Multisectoral analysis of drought impacts and management responses to the 2008-2015 record drought in the Colorado Basin, Texas: A blueprint for regional multisectoral drought impact assessment

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Abstract. Drought has long posed an existential threat to society. Engineering and technological advancements have enabled the development of complex, interconnected water supply systems that buffer societies from the impacts of drought, enabling growth and prosperity. However, increasing water demand from population growth and economic development, combined with more extreme and prolonged droughts due to climate change, pose significant challenges for governments in the 21st century. Improved understanding of the cascading multisectoral impacts and adaptive responses resulting from extreme drought can aid in adaptive planning and highlight key processes in modelling drought impacts. The record drought spanning 2008~~—~~ to 2015 in the Colorado Basin in the state of Texas, United States serves as an outstanding illustration to assess multisectoral impacts and responses to severe, multi-year drought. The basin faces similar water security challenges as across the Western U.S., such as: groundwater depletion and sustainability, resource competition between agriculture and growing urban populations, limited options for additional reservoir expansion, and the heightened risk of more severe and frequent droughts due to climate change. By analysing rich, high-quality data sourced from nine different local, state, and federal sources, we demonstrate that characterizing regional multisector dynamics is crucial to predicting and understanding future vulnerability and possible approaches to reduce impacts to human and natural systems in the face of extreme drought conditions. This review reveals that, despite the severe hydrometeorological conditions of the drought, the region's advanced economy and existing water infrastructure effectively mitigated economic and societal impacts.

1. Introduction

Droughts threaten modern civilizations in a variety of ways (van Dijk et al. 2013; ~~van Dijk et al. 2013,~~ Wilhite et al. 2007~~;~~). Prolonged dry spells cause depletion of terrestrial water resources, leading to water use restrictions and shortage (Lund, et al. 2018), reduced crop yields and loss of pasture (Gupta et al., 2020; Kuwayama et al., 2019~~Gupta et al., 2020; Kuwayama et al., 2019~~), impaired electricity generation from hydroelectric and thermoelectric facilities (van Vliet et al., 2016; Voisin et al., 2020), degradation of water quality (Ahmadi and Moradkhani, 2019), forest loss through tree mortality (Brodribb et al., 2020) and forest fire (Littell, et al. 2016), and reduced primary productivity of vegetation (Stocker et al., 2019; Xu et al., 2019). These impacts spawn a myriad of second-order effects. For instance, loss of water-dependent electricity generation can reduce the reliability of the power grid (Turner et al., 2021) or shift generation onto resources that cost more to run or emit more carbon (O'Connell et al., 2019). In some cases, the impacts of a local drought can carry national or global implications, such as by increasing crop prices and altering global food trade networks (Lal et al., 2012; Marston and Konar, 2017).

The need to understand possible impacts from drought is underscored by anticipated intensification of drought in some world regions in the 21st century due to climate change (Cayan et al., 2010; Cook et al., 2018; Trenberth et al., 2014), manifesting large reductions in surface water availability over large portions of the globe (Schewe et al., 2014). In some regions, climate change has already increased the joint probability of hot and dry conditions that produce more severe drought impacts (Sarhadi et al., 2018).

There is no single quantitative definition of drought (Kuwayama et al., 2018). Drought can be defined by many metrics of water deficit, such as reduced precipitation (meteorological drought) often combined with increased potential evapotranspiration, soil moisture deficit ~~impacting~~ affecting vegetation (soil moisture drought or agricultural drought), reduced surface water flows and groundwater levels (hydrological drought), and reduced reservoir storage (reservoir drought) (Van Loon et al., 2015). The intensity and duration of meteorological drought influences the severity of other types of droughts; for example, a short, intense meteorological drought can result in a severe agricultural drought. The impacts of meteorological drought can also be exacerbated by human actions (Van Loon et al. 2016), such as increased diversions from streams resulting in more severe hydrological drought (reduced streamflow) or withdrawals from reservoirs initiating or exacerbating reservoir drought.

Because~~Since~~ extreme drought is rare (by definition), there are a limited number of 21st century case studies available to document and synthesize its impacts. Examining each case is essential to better understanding the complex dynamics of drought propagation, the resulting multisector impacts and responses to drought in modern society, and critical lessons learned to better prepare for future droughts. The aim of this paper is to provide such a case study through a detailed examination of the 2008-2015 drought in the Colorado Basin, TX. ~~The Colorado Basin, Texas~~This region (Figure 1a) faces significant municipal-agricultural-energy--water nexus challenges and offers a compelling case study for multisectoral drought impact analysis. The paper is organized into the following sections: background on the drought of record, e.g., the basin's hydroclimate, water supply, and sectoral water use (Sections 1.1 and 1.2); data and methods (Section 2); analysis of multisectoral impacts and adaptive management responses from drought of record (Sections 3.1 – 3.3~~n~~); and finally, a discussion of insights into multisector impacts and dynamics, limitations, and future work (Section 4) and concluding remarks (Section 5).

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1.1 Basin Geography and Sectoral Water Use

~~The Colorado Basin, Texas (Figure 1a) is facing significant municipal-agricultural-energy water nexus challenges, offers a compelling case study for multi-sectoral drought impact analysis.~~ The Colorado Basin spans 800 km across the central part of Texas and has a drainage area of 102,000 km^2 (Figure 1a). Its headwaters are in the arid north-western part of the state, and surface water flows southeast towards the Gulf of Mexico. The basin is divided into three water management regions (Figure 1a), marked by diverse hydroclimates and distinct differences in water use, reliance on surface water versus groundwater, and sectoral water demand (Table 1). Here, water use refers to total withdrawals, not consumptive use.

The basin's hydrology is characterized by highly variable seasonal streamflow prone to multi-year drought periods (Wurbs, 2021). There is a markedly increasing precipitation gradient from the western upper region (38-45 cm/yr) to the eastern lower region (68-112 cm/yr) (TWDB, 2023a), which greatly influences surface water availability and the ratio of surface water to groundwater use across the basin (Table 1). The sparsely populated, arid upper region has few reliable sources of surface water, no major reservoirs, and is almost entirely dependent on groundwater sourced from the Southern High Plains Aquifer to supply its large agricultural sector (Table 1). In contrast, the highly populated lower region receives more than two-thirds of its annual supply from surface water. Lower region reservoirs are the critical supply for the city of Austin's municipal demands, and for providing reliable water supply for thermoelectric power and lower region agriculture. The middle region is heavily reliant on groundwater for agriculture but uses surface water to meet 60-70% of its municipal demand. Overall, the middle region uses less than 20% of the surface water of the lower region.

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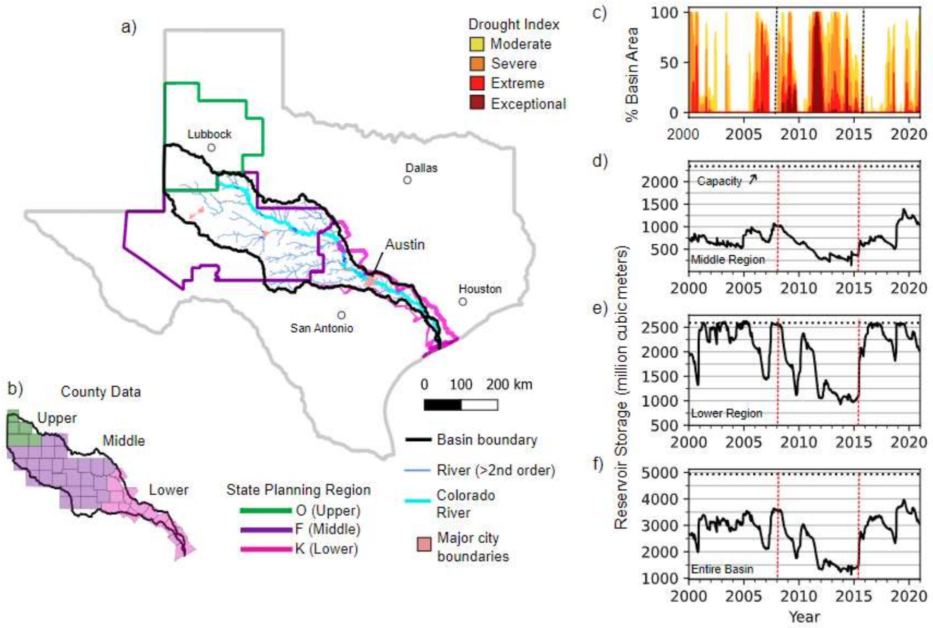

Figure 1: The Colorado Basin (a). The basin spans three state water planning regions: Region O (upper), Region F (middle), and Region K (lower). All regional data presented is based on data from~~only uses~~ counties within the basin footprint (b). U.S. Drought Monitor Drought Index showing the area of the basin under drought from 2000 to 2020 (c). Reservoir storage for the middle region (d), lower region (e), and total basin (f) in million m^3.

Water use and population are also highly unequally distributed amongst the three management regions (Table 1). The sparsely populated, heavily agricultural upper region and densely populated lower region both use more than twice the water of the middle region. Before to the drought (2000-2007), the agriculture sector was the largest water user in all three regions, accounting for 99% of all water use in the upper region and between 50 and 70%, in the middle and lower regions. Municipal use was the second largest sector, representing 25-30% of annual water use in both the lower and middle regions. Industrial and thermoelectric use was less significant in all three regions, accounting for 3-7% of annual use.

1.2 The 2008 – 2015 Drought of Record

The 2008-2015 drought is recognized as the drought of record for two of the middle and lower planning regions in the basin (Texas Water Development Board (TWDB), 2022a). Texas uses the "drought of record" framework for water planning where future water supply is determined based on shortages that would occur under a repeat of the drought of record event. ~~Nielson-Gammon et al., 2020 point out that the "rear-view" drought of record approach could be a potential blind spot of the regional water planning methodology because it overlooks possibility of a more severe event occurring in the future.~~ The 2008-2015 drought period is characterized by a combination of reservoir and meteorological drought, spanning the time between lower basin reservoirs resetting (Figure 1e) and the end of widespread drought conditions (Figure 1c). The drought consisted of two dry periods (2008-2009 and late 2010-2015) separated by a relatively wet year in 2010 (Figure 1c). The drought severity shown in Figure 1c is the US Drought Monitor drought classification index, which is a composite index that incorporates meteorological drought, soil moisture conditions, and surface water impacts (US Drought Monitor, 2023). Before 2008-2015, the region's most severe drought on record took place in the 1950s (TWDB, 2022a). Five key factors that make the two droughts different are a combination of climate (natural) and human system factors:

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(1) Rapid onset of extreme drought. A record low statewide Palmer Drought Severity Index (PDSI) (Palmer, 1965) of -8.06 occurred just 14 months into the 2011-2015 period whereas the drought of the 1950s took 72 months to reach a record low PDSI of -7.77 (TWDB, 2017). The PDSI accounts for precipitation, evapotranspiration, and soil moisture conditions and is standardized to enable comparison between regions (Alley, 1984).
(2) Record meteorological drought combined with prolonged record heatwaves in 2009 and 2011 (hot-dry drought), and the June, July, and August average in 2011 was 1.4 °C higher than the next hottest summer on record (Neilson-Gammon, 2012).
(3) Sustained, multi-year record low reservoir storage in the basin from 2012-2015 (persistent reservoir drought).
(4) Three times larger basin population with 80% of the population increase occurring in the heavily surface-water-reliant lower region has increased the population potentially affected by drought ~~impacts~~ and has also led to increased sectoral competition for surface water.
(5) In the 1950s, the basin was a largely agrarian economy, in contrast with the predominantly urban, industrialized economy in the 21st century (TWDB, 2022b). While population growth has increased the population exposed to drought conditions, the diversification of the regional economy has reduced the basin's economic vulnerability to drought because many of the sectors are not highly water-dependant – representing a shift from a climate sensitive to climate insensitive economy (Tubi, 2020). This is discussed further in Section 3. ~~Section 3the results~~.

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~~**The paper is organized into the following sections: background on the drought of record, e.g., basin's hydroclimate, water supply, and sectoral water use and overview of data sources (Section 2); analysis of multisectoral impacts during**~~

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~~**the 2008-2015 drought of record (Section 3); changes to water planning, policy, and management following the drought of record (Section 4); and finally, a discussion of key challenges facing the basin, potential pathways to a more resilient water future, and a comparison to economic impacts of recent droughts in other advanced economies (Section 5).**~~

~~2. Background and Data~~

~~2.1 Basin Geography and Sectoral Water Use~~

~~The Colorado Basin, Texas (Figure 1a) is facing significant municipal-agricultural-energy water nexus challenges, offers a compelling case study for multi-sectoral drought impact analysis. The basin is divided into three water management regions, marked by diverse hydroclimate and distinct differences in water use, reliance on surface water versus groundwater, and sectoral water demand (Table 1). Here, water use refers to total withdrawals, not consumptive use.~~

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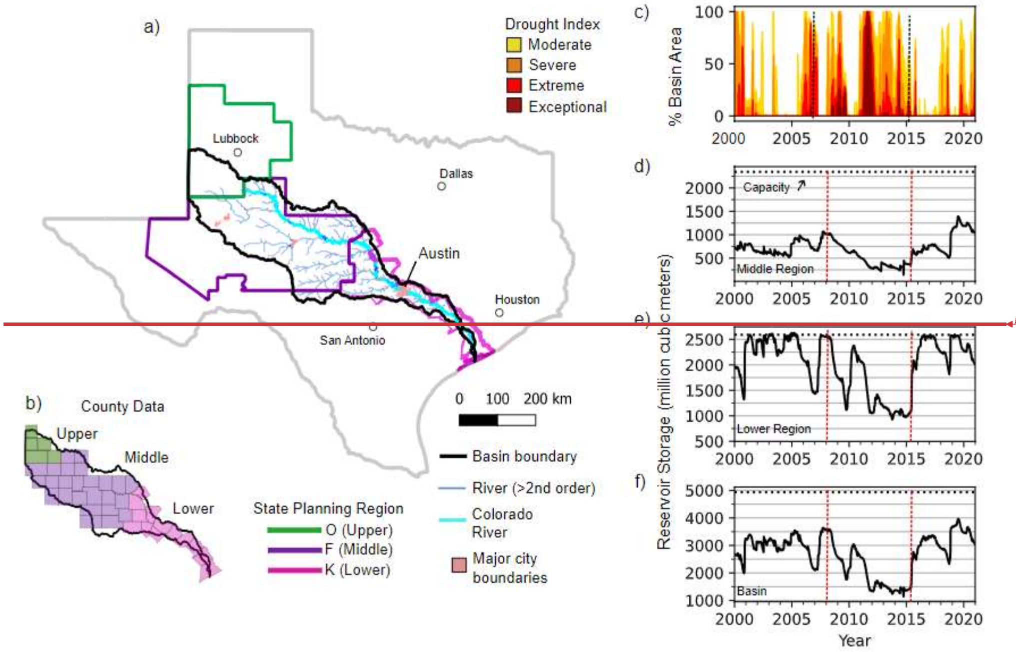

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~~**Figure 1**: The Colorado Basin (a) spans 800 km across the central part of Texas and has a drainage area of 102,000 km^2. Its headwaters are in the arid north-western part of the state, and it flows southeast the Gulf of Mexico along the Texas coast. The basin spans three state water planning regions: Region O (upper), Region F (middle), and Region K (lower). All regional data presented is for counties within the basin footprint (b). U.S. Drought Monitor Drought Index categories for the basin from 2000 to 2020 (c). Reservoir storage for the middle region (d), lower region (e), and total basin (f) in million m^3.~~

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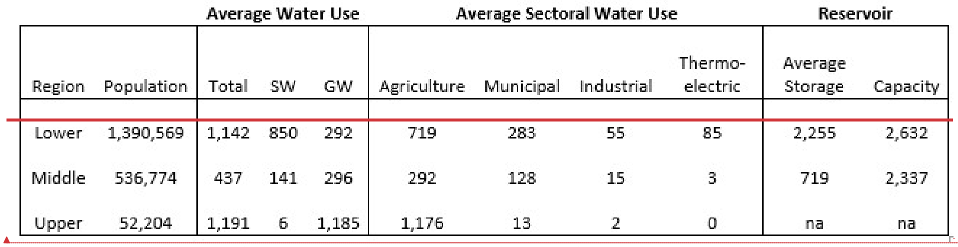
~~Water use and population are unequally distributed amongst the three regions (Table 1). The sparsely populated, heavily agricultural upper region and densely populated lower region both use more than twice the water of the middle region. Prior to the drought (2000-2007), the agriculture sector was the largest water user in all three regions, accounting for 99% of all water use in the upper region and between 50 and 70%, in the middle and lower regions. Municipal use was the second largest sector, representing 25-30% of annual water use in both the lower and middle regions. Industrial and thermoelectric use was less significant in all three regions, accounting for 3-7% of annual use.~~

-	-	**Average Water Use**			**Average Sectoral Water Use**				**Reservoirs**	
Region	**Population**	**Total**	**SW**	**GW**	**Agriculture**	**Municipal**	**Industrial**	**Thermo electric**	**Average Storage**	**Capacity**
Lower	1,390,569 (70)	1,142 (41)	850 (85.3)	292 (16.5)	719 (33)	283 (66.7)	55 (77)	85 (97)	2,255 (75.8)	2,632 (53)

Middle	536,774 (27)	437 (16)	141.5 (14.1)	296 (16.7)	292 (13)	127.5 (30)	14.5 (21)	3 (3)	719 (24.2)	2,337 (47)
Upper	52,204 (3)	1,191 (43)	5.6 (0.6)	1,185 (66.8)	1,176 (54)	13.2 (0.3)	1.8 (3)	0	na	na
Total	1,979,547	2,771	997	1,774	2,187	424	71.3	88.4	2,973	4,969



		Average Water Use			Average Sectoral Water Use				Reservoir	
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Middle	536,774	437	141	296	292	128	15	3	719	2,337
Upper	52,204	1,191	6	1,185	1,176	13	2	0	na	na

Table 1: Summary of regional average annual water use, population, and reservoir storage from 2000-2007. Volumes are in 10^6 m^3. For each region, the percentage of the basin total water use is shown in parentheses – for example, the Middle Region uses 16.7% of the groundwater (GW) and Upper Region agricultural use is 54% of the basin total. The percentages of each column sum to 100. Total volumetric water use for the basin is summed in the last row. SW = surface water. ~~Summary of regional water use, population, and reservoir storage. Annual average water use, sectoral water use, and reservoir storage volumes in 10^6 m^3 (data for 2000 – 2007, pre-drought period) for the three planning regions. Only includes counties shown in Figure 1b.~~

~~2.2 The 2008 – 2015 Drought of Record~~

~~The 2008-2015 drought is officially recognized as the drought of record for two of the three planning regions (lower and middle regions, Figure 1) in the basin (Texas Water Development Board (TWDB), 2022a). This drought period is characterized by a combination of reservoir and meteorological drought, spanning the time between lower basin reservoirs resetting (Figure 1e) and the end of widespread meteorological drought conditions (Figure 1a). The drought consisted of two dry periods (2008-2009 and late 2010-2015) separated by a relatively wet year in 2010 (Figure 1c). Before 2008-2015, the region's most severe drought on record took place in the 1950s (TWDB, 2022a). Five key factors that make the two droughts different are a combination of climate (natural) and human system factors:~~

~~(1) Rapid onset of extreme drought. A record low state-wide Palmer Drought Severity Index (PDSI) of -8.06 occurred just 14 months into the 2011-2015 period whereas the drought of the 1950s took 72 months to reach a record low PDSI of -7.77 (TWDB, 2017).~~

~~(2) Record meteorological drought combined with prolonged record heatwaves in 2009 and 2011 (hot-dry drought), and June, July, and August average in 2011 was 1.4 °C higher than the next hottest summer on record (Neilson-Gammon, 2012).~~

~~(3) Sustained, multi-year record low reservoir storage in the basin from 2012-2015 (persistent reservoir drought).~~

~~(4) Three times larger basin population with 80% of the population increase in the heavily surface water reliant lower region.~~

~~(5) In the 1950's the basin was a largely agrarian economy, in contrast with the predominantly urban, industrialized economy in the 21st century (TWDB, 2022b).~~

2.0 ~~3~~ Data ~~Sources~~ and Methods

The extensive review and analysis of grey literature related to ~~water planning~~drought impacts and management responses are~~is a~~ novel aspects of this study.

