occurs in the Panhandle/West Texas and Rio Grande Valley, while the core municipal demand shift occurs 350-500 miles away in the Triangle. Geospatial incongruity will have major implications for water infrastructure investment needs, since outside of the Rio Grande Valley or the Edwards Aquifer water market, an acre-foot of water not used by farmers may in fact not be readily available to cities or other users.

[24] U.S. Bureau of Economic Analysis, Gross Domestic Product: Agriculture, Forestry, Fishing and Hunting (11) in Iowa [IAAGRNGSP], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/IAAGRNGSP, August 4, 2024

[25] Energy Institute. "Statistical Review of World Energy." Accessed August 4, 2024. https://www.energyinst.org/statistical-review; Texas Oil & Gas Association. "Monthly Energy Economics Review: January 2024 (Revised)." Last modified January 2024. https://docs.txoga.org/files/4156-txoga-monthly-energy-economics-review-jan-2024-revised.pdf

EXHIBIT 6

Water Use Variance by Sector and Type Between 2010 and 2011 in Texas, Acre-Feet



Source: TWDB, Author's Analysis

Building the "Economic Loss Stack" For a Long Duration Drought, By Sector

This section attempts to unpack potential drought-driven losses across key sectors in Texas to provide a more nuanced guide for policymakers contemplating investments to enhance water resilience. The data are presented in a single-year snapshot format but are fundamentally rooted in multi-year loss analysis. Additionally, they are presented in a mixed qualitative and quantitative format, as quantification only would risk imparting a false sense of precision that does not exist in reality when dealing with complex, dynamic systems.

Speaking in directional terms, the annual losses from a major prolonged drought event could plausibly rise to the level of Winter Storm Uri—which caused damages estimated to be at least $195 billion, and potentially, much higher**.** But droughts have much worse net economic impacts than storms. Hurricanes and severe storms can inflict tens of billions of economic losses annually (and sometimes much more). But as Robert Gilmer from the University of Houston pointed out in a 2018 analysis of Hurricane Harvey's damage, initial damages to capital assets are generally quickly offset by reconstruction and recovery activities and within months, a storm's net economic impact is often zero and in some cases even slightly positive.[26]

Expressed differently**, storms are disruptive and damaging but are short-term shocks and often do not affect the economy's root drivers or impose long-term economic or physical constraints on production inputs. Severe droughts are the exact opposite, restricting water resources necessary to grow crops, operate factories, generate electricity, and sustain life. There is no recovery boom let during the drought or after it breaks**. In physiological terms, a protracted drought is like a deteriorating injury, progressing from skin scratch (which could heal fine) to a cut to a deeper flesh wound and ultimately, towards structural damage to bones and connective tissues which risks permanent and disabling structural alterations.

Finally, drought saps risk appetite and stokes fear—which kills growth today and discourages investment that could otherwise fuel growth tomorrow. Drought's direct impacts can be profound but the highest costs over time can come from opportunities missed as investors seek places with water supplies perceived to be more reliable.

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[26] Gilmer, Robert. Harvey in Perspective: The Houston Economy and Hurricanes Past and Present. Institute for Regional Forecasting, Bauer College of Business, University of Houston, February 6, 2018. https://www.bauer.uh.edu/centers/irf/houston-updates-feb18.php

Agriculture, Livestock, and Timber

Initial estimates of the 2011 Drought's impact on Texas agriculture came in at $7.62 billion, plus an additional estimate of nearly $600 million in timber losses.[27] Later full-spectrum analysis that accounted for agricultural losses' flow through impacts to supporting business raised the estimated total loss to between $12 and approximately $17 billion.[28] This compares to a $35 billion inflation adjusted loss experienced by Texas agricultural producers during the entire 1950s drought.[29]

At this point, the author believes it defensible to assume a $15 billion dollar agriculture, timber, and livestock loss from the first full year of a future statewide drought of record **(Exhibit 7).** If the 1950s are a guide, losses will likely ameliorate in subsequent years as farmers change crops, adapt growing practices, and prices rise for crops like cotton where Texas accounts for a material portion of national and global production.

Yet even with adaptation, groundwater drawdowns in key aquifers, especially the Ogallala, and the competition with cities for surface water in the Rio Grande, Colorado, and Brazos watersheds likely ensures enduring pressure and conflict. One potential resolution to this conflict is that farmers may choose to sell much or all of their water (ground and surface rights) to cities and either stop farming or dryland farm. This could start economically offsetting losses attributable to the agricultural sector 3-to-5 years into a drought and beyond.

Potential water sales by agricultural water owners also highlight a growing policy need in Texas—that of developing more water markets in key surface and groundwater areas. Successful case examples already operate in the Lower Rio Grande Valley for surface water and the Edwards Aquifer for groundwater. The Carrizo-Wilcox Aquifer system and Brazos River watershed could offer next generation water market development opportunities.

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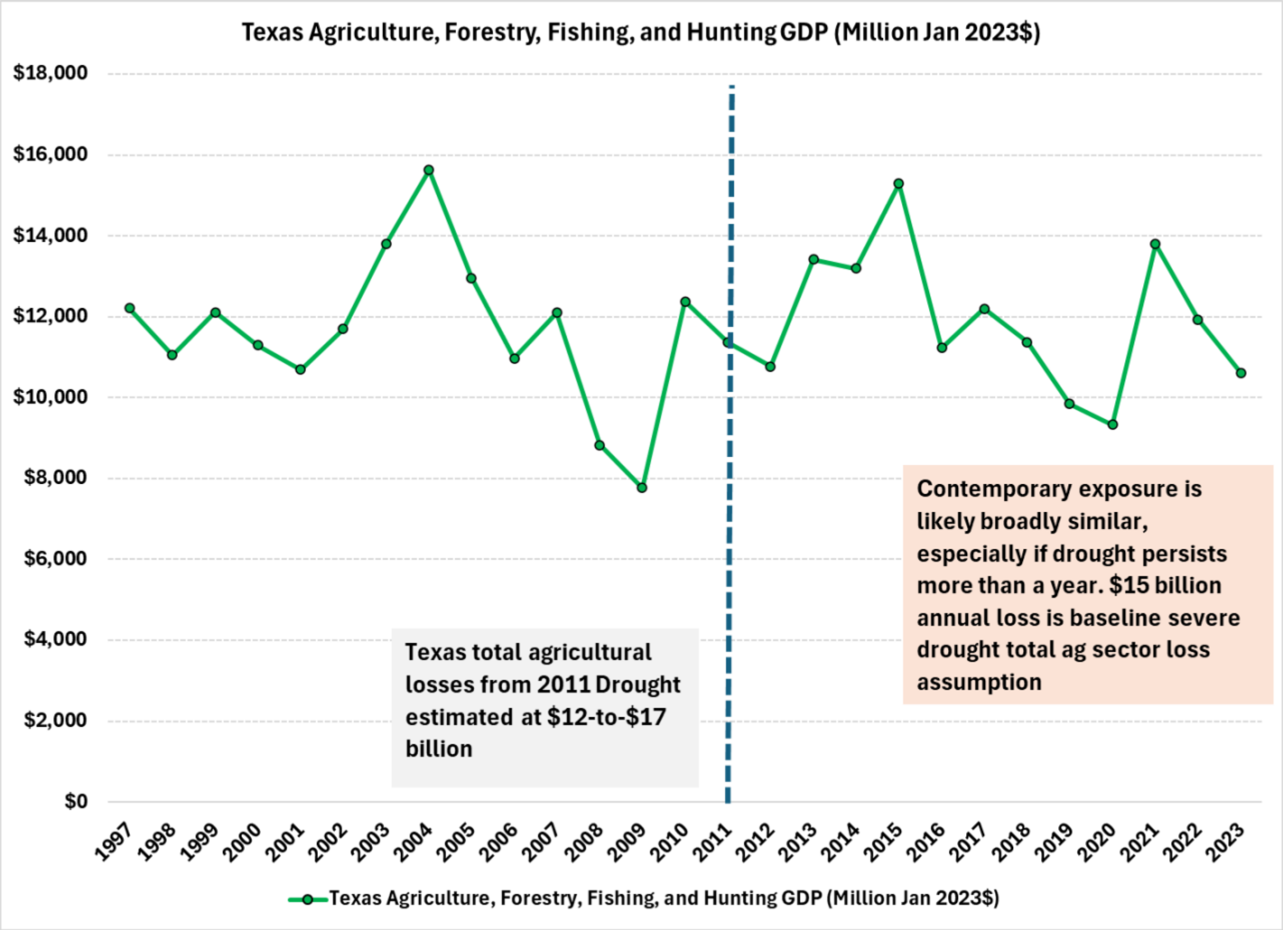
[27] Reuters. "Texas 2011 Drought Costliest in State History: Researchers." Last modified March 22, 2012. https://www.reuters.com/article/world/us/texas-2011-drought-costliest-in-state-history-researchers-idUSBRE82L003/

[28] Guerrero, Bridget. Briefing Paper 09-01-11. Texas A&M AgriLife Extension, 2012. https://agecoext.tamu.edu/wp-content/uploads/2013/07/BriefingPaper09-01-11.pdf; Ziolkowska, Jadwiga R. 2016. "Socio-Economic Implications of Drought in the Agricultural Sector and the State Economy" Economies 4, no. 3: 19. https://doi.org/10.3390/economies4030019

[29] Lowry RL Jr. 1959. A study of droughts in Texas. Texas Board of Water Engineers Bulletin. 5914:1-87

EXHIBIT 7

Texas Agricultural GDP and Losses in 2011 Drought



Source: BEA, Author's Analysis

Energy & Electrical Power Generation

Oil & Gas Industry

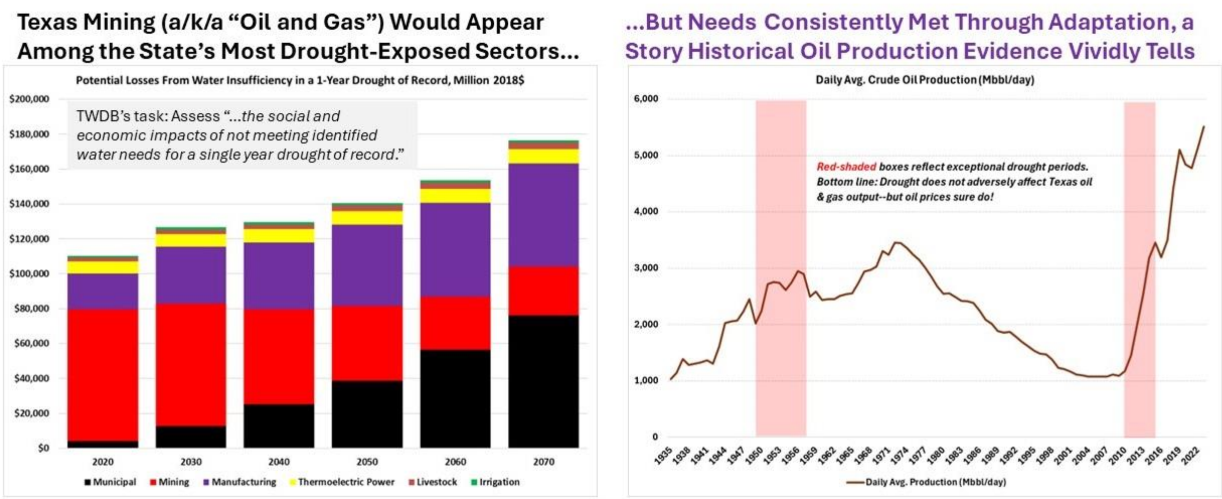
The Texas oil & gas industry has maintained and even grown production through repeated droughts—including the 1950s and 2011. It is perhaps the most climate-adaptable major industry in the state because it has lower overall water requirements and because it has the capacity to internally fund water recycling efforts, as it has done in the booming Permian Basin **(Exhibit 8).**

While fracking is more water-intensive than prior conventional oil production, many large operators by 2018 were already obtaining the majority of their Permian Basin frac water supplies by recycling produced water from oil & gas-bearing formations.[30] Brackish water has also become an important source of oilfield water supplies. These operational adaptations have divorced the most important Texas oilfields from both surface water and traditional sources of subsurface water supply, thus substantially drought-proofing oil & gas production in the state.

[30] Collins, Gabriel. Trash or Treasure? How Is Produced Water's Economic Value Evolving in the Permian Basin? Baker Institute for Public Policy, February 7, 2019.https://www.bakerinstitute.org/sites/default/files/2019-02/import/collins-trash-or-treasure-how-is-produced-water-s-economic-value-evolving-in-the-permian-basin-7-february-2019.pdf

EXHIBIT 8

Projected Drought Risks to Oil Production vs. Historical Operational Reality



Source: EIA (1981-2023 production data), Texas RRC (1935-1980 production data), Author's analysis

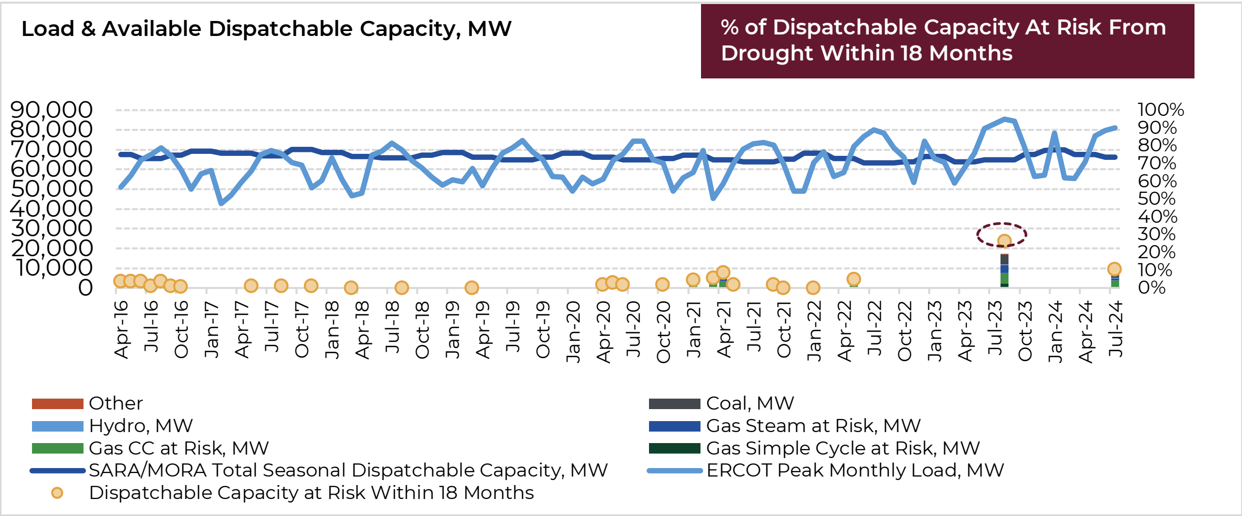
Exposure to drought is not equally apportioned across the oil & gas space. As described above, upstream and midstream operations are generally highly drought-resistant. Downstream refining and petrochemical operations are highly exposed, as facilities often cluster near the estuaries of oversubscribed river systems and single plant complexes can require annual water withdrawals on par with those of small cities. Drought-related chemical plant shutdowns in Altamira, Mexico during the summer of 2024, a situation this report engages in the section on Manufacturing Impacts, offers a cautionary tale for Texas operators.

