MANAGEMENT OF GROUNDWATER AND DROUGHT UNDER CLIMATE CHANGE

A Report for:

California's Fourth Climate Change Assessment

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PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report advances understanding of drought and groundwater management including current and newer strategies being used to address future droughts under climate change.

ABSTRACT

Climate change projections are for higher temperatures and extreme droughts by the end of the 21st century. This will alter the natural recharge of groundwater, including decreased inflow from runoff, increased evaporative losses, and warmer and shorter winter seasons, impacts that are likely to exacerbate already existing groundwater overdraft in many basins. Additionally, the imported surface water that can be delivered from the Central Valley Project (CVP) and State Water Project (SWP) to areas reliant on this water for groundwater recharge and consumptive use is projected to be less reliable and more expensive. Yet groundwater is a critical water supply source during drought when it compensates for reduced surface water supplies. The need for proactive adaptation strategies to address the extreme droughts projected under climate change are frequently discussed, yet there are limited examples of such groundwater management strategies. This paper therefore explores:

1) How groundwater management agencies are planning for drought

2) What new approaches are currently being used that show promise for addressing the more extreme droughts projected under climate change?

First, the paper provides a review of the research on drought and groundwater management including strategies currently used to address drought. Second, case studies illustrate newer and varied approaches being used to reduce drought impacts. Highlighted are the different approaches used by groundwater managers to both increase storage and develop drought reserves. These strategies can help to reduce vulnerability to the extreme droughts projected under climate change. Two additional case studies discuss the limits of a drought reserve strategy and indicate that more is needed under climate change to address the range of basin conditions and the varied needs of communities reliant on groundwater.

Several overall groundwater management trends are noted:

- A shift from voluntary to mandatory requirements for the sustainable management of groundwater after the 2014 passage of SGMA;
- An increase in the use of recycled water from 190,000 AF in 1976 to 714,000 AF in 2016 that can be used for groundwater recharge to enhance storage;
- An increase in the development of groundwater drought reserves;

Suggested future research projects include:

- Benefits and challenges of long-term strategies to manage groundwater under climate change and extreme droughts;
- Practices implemented during past droughts that were effective in reducing drought vulnerability in subsequent droughts

The different approaches presented in this paper to increase groundwater storage specifically for use during drought are important first steps to proactively manage groundwater to adapt to the higher temperatures and future extreme droughts projected under climate change.

Keywords: drought, climate change, groundwater management strategies, drought reserves

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HIGHLIGHTS

Highlights from our review relevant to current planning for drought are listed below.

- Climate change projections are for more extreme droughts and higher temperatures by the end of the 21st century.
- An explicit mention of groundwater droughts is missing from standard drought categories
- A snow drought, where higher temperatures under climate change reduce snowmelt and change the timing of runoff, will affect imported surface water supplies that many groundwater basin managers rely on for consumptive use and for groundwater recharge.
- Drought planning and groundwater management plans rarely intersect. Drought plans give limited attention to sustaining groundwater over the long term, while groundwater plans provide limited attention to drought including the extreme droughts under climate change.
- Limited explicit incentives exist in SGMA for pro-active long-term strategies that account for the extreme droughts projected under climate change.
- Imported surface water remains a major supply source for water purveyors, but the use of recycled water and other water supply sources (e. g. stormwater capture, desalination) have increased since the 1976 drought.
- Regulating groundwater withdrawals are generally modest in scope and less employed than supply-side groundwater management strategies.
- Approaches to recharging aquifers have increased including for example flooding fields for both irrigation and recharge.

The following are several drought management trends that, if continued, can assist in better preparing the state to cope with future extreme droughts under climate change (Table 1).

Table 1: Drought Management Trends

1976 Drought	1987-1992 Drought	2001-2009 Drought	2011-2016 Drought
Voluntary Conservation	Voluntary Conservation	Mandated Conservation SBX-7-20x20x20	EOB-29-15: Mandatory Conservation-25% reduction for urban users
Recycled water use ~190,000 AF	Recycled water use ~279,000 AF	Recycled water use ~669,000 AF	Recycled water use ~714, 000 AF
	Sustainable groundwater management – voluntary plans		2014 Sustainable Groundwater Management Act (SGMA) – mandatory requirements
	Goleta establishes a local drought reserve		Increasing use of local drought reserves

Case studies demonstrate an increase in sustainable groundwater management strategies that can increase drought resilience under climate change (Table 2).

Table 2: Approaches to Increasing Groundwater Storage and Adapting to Future Droughts

Basin	Approach
Orange County Water District	Researched and then managed the basin for groundwater levels to be sustained within an acceptable range that could avoid future and unrecoverable groundwater declines during extended drought periods
Main San Gabriel Watermaster	Established a Stormwater Augmentation Program to help manage the basin's water supplies under "worst case" drought conditions (defined as 15 years under the same condition as the 2012-2016 drought) Established a goal to purchase 100,000 AF of water over 10 years and store as a reserve for future dry periods and "worst case" droughts
Tehachapi Watermaster	Established a recharge component for imported surface water that requires purveyors put a 5-year water supply into the basin to serve as a drought reserve
Monterey Peninsula Water Management District	Negotiated with growers to use water from an overflow pond for groundwater recharge, and in exchange growers have access to a drought reserve supply from the groundwater basin
Goleta Water District	In 1991 began to use SWP water to recover the groundwater basin to 1972 levels (where there were no unacceptable impacts) and then established an additional groundwater reserve to be used only during a defined drought

These different approaches to increase groundwater storage specifically for use during drought are important first steps in adapting to the increasing temperatures and more extreme droughts projected under climate change.

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1: Introduction

1.1 Background and Central Questions

Climate change projections are for more extreme droughts by the end of the 21st century (Mastrandrea et al. 2009; Faunt et al. 2009; IPCC 2013). During drought, groundwater is a critical resource that provides a much larger total (60 percent) of California's overall water supply to compensate for reduced surface supplies and decreased soil moisture (Alley, Reilly and Franke 1999; Gleeson et al. 2012; Famiglietti et al., 2011; Bartolone and Federis 2014; DWR 2015b). The problem is that many groundwater basins in the state are already experiencing ongoing and long-term declines in groundwater levels (Familietti et. al. 2011; DWR 2015b). These declines are more severe during dry periods (Harter and Brewster 2018) and are frequently not recoverable during subsequent wet periods, contributing to the long-term overdraft.

Climate change is projected to result in higher temperatures that will increase surface drying (Collins et al. 2013, Seager et al. 2015; Trenberth, Fasullo, and Shepherd 2015, Williams et al. 2015, Diffenbaugh et al. 2015). This could alter the natural recharge of groundwater and exacerbate groundwater storage deficits. Warmer and shorter winter seasons will lead to more precipitation occurring as rain (instead of snow), reducing reservoir storage, and more short-term high flows will require adaptation to the faster runoff. This will decrease the reliability of imported water delivered from Central Valley Project (CVP) and the State Water Project (SWP) reservoirs and used for active and in-lieu groundwater recharge by many basins. Developing long-term policies to manage groundwater that account for the more extreme droughts projected under climate change is crucial.

Research on the dynamic relationship between groundwater, drought and climate change is relatively limited compared to surface water studies (Brouyère et al., 2004; Hsu et al., 2007; Bates et al., 2008, Clifton et. al. 2010). Moreover, the effects of climate change on groundwater quantity and quality remain uncertain (Jiménez-Cisneros et al. 2014). While both state and local agencies address drought planning and mitigation, the traditional approach is primarily reactive, typically waiting until a drought is already in progress to monitor weather conditions, assess vulnerabilities and impacts, and implement conservation actions through water shortage contingency plans that rarely address groundwater (Mastrandrea et. al. 2009; Clifton et. al. 2010). Moreover, as occurred during California's 2012-2016 drought, conservation measures instituted during drought are generally rescinded after a drought (SWRCB 2016). Many scholars and practitioners discuss the need for proactive drought mitigation strategies and the importance of groundwater as a supply source during drought (Walker, Hrezo and Haley 1991; Dinar 2001; Saenz et al. 2009; Wilhite et al. 2014), yet most drought mitigation strategies are focused on overall supply reliability. There are fewer examples of strategies to manage groundwater that are specifically focused on reducing drought vulnerability, and very few examples of managing groundwater to account for the extreme droughts projected under climate change.

Our paper therefore explores:

1) How groundwater management agencies are planning for drought

2) What new and innovative approaches are currently being used that show promise for addressing the extreme droughts projected under climate change?

Our paper is organized in five sections.

- Section 1 provides an introduction.
- Section 2 reviews the literature on drought, drought management and groundwater management in California, and the strategies being currently used to manage groundwater under drought and climate change.
- Section 3 examines how five groundwater basins manage groundwater to increase storage and reduce drought vulnerability. The emphasis is on more innovative strategies, and particularly on the creation of drought reserves
- Section 4 discusses the limits of a drought reserve strategy
- Section 5 discusses our findings.

1.2 Research Approach

Our general findings and case studies focus on basins that are under the management of agencies that manage adjudicated groundwater basins and agencies initially created by the legislature as Special Act Groundwater Districts. The studies were selected based on detailed reports to the State Water Resources Control Board (SWRCB) that provided detailed information on these two institutional approaches for managing groundwater (Langridge et. al. 2016a, b), as well as follow up interviews we conducted with agency managers regarding current adaptation planning for drought under climate change.

An adjudicated water basin is where a court evaluates the claims of all water users taking water from the defined groundwater basin, quantifies the available supply, assigns water rights, apportions the groundwater among the claimants with specification of some conditions to manage the basin, and appoints a Watermaster to manage the basin pursuant to the court decree. Adjudicated basins cover much of Southern California including Los Angeles and Inland Empire as well several coastal areas, all of which will be seriously impacted by a future extreme drought (Figure 1).

Figure 1: California's Adjudicated Groundwater Basins

In comparison, the Special Act Groundwater Districts were established by the legislature for overall management of a basin and are located throughout the state with a concentration along the coast (Figure 2). Many exhibited significant water supplies shortages during the 2011-2016 drought. The Special Act Groundwater Districts discussed in this report are now Groundwater Sustainability Agencies under the 2014 Sustainable Groundwater Management Act (SGMA). Overall, the selected basins represent diversity with respect to geographic location, land use and demographics.

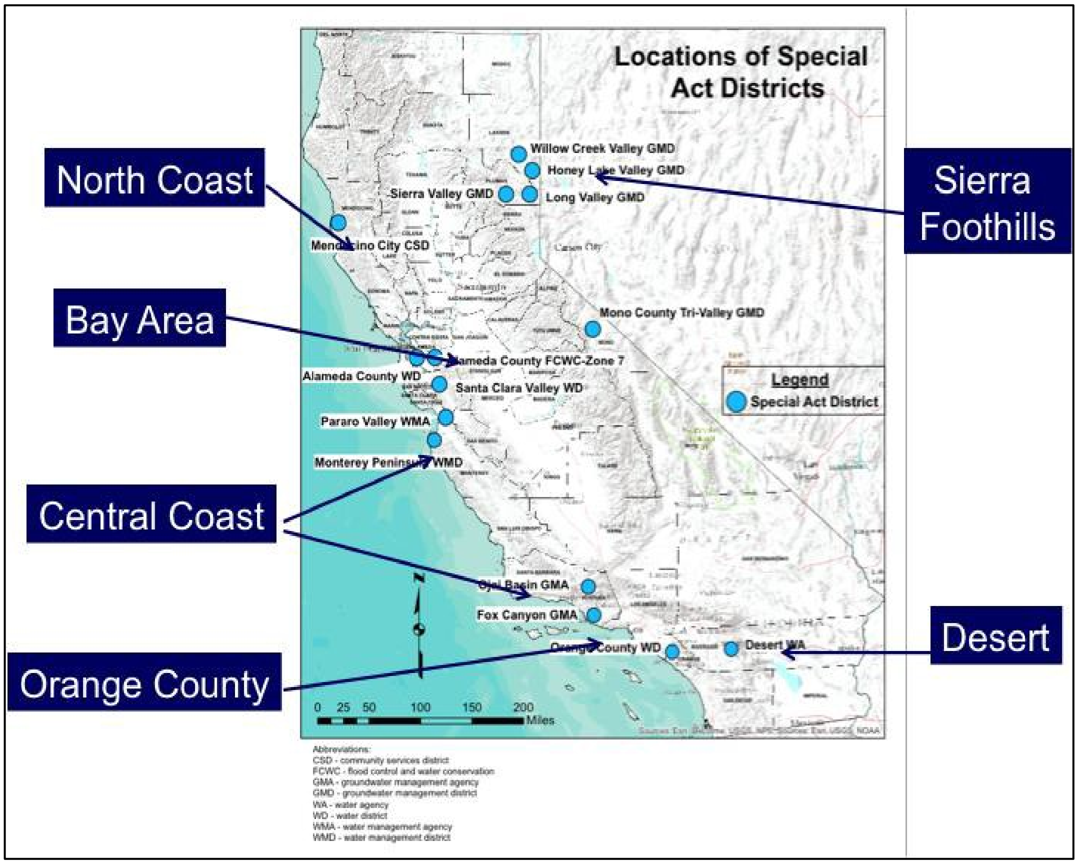


Figure 2: California's Special Act Groundwater Districts

1.3 Data Sources

For the background and literature review, searches for "groundwater," "drought" and "climate change" were conducted. For example, one search used the Web of Science Core Collection database to identify the most frequently cited papers for "Groundwater" and "Drought (N=2,097), refined for California (N=119) and most cited in the field (N=4). We refined the search to review the most frequently cited article. Another search mined the USGS's publication database for Groundwater and Climate Change (n=310), filtered by State (California).