We obtained ~~2.1 Data Sources~~

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d~~D~~ata ~~was obtained~~ from a diverse array of publicly available sources to understand and characterize the breadth of multisectoral impacts ~~(Section 3)~~ and management responses ~~(Section 4)~~ in the basin (Table 2). Table 2 provides a description of each data type, citing the temporal and spatial resolutions and the period of record, and links to all dataset sources are in the references.~~Much of the data was available at the annual temporal resolution at the county scale. For these cases, we primarily aggregated the county-level data for each of the three planning regions. Some of the data categories contained an overabundance of records, either hundreds or thousands of locations with hydrological time series data (streamflow, water quality) or numerous metrics associated with annual, county-level data (GPD, employment, crop). To determine region-specific drought impacts, we referenced region-specific literature and regional planning documents to inform most relevant locations and metrics. Data on water supply planning and management were primarily sourced from regional water plans for the three water planning regions, and were supplemented by municipal and utility planning reports, where appropriate. A unique aspect of this study is the extensive review and analysis of grey literature related to water planning. Our characterization of impacts and planning responses is informed by reviewing thousands of pages of planning documents and reports. Our analysis was also informed by interviews with subject matter experts who have experience in city, regional, state, and utility-scale water planning. Data on county-level water supply projects was assembled from each of the regional water plans into a database with supply type, unit cost, supply volume, and sector. Costs were converted to 2022 values using the annual consumer price index for time series data on sectoral GDP (3.5) and water supply unit cost analysis (4.2).~~

Data Category	**Description**	**Source/Agency**
Water U~~u~~se	Annual sectoral SW and GW volumes by county (2000 -~~-~~ 2020)	TWDB, 2023b
Reservoir Storage	Daily reservoir storage (1940 - 2021)	TWDB, 2022c
Streamflow	Daily gauged streamflow (2000 - 2020)	USGS, 2023
Water Q~~q~~uality	Field water quality samples at river and lakes monitoring locations (2000 - 2020)	TCEQ, 2023
Crop	Annual crop production and harvested area by county (2000 - 2020)	USDA, 2023
Cattle	Annual cattle herd size by county (2000 - 2020)	USDA, 2023
Population	Decadal estimates (1940 - 2020) and ~~,~~ annual estimates (2001 - 2020) by county	US Census, 2022 TWDB, 2022c
Wildfire	Annual acres burned by county (2008 - 2015), acres burned state-wide (2002 - 2021)	NOAA, 2022
Gross Domestic Product (GDP)	Annual sectoral GPD by county (2000 - 2020)	BEA, 2022
Employment	Annual sectoral employment by county (2000 - 2020)	BEA, 2022
Energy Production	Monthly production by power plant (2001 - 2021)	EIA, 2022
Drought Classification	Weekly drought classification (% area under each drought threshold) for the basin (2000 - 2020), weekly drought classification maps (2008 - 2015)	U.S. Drought Monitor, 2023
Well installation by sector	Annual well installations by sector by county (2001 - 2021)	TWDB, 2022d

Planned future supply	Recommended water supply projects to meet future sectoral demand. County-level data aggregated for each planning region. (2011, 2016, 2021)	Regional Water Plans*
Unit cost by supply type	Unit cost for each recommended water supply project. County-level data aggregated for each planning region (2011, 2016, 2021)	Regional Water Plans*

Table 2: Data sources for multisector impacts and water management response characterization. *Regional water plans include 2010, 2015, and 2020 regional plans for each of the planning regions.

~~3. Analysis of Multisector Dynamics and Impacts~~

~~**2.2 Methods**For these cases, we primarily aggregated the county-level data for each of the three planning regions. Some of the data categories contained an overabundance of records, either hundreds or thousands of locations with hydrological time series data (streamflow, water quality) or numerous metrics associated with annual, county-level data (GPD, employment, crop). To determine region-specific drought impacts, we referenced region-specific literature and regional planning documents to inform most relevant locations and metrics.The primary temporal and spatial scales of analysis for drought impact metrics was annual resolution at the planning region scale. The only exceptions are streamflow and reservoir storage which are continuous daily data, and water quality which is only available during reported sampling times.~~ Much of the data was available at annual temporal resolution at the county spatial scale. For these cases, we primarily aggregated the county-level data ~~for each of the three planning regions~~ to determine annual statistics related to drought impact for each of the three regions in the basin. The only exceptions are streamflow and reservoir storage which are continuous daily data, and water quality which is only available during reported sampling times. In some cases, the data categories contained an overabundance of records. For example, there were hundreds or thousands of locations with hydrological time series data (streamflow, water quality) and numerous metrics associated with annual, county-level GDP, employment, and crop data. For these cases, literature and planning documents helped guide ~~to~~the selection of metrics and locations for analysis. We used the data sources in Table 2 to assess impacts to sectoral water use, reservoir storage, agriculture production, landcover and the environment, the economy, and energy production. The topical focus areas for drought impacts were informed by peer-reviewed literature and regional water planning documents. Costs for sectoral and regional GDP were converted to 2022 dollars using consumer price index data.

~~We organize our analysis A summary of the multisector dynamics of the 2008-2015 drought of record is illustrated in Figure 2 using a directed acyclic graph (DAG). A DAG, also known as an influence diagram, is a compact way to present complex causal relationships pictorially; it can also be implemented mathematically to understand causal inferences (not performed for this study) (Howard and Matheson, 2005; Schachter, 1987). Each node represents a state variable, and each arrow shows the direction of influence. Feedback loops are not permitted in influence diagrams—those would need to be shown by connecting the relevant nodes between two influence diagrams across a time step.~~

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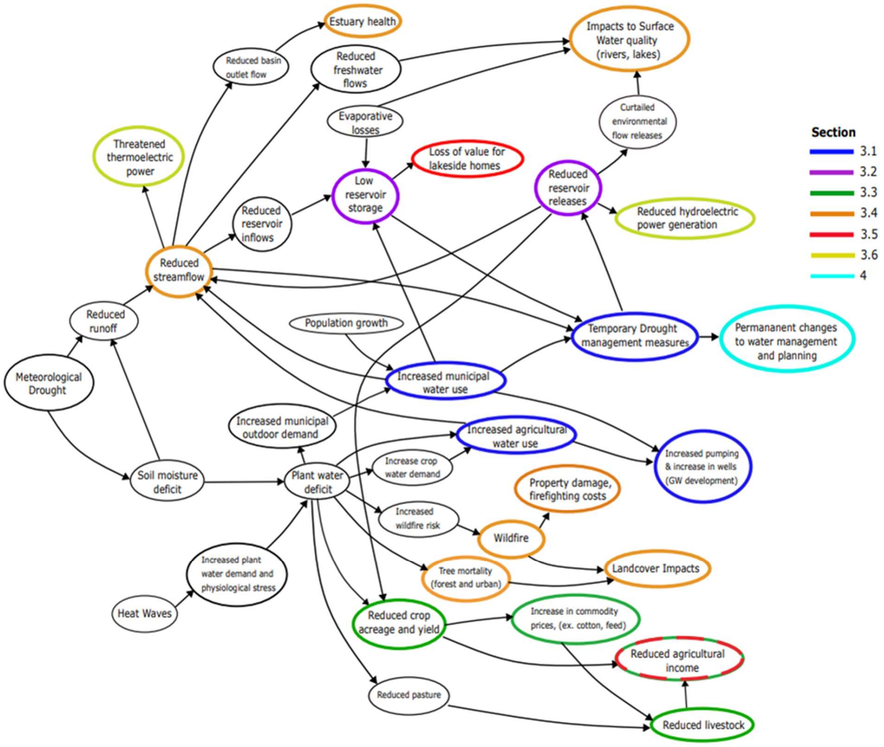

~~**Figure 2:** Influence diagram describing multisector impacts and interactions during the drought. Arrows depict influence of upstream state variables on a downstream state variable and can be interpreted as connecting causes and effects. Colors indicate multisector impacts covered in each of the corresponding results sections.~~

~~For our purposes, Figure 2 shows the cascading impacts that stemmed from the initial trigger of severe meteorological drought. The numerous nodes and links convey the highly multisectoral, interconnected nature of drought impacts; most nodes are influenced by multiple upstream states and contribute to multiple downstream outcomes. The influence diagram also provides an efficient framework to trace downstream outcomes (what resulted from state X?) or upstream causes (what sequence of states led to outcome Y?). The diagram presented here is not intended to be exhaustive but aims to capture key impacts covered in this review. Indeed, many of the individual nodes or drought categories within the diagram could be the subject of in-depth studies on their own. The aim of this work is to highlight the variety and causal nature of multisectoral impacts during drought. As a static illustration, Figure 2 does not provide information on the temporal nature (timing, frequency, duration) or severity of impacts. For example, some impacts occurred months into the drought (agriculture in early 2008) while others took years to develop (estuary impacts did not occur until 2011). Some were brief but intense (wildfire) and others were prolonged (reservoir drought from 2011-2015). We note these temporal dynamics in the text.~~

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~~This section provides context for the causal relationships, temporal characteristics, and severity of drought impacts across multiple sectors in the Colorado Basin. The following subsections provide analysis of impacts to sectoral water use (3.1), reservoir storage (3.2), agriculture (3.3), the environment (3.4), the economy (3.5), and the power sector (3.6), and Figure 2 is color-coded to the endpoint impacts discussed in each subsection.~~

To understand the substantive ways that the drought shaped water planning in the basin, we conducted a comprehensive review and analysis of data in regional water management plans from 2011, 2016, and 2021 for each of the three regions in the basin. Regional water plans in Texas are issued on a 5-year planning cycle and have been mandated by state law since 1997 in response to severe drought conditions in 1995 and 1996 (Wurbs, 2015). An advantage of the relatively short 5-year planning cycle is the ability to respond to recent changes in water availability and sectoral demand. Future shortages are calculated based on the difference between projected future demands (based on estimated sectoral growth) and available supply under drought of record conditions. The 2011 plans were developed before the most severe and prolonged impacts, the 2016 plans were influenced by record drought in 2011 and persistent drought conditions, and the 2021 plans were created with full understanding of the drought of record~~.Data on water supply planning and management were primarily sourced from regional water plans for the three water planning regions, and were supplemented by municipal and utility planning reports, where appropriate.~~

Our analysis of planning and management responses was additionally supported by publicly available reports from utilities and municipalities in the basin and ~~The extensive review and analysis of grey literature related to water planning and management is a novel aspect of this study~~was also informed by interviews with subject matter experts who have experience in city, regional, state, and utility-scale water planning and management. We quantify water management and planning responses by aggregating county-level data from the regional plants on planned water supply projects. The planned supply data included information about the supply type (e.g., new groundwater wells, reuse, desalination etc.), the unit cost of each supply project for which there were over 1,186 individual projects ($\$/m^3$), supply volume, and sector supplied by each proposed project. Water supply costs were converted to 2022 values using the annual consumer price index. ~~Drought often drives management responses and innovation (Lund, et al. 2018; Van Loon et al., 2016). To understand the substantive ways that the drought shaped water supply planning, we conducted a comprehensive review and analysis of data in regional water management plans from 2011, 2016, and 2021 for each of the three regions in the basin (Region F, 2010, 2015, 2020; Region K, 2010, 2015, 2020; Region O, 2010, 2015, 2020). Our analysis was additionally supported by publicly available reports from utilities and municipalities in the basin.~~

~~High-level ishowing the relationships between types of droughts, multisectoral impacts, and adaptation responsesOvals represent state variables while the rectangle is a decision node. between state variables indicate the direction of influence and the arrow into the decision node represents information available at the time of the decision~~

The last results section (3.3) presents a synthesis of our analysis of the multisector impacts during the 2008-2015 drought of record ~~presented as~~in the form of a directed acyclic graph (DAG). ~~where each node represents a state variable, and each arrow shows the direction of influence.~~ A DAG, also known as an influence diagram, is a compact way to present complex causal relationships pictorially; it can also be implemented mathematically to ~~understand~~model causal inferences (not performed for this study) (Howard and Matheson, 2005; Schachter, 1987). The influence diagram in S~~s~~ection 3.3 is a novel product of this study and is ~~, created by synthesizing our findings of drought impacts in the Colorado Basin, TX~~ based on the ~~our~~ review of ~~of~~ thousands of pages of regional water planning documents, ~~reading~~ over a hundred academic papers and reports, and the analysis~~zing~~ of ~~the~~ 15 datasets ~~presented in this study~~ (Table 1). As a preview to the detailed influence diagram in S~~s~~ection 3.3, Figure 2 presents a~~A~~ ~~simplified~~high-level DAG showing the relationship between ~~evolution of~~ drought dynamics, impacts, and

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Commented [RJS10R9]: In fact, unless a reviewer asked for more explanation in this caption, I would definitely delete this sentence planning/management responses~~ is shown in Figure 2~~. In an influence diagram, each oval represents a state variable, each rectangle represents a decision, and each arrow shows the direction of influence. Figure 2 shows the following relationships. ~~Reduced precipitation (~~M~~m~~eteorological drought~~)~~ can lead to~~causes a~~ soil moisture ~~deficit~~drought (not shown here, but also influenced by evapotranspiration). Together, these two types of droughts~~y reduced surface water flows (~~lead to hydrological drought (by reducing surface flows)~~)~~ that in turn ~~impact reservoir storage (~~can lead to reservoir drought (reduced storage)~~)~~. The combined effects of soil moisture, hydrological, and reservoir droughts ~~propagate ~~cause a wide variety of human and natural system impacts (Section 3.1) and planning and management responses (Section 3.2)~~ that are covered the corresponding results sections~~.

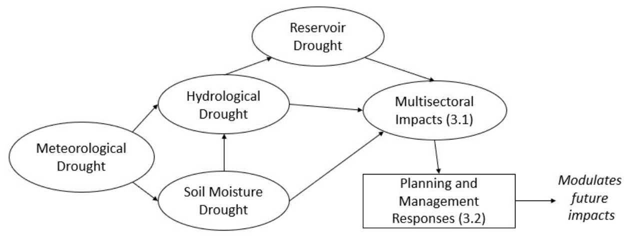

Figure 2: High-level influence diagram showing the relationships between types of droughts, multisectoral impacts, and adaptation responses.

