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Groundwater and Drought Resilience in the SGMA Era

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ABSTRACT
Projections are that climate change will increase drought risk and intensity globally. Groundwater is critical during drought, but worldwide aquifers are experiencing unrecoverable groundwater declines. California is ideal to explore strategies for managing groundwater for drought resilience. Many areas rely on groundwater, yet multiple basins are in overdraft. Management was historically centered in local water districts, but in 2014, the state passed the Sustainable Groundwater Management Act (SGMA) establishing mandatory groundwater management rules. This paper discusses strategies used prior to and post SGMA to sustainably manage groundwater for drought resilience, and evaluates the effectiveness of these strategies. It highlights two recent approaches that can increase drought resilience under climate change: flood-MAR – using flood flows for both recharge and irrigation; and the development of locally sited groundwater drought reserves that can serve as a buffer during extreme droughts.

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Introduction

Projections are that over the next century regional precipitation declines and widespread warming under climate change will increase drought risk and intensity in many parts of the world (Diffenbaugh, Swain, and Touma 2015; Cook, Mankin, and Anchukaitis 2018). Moreover, severe droughts are already a reality. In 2011, Texas experienced its driest 12 months ever. Globally, drought struck several major breadbasket regions simultaneously in 2012, adding to food price instability (Center for Energy and Climate Solutions 2020). The development of long-term strategies for drought resilience is crucial.

Groundwater, an essential life-sustaining resource for billions of people worldwide, provides an invaluable buffer against precipitation variability and water shortages during drought (FAO 2016). Throughout the 1976 drought in California, it was primarily the state's groundwater resources that prevented a potential disaster (Dziegielewski, Garbharran, and Langowski 1993), and groundwater served as a critical water source during the droughts in Southeast Asia (Shivakoti et al. 2019), Brazil, and Australia (Famiglietti 2014) over the past decade. During drought, additional groundwater is withdrawn to compensate for reduced surface water availability, while at the same time lower precipitation reduces groundwater recharge. Without sufficient recharge during

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wet periods, groundwater aquifers can be depleted over time and lose their inherent ability to serve as a buffer during dry periods (Shivakoti et al. 2019).

California serves as an ideal region to explore strategies for managing groundwater basins to retain their function as drought buffers. The state's climate is characterized by periodic droughts when groundwater provides up to 60% of overall water supply (DWR 2015). Many cities and rural areas depend entirely on groundwater, such as the Central Coast where groundwater supplies 90% of all drinking water (Water Education Foundation 2020). Similar to basins worldwide, many aquifers are in overdraft (i.e. declining groundwater levels with associated loss of storage) (DWR 2015), limiting the use of this resource as a critical supply source during drought.

For over a century, there was political resistance to groundwater regulation in California, and management was historically centered in local water districts with limited rules for withdrawals (Leahy 2016). The legislature designated fifteen of these districts as special act districts (SADs) with enhanced regulatory ability to manage their basin (Water Code § 10723). An additional twenty-six groundwater basins were adjudicated (California Code, Code of Civil Procedure – CCP § 830), where users went to court to establish water rights and a court-appointed Watermaster subsequently managed the basin pursuant to the court judgment. From 2012 to 2016, California experienced the most severe drought on record with accumulated moisture deficits worse than any previous continuous span of dry years. This increased groundwater overdraft in many basins and triggered emergency actions at state and local levels (Mann and Gleick 2015). Concerned with drought-exacerbated groundwater storage loss, the California legislature passed the Sustainable Groundwater Management Act (SGMA; AB 1739, SB 1168 and 1319) in 2014 establishing mandatory management rules (Leahy 2016).

This paper explores whether strategies to manage groundwater in the SGMA era are likely to increase drought resilience. It first provides an overview of the regulatory structure of SGMA, noting the act's failure to address the significant accumulated groundwater deficits that existed in many basins prior to the act's passage in 2014. The paper then details approaches that were promoted to address water shortages under drought prior to 2014. It discusses whether these strategies, all of which continue post SGMA, are sufficient to increase drought resilience in the future. We emphasize two more recent strategies that show promise for both enhancing groundwater storage and increasing drought resilience in the SGMA era: (1) Using flood flows for irrigation and aquifer recharge, and (2) The development of locally sited groundwater drought reserves that can avoid unrecoverable groundwater level declines to local aquifers when pumping increases during drought.

