Impact of Groundwater Management on Drought Responses in the Southwest

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1. INTRODUCTION

The severity of the megadrought in the southwestern United States is unprecedented and many efforts are being made to quantify the effects on human and natural systems. Studies have shown that the current megadrought is the worst in the past 2 centuries (Murphy & Ellis, 2019). This long-term drought can cause decreases in soil moisture, increases in evapotranspiration, and decreases in gross primary production (Dannenberg et al., 2022; Overpeck & Udall, 2020; Williams et al., 2020; Zhou et al., 2019). However, the effect of drought on groundwater is difficult to quantify. In some ways groundwater is disconnected from meteorological processes due to surface processes and delayed recharge, but it is highly influenced by human systems. The effect of drought on all of these systems can also change spatially over time as regions experience long-term drying (Liu et al., 2017). The question remains is the western drying of groundwater true everywhere in Arizona given we have very heterogeneous local systems?

Groundwater is connected to natural systems in various ways, primarily through plant interactions and recharge zones. Plants, including shrubs and trees, primarily withdraw water from shallow groundwater within the top 3-5 meters of the soil. Areas with plants like riparian zones or river beds have been identified as major recharge zones for the groundwater. Plants like trees are great identifiers for soils with high hydraulic conductivity (Ahring & Steward, 2012). Recharge can also occur at the base of mountains from snowmelt, called mountain block recharge (Markovich et al., 2019). This form of recharge is very important for areas like the Tucson and Phoenix areas. Deeper, confined aquifers can have recharge zones many miles away from the main system. Lack of recharge from snowmelt or lack of rainfall in recharge zones can cause groundwater depletion.

However, in the southwest groundwater is majorly connected to human systems. There are policy controls on groundwater drilling and withdrawals. Nevada, Utah, Colorado, New Mexico, and Arizona have groundwater subbasins with mandatory permitting regimes, while California and Texas have areas with discretionary permitting regimes (Perrone et al., n.d.). In some areas with mandatory permitting regimes like Arizona, groundwater withdrawals have some pumping limitations for large wells (ADWR, 2019). Most wells in Arizona are small unregulated municipal wells.

Some areas with limitations to groundwater withdrawals or well drilling also have infrastructure to help replenish the groundwater. The Central Arizona Project, constructed in 1993, delivers Colorado River Water to Central and south-central Arizona ("Water Quality Guidance," n.d.). People within these delivery areas can get credits for using CAP water instead of pumping groundwater (Bernat et al., 2020). The Arizona Water Banking Authority was created in 1996 to help quantify these credits and keep track of groundwater withdrawals (Milman et al., 2021). Arizona also tries to recharge the aquifer through constructed recharge basins called Underground Savings Facilities (*Storage Facility Types | Arizona*

Water Banking Authority, n.d.). Because of these types of facilities and water accounting, Arizona is considered a leader in Managed Aquifer Recharge and groundwater policy (Alelaimat et al., 2023; Megdal, 2022).

We are at a very pivotal point in history regarding water in the west as Colorado River Water shortages are happening and legislation regarding how to maintain life continues. Arizona, Nevada, and Colorado recently agreed on a new proposal for post-2026 measures to preserve the Colorado River, where governor Katie Hobbs acknowledged California is finally taking cuts despite a history of resistance to giving up river allocations(Hobbs, 2024; MacEachern et al., 2024). Also, Arizona is drafting a second phase of an Environmental Impact Statement to help drought mitigation by taking further Colorado River cuts (Silversmith, 2023). California too is investing billions of dollars in drought management by modernizing water systems, improving stormwater capture, storage, and helping general drought mitigation to communities in need (CDWR, 2022).

Our previous work has shown groundwater levels and total water storage are decreasing across Arizona (Tadych et al., 2024). These trends are more concentrated in unregulated areas and places without surface water access (Tadych, 2022; Tadych & Condon, 2023). More specifically, areas with direct surface water connections or water deliveries from the Colorado River through the Central Arizona project showed less long-term groundwater declines (Tadych et al., 2024; Tadych & Condon, 2023).

However, data limitations have caused the effects of drought on groundwater to not be properly quantified while also considering the unique areas in the southwest. GRACE is helpful for learning total water storage changes regionally (Save, 2020; Save et al., 2016; Scanlon et al., 2015). Unfortunately it is very difficult for parsing out at smaller scales and requires modelling to understand groundwater changes given its very coarse spatial resolution of 300km x 300km despite downscaling measures (Rateb et al., 2020; Scanlon et al., 2015; Tadych et al., 2024). Groundwater monitoring wells exist but the spatial variability is limited (ADWR, 2020b, 2020a; Scanlon et al., 2015).

We are taking our database of 250,000+ groundwater wells, as well as satellite data from GRACE, and using drought indices to determine what is the historical relationship between drought and groundwater in Arizona. Our study is unique because of our novel data approach and because we are bringing our knowledge of the heterogeneity of the state to answer these questions regarding recent groundwater responses to drought.

