The Sustainable Groundwater Management Act's Impact on Groundwater Withdrawl in the Sacramento Hydrologic Region

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ABSTRACT

Groundwater is a critical component of California's water supply. Until very recently, there were no statewide regulations controlling groundwater extraction, which has led to overdraft, subsidence, and decreased groundwater quality as overlying users treat groundwater as a common pool resource. This historic absence of statewide regulations, as well as current conditions of overdraft and future hydrological disruptions caused by climate change, makes groundwater management one of the most important challenges facing the state of California. The Sustainable Groundwater Management Act became law in 2014, with the purpose of mitigating the negative impacts on California's groundwater resources by 2042. The study design assesses whether the anticipation of future regulation impacted groundwater extraction patterns in the five years directly following regulatory implementation. The outcome variable is groundwater extraction from regulated and unregulated basins, estimated with groundwater elevation data from monitoring stations in sixteen different groundwater basins in Northern California. I employ a difference-in-differences regression model to analyze the treatment effect of policy intervention, and ensured the validity of the regression model by using an event study to confirm that the control group is an accurate counterfactual to the treatment group. The study demonstrated no evidence that the implementation of groundwater regulation had a measurable differential impact on groundwater withdrawal. The limited immediate observed impacts are the result of difficulties in regulatory compliance as well as legislative oversights, leading to inertia in achieving the goals of SGMA's novel approach to groundwater management.

KEYWORDS

difference-in-differences regression, hydroeconomic modelling, Central Valley, climate change, California

INTRODUCTION

In 2012, California entered into what would become one of the most severe droughts in the state's instrumentally recorded history (Robeson 2015). This ultimately became a four year prolonged drought that was the most severe drought event in the region in over 1200 years (Grifin and Anchukaitis 2014). This drought had broad impacts on economic, industrial, environmental, social, and political aspects of California society. Californian citizens became more conscious of their water consumption as local and statewide policies implemented mandatory water conservation efforts (Palazzo et al. 2017). While much of the attention from news and social media focused on the drought's impact on surface water sources, groundwater resources in California were profoundly and irreversibly altered as a result of this drought. Exactly as the name implies, California's groundwater resources consist of water that exists in underground aquifers of porous rock and gravel. Groundwater aquifers are the largest source of water in California (Tanaka et al. 2006), and the resource is used widely across the state. Roughly 85 percent of Californians rely on groundwater at some level (Chappelle and Hanak 2017) and groundwater supplies at least 40 percent of the demand for California's immensely productive agricultural sector (Moran and Wendell 2015). California has already exhausted all potential freshwater sources, and increasingly relies on groundwater to meet the state's immense freshwater demand. This dependence on groundwater led to systemic over-extraction of the resource. By the time the state government declared the end of the drought in 2017, Central Valley groundwater aquifers had lost roughly 20 cubic kilometers of groundwater (Xiao et al. 2017). Anthropogenic withdrawal rates greatly surpassed the natural replenishment rate of groundwater aquifers, essentially classifying groundwater as a nonrenewable resource (Konikow and Kendy 2005). While the drought was temporary, its impact on the landscape of California's freshwater resource system would ultimately be permanent.

California climate and hydrology

Droughts are a natural component of California's climate. California is an arid state with a Mediterranean climate where most precipitation occurs during the winter months, leading to hot and dry summers. In addition to these annual fluctuations in water supply, droughts periodically occur due to natural cyclical atmospheric volatility. High pressure ridges off the coast of California occasionally form as a result of sea surface temperature forcing (Ropelewski and Halpert 1986). These pressure ridges deflect to the North and South precipitation that would otherwise reach California. Additionally, California precipitation is impacted by El Niño-Southern Oscillation (ENSO) events, or cyclical fluctuations in atmospheric and ocean temperatures off the state's coast (Schonher and Nicholson 1989). The historic 2012 drought was the result of an overlap between these two phenomena, the formation of a pressure ridge and an ENSO event, with anthropogenic climate warming (Seager et al. 2015). Droughts like this are unavoidable, inextricably linked to California's unique geographic, atmospheric, and climatological features. However, the severity of drought impacts on society in California are profoundly influenced by anthropogenic factors. Unsustainable water management practices greatly intensify the effect that these natural events have on the people and wildlife of California.

Anthropogenic Impacts

Groundwater overdraft

Although drought events are a fundamental part of life in California, anthropogenic water demand has introduced great pressure to available freshwater resources. Meeting the demand of California's cities, industry, and agriculture has necessitated the pumping of over 15 million acre feet per year (Criss and Davisson 1995). Aquifers require thousands of years to accumulate that quantity of water naturally as water percolates through overlying soil layers. Each year, groundwater users in California are removing water from aquifers at rates that greatly surpass the natural rate of replenishment, (Famiglietti et al. 2011) removing over 2 million acre feet of water more than is naturally replenished (Chappelle and Hanak 2017) in a process known as groundwater overdraft. As unsustainable extraction causes groundwater withdrawals to exceed aquifer recharge, the resulting groundwater overdraft has a number of deleterious impacts on the resource as a whole, and its viability over long periods of time (Zekster et al. 2005).

For groundwater users, the most significant effect of falling groundwater levels is that it requires drilling ever deeper wells to access the water (Forsythe et al. 2018). In severe cases, it may trigger a race to drill increasingly deep wells until either the groundwater is exhausted, or the marginal pumping costs of groundwater exceed its use value (Harou and Lund 2008). Increased extraction costs as a result of falling water levels poses particular threats to high-value agricultural crops in California that rely on inexpensive irrigation to remain profitable (Knapp and Schwabe 2015). By removing water in this unsustainable pattern, pumpers make it progressively more difficult to access the resource in the future. In some parts of California, groundwater levels have fallen over 200 feet (USGS 2003). Perhaps the most impactful consequence of excessive groundwater extraction is its potential to reduce overall groundwater storage capacity. Once water is removed below a certain threshold, there is not enough water to support the overlying weight, and the aquifers collapse in on themselves (Döll et al. 2012). After compaction these aquifers permanently lose the capacity to store groundwater in the future. A 2007 drought alone caused the permanent loss of roughly 2 percent of total groundwater storage capacity in the Central Valley (Ojha et al. 2018). When that impact of a single drought is projected onto the last hundred years of overdraft, where 140 cubic kilometers of groundwater were removed from Central Valley aquifers, (USGS 2013) it is clear that California groundwater storage is already greatly reduced. Additionally, the compaction of groundwater aquifers as a result of excessive groundwater withdrawal is the primary forcing of land subsidence (Forsythe et al. 2018). One final negative consequence of overdraft is saltwater intrusion, a phenomenon where coastal aquifers are contaminated by saltwater. As groundwater is extracted, its water pressure falls and creates a vacuum that saltwater from the ocean fills. As saltwater mingles with freshwater, the resulting groundwater pollution can range from being a minor nuisance to rendering the entire groundwater aquifer undrinkable (Barlow and Reichard 2010).

Major sources of groundwater demand

Groundwater holds near ubiquitous importance in the economic and social structures of California. For roughly 85 percent of the people in California, groundwater is a significant portion of the water supply, while some communities rely on the resource as their only supply of water (Chappelle and Hanak 2017). While all sectors of the Californian economy are dependent on uninterrupted access to freshwater resources, the agricultural sector is the largest source of human water use by far. Overall, agricultural activity accounts for 76 percent of all human water use in

California, while all urban water consumption only represents 21 percent (CADWR 2013). This water is used to irrigate the 25.3 million acres of land devoted to the agriculture sector, which generated over $50 billion from output of the state's farms and ranches. To produce this output and provide such a valuable service to the state economy, the agricultural sector relies heavily on groundwater for growing crops and raising animals. During a typical year, 40 percent of the water used by the agricultural sector comes from groundwater (Kiparsky 2016). In drier years such as periods of drought, the agricultural sector increasingly relies on groundwater extraction to offset depleted surface water levels. In these years groundwater supplies as much as 70 percent of agricultural water demand (Howitt et al. 2015).

Although agriculture has been a dominant, and water-intensive, component of the California economy for decades, it has seen some impactful changes in recent decades. California agriculture has shifted in last few decades to higher revenue perennial crops such as nuts, grapes, rice, or alfalfa that are more water intensive (CDFA 2019). This agricultural shift has increased agricultural revenue by over 6 billion dollars since 1998, but has also greatly increased the water intensity of California agriculture (Chappelle and Hanak 2017). While the transition to more water-intensive crops is a trend that has negative impacts on the water supply, it is neither the only nor the most severe trend that will have impacts on the future viability of California groundwater resources.

Anthropogenic exacerbations

The problems brought about by past mismanagement of groundwater resources will only be exacerbated as anthropogenic forces impact California in the future. Climate change resulting from human activities will worsen many of the problems that currently face California's groundwater resources. Climate models predict that the average warming will reach between 1.7 and 5.8 °C hotter in California by 2100 (Cayan et al. 2008, Hayhoe et al. 2004). The long term impacts of climate change on California have been meticulously studied, and are expected to deleteriously impact California's systems of water acquisition and distribution in several ways. Higher average temperatures brought about by climate change are predicted to intensify the state's arid climate by reducing average annual precipitation and increasing evaporation (Hayhoe et al. 2004, Diffenbaugh et al. 2015). Anthropogenic warming will also exacerbate drought conditions as a consequence of increased evaporative demand (Seager et al. 2007, Williams et al. 2015). Additionally, the increased evaporative demand resulting from anthropogenic climate change will increase the severity of California's natural drought cycles (Mann and Gleick 2015). Climate models predict a positive correlation between increased warming and frequency of drought-inducing pressure ridges (Swain et al. 2014), as well as the severity of ENSO cycles (Yoon et al. 2015). It is not a coincidence that from 2012 to 2014, California experienced the worst years of the drought contemporaneously with the three most severe years of drought in state history. Since groundwater is used more heavily in dry years, all of these impacts of climate change ultimately reinforce the existing extractive pressures already negatively affecting groundwater resources (Swain et al. 2014).