Data sources for our general findings and for the case studies included judicial judgments and stipulated agreements from adjudicated basins and enabling legislation for Special Act Districts in California; Watermaster reports; federal, state, and local agency reports; consultant reports; legal reports; media; and academic and trade journals. Telephone interviews were conducted with basin managers and consultants. Each case study was reviewed by a stakeholder in the basin, often the basin manager or technical staff.

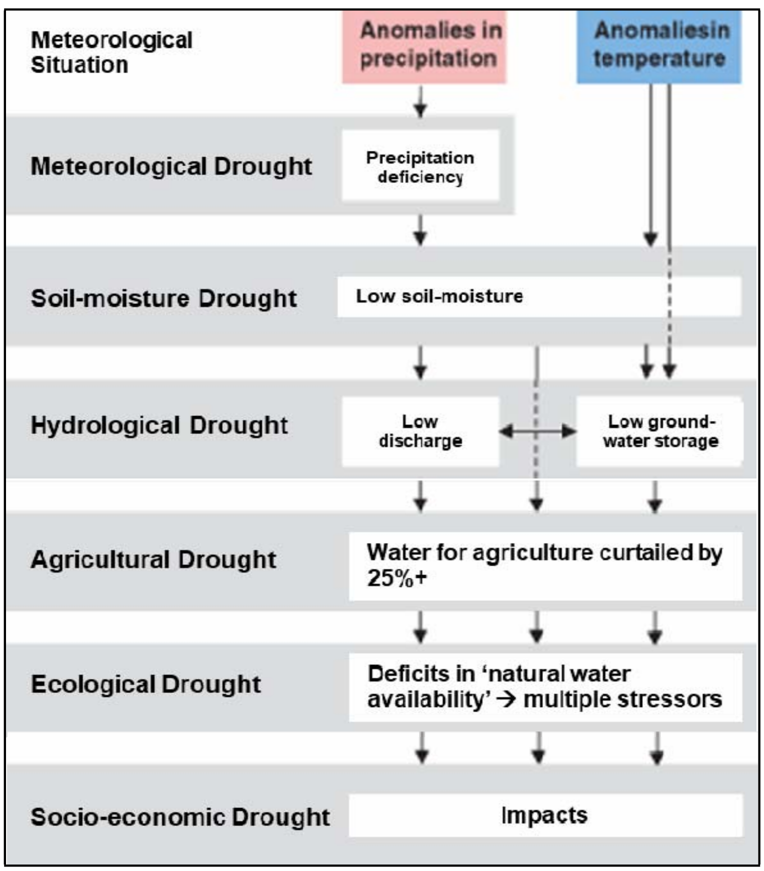
2: Background and Literature Review

2.1 Drought

2.1.1 Drought Definitions

There is no definitive definition of a drought's onset or when it officially ends. This creates challenges in planning for needed water supplies during a dry period. One definition of 'drought' is, "A sustained period of below-normal water availability … with spatial and temporal characteristics that vary significantly from one region to another" (Van Loon 2015: p. 361). In general, deficits in any of the following three processes can be tied to drought propagation: precipitation, soil moisture, and streamflow or runoff—all with implications for groundwater storage.

Many drought indices were developed in recent decades to characterize and compare aspects of drought severity, duration and/or spatial extent in a consistent manner (Mishra and Singh, 2010). These include indices focused on meteorological, hydrological, agricultural and other dimensions of drought. Each drought characterization in Figure 3 relies on anomalies in precipitation or temperature, or a combination of both. A 'hydrological drought,' for example, is where there are deficits in discharge or runoff (Van Loon 2015; USGS 2017; Wehner 2017). Researchers also include ' socioeconomic drought' where water supplies cannot satisfy demand, leading to societal, economic, and environmental impacts (Dinar and Mendelsohn, 2011; Zseleczky and Yosef 2014; Van Loon 2015).



Source: adapted from Van Loon (2015)

Figure 3: Drought Categories and Interactions

An explicit mention of groundwater drought is missing in Figure 3. One method to measure groundwater drought is via a network of wells that monitor the depth of the water table. The data is then compared to the historical record of the well. Another method to monitor groundwater storage is via satellite observations (NOAA 2018). Also note that groundwater drought is often discussed in the context of 'hydrological drought' where "a groundwater drought often shows long periods of below-normal groundwater levels" (Van Loon 2015: p. 364). Hydrological drought can lead to groundwater drought through changes to baseflow, and through changes to runoff, and subsequently to groundwater recharge. Bloomfield and Marchant (2013) discuss a methodology for a Standardized Groundwater Level Index (SGI) that can potentially provide a quantification of groundwater drought.

The additional concept of 'snow drought' for snow-dominated mountain watersheds is also of significance for the state as the climate changes. Hatchett and McEvoy (2017) define 'warm snow drought' as "above or near average accumulated precipitation coinciding with below average snow water equivalent at a point in time." In comparison, 'dry snow drought' is defined as "below average accumulated precipitation and snow water equivalent at a point in time." Snow drought is discussed further in section 2.1.3.

2.1.2 Climate Change Global Processes and Drought

Anthropogenic climate change has the potential to produce anomalies in temperature and precipitation, which are critical physical drivers of drought. Glantz et al. (1991) point to local and state level changes in drought intensity and severity as increasingly linked to global processes, collectively referred to as teleconnections and defined as atmospheric and oceanic interactions between widely separated regions.

Beyond an average warming trend globally, the Intergovernmental Panel on Climate Change (IPCC) states: "it is virtually certain that there will be more hot extremes" (Collins et al. 2013: p. 1065). In the US, scientists assert, with very high confidence, that extreme temperatures are projected to increase more than the averages, with increasing number of days per year above 90°F. As global temperatures rise, under the worst-case climate scenario (RCP 8.5), scientists expect anthropogenic warming to exacerbate surface drying and soil moisture deficits (Collins et al. 2013: p. 1032, Seager et al. 2015; Trenberth, Fasullo, and Shepherd 2015; Williams et al. 2015, Diffenbaugh et al., 2015). While drought is a common and recurrent feature of the North American climate, as temperatures increase scientists also project decreases in surface soil moisture (Cook et al. 2007; McCabe et al. 2004; Nigam et al. 2011; Schubert et al. 2004a, b; Seager et al. 2005; Wehner et al. 2017).

2.1.3 California Droughts

Historically, great droughts punctuated California's semi-arid Mediterranean climate. Tree-ring studies show that California often experienced long periods of dryness, sometimes followed by several wet years. A long, mid-Holocene drought occurred, and two mega-droughts persisted in the medieval era between AD 900 and AD 1400. These were complemented by large frequent wildfires, and were much longer and more severe than any the state experienced in the last 200 years. Mega-droughts in the Southwestern US peaked during the exceptionally dry 12th, 13th and 15th centuries (Cook et la. 2004). Even during "wetter" periods like the 20th century, extended and multi-year dry conditions were experienced (Griffin and Anchukaitis 2014).

The recent effects of climate change on precipitation in California are more difficult to determine. Berg and Hall (2015) analyzed the results of 34 global climate models and concluded that while "models disagree on the sign of projected changes in mean precipitation" for the state, "in most models the change is very small compared to historical and simulated levels of inter-annual variability." However, rising temperatures will exacerbate drought conditions. Cayan et al. (2008 p.21) found that in recent decades the state has become measurably warmer, and "temperatures are projected to rise significantly during the 21st century". From 2014 through 2017 temperatures were notably warm with 2014 being the warmest on record for the state (Office of Environmental Health Hazard Assessment 2018). In the 2011-2016 drought, record high temperatures and a long-term warming trend intensified the impacts of limited precipitation (Berg and Hall 2015a; Diffenbaugh, Swain, and Touma 2015; Williams et al. 2015; Seager et al. 2015).

Local and imported surface water supplies will also face disruptions due to climate change. For example, impacts on Colorado River flows are predicted to be serious, especially if substantial reductions in greenhouse gas emissions do not occur (Udall and Overpeck 2017). Recent estimates of Colorado River's water flow sensitivity to warming temperatures suggest a decrease in flow depending on the modeled changes. Continued business-as-usual (BAU) warming will drive temperature-induced declines in river flow, conservatively ~20 percent by midcentury and ~35 percent by end-century. This will have a particular impact on districts in Southern California that rely on imported surface water from the Colorado River.

Mountain snowpack, referred to as snow-water content, is a critical source of water for many California areas. The snowpack is a natural reservoir of frozen water that gradually melts beginning in the spring and flows into reservoirs managed by the SWP and the CVP and local areas. Sierra Nevada mountain snowpack, relied on by the SWP, accounts for about 30 percent of the surface water used by communities, agriculture and industry across California. Many groundwater basin managers rely on the imported surface water for consumption, and importantly for groundwater recharge (Reich et al. 2018).

Climate change models project that in the Sierra Nevada under a BAU scenario, temperatures will experience a 7 degree Fahrenheit rise in average springtime temperatures and a 64 percent drop in average springtime snowpack volume by the end of the 21st century. The higher temperatures will also change the timing of runoff and consequently affect reservoir storage (Reich et al. 2018). Moreover, evidence demonstrates that climate change is already affecting Sierra Nevada snowpack. During 2011–2015, it was 25 percent smaller than it would have been without human-caused warming, and 2016–2017 snowpack was 20 percent smaller. Models also project that future climate change will cause even greater reductions in snowpack in extreme years (Reich et al. 2018).

Under end-of-century BAU warming, in a drought period like 2011–2016, projections show that the Sierra Nevada will lose 85 percent of its snow, and in a wet year like 2016–2017 it will lose two-thirds of its snow (Reich et al. 2018).

In line with these projections, the California Department of Water Resources (DWR) predicts that "SWP deliveries will decrease by 5.6 percent due to climate change and environmental concerns in the delta" depending on adaptation strategies (Kerckhoff et al. 2013). Additionally, SWP water will likely cost more in the future (Tanaka et al. 2011; Harou et al. 2010).

It is notable that SWP deliveries were reduced significantly during the 2011-2016 drought. A comparison of fall 2017 measurements after that wet year to pre-drought fall 2011 measurements demonstrates the lingering effects of the 2012 – 2015 drought years. Approximately 47 percent of the wells displayed lower groundwater level elevations (decreases greater than five feet) in fall of 2017 compared to fall 2011. Approximately 44 percent of the wells showed less than five feet of change, and only approximately 9 percent of wells statewide displayed increases in groundwater level elevations greater than five feet (DWR 2017).