Electricity Generation & the Texas Grid

The Texas electricity generation sector is more exposed to drought than upstream oil & gas activities are. ERCOT, whose grid serves 90% of electricity load in Texas, publishes periodic Drought Risk Analyses. Perhaps the most striking Drought Risk Analysis in recent years came in August 2023, when much of the state (including the normally wet Houston area) had been gripped by months of drought and a long string of days with temperatures of 100°F or higher. The analysis predicted that if the drought had continued for another 18 months, about 25% of summer dispatchable power generation capacity on the ERCOT grid could have been at risk of having insufficient water supplies to sustain full operations **(Exhibit 9).**

EXHIBIT 9

ERCOT Dispatchable Capacity Deemed at Risk from Drought vs. Dispatchable Seasonal Capacity and Monthly Peak Load



Source: ERCOT, Author's Analysis

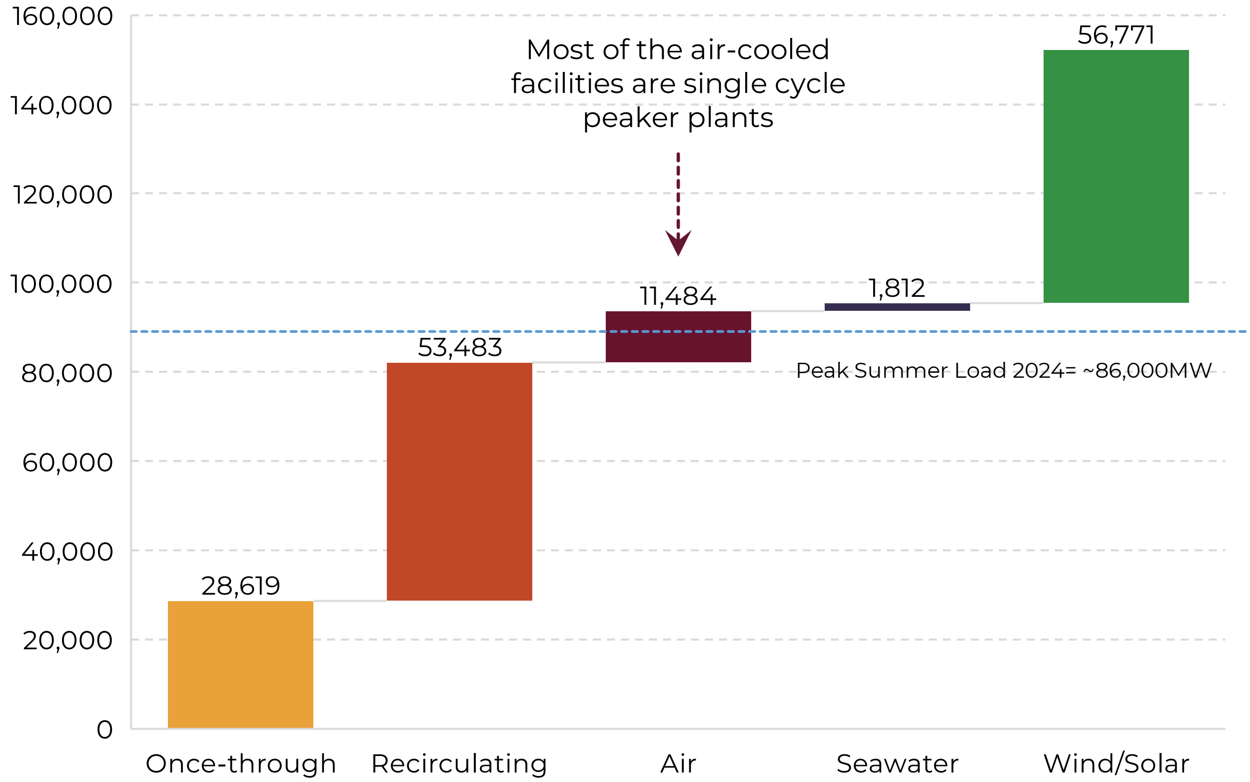
The August 2023 assessment in particular highlighted several important factors that are likely to endure moving forward on the Texas power grid. First, the key pillars for dispatchable electricity for Texas' grid, including natural gas, nuclear, and coal-based generation, face substantive risks to continued generation during long, severe droughts. Indeed, it suggests that a severe drought lasting anything more than two years could realistically start to imperil key parts of the Texas electricity generation system.

This would be a serious problem in a state that already has greater electricity demand than most countries and which is effectively an electricity island with only small interconnections to neighboring grids. The problem would be amplified by the fact that for significant parts of the year, daily peak power loads in Texas now match or exceed available dispatchable (a/k/a thermal) power generation capacity—the precise facilities exposed to water-related vulnerabilities. The assessment also shows that even when Texas overall is not in a severe drought (D2-D4 on the Palmer Drought Severity Index) localized drought in specific key areas, such as the Brazos Basin or lakes in the Dallas area can have potentially outsized impacts on the grid given the concentration of water-intensive thermal power generation in those places.

The current trend of gas-fired generation plants displacing coal generators does not automatically reduce drought exposure. The author reviewed data and satellite imagery for more than 700 operational utility-scale power plants in Texas (generally 50 MW or higher nameplate capacity) to assess their cooling system type. Of the more than 350 thermal power facilities with approximately 93 gigawatts of capacity, the majority had some degree of reliance on water for cooling. Of these, nearly 29 gigawatts' worth are "once-through" designs that require massive volumes of water from a lake or river and would potentially have to reduce generation or in a worst case, shut down, during a prolonged severe drought **(Exhibit 10).**

EXHIBIT 10

Texas Power Plants by Cooling Type, Nameplate Capacity in MW



Source: Global Energy Monitor, Google Maps, Texas Parks and Wildlife Department, Author's Analysis

Relatedly, the rising proportion of wind and solar capacity do not reduce drought risk to the extent which one might initially expect. This is because gas power plants are critical to compensate for intermittency from wind and solar resources that may not deliver power reliably during hot still periods (wind) or gray, freezing, and still Polar Vortex events (wind and solar both impacted). Battery storage does not come close to compensating for potential lost thermal generation, especially for long-duration events like Winter Storm Uri that eclipse renewables' generating capacity and exceed the 2-to-4-hour discharge capabilities found in most grid-connected batteries in Texas.

As such, in a prolonged severe drought, there is an underappreciated risk that multiple gas power plants could face water-related reductions in power output and the grid could be destabilized, potentially forcing a load-shed event and blackouts like Texas experienced during Winter Storm Uri in February 2021. Under severe enough drought conditions, a load shed would last far longer than the 4-to-5 days much of Texas suffered under Uri.

Perhaps the signature example is the R.W. Miller gas-fired plant on Lake Palo Pinto, which had to cease operations for 6 months during late 2014 and early 2015 due to low lake levels caused by drought. There are others that experienced water stress during this period. During the 2011 drought, Luminant had to import water from the Sabine River to top up Martin Lake, which cools its 2.7 GW coal plant of the same name.[31]

Similarly, the Coleto Creek Power Plant had to pump water from the Guadalupe River between July 2011 and February 2013 to ensure sufficient water in its eponymous cooling lake to remain compliant with the temperature limits of its discharge permit.[32] Highlighting future risks, at least one study suggests that more than a dozen large Texas power plants could face curtailments due to effluent temperature limits in a future multi-year severe drought.[33] Temperature limits are imposed under the federal Clean Water Act to manage thermal pollution and its impacts on aquatic life.

Second, the August 2023 ERCOT assessment suggests amplified risks relative to conditions as existed during the 2011 Drought. An ERCOT official noted in September 2011 that an additional year of severe drought could imperil “several thousand megawatts of generation”—only a fraction of the capacity ERCOT believed could be at risk within 18 months in its August 2023 assessment.[34] Texas now has a substantially larger population and economy than it did in 2011 and electricity peak loads are more than 25% higher than they were then **(Exhibit 11). Pressure is likely to continue, as recent analysis from the Baker Institute for Public Policy’s Center for Energy Studies suggests that in Texas, a 1% increase in population will yield a 0.65% increase in average annual electricity load.[35]**

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[31] Bridget R Scanlon et al 2013 Environ. Res. Lett. 8 045033

DOI 10.1088/1748-9326/8/4/045033

[32] Guadalupe-Blanco River Authority. Guadalupe River Basin Summary Report: 2013 Update. 2013. https://www.gbra.org/wp-content/uploads/2021/05/basinsummary-2013j.pdf

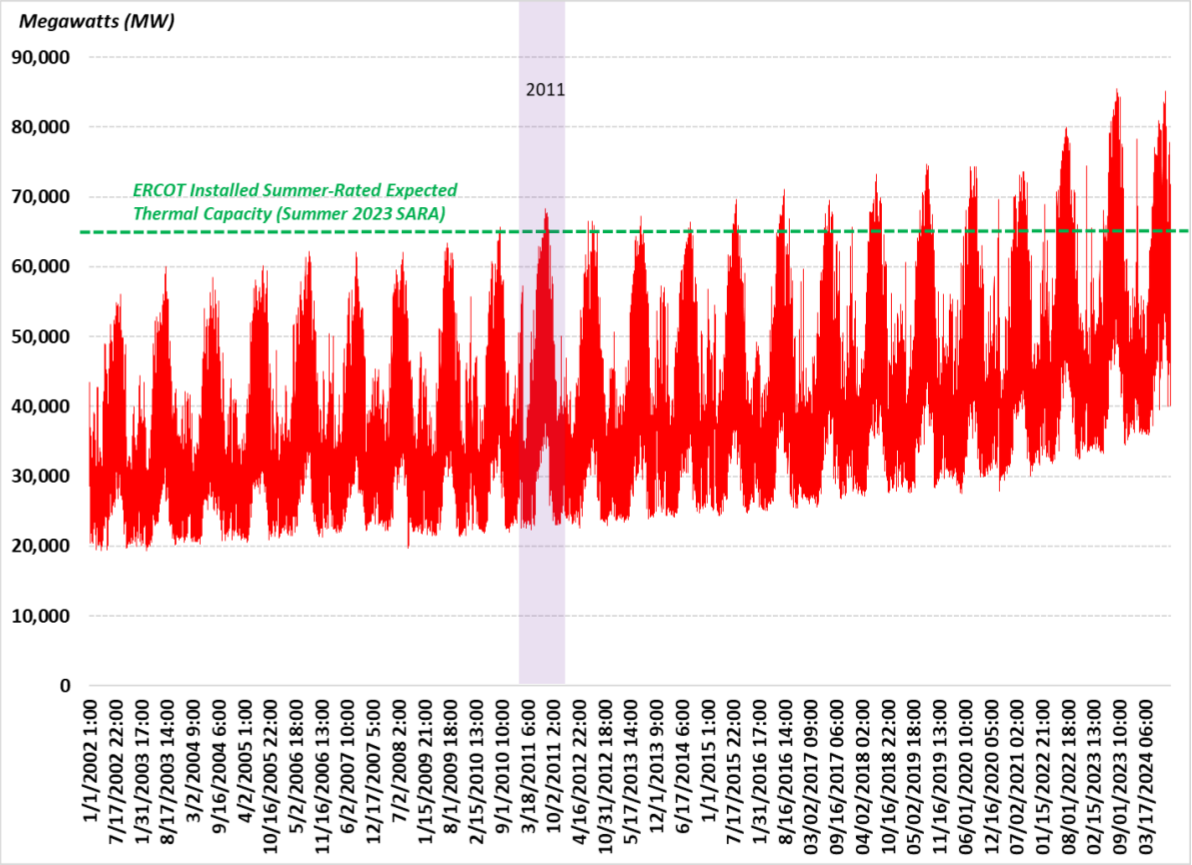
[33] Yan, Y E, Tidwell, V C, King, C W, Cook, M A, SNL), University of Texas at Austin), and PNNL). 2013. "Impact of future climate variability on ERCOT thermoelectric power generation". United States. https://doi.org/10.2172/1069222. https://www.osti.gov/servlets/purl/1069222

[34] Galbraith, Kate. "Drought Could Pose Problems for Texas Power Plants." The Texas Tribune, 16 September 2011. https://www.texastribune.org/2011/09/16/drought-could-post-problems-texas-power-plants/

[35] Hartley, Peter R., Kenneth B. Medlock III, and Shih Yu (Elsie) Hung. “ERCOT and the Future of Electric Reliability in Texas.” Baker Institute for Public Policy, 2024. https://www.bakerinstitute.org/sites/default/files/2024-01/BIPP-CES-ERCOT-Reliability-020724.pdf.

EXHIBIT 11

ERCOT Hourly Load, 2002-2024 YTD



Source: ERCOT, Author's Analysis

Third, surface water evaporation in a prolonged drought would accelerate depletion of key Triangle reservoirs, many of which are between 60 and 80 ft deep **(Exhibit 12).** Insufficient water can either physically prevent a plant from taking in necessary cooling water or else, force plants to discharge cooling water at higher temperatures than would normally be the case. Elevated discharge water temperatures would inflict serious long-term harms by essentially cooking aquatic ecosystems. In prolonged scenarios, power plants that discharge excessively warm water back into lakes and rivers could over time raise the water body's temperature and create a spiral of progressively falling power generation as warmer and warmer water reduced plants' thermal efficiency.[36] Falling reservoir levels would also place cities and power generators in a competition for which the fundamental outcomes are bad—either municipal water supplies are rationed severely, the electricity grid gets severely strained, or potentially, both.

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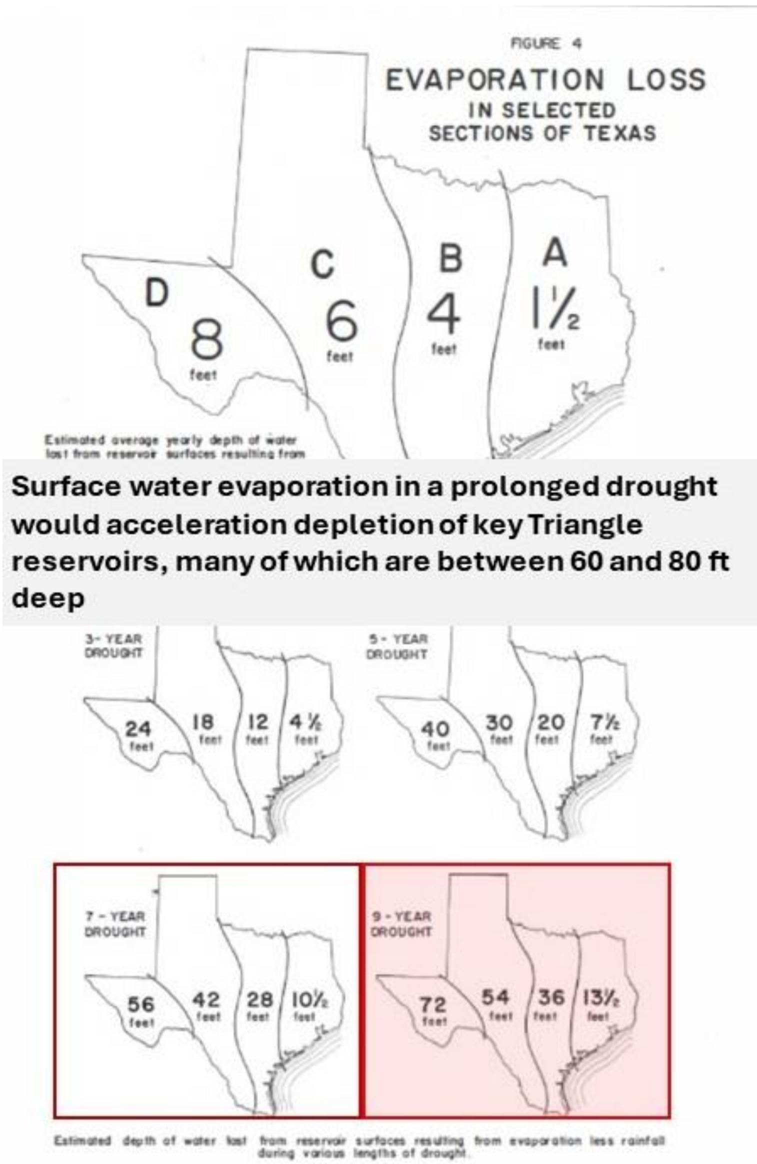
[36] Miara, A., Vörösmarty, C. J., Stewart, R. J., Macknick, J., & Tidwell, V. C. (2018). The power of efficiency: Optimizing environmental and social benefits through demand-side management in the United States energy-water nexus. Environmental Research Letters, 13(3), 034033. DOI: 10.1088/1748-9326/aaaf21

EXHIBIT 12

Forecast Evaporation Rates for Reservoirs Across Texas During Drought



Surface water evaporation in a prolonged drought would acceleration depletion of key Triangle reservoirs, many of which are between 60 and 80 ft deep

Source: TWDB

The consequences of failing to address power sector drought risks could be substantial. Texas households and businesses would suffer, with the attendant humanitarian and political implications. Electricity generation shortfalls would likely trigger manufacturing curtailments as grid managers seek to reduce system load. This imposes drought impacts on facilities that may themselves have sufficient water supplies to operate but are forced to alter operations due to power shortages. China's Sichuan province experienced precisely such an event in the summer of 2022 as drought reduced hydroelectricity production amidst a particularly hot summer.[37] Drought-induced thermal power curtailments could have similarly disruptive effects in Texas.

Manufacturers in Texas have, to the author's knowledge, not yet experienced a drought-driven electricity shortage. Nevertheless, the potential impact bear consideration given that a meaningful portion of the state's dispatchable generation resources face drought risk and given that unlike in 2011, Texas now has no "cushion" because on hot and cold days, ERCOT electricity load typically exceeds available dispatchable generation capacity for substantial portions of each day. Furthermore, nighttime loads—especially during summer—are now consistently high enough that significant thermal power impairments on low-wind nights could also cause power shortages.