Methods

We reviewed groundwater agency documents from across California and highlight management approaches from 22 including: 8 adjudicated groundwater basins, 8 SADs that became GSAs and 6 new GSAs (Figure 1). These agencies encompass a spectrum of groundwater management institutions, approaches to drought management, and locations with both urban and agricultural areas represented. Basin conditions varied and

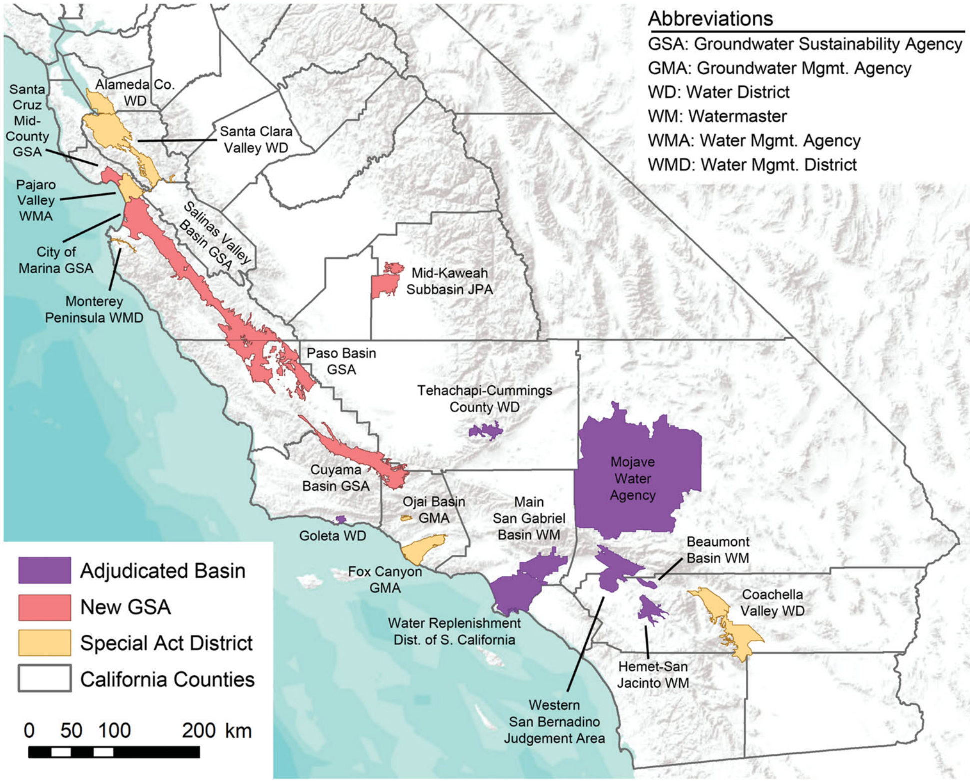

Figure 1. Southern and Central California groundwater management agencies reviewed in this article.

included problems with declining groundwater levels, accumulated overdraft, ongoing salt-water intrusion and water shortages especially during drought. Because northern California is projected to become wetter under climate change (Bedsworth et al. 2018), we focused on southern and central California agencies. Reports for the State Water Resources Control Board (SWRCB) and other research documents and technical reports provided detailed information on adjudicated basins and SADs (c.f. Langridge et al. 2016; Langridge, Sepaniak, and Conrad 2016). Post-SGMA, new groundwater sustainability plans, alternative reports, and adjudicated basin reports posted on the state's SGMA portal and on agency websites were examined. Interviews with agency staff provided additional information.

Regulatory Structure of SGMA

Overview

SGMA requires 94 groundwater basins designated by the state as medium and high priority related to their chronic groundwater overdraft to form local groundwater sustainability agencies (GSAs) and produce groundwater sustainability plans (GSPs; DWR 2019) to bring basins into sustainability. The state provides criteria to evaluate GSPs and their implementation (Water Code §§ 10727, 10728), and can step in if the criteria are not met (Water Code § 10735). SGMA also provides the fifteen SADs the option to become the GSA within their established boundaries (Water Code § 10723), which most have done. Basins adjudicated prior to 2015 are exempt from SGMA, but they must report specific data to the state, and the state may intervene in new adjudications to provide guidance (Water Code § 10720.8).