1. METHODS

This study is a continuation of a previous study which classified Arizona into groundwater management polygons, percent groundwater dependence, and access to surface water (Figure 1). Most of the same methods were followed and can be found in Tadych et al. (2024). However, these methods were expanded by updating groundwater and satellite data, providing more data filters for our well database, and downloading drought metrics.

First, we downloaded groundwater level data from Arizona Department of Water Resources and created databases following Tadych et al. (2024). The wells in this database have depth to water measurements from the surface, so more positive values mean the water table is declining. Using all groundwater wells with a depth to water measurement (in feet), we calculated the annual average depth to water for the whole state from 1975-2022 and compared this to our drought metrics described below and total water storage. For calculating trends at smaller spatial scales, we then filtered our well database to only include wells with at least 15 years of data from 2000-2022. The year 2000 was chosen because it is close to the beginning of the GRACE launch but also because this is the year that water levels in Lake Mead started to decline rapidly. In this way, we ensure our data is not skewed by new or discontinued wells but are capturing trends for the past two decades. This filtering left 1,788 wells with reasonable spatial variability (Figure 1).

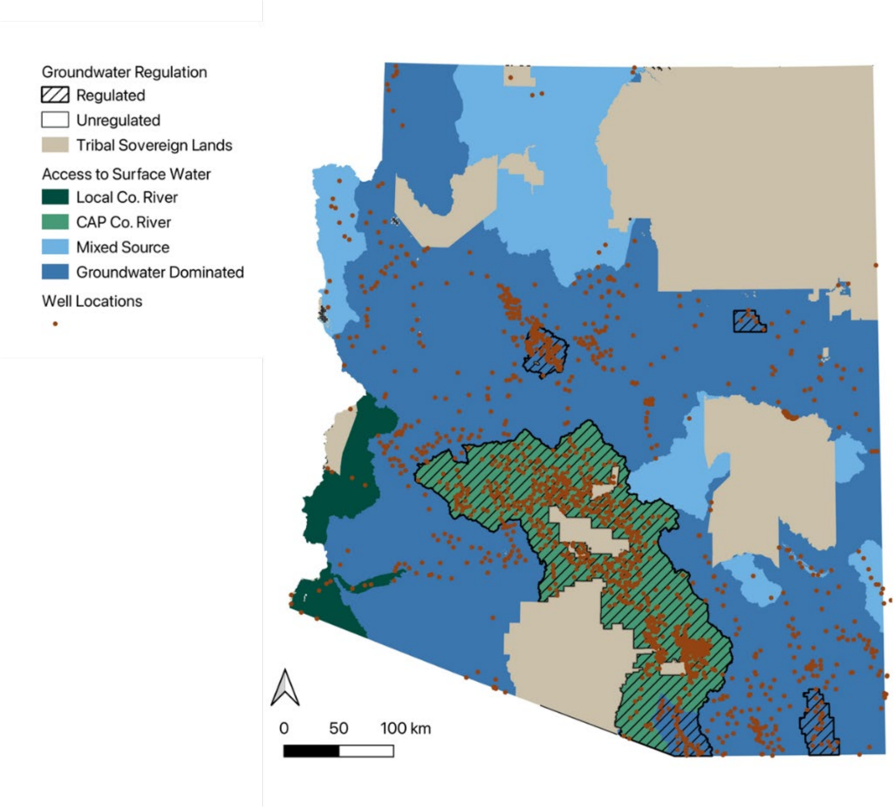

Figure 1: Map of Arizona showing state regulated groundwater pumping zones, access to surface water sources, and locations of monitoring wells used in this study.

For our regional and case study analysis, the polygons in Figure 1 were used as well as city limit polygons from the census bureau and groundwater subbasin boundaries from ADWR (ADWR, 2021; Bureau, 2018). Each case study was selected based on agricultural activity, city limits, legal controversies, or media articles describing water issues in the region. This resulted in the cities of Phoenix (only urban land), Tucson, and Flagstaff being used in this study. The Groundwater subbasins investigated were Yuma, Wilcox, Gila Bend, Ranegras Plain, McMullen, Harquahala, Salt River, Verde, and Little Colorado River subbasins. Only a few of these case studies are investigated in detail in section 3.3.

We then downloaded the latest GRACE total storage anomalies provided by the GRACE satellite mission to spatially validate our well data. More specifically Global CSR GRACE RL0602 Mascons (Version 2) were used (Gharari & Knoben, 2019; Save, 2020; Save et al., 2016). This dataset was selected because it performed the best for the Lower Colorado River Basin region, contains corrections to remove north to south striping and does not require any further post-processing (Scanlon et al., 2015). The native spatial resolution of GRACE is 1 degree, the mascon product we are using here is downscaled to ¼ degree. GRACE and GRACE-FO data is available from 4/5/2002 to 12-31-2022 monthly, with a one-year gap from June 2017 to May 2018 when the twin GRACE satellites were updated to GRACE-FO satellites. The GRACE and GRACE-FO anomalies reported in these mascon solutions are relative to a 2004 – 2009 mean and are reported as changes in centimeters of Liquid Water Equivalent (LWE). Change in Liquid Water Equivalent is essentially the increase or decrease of thickness of water in each region relative to a certain period (2004-2009). Due to its coarse spatial resolution, only average data from the statewide spatial scale was used here.