Electric power interruptions attributable to drought-induced water shortages will amplify economic damages across all key economic sectors. A recent study that quantified the value of lost electricity load to medium and large commercial customers within ERCOT suggests that the cost of each unserved megawatt hour of electricity is approximately $35,000 for a one hour outage, trailing down to $13,500/MWh for a 16-hour outage (which this analysis uses as a proxy for the costs of longer-duration outages).[38] Actual cost data from the most recent major blackout—Winter Storm Uri in February 2021--show that for some industries the impacts can be even higher. During that outage, Samsung, NXP, and Infineon all had to temporarily shut down semiconductor production facilities due to lack of electricity and Samsung alone claimed $400 million in losses from the roughly weeklong event.[39]

Impacts compound because complex facilities can take weeks to resume production at full capacity after even a few days of electricity supply interruptions. This was the case for Samsung after Uri as well as refineries and petrochemical plants on the Texas Gulf Coast, which suffered operational disruptions on par with (and in some cases, worse than) what facilities have experienced during major hurricanes.[40] Uri was a simultaneous large-scale power and gas (feedstock) disruption and a drought-driven power disruption alone would likely not be as acutely severe but it nonetheless illustrates the compounding systemic impacts that can result from power supply interruptions.

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[37] He, Laura. "China's Sichuan Province to Shut Down All Factories for Six Days to Ease Power Crunch." CNN, August 16, 2022. Accessed August 4, 2024. https://www.cnn.com/2022/08/16/economy/sichuan-factories-power-crunch-china-heat-wave-intl-hnk/index.html; Gabriel Collins and Gopal Reddy, "How China's Water Challenges Could Lead to a Global Food and Supply Chain Crisis" (Houston: Rice University's Baker Institute for Public Policy, November 14, 2022), https://doi.org/10.25613/526F-MR68; Collins, Gabriel, and Gopal Reddy. "China's Growing Water Crisis." Foreign Affairs, 2022. Accessed August 4, 2024. https://www.foreignaffairs.com/china/chinas-growing-water-crisis

[38] "Value of Lost Load Study Final Report," Project No. 55837, Public Utility Commission of Texas, 22 August 2024, https://interchange.puc.texas.gov/Documents/55837_12_1421762.PDF

[39] "Samsung, NXP, and Infineon Chip Fabs Shut Down Texas Amid Record Storm." DatacenterDynamics, February 2021. https://www.datacenterdynamics.com/en/news/samsung-nxp-and-infineon-chip-fabs-shut-down-texas-amid-record-storm/; https://www.law360.com/articles/1828786/samsung-unit-says-exclusion-doesn-t-apply-to-storm-losses

[40] Jesse Thompson, "Texas winter deep freeze broke refining, petrochemical supply chains ," Southwest Economy, Second Quarter 2021, Dallas Fed, https://www.dallasfed.org/research/swe/2021/swe2102/swe2102c

Manufacturing

Water shortages affect manufacturing activity through either outright physical water deprivation or else, through disruptions to electricity supplies (as described in the section immediately above).

Insufficient water supplies can force output reductions or even outright shutdowns at industrial facilities like chemical plants, which can have water use requirements equal to, and sometimes exceeding, those of medium-sized municipalities. An extant example comes from the Altamira industrial complex in Mexico, where since May 2024, several large petrochemical and chemical plants have had to curtail operations and, in some cases, temporarily shut down and declare force majeure due to insufficient water supplies in the local system caused by extreme drought conditions.[41]

The author can only find one confirmed example of a major manufacturing facility being shut down due to drought in Texas: the Rio Grande Valley Sugar Growers mill, which shuttered in March 2024 due to lack of water within the Rio Grande basin, eliminating 250 full time jobs and an estimated $100 million' worth annual economic impact in the surrounding region.[42] Other industrial facilities were challenged by the 2011 Drought, including Dow Chemical. But none shut down or reported materially de-rating their output.

There are several potential responses manufacturers may undertake in response to drought and each has different magnitude and duration of economic impact. Under the most acute water shortages, such as the Altamira case in Mexico, plants can be temporarily shut down. Texas's chemical industry is likely the manufacturing sector most exposed to potential drought shutdowns given its water intensity and concentration at the end of overstressed rivers along the Gulf Coast, particularly the Brazos, Colorado, and Nueces. The chemical industry's annual contribution to the Texas economy exceeds $50 billion, meaning that each 1% of production curtailment by value would cost nearly $1.5 million/day.[43]

Idling facilities in a key production cluster like that found near Freeport could impose direct costs of $10 million or more per day, with larger downstream effects on a range of supply

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[41] Somos Tamaulipas. "Crisis Hídrica Detiene a Plantas Industriales en Altamira." Last modified June 1, 2024. https://somostamaulipas.mx/2024/06/01/crisis-hidrica-detiene-a-plantas-industriales-en-altamira/.; Milenio. "Industria en Altamira Planea 100 MDD para Invertir en Almacenar Agua." Last modified July 30, 2024. https://www.milenio.com/negocios/industria-altamira-planea-100-mdd-invertir-almacenar-agua.; Cobertura 360. "Paran Plantas del Corredor Industrial de Altamira por Crisis de Agua." Last modified May 17, 2024. https://cobertura360.mx/2024/05/17/vigilante/paran-plantas-del-corredor-industrial-de-altamira-por-crisis-de-agua/

[42] KSAT. "Texas' Only Sugar Mill Shuts Down After 50 Years Due to Water Shortage." Last modified March 1, 2024. Accessed August 4, 2024. https://www.ksat.com/news/local/2024/03/01/texas-only-sugar-mill-shuts-down-after-50-years-due-to-water-shortage/

[43] Texas Comptroller of Public Accounts. "Chemical Manufacturing Supply Chain." Last modified 2021. Accessed August 4, 2024. https://comptroller.texas.gov/economy/economic-data/supply-chain/2021/chem.php

chains given the plants' vital global role, a phenomenon illustrated by impacts caused when plants on the Texas Coast went offline during Winter Storm Uri in 2021.[44] Uri inflicted total losses on the Texas economy of between $80 and $130 billion, a material portion of which stemmed from disruptions to industrial output.[45] In addition to economic costs, unscheduled startup and shutdown procedures caused by water or power availability challenges can amplify safety risks for workers and fenceline communities.[46] Large chemical production facilities have a complex operational homeostasis that can be seriously disturbed by input supply problems.

i. Manufacturing Sector Responses to Drought

The second response is to adapt and press forward on the basis that water intensity can be reduced and the overall plus factors for doing business in Texas—governance, physical space, workforce, and feedstock availability—offset water risks. This is certainly the case for the chemical sector. Even before the 2011 Drought, Dow had to regularly divert water from an intake nearly 50 miles upstream from the Gulf on the Brazos River when dry conditions reduced river flows and saltwater migration upstream to the Brazoria pump station made water too saline for some processes.[47] Key water-intensive facilities have also responded with investments in water efficiency measures. For instance, after the 2011 Drought, Dow Chemical's Freeport plants implemented measures that collectively reduced freshwater needs by approximately 14,000 acre-feet/year.[48]

The 1950s drought also saw manufacturers forge ahead in Texas. Industrial production in the Federal Reserve's Eleventh District, overwhelmingly dominated by Texas, surged for both durable and non-durable goods (Exhibit 13) throughout the Drought of Record of the 1950s.

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[44] S&P Global Commodity Insights. "Factbox: Deep Freeze Prompts Force Majeures, Shutdowns at US Gulf Coast Petchem Plants." Last modified February 16, 2021. Accessed August 4, 2024. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/chemicals/021621-factbox-deep-freeze-prompts-force-majeures-shutdowns-at-us-gulf-coast-petchem-plants

[45] Lo Prete, Chiara, and Seth Blumsack. Enhancing the Reliability of Bulk Power Systems Against the Threat of Extreme Weather: Lessons from the 2021 Texas Electricity Crisis. IAEE Energy Economics Education Foundation, December 2023. https://www.iaee.org/eeep/eeepexec/eeep12-2-Lo%20Prete-exsum.pdf

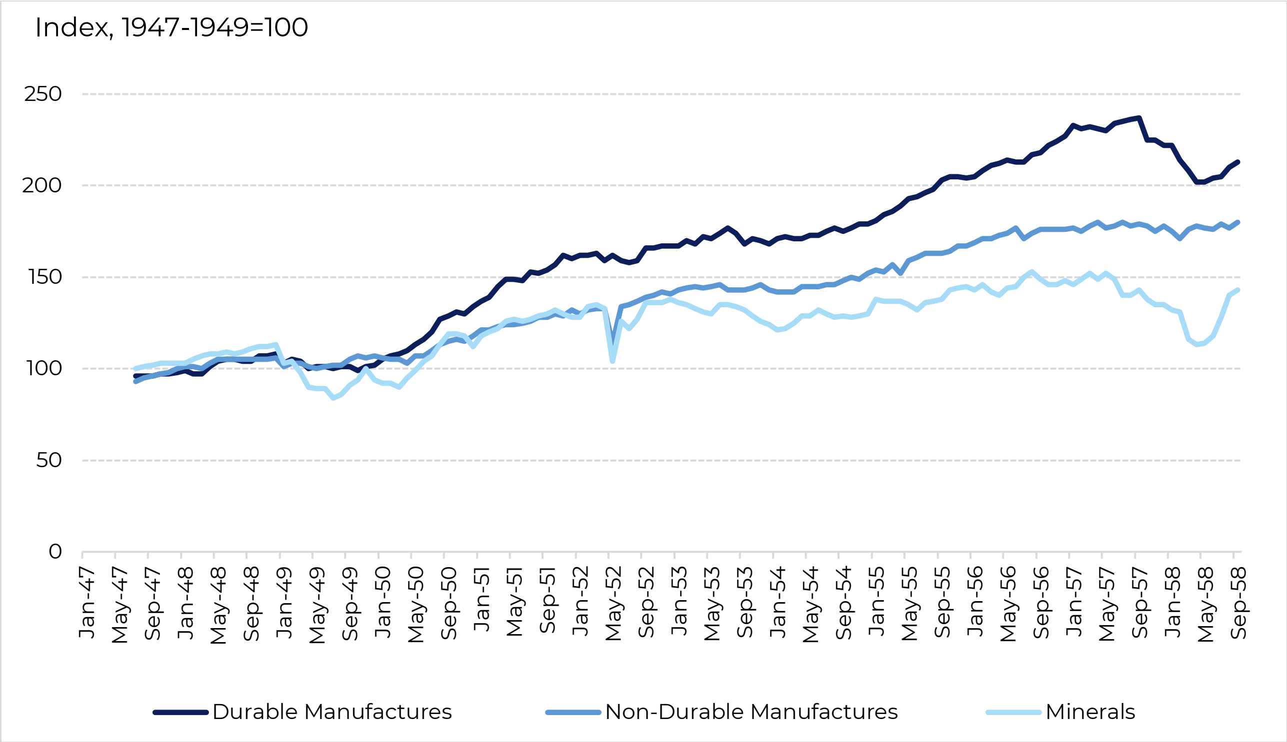
[46]Int-Enviroguard.** "Dangers of Start-up and Shutdown Operations." Last modified December 6, 2023. https://int-enviroguard.com/blog/dangers-of-start-up-and-shutdown-operations/.

[47] Region H Water Planning Group. "Brazos SWB." Accessed August 4, 2024. https://www.regionhwater.org/downloads/Draft_Chapters/Chapter%204/zAppendix_B/4B-39_Brazos_SWB.pdf

[48] Texas Commission on Environmental Quality. "Dow Chemical Company TEEA 2013 Winner: Water Conservation." Last modified 2013. Accessed February 5, 2024. http://web.archive.org/web/20240205205705/https://www.tceq.texas.gov/p2/events/teea/winners/winners-2013/dow-chemical-company

EXHIBIT 13

Texas Monthly Industrial Production Index, June 1947-September 1958 (1947-1949=100)



Source: Federal Reserve Bank of Dallas. "December 1958," Review (Federal Reserve Bank of Dallas) (December 1, 1958). https://fraser.stlouisfed.org/title/5730/item/575667, accessed on August 6, 2024.

In one of the most prominent examples from that era, Alcoa began building a world-scale aluminum smelter near Rockdale in 1950 to produce metal for US defense needs during the height of the Korean War and brought the plant online in 1953.[49] The plant was very water-intensive given its reliance on a 1.1 GW lignite-fired power plant cooled with surface water from a Brazos River tributary. Historical accounts suggest that the strongest motivation for sitting the plant in Rockdale, an area subject to water stress, was the presence of abundant coal to fuel its operations.[50]

This dynamic echoes throughout Texas industrial history. Water does matter for industrial siting, a reality the author found when he surveyed a dozen chemical producers with major

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[3] The author thanks Logan Harrell of the Texas Chemistry Council for facilitating this survey effort and the respondents for taking the time to share their knowledge.

[49] Lozano, Cadelyn. "Alcoa." Accessed August 4, 2024. https://www.rockdaletx.gov/DocumentCenter/View/5208/CADELYN-LOZANO---Alcoa

[50] Graham, Joy. "Alcoa in Rockdale, Texas." Rockdale Reporter, April 25, 2013. Accessed August 4, 2024. http://www.milamcountyhistoricalcommission.org/newspaper_208.php

presence in Texas.[3] But only half of respondents cited it as "the most important factor." One possible explanation is that while water can be found along the Gulf Coast in sufficient quantity to support industrial operations, Texas has other competitive differentiators that are more singular to the state—foremost among them proximity to low-cost, abundant natural gas, NGLs, and crude oil. Indeed, Dow and other water-intensive petrochemical firms continued investing heavily in Texas after the 2011 drought as they sought to cement access to low-cost feedstocks.[51]

The presence of a deep and dependable local supply chain, talented workforce, and a welcoming political climate can also induce businesses to keep investing despite challenges securing some primary input materials. In addition to the petrochemical examples cited above, a similar dynamic has arguably played out with respect to electricity and water both in Central Texas. Samsung Austin Semiconductor has invested more than $18 billion in its Austin Campus over the past 28 years.[52] Despite losing approximately $400 million from a plant shutdown during the 2021 Freeze, Samsung's existing footprint, ability to self-source water, and an injection of federal CHIPS Act funds helped persuade management to commit to invest $17 billion in a second fab facility in Taylor about 20 miles from its existing Austin complex.[53]

ii. Key Economic Consequence of Drought on Manufacturing: Missed Investment Opportunities

Ensuring water supplies is a key portion of the competitiveness portfolio that Texas must invest in to ensure future dynamic growth and underpin our ability to attract critical industries of the future. This illustrates one of the most important contingent losses factors this report engages: the risk of foregone investments and opportunities.

To quantify the impact of a single corporate decision that might have been influenced in part by water supply concerns, consider Micron's decision to site a massive fab complex near Syracuse, NY rather than Lockhart, Texas. Over the next 20-odd years, Micron states that it intends to invest as much as $100 billion in a multi-plant "megafab."[54] Approximately $20 billion of the total would be deployed by 2030, an average of more than $6 billion annually. If

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[51] Tom Brown, "Dow unveils $4bn of new capacity investment to 2022," ICIS, 11 May 2017, https://www.icis.com/explore/resources/news/2017/05/11/10105796/dow-unveils-4bn-of-new-capacity-investment-to-2022/

[52] Samsung Semiconductor. "Samsung Austin Semiconductor Pumps $13.6 Billion into Central Texas Economy in 2022 – Additional Investment of $4.2M for Community Organizations in 2023." Last modified October 12, 2023. Accessed August 4, 2024. https://news.samsungsemiconductor.com/global/samsung-austin-semiconductor-pumps-13-6-billion-into-central-texas-economy-in-2022-additional-investment-of-4-2m-for-community-organizations-in-2023/

[53] Mekelburg, Madlin. "Samsung Chip Plant Sues Insurer Over $400 Million Storm Claims." Bloomberg Law, February 7, 2023. Accessed August 4, 2024. https://news.bloomberglaw.com/insurance/samsung-chip-plant-sues-insurer-over-400-million-storm-claims; U.S. Department of Commerce. "Biden-Harris Administration Announces Preliminary Terms with Samsung Electronics to Establish Leading-Edge Semiconductor Ecosystem in Central Texas." Last modified April 15, 2024. Accessed August 4, 2024. https://www.commerce.gov/news/press-releases/2024/04/biden-harris-administration-announces-preliminary-terms-samsung

[54] Micron Technology Inc. "Fact Sheet: Micron Makes Historic Megafab Investment in Central New York." Last modified June 6, 2023. Accessed August 4, 2024. https://www.micron.com/manufacturing-expansion/ny/fact-sheet

the remaining $80 billion were deployed between 2030 and 2045, that would be an average spend of over $5 billion per year. The total impact could be as many as 50,000 jobs added.