2.1.4 Planning for Drought

Strategies to reduce drought vulnerability are complicated by the difficulty of defining a drought's cause, onset, or duration (Wilhite 2000, Van Loon 2015). Moreover, a groundwater drought is inherently less visible, but can still be a "very severe hazard" compared to other natural hazards (Wilhite 2000: p. 6). Primary approaches to managing drought include:

- Providing drought information—e.g. the Palmer drought severity index
- Conducting vulnerability and impact analyses
- Developing drought mitigation plans that emphasize conservation and new supplies

In California, no single state agency has sole responsibility over drought planning and mitigation. The 2010 Drought Contingency Plan (DCP) lays out a governance structure with responses to be led by drought coordinators at the DWR and then the California Office of Emergency Services (OES) and coordinated through a Drought Task Force to be established by the Governor. The state also produces a State Hazard Mitigation Plan that discusses drought with a focus on precipitation forecasting, drought monitoring, drought impacts, and water use efficiency and conservation approaches, and it provides a list of grants both for drought relief and to stimulate drought mitigation strategies. The state also provides assistance for resolving drought-related water supply and water quality emergencies, conservation, waste-water recycling, and storage enhancement (see *https://drought.ca.gov/pdf/State-Funding-Program-Matrix-04-08-15.pdf)* for a list of state and federal assistance programs related to drought).

Drought planning is also part of other planning processes including:

- Integrated Regional Water Management Plans (IRWM) require the inclusion of water supply-related planning and projects as well as climate change impacts.
- Urban Water Management Plans (UWMP) require urban water suppliers to develop water shortage contingency analysis of supply reductions, and sufficient supplies need to be available in a single dry year & multiple dry years (usually a 3 year drought), and optional consideration of climate change.
- Agricultural Water Management Plans (WMP) (SBX7-7) should include an analysis of climate change effects on future water supplies and potential impacts.
- County Hazard Mitigation Plans.

Several problems are noted with drought planning:

- "Demand hardening" can occur as a result of long-term conservation measures (outdoor use restrictions, rebate programs, and price structure changes) that make it difficult for utilities to induce further reductions in water use during drought.
- Most water utilities receive their revenues from water consumption, so there can be a negative incentive to require conservation during non-drought periods.
- Existing drought planning does not sufficiently include or protect water users like private well owners or small water systems serving disadvantaged communities.

- Many drought projects focus on increasing storage for supply reliability (see for example Bureau of Reclamation Drought Resiliency Projects 2018), but projects do not necessarily specify whether and how water will actually be available for future droughts.

Moreover, drought planning is primarily reactive. Drought measures to conserve water are generally instituted after a drought is declared, and frequently they are rescinded after a drought is declared to be over. For example, during the 2012-2016 drought, the Governor declared several drought emergency proclamations and executive orders (*see https://www.gov.ca.gov/wp-content/uploads/2017/08/11.13.15_EO_B-36-15.pdf*), and the SWRCB adopted an emergency regulation in 2015 addressing conservation that required an immediate 25 percent reduction in overall potable urban water use that incorporated a sliding scale for setting conservation standards for the state's 411 large urban suppliers. In May 2016, the SWRCB eliminated the 2015 mandatory standards for 379 suppliers, allowing them to now temporarily set their own conservation standards through January 2017 (SWRCB 2016). During this time a supplier only had to self-report that it had a sufficient supply available to prevent shortages during a three-year drought. Moreover, the role of groundwater in calculating the voluntary conservation standards was not clarified. On May 31, 2018, a more proactive conservation policy was established when Governor Brown signed two bills, SB 606 and AB 1668, that now require cities, water districts and large agricultural water districts to set an annual water budget that provides a target for water use by 2022. The State Water Resources Control Board (SWRCB) must approve the target, and there are potential fines, increased during drought emergencies, if the targets are not met.

In considering the importance of groundwater as a supply source during drought, it is notable that drought planning and groundwater management plans are generally not integrated. Drought plans give limited attention to sustaining groundwater over the long term, while groundwater plans provide limited attention to drought. This is despite groundwater's role as an essential supply source for the state and, importantly, a backstop during drought.

2.2 Groundwater

2.2.1 Groundwater Management in California

"Groundwater" is generally defined as water that moves through the soil and is found in the spaces between soil particles and cracks in underground rocks located in the saturation zone. In California, groundwater is legally defined as percolating water and does not include the underflow of a surface stream or underground streams that flow in known & definite channels (defined as surface water). The state has no permit system for groundwater withdrawals notwithstanding the long-term accumulated groundwater overdraft in many basins.

For over a century local agencies and districts, including Special Act Districts, were the primary groundwater management institutions. The courts managed additional groundwater basins pursuant to adjudication, and local ordinances could address groundwater management (DWR Bulletin 118 Update 2003)

Despite numerous formal legislative findings about the severity of the broader effects of groundwater overdraft (e.g., Cal. Water Code §§ 12926(b), 13701(c)), in most basins restrictions on pumping were limited and there was a failure to control overdraft (Cooley et al., 2009; Hanak, 2003, Langridge et. al. 2016 a,b).

2.2.2 2014 Sustainable Groundwater Management Act

California legislators confronted the challenge of addressing overdraft and its impacts when they passed the 2014 Sustainable Groundwater Management Act (SGMA - AB 1739, SB 1168, and SB 1319). The SGMA established new requirements for 127 high and medium priority groundwater basins as designated by the California Statewide Groundwater Elevation Monitoring System (CASGEM: SBx7-6, AB 1152, 2009) including those in overdraft. These basins were required to form groundwater sustainability agencies (GSAs) and to develop groundwater sustainability plans (GSPs) to manage the basins, with the state creating criteria to evaluate local GSPs and their implementation. Basins adjudicated prior to 2015 are exempt from SGMA but are required to report specific data to the state, and the state may intervene in any new adjudication to provide guidance to ensure consistency with SGMA objectives (Langridge et. al. 2016a). Special Act Groundwater Districts had the option to become the GSA within their established boundaries, and most elected that option (Langridge et. al. 2016b).

Recognizing the importance of avoiding negative impacts, the SGMA defines 'sustainable groundwater management' as: "The management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results". Undesirable results are defined in SGMA as one or more of the following effects caused by groundwater conditions occurring throughout the basin:

- Chronic lowering of groundwater levels indicating a significant and unreasonable depletion of supply.
- Chronic lowering of groundwater levels indicating a significant and unreasonable reduction of groundwater storage.
- Significant and unreasonable seawater intrusion.
- Significant and unreasonable degraded water quality.
- Significant and unreasonable land subsidence that substantially interferes with surface land uses.
- Surface water depletions that have significant and unreasonable adverse impacts on beneficial uses of surface water (SGMA Section 10727.2b).

A major issue is that the SGMA does not require restoration to pre-2015 conditions. This could be a problem in basins with already significant overdraft and drying up of shallow wells, as well as other pre-2015 undesirable effects. Additionally, while SGMA requires "basin stabilization," and promotes "management of regional water resources for regional self-sufficiency and drought resilience," the lack of specific requirements or incentives to address accumulated overdraft and concomitant reduced storage could increase drought vulnerability.

Notably, SGMA provides no explicit incentives to manage groundwater with pro-active long-term strategies that move beyond conservation to account for the more extreme droughts projected under climate change.

2.2.3 Groundwater Management Under Drought and Climate Change

Managing groundwater to reduce vulnerability to drought under climate change requires:

- A definition of unacceptable impacts of overdraft in a basin

- Development of a basin's water budget that provides for groundwater levels that will avoid unacceptable overdraft impacts under normal climatic conditions
- Calculation of an additional groundwater buffer or reserve to avoid increased declines in groundwater levels during an extreme drought when withdrawals increase, and where levels have historically failed to recover over the long term
- Development of a management approach to a) recharge aquifers to reduce and eventually halt overdraft, b) recover groundwater to levels where the recovery of groundwater storage after future droughts is possible, and c) develop and sustain a drought reserve to provide an additional buffer during an extended dry period.

The sustainable yield of a basin is frequently used to determine the amount of groundwater that can be pumped from a basin to balance inflows and outflows. This balance is important to avoid long-term groundwater storage declines that can increase vulnerability to the extreme droughts projected under climate change. While the earlier concept of safe yield emphasized aquifer dynamics (Bredehoeft 1997, Kalf and Woolley 2005), the definition of sustainable yield today also incorporates societal inputs regarding both unacceptable impacts and groundwater basin management goals (Alley and Leake 2004, Gleeson et. al. 2012, Rudestam and Langridge 2013).

Key issues are that determining a water budget and calculating the sustainable yield are complex and challenging processes that can require modeling studies and fieldwork. In addition, unacceptable impacts from pumping need to be defined (Rudestam and Langridge 2013). This complexity can be seen by the lack of a definition, and technical agreement about, the safe - sustainable yield in many adjudicated groundwater basins in California where quantification is generally required pursuant to a court decree (Langridge et. al. 2016a). This complexity is also visible in non-adjudicated basins (Langridge et al. 2016b). As a result, basin managers have established different criteria for sustainable yield. Examples are shown in Table 3.

Table 3: Safe Yield Criteria

Sustainable/Safe Yield (SY)	Approach
Native SY	Usually precipitation, - Can include return flows from artificial water
Managed SY	Often includes artificial water or return flows from artificial water
Production SY	Equal to the average net natural water supply plus expected return flow from previous year's water production
Operating SY	A quantity of water that may be pumped in a particular fiscal year, free of a replacement water assessment (Main San Gabriel Basin adjudication judgment (Langridge et al. 2016a)
Cumulative SY	"…maximum average annual amount of water that can be extracted from the surface water resources over a period of time sufficiently long to represent or approximate long-time mean climatological conditions… without resulting in long-term progressive lowering of groundwater levels" (San Bernardino Basin Area adjudication judgment 1969)

2.2.4 Traditional Strategies for Groundwater Management under Drought

A core policy question centers on whether groundwater management policies to build drought resilience should focus on a) developing additional surface supplies to meet demand and potentially recharge aquifers or b) curbing overall water use and reducing groundwater withdrawals. Some current policies to increase groundwater supplies or reduce groundwater demand are listed in Table 4 and are discussed in sections 2.2.4.1- 2.2.4.7.

Table 4: Examples of Supply-side Side and Demand-side Side Approaches to Managing Groundwater to Increase Storage and Reduce Drought Vulnerability

Supply Side Approaches	Demand Side Approaches
• Increase storage capacity by building reservoirs and dams • Desalinate seawater • Expand rain-water storage • Remove invasive non-native vegetation from riparian areas • Develop aquifer storage and recovery systems (ASR/MAR) using treated wastewater discharges • Increase recycled water • Develop strategies to avoid groundwater loss from contamination	• Reduce water demand for irrigation by changing the cropping calendar, crop mix, irrigation method and area planted • Increase incentives to reduce water demands for landscaping • Establish permit systems or other regulatory or adjudicative restrictions on withdrawals • Expand use of economic incentives (e.g. metering and pricing) to encourage reduced withdrawals

2.2.4.1 Conservation

Increasing conservation and water use efficiency through economic and other incentives are frequently promoted as a demand reduction approach, with suggestions for adequate financial investment in water-saving technology, and economic instruments to encourage reduced water consumption (Foster & Kemper 2003; Foster & Garduño 2012). But conservation can also be a supply side approach if saved water is primarily used as a new supply source. This can actually increase vulnerability to future droughts if the new supply source is used for development (Langridge et al. 2012).

2.2.4.2 Imported Water

Imported surface water is still a significant source of supply in many groundwater basins. Table 5 illustrates the large number of adjudicated groundwater basins and Special Act Groundwater Districts that rely on imported surface water (Langridge et. al. 2016 a,b). While many basins are increasing the use of local recycled water (Table 6) the ratio of recycled water to water imported from the SWP is still small in many basins. The challenge will be to continue to increase recycled water for consumption in the future as SWP water is projected to be less reliable and more expensive under climate change and future drought conditions.

Table 5: Imported Surface Water for Adjudicated Basins and Special Act Groundwater Districts

	Adjudicated Basin
Imports	***19 Southern California Basins*** ***2 Coastal Basins***
No Imports	***4 Coastal Basins***

	Special Act Districts
Imports	***4 Large Urban Basins*** ***3 Smaller Basins***
No Imports	***4 Coastal Basins 4 Rural Inland Basins***

2.2.4.3 Recycled Water

Supply sources have shifted over time and as noted recycled water use has increased (Table 6), particularly for the Central Valley, Los Angeles and Santa Ana Regions (Pezzetti and Balgobin 2015)

Table 6: Recycled Water Use in California (Pezzetti and Balgobin 2015)

Year	Recycled Water Use
1970	~175,000 AF (216 M)
1987	~ 267,000 AF (392 M)
2009	~ 669,000 AF (825 M)
2015	~714,000 AF (881 M)

In California, the SWRCB and its nine Regional Water Quality Control Boards (RWQCB) grant the permits for the use of recycled water. In July 2014, the regulatory authority was moved from the California Department of Public Health (CDPH) to the SWRCB, which now reviews and establishes water recycling criteria and regulations.