Finally, increased temperature due to climate change will significantly impact the timing of water delivery in CA, causing both drier winters and winters of flooding that overwhelms water storage systems (Pierce et al. 2013). Not only does this threaten communities living on the 7 million acre feet on floodplain in CA (CADWR 2013), it also decreases water availability in the driest periods of summer months. While these impacts will have negative impacts on all Californians, the agricultural sector are most vulnerable (Tanaka et al. 2006). The most pronounced impacts of climate change will not be experienced by Californians for several more decades, making it all the more important to immediately begin preparations for the long term sustainability of the state's water resources. Without any potential for alternate water sources in the future, extractive pressure on groundwater will continue to increase.

Climate change will exacerbate both supply and demand issues already greatly threatening groundwater resources that are already critically endangered. Groundwater overdraft that continued unabated for years was the driving force behind widespread conditions of overdraft. The groundwater overdraft is the primary cause of deleterious phenomena such as land subsidence, declining water levels, and disappearing groundwater storage capacity. Future projections of anthropogenic climate change will only exacerbate these existing problems, as climate models predict more frequent and severe drought in California. The 2012 drought exposed the vulnerabilities of California's water system, and provided ample evidence that existing groundwater management practices were harmfully unsustainable.

Groundwater Regulations

Historical regulatory lapses

All of the problems California currently experiences resulting from groundwater overdraft are direct consequences of the state's historic lack of comprehensive statewide groundwater management regimes. The intricate connection between groundwater and surface water is not reflected in California's legal doctrine. Surface water in California has extensive and complex regulations based on a hybridization of appropriative and riparian rights doctrines, groundwater has historically been subject to almost no government regulation. In comparison, the only significant laws regarding groundwater come indirectly from several disparate legal doctrines. Until very recently, there was no statewide legislation regulating groundwater management or extraction, incentivizing groundwater users to withdraw groundwater with little regard for conservation. California property law allows landowners access to any groundwater that may exist below them, with very little limitation on how much water they could pump as long as they abide by the state's constitutional requirements that the water be used for reasonable and beneficial purposes (Forsythe et al. 2018). To enforce this, the California Water Code endows state agencies with the ability to take regulatory action to prevent waste of water, including unreasonable use or diversions (Bartkiewicz et al. 2006). With multiple landowners claiming rights to the same groundwater basin, many groundwater basins end up being treated as a common pool resource. The implications of this style of resource use inherently leads to over-extraction (Gardner et al. 1990). When this occurs, two outcomes are possible. First, groundwater stakeholders can appeal to the courts, which have the power to apportion water to all stakeholders, making the shared resource an adjudicated basin. The other option is for groundwater users to become engaged in a race to dig the deepest wells and thereby pump their neighbors out of access to the water supply. In either case, this lack of centralized state groundwater regulation led to civil conflicts and dramatic decreases in groundwater availability in the majority of the state's groundwater aquifers.

In the absence of a statewide groundwater management regime, the decentralized local regulations governing the resource provided little to incentive for groundwater users to conserve the resource. The problems of groundwater overdraft, and their connection to California's policies were recognized by legislators and groundwater users for many years, but it was not until the historic drought of 2012 that these legal oversights became a prominent topic.

Paradigm shift

By the spring of 2014, the drought continued to detrimentally impact California, and the California state legislators felt pressures to find political solutions to mitigate the anthropogenic damage to state water resources. In April, the Chair of the Senate Committee on Natural Resources and Water introduced Senate Bill 1168 focusing on applying state-level oversight to the many different, separately managed groundwater basins in the state. Catalyzed by the ongoing drought and reinforced by the mention of groundwater's importance in the California Water Action Plan earlier that year, (Forsythe et al. 2018) the legislation ultimately became a package of three-bills intended to prevent the deleterious consequences of groundwater overuse. These bills were collectively called the Sustainable Groundwater Management Act (SGMA). SGMA was signed into law by Governor Jerry Brown in September of 2014, and came into effect on January 1, 2015.

SGMA represented the first statewide regulations and protections of underground aquifers in California history, intending to achieve sustainable groundwater use through four key stages: (1) Basin Definition, (2) GSA Formation, (3) GSP Development, (4) GSP Implementation and Basin Management. The California Department of Water Resources (CADWR) was put in charge of implementing the regulatory statutes of SGMA.

The first stage of SGMA required assigning boundaries to these underground aquifers, qualitatively assessing each basin, and ultimately generating a quantified scale of the severity of overdraft in each basin. CADWR differentiated California's 515 different water basins into four distinct categories. These classifications are high priority, medium priority, low priority, and very low priority. The technical process of organizing basins into each category is based on a prioritization score calculated by the state department of water resources. The department used 8 different factors in calculating the prioritization scores, which were: (1) overlying population. (2) population growth rate (3) number of public supply wells drawing on the basin (4) total wells drawing on the basin (5) overlying irrigated acreage (6) degree of reliance on the basin for people living above it (7) documented impacts on the groundwater such as overdraft, subsidence, or quality deterioration (8) any other information deemed relevant by the department (CADWR

2016a). On January 31, 2015 CADWR published its initial basin prioritization decisions in the California Water Code, and allowed for a period of public comment where basin managers could apply to have their score altered. After reviewing applications for modifications to the basin boundaries and prioritization scores, the department published the updated boundaries and prioritization scores in the 2017 Bulletin 118 – Interim Update. Few changes were actually implemented, and the basin boundaries remained relatively unchanged in the 2019 updated map, included in the appendix (CADWR 2016b).

The next stage of SGMA's regulatory implementation began while the final details of the groundwater basin map were being clarified. With a basic idea of groundwater boundaries and their severity of overdraft established, CADWR then needed to establish which entities or organizations would be responsible for achieving sustainable management in each groundwater basin. Rather than leaving the management of this important resource to large state-level bureaucracies, the provisions of SGMA focus on emphasizing local management and control. There is a vast array of diversity in the specific environmental features of the groundwater basins themselves, as well as the overlying local government management practices. SGMA's legislative approach recognizes the importance of tailoring individual regulatory regimes to the idiosyncrasies of each basin (Forsythe et al. 2018). A universal policy at the state level that ignores these differences and treats all basins equally would lead to cumbersome bureaucracy and inefficiencies that would become obstacles to achieving sustainable groundwater management. Instead, the approach of SGMA focuses on providing flexibility for each groundwater basin, within a looser statewide framework. SGMA stipulates that each groundwater basin be managed by a single entity, or Groundwater Sustainability Agency (GSA) by June 30, 2017. These GSAs could be formed by local public agencies, in collaboration with a collection of multiple different stakeholders including groundwater users and resident government representatives. Additionally, the state can step in to create a GSA if local agencies are unable to do so by the deadline. According to California Water Code 10735.2(a), only basins designated as high or medium priority had to establish GSA's by this deadline. Basins designated as low or very low priority were not subject to these regulatory requirements, which would carry through to the rest of SGMA's implementation. Essentially, throughout SGMA only the high and medium priority basins are focused on, while low and medium are left unregulated. 94 of the 515 different groundwater basins in California are classified as high or medium priority. While this is less than 20% of the total number of basins, these high and medium priority basins account for 96% of all groundwater use in the state of California (CADWR 2015).

Once each basin had identified a unique management authority, the next stage of SGMA required them to outline their specific strategies. SGMA requires that GSAs organize a comprehensive outline for the strategies and resources into a Groundwater Sustainability Plan (GSP). This one document will serve as the fundamental tool that GSAs will refer to in their efforts to achieve sustainable groundwater management. High and medium priority basins must submit their GSPs by January 31, 2022, while low and very low priority basins are not required to submit GSPs at all (CADWR 2014). While much of the responsibility for organizing, implementing, and enforcing GSPs is in the hands of GSAs, CADWR still represents the state's interests throughout this process. Most notably, CADWR evaluates the measurable goals outlined in each GSP, and may recommend alterations to the plan itself or its implementation. The State Water Resources Control Board assists in enforcing GSPs as well. Additionally if a groundwater management agency fails to submit their GSP by the deadline, or if the GSP is inadequate, the state will generate and enforce their own management strategy through CADWR (Nelson and Perrone 2016). Each GSP must also contain an emergency contingency plan, to be as prepared as possible for unpredictable events that may impact the water supply, such as droughts, wars, or worldwide pandemics.

The efficacy of each GSAs ability to meet the objectives outlined in their GSPs relies heavily on an open and frequent two-way communication between local agencies and CADWR. The GSAs must actively monitor groundwater levels, collecting and communicating that data to the department. In exchange, CADWR commits to regularly updating local agencies by disseminating new information and insights as they become available. As part of this communication network, CADWR compiles a series of documents containing suggested regulations and best management practices. These documents focus decades into the future, and are specifically designed to flexibly account for the uniqueness of each individual basin (Forsythe et al. 2018). The main purpose of these GSPs is to prepare how each agency will achieve sustainable yield of groundwater. SGMA defines sustainable yield as the amount of water that can be extracted annually, over many years, without producing "undesirable result", as specified by the California Water Code. This is a fairly nebulous term that lacks substantive specific wording to guide GSAs, but is the entire goal of SGMA (Miro and Famiglietti 2018). These undesirable results may include chronic depression of groundwater levels, reduced groundwater storage, land, saltwater intrusion, and other such deleterious consequences.

The final stage of SGMA's implementation centers on achieving the sustainability goals outlined in each groundwater basin's GSP. While each stage preceding this has already occurred, or will occur within the next several years, SGMA does not require that GSAs of high and medium priority basins achieve their sustainability goals until 2042. As GSAs work towards administering their GSPs, CADWR regularly monitors their progress, requiring comprehensive updates every five years. SGMA equips local water agencies with the legal ability to enact a various range of different policy tools to achieve sustainable groundwater management. These tools exist on a spectrum ranging from methods that focus on preventing over-extraction to those that center on promoting groundwater recharge. On the preventative end, SGMA empowers GSAs to adopt regulations or ordinances that limit groundwater extraction, such as limiting pumping quantities, suspending new wells, or decreasing the density of existing wells. To promote recharge, GSAs may pursue efforts to artificially recharge groundwater aquifers or may import water from less-stressed areas outside the agency's boundaries. Additionally, GSAs are able to enact fees on groundwater users to fund the costs of these programs (Nelson and Perrone 2016).