Micron cited water as one of seven core reasons that Central New York made an “ideal home” for siting its planned megafab.[55] The volumes required are tremendous, with Onondaga County Water Authority (the local supplier) saying that when Micron announced the project in 2022 it anticipated needing 20 million gallons per day (22,400 AFY) of water but in 2023 revised the number to 48 million gallons per day by 2043.[56] Water would need to be imported from Lake Ontario to meet that demand call, which approximates the water supply capacity of the Vista Ridge Pipeline that moves water from Burleson County into San Antonio.[57]

While it is not conclusive that water was “a” or “the” decisive factor that tipped Micron’s decision in New York’s favor, the case illustrates that major industrial investors’ confidence in future water supplies will have multi-billion-dollar economic consequences for Texas. Accordingly, investments in water supply stability will be growth facilitators. The costs of “investments missed” are especially meaningful because once a factory or facility is sited somewhere else, the benefits are anchored in the location henceforth with no prospect of returning to Texas.

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[55] “Frequently asked questions – State Environmental Quality Review Act (SEQRA),” Micron, https://www.micron.com/manufacturing-expansion/ny#accordion-4c70dc7aef-item-8cd64e0b8e (accessed 14 October 2024)

[56] Kearns, Charlie. "It Could Cost $625 Million to Bring Water from Lake Ontario to Micron. It’s Not Clear Who’s Paying." New York Rural Water Association, November 8, 2023. Accessed August 4, 2024. https://www.nyruralwater.org/news/it-could-cost-625-million-bring-water-lake-ontario-micron-it’s-not-clear-who’s-paying

[57] New York Rural Water Association. (2023, November 8). It could cost $625 million to bring water from Lake Ontario to Micron. It’s not clear who’s paying. Retrieved from https://www.nyruralwater.org/news/it-could-cost-625-million-bring-water-lake-ontario-micron-it’s-not-clear-who’s-paying

MUNICIPAL EXPOSURE

Municipal Impacts

Texas's population is currently nearly 85% urban, meaning that more than 24 million Texans make their home in a city or town.[58] Accordingly, policymakers face complex challenges. On one hand, small town and rural water systems are often hit especially hard by drought and extreme weather events. Dry periods of more than a few months can place them under severe strain, as shown most recently by the town of Gunter (which nearly ran out of water in summer 2022 as overworked water wells malfunctioned) and Concan near San Antonio, which had to truck water in to supply residents.[59]

On the other end of the spectrum, major Texas cities' water systems are each supporting populations bigger than those of multiple US states and municipal economic and industrial bases equal to or exceeding those of many countries. And size does not immunize them from drought impacts. Bigger cities in Central Texas often implement watering restrictions as summertime drought conditions intensify. Dallas and Houston are generally wetter, but in the late summer of 2023, Houston for the first time in many years imposed restrictions on watering. In a major drought, all of these areas could be affected simultaneously, as was the case in 2011.

Reduced river flows in the Brazos, Colorado, and Trinity River systems would be particularly problematic given that every major Triangle city other than San Antonio depends on surface water from these watersheds. And even San Antonio is drought-exposed given that its baseload water supply comes from the precipitation-sensitive Edwards Aquifer. The Dallas-Fort Worth area faces perhaps the most acute drought risk because it is far larger than Austin and lacks high-volume local groundwater supplies. Austin follows given the steady reduction in demand coverage from the LCRA Highland Lakes as population and water usage grow while reservoir capacity stays fixed and confronts climate volatility. The City of Georgetown's 2023 decision to reserve up to 70,000 AF/year of Carrizo-Wilcox groundwater supplies from EPCOR reveals local officials' eroding confidence that surface water can continue meeting the region's needs as virtually all of the LCRA's firm yield surface water is already contracted.[60]

With such pressures mounting, two core questions arise. First, what happens economically to a city in the event of a truly acute and sustained water supply crisis? To better understand that, we will examine the city of Wichita Falls' experience during and after the 2011 drought.

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[58] John Brannen. Kinder Institute for Urban Research. "After Census redefines urban and rural, Texas remains steadfastly both." Urban Edge, Rice University, 5 January 2023. https://kinder.rice.edu/urbanedge/census-redefines-urban-rural

[59] Méndez, María. "Texas Is Facing Its Worst Drought Since 2011. Here's What You Need to Know." The Texas Tribune, August 19, 2022. Accessed August 4, 2024. https://www.texastribune.org/2022/08/19/texas-drought-water-conservation/

[60] Georgetown Utility Systems. "Carrizo-Wilcox Aquifer Water Supply Project." Accessed August 4, 2024. https://gus.georgetown.org/water/where-does-georgetown-get-its-water/water-supply-project/

Second, what are the options for state and city authorities seeking to harden municipalities against drought and do the costs of ensuring water supplies potentially begin to undermine the very growth opportunities they are intended to facilitate?

Water Crisis Economic Impact Case Study: Wichita Falls and the 2011 Drought

From 2011 to 2015, Wichita Falls grappled with an extreme drought that caused water levels in its water supply system to fall to less than 20% of capacity.[61] In response, the city had to impose draconian restrictions on water usage and institute a direct potable reuse (DPR) system that treated municipal wastewater and blended it back into the drinking water supply, a practice that continues to this day and marks Wichita Falls as one of only two cities in Texas to use DPR.[62] The other water system is the Colorado River Municipal Water District, which operates a water reclamation plant near Big Spring that treats some of the city's municipal wastewater and blends it with raw water that then goes to supply the CRMWD's member cities, including Big Spring, Odessa, Midland, Snyder, and others.[63] Wichita Falls continues reusing wastewater for municipal drinking water supplies but has changed its process to indirect potable reuse ("IPR") with treated effluent pumped into Lake Arrowhead, one of the city's main drinking water supply sources.[64]

As a result of the water supply crisis and ensuing restrictions, water use in the Wichita Falls Metropolitan Statistical Area (dominated by the city itself) plummeted **(Exhibit 14).** Agriculture saw the biggest reduction but municipal use at the peak of the crisis was also slashed by roughly half relative to average use levels in the preceding five years.

Although the area's economic output did not plummet, Wichita Falls' mayor stated later in a letter to the public that income losses in the area "exceeded $1 billion."[65] The acute water crisis lasted for approximately four years, suggesting an average annual income loss of approximately 2.8% relative to the area's total economic output.

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[61] Cusick, Daniel. "'In Hell': Nowhere Has Been Drier Than This Stretch of Texas." E&E News, July 14, 2021. Accessed August 4, 2024. https://www.eenews.net/articles/in-hell-nowhere-has-been-drier-than-this-stretch-of-texas/

[62] Dahl, Richard. "Advanced Thinking: Potable Reuse Strategies Gain Traction." Environmental Health Perspectives 122 (2014): A332. Accessed August 4, 2024. https://ehp.niehs.nih.gov/doi/full/10.1289/ehp.122-A332

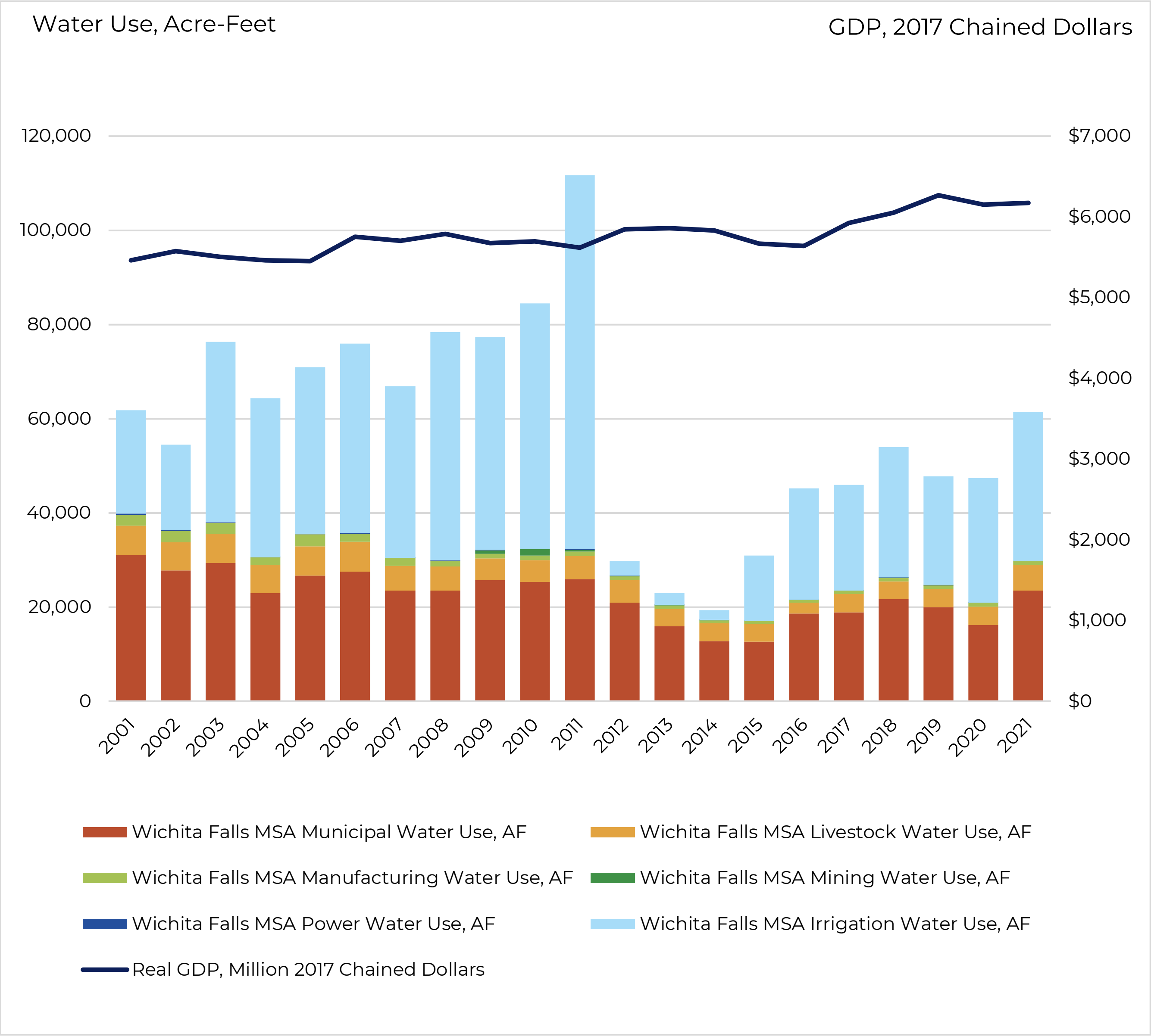
[63] Source: Colorado River Municipal Water District. "Reuse." Accessed November 6, 2024. https://www.crmwd.org/water-sources/reuse/.

[64] Source: City of Wichita Falls, Texas. "Resource Recovery." Accessed November 6, 2024. https://wichitafallstx.gov/691/Resource-Recovery.

[65] City of Wichita Falls. "Lake Ringgold." Accessed August 4, 2024. https://wichitafallstx.gov/2085/Lake-Ringgold

EXHIBIT 14

Wichita Falls MSA Water Use and GDP



Source: BEA, TWDB, Author's Analysis

Drought Impacts on Other Texas Cities

In economic terms, drought for Wichita Falls thus resembled driving a pickup truck with the parking brake left on—the vehicle moved but with significant penalties compared to how it could have driven absent the restraint. The implications for larger Texas metros are substantial, especially for those, which like Wichita Falls, obtain essentially all their municipal water supply from surface water assets. Translating that same 2.8% income loss rate to the $700 billion GDP of the Dallas-Fort Worth-Arlington Metropolitan Statistical Area suggests that municipal economic exposure in a future drought as intense as that which impacted Wichita Falls from 2011-2015 could be on the order of $17 billion/year.[66] Readers should note that the larger Triangle suburbs and their cities host many more high-dollar manufacturing and industrial facilities than Wichita Falls does, and so the "bad-case" disruption numbers raised in this section could be significant underestimates if Texas suffered a widespread drought similar to, or worse than, that of the 1950s.

Water supply pressure on the DFW Metroplex would likely transmit downstream to the Houston metro area, which also depends heavily on the Trinity River system shared with its northern neighbor. The Houston MSA's income loss exposure could amount to $16 billion annually.[67] Applying the same loss ratio to the Austin-Round Rock MSA as Wichita Falls appeared to have suffered suggests potential economic losses of roughly $7 billion/year.[68] Corpus Christi could suffer income losses of $1 billion annually (and potentially higher if petrochemical plants and refineries could not secure sufficient water to maintain full operations).

Adding these numbers up suggests that if the Wichita Falls loss estimate numbers are reasonably accurate, a new Drought of Record that lasted for several years could—absent sufficiently robust water infrastructure—potentially inflict economic damage on the order of at least $40 billion per year or more on large, surface-water dependent municipalities across Texas (Exhibit 15). The impacts would be concentrated in the Triangle, which now accounts for about 70% of the Texas population and a proportionate share of economic output.[69]

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[66] U.S. Bureau of Economic Analysis, Total Gross Domestic Product for Dallas-Fort Worth-Arlington, TX (MSA) [NGMP19100], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/NGMP19100, August 7, 2024

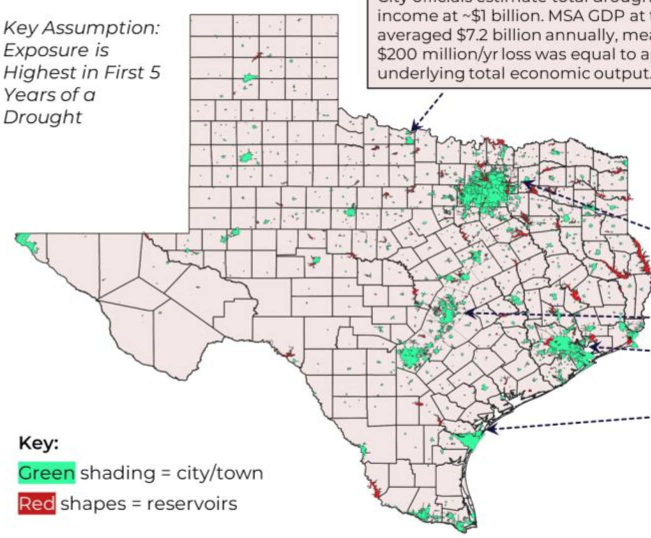
[67] U.S. Bureau of Economic Analysis, Total Gross Domestic Product for Houston-The Woodlands-Sugar Land, TX (MSA) [NGMP26420], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/NGMP26420, August 7, 2024

[68] U.S. Bureau of Economic Analysis, Total Gross Domestic Product for Austin-Round Rock, TX (MSA) [NGMP12420], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/NGMP12420, August 7, 2024

[69] Harper, K. B., & Runnels, A. (2023, November 20). Texas 2023 population growth and changing demographics. The Texas Tribune. https://www.texastribune.org/2023/11/20/texas-2023-population-growth-demographics/

EXHIBIT 15

Key Texas Municipalities' Potential Full Spectrum Economic Loss in a Future Drought of Record



What Happens if Wichita Falls Loss Ratio is Adjusted to 2.5% and Applied to Other Texas MSAs With High Surface Water Exposure?

MSA	Surface Water Exposure as % of Total Use in 2021	2022 GDP, Billion$	Potential Annual Income Loss, Billion USD
DFW	87.3%	$689	$17
Austin	78.5%	$222	$6
Houston	73.2%	$633	$16
Corpus Christi	89.0%	$28	$1
Total			$40

Note that two economics professors at MSU Texas, Drs. John Martinez and Robert Forrester, used a vector autoregressive model to estimate annual income loss in the Wichita Falls MSA during the drought at $292 million annually. I am adjusting my numbers downward to err on the side of conservatism and assuming a loss of $200 million, which I then use to determine the lost income/underlying GDP ratio.
https://www.timesrecordnews.com/story/news/2021/11/24/historic-drought-cost-local-area-more-than-1-billion/8720944002/

Source: City of Wichita Falls, TWDB, Times Record News, Author's Estimate

Water shortages can exert economic impacts along several distinct vectors in a municipal context.[4] A critical issue is that **water scarcity that either discourages residents and business from voluntarily coming to the city and/or forces a growth moratorium. The compounding effect of growth foregone would be enormous given that the major Triangle cities and their suburbs alone account for approximately $2 trillion in economic activity today and are poised for further growth provided that water and other key inputs are available.**

Some arid zones in the American West such as parts of the Phoenix area have begun restricting new home construction due to water supply concerns.[70] The problem set's leading edge is visible in high-growth parts of Texas such as the cities of Heath[71] and Conroe,[72] where water supplies and transmission infrastructure have struggled to keep pace with growth. These situations do not yet mirror circumstances in the Western US where water supplies are insufficient at a macro regional or statewide-level, but nonetheless offer cautionary indicators.