~~Regional water plans are issued on a 5-year planning cycle and have been mandated by state law since 1997 in response to severe drought conditions in 1995 and 1996 (Wurbs, 2015). An advantage of the relatively short 5-year planning cycle is the ability to respond to recent changes in water availability and sectoral demand. However, Nielson-Gammon et al., 2020 point out that a current blind spot of the regional water planning methodology is the "rear-view" drought of record approach that uses the worst historical drought as the basis for determining future water needs. Using the "drought of record" framework, water supply needs are based on shortages that would occur under a repeated drought of record event. Future shortages are calculated based on the difference between projected future demands (based on estimated sectoral growth) and available supply under drought of record conditions.~~

~~The 2011 plans were developed during 2007-2010 before the most severe impacts had occurred and prolonged drought had set in, the 2016 plans were developed after the basin had experienced record drought in 2011 and unabating drought conditions from 2012 to mid-2015, and the 2021 plans were created with full understanding of the new drought record. The drought resulted in large increases in proposed investments to meet long-term water needs, with the largest increase in planned projects in the lower region ($3.63 billion increase from 2011 to 2016 and an additional $623 million from 2016-2021) and moderate increases to the middle basin ($281 million from 2011 to 2016 and an additional $410 million from 2016-2021) (regional costs converted to 2022 dollars). Notably, the drought did not cause any major changes in the upper region due to its low sectoral demand outside of agriculture and there is no economically viable alternative irrigation supply other than continued use of groundwater.~~

3.0 Results

We first present analysis of multisectoral impacts during the 2008-2015 drought of record (Section 3.1), followed by changes to water planning, policy, and management during and following the drought of record (Section 3.2), and conclude with an

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influence diagram summarizing multisectoral impacts and interactions based on our analysis (Section 3.3). ~~(insert intro text about what's coming – like an outline)~~

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~~As shown in Figure 2, we developed an influence diagram showing the cascading impacts that stemmed from the initial trigger of severe meteorological drought. The numerous nodes and links convey the highly multisectoral, interconnected nature of drought impacts; most nodes are influenced by multiple upstream states and contribute to multiple downstream outcomes. The influence diagram also provides an efficient framework to trace downstream outcomes (what resulted from state X?) or upstream causes (what sequence of states led to outcome Y?). The diagram presented here is not intended to be exhaustive but aims to capture key impacts covered in this review. Indeed, many of the individual nodes or drought categories within the diagram could be the subject of in-depth studies on their own. The aim of this work is to highlight the variety and causal nature of multisectoral impacts during drought. As a static illustration, Figure 2 does not provide information on the temporal nature (timing, frequency, duration) or severity of impacts. For example, some impacts occurred months into the drought (agriculture in early 2008) while others took years to develop (estuary impacts did not occur until 2011). Some were brief but intense (wildfire) and others were prolonged (reservoir drought from 2011-2015). We note these temporal dynamics in the text.~~

~~The following subsections follow the color-coded sections in the diagram and describe our findings regarding the impacts to sectoral water use (3.1), reservoir storage (3.2), agriculture (3.3), the environment (3.4), the economy (3.5), and the power sector (3.6).~~

Commented [MOU11]: Why not include the material in Section 4 here in this section as well? It is part of the influence diagram…

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3.1 Multisectoral Impacts

This section covers multisectoral impacts during the 2008-2015 drought. Available data is presented before and after the drought to provide context on how sectoral impacts compared to the pre-drought and post-drought period. The following sub-sections are covered: multisectoral water use of surface water and groundwater (3.1.1), reservoir drought in the middle and lower regions (3.1.2), impacts to agricultural production (3.1.3), environmental impacts (3.1.4) (wildfire, drought-driven tree mortality, streamflow, surface water quality, and environmental flows), economic impacts (3.1.5), and impacts to energy production (3.1.6).

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3.1.1 Multis~~S~~ectoral Water Use

~~As shown in Figure 2, water use data for the basin indicated that meteorological drought impacts propagated to alter sectoral demand (e.g., agriculture, municipal), sectoral water availability (e.g., surface water), and surface water and groundwater use.~~ The onset of the drought in 2008 marked the highest amount of water use in the middle and upper regions (from increased groundwater use), while 2011 was the largest annual water use in the lower region (from both increased surface water and groundwater use) (Figure 3). Notable regional differences in year-to-year variability of water use during the drought were driven primarily by agriculture (Figure 3), while municipal use (second largest sector) showed comparatively little absolute (volumetric) fluctuation when compared to total water use within each region (Figure 3). ~~As the drought progressed,~~ Su~~su~~rface water use declined in the middle and lower regions as the drought progressed,~~,~~ reflecting reservoir conservation measures and temporary drought management measures enacted by municipal water providers (SI Figure 1). During the last three years of the drought

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(2013-2015), surface water use in the lower region was 40% less than that from 2008-2010, while ~~in the middle region,~~ surface water use decreased by 19% in the middle region. In contrast, average groundwater use in the middle and lower regions showed little change during the drought~~ with the lower region increasing by 5% and the middle region decreasing by 8%, when comparing groundwater use during 2008-2010 versus 2013-2015~~. The declining trend in groundwater use in the upper region that started during the drought does not have an obvious explanation because it does not reflect comparatively large reduction in irrigated acres for major crops. One plausible explanation would be adoption of more efficient irrigation technology, but we do not have data to support that hypothesis.

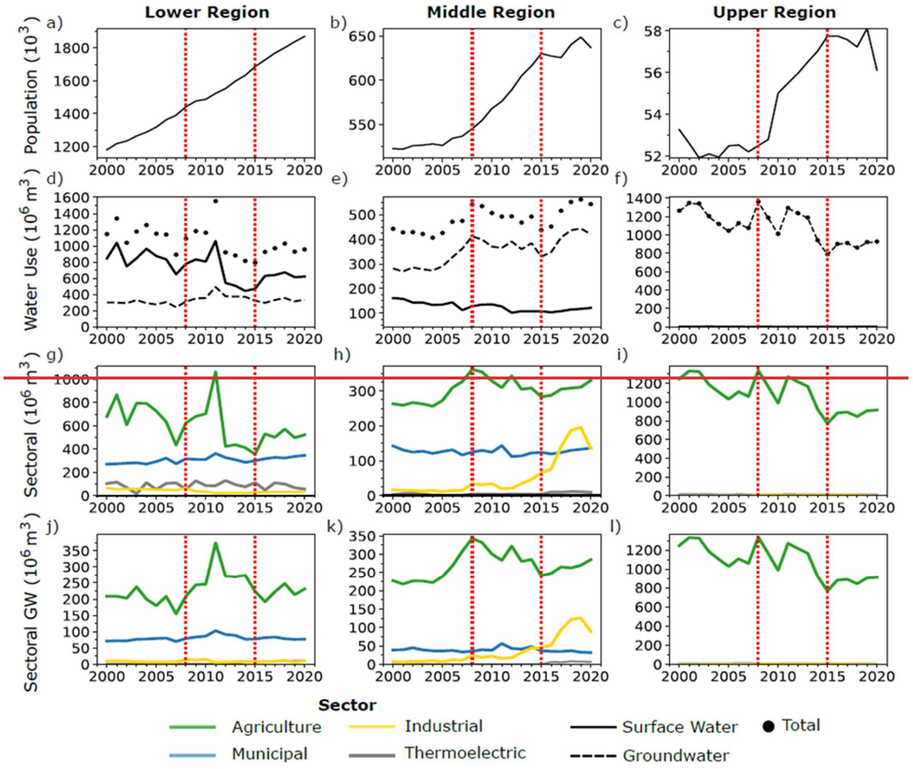
Comparing annual agricultural use during and following the drought revealed significant shifts in surface water and groundwater use for the two largest sectors in the basin (Figure 4). Compared to the pre-drought period (2000-2007), agricultural surface water use during the drought declined by an average of 36% in the lower region and 38% in the middle region, and these reductions persisted over the 2016-2020 post-drought period (Figure 4a). Following reservoir conservation measures in 2012, lower basin agricultural surface water use was 65-77% less than during the pre-drought period. A consequence of reduced agricultural surface water availability in the lower region was an increase in groundwater use (Figure 4a) and well installations (SI Figure 2) during the drought and post-drought periods (Figure 2). Average agricultural groundwater use in the lower region was 33% higher compared to the pre-drought period and in 2011 it was 84% higher, while in the middle region average use was 21% higher during the drought and 42% higher in 2008.

~~. Thiss A notable multisectoral use trend unique to the middle region was a remarkable 150% increase in industrial water use from 2008 to 2020 (Figure 3h). This growth was almost entirely associated with unconventional (fracking) oil and gas development (Region F, 2020), which often uses non-potable sources and was not influenced by drought, thus not considered a drought impact.~~

~~A sectoral use trend unique to the middle region was rapid growth of industrial use from 2008 to 2020, which increased over 150% between 2008 and 2015 and continued to grow from 2016-2020 (Figure 3h). This growth was almost entirely associated with unconventional (fracking) oil and gas development (Region F, 2020). Oil and gas development often uses non-potable sources, such as saline or brackish groundwater and treated municipal wastewater, so this sectoral use does not have to compete with fresh sources needed by municipalities or agriculture (Region F, 2020). While this large sectoral increase occurred during the drought, it was not influenced by drought and is not considered a drought impact (i.e., not in Figure 2). Thermoelectric water use in the basin increased by an average of 12.4% during the drought compared to the pre-drought period and two of the highest use years occurred during the drought (2009 and 2012). Although not visually apparent on Figure 3j due to its relatively small magnitude compared to other sectoral water uses, there was a 540% increase in groundwater use for thermoelectric water supply in the lower region following the drought (1.58 million m3/yr from 2008-2013 growing to 10.17 million m3/yr from 2015-2020), reflecting a transition to a more drought-tolerant supply.~~

Commented [SN14]: Since this not an impact of drought, suggest moving it to the end, and condense it given the lack of relevance.

Commented [FSB15]: Reviewer 2 comment: "Elaborate on what you mean by "reflecting a transition to a more drought-tolerant supply" in line 185. Provide specific details or context to make this statement clearer."
We can briefly expand on this statement, which is in reference to thermoelectric plants increasing their supply from GW.


Lower Region
Middle Region
Upper Region
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
Population (10^3)
Water Use (10^6 m^3)
Sectoral (10^6 m^3)
Sectoral GW (10^6 m^3)
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Thermoelectric
Surface Water
Groundwater
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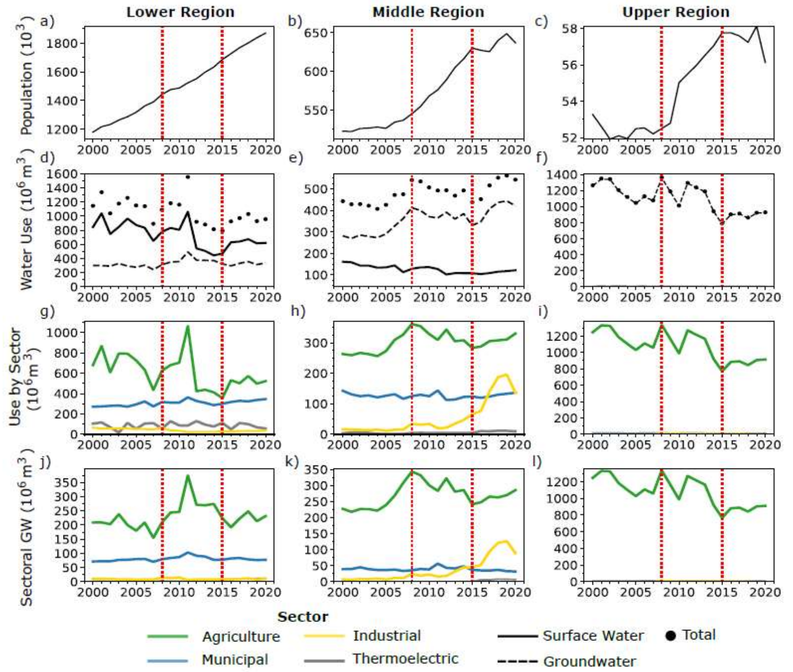

Figure 3: Population growth (a-c), annual surface water **(SW)** ~~(SW)~~ and groundwater (GW) use (d-f), total sectoral use (SW + GW) (g-i), and sectoral GW use (j-l) from 2000 – 2019 in the three planning regions. This data only includes counties shown in Figure 1b.

~~Comparing annual municipal and agricultural use during and following the drought reveals significant shifts in surface water and groundwater use for the two largest sectors in the basin (Figure 4). Compared to the pre-drought period (2000-2007), agricultural surface water use during the drought declined by an average of 36% in the lower and 38% middle region, and these reductions persisted over the 2016-2020 post-drought period (Figure 4a). Following reservoir conservation measures in 2012, which curtailed agricultural supply (Figure 2), lower basin agricultural surface water use was 65-77% less than the pre-drought period. A consequence of reduced agricultural surface water availability in the lower region was an increase in groundwater use (Figure 4a) and well installations (SI Figure 2) during the drought and post-drought periods (Figure 2). Average agricultural groundwater use in the lower region was 33% higher compared to the pre-drought period and in 2011 it was 84% higher, while in the middle region average use was 21% higher during the drought and 42% higher in 2008.~~

Increased municipal surface water use in the lower region during and following the drought (Figure 4b) is reflective of the large population growth in the region, which grew by over 450,000 residents between 2008 and~~-~~ 2020 (Figure 3a). In contrast, municipal surface water use in the middle region was on average 11% lower during the drought and 15% lower following the drought (Figure 4b). Municipal surface water use in the upper region, while small in magnitude (Figure 3g), showed even larger declines than the middle region (Figure 4b). A consistent pattern in municipal groundwater use shared by all three regions was increased use during the drought followed by reduced use after the drought, suggesting temporary shift towards groundwater to

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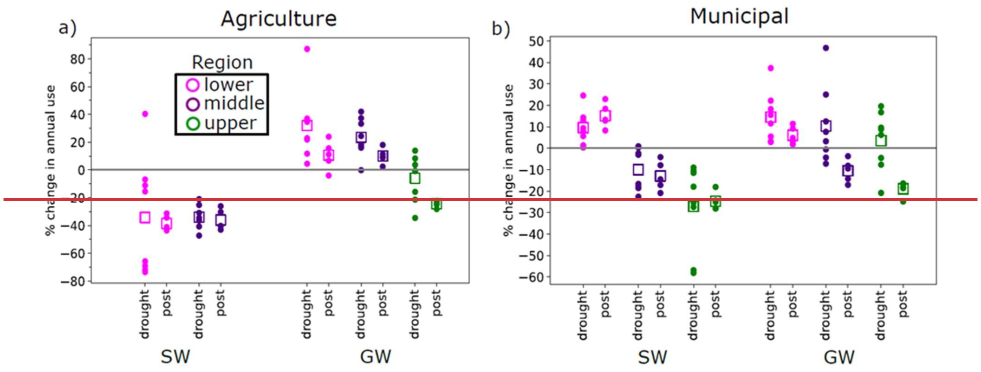
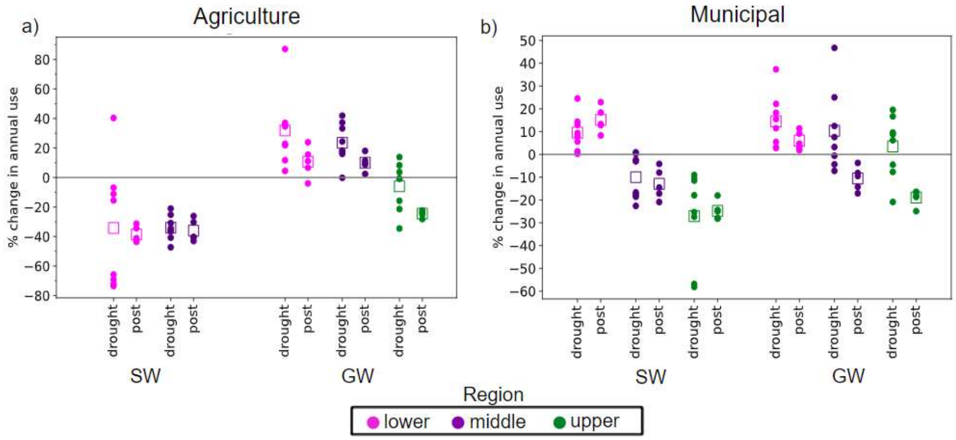
compensate for reduced surface water supply (Figure 2). Only in the lower region ~~has~~ municipal groundwater use in the post-drought period remained higher than during the pre-drought period, likely related in some degree to accommodating the large population increase from 2008-2020.





~~**Figure 4:** Change in agricultural (a) and municipal (b) surface water (SW) and groundwater (GW) use during the drought (2008-2015) and post drought (2016-2020) periods compared to the pre-drought 2000-2007 period. Annual values are open circles and time period means are open squares. No SW for agricultural use in the upper region is why it is omitted from (a).~~

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We can move the legend to the right of the two figure panels.

Figure 4: Change in agricultural (a) and municipal (b) surface water (SW) and groundwater (GW) use during the drought (2008-2015) and post drought (2016-2020) periods compared to the pre-drought 2000-2007 period. Annual values are circles and period means are open squares. No SW is reported for agriculture in the upper region and it is therefore omitted from (a).

Thermoelectric water use in the basin increased by an average of 12.4% during the drought compared to the pre-drought period and two of the highest use years occurred during the drought (2009 and 2012). Although not visually apparent in Figure 3j due to its relatively small magnitude compared to other sectoral water uses, there was a 540% increase in groundwater use for thermoelectric water supply in the lower region following the drought (1.58 million m^3/yr from 2008-2013 growing to 10.17

million m^3/yr from 2015-2020). This suggests a transition towards a more drought-resilient supply as groundwater is less sensitive to reduced surface flows. A notable multisectoral use trend unique to the middle region was a remarkable 150% increase in industrial water use from 2008 to 2020 (Figure 3h). This growth was almost entirely associated with unconventional (fracking) oil and gas development (Region F, 2020), which often uses non-potable sources and was not influenced by drought – it is thus not considered a drought impact.