SGMA represents an unprecedented innovation in California's groundwater management regime. To successfully achieve the significant transition from decentralized local governance to a statewide framework, the provisions of SGMA rely on orchestrated collaboration between local GSAs and state agencies. While the logistical operations of sustainable management planning are left to the GSAs, CADWR and the State Water Resources Control Board assist in developing and enforcing GSPs, and provide guidance to GSAs through their regular Best Management Practices documents. Despite legislators' best efforts, SGMA may face obstacles in overcoming the inertia established by decades without any comprehensive statewide groundwater regulation. Time will tell whether SGMA is able to impel groundwater users in California to achieve its stated groundwater management goals.

Research Objectives

The intent of this study is to examine the relationship between SGMA's implementation and groundwater extraction patterns in the Sacramento River Hydrologic region, using groundwater elevation data as a proxy. This is an important area of research because it has not been covered by the existing academic literature. Most of the research on the subject focuses on the specific legislative strengths and weaknesses of SGMA, or highlights the most effective ways for GSAs to achieve their sustainability goals. Very little attention has gone to scientifically assessing whether SGMA has yet had an impact on California groundwater, and whether that impact has been beneficial or detrimental.

A lack of scientific focus on this topic is due to the fact that SGMA is still in its earliest stages of implementation and enforcement, and it is improbable that any significant changes have yet occurred. However, a longstanding theory in natural resource economics postulates that expected regulations can impact extraction patterns even before coming into effect (Hotelling 1983). Depending on exogenous conditions, this anticipatory response to an inevitable future policy can either a positively or negatively affect the regulated resource (Karp 2017). Given the extreme depletion of groundwater as a result of anthropogenic demand, these implications for nonrenewable resources are applied to analyze the effect of SGMA on groundwater elevations in regulated basins. The introduction of a policy intervention in the form of SGMA can lead to three different anticipatory responses, each with distinct repercussions for groundwater elevations in California. Firstly, groundwater users could attempt to begin conservation efforts immediately, thus ensuring that they avoid potential penalties in the future. Conversely, groundwater users could do the exact opposite, and increase groundwater consumption in the immediate periods following SGMA to maximize profits before GSAs are established or GSPs are prepared to be enforced. Finally, there could be no significant changes at all, signifying that groundwater users exhibit may be slow to initially respond to the expectation of a future a sweeping regulation by changing groundwater extraction patterns. This regulatory inertia could also be the result of a combination of increased and decreased extraction that ultimately results in overall pattern similar to before SGMA.

Literature Review

SGMA is a monumentally important event in the history of California's groundwater management regime. As such, the scientific community has devoted profuse amounts of research and yielded a plethora of academic literature on the topic of SGMA. Much of the scientific research devoted to SGMA focuses on evaluating the most effective regulatory strategies for achieving the sustainability goals outlined in the provisions of SGMA. This research highlights strategies for incentivizing groundwater recharge and replacing groundwater demand as areas with the most potential for yielding successful sustainability results. From the opposite perspective, other sections of the academic literature focus on the potential shortfalls of SGMA that may prevent GSAs from reaching sustainable groundwater management.

The scientific research that focuses on the most efficacious ways to achieve SGMA's goals is demarcated into two distinct categories. According to the academic literature, the most propitious regulatory mechanisms can be classified as either an incentive structure for artificial groundwater recharge, or a mechanism for replacing the groundwater used in certain activities with an alternate source of viable freshwater (Kiparsky 2016). Regulatory strategies that promote artificial recharge mitigate the deleterious impacts of overdraft by replacing extracted groundwater with surface water pumped below ground (Moran and Wendell 2015). This water can come from a variety of sources that are not currently exhaustively drawn upon. Desalinated seawater is one potential source of freshwater for artificial recharge, especially in basins with more severe overdraft where water is more valuable (Badiuzzman et al. 2017). Additionally, GSAs could promote using recycled stormwater for artificial recharge by drawing on innovative techniques from the energy sector (Kiparsky 2016). Using net-metering, GSAs can provide economic incentives to groundwater users that invest in pumping infrastructure to divert stormwater runoff into groundwater aquifers. Stormwater recycling and desalination are also promising tools for finding replacements to groundwater that will meet California's groundwater needs without causing overdraft (Harou and Lund 2008). While these methods involve high operating costs, they can be funded by the billions of dollars that California farmers would save from avoiding the damages associated with overdraft (MacEwan et al. 2017). Another incentive structure for replacing groundwater can come from expanding California's existing water markets (Brewer et al. 2008). If GSAs can employ SGMA's legal provisions to provide a more robust policy framework, these markets can improve management flexibility and allocate groundwater to where it is most needed (Aladjem et al. 2017). While these markets are a useful tool, their functionality is limited, and must be accompanied by other management strategies to achieve groundwater sustainability (Koundouri 2004). Ultimately, none of these individual mechanisms will be sufficient for achieving SGMA's sustainability requirements, but collectively they can reinforce and complement one another in a way that greatly empowers GSAs to achieve sustainable management.

An additional section of the academic literature focuses on SGMA's shortfalls, which are especially relevant in the context of the results suggested by this study, that SGMA has not had a differential impact on regulated groundwater basins. These explanations, and their context within the broader academic literature will be further presented in the discussion section. This study, like others in the academic literature, cannot discern the precise driving mechanisms behind its findings. Rather, there are a plethora of different causal explanations for the observations of the study, and no single explanation suffices on its own. At best, this study serves to organize the coalescence of multiple contemporaneous influences on the data for more effective and insightful analysis.

METHODS

Study site

The Central Valley is California's major agricultural hub, and experiences the most severe conditions of groundwater overdraft of anywhere else in the state, (Williams et al. 2015) making it the most suitable region for this study. The Central Valley is divided into three hydrologic regions. From North to South, these regions are: the Sacramento Valley Hydrologic Region, the San Joaquin River Hydrologic Region, and the Tulare Lake Hydrologic region. I chose the Sacramento River Hydrologic Region, the northernmost region of the Central Valley, for this study due to its high agricultural activity and the mildness of the region's groundwater overdraft relative to the rest of the Central Valley. The study design requires a robust control group populated by basins that have not historically experienced severe overdraft, and the Sacramento River Hydrologic Region had the most balanced proportion of these basins. Additionally, these hydrologic regions lack critically overdrafted basins that may introduce bias into the study. Most of the annual overdraft of 2 million acre-feet per year occurs in the other two Central Valley hydrologic regions (Hanak et al. 2011), meaning that any findings from the Sacramento River region would be much more pronounced if extrapolated to these regions.

Data sources

In 2009, the California state legislature passed Senate Bill x7-6, which mandated that the state's Department of Water Resources work with local water agencies to acquire data on groundwater elevation fluctuations in state basins. As a result, CADWR implemented the California Statewide Groundwater Elevation Monitoring (CASGEM) Program to collect, organize, and publicly disseminate this data. I accessed the CASGEM online data portal through CADWR's water data library to collect the data used in this study. I then aggregated reliable groundwater measurements taken on a monthly basis into a dataset containing nearly 50,000 groundwater measurements taken from 1992 through 2019. This is the dataset that was used for the study. Most monitoring stations began collecting data around 2008, so data from the years prior to that are relatively nugatory. The measurements were collected from 453 individual groundwater monitoring stations across 16 different groundwater basins in the Northern portion of California. Of the 16 basins, 8 are categorized as High priority, 5 as Medium priority, and 3 are Very Low priority. 15 of the groundwater basins are located in the Sacramento Valley Hydrologic Region, the upper region of California's Central Valley, running from Sacramento to a portion of the Oregon border in Modoc County, including much of northeastern California. The other basin is located in the North Coast Hydrologic Region, directly west of the Sacramento Valley region. Maps of these hydrologic regions and groundwater basins are included in the appendix. Each basin contained multiple monitoring stations that took groundwater measurements on a monthly basis. The metric for these groundwater measurements is the distance in feet between the ground surface level and the highest level of the underground water. The ground surface level measurement is calibrated to the North American Vertical Datum of 1988, (NAVD88) the universal measurement for sea-level in the United States (NGS 2018). This metric calculates groundwater elevation as the difference between the water depth and the reference point elevation, and is the accepted procedure for monitoring groundwater according to the provisions of SGMA (CADWR 2016a).

The organized dataset contained groundwater measurements spanning over a decade organized by each groundwater basin. I then incorporated information on the SGMA prioritization status of each basin, in order to have that response variable included in the study. I used DWR's Basin Prioritization Dashboard, an online map that shows the prioritization status and score of each groundwater basin. The final portion of my dataset management was to assign groundwater basins to the treatment and control groups depending on their prioritization scores. The regulatory requirements of SGMA only apply to high and medium priority basins, so any groundwater basin with that prioritization status was placed into the treatment group, and given a dummy variable value of 1 for identification. All of the other unregulated basins were designated as the control group, and assigned a dummy variable value of 0.

There are several advantages to using data from the CASGEM program. Firstly, the data were easy to access and clearly organized online, making dataset management much easier. Along those lines, data from the CASGEM program were collected using universal testing procedures and reporting metrics, minimizing any potential biases coming from human error or conversion mistakes. Most importantly, the reports of government science agencies are trustworthy and accurately reflect the reality of California's groundwater basins. The salient information is an accurate representation of groundwater conditions in the state.