In a Texas context, low water recycling rates, additional headroom for more conservation, proximity to aquifers for extraction and storage, and the nearby Gulf of Mexico likely would mean that in a future water crunch, the discussion will not be one of administratively imposing growth moratoria, but rather, how much are we willing to pay for drought-resistant water resources? In a nutshell, it would likely send an economic signal that would unleash a combination of "One Water thinking" with more cities approaching water the way Austin and San Antonio already do, and a substantial increase in major hydraulic engineering projects that ensure water supplies to a state and population that have so many other good things going for them that a "can do" approach will likely win the day.[73] Put more bluntly, Texans would likely find a bipartisan consensus in support of investing $25, $50, or $100 billion to unlock another trillion in growth. Houston is an example of this, where major storms and floods tend to prompt multi-billion-dollar infrastructure investments rather than growth restrictions.[74]

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[4] One is contamination from droughts that reduce inflow into reservoirs, lower water levels, and raise temperatures. As the author told the Texas Tribune during a 2021 interview, "If you have situations where more parts of the state are pulling from lower reservoirs, rivers that are flowing less and warmer water temperatures, there's a real concern about what pathogens end up in [the water] system."
On a large water system, hundreds of thousands of people could potentially be affected. Perhaps the signature example of a municipal water contamination event in the United States comes from a 1993 cryptosporidium outbreak in Milwaukee that sickened about a quarter of the city's population and inflicted an estimated $210 million (2024$) in medical and productivity-loss costs as well as forcing the city to invest a much larger sum to improve infrastructure to prevent a recurrence. Texas has recently had cautionary experiences of how disruptive a municipal contamination event can be. The most poignant was not drought-related but nonetheless illustrates potential impacts. In 2020, the death of a 6-year-old child revealed that Lake Jackson's public water system had suffered contamination with the naegleria fowleri brain eating amoeba. The city then had to purge the system for 60 days. Reinforcing concerns, Texas has, over the past decade, experienced a crescendo of Boil Water Notices, more than doubling in 2021, 2022, and 2023 relative to the prior trend level

[70] See, for instance: Trotta, Daniel. "Arizona Restricts Phoenix Home Construction Amid Water Shortage." Reuters, June 2, 2023. https://www.reuters.com/world/us/arizona-restricts-phoenix-home-construction-amid-water-shortage-2023-06-02/

[71] NBC DFW. "City of Heath Plans Six-Month Pause in Residential and Commercial Development." . Accessed November 6, 2024. https://www.nbcdfw.com/news/local/city-of-heath-plans-six-month-pause-in-residential-and-commercial-development/3384591/.

[72] City of Conroe, Texas. Ordinance 2715-24: Temporary Development Moratorium. Accessed November 6, 2024. https://cms3.revize.com/revize/conroetx/Documents/Services/Engineering/Infrastructure%20Concerns/Development%20Moratorium/Ordinance%202715-24%20-%20Temporary%20Development%20Moratorium.pdf.

[73] See, for instance: City of Austin. WATER FORWARD: One City, One Water - A Plan for the Next 100 Years. City of Austin, 2024. https://services.austintexas.gov/edims/document.cfm?id=423258

[74] See, for instance: Harris County Flood Control District. 2018 Bond Program. Harris County Flood Control District, 2018. https://www.hcfcd.org/2018-bond-program. https://news.stanford.edu/stories/2023/01/droughts

Engineering to mitigate climate challenges—something humans have done for millennia—does come with a financial price tag attached. In this way, water scarcity also raises questions about affordability, which feeds into livability and ultimately, Texas's attractiveness as a place to live. A recent study by researchers at Stanford University suggests that for water to be considered "affordable," it would need to cost 4% or less of a household's income.[75]

Median household income in Texas as of 2022 was approximately $72,000.[76] Four percent of this amount is $2,880. If a household uses 8,000 gallons of water monthly, its annual consumption of 96,000 gallons amounts to a bit less than 1/3 of an acre foot. Therefore, so long as delivered water costs stay at or below $9,000 per acre-foot (which is about 3 times the current level based on data from the Texas Municipal league), consumers at least in theory find water to be "affordable." Unfortunately, using a median number masks the large number of households with sub-median incomes who would encounter affordability challenges much faster—perhaps at or just slightly above present water price levels in many cities.

This matters because lived experience in San Antonio and other Central Texas cities—the proverbial "canaries in the water mine"—shows that when cities must diversify beyond their original baseload water supplies, new sources are frequently substantially more expensive. **Exhibit 16** shows how this dynamic has played out in San Antonio, which has augmented its traditional (but drought-exposed) Edwards Aquifer water resources with the 142-mile Vista Ridge Pipeline and the H2O Oaks brackish desalination plant, among other newer sources. Each costs a multiple of what raw water from the Edwards does.

The focus on raw water costs is appropriate because once treated water hits the "Citygate" and enters the distribution system, the physics (and therefore the cost) of moving molecules to customers from the Edwards Aquifer or a legacy surface water resources are no different than those of water imported from the distant Carrizo-Wilcox Aquifer or future desalination plants on the Gulf Coast.

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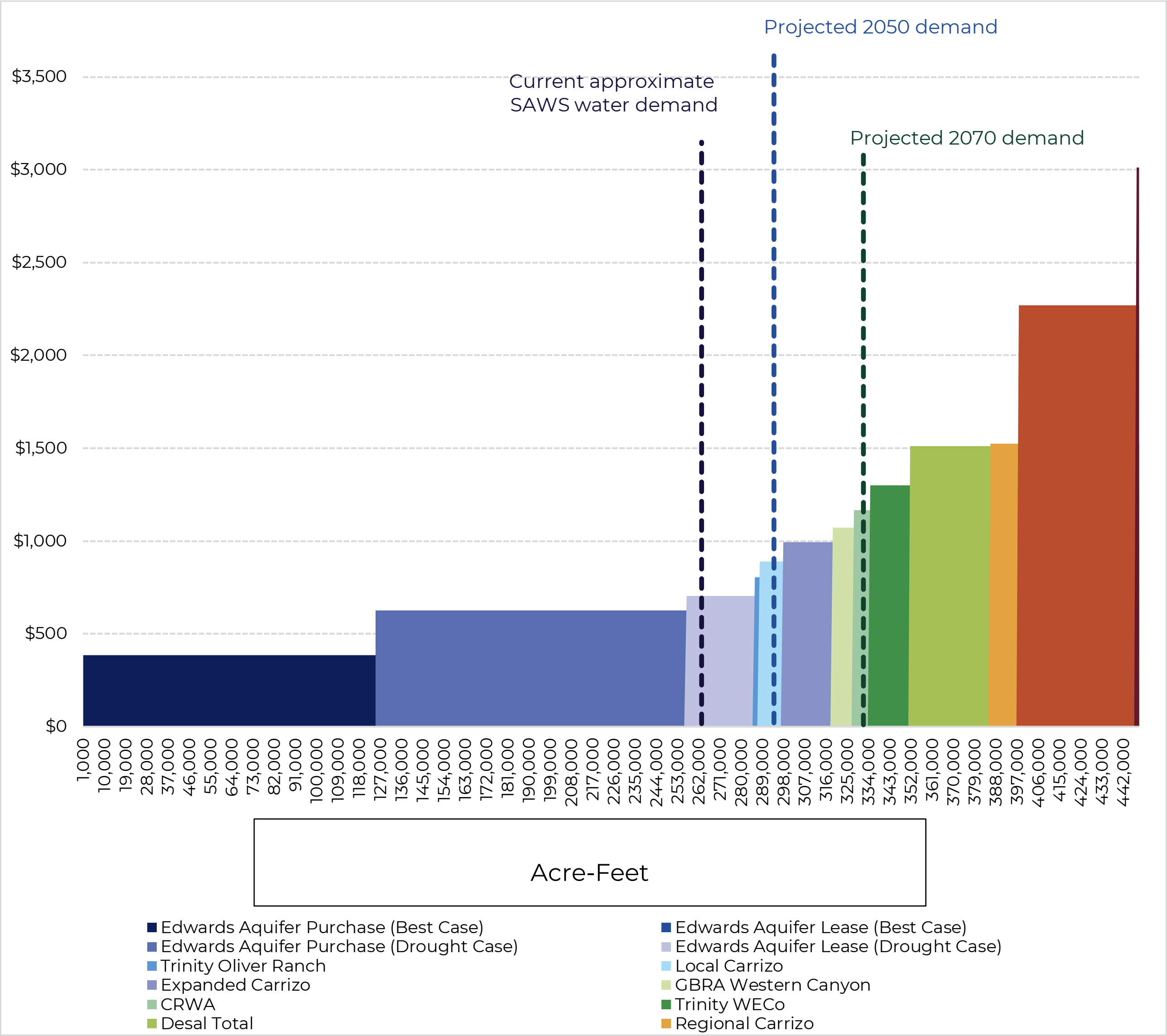
[75] "New Stanford research shows droughts can make water unaffordable for low-income households," Stanford Report, 19 January 2023, https://news.stanford.edu/stories/2023/01/droughts-increase-costs-low-income-households

[76] Texas Comptroller of Public Accounts. "Texas Economic Data by Region: Statewide Overview." Comptroller.Texas.gov, 2024. https://comptroller.texas.gov/economy/economic-data/regions/2024/statewide.php

EXHIBIT 16

SAWS Volume-Weighted Water Supply Cost Curve, $/AF



Source: San Antonio Water System, Author's Analysis

WATER RESILIENCE AND INFRASTRUCTURE OPPORTUNITIES

Drought-resistance diversification of water supplies challenges most surface water assets due to the impacts of climate volatility. Lack of precipitation (at times) and extreme precipitation at other times both reduce the reliability and usability of surface water.[77] Under severe but short-term water shortage conditions, groundwater is the flywheel that keeps Texas water supplies balanced.[78] For more prolonged and structural shortages of the type that this report fundamentally focuses on, core alternative water supplies will include stretching the supply base through conservation and more efficient transmission & use of water, local water recycling, long-distance groundwater imports, aquifer storage and recovery ("ASR"), and potentially even desalination.

Conservation is often one of the lowest cost options for enhancing water supplies. A Texas now home to more than 30 million people uses about half as much water per capita now as it did in 1950, despite becoming more electricity-intensive over that same timespan **(Exhibit 17).** Looking out over the next 50 years, Texas could bring its water use down much further.

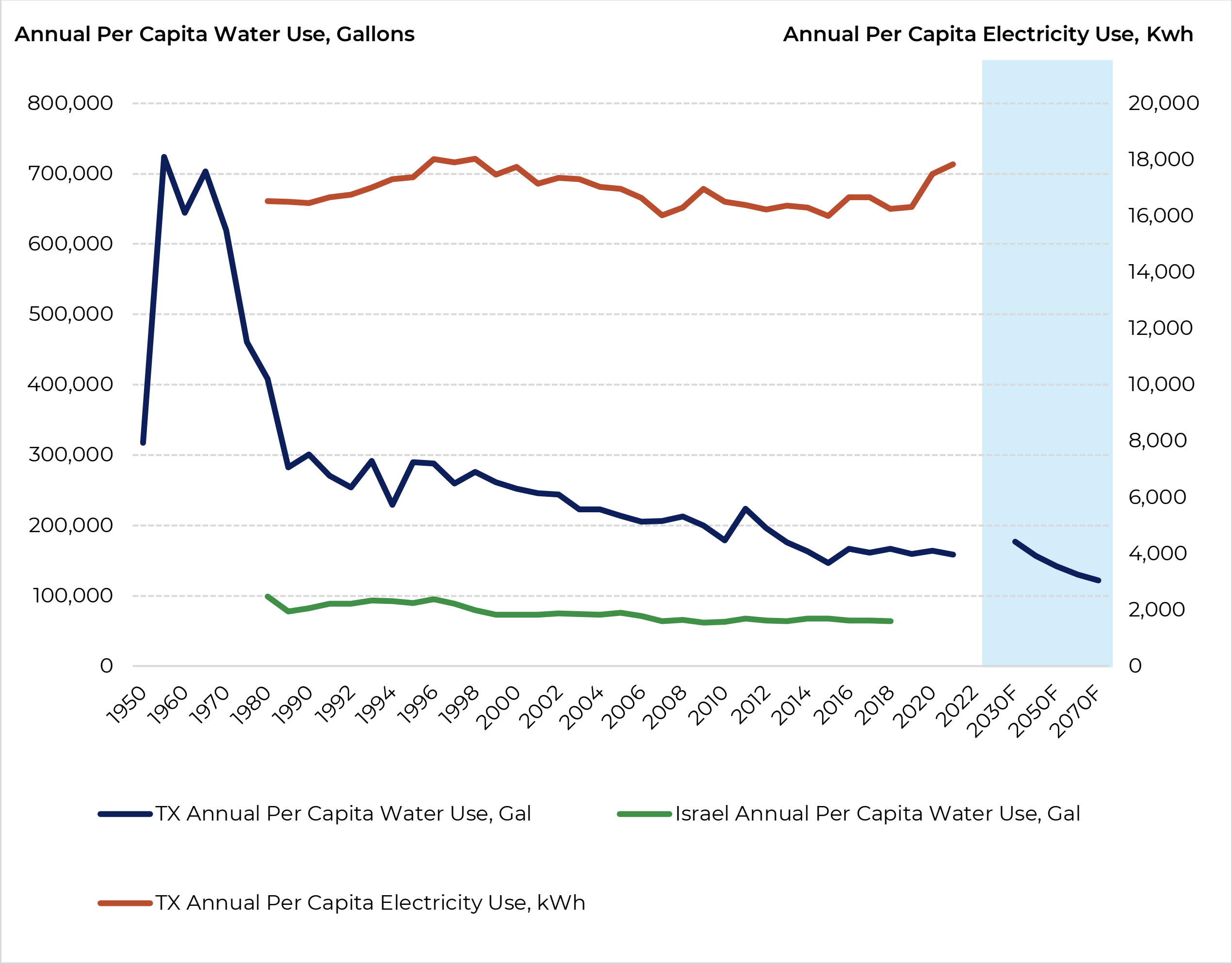
Israel, the gold standard for efficient water use among advanced economies, shows how a combination of continuing technological improvement, consumer education, and investments in infrastructure could conceivably bring water usage per capita down to levels where even if the Texas population doubled, water usage could be kept at something close to present consumption. This would become particularly true if the Legislature encouraged large industrial water users along the Texas coast, which are among the state's largest surface water rights holders, to make greater use of seawater and desalinated seawater to free up freshwater for human consumption upstream.

[77] John W. Nielsen-Gammon and William J. Baule Texas A&M University, College Station, Texas, "Projected Changes in the Runoff Spectrum in Texas," August 13, 2024 draft

[78] Collins, Gabriel. "Economic Valuation of Groundwater in Texas." Texas Water Intelligence. September 20, 2018. Accessed July 28, 2024. https://texaswaterintelligence.com/2018/09/20/economic-valuation-of-groundwater-in-texas-2/

EXHIBIT 17

Texas Per Capita Water Use From 1950 through 2070 (Forecast) vs. Electricity



Source: EIA, Kramer, I., Tsairi, Y., Roth, M.B. et al. Effects of population growth on Israel's demand for desalinated water. npj Clean Water 5, 67 (2022). https://doi.org/10.1038/s41545-022-00215-9, TWDB, USGS

Water recycling or re-use represents another low-cost option. The San Antonio Water System proactively pursued water recycling beginning in the mid-1990s now runs one of the largest direct water recycling systems in the United States, capable of supplying 25,000 AF/year.[79] Given that wastewater must be treated regardless, this recycled water likely effectively costs less per acre-foot than the City's baseline supplies of Edwards Aquifer groundwater. Cost advantages combine with the close by physical availability (i.e. treatable water constantly

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[79] San Antonio Water System. "Recycled Water Program." San Antonio Water System. Accessed July 28, 2024. https://www.saws.org/your-water/management-sources/recycled-water-program/

enters municipal wastewater facilities). Groundwater imported from afar is more expensive—potentially on the order of $2,000/acre foot delivered into the city system.[80]

Desalination is a third option. It is attractive because of the perceived limitlessness of the Gulf of Mexico. Indeed, as journalist Seamus McGraw was writing "*A Thirsty Land: The Making of an American Water Crisis*" some years ago, an unnamed senior Texas Water Development Board purportedly told him that "*The Gulf of Mexico helps me sleep at night.*"[81] The problem is that accessing that limitless water entails huge energy use, meaningful environmental impacts of rejection brine, and cost.