2.2.4.4 Reducing Withdrawals

Reducing demand through regulating withdrawals is less employed. (Hoogesteger and Wester 2017, Langridge et. al. 2016a, b). Several approaches are shown in Table 7 (Langridge et. al. 2016a, b).

Table 7: Approaches to Regulating Groundwater Withdrawals (Langridge et. al. 2016a, b)

Adjudicated Basin	Approaches to Regulating Withdrawals
West Coast	Some limits but extractions more than double the proposed limit
Mojave	Modest decrease each year based on past withdrawals
Santa Maria	Minimal – Overlyers only cut back in a severe water shortage

Special Act District	Approaches to Regulating Withdrawals
OCWD	Uses a replenishment fee proportional to pumping
FCMGA	Charges a modest extraction fee based on crop type
Zone 7	If a fixed annual quota is exceeded there is a recharge fee

Establishing and implementing extraction and use permits can be difficult and incomplete due to considerable legal and administrative issues. Notably, in 2017, four of the five water districts highlighted in Section 3 are currently developing groundwater drought buffers or reservoirs–a very recent and less traditional strategy.

2.2.4.5 Recharging Aquifers

"Water in aquifers continues to be the most effective strategic weapon against drought."

(ACE 1993)

Recharge strategies to reduce and eventually halt overdraft, along with the development of a drought buffer, can help to avoid future unrecoverable declines during a drought. This can contribute to building long-term drought resilience under climate change.

Recharge is a complex process that is affected by precipitation and the infiltration of river flows as well as the properties of land, vegetation, soil, climate, and human activities such as irrigation and pumping (Meixner et. al. 2016). Aquifers can be recharged through several processes:

1. Natural recharge: This can occur as part of hydrologic cycle or be the result of water seeping or percolating into an aquifer from surface water sources including streams, rivers, lakes, surface water conveyance facilities and irrigation water. Soil types, plant cover, land slope, and rainfall intensity influence the rate of percolation.
2. Active recharge: Also referred to as managed aquifer recharge (MAR), enhanced recharge, artificial managed recharge, or aquifer storage and recovery (ASR), is where water is pumped or injected into wells or spread over a land surface to allow it to seep into the aquifer. Imported surface water is frequently used.
3. In-lieu recharge: Groundwater extraction is reduced and instead parties use more available surface water supplies for consumption, and these often include imported surface water.
4. Irrigation recharge: Excess irrigation water that percolates to the water table (Scanlon et al., 2002; Sanford, 2002)

The following discussion focuses on active and in-lieu recharge as approaches to enhance groundwater levels, thereby providing "water in the ground" that can potentially be utilized during drought.

The term 'Managed Aquifer Recharge' (MAR) is defined as 'intentional storing and treatment of water in aquifers' for later recovery or environmental purposes (Gale and Dillon 2005). MAR techniques include surface spreading basins, vadose zone dry wells, and direct injection into wells to recharge aquifers. MAR can be used to meet municipal and agricultural water demands in water-scarce regions, as well as assist in the reuse of wastewater. Groundwater in recharged basins can potentially serve as a buffer during periods of drought (Megdal and Dillon 2015). Scanlon et al. (2016) demonstrate that in California's Central Valley and Arizona's active management areas, MAR helped to reverse some historically declining groundwater level trends.

Studies on wide-ranging opportunities for implementing MAR programs include: modeling tools (Ringleg et al. 2016), economic and financial analysis, multi-disciplinary approaches that incorporate geophysical and hydrological information, and information on stakeholder and community engagement in program implementation and success (Megdahl and Dillon 2015).

Climate extremes, including intensive droughts, frequently end with floods. This offers an opportunity to capture excess runoff (flood flows) for recharge and storage. The intensity of flood extremes is projected to increase with climate change (Tebaldi et al. 2006) creating additional opportunities for storing water for use during drought extremes. Vázquez-Suñé et al. (2007) found that recharge from flooding helps explain major head recoveries. Blachard et al. (2014) examined capturing flood flows for recharge in California's agricultural San Joaquin Valley using a conceptual model that demonstrated that flood flow capture when integrated with irrigation is more cost-effective than groundwater pumping. 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 agricultural regions in California including: deep percolation; root zone residence time; topography; chemical limitations; and soil surface condition. Kochis and Dahlke (2015) analyzed the magnitude, frequency, duration and timing of high-magnitude streamflow for 93 stream gauges covering the Sacramento, San Joaquin and Tulare basins in California. Their results show that in an average year significant high-magnitude flow is exported from the Central Valley to the Sacramento-San Joaquin Delta, often at times when environmental flow requirements of the Delta and major rivers are exceeded, suggesting that significant unmanaged surface water is physically available for recharge.

2.2.4.6 Conjunctive Use

Conjunctive use programs typically involve either substitution of surface water in lieu of groundwater pumping, or underground storage of surplus surface water in wet periods for subsequent withdrawal in times of scarcity – the aquifer serves as an underground reserve that can be drawn upon to a greater or lesser degree as the quantity of available surface water varies. Conjunctive use of surface water and groundwater can enable aquifers to recharge and help to mitigate the water supply stress in responding to climate change and drought. In many instances imported surface water through the CVP and SWP is used for conjunctive use.

Optimization models have been proposed for conjunctive use of surface water and groundwater (Sethi et al., 2002; Vedula et al., 2005), primarily for planning cropping patterns and irrigation water management (Zhang 2015). Earlier models failed to consider the impacts of future climate change. Recent research is attempting to incorporate climate change impacts into the planning and management of conjunctive water use (Sullivan and Meigh 2005; Hanson and Dettinger 2005; R. T. Hanson et. al. 2012; Hoekema and Sridhar, 2013; Pingal, Jat and Kare 2014).

Zhang (2015) provides an excellent review of approaches for supporting conjunctive water use planning and management, and some challenges to implementing conjunctive use as well as addressing groundwater management under climate change. Examples include:

- A mismatch between large-scale global or regional climate models and small-or medium-scale hydrological processes (Arora and Boer, 2001; Merritt et al. 2006; Young et al. 2009), and the need for more effective downscaling methods (Hanson and Dettinger 2005; Mileham et al. 2009).
- Uncertainties in the structure and selection of global climate models for climate change impact studies. The high sensitivity of water resources systems to future climate change projections (Dessai and Hulme, 2007; Kay et al., 2009; Prudhomme and Davies, 2009; Lespinas et al., 2014) can affect water management strategies (Candela et al. 2012).
- Limited long-term groundwater data and information that impairs investigations of the responses of groundwater systems to climate change (Taylor et al., 2013).

2.2.4.6 Water Markets, Water Transfers, and Groundwater Banking

Water transfers are the transfer of the right to use water from one water user to another. Water markets enable the temporary, long-term, or permanent transfer of the rights to use water in exchange for compensation. While often a market transaction is between a willing buyer and a willing seller, it is also a negotiation with a number of parties with important and legitimate interests in the water that need to be accommodated.

Water transfers can provide water supplies in dry times and enable the movement of water to places of critical need, especially during a drought. Because most water is used for irrigation globally as well as in California, water is frequently leased or sold by farmers or irrigation districts who transfer/market water to other farmers with scarce supplies and higher value crops, to growing cities or to water providers that supply cities, and to environmental programs. Transfers are often used for “conjunctive use” of groundwater and surface water.

Informal conjunctive-use programs and water transfers operated in many parts of California for as long as the state’s large water projects made substitute surface water available. The state began a drought water bank after the 1976 drought, and then turned over some of the facilities to non-state entities. The 1987-1992 drought accelerated water markets and transfers. Water banks located in Kern County and Southern California built up reserves of nearly 3.4 million AF by 2006. In Kern County, withdrawals have sparked controversies because they occurred during times when overall groundwater levels were falling (Hanak and Stryjewski. 2012). Water transfers can have significant land use consequences, e.g. shifting land use from agriculture to municipal use.

3: Case Studies – Managing Groundwater for Drought Under Climate Change

Section 3 focuses on five case studies - two adjudicated groundwater basins, and three special act districts that are currently GSAs under SGMA. Each uses traditional approaches to improve groundwater conditions. Additionally, they have introduced strategies to prevent groundwater levels from trending down over time when there are increased withdrawals that occur during drought with insufficient recovery during wet and normal years. One basin researched, established and now sustains an acceptable range for groundwater levels to avoid reduced storage over time. Four emphasize the development of drought reserves to increase storage that is specifically to be used as a buffer for future droughts rather than for other projects. Goleta first established its drought reserve in 1991. More recently, the other basins have used a variety of approaches to develop drought buffers.

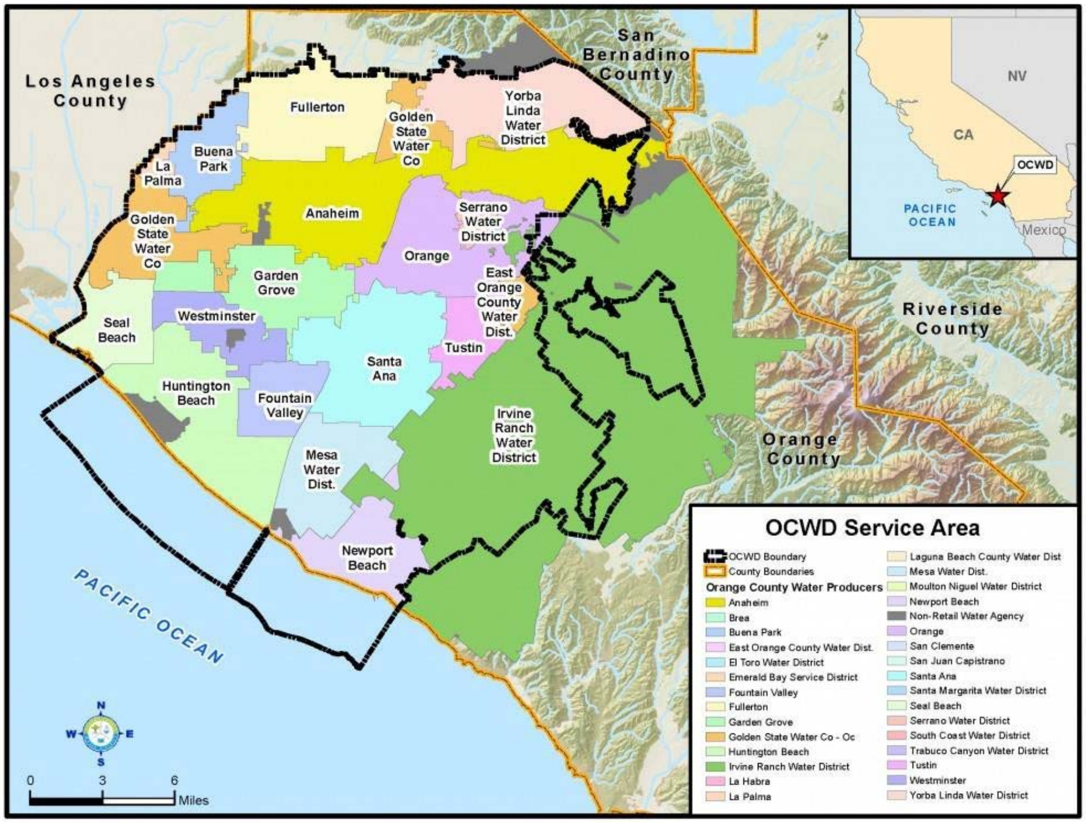
These strategies reflect a focus on managing groundwater to better adapt to drought conditions and are a proactive first step in addressing the extreme droughts projected under climate change.