~~Municipal surface water use in the upper region, while small in magnitude (Figure 3g), showed even larger declines than the middle region (Figure 4b). A consistent pattern in municipal groundwater use shared by all three regions was increased use during the drought followed by reduced use after the drought, suggesting temporary shift towards groundwater to compensate for reduced surface water supply (Figure 2). Only in the lower region has municipal groundwater use in the post-drought period remained higher than the pre-drought period, likely related~~ in some degree ~~to accommodating the large population increase from 2008-2020.~~

3.1.2 Reservoir Drought

~~Due to the reliance on reservoir storage for water supply in the middle and lower regions, reservoir drought is a key aspect of the drought and a nexus of multisector interactions (Figure 2). The magnitude of sectoral disruption and the speed that reservoir drought develops depends on region-specific sectoral water demands and overall reliance on surface water. Prior to the drought, the lower region used 5-6 times more surface water than the middle region (Table 1).~~ In 2008, a~~A~~t the onset of the meteorological drought, middle region reservoirs were less than 50% full, and were already ~~can be considered to already have been~~ in the midst of a long-term reservoir drought (Figure 1d).~~, while~~ I~~i~~n contrast, lower region reservoirs were completely filled at the onset of the drought (Figure 1e). ~~Conditions only worsened in the middle region as the drought progressed and storage did not recover to the 2008 pre-drought conditions until 2018.~~ However, because of much lower agricultural surface water use (less than ~~1/10th~~one-tenth of the lower region), the middle region is not susceptible~~prone~~ to large interannual ~~variability~~ declines in storage from supplying large quantities to irrigators (Figure 1d). Additionally, surface water use from other sectors ~~(ex. municipal, thermoelectric)~~ in the middle region was~~is~~ much smaller than the lower region ~~as well~~ (Figure 3 e, h, k). In fact, the total surface water use in the middle region during 2000-2007 was 47% less than ~~the~~ municipal use *alone* in the lower region. In contrast to the gradual storage declines in the middle region during the drought (Figure 1d), in both 2008-2009 and 2011, there were sharp declines in lower region reservoir storage ~~declined more~~ ~~sharply, by~~ with over 40% drops in total storage during each one- or two-year period (Figure 1e). Reservoir releases for surface water irrigation were the largest driver of large annual storage declines in the lower region, but significant municipal demand also contributed to storage declines during the most severe meteorological drought years.

~~The~~ M~~m~~iddle and lower region reservoirs~~s both~~ experienced sustained record low storage during the second half of the drought (2012-2015). During this period, storage levels in the lower region fluctuated between 40-50% capacity and in the middle region between 10-20%. ~~Based on the annual surface water use under drought conservation measures during the 2012-2015 period, storage levels represented around two years of supply in each region. Low reservoir storage was the primary cause of agricultural water shortages for surface water-dependent irrigators in the lower region, municipal water use restrictions in the middle and~~

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~~lower regions, reduced hydropower generation, and exacerbated environmental flow and water quality issues (Figure 2). A series of large precipitation events in 2015 ended the drought and replenished lower region reservoirs, which by 2016 were completely full, while the middle basin storage only recovered to 25% capacity (Figure 1d). However, the middle region considers 2015 the end of the drought of record, reinforcing the region-specific nature of reservoir drought impacts.~~

A specific feature of the 2011 to 2015 period that caused ~~maintained~~ severe reservoir drought to persist in the lower region was the absence of any large storm events to replenish storage. In 2011, inflows to lower region reservoirs were the lowest on record, and only 10.6% of average annual inflows ~~during~~ from 1942 to 2017 (Austin Water, 2018). To contextualize how unprecedented 2011 inflows were, the lowest inflows during the 1950's drought were approximately four times greater than in 2011 (Austin Water, 2018). Inflows to the lower region reservoirs continued at record-low levels from 2012 to 2014, all lower than the worst year of the 1950's drought. Evaporative losses further exacerbated low surface inflow and contributed to reservoir drought ~~(Figure 2). Mean annual evaporative losses in the basin are estimated to be 7.2% of reservoir capacity (Wurbs and Ayala, 2014).~~ In 2011, lower region evaporative losses exceeded reservoir inflows, with an estimated 239 million m^3 lost to evaporation — equivalent to ~10% of lower region storage capacity and approximately the total annual municipal demand of the highly populated lower region (LCRA, 2022). ~~Evaporative losses in the lower region ranged from 239 million m^3 in 2011 to 135 million m^3 in 2014 (LCRA. 2022). Even at their lowest level in 2014, evaporative losses were equivalent to around two-thirds (60-70%) of lower region municipal surface water use.~~ A series of large precipitation events in 2015 ended the drought and replenished lower region reservoirs, which by 2016 were completely full, while the middle basin storage only recovered to 25% capacity (Figure 1d).

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~~Of the many factors that produced reservoir drought (Figure 2), the two most significant were 1) persistent record low inflows and 2) large releases to agriculture in 2008-2009 and 2011. The decision to release large amounts of water to irrigators that accelerated the development of reservoir drought was based on decades of experience where storage typically recovered within a year or two of large storage declines. A permanent outcome of the drought was the adoption of more conservative reservoir management policies (Figure 2), discussed in Section 4.3.~~

3.1.3 Agricultural Production~~Impacts~~

Reduced agricultural production was one of the most ~~disruptive~~ notable impacts of the drought. ~~Due to the direct dependence of vegetation health on soil moisture (Figure 2), agriculture is typically one of the earliest and most impacted sectors from meteorological drought (Van Loon et al., 2015). To illustrate agricultural impacts in the basin, county-level crop acreage and production data from United States Department of Agriculture (USDA) was aggregated for four major crops (Figure 5). Cotton is a major crop in the middle and upper regions, winter wheat is mainly grown in the middle region, and corn and rice are only major crops in the lower region (Figure 5a).~~

The simultaneous stressors of increased plant water demand and physiological stress from high temperatures ~~are~~ were the main drivers leading to diminished yields and high abandonment rates ~~in the region~~ during the hot, dry drought conditions in 2008-2009 and 2011 (Figure 5~~2~~) (Anderson et al., 2012~~1~~; TWDB, 2022b; Nielson-Gammon, 2012). For ~~all of~~all three~~e~~ major crops (corn, cotton, winter wheat) but rice~~,~~, these years were generally associated with the lowest harvested acreage, production, and yield~~,~~ (Figure 5 b-m)~~) resulting in large agricultural economic losses (Figure 2)~~ (Anderson et al., 2012~~1~~; TWDB, 2022b).

The severity of impacts varied by region due to the spatial heterogeneity of drought (SI Figure 3) and differences in the proportion of irrigated versus dryland crops. Because dryland farming relies on precipitation to meet plant water needs, it is more vulnerable to meteorological drought than irrigated farmland that can supplement precipitation deficits. The middle basin, with 29% production in irrigated ~~Differences in the proportion of dryland~~ cotton, had generally lower cotton yields than the upper region with 55% of production irrigated ~~between middle (29% production irrigated) and upper regions (55% production irrigated) explain typically lower yields for cotton in the middle basin~~ (Figure 5j). A higher proportion of dryland farming was also related to larger reductions in total production and harvested acres during the most severe drought years (Figure 4 b, f). Compared to 2010, in 2011 cotton acreage in the upper region declined by 64% while acreage in the middle region decreased by 87.5%. Texas is one of the major global producers of cotton and comprises a large enough fraction of supply that the severely reduced production in 2011 contributed to the unprecedented price spike in cotton, which increased 153% between March 2010 and March 2011 (U.S. Bureau of Labor Statistics, 2011). Cotton acreage and production gradually recovered to pre-drought levels over 2012-2015. Winter wheat is another example of severe yield, acreage, and production declines for dryland crops (Figure 5 d, h, l). Before the drought, less than 10% of annual production was for irrigated wheat—even during the drought only 16% of production was irrigated. In 2009 and 2011, wheat production declined by 64% and 86%, respectively, compared to the preceding year. Corn is also primarily dryland and had reduced production and yield in 2009 and 2011 but by 2013 production recovered to levels greater than before the drought (Figure 5 g, k). Corn continued to increase following the drought with post-drought area and production almost doubling relative to pre-drought levels (Figure 5 c, g).

Rice differs from the three other crops because it is primarily irrigated by surface water flood irrigation. The abrupt decrease in rice production from 2012-2015 was a result of curtailment of lower region reservoir releases. 2012 was the first time in the basin's history that agricultural water deliveries in the lower basin were curtailed, and curtailments continued- until 2015. Most ~~the of~~ surface water deliveries for rice are classified as interruptible, which can be reduced or entirely cut off if reservoir storage falls below defined drought trigger levels.

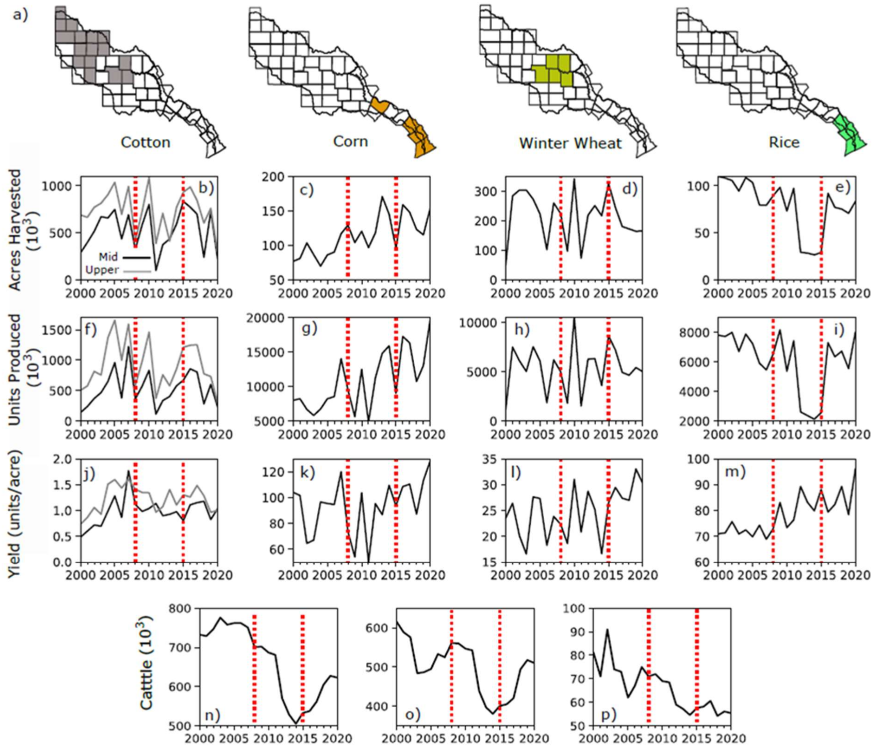

Figure 5: Locations of major crop production (a). Harvested acres (b-e), units produced (f-i), and yield (j-m) for the four crops. Crop-specific units of production: 480-pound bales for cotton, bushels for corn and wheat, and 100-pound units for rice. Cattle herd data for each region (n-p). This data includes all counties shown in Figure 1b~~in each region~~.

~~Compared to average agricultural gross domestic product (GDP) during 2000-2007, average GDP in the basin over 2008-2015 was $574 million lower (35%) and in 2011 $913 million lower (56%) (all values inflation adjusted to 2022). The upper region was more severely impacted and disproportionally so due to its large agricultural sector. During 2008-2015 upper region agricultural GDP was reduced by 51%, while the middle and lower regions were only reduced by 26% and 24%. Agriculture comprises around 15% of the upper region GPD compared to less than 0.5% in the other two regions.~~

An adaptive response during drought is to temporarily switch to lower water demand, more drought-tolerant crops (Fisher et al., 2015; Glotter and Elliott, 2016). Temporary increase in sorghum production in the upper region is a potential example of crop switching (SI Figure 4). Increased sorghum, combined with decreased wheat and cotton also occurred during the 1950's Texas drought (TWDB, 2022b). Sorghum has lower water requirements and is more drought-tolerant than cotton or wheat (TWDB, 2022b). The largest single-year increase in sorghum production occurred in the upper region in 2008 with a 350% rise, while cotton production dropped by 55% compared to 2007~~, sorghum production increased by 350%~~. Sorghum production in the lower

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and middle regions did not show evidence of crop switching, and both regions displayed a long-term decline in sorghum production from 2000 to 2020 (SI Figure 4).

~~The severity of impacts varied by region due to the spatial heterogeneity of drought (SI Figure 3) and differences in the proportion of irrigated versus dryland crops. Dryland farming is reliant on precipitation to meet plant water demand, and therefore is more vulnerable to meteorological drought than irrigated farms that can supplement precipitation deficits. Differences in the proportion of dryland cotton between middle (29% production irrigated) and upper regions (55% production irrigated) explain typically lower yields in the middle basin (Figure 5j), and larger reductions in production and harvested acres during the most severe drought years (Figure 4 b, f). Compared to 2010, in 2011 cotton acreage in the upper region declined by 64% while area in the middle region decreased by 87.5%. Cotton acreage and production gradually recovered to pre-drought levels over 2012-2015. Winter wheat is another example of severe yield, acreage, and production declines for dryland crops (Figure 5 d, h, l). Prior to the drought, less than 10% of annual production was for irrigated wheat and even during the drought only 16% of production was irrigated. In 2009 and 2011, wheat production declined by 64% and 86% compared to the preceding year. Corn is also primarily dryland and had reduced production and yield in 2009 and 2011 but by 2013 production recovered to levels greater than before the drought (Figure 5 g, k). Corn continued to increase following the drought with post-drought area and production almost doubled relative to pre-drought levels (Figure 5 c, g).~~

~~Cotton is by far the largest and most significant crop in the basin. Cotton acreage is typically more than double the combined areas of winter wheat, corn, and rice (Figure 5). Texas is one of the major global producers of cotton and comprises a large enough fraction of supply that the severely reduced production in 2011 contributed to the unprecedented price spike in cotton, which increased 153% between March 2010 and March 2011 (U.S. Bureau of Labor Statistics, 2011).~~

~~Rice differs from the three other crops because it is primarily irrigated by surface water flood irrigation. The decrease in rice production from 2012-2015 was a result of curtailment of lower region reservoir releases. 2012 was the first time in the basin's history that agricultural water deliveries in the lower basin were curtailed, and curtailments continued from 2013-2015. Most of the of surface water for rice is classified as interruptible supply, which can be cut off if reservoir storage falls below trigger levels. Thus, the 60-70% reduction in rice production from 2012-2015 was a cascading impact of reservoir drought (Figure 2).~~

~~A potential adaptive response during drought is to temporarily switch to lower water demand, more drought-tolerant crops (Fisher et al., 2015; Glotter and Elliott, 2016). Temporary increase in sorghum production in the upper region is a potential example of crop switching (SI Figure 4). Increased sorghum, combined with decreased wheat and cotton also occurred during the 1950's Texas drought (TWDB, 2022b). Sorghum has lower water requirements and is more drought-tolerant than cotton or wheat (TWDB, 2022b). The largest single-year increase in sorghum production occurred in the upper region in 2008, while cotton production dropped by 55% compared to 2007, sorghum production increased by 350%. Sorghum production in the lower and middle regions did not show evidence of crop switching, and both regions display a long-term decline in sorghum production from 2000-2020 (SI Figure 4).~~

The drought also caused large reductions in cattle in the middle and lower regions, with a 17% (224,000) decrease from 2011 to 2012. Exceptionally low spring precipitation in 2011 prevented development of dryland crops for cattle feed and adequate forage growth for pasture~~ (Figure 2)~~ (Nielson-Gammon, 2012), which reduced available feed and increased feed prices (Countryman et al., 2016). Cattle numbers did not increase until 2015 and through 2020 herd sizes had not yet recovered to pre-drought numbers (Figure 5).

~~Economic losses for ranchers were related to increased need to purchase feed, higher feed costs because of reduced availability, and lower sale price for cattle because the market was flooded by supply, as ranchers couldn't afford to maintain herd sizes (Countryman et al., 2016). Feed prices continued to increase in 2012 and 2013 due to the 2012 drought that impacted much of the Central U.S. feed supply chain (Countryman et al., 2016). This reduced profitability for livestock caused ranchers to further reduce herd sizes (Figure 5 n-p) (Countryman et al., 2016). Cattle did not increase until 2015 and through 2020 herd sizes had not yet recovered to pre-drought numbers (Figure 5).~~

3.1.4 Environmental Impacts

3.1.4.1 Wildfire and Landcover

~~Drought increases wildfire risk by reducing plant moisture which increases the flammability of vegetation and likelihood of ignition, and increased flammability of parched vegetation can lead to more rapid spread and more intense burns (Figure (Littell et al., 2016).~~ The dry and abnormally hot conditions in 2008 and 2011 (Neilson-Gammon and McRoberts, 2009; Neilson-Gammon 2012) ~~were~~ produced the two most severe wildfire years in the state ~~during the drought period~~ (SI F~~f~~igure 5), and the record dry and hot conditions in 2011 ~~produced~~ led to the worst wildfire year in the state's history (Texas A&M Forest Service, 2011). 2011 accounted for 52% of the total area burned in the Colorado Basin over the drought period. However, the fraction of burned area in 2011 varied widely over the different regions, with over 88% in the upper region, 50% in the middle, and 40% in the lower~~, and the two worst drought years (2008 and 2011) accounted for 57% in lower region, 88% in middle, and 90% in upper~~ (SI Figure 5). The upper and middle regions are mostly~~re~~ arid~~ and~~ grassland and ~~s/~~shrubland~~s~~, which were more ~~impacted~~ affected by hot/dry drought-driven wildfires (Nielson-Gammon, 2012) compared to the forest-dominated lower region.

~~The record wildfires in 2011 are considered to have been partially a result of increased fuel, due to the wet year in 2010 that led to grass and shrub growth (Nielson-Gammon, 2012). A similar correlation has been observed in other Western US states where wet years followed by severe drought are often associated with increased wildfires (Seasta et al., 2016). The record wildfires of 2011 are considered to be combination of 1) additional fuel combined with 2) increased flammability from extreme drought, and 3) unusually windy spring weather that enhanced wildfire spread (Neilson-Gammon, 2012).~~ Firefighting costs for Texas were estimated at $48 million (Neilson-Gammon, 2012). Of the estimated $500 million in fire-related losses in 2011, $325 million (65%) was associated with the Bastrop Complex fire located in the lower region city of Bastrop that~~and~~ remains the costliest fire in state history (Texas Standard, 2021).