There are also several drawbacks to the dataset that I use in this study. The first and most important drawback is that I am analyzing groundwater extraction patterns using groundwater elevation data, rather than data on specific amounts of groundwater withdrawal. This is because there is no reliable data that exists on total groundwater extractions from all different groundwater users in multiple basins, taken on a recurring timescale. Since I was unable to directly find groundwater extraction data, the study design uses groundwater elevation as a proxy for withdrawal. There is a direct and intimate relationship between these two variables. As groundwater users withdraw more water from the aquifers, groundwater levels fall. Similarly, when extraction decreases, groundwater elevations are able to rise due to slow natural recharge. Thus, using groundwater elevation as a proxy for studying extraction patterns is a viable, if imperfect, research mechanism. Another important limitation involves the limited geographic scale of the data. Because the data are from the Sacramento Valley region only, my analysis will not provide a holistic snapshot of all Central Valley groundwater impacts resulting from the implementation of SGMA. While the Sacramento Valley region is a part of the Central Valley, it is the northernmost region that receives much more rainfall than other two, and therefore experiences less groundwater overdraft. Though this was an initial concern for the integrity of analysis, it ultimately proved beneficial for the overall design of the study. My study design requires a control group consisting of groundwater basins not designated as high or medium priority. These are virtually inexistent in the Southern portion of California, with areas like the San

Joaquin Hydrologic region composed almost entirely of high priority basins. By focusing on hydrologic regions in Northern California, I have a higher proportion of data from unregulated groundwater basins, leading to a more robust control group. While the results of the study will not provide a holistic view of the groundwater trends in the entire state, I can assume that any findings will be more pronounced in Southern California basins, since the Northern California region is much less water-stressed than the South.

Research framework and data processing

Difference-in-differences regression model

The Difference-in-Differences (DID) regression model is a tool that enables estimation of the impact of a policy treatment by comparing changes in the dependent variable over time between the regulated and unregulated groups. The model uses the unregulated control group as a counterfactual to study the impact of treatment from the observational data. The theory behind the model posits that the two different groups would experience the same unobserved impacts in the absence of any treatment intervention. Thus, in the period directly following the introduction of a policy, the impact on the two groups can be quantitatively measured by evaluating the differential trends in the observational data from each of the two groups.

In this study, the dependent variable is the distance between groundwater levels, and the treatment is the implementation of the Sustainable Groundwater Management Act in September of 2014. The treatment group consists of the groundwater basins designated as high and medium priority that are regulated under SGMA. The control group consists of the lower priority basins in the state that are not subject to the regulatory impact of SGMA. The goal of the regression is to distinguish whether the implementation of SGMA impacted high and medium priority basins differently than lower priority basins. The DID regression follows this basic formula:

$$Q = \alpha + \beta_1 PostPolicy + \beta_2 Priority + \beta_3 (Priority * PostPolicy) + \epsilon \tag{1}$$

where Q is the distance between the groundwater level measurement and the surface of the ground, referenced to NAVD88. *PostPolicy* is a dummy variable that indicates whether a measurement was taken before or after SGMA was passed. *PostPolicy* returns zero for all groundwater measurements taken in the months before the passage of SGMA in September of 2014, and one for all the months after the passage of SGMA. This coefficient represents the change in groundwater levels for the control group from before and after SGMA. *Priority* is an indicator for whether or not a groundwater basin was designated as high or medium priority, and therefore in the treatment group. This coefficient expresses the difference in groundwater levels between the treatment and the control basins, before SGMA. The *Priority*PostPolicy* interaction variable measures the treatment effect, and represents the difference between the treatment and control basins after SGMA. This β_3 coefficient is the most important for answering my central research question of whether SGMA has had a differential impact on California groundwater basins. α represents the regression constant, which shows the initial groundwater level average for the control basins before SGMA. Finally, ϵ is the regression error term, a value that captures any additional variations in the dependent variable that were not caused by the independent variables. This regression was performed using groundwater elevation measurements from all years of the study and using an abbreviated study period. I also performed an identical regression using only data from measurements taken after September 2009. This shortened regression provides a roughly ten year study window, with data from five years before and after the passage of SGMA. Reducing the timeframe for data included in the regression serves to evaluate whether data from earlier years introduced unnecessary bias to the study, increasing the robustness of the study results. I also performed a third adaptation of the basic regression model using log-transformed data. Log-transformation controls for high variability in the data, which occurs from drastic variability in the data across different basins and different years. Thus, the log-transformed regression makes the estimates derived from the data more interpretable.

While the DID regression model can generate valuable insights into the movement of the data over time, the basic model outlined in Equation (1) is limited. The major limitation of this regression model is that it is susceptible to skews in the data caused by omitted variable bias. This would occur when the regression model is impacted by exogenous biases from variables that I did not include in the regression, but potentially had some impact on groundwater elevation. These sources of omitted variable bias could include agricultural intensity of the overlying population, surface water abundance, residential water use patterns, or the presence of fracking operations or other water-intensive industry, among others. To make the robustness of the regression to these unobserved influences on the regression estimation, I included fixed effects for the basin and the year in the model. The basin fixed effects control for all average time-invariant differences across individual groundwater basins. Such variables include alternate starting depths of groundwater, varied overlying zoning patterns, and diverse soil compositions, among many other unobserved differences. The basin fixed effects capture this time-invariant heterogeneity in the data. The time fixed effects control for time-variant average differences affecting all of the groundwater basins in the study. For example, these fixed effects prevent biases that result from annual differences in precipitation that may cause certain years to experience more groundwater withdrawal than others on average. Together, these two fixed effect coefficients absorb observable or unobservable predictors that influence groundwater elevation but were not explicitly included in the regression model. Without fixed effects these impacts would be unexplainable. Thus, the fixed effects increase the clarity of the model and allow for more accurate analysis and interpretation of the interactions between the variables of interest and the dependent variable.

$$\textbf{(2)} \qquad Q_{iy} = \alpha + \beta_1 PostPolicy + \beta_2 Priority + \beta_3 (Priority * PostPolicy) + \alpha_i + \alpha_y + \epsilon_{iy}$$

where Q_{iy} is the groundwater level of basin *i* in the year *y*. The variables that correspond with β_1, β_2, and β_3 are the same as in Equation (1). The basin fixed effect, α_i, controls for naturally occurring variations across each basins, and the time fixed effect, α_y, captures variance in all basins across each year that sampling occurred. The variables that represent the regression constant and error term, α and ϵ, are also treated the same as in Equation (1). Like the basic regression model, the fixed effects regression model was repeated using log-transformed data.

While the fixed effects regression model avoids many of the limitations of the basic regression model, it is not sufficient to use as the only model in the study. By soaking up the variation in precipitation across different years, the fixed effects could dampen the treatment effect of groundwater elevation changes and under-represent the SGMA's actual impact. This same phenomenon would occur with the basin fixed effects would, reducing the regression coefficients corresponding to basin prioritization. No regression model is flawless, but fixed effects avoid many of the limitations of the basic regression model. Fixed effects control for variables that may be correlated with the treatment effect that would otherwise introduce bias to the results. While the fixed effects models provides a more accurate representation of the differential groundwater trends, I include both regression models in my analysis, as the basic regression model may yield exaggerated regression results that would provide valuable insights into SGMA's impact on California groundwater elevation.

Tests of validity and robustness

The difference-in-differences regression is a powerful tool for finding and analyzing the impact of certain events on panel data for the response variables of interest. In order for the regression to function properly, however, it makes several assumptions that must be shown to be valid in order to for the results of the DID regression to be legitimate.

The first assumption of the DID model is that the composition of the treatment and control groups does not change over the course of the study. The research design satisfies this assumption, as a groundwater basin cannot change from being a high or medium priority basin once the designation has been established, and therefore a basin could not have switched from the treatment to the control group or vice versa over the course of the study's timeframe. There was a brief period after CADWR announced the initial basin boundaries and designations where management agencies could submit public comments and petition for a change in prioritization status. These boundary readjustments were published in CADWR's Bulletin 118, and listed several basin in my study as having been approved for boundary modifications. These were slight adjustments of the official border of the groundwater basin, and had no impact on the prioritization status of the monitoring wells included in this study. Thus, CADWR's Bulletin 118 reaffirmed that none of the basins included in this study had changed status after the initial judgement (CADWR 2016a).

The second assumption of the DID model requires that any trends in the dependent variable have no influence on the allocation of the control and treatment groups. At first glance, it would appear that this study's approach violates the assumption, as SGMA was designed to impact only groundwater basins experiencing overdrafted groundwater levels. However, treatment under SGMA is entirely decided by a basin's prioritization score, not by groundwater levels. As mentioned in the introduction, these prioritization scores were calculated by weighing eight different factors in a calculated decision making matrix. These factors were all used because they influence groundwater levels in some way, however they are all indirectly related to the fluctuations in groundwater level. In many cases it was the potential threat of overdraft in future years that decided the prioritization scores rather than any existing observable groundwater elevation trends. Because all of the factors that determined the allocation of treatment do not directly relate to groundwater levels, the dependent variable in the study had no influence in determining which basins were assigned to the treatment or control groups. Thus, this assumption ultimately holds valid.

The final and most important assumption of the DID model is the parallel trends assumption. The integrity of the DID regression model rests on the assumption that the control group is an accurate counterfactual for the treatment group. This is due to the fact that the fundamental theory behind the DID model requires that both treatment and control groups would have been impacted by the same exogenous variables, and would have followed similar patterns in the absence of any policy intervention. Thus, treatment effects can be quantified in the regression once a policy is actually introduced that differentiates the two groups. The parallel trends assumption posits that, in order to accurately estimate the impact of a treatment on regulated and unregulated groups using observational data, the basins must have been following the same trends before treatment ever came into effect. If this were not the case, it would be impossible to interpret the treatment effect.