3.1 Orange County Water District (OCWD)

OCWD is notable for two strategies that can reduce groundwater storage losses over time and therefore increase drought resilience:

1) Researching and then managing the basin for groundwater levels to be sustained within an acceptable range that could avoid future and unrecoverable groundwater declines during extended drought periods

2) Major programs to increase groundwater recharge using recycled water to sustain the acceptable range for groundwater levels



Source: OCWD 2018

Figure 4: Orange County Water District

The state legislature established the OCWD as a Special Act District (SAD) in 1933 (OCWD 2014). Its boundaries cover the northern and central portions of the Coastal Plain of the Orange County Groundwater Basin (OCGB), (Basin 8-1 in DWR Bulletin 118) (Figure 4). The enabling legislation provided OCWD with authority to manage its groundwater basin including the importation of supplemental water, the capture of flood and runoff water, and the protection of surface water rights for Orange County (OCWD 2014, 2015a). OCWD's original service area encompassed 254 square miles with a population of 120,000, and agriculture dominated. Its service area has expanded to 381 square miles, primarily municipal land use and a population of 2.4 million (OCWD 2015b). OCWD currently provides water to 19 retail agencies in north and central Orange County. Since OCWD's creation, groundwater production has increased significantly. Approximately 200 large-capacity municipal and privately-owned supply wells account for 97 percent of production. All entities that operate large-capacity wells must equip their wells with meters and report their production totals every six months.

Similar to other coastal basins with seawater intrusion, OCWD relies on two seawater barriers that increase drought resilience because they enable greater drawdown of the basin without causing seawater intrusion. During the 2012-2016 drought, the seawater barriers prevented seawater intrusion despite groundwater level declines (OCWD 2015).

OCWD manages the basin by providing water as needed for development without mandating reduced water use. Instead it maximizes available water supplies by expanding its capacity for groundwater recharge from four sources: Santa Ana River base flows and storm flows, imported surface water from the SWP and the Colorado River, and recycled water. Their goal is to use these sources to recharge the groundwater basin sufficiently to meet user needs while avoiding seawater intrusion. Table 8 is a comparison of recharge sources in 1999-2000 and 2013-2014.

Table 8: Groundwater Production & Recharge Sources (AF)

Water Year	Santa Ana River Base Flow	Santa Ana River Storm Flow	Recycled Water	Imported Water	Incidental Recharge	Groundwater production
1999-2000	150,000	39,000	6,000	78,000	82,000	341,000
2013-2014	65,000	25,000	66,000	53,000	31,000	339,000

Source: OCWD 2015a

About 200 million of gallons per day of wastewater, from over 2.5 million customers, are sent to the Orange County Sanitation District (OCSD), where it is treated. About 130 million gallons of this treated wastewater is sent to OCWD's Groundwater Replenishment System (GWRS) where it is purified to exceed drinking water standards. The GWRS water is then put back into the basin where it blends with all the other water supplies and is ultimately reused.

OCWD uses several mechanisms to regulate withdrawals. The OCWD Board establishes an annual production percentage (BPP) and a replenishment assessment (RA). The BPP is the amount of water cities and water districts can pump from the basin as a percentage of their total water demands and the RA is the charge for each AF of water pumped up to the BPP. If the RA is exceeded, an additional Basin Equity Assessment (BEA) is charged (OCWD 2014).

OCWD's reliance on river flows and imported surface water for recharge combined with its lack of authority to curtail pumping could make it difficult to withstand an exceptionally severe drought. To address drought vulnerability, OCWD is a leader in MAR with a system of recharge basins, pipelines and dams that collect and recharge runoff. OCWD is counting on its expanded and locally controlled Groundwater Replenishment System (GWRS) to counter reduced surface water supplies. The GWRS total production is currently 100 MGD, at about half the cost of imported surface water supplies.

Average annual overdraft for the immediate past five water years (2012-13 through 2016-17), defined in terms of extractions versus natural replenishment, was 156,000 AF. Accumulated overdraft (sometimes specified as cumulated overdraft) is generally defined with respect to the aggregate amount of groundwater removed from groundwater supplies during all preceding water years that has exceeded the quantity of non-saline water replenishing the basin during that period (see for example WRD Engineering Survey Report 2011 citing Section 60023 of the WRD Act). It can reflect changes in the amount of storage in the basin over time. A large amount of accumulated overdraft can reduce the groundwater available during a drought. The accumulated overdraft

(Table 9) is defined in the OCWD Act as the quantity of water needed to be replaced at the basin's intake area to prevent landward movement of salt water into the fresh groundwater body (OCWD Draft 2016-17 Engineering Report).

Table 9: Recent Accumulated Overdraft

2014 - ~342,000
2015 - ~398,000
2016 - ~377,000
2017 - ~328,000

OCWD does not maintain the basin storage level at a "full basin" condition. Instead, the basin is operated to continuously fluctuate within a safe operating range to avoid groundwater elevations dropping to levels that result in adverse impacts, shown in Table 10. Focusing on strategies that sustain a safe operating range can keep accumulated overdraft from increasing and potentially have groundwater available to cope with the future extreme droughts projected under climate change without increasing adverse impacts to the basin.

Table 10: Benefits and Constraints of Available Storage Space

Amount below full basin condition (AF)	Constraints	Benefits
Less than 200,000	Increased out-of-basin flows Too high GW levels in some areas Decreased opportunity for recharge *when* low cost water is available	Lower pumping cost More water for dry years
200,000 - 350,000	Somewhat more risk of saltwater intrusion	Minimal impacts from high GW levels More opportunity for recharge *when* low cost water is available Less out-of-basin flows
350,000 – 500,000	Somewhat more risk of saltwater intrusion Loss of some wells Greater risk of land subsidence Need for more imported water	Minimal impacts from high GW levels More opportunity for recharge *when* low cost water is available Less out-of-basin-flows

The upper limit of the operating range is defined by a full basin condition, which represents the zero-overdraft benchmark. The lower limit of the operating range is considered to be 500,000 AF overdraft and represents the lowest acceptable level in the basin, not the lowest achievable. This level also assumes that all water from the Metropolitan Water District of Southern California (MWD) stored in the basin (e.g., Conjunctive Use Storage Project and Super In-Lieu) has already been withdrawn. Although it is considered to be generally acceptable to allow the basin to decline to 500,000 AF overdraft for brief periods due to severe drought conditions and lack of supplemental imported water supplies, it is not considered an acceptable management practice to intentionally manage the basin for sustained periods at this lower limit due to the likelihood of seawater intrusion, depletion of the drought supply, pumping will be detrimental to some wells, increased pumping costs and electrical costs and increased potential for color upwelling from their deep aquifer (OCWD 2015b).

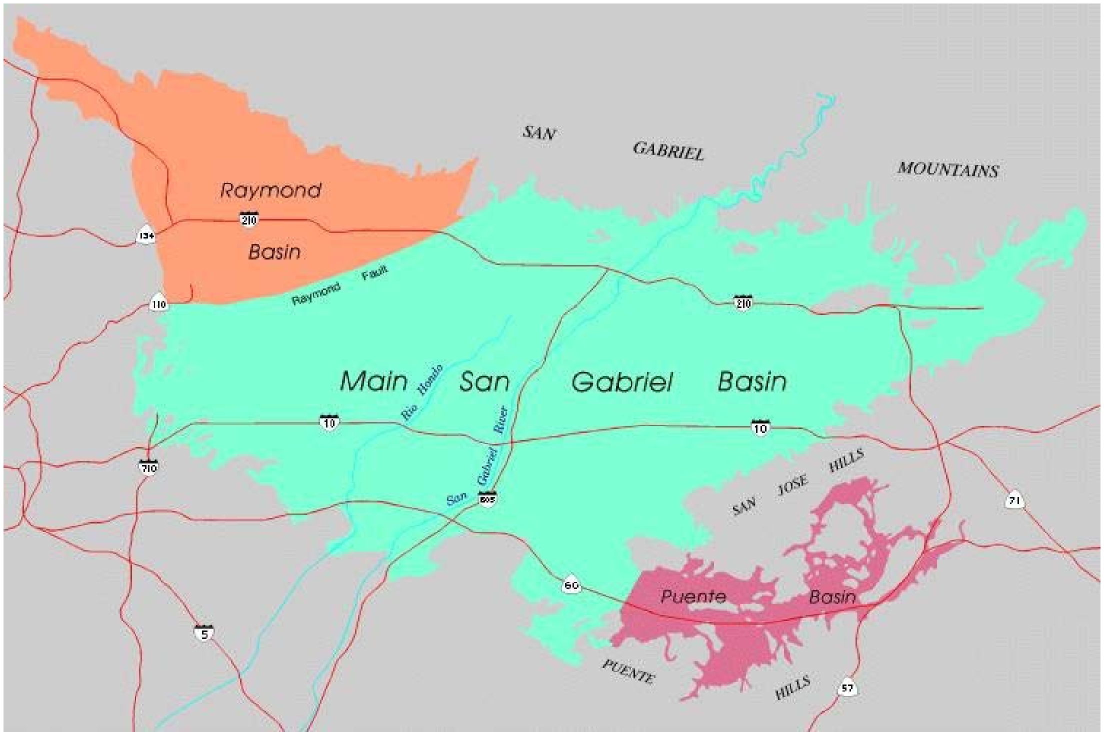
The 2011-2016 drought did lead to decreased recharge and increased pumping. Groundwater levels fell, but they remained within the normal operating range. During the wet 2016-2017 year, OCWD purchased as much water as it could from the MWD that was used for in-lieu recharge of the basin. After the 2016-2017 drought, the basin storage level was approximately 222,000 AF, within the "safe" operating range (OCWD 2018).

OCWD also uses a scenario framework to assess management goals under climate change. Rather than examining every single climate model or assigning probabilities to different outcomes, OCWD examines a few different plausible climate scenarios and adaptations and then looks at its water system's sensitivity to those changes (Lyles 2017).

3.2 Main San Gabriel Adjudicated Groundwater Basin

The Main San Gabriel Basin is notable for its comprehensive management, including careful monitoring of the basin, and for its newly instituted innovative program that proposes to establish a potential drought reserve.

The Main San Gabriel Basin (MSGB), Figure 5, occupies most of the San Gabriel Valley. It is an adjudicated groundwater basin that is geographically situated in the southeasterly portion of Los Angeles County and bounded on the north by the San Gabriel Mountains. The surface area of the MSGB encompasses about 107,000 acres and there is approximately 8.6 million AF of groundwater in storage. It is one of the largest groundwater basins in Southern California, providing residents of the San Gabriel Valley with an average of 225,000 AFY of groundwater during fiscal years 2007-08 through 2016-17 (MSGB Watermaster Annual Reports 2010-2017).



Source: San Gabriel Valley Water Association 2018

Figure 5: Main San Gabriel Adjudicated Basin

The San Gabriel River and Rio Hondo, a dis-tributary of the San Gabriel River, drain the watershed. Average precipitation over the past 20 years (fiscal years 1997-98 through 2016-17) is approximately 15.8 inches, whereas the historical long-term average is 18.5 inches (Main Basin Watermaster, 2017-18 Operating Safe Yield Report). The major sources of natural recharge to the MSGB are infiltration of rainfall on the valley floor and stormwater runoff from the nearby mountains (MSGB Watermaster, 2016-17 Annual Report). The MSGB is one of several groundwater basins (including the Puente, Raymond and Central basins) to receive the benefit of mountain runoff, and the MSGB interacts hydrologically and institutionally with adjoining basins, including the Raymond, Puente, Central Basins.

In the mid-1800s, agriculture and ranching were the dominant economies. The MSGB's current land use is primarily urban. Municipal water purveyors are the primary pumpers, although there is a lesser amount of production by rock and gravel companies. Most communities depend almost entirely on the groundwater basin for their water supply, with indirect access to untreated imported surface water (MSGB Watermaster, 2016-17 Annual Report).

Replenishment of the MSGB consists of natural local sources (precipitation and runoff from the San Gabriel Mountains) and untreated imported surface water from the SWP via the MWD's imported surface water system and facilities that are owned and operated by the San Gabriel Valley Municipal Water District (MSGB Watermaster Salt and Nutrient Plan 2016). MSGB demand is met with local groundwater, treated local surface water, recycled water for non-potable purposes and treated imported surface water. In addition, an average of about 40,000 AFY of untreated imported surface water is delivered for MSGB replenishment.

The 17 spreading basins in the MSGB cover more than 1,100 acres, and existing facilities have a spreading capacity of more than 600,000 AFY if water is available and fully used. The typical operating range for groundwater levels is between 200 and 250 feet MSL. The Watermaster, responsible agencies (the three municipal water districts), and MSGB producers operate a series of Cyclic Storage Agreements whereby untreated imported surface water may be stored in the MSGB and withdrawn in the future when imported surface water supplies are not available to meet a replacement water requirement (MSGB Watermaster Operating Safe Yield Report 2017-18).