In addition to vegetation loss from fires, the extreme dry and hot conditions during 2011 caused widespread tree mortality in the middle and lower regions, due to depleted deep soil moisture that typically buffers trees from short-term drought (Nielson-Gammon, 2012). Estimates indicate that there was an 8-10% canopy loss in the middle and lower regions (Schwantes et al. 2017). A statewide study by Moore et al. 2016 found single-year mortality percentages of 6-6.6% in the middle region and 7.4-9.7% in the lower region, similar to the estimates from Schwantes et al., 2017. Crouchet et al. (2019) studied tree mortality in the middle region and found a 9×~~x~~ increase in mortality compared to a typical year. The upper region was not affected by tree mortality because it is scrubland largely devoid of tree cover. Tree mortality also affected cities, with mortality rates in parts of Austin reaching 20% in 2011 (NASA, 2019). While the record hot, dry conditions in 2011 have been the focus of most studies, Klockow et al. (2018) found pest-driven mortality increased during 2012-2015 in Eastern Texas and hypothesized that this was related to physiological stress induced by 2011 combined with the continuation of drought conditions.

3.1.4.2 Streamflow, Surface Water Quality, and Environmental Flows

~~Reduced streamflows (hydrological drought) caused primarily by prolonged and severe meteorological drought, were further exacerbated by sectoral surface water use and reservoir management (Figure 2).~~ To contextualize the severity of the hydrological drought, streamflow at six locations in the basin are summarized using flow-duration plots (Figure 6 a-f). Locations a-c are located along the mainstem of the Colorado River, ~~the main river in the basin,~~ while locations d-f are tributaries (Figure 6j). Figure 6 a-c additionally show the flow duration curves for the 2000-2007, 2008-2015, and 2016-2020 periods. The curves for the pre-drought (2000-2007) and drought (2008-2015) periods were used to calculate percent reduction in flow over the entire range of exceedance probabilities (Figure 6 a-f). Median to low flows are critical for stream habitat and water quality (Caldwell at al., 2018; Konrad et al., 2008; Wineland et al., 2021), while high flows are important for replenishing reservoir storage (Figure 2).

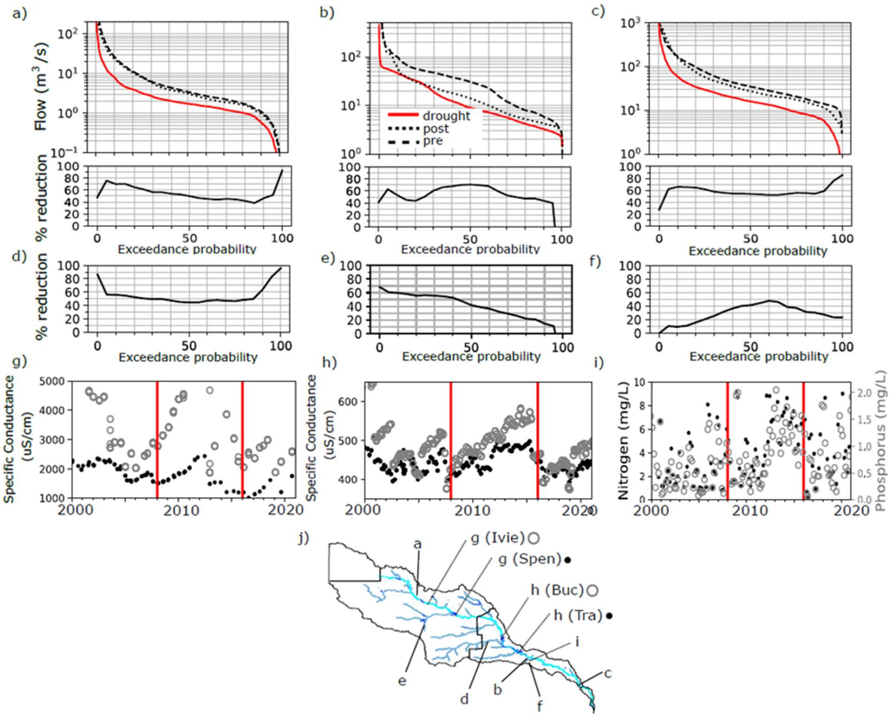

Figure 6: Flow duration curves for the pre-drought (2000-2007), drought (2008-2015), and post drought (2016-2020) periods for three locations along the Colorado River, TX (a-c). Percent reduction in exceedance probability flow for the drought period

compared to the pre-drought period (a-f) for six locations (three~~3~~ for the Colorado River and three~~3~~ for tributaries). Specific conductance data at two middle region reservoirs O.H. Ivie (Ivie) and Spence (Spen) (g) and two lower region reservoirs Buchanan (Buc) and Travis (Tra) (h). Nitrate and phosphorus data for the Colorado River downstream of Austin (i). Locations of discharge and water quality data (j) and denoted symbols for subplots g and h that show data for two reservoirs.

During the drought, flows along the mainstem were generally 40-60% lower across the spectrum of flow percentiles (i.e., the high, median, and low flows were all heavily reduced), while the tributary locations had more heterogeneity in their flow reductions. The San Saba location (Figure 6d) showed greater than 45% reduction across all flow percentiles, while the spring-fed South Concho (Figure 6e) and Barton (Figure 6f) locations had had less severely affected low flows (often considered to be defined by the 90th or 95th flow exceedance percentiles). Prolonged hydrological drought can affect groundwater levels, which can in turn affect streamflow by reducing groundwater baseflow and spring discharge (Smith, 2013; Smith et al 2015), demonstrated by reduced flows at spring-fed locations e and f (Figure 6j). Due to the reservoirs being at critical levels between 2012 and 2015, environmental flow releases were reduced by about 86%, decreasing from 38 to 40.7 million m^3 in 2011-2013 to only 5.7 million m^3 in 2014, and there were no releases in 2015 (LCRA, 2022), affecting low flows downstream of major reservoirs.

Water quality impacts included increased salinity, algae, metals, and nutrients (nitrogen and phosphorus), which are surface water quality impacts commonly associated with drought (Mosley, 2015). Reduced surface flows affect water quality by increasing the concentration of pollutants in surface water from both point source pollution (e.g., treated wastewater outflows) and non-point source pollution (e.g., runoff from agricultural or urban land) (Mosley, 2015). The example we provide is for a segment of the Colorado River downstream of one of Austin's two water treatment plants (Figure 6i), which shows consistently elevated nitrogen and phosphorous concentrations during 2012-2015. Low streamflow also affected water quality in the Matagorda Bay estuary where the Colorado River discharges into the Gulf of Mexico. Discharge from the Lower Colorado River to Matagorda Bay in 2011 was 274 million m^3, representing a decrease of over 78% compared to the average annual discharge of over 1.2 billion m^3 between 1980 and 2010, marking the lowest on record since 1977 (TWDB, 2015). This historically low freshwater input resulted in increased salinity levels in the estuary that reduced habitat suitability for oyster, crab, shrimp, and fish, affecting commercial fishing operations and estuary health (TWDB, 2015).

~~During the drought, flows along the mainstem were generally 40-60% lower across the spectrum of flow percentiles (i.e., the high, median, and low flows were all heavily reduced), while the tributary locations had more heterogeneity in the nature of their flow reductions. The San Saba location (Figure 6d) showed greater than 45% reduction across all flow percentiles, while the spring-fed South Concho (Figure 6e) and Barton (Figure 6f) locations had less severe impacts to low flows (often considered to be defined by the 90th or 95th flow exceedance percentiles). Prolonged hydrological drought can affect groundwater levels, which can in turn affect streamflow by reducing groundwater baseflow and spring discharge (Smith, 2013; Smith et al 2015), demonstrated by reduced flows at e and f (Figure 6j).~~

~~Reduced streamflow caused surface water quality impacts in streams and lakes in the middle and lower regions, and even the coastal estuary at the basin outlet (Figure 2). Water quality impacts included increased salinity, algae, metals, and nutrients (nitrogen and phosphorus), which are surface water quality impacts commonly associated with drought (Mosley, 2015). One way that reduced flows affect water quality is by increasing the concentration of pollutants in surface water. observed both in point source pollution (ex. treated wastewater outflows) and non-point source pollutants (ex. runoff from agricultural or urban land) (Mosley, 2015). The example we provide is for a segment of the Colorado River downstream of one of Austin's two water~~

~~treatment plants (Figure 6i), showing consistently elevated nitrogen and phosphorous concentrations during 2012-2015. Low streamflow also affected water quality in the Matagorda Bay estuary where the Colorado River discharges into the Gulf of Mexico. Discharge from the Lower Colorado River to Matagorda Bay in 2011 was 274 million m^3, representing a decrease of over 78% compared to the average annual discharge of over 1.2 billion m^3 between 1980 - 2010, marking the lowest on record since 1977 (TWDB, 2015). This historically low freshwater input resulted in increased salinity levels in the estuary that reduced habitat suitability for oyster, crab, shrimp, and fish 1977 and impacted commercial fishing operations (TWDB, 2015).~~

In the lower region, the drought led to elevated nitrogen levels in reservoirs that caused increases in microalgae population and a shift towards more harmful algae strains (Gamez, et al. 2019), specifically cyanobacteria, which can produce harmful algal blooms (Beversdorf et al., 2013). Water quality in middle region streams and reservoirs was affected by ~~impacted from~~ naturally high levels of chlorides, sulfates, trace contaminants (ex. arsenic), and total dissolved solutes from~~in~~ groundwater baseflows (Region F, 2015). Duringe ~~to~~ hydrological drought, groundwater baseflow comprises~~comprised~~ a larger fraction of stream~~river~~ flow (Jones and van Vliet, 2018), which result~~eding~~ in degraded surface water quality in the middle region. ~~. If groundwater has high solute concentrations or trace contaminants, the increased baseflow fraction during drought has been shown to degrade surface water quality (Jones and van Vliet, 2018).~~ Reservoir water quality was further degraded by evaporation that concentrateds solutes. Specific conductance data (proxy for solute concentration~~levels~~) for two key middle region supply reservoirs (O.H. Ivie and Spence) show solute concentrations steadily increasing from 2008 to ~~-~~2013 (Figure 6g). Fresh inflows in 2013 substantially reduced solute concentrations in these reservoirs, though total storage in the middle basin changed little ~~had little change~~ (Figure 1b). The two main lower region reservoirs (Buchanan and Travis) also showed increasing solute concentrations during the drought (Figure 6h), but their magnitude was much smaller and was not a concern for potable water quality.

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3.1.5 Economic Impacts

It is difficult to precisely quantify and directly attribute economic impacts to drought (Naumann et al., 2021; Stahl et al., 2016). However, sectoral data on employment, G~~P~~DP, and population growth at regional and basin scales enables a first-order assessment of whether any explainable changes coincide with the drought period.

Population growth in the basin, including the rapidly growing Austin metro area, remained constant throughout the 2008-2015 period and did not show a reduced growth rate at any point during the drought (Figure 3 a-c), even during (2011-2015) when strict water conservation measures were in place. Additionally, key economic metrics of total GDP (Figure 7) and employment (SI Figure 6) both showed steady and sizeable growth throughout the drought. As shown in Figure 7, GDP decline in the middle and upper basins can be attributed to the oil and gas sector, which is unrelated to the drought. Compared to average agricultural GDP during 2000-2007, average GDP in the basin over 2008-2015 was \$574 million lower (35%) and in 2011 \$913 million lower (56%) (inflation adjusted to 2022). The upper region was more severely affected and disproportionally ~~so~~ due to its large agricultural sector. During 2008-2015 upper region agricultural GDP was reduced by 51%, while the middle and lower regions were only reduced by 26% and 24%. ~~Agriculture comprises around 15% of the upper region GPD compared to less than 0.5% in the other two regions.~~ While the drought had significant negative impacts on the agricultural sector GDP, agriculture represents a small fraction of total GDP and regional employment. ~~Agriculture comprises around 15% of the upper region GPD compared to less than 0.5% in the other two regions.~~ Even in the upper basin, where 99% of water use is for irrigation, agriculture accounts for less than ~~15% of jobs and~~ 15% of GDP, whereas it's less than 0.5% in the other two regions. However, agricultural impacts would have been more severe if losses were not partially offset by federal assistance and crop insurance (TWDB, 2022b). For example, at the state level there were $2.6 billion in insurance payments (Collins and Bulut, 2012), while state-level losses were estimated at $13 billion (Anderson et al., 2012). However, the losses reported by Anderson et al. (2012) are gross revenue so the $2.6 billion likely made up for a large fraction of lost profit.

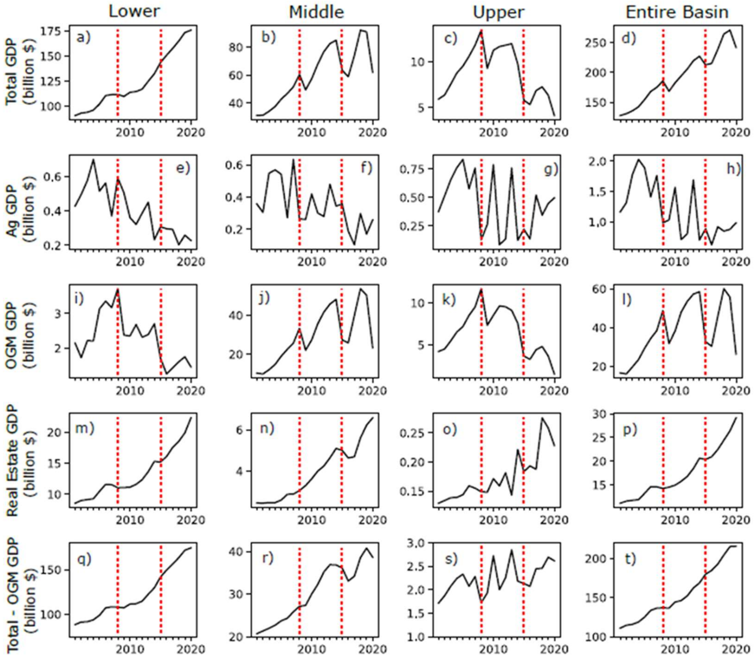

Figure 7: Regional annual GDP for all sectors (a-c), agriculture (e-g), oil, gas, and mining (OGM) (h-j)., real estate (k-m), and all sectors minus ~~oil, gas, and mining (~~OGM~~)~~ (n-p).

~~Population growth in the basin, including the rapidly growing Austin metro area, remained constant throughout the 2008-2015 period and did not show a reduced growth rate at any point during the drought (Figure 3 a-c), even during (2011-2015) when strict conservation measures were in place. Additionally, key economic metrics of total GDP (Figure 7) and employment (SI Figure 6) both showed steady and sizeable growth throughout the drought. As shown in Figure 7, GPD decline in the middle and upper basins can be attributed to the oil and gas sector that is unrelated to the drought. Compared to average agricultural gross domestic product (GDP) during 2000-2007, average GDP in the basin over 2008-2015 was $574 million lower (35%) and in 2011 $913 million lower (56%) (all values inflation adjusted to 2022). The upper region was more severely impacted and disproportionally so due to its large agricultural sector. During 2008-2015 upper region agricultural GDP was reduced by 51%, while the middle and lower regions were only reduced by 26% and 24%. Agriculture comprises around 15% of the upper region GPD compared to less than 0.5% in the other two regions.~~

~~While the drought had significant negative impacts on the agricultural sector GDP, agriculture represents a small fraction of total GPD and regional employment. Even in the upper basin, where 99% of water use is for irrigation, agriculture accounts for less than 15% of jobs and 15% of GDP. However, agricultural impacts would have been far more severe if losses weren't partially offset by federal assistance and crop insurance (TWDB, 2022b).~~

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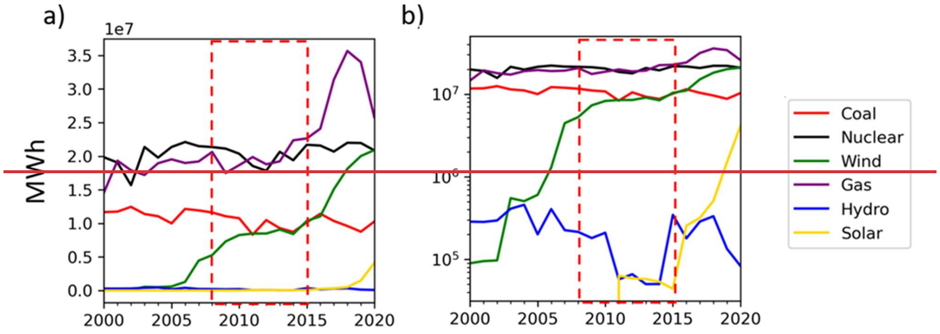
Aside from agriculture, a specific sector harmed by the drought was the real estate market for lakeside homes, whose values are strongly tied to the recreational and aesthetic value of lakes. An analysis by Morris (2019) of home values around the lower region reservoir Lake Travis showed that the drought had large adverse effects on property values. Accounting for both loss of value and lost appreciation, lakeside homes incurred over $2 billion in estimated losses between 2011 and 2015 (Morris, 2019), whereas the real estate market in Austin and the lower region exhibited strong growth throughout the drought (Morris, 2019) (Figure 7).

Our finding that the drought had little apparent overall effect on the basin-wide economy is in line with assessments of the 2001-2009 Millennium Drought in Australia (Van Djik et al., 2013) and the 2012-2016 drought in California, United States (Lund et al., 2018). Highly connected domestic and global trade networks in the 21st century have greatly reduced the economic and societal impacts of drought (Lund, 2016, Lund et al., 2018). Water supply infrastructure also buffers social impacts and economic disruption (Lund 2016). The combined factors of highly engineered regional water supply and domestic-global trade networks help explain why the drought did not hinder population and economic growth.