For an initial, rudimentary test of the validity of the parallel trends assumption, I graphed the average groundwater elevation in every month for the treatment and control groups. (Figure 1) This provides a rough visual interpretation of the data, and should depict whether any glaring discrepancies existed in the validity of the assumption. As a cursory tool for initial analysis of the parallel trends assumption, the graph provides a weak visual confirmation that the assumption is valid. Both groups follow very similar trajectories, rising and falling in response to the same exogenous influencing factors. While this method helps to visualize the trends, it is not sufficient to accurately and holistically prove that the parallel assumption is true. There are a multitude of unobservable factors that influence the groundwater elevation heterogeneity depicted by the graph. A more robust statistical analysis is necessary to categorically prove the validity of the parallel trends assumption. I performed an event study to account for these unobserved variables and more thoroughly confirm the validity of the parallel trends assumption.

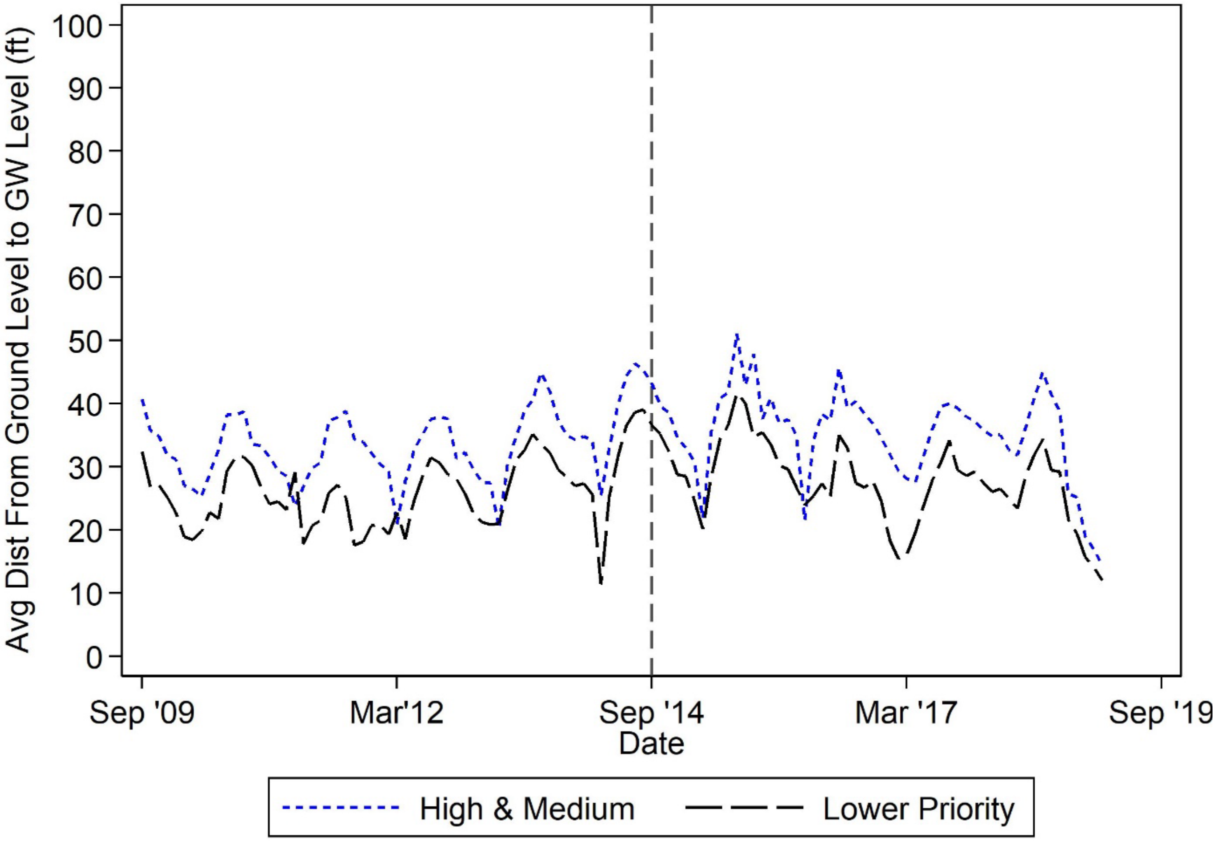

Figure 1. Groundwater elevation averages in treatment and control basins. The outcome variable is the distance between the surface of the ground and the groundwater basin, in feet, referenced to NAVD88 standards. The blue dotted line represents elevation averages for the treatment group, and the control group is represented by the dashed black line.

The event study follows the following equation:

$$\text{(3)} \qquad \sum_{t=-4}^{4} \beta_t D_{t,im} + \alpha_i + \alpha_y + \epsilon_{imt}$$

where $D_{t,im}$ is a dummy variable that indicates whether or not a basin is in the high or medium priority group. The temporal fixed effects consist of eight time periods *t*, and each time period consists of two-month intervals. The time periods center on September 2014, the month in which SGMA passed into law, with four time periods before SGMA's implementation and four after. For example, this means that time period D_{-1} references July 2014, two months before September 2014. Similarly, time period D_{+1} refers to November 2014, two months after, and so on. The equation includes fixed effects for each of the 16 different groundwater basins in the study. To mitigate perfect collinearity in the regression, I omit the period immediately preceding SGMA's passage, D_{-1}. Similarly to the regressions, α_i and α_y are fixed effects for the individual groundwater basins, and the year in which a measurement was recorded.

The event study compares basins in the treatment group to unregulated basins in the control group across multiple 2-month intervals, both preceding and succeeding SGMA. B_t represents the changes in the treatment coefficient of regression variables over time. If the treatment and control basins are following parallel trends in the pre-SGMA period, there should be no β_t trend that is statistically different from zero. Thus, to confirm the validity of the parallel trends assumption, the event study must demonstrate that none of the treatment coefficients from periods before the implementation of SGMA deviated significantly from zero.

RESULTS

Regression Models

Basic difference-in-differences regression model

I present the results of the Diff-in-Diff regression defined by equation (1) below (Table 1). Table 1 represents the results of the basic regression model without fixed effects. In the table, column 1 contains resulting regression coefficients, and column 2 contains the coefficients from the regression framework, but using log-transformed data. Finally, column 3 contains the regression coefficients from using untransformed data, but with data points taken from measurements more than 60 months before SGMA passage dropped.

Table 1 shows several important patterns that appeared in the regression. First, nearly all of the regression coefficients were reported as statistically different from zero at the 1% significance level. The only value that was not statistically significant was the treatment coefficient in the shortened timeframe regression, an interaction variable between the *PostPolicy* and *Priority* coefficients. This is because there were fewer data in this regression, leading to larger standard error values that are more likely to include zero. The second important finding relates to

Table 1. Regression results from basic model. The outcome variable is the distance between the surface of the ground and the groundwater basin, in feet, referenced to NAVD88 standards. Standard errors in parentheses. Asterisks indicate the following: *p<0.10, **p<0.05, ***p<0.01

	(1) **GW Elevation**	**(2)** **Log GW Elevation**	**(3)** **Shortened Timeframe**
PostPolicy	3.3787***	0.1117***	2.2615***
	(0.0703)	(0.0228)	(0.7839)
Priority	9.1980***	0.3486***	7.7576***
	(0.4418)	(0.0143)	(0.5848)
Treatment	-1.7131**	-0.0575**	-0.0917
	(0.7861)	(0.0254)	(0.8796)
_cons	25.4887***	2.7816***	26.6060***
	(0.3983)	(0.0129)	(0.5210)
Mean of Dep. Var.	33.5215	3.0865	33.5918
Num. of Obs.	48,810	48,297	33,177
R squared	0.0122	0.0166	0.0100

the sign of the regression coefficients. All three of the different regressions, reported in separate columns, showed the same trend in the data. I found that both the treatment group of high and medium priority basins, and the control group of lower priority basins experienced decreasing groundwater levels in the period after SGMA was passed. However, the regression reported that groundwater levels in the treatment group declined at a lower rate than the groundwater levels in the control group. The third and final important result of the diff-in-diff regression analysis relates to the size of the coefficient variables. When the study is limited to only include measurements taken five years after the passage of SGMA and beyond, the coefficients corresponding to the different treatment variables were slightly smaller. In other words, the coefficients for all of the variables in Equation (1) were closer to zero in the shorter timeframe than in the original regression.

Upon analysis of both columns, I found that groundwater levels in control basins fell by 2.2-3.3 feet over the course of the study period of interest (roughly 10 years, five years before

SGMA passage and five years after). This translates to a 10% average reduction in groundwater levels after the implementation of SGMA. This value was calculated using the observations presented in table 1, by dividing the observed *PostPolicy* coefficient of 3.37 by the dependent variable mean of 33.52 feet distance between ground surface level and groundwater elevation. The log-transformed regression shows the same trend, with groundwater levels in control basins falling by 11.8%. The percent change in log-transformed data was calculated using the equation: *percent_change*=100*(e^{β} – 1), where β is the log-transformed *PostPolicy* coefficient. Treatment basins also experienced a lowering of groundwater elevations, however decreases in the treatment groups was only between 1.6 and 2.2 feet, or a 4.8% reduction relative to levels in the period before SGMA. Overall, the basic regression model found that groundwater elevations in the treatment basins decreased 50% less than the observed declines in the control basins.

Difference-in-differences regression model with fixed effects

For the results of the fixed effects regression indicated by equation (2), column 1 presents the resulting regression coefficients, and the coefficients from using log-transformed data are in column 2 (Table 2). For both columns, the dependent variable is the distance between ground surface level and groundwater elevation. Therefore, more positive coefficients indicate decreasing groundwater levels, while negative coefficients show recharging aquifer volume. Each row of the tables shows the regression coefficients for the parameters of interest, with the standard errors in parentheses below each. In the top row, *PostPolicy* coefficients are the same as β_1 in equation (1). Similarly, *Priority* parallels β_2, Treatment parallels β_3, and _cons parallels the regression constant, α.