The judgment allowed for production in excess of water rights, but producers who pump over their water rights incur a replacement charge. In both average years and drought years, groundwater supply is about 225,000 AFY of which about 42 AF of groundwater production (about 19 percent) is replaced by untreated supply sources. During drought years, additional groundwater is withdrawn from storage to make up for lack of rainfall and stormwater percolation.

During the 2012-2016 drought, there was insufficient rainfall (and consequently insufficient deep percolation of rainwater and stormwater). As a result, almost 400,000 AF of groundwater was pumped from the MSGB in excess of local replenishment to meet water demands. The pumped groundwater could not be replaced because of the lack of rainfall and unavailability of imported replenishment water. This led to a decrease of about 50 feet in elevation at the Baldwin Park Key Well. Moreover, during the rainfall in 2016-2017, there was little recharge of the MSGB because the ground in the San Gabriel Mountains soaked up the rainfall, leaving little stormwater runoff for rivers, reservoirs and groundwater basin recharge. Thus, the groundwater produced to meet demand now needs to be replaced (Table 11)

Table 11: Key Well Level in MSGB (since entry of judgment)

Historic Low	172.2 ft.	October 7, 2016
Historic High	329.1 ft.	May 19, 1916
2018 Level	180.9 ft.	May 25, 2018

Source: Main San Gabriel Watermaster 2018

Key traditional strategies to reduce drought vulnerability include development of new replenishment facilities, use of recycled water for non-potable uses, and water conservation by retail customers.

More innovative programs initiated after the 2011-2017 drought (MSGB 2016-2017) that will increase resilience under the more extreme droughts projected under climate change include:

- **Holding the Operating Safe Yield (OSY "the amount of water that can be safely extracted" *http://www.watermaster.org/about-us*) low. This incentivizes decreased groundwater pumping to meet demand because any water pumped over the OSY requires users to pay a replenishment fee. This strategy can also increase the funds to purchase untreated imported surface water for replenishment.**
- **Developing the Resource Development Assessment - Stormwater Augmentation Programs to help manage the Main Basin's water supplies under "worst case" drought conditions (defined as 15 years under 2012-16 drought conditions). The goal is to purchase 100,000 AF of water over ten years and store it for future need. The total volume purchased and stored in the program in 2018 is ~ 12,760 AF.**

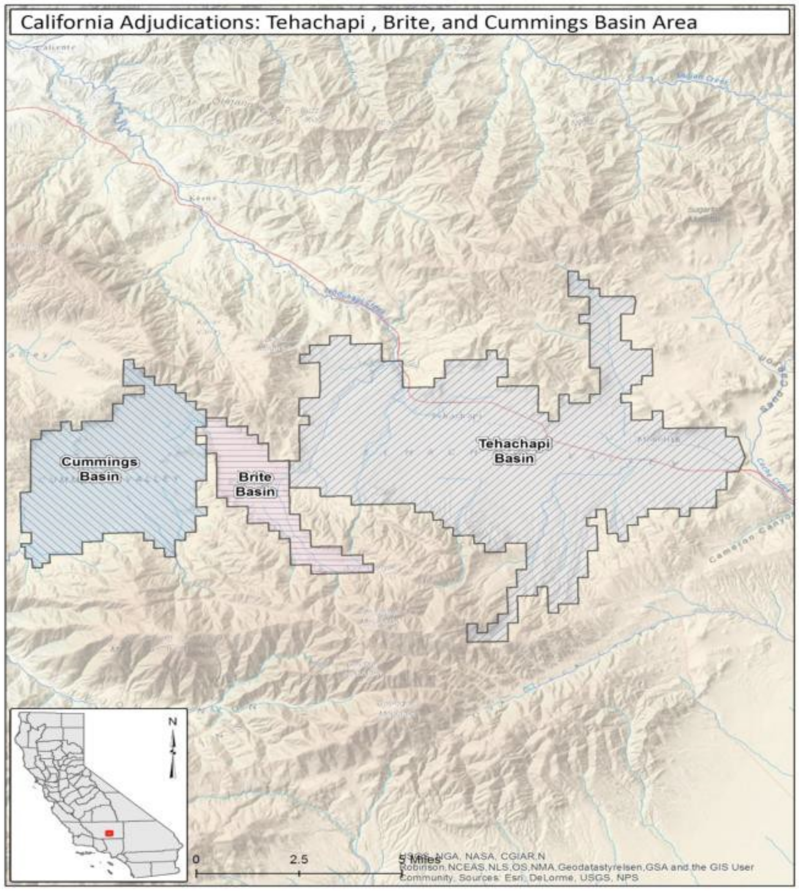
- **The untreated imported replenishment water will also be used to maintain the Key Well elevation above 170-180 feet in the event of future severe droughts.**

3.3 Tehachapi Adjudicated Groundwater Basin

Tehachapi is notable for a new program requiring that groundwater users bank a 5-year water supply into the basin to serve as a drought reserve.

The Tehachapi groundwater basin (Figure 6) is located in the Tulare Lake Hydrologic Region, but due to its higher elevation, approximately 4,000 feet above mean sea level, it is isolated from the Tulare Lake groundwater basin. It is bordered on the north by the Sierra Nevada, and on the south by the Tehachapi Mountains that rise 8,000 feet above the basin. The basin's surface is generally the Tehachapi Valley floor and it is frequently described as a bowl, the sides of which are composed of impervious materials. It is about nine miles long and five miles wide at its widest, and it is oval shaped and elongated east and west. Surface outflow from Tehachapi Valley occurs during time of heavy storms via Tehachapi Creek to the west, and water is impounded in Proctor Lake (TCCWD 2016). Average precipitation in the region is 10–14 inches (Tehachapi Regional Urban Water Management Plan 2015).

The area is rural, and land use is primarily agricultural. Groundwater users include agriculture, water purveyors, mutual water companies, industrial facilities, and public entities pumping for their own use. The entire region's population has grown from approximately 28,400 to approximately 35,000, but growth has tapered off in the past few years (Tehachapi Regional Urban Water Management Plan 2015).



Source: SWRCB

Figure 6: Tehachapi Groundwater Basin

The Tehachapi Groundwater Basin is adjudicated and managed by the Tehachapi-Cummings County Water District (TCCWD) as Watermaster. A major reason for the adjudication was to facilitate importing water into the basin to reduce pumping, and to secure a federal loan to construct transmission facilities. TCCWD purchases SWP water through contracts from the Kern County Water Agency (TCCWD 2015).

TCCWD is also the wholesale water supplier for the area, providing SWP water supplies that are used primarily for agriculture with some commercial, industrial, and urban uses (Table 12). The water suppliers in the area are entirely dependent upon groundwater for domestic use.

Table 12: 2016 Imported Surface Water Deliveries

Agriculture	1,445 AF
Municipal and Industrial	248 AF

Source: TCCWD 2016:11

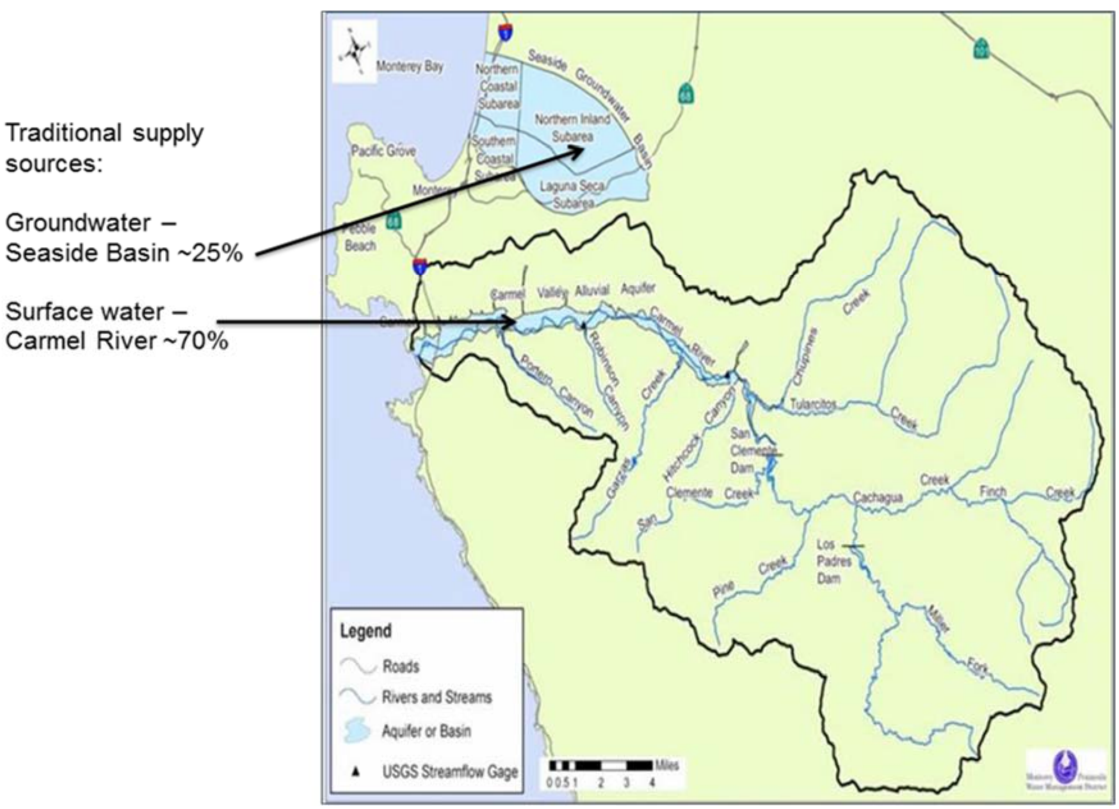
A groundwater modeling study of the Tehachapi Basin that was completed in 2009 found the safe yield of the basin to be about 5,317 AFY, with annual extractions averaging about 3,591 AF. The TCCWD monitors selected wells seasonally for groundwater levels, which have increased since the adjudication (Tehachapi Regional Urban Water Management Plan 2015). Groundwater pumping in 2013 was approximately 5,302 AF, less than the basin's safe yield (TCCWD 2015).

In 2011, TCCWD adopted a new Municipal and Industrial Agreement that established a recharge requirement for imported water. The Agreement requires water purveyors to put a 5- year water supply into the basin, which would be equal to a 5-year imported water requirement, to serve as a drought reserve. This can be accumulated over a 10-year period. During the 2011-2016 drought water users were able to tap into their banked water (Martin 2018). Agricultural users are not required to do this, but their incentive to reduce pumping is the cost of the water. TCCWD also has recharge facilities, and its comprehensive conservation policy enables the injection of some imported surface water as a drought reserve (TCCWD 2016). Monterey Peninsula Water Management District (MPWMD).

3.4 Monterey Peninsula Water Management District (MPWMD)

MPWMD is notable for a) its use of a coastal distribution system to provide growers with recycled water in-lieu of pumping groundwater, b) investment in a new major recycling facility, and c) the provision of a drought reserve supply for growers.

The Monterey Peninsula is home to valuable agriculture, diverse urban centers, and spectacular natural resources. The area is dependent on local rainfall and runoff and is not served by a state or federal water project. Tourism and agriculture are drivers of the economy. Traditional water supply sources included groundwater from the Seaside Basin and surface water from the Carmel River (Figure 7).



Source: MPWMD 2018

Figure 7: Monterey Traditional Water Supply Sources

The Carmel Valley basin is small and includes water-bearing deposits that are directly linked with the Carmel River. Average precipitation in the area is 17-19 inches per year. An estimated 85 percent of the aquifer's recharge comes from the Carmel River, and groundwater levels rapidly recover in the presence of surface water. Estimates of its storage capacity range from 48,200 to 60,000 AF (DWR 2003a). The river itself has an annual runoff of 74,400 AFY, which accounts for approximately 70 percent of domestic water supply in the MPWMD area (Monterey Peninsula, Carmel Bay, and S. Monterey Bay IRWM Plan Update, 2014).