The infrastructure and energy required generally makes desalination among the most expensive water sources at present. The plants now under construction in Corpus Christi are projected to deliver water at a cost of more than $3,000 per acre-foot.[82] Desalination energy needs are steep but not insurmountable. Desalinating seawater using reverse osmosis requires 3.5-to-4.5 kWh of electricity per M^3.[83] There are approximately 1,234 M^3 in an acre-foot. Thus, desalinating an acre foot of seawater requires between 4,319 and 5,553 kWh of electricity. Using the mid-range of those numbers suggests desalinating a million acre-feet of seawater via RO requires 4.9 million MWh of electricity. If the plant runs at a steady rate 24-7 (allowing a week each year for maintenance), that means 8,592 run hours per year.

This in turn yields an annual average electricity load of about 570 MW per million acres of seawater desalinated. That is roughly the grid load of 5-to-6 hyperscale data centers. It is significant but could be accommodated. Put somewhat differently, adding a single additional reactor apiece at the South Texas Project and Comanche Peak nuclear power stations could provide carbon-free support for desalinating about 4 million acre-feet per year of seawater via reverse osmosis. That is equal to about half of total projected Texas municipal water use in 2070.

Desalination has a nearly 65-year-old history in Texas. In June 1961, President John F. Kennedy inaugurated a million gallon/day (1,120 AF/yr) desalination plant at Dow Chemical's complex in Freeport."[84] The plant, with its 12 eight-story tall distillation tubes powered by a coal furnace, supplied water at a cost of $1.25 per thousand gallons—approximately 4 times the cost of natural water sources **(Exhibit 18).**[85]

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[80] Gabriel Collins, "Economic valuation of groundwater in Texas," Texas Water Journal Volume 9, Number 1, May 21, 2018, https://journals.tdl.org/twj/index.php/twj/article/view/7068/pdf, (50-68)

[81] https://www.texasmonthly.com/arts-entertainment/drought-to-come-agriculture-water-crisis/

[82] Autocase Economic Advisors. Coastal Bend Water Supply Options Analysis. November 2022. Accessed July 28, 2024. https://capetx.com/wp-content/uploads/2022/11/Coastal-Bend-Water-Supply-Options-Analysis-Nov-2022-Final.pdf

[83] Jungbin Kim, Kiho Park, Dae Ryook Yang, Seungkwan Hong, A comprehensive review of energy consumption of seawater reverse osmosis desalination plants,Applied Energy, Volume 254,2019,113652,ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2019.113652

[84] White House Audio Collection. Remarks Upon Activating by Remote Control the Saline Water Conversion Plant at Freeport, Texas, 21 June 1961, https://www.jfklibrary.org/asset-viewer/archives/jfkwha-040-003 (2:17-2:23)

[85] Jacob Roberts and Kenton G. Jaehnig, "Nor Any Drop to Drink." Science History Institute Magazine. Accessed July 28, 2024. https://www.sciencehistory.org/stories/magazine/nor-any-drop-to-drink/

EXHIBIT 18

Vice President Lyndon B. Johnson Presides Over Inauguration of Desalination Plant in Freeport, TX, 21 June 1961

Source: https://www.sciencehistory.org/stories/magazine/nor-any-drop-to-drink/

Desalination's energy intensity and the associated elevated economic costs exemplified both the promise of drought-proof water supplies and the associated challenges. Freeport's desalination plant shut down in 1969 after Congress refused to appropriate additional subsidies to support the sale of water at $0.30/kgal, as opposed to the aforementioned $1.25/kgal it cost the government to produce water from the facility. The historic drought of the 1950s was receding into memory, the state's expanding roster of reservoirs was full, and there was little appetite to pay 4 times the price for drought-proof water amidst ample rainfall.

Larger plants impose much larger per consumer charges across the water rate base. Australia illustrates the potential complexity of the situation that can result under volatile climate conditions where drought and deluge alternate unpredictably. During the Millenium Drought from 1997-2009, multiple large Australian cities including Melbourne, Perth, and Sydney constructed expensive desalination plants to ensure water supplies. Then the rains returned, surface water storages refilled, and most desalination plants aside from Perth's were put on care and maintenance mode or placed in "hot standby mode" ready to in case drought returned—at a cost of a hundred million dollars annually or more for each of the large plants.[86] Such long-term cost burdens for what essentially becomes a “take or pay” cost borne by ratepayers can be politically fraught.[87]

There are two fundamental modes of operation for a capital-intensive large desalination plant. One is to use desalination as a water demand chaser, ramping up output when needed to compensate for supply challenges and otherwise operating at partial capacity. This is what the Sydney Desalination Plant in Australia has done.[88] The facility went into care and maintenance mode after rains in 2012 refilled the reservoirs serving the city. In September 2019 (after significant reconstruction following damage from a 2015 tornado), the plant commenced full production of water in response to drought conditions.[89]

Following wildfires and torrential rains in 2019, 2020, and 2021 that created water quality challenges, Sydney officials chose to keep the plant online at reduced capacity, with the ability to ramp up in the event of water supply disruptions **(Exhibit 19)**.[90] El Paso Water Utilities’ Kay Bailey Hutchison Desalination Plant runs on a similar basis, with officials noting that it was built to deal with drought, emergency situations such as the loss of surface water supplies or extreme weather events, growth, and brackish water intrusion into local aquifers.[91]

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[86] Western Sydney University. (2019). Cities turn to desalination for water security, but at what cost? Western Sydney University News Centre. https://www.westernsydney.edu.au/newscentre/news_centre/story_archive/2019/cities_turn_to_desalination_for_water_security,_but_at_what_cost

[87] Ben-David, R. (n.d.). Paying for the Victorian Desalination Plant. Presented at the Water 2013 Conference. Essential Services Commission of Victoria. https://www.esc.vic.gov.au/sites/default/files/documents/Paying-for-The-Victorian-Desalination-Plant.pdf

[88] Karamihas, R. (2022, November). Water E-journal November 2022. Water E-journal. Retrieved from https://14568786.fs1.hubspotusercontent-na1.net/hubfs/14568786/Water%20e-journal/2022/November%202022/Water_E-journal_November_2022_040.pdf

[89] Ibid. 2-4

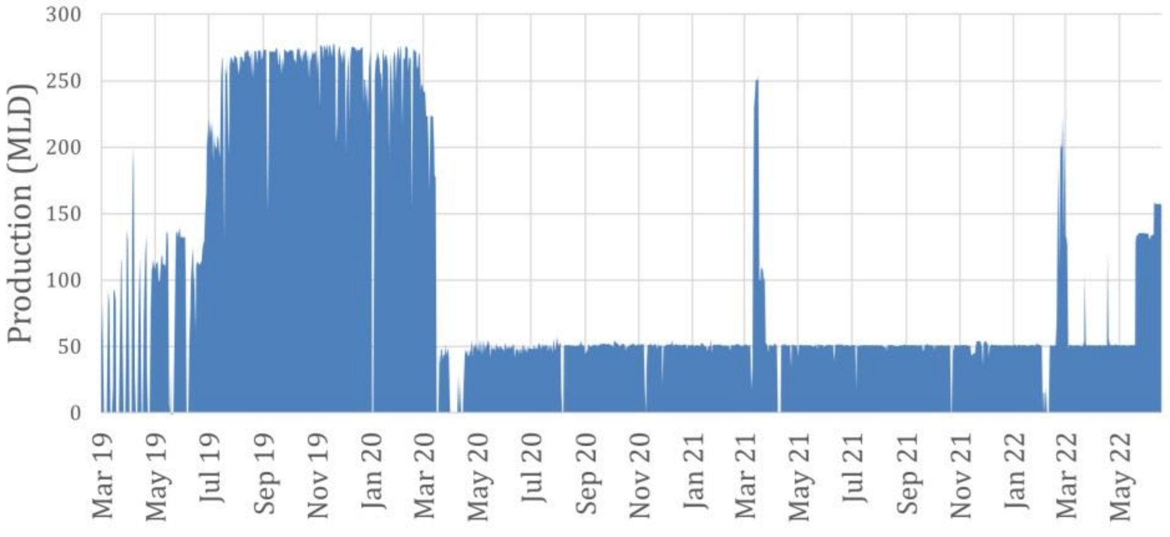
[90] Ibid. 9

[91] Reinert, S. (2017). Texas Desalination: Water Supply Solutions for the 21st Century. Retrieved from https://www.texasdesal.com/wp-content/uploads/2017/12/Scott-Reinert.pdf

EXHIBIT 19

Sydney Desalination Plant Daily Water Production and Operating History, Million Liters/Day (2019-2022)

Note: One million liters equals 0.81 acre-feet



Source: Australian Water Association Water E-Journal

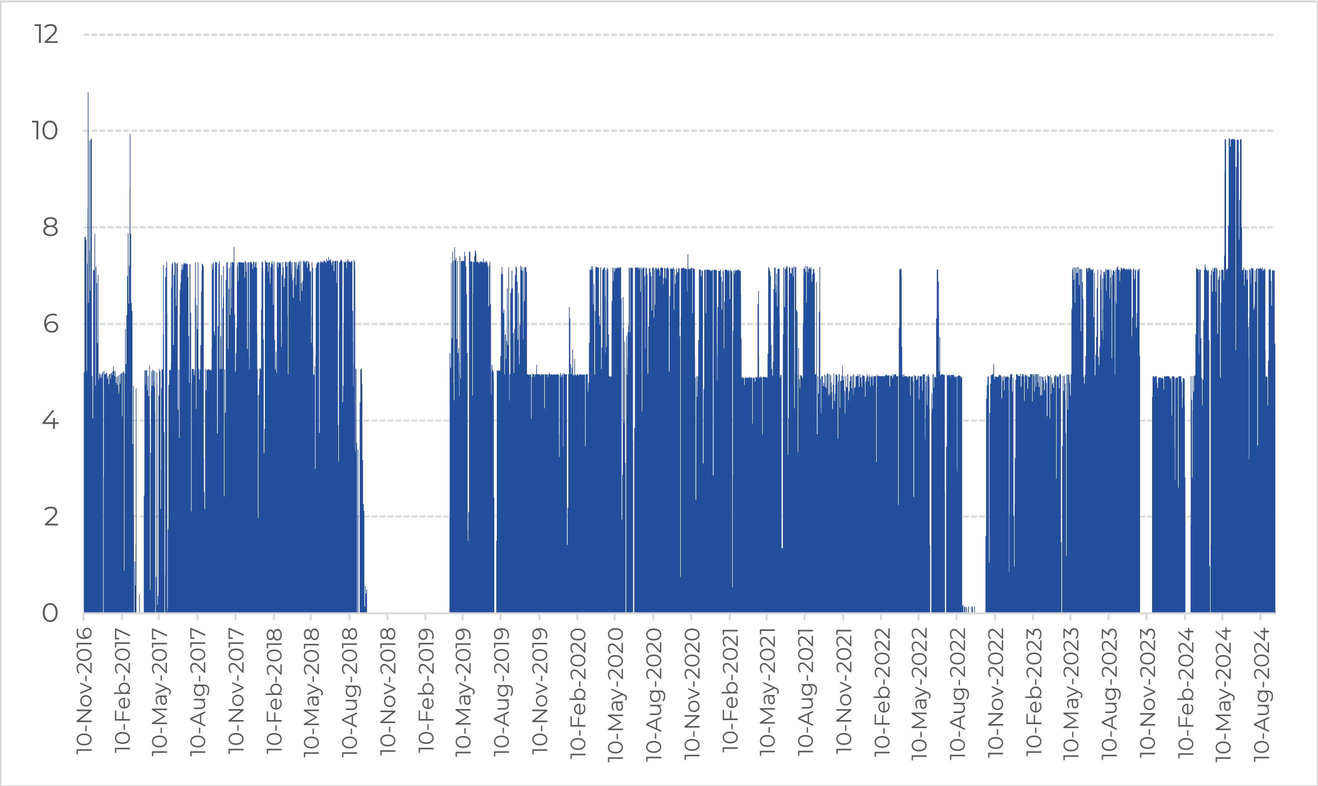
The second mode is to prioritize dispatch of water from the desalination facilities under the economic logic that no matter the run rate, capital costs passed on to ratepayers will be the same and under the water security logic that desalinated water displaces molecules from more drought prone sources. In some cases, it can also allow water from more weather-sensitive sources to be stored in aquifer storage and recovery systems for later use.

A recent Texas example of this approach to high capital cost water supply systems comes from San Antonio Water System's H2Oaks brackish water desalination facility, which has now operated for approximately 8 years and whose daily production data reveal it to be a baseload producer that retain the capacity to surge volumes on short notice in response to supply disruptions or drought **(Exhibit 20).** A second example would be SAWS' Vista Ridge pipeline, which is now the city's second-largest source of water after the Edwards Aquifer and maintains a fairly steady monthly supply volume regardless of rainfall fluctuations.[92]

[92] Post Oak Savannah Groundwater Conservation District. (n.d.). Vista Ridge Dashboard. Retrieved from https://posgcd.org/vista-ridge-dashboard/

EXHIBIT 20

SAWS Brackish Water Desalination Facility Daily Production, Million Gallons



Source: SAWS, Author's Analysis

Shifting Dynamics in Favor of More Desalination in Texas

Cost challenges still endure—as epitomized by the substantial cost inflation for Corpus Christi's proposed Inner Harbor desalination plant.[93] That said, desalination may be more feasible now than it was two generations ago. Fast forward to the present time and Texas now has more than three times the population it has when LBJ inaugurated the Freeport desalination plant. By 2070, it could have nearly 6 times the population it did in 1961.

With greater sustained pressure on source water availability, the high cost (or outright unavailability) of new surface water projects, competition for Carrizo-Wilcox groundwater, subsidence concerns in the Houston area, and the lower water-intensity of today's Texas economy relative to that of the 1960s, desalination could prove more competitive **(Exhibit 21)**.

[93] Michal Gibson, "The real cost of the future desal plant," KIII TV, 19 January 2024, https://www.kiiitv.com/article/news/local/cost-of-future-desal-plant/503-a42e9942-97f6-4e28-bbe3-4efa750e6e78

EXHIBIT 21

Estimated Delivered Cost at Consumer Tap of Various Water Resources

	Legacy Surface Water Cost	Base Case City Water Cost	"Best" Desalination Case	"Long Distance Groundwater Case"	"First of Kind" Desalination Case
Local Distribution Operations Subtotal, $/AF	$543	$543	$543	$543	$543
Est. Debt Finance and Other Cost for Local System, $/AF delivered	$487	$487	$487	$487	$487
Sourcewater Cost at Citygate, $/AF	$225	$605	$716	$1,500	$3,000
Total Delivered Cost, $/AF	$1,255	$1,635	$1,746	$2,530	$4,030
Total Delivered Cost, $/KGAL	$3.85	$5.02	$5.36	$7.76	$12.37

Source: SAWS, TWDB, Coastal Bend Water Supply Study, Author's Analysis

There are also opportunities for public-private partnerships that bring water-intensive industrial interests together with municipal entities to enhance water resilience and spread financial cost and risk through a consortium approach. The author's survey of a dozen chemical producers with significant Texas operations, many of them world-scale and adjacent to the Gulf Coast, suggests that multiple industrial parties have contemplated desalination as a possible water supply option but found it too expensive. That said, there is precedent for large industrial entities in water-stressed areas even building their own desalination facilities—as Reliance has done for its refinery in Jamnagar, India, a plant twice the capacity of Marathon's Galveston Bay plant and the largest refinery in the world.[94] Jamnagar's onsite desalination plant can produce nearly 50,000 AFY of water—the size of the Vista Ridge Pipeline.

Desalination could also provide financial opportunities for surface water rights holders with diversion points near the coast who, under the provisions of Senate Bill 1430 (became law in September 2017), can apply to divert volumes of water at other locations in the river basin (likely upstream) that are equivalent or less than to the desalinated water they use at the

[94] Tam Nguyen, "Water Sustainability Builds Agriculture, Provides Natural Habitat At India's Jamnagar Refinery," Bechtel, 15 October 2017, https://www.bechtel.com/newsroom/blog/sustainability/water-sustainability-indias-jamnagar-refinery/

coast.[95] Among other things, this could position large industrial parties that build coastal desalination facilities to offset costs by marketing water to upstream users. They could likely sell reservation contracts and then charge additional fees for physical water withdrawn at the upstream diversion points. Such structures would enhance their operational resilience while also helping proactively ameliorate water supply pressures upstream in key basins, serving both their private interest and bolstering their broader social license to operate.