Table 2 reports the values from the secondary regression analysis performed to increase the robustness of the primary regressions findings, including fixed effects in the regression design to capture time-variant and time-invariant influences that would have introduced bias into the regression model if they were not controlled for. As such, Table 2 in many ways elaborates on the findings reported in Table 1. While important on its own, the results of the secondary regressions

Table 2. Regression results from fixed effects model. The outcome variable is the distance between ground surface and groundwater elevation, in feet, referenced to NAVD88 standards. Standard errors in parentheses. Asterisks indicate the following: *p<0.10, **p<0.05, ***p<0.01

	(1) **GW Elevation**	**(2)** **Log GW Elevation**
PostPolicy	-2.519925	-0.0097298
	(2.445367)	(0.0650268)
Priority	33.98881***	1.10485***
	(3.048731)	(0.0683507)
Treatment	1.207147	0.0034281
	(2.181511)	(0.0575857)
_cons	15.43414***	2.689859
	(3.125117)	(0.0844361)
Mean of Dep. Variable	33.59187	3.082263
Num of Obs.	27,247	40,320
R squared	0.2120	0.3282
Basin FE	X	X
Year-of-Avg FE	X	X

are most valuable when analyzed in comparison to the other study method. The most important result to notice from this regression analysis is that, in both columns of Table 2, the reported coefficients for *PostPolicy* and Treatment not statistically different from zero. However, *Priority* and _cons are the only statistically significant reported coefficients, different from zero at a 1% significance level. The statistically insignificant coefficients from the fixed effects regression also show that the treatment and control basins both increased in groundwater level across the pre and post periods, with groundwater levels of treatment basins increasing less than observations from the control group.

Event study

To validate my findings from analysis of the DID regression model estimates, I evaluate the parallel trends assumption using the event study model (Figure 2). Figure 2 plots the treatment coefficient obtained by the DID regression in solid black, surrounded by the 95 percent confidence intervals in grey. The vertical red line displays the date of SGMA's passage, and divides the graph into the pre- and post-treatment study periods. The omitted dummy is D_{-1}, corresponding to the two month interval directly before the SGMA became law. The periods before SGMA's passage show loose evidence in support of the parallel trends assumption. In all but one of the periods, the dashed grey confidence interval lines bound zero. In these periods, this shows that the treatment coefficient is not statistically different from zero, and thus the control and treatment groups are not experiencing any differential trends. However, the period directly before SGMA deviates and the confidence interval no longer contains zero.

The event study provides value to the study beyond just validating the parallel trends assumption of the DID regression model. The event study model also depicts the dynamic fluctuations of the treatment effect coefficients over time. After the passage of SGMA in September 2014, treatment effect coefficients differed statistically from zero in four distinct places. First, in the two-month period immediately preceding SGMA's implementation, period D_{+1}, coefficients increased slightly, showing signs of increased distance between groundwater levels and ground surface, or decreased groundwater elevation. In all of the other periods that preceded SGMA's passage, the 95 percent confidence intervals did not stray from a position where they bounded zero. In this period directly before SGMA's passage into law, the confidence intervals deviated from zero, indicating that the treatment coefficients were no longer statistically indistinguishable from zero. As this was the two-month period before D_0, this period occurred around November 2014. Then, in the period immediately following SGMA's passage, the treatment coefficients again trended upwards enough to no longer include zero in their confidence intervals. In two consecutive periods, D_{+2} *and* D_{+3}, the treatment coefficients fell below zero, indicating an increasing recovery of groundwater elevations. Finally, groundwater levels once again receded in the final periods of the event study, as indicated by the treatment coefficients once again increasing to positive values.

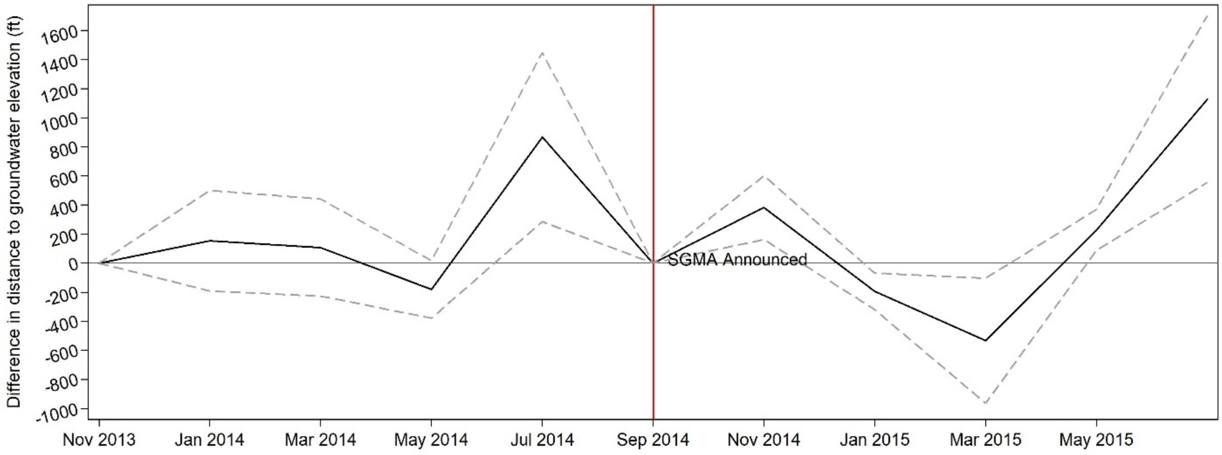

Figure 2. Event study. The figure displays the treatment coefficient estimates obtained from equation 3. The y-axis depicts distance between ground surface and groundwater elevation of basin *i* in year *y*. Upper and lower 95% confidence intervals are depicted in gray.

DISCUSSION

The study results have key implications for the analysis of SGMA's impact on groundwater withdrawal patterns in California's Sacramento Valley Hydrologic Region. The Difference-In-Differences regression model results show that the impact of SGMA on groundwater extraction was not statistically different from zero. The opposing findings from the basic and fixed effects regression model do not negate this result. In the five years following the passage of SGMA that the study's post-period consist of, there was no significant difference between groundwater trends in the treatment and control basins. The results answer the original study research question by proving that SGMA has not yet led to a measurable change in groundwater extraction patterns. In the subsequent paragraphs I will draw upon the broader academic literature to explain these findings, focusing on four distinct possible explanations. Additionally, the findings from the event study model raised questions about the validity of parallel trends assumption, but ultimately supported the DID model, and provided further detail into the groundwater extraction patterns in the period following SGMA's implementation. These overall study findings are congruent with the broader academic literature on the subject of California groundwater economics and the efficacy of SGMA. When contextualizing my study within the existing scientific consensus on the topic, this can elaborate on why these findings occurred given the ongoing circumstances affecting California's groundwater over the course of this study.

Summary

Event Study

In three distinct periods in the event study, the regression coefficients deviated to the point where their standard errors no longer contained zero. Of these three distinct moments where the coefficients strayed from being statistically indistinguishable from zero, one occurred before SGMA was implemented, and the other two occurred afterwards. The most important of these three periods is the deviation that occurred in the two-month period immediately before SGMA's passage, period D_{-1}. In order to prove the validity of the DID regression model's parallel trends assumption, the event study must exhibit pre-treatment regression coefficients that are statistically significant. Absent any explanation, this would greatly the validity of the parallel trends assumption, and undermine the validity of the entire regression model. However, understanding the political events transpiring in this period clarifies that these event study observations can largely be explained by uncontrolled variance resulting from speculation on an unfinished legislation. SGMA was introduced to the state legislature in April, four months before it ultimately passed in September. During the months that SGMA was being drafted and revised, word would have spread from Sacramento to groundwater users across California that a sweeping new groundwater legislation would soon be introduced. Since nobody yet knew the legislative scope or stringency in regulating groundwater extraction, different speculation would have caused volatile responses as evidenced by the groundwater extraction patterns. Groundwater users may have been incentivized to increase extraction to maximize profits in periods before the regulation came into effect, which would explain the increasing treatment effect coefficients. Conditional on these exogenous factors, this deviation in the period immediately preceding SGMA's passage does not invalidate the event study's confirmation of the parallel trends assumption.

The two deviations from zero after SGMA's implementation are can reasonably be interpreted as the result of unobserved stochastic influences from groundwater users' immediate reactions to the new regulation. While these two deviations provide insight into specific directional trends in the treatment effect coefficients following SGMA's passage, these results are not as meaningful as the overall results of the DID, and not worth detailed analysis.

Regression

The central research question of this study seeks to analyze whether SGMA's implementation has any impact on groundwater extraction in Northern California groundwater basins. The study results ultimately demonstrate that there has not been any statistically significant treatment effect that would indicate an anticipatory reaction to SGMA from groundwater users.

Basic regression model. The initial findings of the basic regression model indicated that, while SGMA has yet to reverse the overall trend of declining groundwater levels in California aquifers, the regulation is correlated with a slower rate of decline relative to unregulated basins. The primary regression found a statistically significant negative coefficient for the treatment effect. The interpretation of this is that treatment basins, after the implementation of SGMA, experienced a lesser degree of groundwater decline relative to the control basins. The shortened regression and the regression using log-transformed data both yielded similar results. However, the coefficient estimates from the shortened timeframe regression were slightly closer to zero than the estimates from the original regression. Several plausible explanations exist for this observed dulling of the regression coefficients. Most plausible is that it is because a narrower study time frame inherently contains fewer observations, which increases the standard error and makes differences in the pre-treatment basins more difficult to pick up. This would make the interactions of the treatment coefficients on the data appear less pronounced, as was observed in the study. Overall, the basic regression model not only supports the initial hypothesis that SGMA had a differential impact on groundwater elevations in the treatment basins, but demonstrates that the impact has benefited those treatment basins by reducing the decline in groundwater elevation. However, when fixed effects were introduced, the more complex regression lost any statistically significant findings demonstrating differential impact from SGMA's implementation on the treatment group relative to the control group.