The Seaside Groundwater Basin lies beneath a coastal plain within the Salinas Valley and extends westward beneath Monterey Bay. It is divided into three aquifers: the deepest is the Santa Margarita, then Paso Robles, and both are used for production. The Dune Sands aquifer is the shallowest (MPWMD 2008). The basin's total storage is estimated at 1 million AF. Recharge occurs from deep percolation from rainfall and irrigation flows, septic systems, and possibly streams (DWR 2003 b). The service area of the MPWMD includes six cities, which account for the majority of water use in the district.

In 1997, the legislature established the Monterey Peninsula Water Management District (MPWMD) (Assembly Bill 1329, 1977; California Water Code Appendix 118), and voters approved the District in 1978. It was created in the wake of the 1976-77 drought, which highlighted serious water supply constraints on the Monterey Peninsula. The goal was to establish an agency with authority to manage surface water and groundwater in an integrated manner, and to address seawater intrusion (Yates et. al. 2005, MPWMD 2018). The boundaries of MPWMD include portions of the Carmel Valley Basin and the Seaside Area Sub-basin of the Salinas Valley Groundwater Basin. MPWMD's population is ~112,000.

The legislature granted MPWMD significant authority over multiple aspects of water management within its service area. MPWMD manages and controls—but does not deliver— water to the residents and businesses of the Monterey Peninsula, Seaside, and portions of Carmel Valley. The four key elements of its mission are: (1) integrated management of ground and surface water sources; (2) water conservation, including rationing if required; (3) water reuse and reclamation; and (4) protecting environmental quality, fish and wildlife in the Monterey Peninsula and Carmel River Basin (Monterey Peninsula IRWM Update 2014). MPWMD manages surface water supplies from the Carmel River that are stored in the San Clemente and Los Padres reservoirs, and groundwater pumped from municipal and private wells in the Carmel Valley and Seaside Coastal area. It also sells treated wastewater for use on golf courses and open space in Pebble Beach.

Most of the communities served by MPWMD receive their water through a system privately owned and operated by California American Water (Cal Am). Those not served by Cal Am are on private wells. MPWMD's boundaries coincide with those of the Cal Am Company's Monterey District, and also include the majority of the Carmel River Watershed and the Seaside Groundwater Basin (Yates et. al. 2005). Of the 20,000 AFY of water produced within MPMWD, 15,000 AF is produced by Cal-Am (MPWMD 2005). In the Carmel Valley basin, the primary water user is Cal-Am, but MPWMD has a joint permit with Cal-Am to divert water during the wet season for Seaside basin replenishment (SWRCB Order 2009-0060).

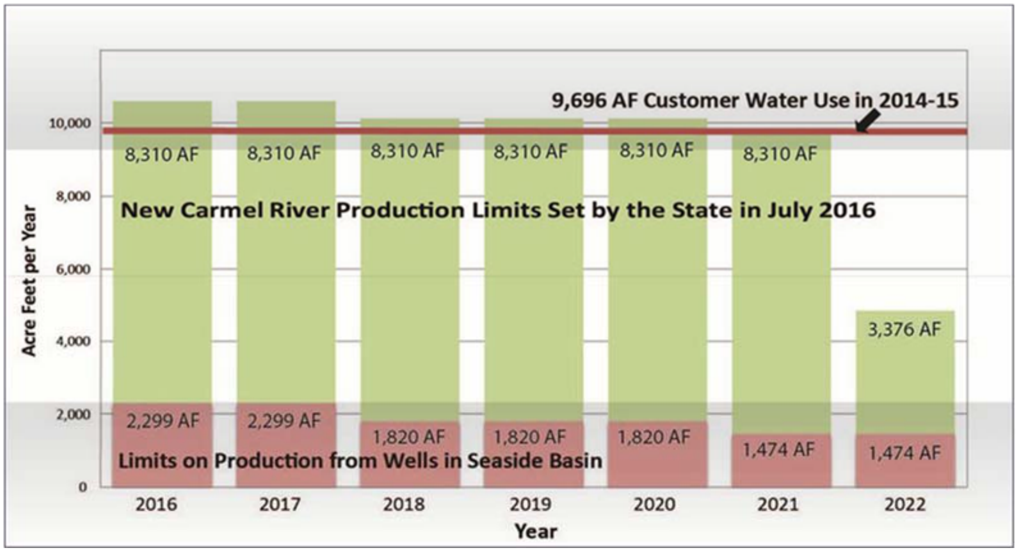
The MPWMD advises Cal Am on rate policy, issues water permits for new construction and re-models, monitors water extraction, and attends the California Public Utilities Commission (CPUC) rate hearings, held every three years to approve rates charged to consumers and businesses. It has jurisdiction over Cal Am's operations within its boundaries, including setting water production levels, and setting water use fees to enable it to carry out management activities to achieve its goals.

It also runs water metering programs for all wells within its region, monitors surface and groundwater levels, determines release rates from reservoirs to meet instream flow requirements, implements water conservation programs and rationing during droughts, and conducts watershed management and restoration activities in the Carmel River Watershed. It also holds the authority to approve new or expanded water distribution systems, including changes to private wells (Monterey Peninsula IRWM Plan Update, 2014). But MPWMD's authority in the area is not exclusive. In 1990, the State Legislature established the Monterey County Water Resources Agency (MCWRA, formerly the Monterey County Flood Control and Water Conservation District). MCWRA's powers also include management of groundwater, in cooperation with MPWMD (Langridge et al. 2016a).

Seawater intrusion has been an ongoing potential concern. Groundwater extraction primarily for agricultural use has exceeded the recharge rate and seawater intrusion continues to move inland as growers rely on groundwater production for irrigation water. Projected droughts under climate change are anticipated to intensify this reliance and speed up the rate of saltwater intrusion. In 1995, the SWRCB ruled that downstream of river mile 15, the aquifer close to the river is a subterranean stream, and as such SWRCB holds permitting authority. The SWRCB then ordered reduced pumping from the Carmel Valley aquifer (SBO 95-10), leading to increased pumping in the Seaside Basin. In 2009, the SWRCB issued a second order to reduce pumping from the Carmel Valley system (Monterey Peninsula IRWM Plan Update, 2014).

Then, in 2006, the Seaside Basin was adjudicated after withdrawals that were almost twice the average safe yield resulted in declining groundwater levels. The adjudication judgment determined that two cities and other entities had water rights in the basin (California American Water v. City of Seaside et al. Case No. M66343, Amended Decision, 2007). The adjudication judgment requires that groundwater pumping be reduced from the then average of 5,600 AF to a safe yield of 3,000 AFY by 2021 in order to avoid seawater intrusion. The Court established a collaborative Watermaster composed of 13 voting members representing nine parties, with MPMWD having one vote (Langridge et al. 2016a).

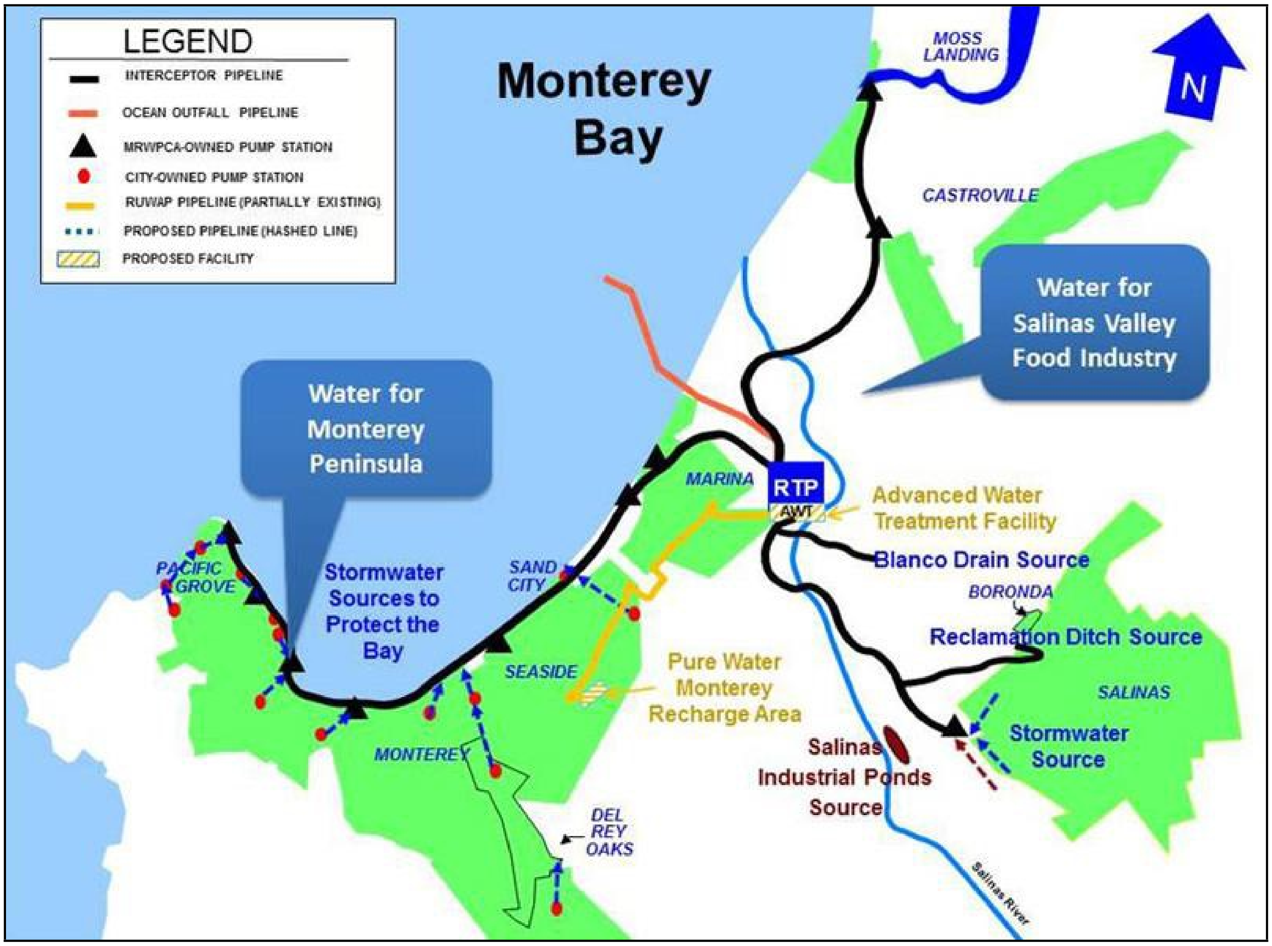
The area thus received a double requirement for cutbacks in early 2000, with Cal Am needing to find replacement supplies for 2/3s of annual Carmel River diversions, and groundwater production cutbacks in the Seaside basin required by the adjudication to achieve safe yield by 2021. The region's estimated need was 4,846 AFY by 2022 with an additional 5,600 AFY to serve legal lots of record and meet Monterey County General Plan requirements.



Source: Jonathan Lear

Figure 8: The Supply Gap

To address the "supply gap", (Figure 8), Cal Am is proposing a desalination plant. While MPWMD supports a potential desalination project, its efforts are currently focused on an expanded and advanced recycled water project, Pure Water Monterey (Figure 9). It will be jointly developed by two public agencies –MPWMD and Monterey One Water. Pure Water Monterey will be less expensive than desalination. Pure Water Monterey will provide both purified potable water for domestic use, as well as a supply for irrigating the agricultural areas in the Salinas Valley. The project will be the first of its kind to use not just wastewater, but stormwater, food industry processing water, and impaired surface waters of the State (Pure Water Monterey 2018).



Source: Jonathan Lear

Figure 9: Monterey Pure Water

The Seaside Groundwater Basin will be replenished with the treated water through injection wells that will supplement supply and decrease the impact of groundwater overdraft and the associated risks of seawater intrusion. The Pure Water Monterey Program includes several benefits: advanced water treatment facilities for indirect potable reuse for the Monterey Peninsula, improvements to the Salinas Valley Reclamation Project, and additional recycled water to agriculture via the Castroville Seawater Intrusion Project (Seaside Basin Replenishment Project 2018).