SGMA provides a unifying set of standards for bringing overdrafted basins into sustainability. The technical interpretation and implementation of these standards is left up to local agencies that must meet specific requirements for groundwater sustainability with state oversight to ensure compliance. SGMA defines sustainability as "the management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results;" which include persistent lowering of groundwater levels, significant reduction in groundwater storage, salt water intrusion, degradation of water quality, significant land subsidence and surface water depletion (Water Code § 10721(v,x)). Timelines are dependent on the degree of overdraft, and GSAs must establish specific quantitative, measurable objectives for avoiding undesirable impacts.

Problem of Accumulated Overdraft

Many basins already had a significant loss of storage by the time of SGMA's passage, limiting the availability of groundwater to serve as a strategic reserve during drought. For example, the adjudicated Mojave Basin had an accumulated storage loss of 2,500,000 AF in 1999 (USGS 2001) that is essentially unchanged in the SGMA era (Mojave Basin Watermaster 2020), and the adjudicated West Coast basin had an accumulated storage loss of 1,080,000 AF in 1951, which improved to 766,465 AF in 2019 but remains significant (Water Replenishment District 2020). SGMA avoided the issue of accumulated overdraft by just requiring "basin stabilization," and management is only required to address groundwater storage loss that may occur after the enactment of SGMA. This reduces GSP motivation to reduce the deficits accumulated prior to 2014, despite the importance of having sufficient groundwater in storage as a drought buffer.

Groundwater Management Strategies and Drought Resilience

SGMA promotes the management of water resources "for regional self-sufficiency and drought resilience" (DWR 2015), and this section discusses whether strategies promoted prior to SGMA and continued after 2014 are likely to achieve this goal. We highlight two emerging strategies, Flood-MAR and the establishment of local groundwater drought reserves that show promise post-SGMA for both increasing groundwater storage and enhancing drought resilience.

Demand Management

Conservation and water use efficiency through economic and other regulations and incentives were promoted in the past half-century, frequently as a reactive strategy to cope with water shortages during drought. They were mostly voluntary, with state

Table 1. Groundwater drought reserves strategies used by water agencies.

District	Drought reserve strategy
Goleta WD	SWP water must first be used to replenish the basin and then to establish a drought reserve for use only during a declared drought. When new service connections occur, the annual storage commitment to the drought reserve must permanently increase by 2/3rds of any release for additional uses.
Tehachapi-Cummings County WD	Imports SWP water for recharge. A 2011 agreement requires water purveyors to put a 5-year water supply into the basin to serve as a drought reserve. This can be accumulated over a 10-year period. Agricultural users are not required to do this, but their incentive to reduce pumping is the cost of the water.
Main San Gabriel WD	Has a program to purchase 1000 AF of water over 10 years for "worst case" drought conditions (defined as 15 years under 2012–2016 drought conditions).
Monterey Peninsula WMD	Negotiated with Salinas Valley growers to use purified irrigation return water from overflow ponds for recharging the neighboring Seaside basin. In turn, some of this water was reserved for growers to use during a drought.
City of Marina GSA	Requires that a minimum groundwater reserve of 15% of its available supply be retained to ensure the long-term protection of the City's water supply. If demand exceeds this amount, new development cannot proceed until conservation or new water sources can offset the new demand.
Santa Cruz Mid-County GSA	Formed an agreement between two of its member agencies. One agency reliant on local surface water receives significant stormwater in wet years, some of which will be diverted and sold to the other agency that relies on groundwater, who then reduces pumping and stores water for use in drought.

grants sometimes used as incentives. Yet, research by the Alliance for Water Efficiency (2020) showed statistically significant savings during mandatory statewide drought restrictions, while calls for voluntary conservation during non-drought periods generally did not. However, conservation rules in California that were required during drought were mostly rescinded after the drought ended, as occurred during the 2012–2016 California drought (SWRCB 2018). New legislation in 2018 has called for the creation of new urban efficiency standards by 2023 (SB 606 and AB 1668). Conservation can be a powerful tool to promote the goal of drought resiliency, but with a caveat that a key strategy to achieve that goal is to reserve some conserved water during wet periods to be used solely as a buffer during dry periods.