Fixed effects regression model. The treatment coefficients in the fixed effects regression models were not statistically distinguishable from zero. Both the original fixed effects regression, and version using log-transformed data reported treatment coefficients that were not significantly different from zero. On its own, this indicates that SGMA has not had any differential impact on groundwater elevations between the treatment and control basins. When analyzed in the context of the findings from the basic regression model, the conclusion that SGMA has not led to any changes in groundwater extraction patterns in anticipation of future regulation still holds. However the findings are now more nuanced, showing signs that if these results were exaggerated, or compounded over future years, there may ultimately be significant differential impact.

Overall, the findings that SGMA has not yet been impactful on groundwater extractions are congruent with the academic literature. The extensive research on SGMA and groundwater economics show that there are many limitations, faults, or other reasons why SGMA may not be perfectly efficient in meeting its sustainability goals, especially in the years immediately following its implementation. The different explanations can be divided into two distinct categories. The first explains SGMA's shortcomings as faults in the actions of the groundwater users and their responses to the policy intervention represented by SGMA. These reasons include failure to reinvest conserved water, wariness of government regulation, and general myopic resource exploitation. The second category of explanations focuses on failures of the specific legislative features of SGMA itself. Problems such as nebulous sustainability goals, barriers to conflict resolution, lack of input from the scientific community, and bureaucracy in organizing GSAs are all reasons.

Potential explanations

Problems associated with groundwater use

Uncertain social acceptance of policy may present obstacles to SGMA efficacy. One way that the lack of SGMA impact can be explained is by the uncertainty over whether groundwater users will abide by the new legislation. Lack of cooperation from groundwater users can present significant obstacles to the GSAs achieving their sustainability goals, especially if the resistance comes from farmers that compose the majority of groundwater use (Owen et al. 2019). Central valley farmers may see SGMA as an unnecessarily burdensome regulation, and therefore be less willing to comply. Farmers in Yolo County specifically, which overlies a groundwater basin included in this study, have expressed their views on state regulations. Interviews conducted with twenty Yolo County farmers found that these farmers viewed regulations as a larger challenge to their success than drought conditions (Niles and Wagner 2017). Along with distrust of the democratically dominated state government can present burdens to the goals of SGMA being voluntarily adopted by many groundwater users in the state. Antipathy towards state government and negative views of regulation all contribute to explaining why groundwater users in Northern California did not make dramatic changes in their extraction patterns as a result of SGMA coming into effect, and why the regression did not report any differential treatment effect.

Even if farmers comply, and take efforts to conserve water or reduce groundwater consumption, it may not be sufficient to yield changes in groundwater elevation within the short time frame of the study. While the water intensity of Central Valley agriculture has decreased due to adoption of more efficient irrigation practices like drip irrigation, the water savings frequently are not used to replenish depleted aquifers. Rather, the water savings are used to expand agriculture into areas that previously had not received water, to shift production to higher value crops that use more water, or to sell in California's water exchange market (Niles and Wagner 2017). Not only does this maintain high demand for water, but it also reduces the amount of water that ultimately replenishes groundwater aquifers by increasing the proportion of water evaporates or is sequestered by crops. By decreasing the relative abundance of irrigated water that reaches groundwater basins, this practice threatens the primary source of natural recharge for California's aquifers (Criss and Davisson 1997). The most promising solution to the vulnerability of natural recharge sources is to develop new artificial recharge projects, and expand existing ones in the state. Artificial recharge can mitigate declining water tables by pumping freshwater back into the groundwater basins. To avoid conflicts with the pressing freshwater demand across the state, this water can come from diverted flood flows, stormwater runoff, or other freshwater sources that are currently not utilized for agricultural or urban water demand (Bachand et al. 2016, Kiparsky 2016).

One final explanation for the observed trends that comes from the groundwater users' side could be that the hard work and daily struggle of farming does not lend itself to participation in aspects required to achieve SGMA. Farm ownership and farm work are difficult careers that often leave workers unable to save much of their income. With average net farm incomes below the poverty line, (Blank et al. 2005) farmers may be too busy making ends meet to focus on regulations focused on goals for several decades away. Especially vulnerable, and therefore less likely to participate in early groundwater conservation as a result of SGMA, are smaller farm owners that typically receive lower profit margins (Blank et al. 2005) and migrant or seasonal farmworkers that are exposed to a number of other exogenous impacts to their health and livelihoods (Arcury and Quandt 2011). Besides leaving these workers less empowerd to focus on SGMA's relevance, these vulnerabilities also serve as an obstacle for individuals who do want to participate in the decision making process for their local GSA. The opportunity cost of time is negatively correlated with farm size. Thus, workers on smaller farms are less able to afford to take the time off for discussions amongst stakeholders or GSA meetings (Rudnick et al. 2016). Additional power asymmetries may compound this problem and diminish the proportional power of small-scale individual farm owners in the decision-making process.

There is no single causal factor that explains the absence of a positive treatment effect from SGMA on mitigating groundwater overdraft in the Northern Central Valley. Rather, it is a combination of a multitude of different factors and phenomena that collectively influenced these results. There is evidence that the actions and attitudes of California's groundwater users may explain some of these findings. However, these trends are not the result of myopia and selfishness so much as the difficult systemic conditions that constrain many groundwater users' viable options for regulatory embracement. While groundwater users certainly a factor, much of the explanation for SGMA's lack of influence is in the legislation itself and its enforcement.

Faults in SGMA itself

The most innovative and powerful aspect of SGMA's legislative approach may also be the most responsible for its lack of impact in the study period. SGMA goes about by offering significant local control of regulatory strategy within a loose statewide framework. This approach is essential to the overall efficacy of SGMA, yet it may also have some inherent drawbacks that limit the legislation's effectiveness in the immediate time period focused on in this study. Local control can reduce system flexibility (Sax 2003), or lead to a fragmented regulatory mosaic where unnecessary bureaucracy and inefficiency inhibit progressive action (Moran and Wendell 2015). The absence of state control could even be counterproductive to SGMA's mission, as it may not provide enough regulatory structure to guide GSAs in their decision making and enforcement, processes that require expert insight and evaluation to succeed (Nelson and Perrone 2016). Besides difficulties navigating the balancing act of allocating the appropriate amount of state control, another obstacle to achieving the sustainability goals of SGMA may come from the difficulty of organizing a diverse array of stakeholders into a single management agency. In order to achieve sustainability within the timeframe outlined by SGMA, GSPs must reflect the insights and experiences of a broadly diverse group of interested parties. Besides the direct input of farmers, towns, industries and other local groundwater users, GSAs must solicit input from groundwater experts, environmental groups, statewide agencies, and legal consultants in order to be most effective (Kiparsky 2016). Scientific expertise, while particularly important in these decision-making processes is typically underrepresented, and this mismatch may inhibit successful groundwater management (Gurdak 2018). At best, scientific knowledge is ensured to be reflected in CADWR's Best Management Practices documents, though the scientist's findings and insights may not be utilized. Many GSAs are already overwhelmed with trying to consolidate the opinions of their basin's many different parties of interest. Some GSAs have had to communicate with over fifty distinct parties through the process of drafting and implementing their GSP (Forsythe et al. 2018). Organizing these different stakeholders and negotiating potentially opposite views on how to manage their shared resource is an incredibly time-consuming and laborious process, which may very well take years to successfully accomplish. No doubt, the process of negotiating a single document to adhere to the needs of such diverse interests led to conflicts. Achieving sustainable management of common pool resources such as groundwater requires, among other things, active monitoring, punishments for rule breakers, and pathways for conflict resolution among the GSAs (Ostrom, 2002). While conflicts are present and cause delays, many of the tools that may mitigate these issues are not yet in place. Tools such as groundwater trading mechanisms to reduce conflict and redistribute water to where its marginal benefit is greatest take long to implement, and until these resolution mechanisms are in place, progress will be delayed. Given these constraints, and the timeline of SGMA's requirements relative to the timeframe of the study, it is understandable that the organizing effort of preparing GSAs and GSPs were prioritized over initial efforts to conserve groundwater by taking up everyone's time and energy.

Besides the inherent difficulty for groundwater management agencies to carry out regulatory requirements, SGMA was also limited by the lack of clarity in its definitions for the ultimate goals of the legislation. SGMA reports that GSAs will be evaluated on their ability to achieve sustainable yield and avoid "undesirable results" within their groundwater basin. Sustainable yield essentially refers to the maximum quantity of groundwater that can be withdrawn from an aquifer without causing deleterious outcomes such as overdraft. There are multiple different methods of calculating this value, which can have drastically different implications for the required stringency of regulation. Given this obscurity, some hydrological experts question the validity of using sustainable yield as the objective for groundwater management (Alley 2004). Employed in SGMA, the definitions of sustainable yield are inherently nebulous, and not clearly defined. This nebulous definition that underpins all of SGMAs regulatory requirements may provide legal flexibility for GSAs to evade their full regulatory responsibility, leading to incomplete groundwater protection (Miro and Famiglietti, 2018). Besides being counterproductively vague, the obscure goals of SGMA may catalyze litigation over specific interpretations of the sustainable yield definition, which are costly and time consuming (Nelson and Perrone, 2016). Legal uncertainties around SGMA's objective definitions are particularly problematic, as they force management agencies to spend time judiciously protecting against potential litigation (Moran and Wendell 2014). Avoiding lawsuits and maximizing management efficiency, requires cooperation and input from all groundwater users, even those that resist compliance (Quinn 2019). While frustratingly time-consuming, this process is essential in order to both avoid negative responses to groundwater management attempts, and to ensure that holistic policies are crafted drawing from every stakeholder's opinion. To avoid confusion or potential legal recourse, GSAs and groundwater users not incentivized to take early sweeping action, thereby preventing any noticeable groundwater elevation trends in these early years of SGMA's enforcement.