Next, we compare groundwater and total water storage to two drought metrics. Palmer Drought Severity Index (PDSI) and Palmer Hydrological Drought Index (PHDI) were selected as the primary drought indices for this study as they are well established and provide useful aggregate metrics of drought severity (Goodrich & Ellis, 2006; Svoboda et al., 2016; Vicente-Serrano et al., 2010). PDSI calculates monthly dryness from precipitation, temperature, and water capacity of soils. PHDI is calculated similarly to PDSI but modified to take into account the effect of long-term dryness on water storage, streamflow and groundwater (Svoboda et al., 2016). Both datasets are made available online at multiple spatial scales on a monthly time-step from The National Oceanic and Atmospheric Administration/National Climatic Data Center (NOAA/NCDC) (Climate Division Datasets (NClimDiv), n.d.; Vicente-Serrano et al., 2010). For this study we used the state-level spatial scale to better cross compare drought periods between various case studies.

Using the PDSI and PHDI we identified the most severe drought periods for Arizona. We define a value of -3 or less as a severe drought for both metrics. This threshold results in six severe drought periods shown in Figure 3. Note that due to the declining trend in both PDSI and PDHI over time, these droughts are more likely to occur in later years. Additionally, there are two exceptions to the -3 drought threshold. First, we included 1989-1990 as a drought period even though the PDSI and PDHI values for 1990 are only -2.28 and -2.97 respectively. We determined that this was very close to the threshold and the most significant drought in the period before 1995. We also included 2013 as a severe drought year to avoid splitting the 2012 drought into two separate drought periods.

The metrics to measure the severity of groundwater levels during drought from our filtered database consisted of multi-step process (Figure 2). First, depth to water anomalies were calculated by subtracting the annual depth to water level from the linear trend (linear regression) during the 2000-2022 period. This is a general indicator of the total magnitude of the groundwater impacts from the long-term drying as observed in Tadych et al (2024). With these groundwater anomalies we calculated correlations with PDSI using Pearson and Spearman correlations tests. We test correlation using r squared (R^2) and Spearman Rho. Both test correlation strength but Spearman's Rho is a non-parametric test and is less sensitive to outliers than r squared. Then we determined the maximum drawdown during a severe drought period by determining the maximum anomaly during a severe drought period (Figure 2). This is a better metric to determine the severity of groundwater declines from drought, where positive values mean dryer wells during the drought period of interest.

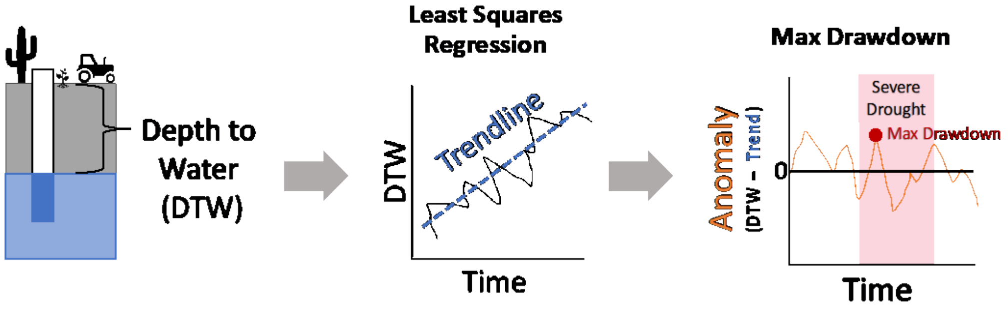

Figure 2: Conceptual figure of our workflow for processing groundwater levels to calculate Maximum Drawdown during Severe Droughts.

2. RESULTS & DISCUSSION

We evaluate the relationship between groundwater and drought in Arizona by splitting this section into the various spatial scales examined. First, we compare depth to water and total water storage statewide with PDSI and PHDI for the period 1975 – 2022. Second, we compare regional depth to water anomalies to PDSI and severe droughts from 2000-2022 by groundwater management polygons and access to surface water polygons. Lastly, we considered areas in parts of Arizona with unique human activities and focused on groundwater trends at those smaller scales.

Section 3.1 Statewide relationship to Drought

We use all well data from ADWR to determine the statewide relationship to drought and validate our results using GRACE total water storage data. Figure 3 shows time series of yearly PDSI and PDHI averaged across the state, in addition to state averaged groundwater levels and total water storage. In general, we find as droughts increase in number and severity, groundwater and total water storage is also declining in Arizona (Figure 3). Both meteorological and hydrological drought indicators are showing a drying trend over time. Also, the number of severe droughts went from two between 1975-2000 to five in the past 23 years. The decreases in total water storage have become steeper since 2010 and our groundwater well data shows these declines are not isolated to surface processes. In fact, depth to water across the state is at historical low in 2022.