Other strategies to control or influence water demand and pumping during both drought and non-drought periods were less frequent and more limited in scope prior to SGMA. They included: withdrawal and use permits, drilling bans, establishing a groundwater rights system with assigned volumes, electricity pricing (affecting pumping costs), groundwater replenishment fees and pumping taxes (often where a pumper withdrew in excess of their allocation), land fallowing, and the regulation of drilling companies. Such demand management strategies are an important approach to bring a basin into sustainably, and they can also be used to contribute to establishing drought reserves if water demand is maintained below available supply (see City of Marina GSA in Table 1).

While demand reduction strategies are becoming more prominent under SGMA, this approach is still uncommon. For example, only 20 percent of GSPs in significantly overdrafted basins in California's Central Valley are focusing on managing demand (PPIC 2020). Within the Central Coast, only 3 out of 20 basins have announced plans to regulate water allocations in their GSPs. Another issue is that in some basins demand hardening has occurred where there is a reduced ability during future droughts to enact emergency conservation measures. For example, in Santa Cruz County efficiency-based conservation measures have almost reached their limits.

Supply Management

Prior to SGMA, increasing water supplies was a major groundwater management focus to avoid having users reduce withdrawals, and this continues. The development of new water supplies includes imported water, recycled water, and desalinated water. While these supply sources can contribute to recharging basins and developing drought resilience, each also has limitations.

Imported surface water, primarily from California's State Water Project (SWP), was and remains a dominant water source for many Southern California agencies and some coastal districts. A large number of adjudicated groundwater basins (21 out of 26) and SADs (7 out of 15) continue to be reliant on this water (Langridge, Sepaniak, and Conrad 2016; Langridge et al. 2016). Under climate change and additional environmental constraints, imported water is projected to be less reliable and more expensive in the SGMA era (Harou et al. 2010). Groundwater agencies are therefore trying to increase recycled water and desalinated water to diversify their supply with more "drought proof" sources.

Recycled water was gradually promoted pre-SGMA as a drought-proof water source. Its annual use gradually increased from 175,000 acre-feet/year (AFY) in 1970, to 669,000 AFY in 2009. However, it still represented only 7.1% of urban use and 0.7% of agricultural water use (Pezzetti, Mills, and Cano 2018). The SWRCB has nevertheless set a target of achieving 2.5 million AF of recycled water statewide by 2030 (SWRCB 2012). Examining the increase in recycled water since 1970, Pezzetti, Mills, and Cano (2018) point out that the 2009–2015 increase in recycled water was lower than expected, due in part to mandatory urban water use reductions during the 2012–2016 drought that impacted flows to wastewater treatment plants. This suggests recycling is not necessarily a panacea as a drought-proof water supply source. Other concerns with recycled water are the costs and the distance from wastewater treatment plants.

Desalinated water can also provide an additional source of fresh water and multiple large desalination facilities along the California coast continue to be both proposed and constructed as a potential "drought-proof" supply (Cooley and Donnelly 2016). There were 11 desalination plants in the state in 2019, and in 2018 the legislature approved $34.4 million in grants for 8 new desalination projects (Water Education Foundation 2018). While the cost of desalination has fallen over time, it remains an expensive water-supply option. Additional challenges include that more energy is required to produce water from desalination than any other supply option; it produces highly concentrated salt brines that are difficult to dispose of; it can pose a threat to marine organisms, and the development of desalination facilities is frequently controversial.

Recharging Aquifers

Overview

The recharge of aquifers is critical for groundwater to serve as a water source during drought. Recharge occurs naturally when water percolates into an aquifer from surface water sources. Recharge also can occur when other water supplies are used in-lieu of groundwater. For example pre-SGMA, the Monterey Peninsula Water Management District and the Pajaro Valley Water Management District established coastal distribution systems where agricultural groundwater users are provided with recycled water for their crops in lieu of using groundwater.