Locking in Water Resilience Offers Major Infrastructure Improvement Opportunities

All these options require intensive infrastructure investment. Conservation also requires construction due to the simple reality that water systems in Texas lose a lot of expensively obtained and treated water before it ever makes it to the customer. Over the past decade, TWDB audits suggest that utilities in Texas lose an average of about 700,000 acre-feet per year from their systems—versus approximately 4.4-to-4.5 million feet of total annual municipal usage in the state.[96]

Losses on such a scale illustrate the substantial investment needs—and associated opportunities. The EPA's 2021 Drinking Water Infrastructure Needs Survey and Assessment estimates $70 billion worth of investment needed **(Exhibit 22).** Counting wastewater infrastructure and additional needs articulated in the 2022 Texas State Water Plan more than doubles the total. The 50-year price tag for reliable water infrastructure in Texas now stands at nearly $154 billion.[97]

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[95] Texas Legislature. Senate Bill No. 1430. 85th Legislature, Regular Session (2017). Accessed July 28, 2024. https://capitol.texas.gov/tlodocs/85R/billtext/pdf/SB01430F.pdf#navpanes=0

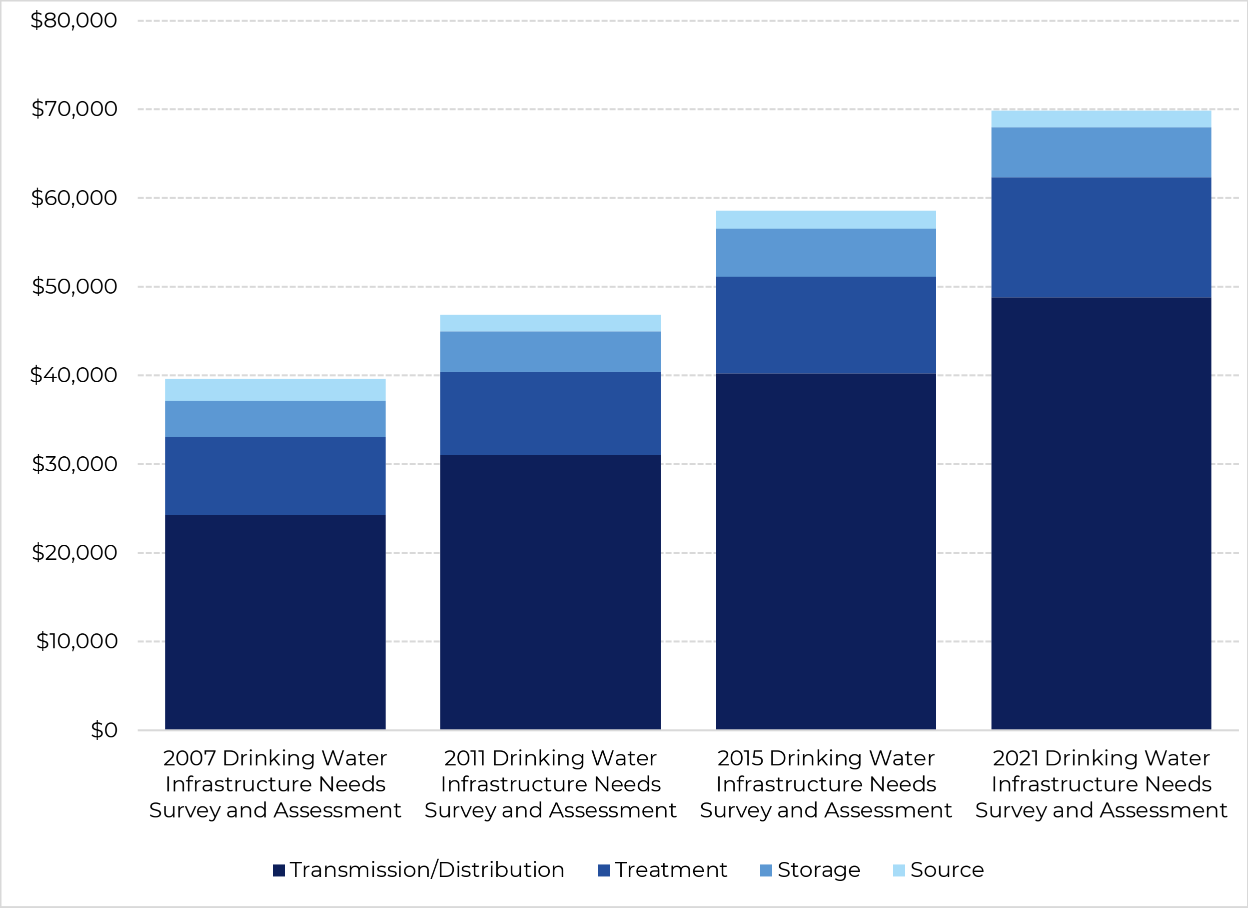
[96] Texas Water Development Board. Water Loss Audit and Conservation Annual Report Data. Texas Water Development Board. https://www.twdb.texas.gov/conservation/municipal/waterloss/historical-annual-report.asp

[97] Jeremy Mazur, "Assessing Texas' Water Infrastructure Needs," Texas 2036, October 2024, https://texas2036.org/wp-content/uploads/2024/10/TxWater-Infrastructure-Assessment_Texas-2036_2024.pdf

EXHIBIT 22

Texas Water Supply Investment Needs

Million USD, Inflation-Indexed to January 2024 Price Level



Source: EPA Drinking Water Infrastructure Needs Surveys, Author's Analysis

Such massive needs create a major opportunity to attract investments and create construction jobs. Research from the International Monetary Fund suggests that in advanced economies like Texas each $1 million in public money spent on water & sanitation projects generates between 3 and 6 jobs.[98] Texas could thus see an uplift of 3,000 to 6,000 jobs from every $1 billion' worth of incremental investment in enhancing the state's resilience and water supply security.

On the high end, each additional billion spent could thus drive construction employment akin to that created when ExxonMobil and SABIC built the world-scale Gulf Coast Growth

[98] Moszoro, Marian W., The Direct Employment Impact of Public Investment (May 1, 2021). IMF Working Paper No. 2021/131, Available at SSRN: https://ssrn.com/abstract=4026307

Ventures petrochemical facility near Corpus Christi.[99] Given that many of these projects could proportionally lessen the need for large dams and groundwater export projects, the bonds to finance them could potentially gain additional "Green Bond" ESG status advantages.

Construction jobs are an incredibly meaningful but economically smaller part of the equation because the work those folks perform expands the foundational space for additional potential growth that Texas can physically support. Water is not the only key growth input to keep Texas attractive and increase prosperity but it is a necessary one. The most realistic way to think about the issue therefore does not ultimately hinge on how many thousands of near-term jobs are created, but rather, how do the investments we make today support over 30 million Texans now and potentially several million more as the state approaches the Texas Revolution's bicentennial in 2036? In that way, investing in water is similar to investing in the power grid as a public good.

Furthering the analogy, **there is not a preset return on investment but if recent experience is any guide, major Texas metro areas typically produce about $1 in economic activity per gallon of local water supply. At that ratio, every 100,000 AF of incremental water supply can potentially underwrite more than $30 billion' worth of economic activity**.[100] This does not mean that providing the water supplies will automatically yield such a return but their availability is a necessary prerequisite to support demographic and economic growth. Texas's water intensity of growth per capita is likely to fall in coming years as the costs of newer, drought-resistant water supplies rise. Nonetheless, it will still be a net positive number. As a simple illustration, if every 1,000 new residents drove an incremental 75 acre-feet/year in water use before, even halving that intensity number still means that a million additional people require a quantity of water nearly on par with what a Vista Ridge-sized supply project or world-scale desalination plant would provide.

Economic Impacts of Key Water Users' Economic Activities

So how much water do various types of non-agricultural users require? There are two fundamental ways to approach this question, and the study utilizes both. First is the loss perspective, which the next section focuses on. Put bluntly, failing to have sufficient water for Industries A, B, and C could lead to the following economic losses. Second is the corollary—ensuring water supplies that allow Industries A, B, and C to operate as they did before (and just as importantly, attract Industries D, E, and F to locate facilities in Texas) can yield economic returns commensurate to or exceeding the losses we seek to avoid through investment.

Here are a few examples. Assuming 3 people per household, each 1,000 additional residential rooftops could need 750 acre-feet of water per year. Growth in the suburbs will likely be slightly more water intensive given the prevalence of larger yards while densification in larger

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[99] "ExxonMobil, SABIC start operations at Gulf Coast Manufacturing Facility," ExxonMobil, 20 January 2022, https://corporate.exxonmobil.com/news/news-releases/2022/0120_exxonmobil-and-sabic-start-operations-at-gulf-coast-manufacturing-facility

[5] For perspective, a 1,000-acre alfalfa farm in Trans-Pecos West Texas would likely need around 2,500 acre feet, but only generates a few million dollars in economic impact.

[100] Collins, Gabriel. "Economic Valuation of Groundwater in Texas." Presentation to Texas Water Research Network, 14 September 2018, Austin, TX. https://texaswaterintelligence.com/wp-content/uploads/2018/09/collins_twrn_economic-valuation-of-groundwater-in-texas_17-september-2018_posting-version.pdf

cities will likely reduce their water intensity. Among commercial users, a world-scale car factory likely uses somewhere between 600 and 1,000 acre-feet per year, while generating approximately $1 billion in economic benefit.[101] A major hospital likely uses somewhere between 2,000 and 3,500 acre-feet per year while yielding $6 billion or more in positive economic impact (as well as world-class healthcare services).[5]

World-scale oil refineries and petrochemical facilities likely require between 15,000 and 25,000 acre-feet per year of water and generate $750 million to $3 billion in economic impact apiece. The king of water needs per unit of value created among the assets charted in **Exhibit 23** is a large cutting-edge semiconductor manufacturing plant, which is likely to use around 5,000 acre-feet of water each year but yield $15 billion or more worth of local economic impact.[102]

Water unit value analysis does not aim to normatively judge if one economic sector's water use is "better" or "worse" than another's. Rather, this analysis demonstrates what the economic returns to the state and regional economies could be through investments in water infrastructure. Conversely, this analysis points to the potential daily economic loss rates if major users had to curtail operations due to drought (like refining & petrochemicals), as well as the potential capacity to pay for alternative water supplies as a hedge against disruptions. One example of this would be Samsung Semiconductor, which in 2023 signed a high value deal to procure drought-resistant Carrizo-Wilcox Aquifer water for the world-scale fab it is building near Taylor.[103]

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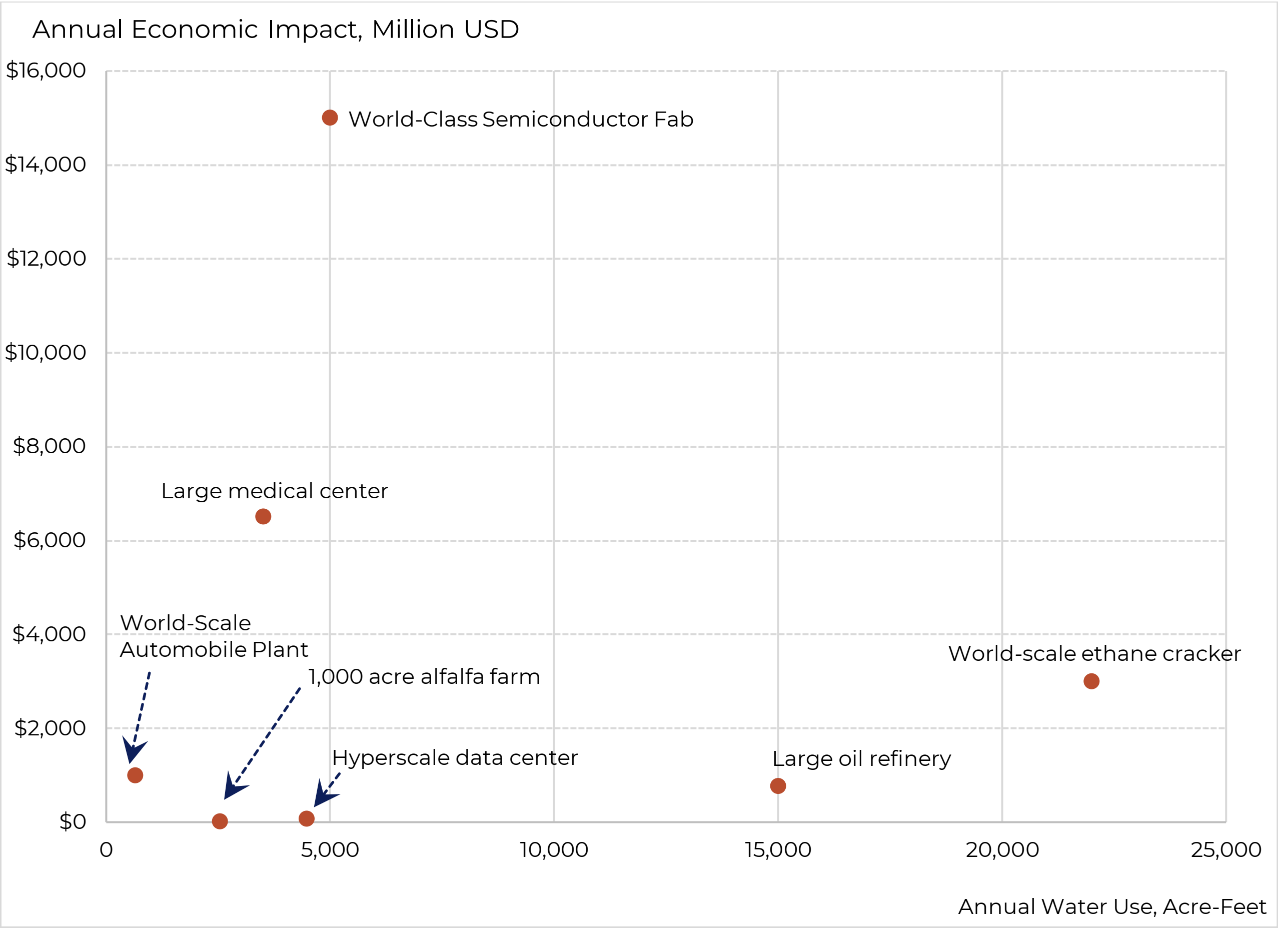
[101] Cristian Agatie, "Tesla Explains How It Achieves Record-Breaking Water Saving at Giga Berlin," autoevolution, 25 April 2023, https://www.autoevolution.com/news/tesla-explains-how-it-achieves-record-breaking-water-economy-at-giga-berlin-213982.html; Fred Lambert, "Tesla Gigafactory Texas achieves production of 4,000 cars in a week, but trails behind Berlin," Electrek, 2 April 2023, https://electrek.co/2023/04/02/tesla-gigafactory-texas-achieves-production-of-4000-cars-in-a-week-but-trails-behind-berlin/

[102] Joanna Allhands, "How much water will TSMC Arizona use? Probably a lot less than you think," USA Today, 12 June 2024, https://www.usatoday.com/story/opinion/op-ed/joannaallhands/2024/06/12/tsmc-arizona-water-use-recycling/74059522007/

[103] "EPCOR Tapped As Water Partner in Central Texas," https://www.epcor.com/about/news-announcements/Pages/2023-07-13-epcor-tapped-water-partner-central-texas.aspx

EXHIBIT 23

Annual Economic Impact vs. Water Use of Selected Industrial and Agricultural Assets



Source: ExxonMobil. (2017, April 19). ExxonMobil and SABIC Select San Patricio County for Proposed Petrochemical Project on U.S. Gulf Coast. ExxonMobil News Releases. Retrieved from ExxonMobil News Release. https://ir.exxonmobil.com/news-releases/news-release-details/exxonmobil-and-sabic-select-san-patricio-county-proposed; Robert Morris University. (2021). Updated Economic Impact Analysis: Petrochemical Facility in Beaver County. Retrieved from Robert Morris University. https://www.rmu.edu/sites/default/files/user_files/Project_Franklin_Economic_Impact_Study_FINAL.pdf; Energy Analytics Institute. (2019, February 17). Fact Sheet: CITGO Petroleum's Three US Refineries. Retrieved from Energy Analytics Institute. https://energy-analytics-institute.org/2019/02/17/fact-sheet-citgo-petroleums-three-us-refineries/; Samsung Austin Semiconductor. (2024). Samsung Austin Semiconductor 2023 Economic Impact Report, https://news.samsung.com/us/samsung-austin-semiconductor-announces-2023-economic-impact-26-8b-central-texas/; https://download.semiconductor.samsung.com/resources/white-paper/Samsung_Austin_Semiconductor_2023_Economic_Impact_Report.pdf; Texas A&M Agricultural Extension, USDA

CONCLUSION

The 1950s drought and the 2011 drought offer key datasets to inform contemporary understanding of how a future high-intensity, long-duration drought could impact key interests across Texas. They also provide real world insights into how various iterations of Texas—one agrarian and rural and the second far more urbanized and industrial—coped and adapted to climate volatility.