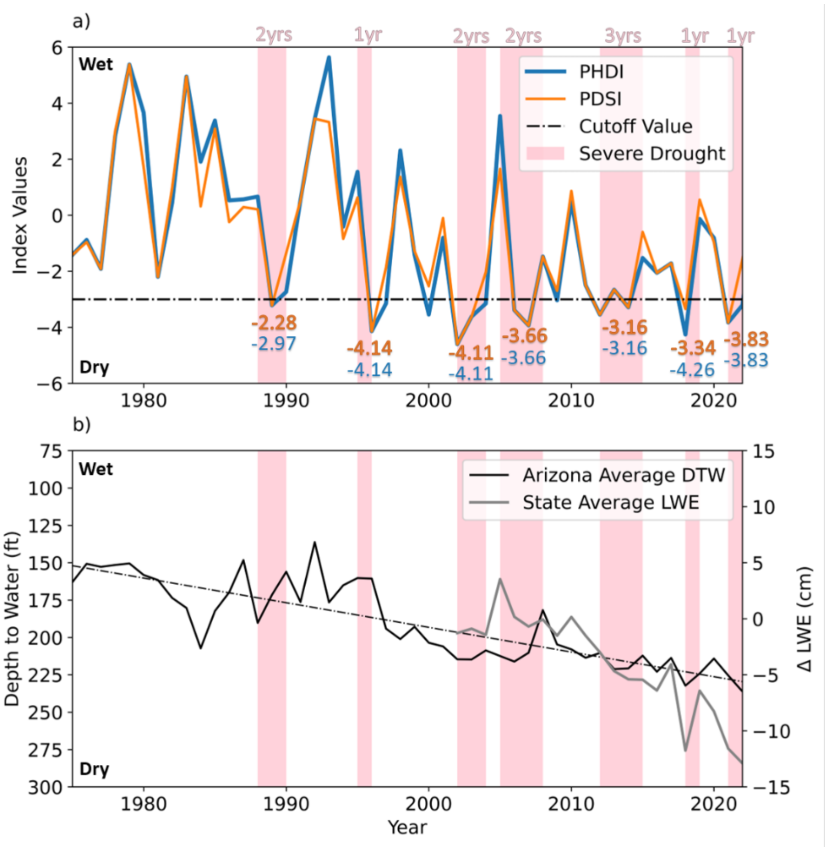

Figure 3: Timeseries of drought indices (a) and groundwater trends (b). PHDI, PDSI, and liquid water equivalent are decreasing over time while depth to water is increasing.

Our detrending analysis shows that drier total water storage anomalies are occurring with more severe droughts since 2000 (Figure 4). However, these anomalies do not always match the depth to water anomalies from our well database. Similarly, GRACE was significantly correlated with dryer drought indices, but our well data was not correlated. This finding is likely because GRACE is capturing all hydrological changes of the entire system, which will either not be reflected or instead will be delayed in well measurements. Well measurements are also not evenly spatially distributed like our satellite data. As a result, we believe well data is not a good indicator of drought effects at the state spatial scale but GRACE performs well.

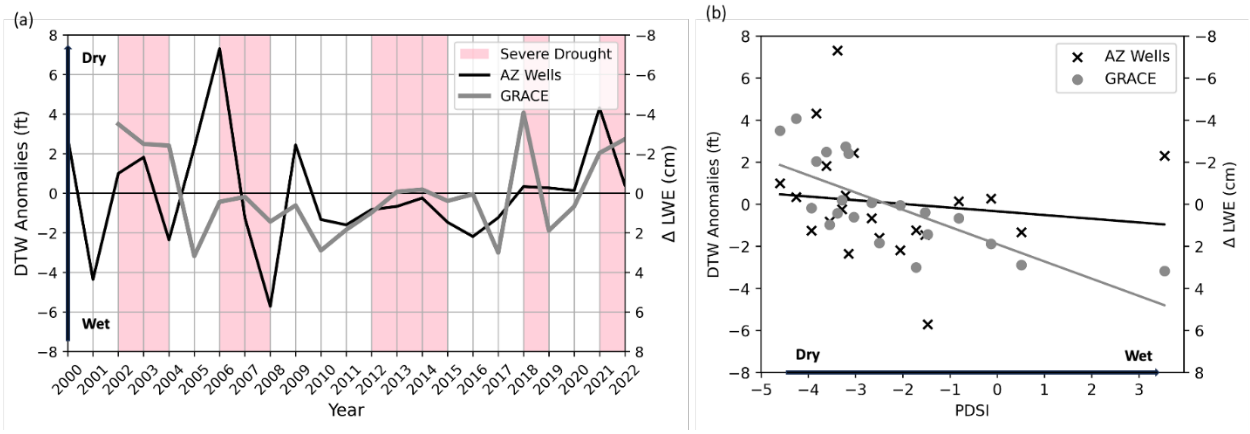

Figure 4: Depth to Water (DTW) Anomalies on the primary axis and Total Water Storage anomalies (Δ LWE) on the secondary axis plotted against time (a) and Palmer Drought Severity Index Values (b).