Recharge can also occur through managed aquifer recharge (MAR) under controlled conditions, also used pre-SGMA. Techniques to get water underground include: (1) spreading, where artificial streams and ponds allow for water to trickle into the ground; and (2) injection wells, where water is directly injected underground. Examples of MAR approaches include the Santa Clara Valley WD (SAD) that utilizes nearly 400 acres of recharge ponds and 91 miles of controlled instream recharge to recharge approximately 100,000 AF annually (Corbett 2018), and the Water Replenishment Dist. of S. CA with 3 seawater intrusion barrier projects that recharge about 70,000 AFY by spreading basins and 30,000 AFY by injection. Since the 1960s, implementation of MAR strategies worldwide has accelerated at a rate of 5% each year but is not keeping pace with increasing groundwater extraction (Dillon et al. 2019).

Flood MAR

A recent strategy for recharging aquifers, flood-MAR, is attracting increasing attention as an approach where flood flows can be used for *both* MAR as well as for irrigation in-lieu of using groundwater. Bachand et al. (2016) found that integrating flood flow capture with irrigation in California's agricultural San Joaquin Valley was more cost-effective than just using groundwater pumping to irrigate land. The risk of contaminating groundwater may be mitigated with source control and sediment detention basins (Ghasemizade et al. 2019). O'Geen et al. (2015) used data on soils, topography and crop type, to develop a spatially explicit index of the suitability for groundwater recharge of land in all California agricultural regions. Kocis and Dahlke (2017) analyzed the magnitude, frequency, duration, and timing of high-magnitude streamflows, finding that in an average year significant flows are available, and could be used for both groundwater recharge and irrigation.

Prior to SGMA, on-farm recharge in surplus flow seasons was informally used in areas of the San Joaquin Valley. With SGMA mandates for sustainability there is a shift in grower receptivity to this practice. As an example, the Mid-Kaweah GSA is designing several on-farm programs to both increase recharge along with irrigating suitable crops, and including a mandatory program where landowners may be required to dedicate a designated percentage of their lands for winter/spring recharge in years with surplus flows (Mid-Kaweah GSA §7.3.4, 2020).

Groundwater Banking

Large groundwater banks that act as an intermediary in the transfer of water from one site to another can be used to create drought resilience with some important caveats. Prior to SGMA, banks for off-site parties were developed in California, including a state groundwater bank after the 1976 drought that was subsequently turned over to non-state entities. These banks serve as investor run storage facilities at one site where they receive and deposit water in wet years that can subsequently be withdrawn as needed and transported for use at a different site, and are they are generally used by large farming operations and water districts. For example, the sizeable Santa Clara Valley Water District banks water in the Semitropic Groundwater Bank located far south.

Problems with the large groundwater banking operations include: withdrawals for off-site parties can affect neighboring local users (Hanak and Stryjewski 2012), the water transfers that are frequently involved can have problematic land use consequences, and importantly, banked water does not have to be specifically reserved for use during inter-annual droughts or to avoid unrecoverable losses of storage during such droughts. Moreover, earlier models failed to consider the impacts of future climate change on the availability of surface water. Recent research is examining how to incorporate relevant impacts into the planning and management of this process (Zhang 2015).

Local Drought Reserves for Drought Resilience

The recharge of aquifers is critical for groundwater to serve as an alternative water source during drought. However, simply putting water back in the ground will only create drought resilience if that water is reserved for emergency drought use. Establishing local drought reserves can avoid the loss of storage that frequently occurs with unrecoverable groundwater declines from increased pumping during drought. Groundwater reserves can also mitigate water shortages for local communities during drought when surface water supplies are reduced. While seemingly obvious as an approach to creating drought resilience, very few management agencies developed local groundwater drought reserves prior to SGMA. In contrast to the large off-site groundwater banks, local banking in the SGMA era is beginning to include requirements that some storage be designated specifically for use during drought. Approaches vary and Table 2 highlights examples of several strategies for such local "drought proofing" (Kabat et al. 2005).

Discussion

Groundwater is an essential source of supply for many communities, and is critical to meet water demands during drought. The conundrum, both globally and in California, is that many basins are in overdraft with associated impacts, and absent robust strategies to build drought resilience this loss of storage will be exacerbated under climate change. SGMA provides important requirements to manage groundwater basins sustainably, and many GSPs demonstrate increased efforts to achieve this goal. Table 1 summarizes trends that if continued in the SGMA era can assist in better preparing the state and local communities to cope with future extreme droughts under climate change.