3.1.6 Energy Production

The power sector notably did not suffer any major adverse impacts during the drought (TWDB, 2022b), and there were no reports of significant outages even during record drought conditions in 2011 (Scanlon et al 2013a). The absence of substantial reliance on hydropower in the basin (on average less than 3% of annual production) resulted in no *significant* impact to~~on~~ power generation from curtailed reservoir releases due to reservoir drought ~~(Figure 8)~~. Additionally, many thermoelectric plants in the basin had already transitioned to low water demand cooling technologies ~~prior~~ before~~to~~ the drought and thus were "pre-adapted" for severe and prolonged drought conditions (Scanlon et al. 2013a). Natural gas facilities with high water efficiency technologies such as combustion turbine and combined cycle (with cooling tower) are prevalent in the middle and upper regions (Scanlon et al 2013b). There is only one high water demand coal plant in the lower basin, which is supported by a guaranteed firm water contract from lower basin reservoirs (LCRA, 2022). Many of the thermoelectric plants also have their own reservoirs, including the South Texas Nuclear Plant in the lower region, ~~which~~ that provide more reliable supply than solely relying on run-of-river diversions. These factors highlight the significance of institutional arrangements and engineered water infrastructure for reducing power sector vulnerability to drought.



~~**Figure 8**: Electricity generation by fuel type for power plants in the Colorado Basin, TX. Annual generation in linear (a) and log10 (b). Data from Energy Information Administration (EIA, 2022).~~

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~~Over the course of~~During the drought ~~,~~wind power production in the basin almost doubled (98% increase), mostly in the water-scarce middle and upper regions.~~, and~~ B~~b~~y 2015 wind production was similar in magnitude to coal power production in the basin (~10 million megawatt hours (MWh) (Figure 8). Solar power did not experience ~~have~~ large growth until after 2015, but between 2015 and 2020 production increased from 44,000 MWh to 4.1 million MWh~~ (Figure 8)~~. By 2020 the c~~C~~ombined wind and solar production ~~by 2020~~ (2.5 million MWh) was more than double coal power and on par with gas power production in the basin. An advantage of wind and solar power in a water-stressed region is electricity generation with zero water requirements. ~~This is an example of how decarbonization and energy transitions can reduce water reliance and water-supply vulnerability of the power sector (Byers et al., 2014, Zohrabian and Sanders, 2018).~~ ~~However, new vulnerabilities can emerge with increased reliance on renewables, such as periods of reduced wind speeds if a large fraction of regional supply is sourced from wind power (Wessel et al. 2021).~~

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3.2 Impacts on Water Planning and Management ~~4. Adaptive Responses to Extreme Drought: Insights from Water Planning and Management~~

The drought resulted in large increases in proposed investments to meet long-term water needs, with the largest increase in planned projects in the lower region (a $3.63 billion increase from 2011 to 2016 and an additional $623 million from 2016 to 2021) and moderate increases in the middle region ($281 million from 2011 to 2016 and an additional $410 million from 2016 to 2021). Notably, the drought did not cause any major changes in the upper region planning due to its low sectoral demand outside of agriculture and no economically viable alternative irrigation source other than continued use of groundwater. The following sections describe changes in planned sectoral water supply (3.2.1), the type, volume, and unit costs of proposed water supply sources (3.2.2), and specific planning and management innovations (3.2.3).

~~Drought often drives management responses and innovation (Lund, et al. 2018; Van Loon et al., 2016). To understand the substantive ways that the drought shaped water supply planning, we conducted a comprehensive review and analysis of data in~~

~~regional water management plans from 2011, 2016, and 2021 for each of the three regions in the basin (Region F, 2010, 2015, 2020; Region K, 2010, 2015, 2020; Region O, 2010, 2015, 2020). Our analysis was additionally supported by publicly available reports from utilities and municipalities in the basin.~~

~~Regional water plans are issued on a 5-year planning cycle and have been mandated by state law since 1997 in response to severe drought conditions in 1995 and 1996 (Wurbs, 2015). An advantage of the relatively short 5-year planning cycle is the ability to respond to recent changes in water availability and sectoral demand. However, Nielson-Gammon et al., 2020 point out that a current blind spot of the regional water planning methodology is the "rear-view" drought of record approach that uses the worst historical drought as the basis for determining future water needs. Using the "drought of record" framework, water supply needs are based on shortages that would occur under a repeated drought of record event. Future shortages are calculated based on the difference between projected future demands (based on estimated sectoral growth) and available supply under drought of record conditions.~~

~~The 2011 plans were developed during 2007-2010 before the most severe impacts had occurred and prolonged drought had set in, the 2016 plans were developed after the basin had experienced record drought in 2011 and unabating drought conditions from 2012 to mid-2015, and the 2021 plans were created with full understanding of the new drought record. The drought resulted in large increases in proposed investments to meet long-term water needs, with the largest increase in planned projects in the lower region ($3.63 billion increase from 2011 to 2016 and an additional $623 million from 2016-2021) and moderate increases to the middle basin ($281 million from 2011 to 2016 and an additional $410 million from 2016-2021) (regional costs converted to 2022 dollars). Notably, the drought did not cause any major changes in the upper region due to its low sectoral demand outside of agriculture and there is no economically viable alternative irrigation supply other than continued use of groundwater.~~

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34.2.1~~1~~ Impact of Drought of Record ~~Impact~~ on Future Sectoral Water Supply Planning

The first part of o~~O~~ur assessment~~review~~ tabulated recommended additional water supply for sectors in each region along with the estimated sectoral shortage in a repeated drought of record (Figure 8~~9~~). We found that m~~M~~ost of the anticipated future supply needs and recommended additional suppl ies~~y~~ we~~a~~re associated with the municipal and agricultural sectors (Figure 8~~9~~), the two largest sectors in the basin. The most prominent planning response was

a~~A~~ nearly 300% increase in planned municipal supply ~~volume~~ for the lower region ~~between~~ between 2011 and 2016 ~~was the largest planning response in the basin~~ (Figure 8~~9~~b). A consistent pattern across all regions wa~~i~~s that recommended new municipal suppl~~y~~ ~~ies~~ far exceeded projected future needs, which suggests ~~is intended to serve as~~ a sizable buffer or "~~"~~safety factor"~~'~~ should a future drought be more severe than the historical reference~~,~~ ~~considering the~~ used bye ~~of~~ the drought of record methodology. In contrast, recommended agricultural supplies typically do~~e~~ not exceed projected needs and are indicative of a lower priority towards preventing agricultural water shortages in the event of drought.~~, and~~ This gap is most notable in the upper region where planned supplies for agriculture were less than 20% of ~~in the case of the upper basin are a small fraction of future needs, and reflect anticipated reduced long-term supply from groundwater depletion (Region O, 2020) and the lower priority for accommodating agricultural shortages. Proposed additional supply for thermal electric power meets lower basin needs, but not middle and upper basin needs. However, the middle basin noted that the power plants included in the regional water plans are~~

~~being phased out in the near future and that projected 30-year demand is not accurate; the upper basin need in 2016 appears anomalous.~~

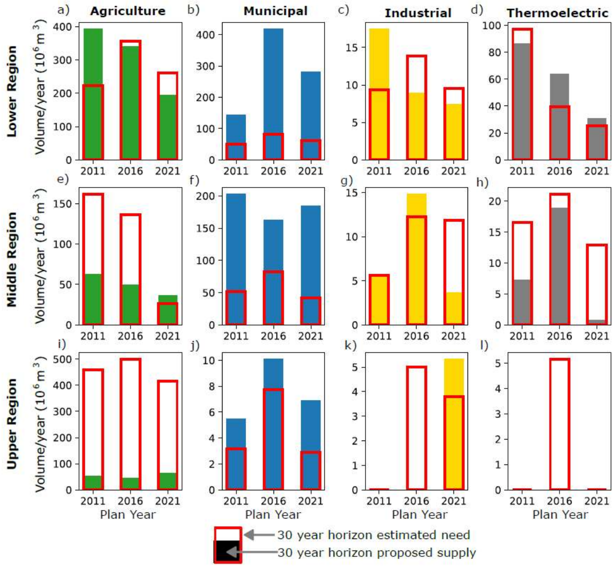

Figure 8~~9~~: Filled bars show 30-year additional recommended supply (~~acre-feet/year~~10^6 m^3 per year) for each sector within each region, while unfilled red bars are estimated annual sectoral needs under a repeat of the drought of record in the same 30-year horizon.

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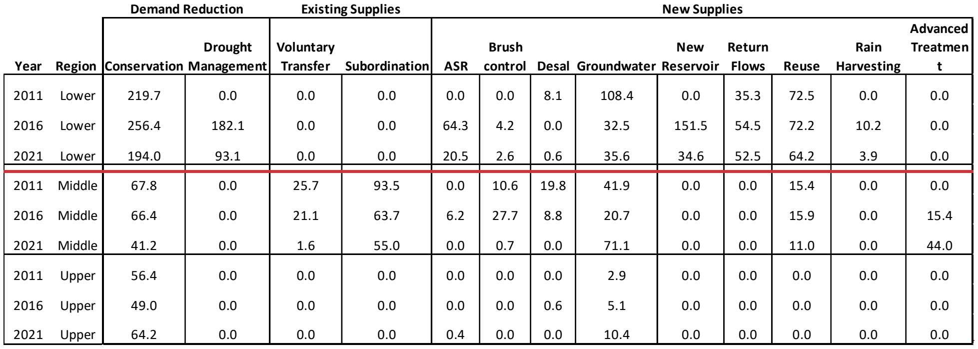
anticipated need, reflecting the anticipated reduction of long-term supply due to groundwater depletion with no feasible alternative supply (Region O, 2020). Proposed additional supply for thermoelectric power met anticipated needs in the lower region, but not the middle and upper regions. However, the middle basin plans note that some middle region power plants included in the regional water plans are being phased out in the near-future and that the projected 30-year demands are not accurate; the upper basin need in 2016 appears anomalous.

3~~4~~.2.2 Water Supply and Management Strategies to Meet Future Supply Needs

The next part of o~~O~~ur analysis~~ also~~ compiled a database of the specific sources of additional supply proposed to meet the recommended supply targets for each planning region in each of the five-year regional water plans from 2011 to 2021 (Table 3). We identified 13 water supply strategies proposed to meet future water needs in the basin (Table 3). T~~T~~he strategies can be classified into one of the following three groups: (1) demand reduction, (2) creation of new supplies, and (3) alternative~~e~~ use of existing supplies. The three regions have notable differences in what combination of the 13 strategies are used ~~they propose using~~ to meet projected needs under a repeated drought of record~~, which reflect different sectoral needs, available supply sources, and strategy cost~~.

		Demand Reduction		Existing Supplies		New Supplies										
Year	Region	Conservation	Drought Management	Voluntary Transfer	Subordination	ASR	Brush control	Desal	GW	New Reservoir	Return Flows	Reuse	Rain Harvesting	Advanced Treatment
2011	Lower	219.7	0.0	0.0	0.0	0.0	0.0	8.1	108.4	0.0	35.3	72.5	0.0	0.0
2016	Lower	256.4	182.1	0.0	0.0	64.3	4.2	0.0	32.5	151.5	54.5	72.2	10.2	0.0
2021	Lower	194.0	93.1	0.0	0.0	20.5	2.6	0.6	35.6	34.6	52.5	64.2	3.9	0.0
2011	Middle	67.8	0.0	25.7	93.5	0.0	10.6	19.8	41.9	0.0	0.0	15.4	0.0	0.0
2016	Middle	66.4	0.0	21.1	63.7	6.2	27.7	8.8	20.7	0.0	0.0	15.9	0.0	15.4
2021	Middle	41.2	0.0	1.6	55.0	0.0	0.7	0.0	71.1	0.0	0.0	11.0	0.0	44.0
2011	Upper	56.4	0.0	0.0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0
2016	Upper	49.0	0.0	0.0	0.0	0.0	0.0	0.6	5.1	0.0	0.0	0.0	0.0	0.0
2021	Upper	64.2	0.0	0.0	0.0	0.4	0.0	0.0	10.4	0.0	0.0	0.0	0.0	0.0



		Demand Reduction		Existing Supplies		New Supplies								
Year	Region	Conservation	Drought Management	Voluntary Transfer	Subordination	ASR	Brush control	Desal	Groundwater	New Reservoir	Return Flows	Reuse	Rain Harvesting	Advanced Treatment
2011	Lower	219.7	0.0	0.0	0.0	0.0	0.0	8.1	108.4	0.0	35.3	72.5	0.0	0.0
2016	Lower	256.4	182.1	0.0	0.0	64.3	4.2	0.0	32.5	151.5	54.5	72.2	10.2	0.0
2021	Lower	194.0	93.1	0.0	0.0	20.5	2.6	0.6	35.6	34.6	52.5	64.2	3.9	0.0
2011	Middle	67.8	0.0	25.7	93.5	0.0	10.6	19.8	41.9	0.0	0.0	15.4	0.0	0.0
2016	Middle	66.4	0.0	21.1	63.7	6.2	27.7	8.8	20.7	0.0	0.0	15.9	0.0	15.4
2021	Middle	41.2	0.0	1.6	55.0	0.0	0.7	0.0	71.1	0.0	0.0	11.0	0.0	44.0
2011	Upper	56.4	0.0	0.0	0.0	0.0	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0
2016	Upper	49.0	0.0	0.0	0.0	0.0	0.0	0.6	5.1	0.0	0.0	0.0	0.0	0.0
2021	Upper	64.2	0.0	0.0	0.0	0.4	0.0	0.0	10.4	0.0	0.0	0.0	0.0	0.0

Table 3: Planned sources of additional supply (10^6 m^3/year) for planning regions in the Colorado Basin. ASR – a~~A~~quifer s~~S~~torage and r~~R~~ecovery; GW – groundwater.

34.2.2.1 Planned New Water ~~Sources of~~ Supply Sources Following the Drought of Record

~~The drought prompted planning regions to consider new sources of water supply.~~ The 2016 regional water plans had six ~~new~~ supply strategies that were not present in 2011 plans: aquifer storage and recovery (ASR), rain harvesting, advanced water

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Formatted: Not Superscript/ Subscript treatment, construction of new reservoirs, and brush control. Another notable change compared to 2011 was a large increase in the u~~U~~se of municipal return flows. While this strategy was not ~~was not a~~entirely new ~~strategy~~ in the 2016 plans, ~~but~~ the over 50% increase in return flow volumes was notable ~~increased by over 50% in the 2016 plan~~ so this strategy is included in this section~~ as well~~.

The new~~se~~ strategies had~~ve~~ a wide range of unit cost~~ (Figure 10~~, with return flows being the least expensive while advanced treatment, rain harvesting, and ASR generally being the most expensive (Figure 9). ASR is primarily a strategy in the lower region, and likely due to its high estimated unit cost~~t (Figure 10)~~ was scaled back in the subsequent 2021 plan (Table 3). Advanced treatment is unique to the middle region and refers to upgrading existing water treatment facilities and building new facilities that can treat surface and groundwater ~~supplies~~ to meet drinking water standards. Expanded advanced treatment ~~capacity~~ would enable the middle region to use groundwater sources that currently exceed standards and treat reservoir water that can exceed standards during periods of drought (Region F, 2015). The use of return flows in the lower region~~basin~~ is primarily for Colorado River diversions downstream of Austin, but one project proposes to import municipal return flows from outside of the basin. ~~The drought accelerated the construction of an off-channel reservoir in the lower basin (Figure 2) that had previously been an alternative recommended strategy in 2011 with a proposed implementation in 2030. The 111 million m^3 reservoir is designed to make diversions from the Colorado River during high flow events to capture water that would otherwise flow to the Gulf of Mexico. Planned to be fully operational by 2024, it is the first new major reservoir in the basin in decades and is the most significant infrastructure project to increase supply of the lower basin. Brush control refers to the selective removal of high-water demand plants (juniper, salt cedar, and mesquite) aimed at increasing groundwater recharge and reducing riparian and shallow groundwater ET. Brush control was scaled back as a strategy in the 2021 plans and is not currently proposed as major source of supply.~~

The drought accelerated the construction of an off-channel reservoir that was proposed for 2030 in the 2011 plan. The 111 million m^3 reservoir is designed to be filled using diversions from the Colorado River during high flow events to capture water that would otherwise flow to the Gulf of Mexico. Brush control refers to the selective removal of high-water-demand plants (juniper, salt cedar, and mesquite) to increase groundwater recharge and reduce riparian and shallow groundwater evapotranspiration (ET). Brush control was scaled back as a strategy in the 2021 plans and is not currently proposed as major source of supply.

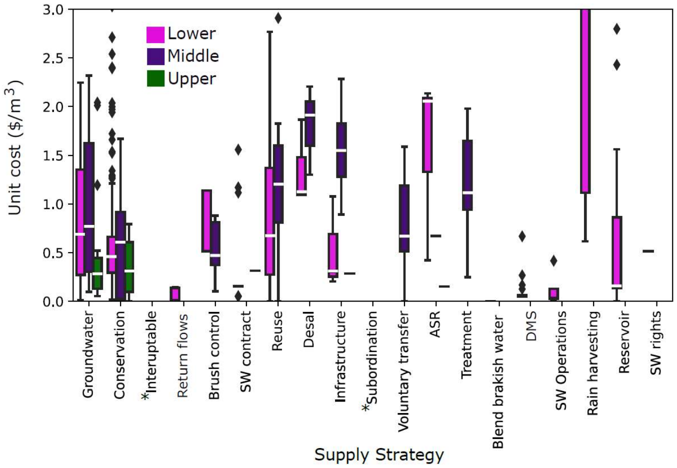

Figure 9~~10~~: Unit cost per cubic meter for water supply strategies compiled from the 2011, 2016, and 2021 regional water plans. Costs converted to 2022 dollars. ASR = a~~A~~quifer s~~S~~torage and r~~R~~ecovery, DMS = t~~T~~emporary d~~D~~rought m~~M~~anagement s~~S~~trategies. No unit cost reported for interruptible supply or subordination. Boxes show the interquartile range, and the median is shown by white lines.