Section 3.2 Drought Trends with Regulation and Surface Water Access

We also wanted to determine if the statewide behavior changes with groundwater regulation or surface water access. Narrowing to our groundwater regulation polygons, we find areas with groundwater regulation have improved drought response over time. This is reflected by less variable anomalies for groundwater regulated regions since 2009 and decreasing drawdown from severe droughts in regulated regions (Figure 5). Unregulated groundwater regions also very high drawdown in the most recent 2021 severe drought. These results seem to point to regulated areas being more resilient to severe droughts in recent years.

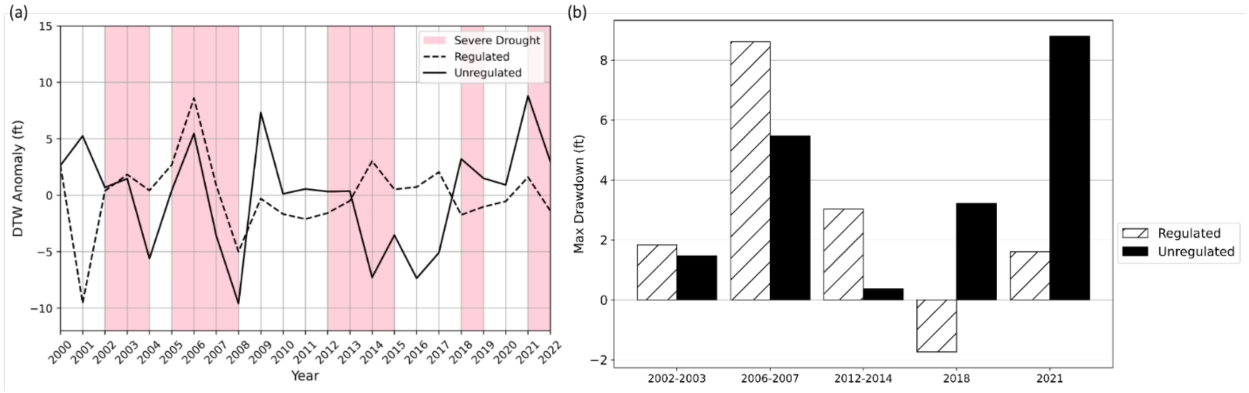

Figure 5: Groundwater Regulated and Unregulated Depth to Water (DTW) Anomalies plotted against time (a) as well as Maximum Drawdown per severe drought period (b).

Parsing these trends further, we find that areas with surface water applications also help lessen the effects of severe droughts (Figure 6). Areas receiving local Colorado River water had the best drought response from 2000-2015. Only in recent droughts are these areas showing the worst drought trends compared to our other regions of interest, comparable to groundwater dominated regions. These findings mirror the decreasing river flows experienced by the Colorado River since 2000.

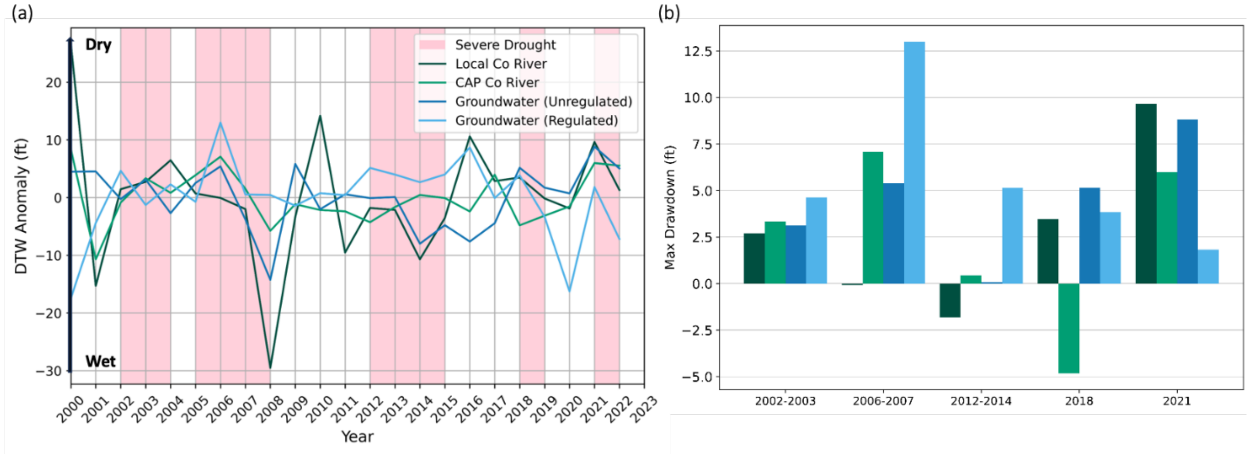

Figure 6: Access to Surface Water Depth to Water (DTW) Anomalies plotted against time (a) and Maximum Drawdown per severe drought period (b).