Study Limitations

The final possible explanation for the results of the study does not stem from potential issues from the groundwater users or the potential setbacks of SGMA, but from the limitations of the study design itself. One potential flaw in the study is that it has no explicit mechanism to control for exchanges in California's groundwater market. Groundwater users can extract from one basin, and sell that water to another basin, which would introduce some bias to the results. The complex water markets are outside of the scope of this study, but an important consideration when interpreting the relationship between observed trends and actual groundwater elevation patterns. SGMA, and its impacts on California's water system, are inherently complex and difficult to understand. It would be impossible to encapsulate all of the regulatory details, potential variables, and influential factors into one study, and so to yield any accurate results this study must limit its scope to only the most relevant information. Another, more parsimonious explanation is that groundwater in the study region is not extracted heavily due to hydrological conditions. The data for this study was collected from groundwater basins predominately in the Sacramento Valley Hydrologic Region, with measurements from one other groundwater basin in the North Coast Hydrologic Region, directly adjacent. Both of these areas are in the northernmost portion of the state of California, where surface water resources are much more abundant than in the rest of the state due to higher levels of precipitation (Moran and Wendell 2015). Due to increased surface water availability and precipitation levels, groundwater basins in the Northern California regions experience much less severe conditions of overdraft than their counterparts in Southern California (Chappelle and Hanak 2017). It would be harder to make significant changes in the first five years when there is not much overdraft that needs to be corrected. The narrow geographic study region has a nugatory impact on results, as even minute changes in Sacramento would have been reported by regression had they occurred, so the study results are still valid in their findings.

Future directions

The scope of SGMA's legislative focus greatly exceeds the time frame that this is able to analyze. The research framework is inherently limited to analyzing past observational data; it is not designed to predict the future of groundwater conditions in California. Over the next twenty two years until SGMA's 2042 deadline for achieving sustainable yield, groundwater conditions will undoubtedly undergo drastic transformations throughout the state. This study framework can be continuously updated with the most recent groundwater data, and can be used to actively monitor SGMA's efficacy as time winds closer to the ultimate deadline. As such it can be used as a dynamic research tool, providing insights into which basins and management styles are most successful in reaching the goals outlined in their GSPs. The study design can even be used to compare groundwater elevations in two basins that adopt different management strategies to analyze which was most effective, providing valuable insights into the efficacy of individual regulatory approaches. Besides expanding the study in its temporal scope, future work can be done to increase its geographic focus. The data from this study come from a small portion of the entire state of California. Thus, the study's results have limited meaning with regards to the diversity of groundwater management issues throughout the rest of the state. Specifically, further research should be done to extrapolate the findings from this study on the rest of California's Central Valley. While the Central Valley is responsible for the majority of deleteriously unsustainable groundwater extraction, it is also the most vulnerable to the consequences of overdraft. As such, it is imperative to continuously monitor this area into the future.

The study focuses exclusively on the management of California's groundwater resources as it specifically relates to issues of available quantity. While groundwater overdraft and its subsequent consequences are a pressing issue that must be addressed, it is unfortunately not the only threat to the safety and reliability of California's groundwater. Besides problems arising from insufficient quantity of groundwater to meet California's needs, the state also suffers from water quality impairments that have severely damaging impacts on the health, safety, and economic viability of its users. Some of the problems with groundwater quality are associated with groundwater overdraft. As excessive groundwater pumping promotes saltwater intrusion into coastal groundwater aquifers, the water becomes progressively less valuable as a resource. Other major threats to California groundwater quality are not the direct consequence of overdraft, but carry equally damaging implications for the future sustainable use of the resource. Agriculture, the major causal agent of over-extraction, is also a prominent source of contaminants that directly impact groundwater aquifers. Pesticides, fertilizers, and other chemical additives used in agriculture across the state have been contaminating groundwater resources in California for decades. Pollution is an especially prominent issue in the Central Valley, where the agricultural sector has the largest presence. The study design uses groundwater elevation measurements to evaluate the policy impact of SGMA on California's groundwater basins, but lacks any experimental design to analyze whether this water is healthy to drink or safe to use in agriculture. Future research should address the increasingly worrying trends of polluted groundwater that renders the water supply entirely unusable. Abundant groundwater supplies are meaningless if unregulated pollution renders the resource hazardous beyond hope of remediation.

Conclusion

From its inception, SGMA was designed to achieve its goals of sustainable yield using future-focused strategies individualized to the unique conditions of individual groundwater basins. Findings that indicate SGMA has not had a statistically significant impact on groundwater elevations in the five years since its implementation do not mean that SGMA has failed in its regulatory aims. On the contrary, this observed delay in observable groundwater elevation recovery is indicative that the legislation is functioning as intended. SGMA's framework recognizes that California's high farm diversity necessitates the inclusion of all stakeholders in order to be most effective. This is a fundamentally time-consuming process of recruiting disparate groundwater users into a single groundwater management regime and accommodating the widest range of needs in the GSPs. While burdensome, this stage is crucial, as it ensures that future management will be informed by the valuable insights and knowledge of individual groundwater users and stakeholders, leading to a holistic and powerful regulatory structure. Rather than hastily enforcing flawed regulations that end up being useless or counterproductive, SGMA's structure focuses on making the right decisions from the onset. Hopefully, this has led to the inclusion of historically disenfranchised groups such as tribal groundwater users and small-scale independent farmers. Whether or not this has occurred will be indicated in the efficacy and equitability with which GSAs achieve their sustainability goals.

When it was first introduced, SGMA was an unprecedented piece of legislation that corrected decades of groundwater overdraft resulting from the absence of any comprehensive statewide management regime. While groundbreaking, SGMA is not a perfect policy. Many concerns remain about whether SGMA can achieve sustainable groundwater management in California in an efficacious and equitable way. The next twenty-two years will present a multitude of unique challenges to individual GSA's as they strive to achieve sustainable yield. Even if the sustainability goals of SGMA are achieved throughout California by 2042, that only covers one distinct portion of California's vast, complex, and vulnerable freshwater supply system. Hopefully, the successes of SGMA's regulatory approach can be applied to the problems of pollution and distribution that impact other aspects of California's freshwater resources. While achieving SGMA's goals of sustainable yield is a necessary step towards protecting the state's most valuable resource, it is not on its own sufficient to ensure the protection of California's freshwater resources in perpetuity.

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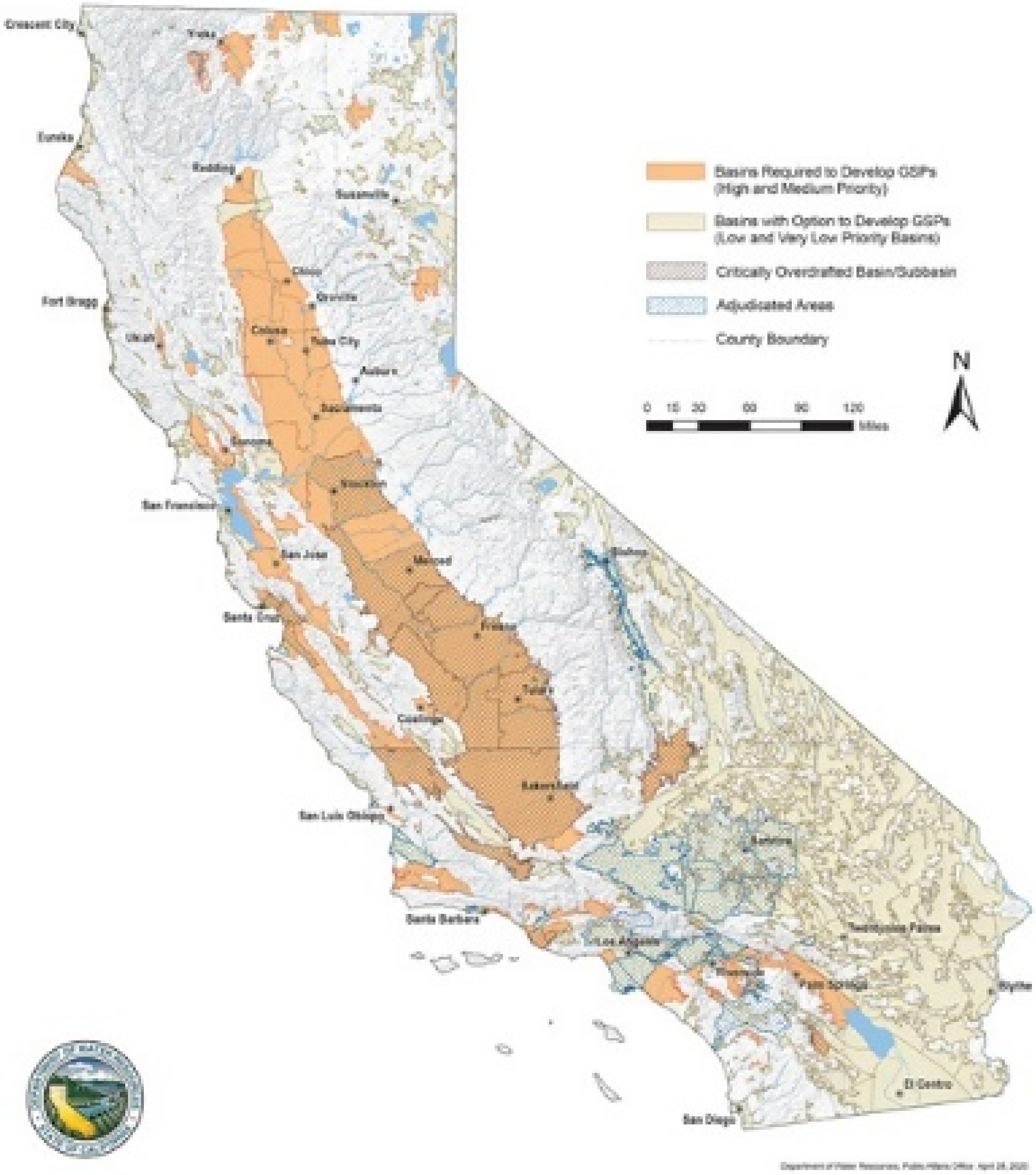
APPENDIX

Appendix A. Maps of California hydrologic regions and groundwater basin prioritization.



Source: California Department of Water Resources

Source: Public Policy Institute of California