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3~~4~~.2.2.2 Supply S~~s~~trategies that Remained the Same or Decreased Following the Drought of Record

Planned supply from ~~-~~groundwater pumping and reuse remained the same or decreased after the drought. New groundwater supply was increased in the middle and upper regions following the drought, but there was a large decrease for the lower region, which was offset by a commensurate increase in groundwater supply from ASR, suggesting effort towards more sustainable groundwater use ~~Additionally, groundwater supply was increased in the middle and u~~(Table 3). ~~However, while total basin groundwater supply was reduced there was an increase in ASR, suggesting efforts towards more sustainable groundwater use. Reuse and groundwater have a wide range of estimated costs (Figure 10). Additionally, groundwater supply was increased in the middle and upper regions following the drought, but there was a large decrease for the lower region (Table 3)~~

We found that r~~R~~euse and groundwater have a wide range of estimated costs (Figure 9). Reuse costs vary depending on whether the reuse is indirect or direct and the intended end use, with potable reuse being more costly than non-potable reuse, in agreement with Cooley et al. 2019. N~~Currently active n~~on-potable reuse ~~in the basin provides~~currently suppl~~y to~~iesy municipal irrigation (parks, golf courses), oil and gas operations in the middle basin, and water for thermoelectric plants (middle and lower regions). The first direct reuse facility in Texas became operational in the middle region city of Big Spring ~~during~~ in 2013. The Big Spring direct reuse facility blends reclaimed water with raw reservoir water that is then treated in water treatment plant, providing 2.32 million m^3/year of supply (Region F, 2015).

Estimates of new groundwater supply costs vary from 0.3 to 0.7 $/m^3 for the lower quartile to over 1 $/m^3 for the upper quartile (Figure 9~~10~~). Major cost factors are proximity to the groundwater source and end use. The top quartile costs are associated with municipal supply projects developed far from the groundwater source that require extensive conveyance infrastructure, whereas the lower costs are associated with local supplies associated with existing wellfields or non-municipal use. An example of a high-cost, municipal supply groundwater project is the T-Bar Groundwater Well Field for City of Midland (middle region) that became operational during the drought. The project added 13.8 million m^3/year of supply at cost of \$209 million. ~~Infrastructure~~ The project ~~included~~ required the installation of 43 wells and a 95 km, 1.2 m diameter pipeline to convey groundwater from the T-Bar Ranch, located outside the basin, to the city of Midland. Estimated unit costs for the project were 1.15 \$/m^3 (2008 dollars) per acre-foot during amortization (first 20 years) and 0.28 \$/m^3 after (2008 dollars) (Region F, 2015).

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~~Tw~~The~~o~~ ~~strategies unique to the middle region are the~~ use of existing supplies through voluntary transfers and subordination are unique to the middle region. ~~The recent drought of record reduced supply from these strategies by 50% (Table 3).~~ Voluntary transfers are the temporary sale of ~~surplus~~ surface or groundwater supply between users within the middle region. Following the drought, available supply from voluntary transfers was reduced by over 90%. Subordination refers to junior water right holders in the middle region purchasing water from more senior downstream rights in the lower region. Under a strict priority system, junior middle basin water rights would not be allowed to make diversions during a drought of record due to legal priority of senior downstream users. However, the middle and lower regions have historically cooperated to ensure adequate essential supply for junior (low priority) middle basin users in critical sectors (~~e~~e.g.~~x.~~,~~.~~ municipal and power) and anticipate continuing to do so in the future (Region F, 2020). However, estimated supply provided by subordination was reduced by 40% following the drought due to reduced estimates of the firm (reliable) supply for the lower region.

3~~4~~.2.2.3 Conservation Strategies

~~Demand reduction through~~ C~~c~~onservation is~~is~~ a key strategy in all the regional plans ~~to meet future demand in all regions~~ and was already a major strategy before the drought (Table 3). Conservation ~~strategies were~~was proposed across all sectors, with the largest ~~conservation savings~~amounts for municipal and agricultural sectors. Our cost analysis found that conservation is often more costly than many existing supplies but is typically less expensive than developing new resources (Figure 9~~10~~).

Municipal conservation approaches include replacing water fixture efficiency, incentivizing low water landscaping, implementing permanent watering schedules ~~(ex. Austin has year-round outdoor schedule, or limiting outdoor use during hot months May 1 to Sept 30th)~~, improved metering, pipeline leak detection and repair, public outreach and education, customer engagement software (custom water use reports and water saving suggestions), and landscape standards for new development (Austin Water, 2018; Region K, 2020).

The city of Austin ~~has already~~has already implemented aggressive conservation measures, which have produced large, sustained reductions in per capita use (Figure 10~~1~~). In 2010, Austin's water utility published a plan to reduce per capita use to 529 L/day by 2020 (Austin Water, 2010). The drought served as an accelerator of this objective (Figure 10). Per capita use fell to below 529 L/day in 2013, seven years ahead of schedule, and the 76-113 L/day per capita reduction achieved during the drought has been sustained in the five years following the drought (2016-2020). Steep and lasting reductions in per capita use were achieved through an array of measures such as education, rebates for installation of drought tolerant landscapes, new ordinances for irrigation systems in new developments, rate increases, and rebates for water efficient fixtures (Austin Water, 2018).

Agricultural irrigation conservation measures include lining ~~of~~ canals, converting~~sion~~ ~~of~~ canals to pipelines, laser-levelling flood irrigation fields (primarily rice in the lower region), increased efficiency (conversion of flood to sprinkler and sprinkler to drip), and real-time metering and monitoring (supports more accurate billing and data to support conservation improvements) (Region F, 2020; Region K, 2020; Region O, 2020). ~~Colaizzi et al., 2009 specifically looked at irrigation conservation measures in the Southern High Plains/Ogallala (upper region) and found the most effective to be expanding use of weather-based irrigation scheduling, converting flood irrigation to center pivot, and replacing high water demand crops like corn with lower demand crops like cotton.~~

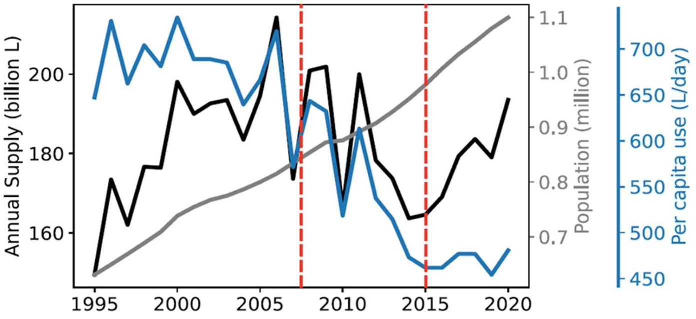

Figure 10~~1~~: Austin Water annual water use (black), population (grey), and per capita water use (blue) from 1995 to 2020. Drought period shown by dashed red lines. Data Austin Water, 2022.

~~-~~Temporary demand management measures were~~is~~ not unique to the lower region but it is the only region where ~~is only~~ temporary demand management is treated ~~explicitly accounted for~~ as a source of supply to offset shortage during a repeated drought of record~~ in the lower region~~. Most temporary demand management efforts are aimed at reducing municipal outdoor use, which ~~is a substantial fraction of total water demand, especially during summer months, and~~ can be highly responsive to temporary reduction measures (Hogue and Pincetl, 2015). For example, o~~O~~utdoor water restrictions in the United States during drought have been shown to reduce residential water demand by ~20-50% (Gober and Quay, 2015; Mayer et al., 2015). ~~Temporary demand management measures include limitations on frequency, timing, and method of outdoor water use.~~ Temporary demand management ~~These~~ measures in the basin (limitations on frequency, timing, and method of outdoor water use) are ~~only~~ implemented under pre-defined drought trigger thresholds such as reservoir storage thresholds (e.g.,~~x.,~~ lower region storage below 60%) and peak daily municipal demand thresholds (e.g.,~~x .,~~ 120% of average daily demand) (Austin Water, 2016). ~~Outdoor water restrictions in the U.S. during drought have been shown to reduce residential water demand by ~20-50% (Gober and Quay, 2015; Mayer et al., 2015).~~

3.24.3 Other Water Management Responses and Planning Innovations

~~Notable changes to water management and planning include updating policies to conserve water more aggressively during future droughts, new laws to improve regional water planning, and modelling advancements to improve water management and planning.~~

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Following the drought, the lower region, which is highly reliant on reservoir storage, ~~has~~ implemented more stringent supply reduction triggers to ~~conserve storage~~conserve storage more aggressively during drought. Before the drought, available interruptible (non-guaranteed) supply was gradually reduced between reservoir storage thresholds of 70% to 15% capacity, and there were no restrictions to firm customers (Region K, 2010). Following the drought, operating rules were revised so that interruptible supplies can now be fully curtailed below 45% capacity (Region K, 2020). Another major change is that lower region municipal firm customers now have drought trigger thresholds at 70% and 45% storage capacity that require corresponding use reductions of 5% and 10-20% (Region K, 2020). Under a scenario worse than the drought of record, firm customers will be subject to a minimum 20% reduction and are encouraged to use alternate supplies (e.g.,~~x.~~ groundwater) (Region K, 2020).

There were ~~also~~ notable modelling capability improvements during and following the drought. The Lower Colorado River Authority (LCRA) who manages lower region surface water supplies added new capabilities of their medium range forecast model used to inform reservoir operations. New features include revised reservoir operating rules, modification of environmental flow requirements, and ~~the~~ incorporation of El-Niño Southern Oscillation forecasts (Anderson and Walker, 2017). A Distributed Hydrology Soil-Vegetation Model (DHSVM, Wigmosta et al., 1994) model is under development for the basin that can produce high-resolution naturalized flow inputs to either the official state Water Rights Analysis Package ~~(WRAP)~~ model (Wurbs, 2020) or the LCRA Riverware (Zagona et al., 2001) operational model for water management modelling studies. The DHSVM model will enable historically based drought of record analysis and ~~also~~ future climate scenarios driven by downscaled global climate model inputs. ~~A modelling advancement implemented in the middle region was to represent sectoral water demand reductions during drought of record conditions (Region F, 2015). This modification to the WRAP model was aimed at improving estimated water supply needs by better representing reductions in water demand during drought conditions.~~

The record drought also prompted Austin~~, the population hub of the basin,~~ to more rigorously evaluate the long-term security of its water supply. In 2014, the Austin Water Resource Planning task force~~, created in 2007,~~ recommended that the city perform its own independent assessment of water supply for the next 100 years (Austin Water~~Forward~~, 2018). The task force recommended assessments occur on 5-year planning cycles, similar to the regional and state water planning cycles. The first long-term study for Austin was published in 2018 (Austin Water~~Forward~~, 2018). A notable feature of the study is the incorporation of future climate uncertainty into the assessment of Austin's long-term water supply, instead of the drought of record approach used in the state regional water planning.

Several state laws were passed, both during and following the drought, ~~targeted at~~to improv~~eing~~ water planning and drought response. In response to numerous threats to municipal supplies during~~in~~ 2011, the ~~the~~ 2012 state legislature passed TAC 357.42(d) requiring each regional planning group to collect information on existing emergency water connections. The law mandates each region to ~~to~~ create and maintain a database of emergency supply connections and the available supply volume of each connection. Before 2016, recommended water management strategies from previous regional plans were not tracked to determine their implementation status. ~~Starting~~ Since ~~in~~ 2016, the TWDB requires each region to conduct a region-wide survey to track the implementation status of all water management strategies recommended in the previous plan. More recently, HB 807 (passed in 2019)~~,~~ is designed to increase regional cooperation in water planning and promote ~~s water supply from~~ ASR by requiring all regional water plans to assess ASR as a strategy (Kramer et al., 2019). While there are currently only six active ASR sites in the state, ~~ASR is considered a promising long-term strategy for conserving groundwater resources. Notably,~~ two ~~of~~

~~the six active ASR sites in Texas~~ are in the lower region of the Colorado Basin and multiple new ASR projects were proposed in the 2016 and 2021 plans for the lower and middle regions (Table 3). HB 807 also requires the TWDB to create an Interregional Planning Council to improve coordination and share best practices between ~~each~~ planning regions (Kramer et al., 2019).

3.3 Influence Diagram of Multisector Dynamics During the Drought of Record

We developed an influence diagram to summarize the insights from our analysis presented in Sections 3.1 and 3.2 (Figure 11). ~~As shown in Figure 2, we developed an influence diagram showing T~~The diagram shows the causal nature of cascading impacts that stem from the initial trigger of severe meteorological drought and highlights the highly multisectoral, interconnected nature of the drought impacts~~; most nodes are influenced by multiple upstream states and contribute to multiple downstream outcomes. The influence diagram also provides an efficient framework to trace downstream outcomes (what resulted from state X?) or upstream causes (what sequence of states led to outcome Y?). The diagram presented here is not intended to be exhaustive but aims to capture key impacts covered in this review. Indeed, many of the individual nodes or drought-categories within the diagram could be the subject of in-depth studies on their own.~~The diagram is not intended to be exhaustive of all potential causal drought impacts and instead aims to capture the notable, basin-specific impacts and responses covered in this study. As a static illustration, the influence diagram does not provide information on the temporal nature (timing, frequency, duration) or severity of impacts. For example, some impacts occurred months into the drought (agriculture in early 2008) while others took years to develop (estuary impacts did not occur until 2011). Some were brief but intense (wildfire), and others were prolonged (reservoir drought from 2011 to 2015). The temporal dynamics and impact severity are described in the preceding Sections 3.1 and 3.2.

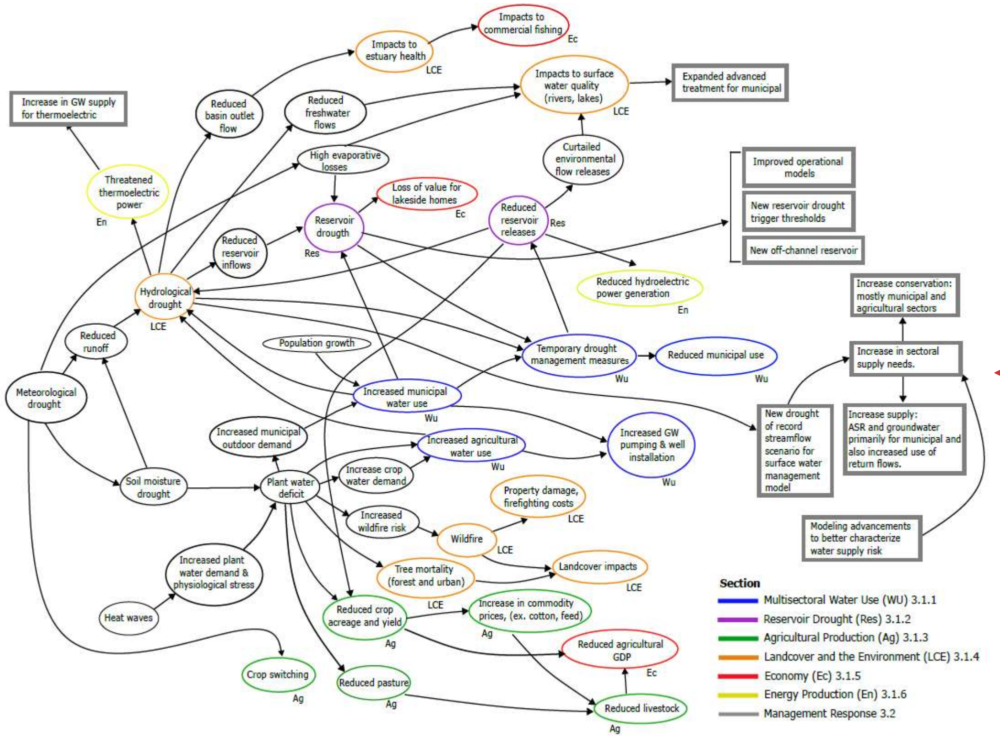

Figure 11: Influence diagram describing multisector impacts and interactions during the drought. Arrows depict influence of upstream state variables on a downstream state variable and can be interpreted as connecting causes and effects. Colors indicate multisector impacts identified in each of the corresponding sections. Squares represent management responses following the drought. Abbreviations for sections provided (e.g., Ec = Economy) next to corresponding states.

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The utility of the influence diagram is that it explicitly captures the interactions and multisectoral connections that may not be easily inferred from the text. For example, from the text alone it may not be apparent that reservoir drought was a nexus of sectoral interactions and what the specific upstream causes and downstream impacts were. The nodes are ~~colored~~coloured based on the sector that was affected — sectors can be the part of the human system or the natural environment. Not all nodes represent sectoral impacts and therefore are not ~~colored~~coloured. For example, wildfire impacts to landcover and the environment were the result of propagating (1) meteorological drought to (2) a soil moisture deficit that (3) produced a plant water deficit that (4) led to increased wildfire risk. The upstream nodes are important to the causal outcome of wildfire impacts but are not themselves sectoral impacts. Also summarized are the notable management responses that resulted from the drought. Some of the major drought impacts that motivated management changes were the severe reservoir drought and the impacts to streamflow, and these responses have clear downstream adaptive responses. An important response without a clear upstream driver was modelling advancements that helped better characterize future drought impacts; these were motivated by the collective and widespread impacts to water availability for human and environmental needs.

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~~Reservoir drought is a key aspect of the drought and a nexus of multisector interactions (Figure 2).As shown in Figure 2, water use data for the basin indicated that meteorological drought impacts propagated to alter sectoral demand (e.g., agriculture, municipal), sectoral water availability (e.g., surface water), and surface water and groundwater use.~~

4~~5~~. Discussion

~~5.1 Long-Term Water Supply Challenges Facing the Basin~~ 4.1 Insight into Multisector Dynamics During the Severe Drought

Drought impacts in coupled human-natural systems are often the result of cascading natural and human factors (Aghakouchak et al., 2021; Figure 11). Some dynamics during severe drought can be expected to occur ~~to some degree~~ in any region such as impacts to landcover due to the propagation of meteorological drought to soil moisture drought, reductions in groundwater recharge, or reductions in streamflow ~~due to reduced precipitation and runoff~~. However, as revealed in this study, the specific multisectoral impacts that result from drought are shaped by region-specific attributes of the human and natural system. Examples of impacts specific to the study basin are the water quality issues in the middle region resulting from groundwater solutes, curtailments of surface water irrigation supply in the lower region, or impacts to estuary health at the basin outlet.