Areas receiving CAP Colorado River water seem to be more stable than other regions (Figure 6). Similarly to groundwater regulated regions, CAP Colorado River areas had the lowest variability with groundwater anomalies. Given the joint surface water and groundwater dependence of this area, it makes sense the drought responses were generally between groundwater dependent regions and areas receiving local Colorado river. There is an exception with the 2018 drought, where areas in the CAP service Area are replenishing the groundwater during this time. The maximum drawdown for this area never exceeded 7.5 ft, even during the more recent 2021 severe drought when CAP curtailments would have begun to preserve Colorado River water. The patterns exhibited here indicate surface water deliveries to this region are helping maintain groundwater levels despite worsening severe droughts.

Interestingly groundwater dominated (regulated) areas had improved maximum drawdown over time. Anomalies reached a peak in 2006 where it had the worst drawdown during the 2006-2007 severe drought compared to all other areas. This area never repeated such large declines in the water table again. When all other areas showed large drawdown during the more recent 2021 severe drought, this groundwater dominated (regulated) region had the lowest maximum drawdown at a mere 2ft. So, although groundwater regulation might not have shown replenishment during severe droughts, it might help stabilize the water table over time by limiting groundwater pumping in this region.

Section 3.3 Case Study Analysis

To better understand these groundwater level trends across the state, we mapped the trends of each well used in this study (Figure 7). In general, some areas have very different groundwater trends depending on where you are in the state and the human activities. For example, some urban areas like Flagstaff, Pheonix, and Tucson are showing improved groundwater over time but adjacent basins with heavy unregulated agricultural activity are showing massive declines. Wilcox, McMullen, Ranegras, and Harquahala groundwater subbasins have numerous drying wells and all are centered around agricultural land. Our findings reinforce the governor of Arizona’s efforts to prioritize some subbasins like Wilcox, Ranegras, and Gila Bend (*Governors Water Policy Council Report*, 2024).

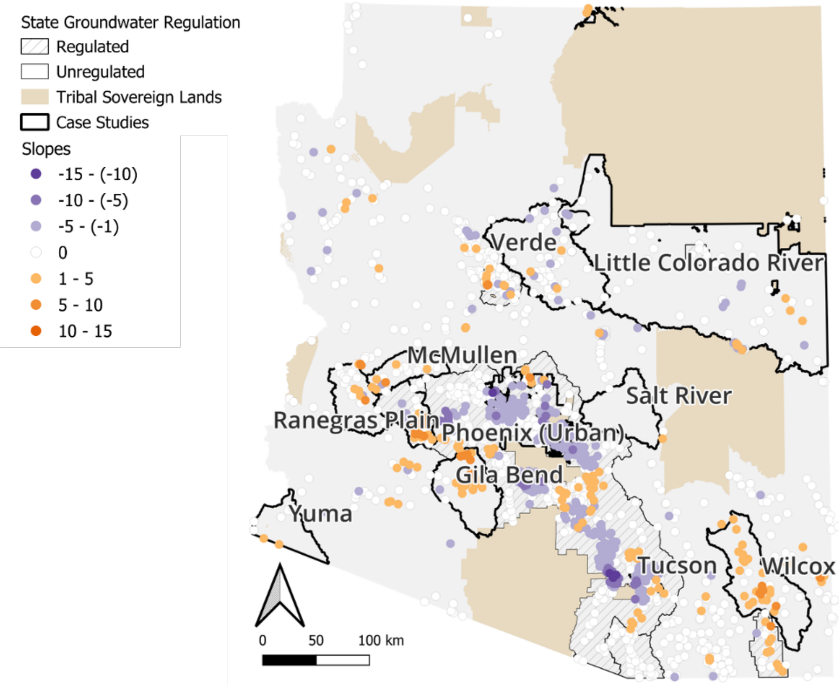

Figure 7: Map of trends in groundwater for each individual well used in this study. Negative slopes indicate improved groundwater over time but positive slopes indicate declining groundwater.

Areas with groundwater replenishment from outside sources or no pump zones exhibit improved drought response over time. This pattern can be seen in Little Colorado River groundwater subbasin, Phoenix, and Tucson case studies (Figure 8a). Both cities have improved groundwater levels and drought responses over time (Figure 8a&b). In the Little Colorado River region, the Zuni Indian Tribe Water Rights Settlement Act of 2003 was passed to restore a sacred lake which had dried from diversions upstream (Zuni Indian Tribe et al, 2002; Zuni Indian Tribe Water Rights Settlement Act of 2003, 2003). This act limited groundwater usage around the region and has surface water allocations just for Zuni lands (Nania, n.d.; *Statement of Theresa Rosier*, 2003). Although some wells in the subbasin are drying, most are recovering or remaining stable.

Figure 8 shows further analysis of Phoenix and Tucson. Not only are they improving groundwater levels over time, but their drought resilience is much better than other areas of the state. Particularly striking is how during the 2021 severe drought, when the larger region was experiencing drawdown, these cities were either net-zero or replenishing groundwater. In Phoenix, the spatial distribution suggests that an equal number of wells are drying and replenishing throughout the city (Figure 8c). In Tucson, the main wells experiencing higher drawdown are focused in the north-central part of the city, which is in a basin between multiple mountain ranges. Mountain front recharging from snowmelt is likely a driver in this net groundwater savings despite drought conditions. These findings speak to the successful water saving and efficiency programs implemented by these cities. Tucson and Pheonix have been improving their residential water efficiency through smart irrigation practices, fallowing land, utilizing dry wells, installing water smart appliances in urban areas, and replenishing groundwater through the Central Arizona Project.