Drought 75 years ago brought physical and demographic changes that shape Texas to this day. Cities were forced to rapidly tap groundwater reserves to supplement rivers shrunk by lack of rain while Dallas had to temporarily supplement its water supply with salty flows from the Red River.[104] Litigation ensued as desperate cities drilled wells and pumped hard to ensure their citizens had sufficient water.[105] Within 20 years of the Great Drought, a crash construction program basically quadrupled reservoir capacity in Texas (the state with almost no large natural lakes).[106]

Texas's rural population declined from a third of the state to just a quarter as farmers and ranchers had to sell herds, seek work in town, and fundamentally remake their lives under Mother Nature's desiccating glare.[107] Populations in Texas's larger cities rose commensurately, with many of today's Triangle Metros seeing significant population bumps between 1950 and 1960 as this climate migration unfolded.

Yet despite all those impacts, the 1950s may no longer be the most appropriate benchmark for a worst-case drought. A 2011 palaeoclimatological study by a team of researchers writing in the Texas Water Journal noted that:

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[104] Historical Groundwater Uses by Municipalities For the Years 1955 Through 1959 For Selected Areas in Texas," Texas Board of Water Engineers, 12 January 1961, https://www.twdb.texas.gov/publications/reports/historic_groundwater_reports/doc/M293.pdf; Pat H. Holland, "Diversions from Red River to Lake Dallas, Texas; and related channel losses, February and March 1954," USGS, 1954, https://www.usgs.gov/publications/diversions-red-river-lake-dallas-texas-and-related-channel-losses-february-and-march

[105] See, for instance: City of Corpus Christi v. City of Pleasanton, 154 Tex. 289, 276 S.W.2d 798 (1955) and Lower Nueces River Water Supply Dist. v. City of Pleasanton, 251 S.W.2d 777 (Tex. App. 1952)

[106] "Texas Reservoirs," Water Data for Texas, https://www.waterdatafortexas.org/reservoirs/statewide

[107] John Burnett, "When the Sky Ran Dry," Texas Monthly, July 2012, https://www.texasmonthly.com/articles/when-the-sky-ran-dry/

"Most water planners in Texas at present use the drought of the 1950s, 1950–1956, as a worst-case scenario. Our reconstructions show, however, that a number of extended droughts of the past were longer and/or more intense than the 1950s drought...Current use by water planners of the 1950s drought as a worst-case scenario, therefore, is questionable. When water managers consider past droughts, population growth, and climate change, it becomes highly probable that the future poses unprecedented challenges."[108]

Today's climate and political-economic structure do not offer the same shock absorbers that Texans of the 1950s could avail themselves of during a drought. The probability of significant near-term costs beyond the agricultural sector as well as lost longer-term opportunities are risks that demand proactive policy solutions. Costs of inaction will be far higher than before. Our present responsibilities require us to adapt our thought processes and resultant financial and physical actions to a new normal of pre-emptive water supply investments to ensure climate resilience and continued growth opportunities for generations to come. The challenges may be unprecedented but Texas proactivity as reflected by the 60-year history of the water planning process offers ample precedent—we just need to put a bit more money behind it. Invest to grow.

[108] MK Cleaveland, TH Votteler, DK Stahle, RC Casteel, JL Banner. 2011.Extended chronology of drought in South central, Southeastern, and West Texas. Texas Water Journal. 2(1): 54-96. Available from: https://doi.org/10.21423/twj.v2i1.2049.

APPENDIX A

Rough Estimate of Water Costs as a Percentage of GDP in Texas

	Muni Use	Muni Residential	Muni Commercial	Residential Delivered Price, AF	Commercial Delivered Price, AF	Muni Total Expenditure on Water, Billion	Rural GW Use	Rural GW Unit Cost	Inflation	Conveyance Premium	Rural GW Expenditure	Rural SW Use	Rural SW Unit Cost	Conveyance Premium	Rural SW Expenditure	Total Est. Water Expenditure, Billion USD	Texas Real GDP, Billion	Water as % of GDP
2002	4,124,762	2,474,857	1,649,905	$1,301	$891	$4.7	8,594,509	$117		25.0%	$1.25	3,560,786	$64	25%	$0.29	$6.23	$796	0.8%
2003	4,035,280	2,421,168	1,614,112	$1,361	$1,030	$5.0	7,752,270	$117	2.0%	25.0%	$1.13	3,336,404	$67	25%	$0.28	$6.37	$841	0.8%
2004	3,990,246	2,394,148	1,596,098	$1,420	$1,022	$5.0	7,796,464	$119	2.0%	25.0%	$1.16	3,577,970	$69	25%	$0.31	$6.50	$921	0.7%
2005	4,527,896	2,716,738	1,811,158			$0.0	6,697,525	$121	2.0%	25.0%	$1.02	3,795,718	$74	25%	$0.35		$1,004	
2006	4,811,294	2,886,776	1,924,518	$1,529	$1,102	$6.5	6,501,648	$124	2.0%	25.0%	$1.01	3,479,143	$77	25%	$0.33	$7.87	$1,108	0.7%
2007	4,354,950	2,612,970	1,741,980	$1,618	$1,194	$6.3	7,528,762	$126	2.0%	25.0%	$1.19	3,240,272	$81	25%	$0.33	$7.83	$1,199	0.7%
2008	4,175,904	2,505,542	1,670,362	$1,667	$1,259	$6.3	8,429,730	$129	2.0%	25.0%	$1.36	3,281,121	$83	25%	$0.34	$7.98	$1,253	0.6%
2009	4,189,950	2,513,970	1,675,980	$1,789	$1,303	$6.7	7,735,331	$132	2.0%	25.0%	$1.27	3,287,162	$87	25%	$0.36	$8.31	$1,179	0.7%
2010	4,212,906	2,527,744	1,685,162	$1,829	$1,357	$6.9	6,286,164	$134	2.0%	25.0%	$1.06	3,338,959	$90	25%	$0.37	$8.34	$1,256	0.7%
2011	4,970,166	2,982,100	1,988,066	$1,616	$1,385	$7.6	8,686,285	$137	2.0%	25.0%	$1.49	3,985,176	$94	25%	$0.47	$9.53	$1,352	0.7%
2012	4,500,005	2,700,003	1,800,002	$1,981	$1,459	$8.0	8,325,678	$140	2.0%	25.0%	$1.46	2,841,108	$97	25%	$0.34	$9.77	$1,430	0.7%
2013	4,283,360	2,570,016	1,713,344			$0.0	7,629,698	$143	2.0%	25.0%	$1.36	2,359,902	$97	25%	$0.29		$1,527	
2014	4,089,212	2,453,527	1,635,685			$0.0	6,993,393	$146	2.0%	25.0%	$1.27	2,374,901	$99	25%	$0.29		$1,592	
2015	4,130,233	2,478,140	1,652,093			$0.0	5,522,963	$149	2.0%	25.0%	$1.03	2,475,373	$107	25%	$0.33		$1,586	
2016	4,307,935	2,584,761	1,723,174			$0.0	6,456,379	$152	2.0%	25.0%	$1.22	3,217,524	$102	25%	$0.41		$1,583	
2017	4,257,325	2,554,395	1,702,930	$2,415	$1,948	$9.5	5,991,447	$155	2.0%	25.0%	$1.16	3,365,846	$103	25%	$0.43	$11.08	$1,667	0.7%
2018	4,260,756	2,556,454	1,704,302	$2,501	$1,937	$9.7	6,511,642	$158	2.0%	25.0%	$1.28	3,421,376	$104	25%	$0.44	$11.43	$1,808	0.6%
2019	4,241,425	2,544,855	1,696,570	$2,591	$2,021	$10.0	6,301,610	$161	2.0%	25.0%	$1.27	3,148,930	$106	25%	$0.42	$11.71	$1,860	0.6%
2020	4,345,418	2,607,251	1,738,167	$2,690	$2,056	$10.6	6,577,971	$164	2.0%	25.0%	$1.35	3,366,075	$106	25%	$0.45	$12.39	$1,799	0.7%
2021	4,428,270	2,656,962	1,771,308	$2,687	$2,123	$10.9	6,257,055	$168	2.0%	25.0%	$1.31	3,190,910	$108	25%	$0.43	$12.64	$2,087	0.6%
2022E	4,528,270	2,716,962	1,811,308	$2,596	$2,170	$11.0	6,257,055	$171	2.0%	25.0%	$1.34	0	$113	125%	$0.00	$12.32	$2,403	0.5%
2023E	4,628,270	2,776,962	1,851,308	$3,448	$2,308	$13.8	6,257,055	$174	2.0%	25.0%	$1.36	0	$115	225%	$0.00	$15.21	$2,563	0.6%

APPENDIX B

Economic Impact Estimates For Selected Global Drought Events

Country	City/Region	Annual Economic Loss, % of GDP	Comments	Source
India	National	-5.00%	High case over multiple years	Gadgil, S. and S. Gadgil (2006). The Indian Monsoon, GDP and agriculture. Economic and Political Weekly, vol. 41, no. 47.
Iran	National	-4.40%	Severe multi-year drought	Salami, Habibollah, Naser Shahnooshi, and Kenneth J. Thomson. "The Economic Impacts of Drought on the Economy of Iran: An Integration of Linear Programming and Macroeconometric Modelling Approaches." Ecological Economics, vol. 68, no. 4, 2009, pp. 1032-1039. https://doi.org/10.1016/j.ecolecon.2008.12.003.
South Africa	Western Cape	-3.40%	2018 measurement around time of Cape Town "near Zero Day" water crisis	ReliefWeb. "Economic Implications of Water Resources Management in the Western Cape Water Supply System." Last modified June 29, 2023. Accessed August 4, 2024. https://reliefweb.int/report/south-africa/economic-implications-water-resources-management-western-cape-water-supply-system
Spain	Catalonia	-2.80%	Multi-Year, Substantial restriction	González, J. F. (2011). Assessing the macroeconomic impact of water supply restrictions through an input-output analysis. Water Resources Management, 25(9), 2335–2347.
USA	Wichita Falls MSA	-2.80%	Long-run	Martinez, John, Ph.D., and Robert Forrester, Ph.D., "Dark Cloud of Uncertainty: 'Great Drought' Cost Area $1 Billion," MSU Texas, Times Record News, November 24, 2021. https://www.timesrecordnews.com/story/news/2021/11/24/historic-drought-cost-local-area-more-than-1-billion/8720944002/.
Brazil	Ferraz de Vasconcelos	-2.47%	Long-run	Sass, Karina Simone & Haddad, Eduardo Amaral & Mendiondo, Eduardo Mario, 2023. "**Impacts of Droughts on Economic Activities in The São Paulo Metropolitan Area**," TD NEREUS 4-2023, Núcleo de Economia Regional e Urbana da Universidade de São Paulo (NEREUS).
India	National	-2.00%	Low case over multiple years	Gadgil, S. and S. Gadgil (2006). The Indian Monsoon, GDP and agriculture. Economic and Political Weekly, vol. 41, no. 47.
Brazil	Rio Grande da Serra	-1.93%	Long-run	Sass, Karina Simone & Haddad, Eduardo Amaral & Mendiondo, Eduardo Mario, 2023. "**Impacts of Droughts on Economic Activities in The São Paulo Metropolitan Area**," TD NEREUS 4-2023, Núcleo de Economia Regional e Urbana da Universidade de São Paulo (NEREUS).
Brazil	Embu Guacu	-1.79%	Long-run	Sass, Karina Simone & Haddad, Eduardo Amaral & Mendiondo, Eduardo Mario, 2023. "**Impacts of Droughts on Economic Activities in The São Paulo Metropolitan Area**," TD NEREUS 4-2023, Núcleo de Economia Regional e Urbana da Universidade de São Paulo (NEREUS).
Australia	New South Wales	-1.60%	Single Year, 2019-2020 drought	Wittwer, G. and Waschik, R. (2021), Estimating the economic impacts of the 2017–2019 drought and 2019–2020 bushfires on regional NSW and the rest of Australia. Aust J Agric Resour Econ, 65: 918-936. https://doi.org/10.1111/1467-8489.12442
Australia	National	-1.60%	Single Year	Lu, L. & Hedley, D. (2004) The impact of the 2002-03 drought on the economy and agricultural employment. *Economic Round-Up*, 3(Autumn), 25–43.
Australia	New South Wales	-1.10%	Single Year, 2018-2019 drought	Wittwer, G. and Waschik, R. (2021), Estimating the economic impacts of the 2017–2019 drought and 2019–2020 bushfires on regional NSW and the rest of Australia. Aust J Agric Resour Econ, 65: 918-936. https://doi.org/10.1111/1467-8489.12441

Australia	National	-1.10%	Single Year	Campbell, R., Crowley, P. & Demura, P. (1983) Impact of drought on national income and employment. *Quarterly Review of the Rural Economy*, 5(3), 254–263.
Australia	National	-0.90%	Single Year	Horridge, M., Madden, J. & Wittwer, G. (2005) The impact of the 2002–2003 drought on Australia. *Journal of Policy Modeling*, 27(3), 285–308.
Developing Countries		-0.85%	Single year Extreme drought	Zaveri, E., R. Damania, and N. Engle. 2023. “Droughts and Deficits: The Global Impact of Droughts on Economic Growth.” Policy Research Working Paper No. 10453. Washington, DC. World Bank.
Mexico	North & Central States	-0.56%	Single Year D4 drought	Banco de México. "Informe Trimestral." August 31, 2022. Accessed August 4, 2024. https://www.banxico.org.mx/publicaciones-y-prensa/informes-trimestrales/recuadros/{3A0127A1-D0C9-7D61-C9AE-E57E127FB39B}.pdf
Australia	National	-0.50%	Single Year	ABS (Australian Bureau of Statistics). (2006) Catalog 5206.0 – Australian National Accounts: National Income, Expenditure and Product, Sep 2006. Feature article: Impact of the drought on agricultural production in 2006–07.
Chile	National	-0.48%	Multi-year drought	Fernández, Francisco J., Felipe Vásquez-Lavín, Roberto D. Ponce, René Garreaud, Francisco Hernández, Oscar Link, Francisco Zambrano, and Michael Hanemann. "The Economic Impacts of Long-Run Droughts: Challenges, Gaps, and Way Forward." Journal of Environmental Management, vol. 344, 2023, 118726. https://doi.org/10.1016/j.jenvman.2023.118726.
Developing Countries		-0.39%	Single Year Moderate drought	Zaveri, E., R. Damania, and N. Engle. 2023. “Droughts and Deficits: The Global Impact of Droughts on Economic Growth.” Policy Research Working Paper No. 10453. Washington, DC. World Bank.
Spain	Catalonia	-0.34%	Modest restriction	González, J. F. (2011). Assessing the macroeconomic impact of water supply restrictions through an input-output analysis. Water Resources Management, 25(9), 2335–2347.
Brazil	Sao Paulo Metro Area	-0.34%	Long-run	Sass, Karina Simone & Haddad, Eduardo Amaral & Mendiondo, Eduardo Mario, 2023. "**Impacts of Droughts on Economic Activities in The São Paulo Metropolitan Area**," TD NEREUS 4-2023, Núcleo de Economia Regional e Urbana da Universidade de São Paulo (NEREUS).
High-Income Countries		-0.30%	Single Year Extreme drought	Zaveri, E., R. Damania, and N. Engle. 2023. “Droughts and Deficits: The Global Impact of Droughts on Economic Growth.” Policy Research Working Paper No. 10453. Washington, DC. World Bank.

From its location in the energy capital of the world - Houston, Texas - the Center for Energy Studies (CES) at Rice University's Baker Institute for Public Policy provides critical insights into the world's complex and evolving energy landscape. By conducting data-centric research and nonpartisan analysis rooted in fundamental principles, the CES provides a trusted voice that investigates the many influences on energy market evolution.

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