Whether drought hazards create significant harm to the human system depends on sectoral exposure and the available mechanisms (engineered or institutional) to mitigate the exposure to the given drought hazard. For example, in a region with agriculture, soil moisture drought has the potential to affect agricultural production, but access to surface water or groundwater can partially or entirely offset impacts. Our analysis showed that extensive irrigation helped partially offset the agricultural impacts in the Colorado Basin, TX. However, as shown in Figure 11, management decisions for one sector can reduce or increase impacts to other sectors or even the same sector in another location. An example of cross-sector impacts in the Colorado Basin was agricultural demand in the lower region hastening reservoir drought, which produced cascading impacts to municipal supply availability (triggering conservation measures) and reduced water availability for environmental flows.

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A characteristic of drought impact propagation not captured in the influence diagram (Figure 11), but highly relevant to the manifestation of sectoral impacts, is that some impacts do not occur until certain state thresholds are crossed. This means~~,~~ that ~~is~~ there can be non-linear or stepwise responses to upstream states. An example of this is that the reservoir release curtailments did not occur until specific trigger thresholds are crossed~~,~~ or impacts to specific stream segments or the estuary ~~at the basin outlet~~ ~~aren't~~do not become adverse until some minimum flow condition is crossed. Other impacts occur across a gradient of upstream state conditions, such as increasing severe and prolonged meteorological drought resulting in progressively more severe soil moisture deficits or progressively more irrigation required to meet plant water demand for agriculture or municipal irrigation.

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Examples of commonly studied sectoral interactions during drought are energy-health, water-energy, energy-water, and water-food (Bluahut, 2020; de Brito, 2021; Hagenlocher et al. 2023, Yates et al., 2024). Our analysis revealed significant water-food impacts because of the harm to agricultural production (Figure 5 and 11). Due to the direct dependence of vegetation health on soil moisture, agriculture is typically one of the earliest and most affected sectors from meteorological drought (Van Loon et al., 2015). While water-food interactions affected agricultural production, domestic and global trade mitigated food-health impacts within the basin. Sectoral exposure and adaptive measures limited the impact of water-energy, energy-water, and energy-health impacts. For example, the pre-adaptation of thermoelectric power plants to lower water requirement technology reduced energy-water impacts as the power sector had a low water footprint (Figure 3). The absence of significant negative water-energy interactions can be explained by the already mentioned low-water-use technology for thermoelectric power combined with hydropower being a minor source of energy in the basin. The rapid growth of renewable wind and soler energy during the drought also reduced negative water-energy and energy-water interactions. This is an example of how decarbonization and energy transitions can reduce water reliance and water-supply vulnerability of the power sector (Byers et al., 2014; Zohrabian and Sanders, 2018). However, increased reliance on renewables can produce new vulnerabilities, such as periods of reduced wind speeds if a large fraction of regional supply is sourced from wind power (Wessel et al. 2021). Also of note, there were no major human health impacts reported during drought and heat waves – undoubtedly, a contributing factor was the absence of any significant water-energy impacts, which enabled the use of AC during dangerous heat conditions. Finally, ~~This is an example of how decarbonization and energy transitions can reduce water reliance and water-supply vulnerability of the power sector (Byers et al., 2014, Zohrabian and Sanders, 2018). However, new vulnerabilities can emerge with increased reliance on renewables, such as periods of reduced wind speeds if a large fraction of regional supply is sourced from wind power (Wessel et al. 2021).~~our analysis did not identify widespread economic impact from the drought. Recent examples from California (Lund et al., 2018) and Australia (Van Djik et al., 2013), along with this study, demonstrate how modern economies are largely decoupled from the agricultural sector. Tubi (2020) terms this a shift from "climate sensitive" to "climate insensitive" economies.

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~~Reservoir drought is a key aspect of the drought and a nexus of multisector interactions (Figure 2). Of the many factors that produced reservoir drought (Figure 2), the two most significant were 1) persistent record low inflows and 2) large releases to agriculture in 2008-2009 and 2011. The decision to release large amounts of water to irrigators that accelerated the development of reservoir drought was based on decades of experience where storage typically recovered within a year or two of large storage declines. A permanent outcome of the drought was the adoption of more conservative reservoir management policies (Figure 2), discussed in Section 4.3.~~

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~~The combination of growing population, the possibility of more severe and prolonged droughts, and an anticipated shift towards hotter, more arid conditions pose significant long-term water management challenges (Banner et al., 2010). In addition to physical limitations on new supplies (ex. aquifer storage and capacity, stream flows, reservoir storage), laws and regulations governing surface water and groundwater use also limit options for expanding water supply. Thus, the basin faces the challenge of finding additional reliable supplies when much of the easily accessible and low-cost surface and groundwater has already been appropriated and developed (Tidwell et al., 2014).~~

~~More arid conditions are anticipated to induce changes in soil moisture (Nielson-Gammon et al., 2020), potentially altering runoff characteristics with important implications for water resources (Saft et al., 2015). A recent study found reductions in annual streamflow in the basin over the 2030-2100 period in almost half of global climate model scenarios considered (Austin Forward, 2018). A 20-30% reduction in water yield for the basin in the 21st century (runoff + groundwater recharge) was estimated in a CONUS-wide study by Brown et al., 2019. Observational data (1900-2017) already indicates significant downward trends in both streamflow and precipitation-streamflow ratios in the basin, with the strongest decline in the central region of the basin (Harwell et al., 2020). Persistent record low surface inflows were a major contributor to the severe reservoir drought conditions from 2012-2015. Analysing the 2001-2009 Millennium Drought in Australia, Van Djik et al 2013 found that a median precipitation decline of 11% below average resulted in a 46% reduction in median streamflow during the drought. This~~

~~highlights the non-linear relationship between precipitation and runoff and the potential threat to surface water availability from even small reductions in annual precipitation.~~

~~A major challenge facing the middle and lower regions is that surface storage capacity is already maximized (i.e., there are no viable locations for additional major reservoirs), but population and associated surface-water reliant municipal demand are expected to continue to grow (Region F, 2020, Region K, 2020). A sobering statistic is that *lowest* per capita storage during the 1950's drought (previous drought of record) is approximately *equal* to the current maximum per capita storage with every reservoir in the basin at full capacity (SI Figure 7). The buffer provided by reservoirs will be further diminished as the basin's population continues to grow.~~

~~Under current groundwater use conditions, only the upper basin is contending with highly unsustainable depletion (Scanlon et al., 2012, Region O, 2020). In the coming decades, agriculture in the upper region will have to adapt to reduced availability from the Southern High Plains aquifer. While current middle and lower region agricultural groundwater use is also sizeable, groundwater availability models don't project that aquifers are being rapidly depleted like they are in the upper region (Region F, 2020, Region K, 2020).~~

4.2 Limitations and Future Work

Limitations for our study are related to historical data availability and the depth of analysis of each sectoral impact. Much of the historical data was not available before the year 2000, preventing comparisons to impacts during previous droughts and the 1950s drought of record. Diminishing quality and availability of historical data is likely an issue in many regions, which limits the number of severe drought events that can be evaluated as multisectoral case studies. Another data limitation is the temporal and spatial resolution of publicly available data. Most of the data was only available at annual temporal and county-level spatial resolution (Table 2). This prevented analysis of sub-annual drought impact dynamics and the coarse spatial resolution prevented understanding the spatial heterogeneity of impacts, for example at the community or user level. Such limitations are discussed by Sevelli et al. (2022), who point out that many impact indicators represent average values and thus limit the understanding of impact heterogeneity.

A challenge for this type of broad analysis that spans both impacts and management responses is distilling the most salient findings into a manuscript-length text. This necessitated a high-level presentation of impacts and responses. Indeed, many of the individual sectors or impacts are often the subject of their own in-depth studies. The utility of this type of analysis is capturing the key multisector dynamics and their interactions within the study region, which can motivate focused follow-on studies looking more closely at specific sectoral interactions. Future work can involve applying a similar approach for other drought events in other regions. Building out a corpus of multisectoral drought impact analyses would improve understanding of how regional characteristics (sectors, hydrology, management, infrastructure) produce certain drought impact typologies and sectoral interactions, which would aid the development of proactive adaptation measures targeted at reducing drought vulnerability across all sectors.

~~5.2 Building a More Resilient and Sustainable Water Supply~~

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~~Multiple recent studies have examined the ‘reservoir effect’ where regions with access to large reservoir storage can be prone to increased vulnerability to severe drought due to lack of supply diversification and lower incentivization for adaptive measures (Di Baldassarre et al 2018, Garcia at al., 2019). The recent drought exposed vulnerability of the lower region’s reliance on surface water and reservoirs. Lund et al. 2018 explains that well prepared water systems typically avoid major negative impacts, and that water management often improves after exposure to water scarcity. The planned diversification of water supply sources following the drought shown by our analysis (Table 3) indicate efforts to reduce reliance on reservoirs. Because of its chronically depleted reservoirs, the middle region was already adopting expanded groundwater, including out of basin groundwater imports, and unconventional supplies (direct and indirect reuse) earlier than the lower region.~~

~~Dependence on reservoir storage, and more generally surface water, can be reduced by increasing groundwater capacity and developing non-conventional water supply sources such as wastewater reuse, desalination (seawater and brackish GW), and ASR. Expanded groundwater capacity can offer a reliable supply for users confronted with more unpredictable surface water resources (Taylor et al., 2013). However, the location, scale, and frequency of groundwater use needs to be carefully evaluated, ideally to ensure that it is sustainable and that it will not adversely impact surface water baseflows (de Graaf et al., 2019). Reuse has the benefit of creating additional supply close to the source of demand, low transmission costs, and low environmental impacts (Grant et al., 2012). However, increased reuse reduces water treatment plant return flows to downstream users. This could be offset by more water being available to downstream users due to reduced upstream diversions, but the trade-off would need to be studied to assess the net impact. Potable reuse may have less environmental impacts and if often a cheaper unit cost compared to desalination (Hadjikakou et al., 2019). However, direct reuse faces larger public perception challenges than indirect reuse or non-potable reuse (Lahnstener et al., 2018). ASR enables storage of surface water during periods of plentiful supply for later use and has the added benefit that stored water is not lost to evaporation. However, ASR is still a developing technology and has high abandonment rates due to a variety of issues such as well clogging, water quality, and insufficient recovery (ratio of injected to recovered supply) (Bloetscher et al., 2014). Managed aquifer recharge (MAR) has been employed since the 1960s and has seen significant growth in the last 30 years (Dillon et al., 2019) is a lower risk alternative to ASR to improve groundwater sustainability.~~

~~Equally important to expanding supply is reducing demand. Demand management encompasses a wide range of actions intended to reduce water use such as increasing efficiency, adopting or changing laws governing water use, and pricing strategies (rate-based), and is considered an essential component of water security (Cosgrove and Loucks, 2015). Conservation is often much cheaper than development of new alternative supplies (Cooley et al., 2019), and was found to be a major component of agricultural and municipal supplies in the basin (Table 3). Demand management for agriculture includes government incentives for more efficient technologies (Fan et al., 2022, Region O, 2020), pumping fees per unit production, and total pumping limits (Hrozencik et al., 2017, Kumar et al., 2011, Rad et al., 2020). For municipal conservation, some research indicates that non-price approaches, such as restrictions, can be more effective than pricing (Kenney et al., 2008), and the Dascher et al. 2014 analysis of consumer behavior in Texas during the 2008-2015 drought suggests that restrictions combined with outreach as most effective. Factors contributing to positive attitudes towards conservation include environmental awareness, education, and having experienced drought (Burton et al., 2007, Dickinson, 2001, Dascher et al., 2014). However, positive attitudes do not always produce behavioural changes (Gregory and Leo, 2003; Miller and Buys, 2008). Few people in the basin (citizens, water managers, politicians) experienced the devastating drought of the 1950s, so the recent 2008-2015 drought was potentially a~~

~~formative experience for the current generation of residents and demonstrated the value of conservation efforts for improving water security.~~

~~Our water supply cost analysis (Figure 10) showed that additional new supply tends to be more costly than existing conventional sources, particularly low-cost surface water. Historical development across the Western U.S. has relied on low-cost sources of unappropriated water or transfers of appropriated water (Tidwell et al., 2014). The increased cost of new supplies or conservation can be accommodated by and is justifiable for municipal and industrial uses, but costs of unconventional sources may be prohibitive for agriculture, where profit margins are slim (Hoppe, 2014). A common adaptive response to potential shortages in high-value sectors (municipal, industrial, energy) is to obtain supply from low value uses, typically from agriculture (Flörke et al., 2018). This practice raises questions about the magnitude of these transfers on food security and regional agricultural production (Brown et al., 2019) and to what extent future water supply will be offset by reductions to agricultural use. Improved management and conservation efforts in the upper region will only slow the timeline to depletion (Scanlon et al., 2012) and large declines in irrigated acreage are anticipated by 2100 (Deines et al., 2020).~~

~~5.3 Impact of Drought to an Advanced Regional Economy~~

~~The economic impact of drought relates to how dependent a region's economy is on water supply and access to trade to offset local impacts (Lund et al., 2018). Highly connected domestic and global trade networks in the 21st Century have greatly reduced the economic and societal impacts of drought (Lund, 2016, Lund et al., 2018). Water supply infrastructure also buffers social impacts and economic disruption (Lund 2016). The combined factors of highly engineered regional water supply and domestic-global trade networks help explain why the drought did not hinder population and economic growth.~~

~~Our finding that the drought had little apparent overall effect on the basin-wide economy is in line with assessments of the 2001-2009 Millennium Drought in Australia (Van Djik et al., 2013) and the 2012-2016 drought in California, United States (Lund et al., 2018). During the 2012-2016, California experienced a 1/3 reduction of water supply but only incurred economic loss equivalent to 0.09% of its economy (Lund et al., 2018), while the Millennium Drought in Australia reduced total GPD by only 0.4% (Van Djik et al., 2013). Recent examples from California, Australia, along with this study, demonstrate how decoupled modern economies are from the agricultural sector. Tubi (2020) terms this a shift from "climate sensitive" to "climate insensitive" economies. They analysed drought impacts in Israel from 1954 to 2017 found that Israel transitioned from a climate-sensitive economy with large percentage GDP and employment in agriculture, to a climate insensitive economy over the 1960s and 1970s, where presently agriculture is less than 2% of GDP and employment (Tubi, 2020). However, it should be acknowledged that agricultural comprises a much larger fraction locally and regionally as exemplified by the upper region of the Colorado Basin, TX where it accounts for 15% of the economy and is also critical to food security and the broader rural economy. However, our findings along with Van Djik et al., 2013 and Lund et al. 2018, suggest that catastrophic drought would be required to substantially reduce the GDP of a modern economy.~~

5~~6~~. Conclusions

~~Our analysis showed~~We found that~~that~~ the drought produced a wide~~n~~ array of environmental impacts, significantly harmed agriculture, threatened water supplies triggering drought conservation measures, and had lasting effects ~~permanentl~~on~~y~~ ~~altered~~

water planning and management. Water supply infrastructure (reservoirs, pipelines, canals, and wells) and temporary demand management responses were key for averting~~ed~~ severe shortages to non-agricultural sectors. We demonstrate the use of an influence diagram as an effective tool for summarizing cascading regional multisectoral impacts and interactions. Insight into the connectivity between impacts can support adaptative planning and help reduce the vulnerability of negative cascades in other regions (Lawrence et al., 2020). Our e~~E~~valuation of regional water management plans revealed~~showed~~ that the drought substantively affected water management planning with large increases in the variety of water supply strategies (supply diversification) and planned municipal supply volume ~~following the drought~~. ~~Our review found that~~ There is no "silver bullet" water management solution for the basin like ~~such as~~ building a large new reservoir ~~to accommodate future growth and reduce vulnerability~~. Instead, a mosaic of supply and demand management strategies are needed to achieve long-term water security. [illegible] more sophisticated water supply~~-~~ planning models ~~being developed and used~~, the enactment of more conservative drought management policies ~~enacted~~, and the passing of several new laws that regulate~~ing~~ water planning. However, the difficult ~~and key~~ task of implementing the expensive water supply projects (over $6 billion in 2022 dollars) is largely yet to be accomplished.

Water planning faces deep uncertainty about future demand (sectors, location, quantity) and availability of supply, ~~(quantity, reliability),~~ and it is therefore ~~it is~~ imperative that both technical and institutional management approaches evolve as better data and modelling techniques become available. As indicated in the title, we feel this study offers a "blueprint" that can be followed by ~~other~~ future regional drought analyses.~~.~~ Our hope is that this work will inspire other comprehensive, multisectoral drought impact studies that improve ~~our~~ understanding of how regional nuances in climate, hydrology, ecosystems, institutional management, water supply infrastructure, and sectoral demand lead to specific drought impacts~~/risks~~ and how these factors influence adaptive planning.

Code availability

The Python scripts for processing and plotting the data presented in the figures ~~will be made~~are available on an associated GitHub repository: https://github.com/IMMM-SFA/ferencz_et_al_2024_NHESS.~~,~~

Data availability

All data presented was obtained from publicly available sources. All data presented in the text and supplemental figures are ~~will be made~~ available on an associated GitHub repository: https://github.com/IMMM-SFA/ferencz_et_al_2024_NHESS.~~.~~

Author contribution

SF, ST, NS, JR conceived the idea for the study. SF performed the data curation and formal analysis. SF ~~and ST~~ wrote the manuscript draft. SF, NS, ST, BS, and JR reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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laboratory operated by Battelle for the U.S. Department of Energy under Contract DE-AC05-76RL01830. All of the data and code supporting this paper is available at: https://github.com/IMMM-SFA/ferencz_et_al_2024_NHESS. ~~WILL ADD LINK UPON ACCEPTANCE.~~

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