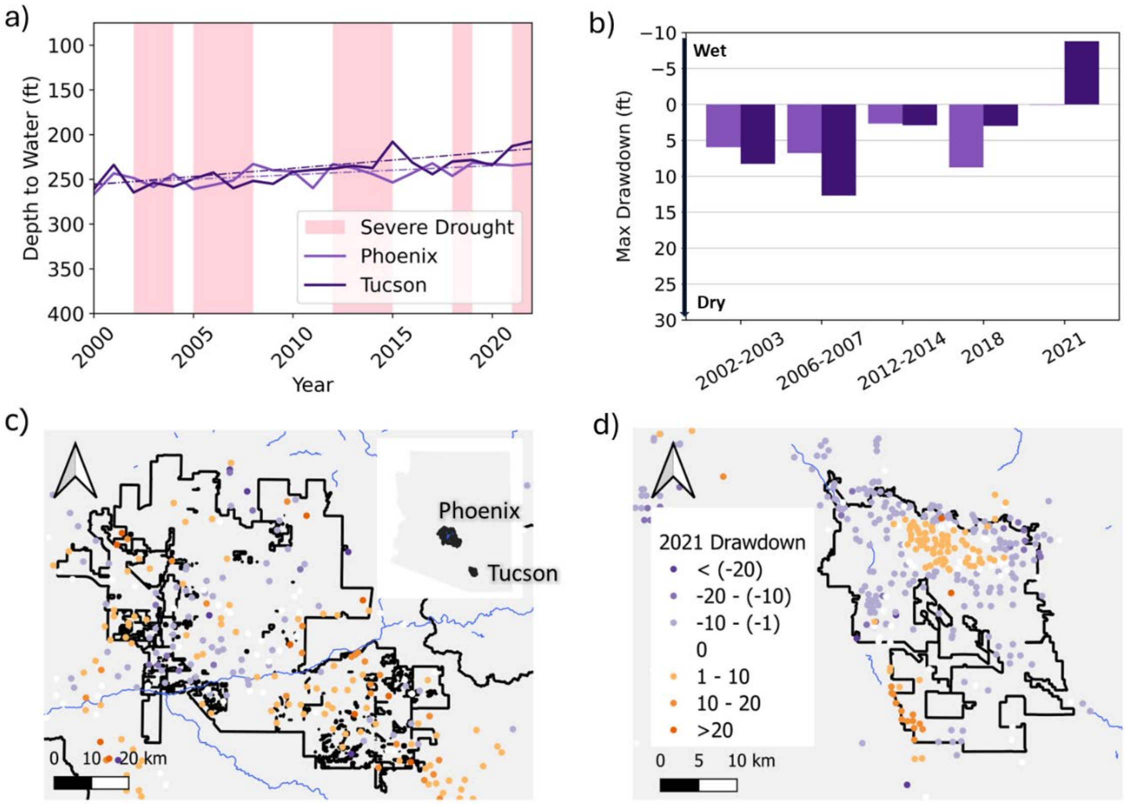

Figure 8: Average Depth to Water readings for Phoenix and Tucson (a), their maximum drawdown per severe drought period (b), map of 2021 Drawdown for Phoenix (c) and Tucson (d).

Another interesting contrast is the Verde and Gila Bend groundwater subbasins as shown in Figure 9. The Verde River is one of the few perennially flowing rivers in Arizona whereas the Gila River is a formerly perennial river. There is also very little human activity and interruptions of the Verde River but along Gila Bend there is significant agricultural activity. The Gila Bend water table has been declining steadily since 2000, at a total drop 150 ft in the past 22 years. However, the drawdown during severe droughts was higher for Verde compared to Gila Bend during severe droughts of the past 12 years. Both subbasins had high drawdown during the 2021 drought but Verde's was much higher at 25ft. These findings indicate that a more natural system will be more responsive to severe droughts but human activities can have harmful effects to the water table over time.