Management plans pre and post-SGMA frequently focused on obtaining new sources of water, groundwater recharge, use of large groundwater banks, and conjunctive use of surface and groundwater. While each of these strategies is important to sustain aquifers, the ongoing decline in groundwater storage suggests that more is required. Scholars note that having sufficient groundwater in storage increases the ability for groundwater dependent regions to cope with water supply variability and can enhance drought

Table 2. Summary of pre- and post-SGMA groundwater management strategies.

Strategy	Pre-SGMA	Post-SGMA
Planning for groundwater sustainability	Primarily voluntary sustainable groundwater management planning with some financial incentives	Mandatory management to achieve sustainability for basins in major overdraft Adjudicated basins must report basin conditions, storage & water used or available for recharge.
Conservation	1976 Drought – voluntary conservation 2007–2009 Drought – mandatory 2012–2016 Drought – mandatory 25% reduction for urban users – rescinded 2017	New bills in 2019 direct water agencies to limit customer's indoor water use to 55 gallons per person per day, down to 50 gallons by 2030
Demand management	Widespread focus on water conservation, especially during droughts (voluntary in 1976, mandatory in 2007–2009 and 2012–2016 droughts). Almost no caps on pumping.	Continuing emphasis on conservation, but efforts viewed as nearing limits in many groundwater-dependent areas. Caps on pumping increasing in GSPs to comply with SGMA (but still limited)
Supply management	Heavy reliance on imported water Recycled water use grew to 669,000 AF in 2009 11 desalination plants, controversy over construction of new plants	Emphasis on diversifying supply Recycled water projected to be 1,250,000 AF by 2030 Funding for 8 new desalination plants, controversy over new plants continues
Aquifer recharge	MAR using spreading basins and injection wells	Increased use of Flood MAR for recharge and irrigation
Large groundwater banks	Used to store imported water that can be withdrawn as needed and transported for use at a different site.	Continued use both seasonally and during drought for large agencies.
Local groundwater reserves	Goleta WD & Tehachapi-Cummings County WD establish locally sited reserves for emergency use only during drought	Increasing agency use of locally sited groundwater drought reserves. Approaches vary. Under SGMA, some set development caps below sustainable yield to create a drought reserve. Others establish a drought storage commitment.

resilience (Langridge and Daniels 2017; Gaupp, Hall, and Dadson 2015). A significant limitation is that SGMA does not address already existing accumulated overdraft, limiting groundwater in storage that may be needed during future extreme droughts.

According to the IPCC, the array of potential adaptive responses available to human societies is very large, including technological, behavioral and managerial strategies (Pachauri et al. 2014). We emphasize two more recent approaches to manage groundwater in the SGMA era that stand out as supporting greater drought resilience. First, Flood-MAR emphasizes using increased flood flows projected under climate change for the double benefit of recharging aquifers and using the water for irrigation so farmers can reduce groundwater withdrawals. Many regions around the world exhibit decadal and other multiyear cycles of extreme precipitation and Flood-MAR can be applicable to these areas; it has recently been extended to Italy (Rossetto et al. 2018). Second, establishing local drought reserves can ensure that agencies will have groundwater specifically available during future extreme droughts. Both of these strategies appear to be growing in the SGMA era.

While many drought adaptation strategies are proposed, the effectiveness of various options to fully reduce risks for vulnerable water-stressed areas during extended and intense drought periods remains understudied. Important questions for future research include (1) under what demographic, economic, and/or ecological conditions do basins adopt more sustainable drought management practices under SGMA and (2) how can the promising groundwater management strategies emerging under SGMA in California be transferred to other regions worldwide?

Conclusion

Adapting to future increased drought conditions under climate change will be challenging for all basins. Our research points to some progress post SGMA to improve groundwater management with some challenges under widely used strategies, and the need for additional approaches that more explicitly address drought resilience. Where precipitation variability and increased extreme events are projected for a region, we point to an increased focus on Flood-MAR and local groundwater drought reserves as warranted for some basins to better prepare proactively for more severe droughts under climate change.

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