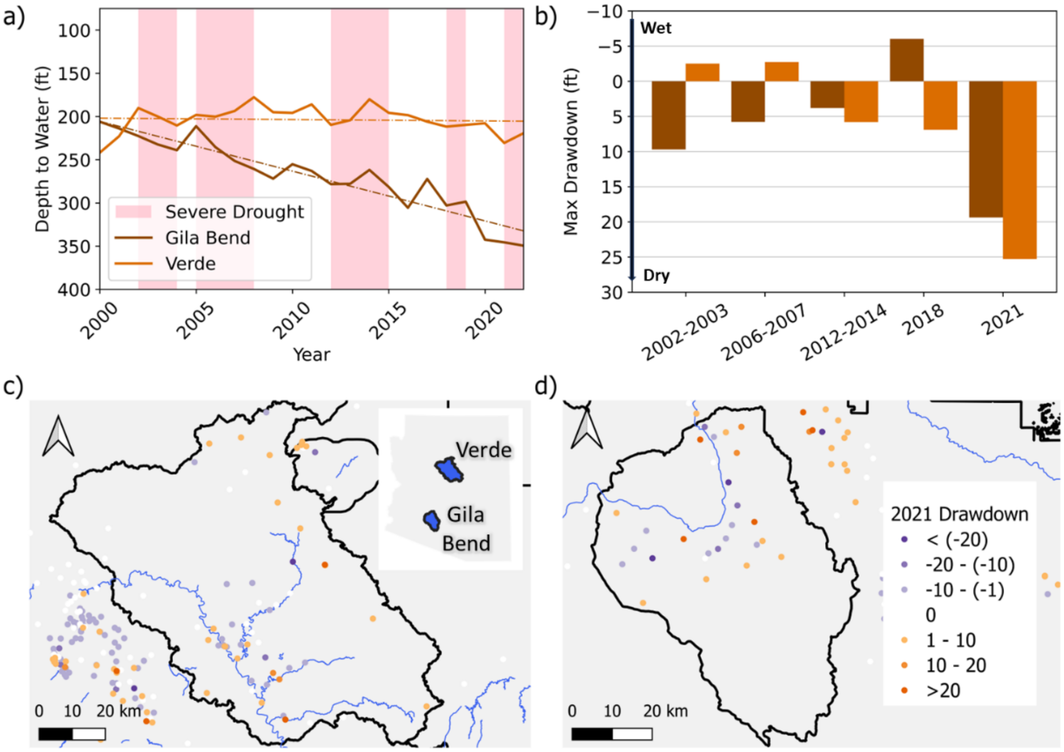

Figure 9: Average Depth to Water readings for Gila Bend and Verde groundwater subbasins (a), their maximum drawdown per severe drought period (b), map of 2021 Drawdown for Verde (c) and Gila Bend (d).

A very important agriculturally productive region we wanted to investigate is the Yuma Subbasin (Figure 10). Since this region has senior water rights for agricultural production, we hypothesized this region would be relatively stable with respect to groundwater. We found this area has slightly worsening drawdown and groundwater levels over time but not as severe as the groundwater dependent basins (Figure 10a&b). The number of wells matching our criteria are unfortunately not numerous; however, map of the 2021 drawdown in this area suggests most wells are replenishing groundwater. This feat is impressive given the primary crops in the area are highly water intensive and supports local farmers claims of their highly water efficient cropping systems.

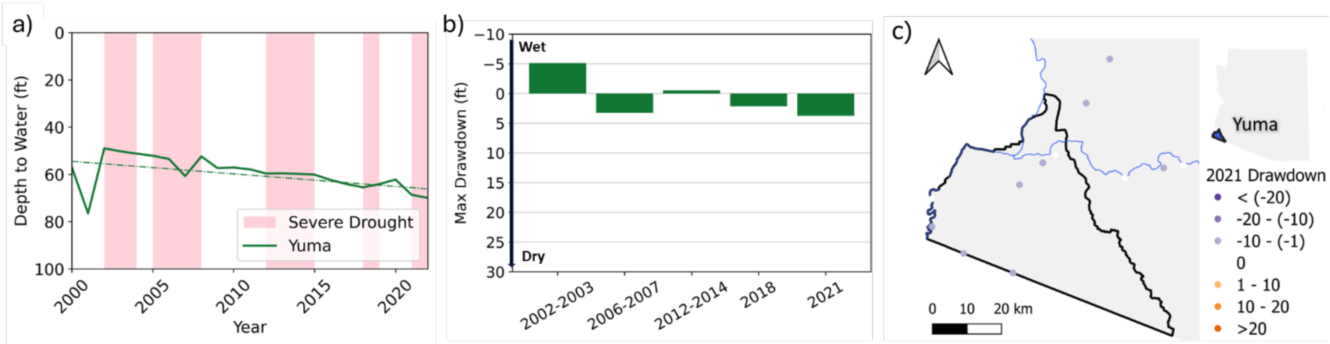

Figure 10: Average Depth to Water readings for Yuma (a), its maximum drawdown per severe drought period (b), and map of 2021 Drawdown (c).

3. **CONCLUSIONS**

This research attempted to quantify the relationship between drought and groundwater at multiple scales. We determined that there is indeed a relationship between decreasing total water storage and drought at the state level. However, the relationship with groundwater levels changes based on where you are in the state, groundwater regulation, surface water application, and human activities.

On the surface, groundwater regulation and surface water applications help with drought responses, but it is more likely due to long-term water conservation efforts. Our case studies showed that all the larger cities considered, including Tucson, Pheonix, and Flagstaff, had less severe drought responses. Areas with groundwater replenishment from outside sources (e.g. Colorado River) or no pump zones can greatly improve drawdown during severe droughts. Water conservation efforts in agriculturally productive regions can also help with drought responses as seen in the Yuma region. Pumping groundwater completely unregulated though, especially for agricultural use, can have severe consequences on groundwater levels.

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