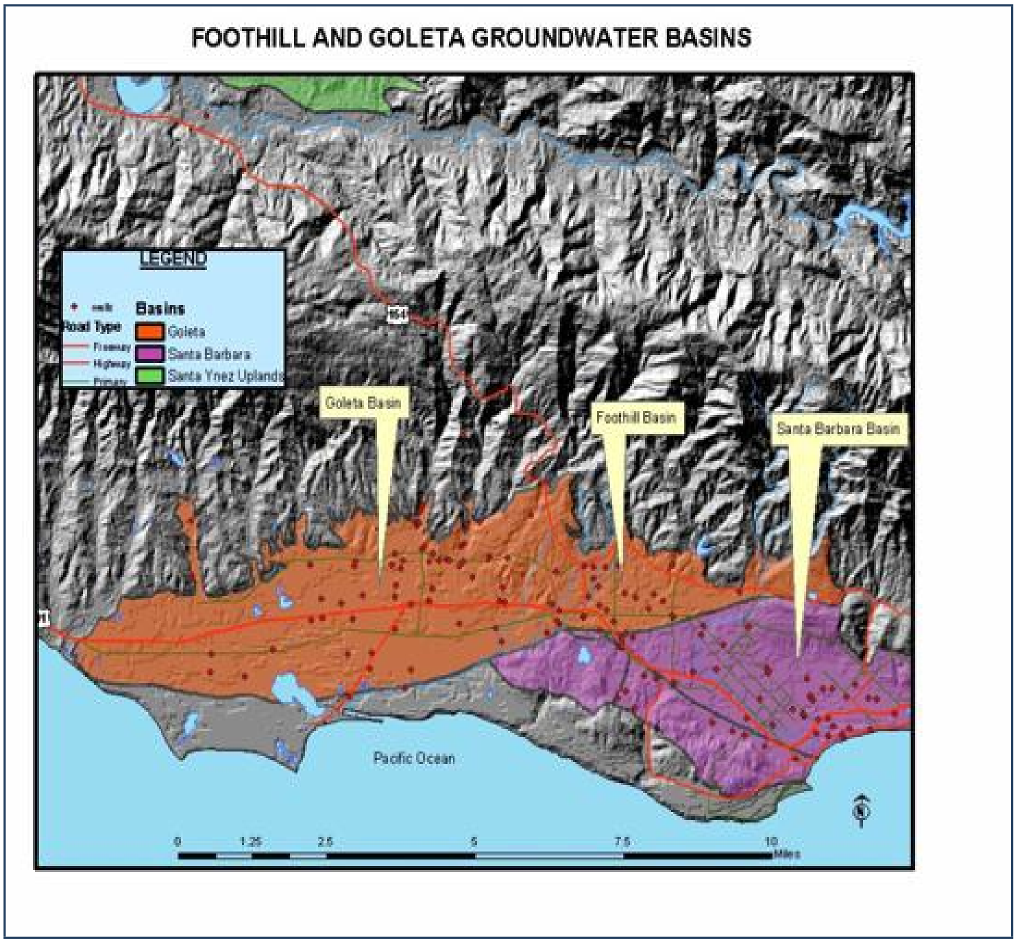
Negotiations with Salinas Valley growers led to diversion and recycling of their previously unused stormwater and agricultural drain water from overflow ponds in the Salinas Industrial Ponds (Pure Water Monterey 2018). This water will be treated at the recycling facility and 3,500 AFY of the recycled water will be recharged into Seaside Basin. Recycled water will also be provided for the Castroville Seawater Intrusion Project's agricultural irrigation system to be used as an in-lieu recharge for that groundwater basin (Lear 2018). The project is also expected to produce a local "drought reserve" of about 200 AFY during wet years, as well as up to 5,900 additional AFY of agricultural irrigation water (Johnson 2016), with 1,000 AF of this water provided to the Salinas Valley growers in a dry year (Lear 2018).

3.5 Goleta Water District

The Goleta Water District (GWD), managing the adjudicated Goleta Groundwater Basin (GGB), has been at the forefront of proactive drought management with a groundwater drought reserve established in 1991. The 2012-2016 drought was particularly severe for that area of the Central Coast, which is still designated to be in a "severe drought" in 2018, and the drought reserve continues to provide an important buffer.

They were also an early proponent of recycled water and have a strong conservation program. They were one of the few management districts to continue the state mandated 2015 drought conservation rules after the requirements were rescinded in 2016.

The Goleta Groundwater Basin (GGB), located along California's south-central coast, is an alluvial plain about eight miles long and three miles wide situated on the coastal plain between the Pacific Ocean and southeastern foothills of the Sant Ynez mountains that are over 500 feet above sea level - Figure 10.



Source: RMC Water & Environment 2014

Figure 10: Goleta Groundwater Basin

Annual average rainfall within the basin ranges from about 16 inches at the coast to about 20 inches in the mountain foothills. Surface drainage is to the south where several creeks empty into the ocean (Santa Barbara County Groundwater Report, 2011). Groundwater typically comprises only 15 percent of the Goleta Groundwater District's (GWD) supplies but was GWD's primary source of supply during the 2012-2016 drought when the availability of surface water supplies was reduced. The 2012-2016 drought was particularly severe for that area of the Central Coast, and in 2018, the area remains in a "severe drought" (U.S. Drought Monitor 2018). GWD is drawing on the increased availability of surface water in 2017 to recharge the GGB and recover groundwater levels, but mandatory drought restrictions remain in effect (GWD 2018a).

Shallow wells were drilled in the GGB as early as 1890. By the late 1930s, deeper wells were being used to develop fruit and nut orchards and groundwater use was estimated to be approximately 3,000 - 6,000 AFY - 3,699,000 – 7,398,000 cubic meters (Upson 1951). Urbanization gradually replaced agriculture, and public water producers became a larger factor in groundwater withdrawals. In 1944, the GWD was formed to provide water to the Goleta Valley. Covering 29,000 acres, the GWD relied solely on local groundwater until the U.S. Bureau of Reclamation's Federal Cachuma Project on the Santa Ynez River began making water deliveries in 1955. By 1970, rapid population growth in the valley and a long-term drought from 1940-1970 had reduced water supplies. The GWD adopted several ordinances to restrict water use, including Ordinance 72-2 in 1973 that began a moratorium on new water service connections (Bachman 2010)

In 1973 a group of overlying landowners in the basin sued the GWD to adjudicate water rights in the north-central part of the groundwater basin (Martha H. Wright et al. v. Goleta Water District et al., 1989). The trial court determined the basin's water rights and safe yield, and a revised final judgment was issued in 1989. Importantly, the GWD was provided with storage and recovery rights in the basin. However, groundwater withdrawals continued while the adjudication was going on, and the drought in the 1980s and early 1990s resulted in water supplies for Santa Barbara County's south coast reaching a critically low level. The GWD had to rely more heavily on groundwater, and groundwater elevations reached historically low levels.

In response to concerns about the groundwater overdraft and the future of its water supplies, in 1991 GWD customers, in a close vote, approved the Safe Water Supplies Ordinance (SAFE) (SAFE Ordinance No. 1991, amended in 1994). SAFE authorizes the importation of SWP water, but specifies that the water be initially used to replenish the basin (4,500 AFY - 5,548,500 cubic meters) and to establish a drought buffer/reserve (an additional 2,500 AFY (082,500 cubic meters). The buffer can only be used for delivery to existing customers when a regional drought results in a reduction in GWD deliveries from Lake Cachuma. Once the basin is recovered to 1972 levels and all other obligations for water delivery are met, the GWD can again provide new service connections up to one percent of the total potable water supply. But notably, when a new service is connected, the annual storage commitment made to the drought buffer is required to permanently increase by 2/3rds of any release for new or additional uses "so that safe water supplies in times of drought shall not be endangered by any new or additional demands."

Thus, under SAFE, GWD can pump its stored water only when groundwater elevations in the basins are above 1972 levels or when a regional drought results in a reduction in the GWD's annual surface water deliveries (SAFE Ordinance No. 91-0, 94-03), and, the drought buffer is defined not by the amount of stored water, but by the increase in groundwater elevations.

The amount of water that can be pumped from the drought buffer has been calculated in GWD's Groundwater Management Plan (GWD, 2016). Modeling studies showed that when the 1986-1991 drought is extended by two years, the drought buffer is only partially used, however it is used considerably at higher levels of water demand during a longer drought, suggesting that maintaining the buffer would be particularly valuable in a long-term drought (Bachman 2011).

The GWD's management approach is to monitor the basin in collaboration with the USGS and use Basin Management Objectives (BMO) to set quantitative groundwater level targets at the lowest measured historical static non-pumping groundwater elevation in each BMO well. When groundwater elevations fall below this target, they do not meet the BMO. This criterion was based on the observation that a groundwater elevation that low in the well in the past did not harm the basin, but a groundwater elevation below that BMO could create potential unacceptable impacts.

The results are positive. Beginning in the 1990s, basin pumping declined largely due to the Wright Judgment and the SAFE Ordinance, and in 2008 water levels were near the highest levels recorded in the basin. The value of the drought buffer was especially apparent during the 2012-2016 drought that extended to 2018 in the region. While many groundwater basins in the state saw a significant decline in groundwater levels in 2014 (DWR 2015a), Goleta basin levels dropped beginning in 2015, but began to recover in the spring of 2017.

In October of 2014, GWD initiated a moratorium on new water connections, but continued to recognize pre-existing water entitlements that were exempt from the moratorium. In 2015, a 16 percent reduction in GWD's projected 12-month supply after 3 yrs of drought as well as the new state emergency regulations resulted in GWD instituting water use restrictions that required 25 percent cutbacks in water use, that were then increased to 35 percent. Additionally, to comply with the SAFE Ordinance, approvals of any additional potable water connections were prohibited because water delivery from Lake Cachuma was below 100 percent. In 2015, despite 2014 and 2015 SWP deliveries of only 5 percent and 20 percent of contracted water respectively, and Lake Cachuma only providing 45 percent of its normal deliveries, GWD's groundwater wells were able to provide over 50 percent of their water deliveries, made possible because of the ongoing investment in its reserves (Goleta Water District 2015).

Goleta also has comprehensive conservation and recycled water programs. GWD was first in California and the United States to offer rebates for retrofitting homes with low-flow toilets. In a SWRCB survey, Goleta residents were the thriftiest water users in Santa Barbara County and 15 among 389 urban communities in California. During the 2012-2016 drought, extended to 2018 in the region, Goleta's 87,000 residents used just under 53 gallons per capita of water per day in September 2015. The statewide residential average for September was 97 gallons (Burns 2015).

In 2017, GWD residential customers reduced their already-low per capita water use during the drought to 48 gallons per customer per day (GPCD).

One question for GWD is whether it should maintain groundwater elevations above or only slightly above 1972 levels during non-drought periods to enhance drought protection for customers. This would result in more costly and less reliable SWP water being used in lieu of groundwater to serve existing and potentially new customers. But as already noted, SWP water availability is variable from year to year and is projected to be less reliable and more expensive in the future. Moreover, the surface water allocation from the Cachuma Project, a significant supply source, is anticipated to decrease in the future due in part to sedimentation in the lake, mandatory releases for fish species, and downstream water rights.

4: Limits to a Local Drought Reserve Strategy

While our case studies in section 3 emphasize the development of groundwater drought reserves as an important and proactive approach to increasing drought resilience, it is important to note that this strategy is not feasible, nor is it a priority, in some basins. Berg and Hall's (2015) analysis of 34 global climate models concluded that extremely wet winters will also increase "to around 2 times the historical frequency, which is statistically significant at the 95 percent level" by the year 2061 and will increase even more after 2061. Thus, for some groundwater basins, the greater frequency of floods is likely to be a serious impact of climate change and the management priority for the basin. This is the case for Six Basins discussed in Section 4.1. Additionally, not every basin has the ability to store groundwater locally as a drought buffer. The Mendocino City Community Services District discussed in section 4.2 is one example.

4.1 Six Basins

The Six Basins in the Inland Empire are a group of adjacent groundwater basins, located just south of the San Gabriel Mountains in eastern Los Angeles and western San Bernardino Counties (Figure 11). Groundwater is pumped from the Six Basins primarily by public water-supply agencies and mutual water companies that supply water for municipal uses. It is a relatively small adjudicated groundwater basin with insufficient room to bank large amounts of water during wet years for use during dry years. Moreover, there is an uneven distribution of recharge facilities in the basin. Along with specific hydrogeologic conditions and complex water rights in the basin, the capacity to bank water for long periods of time is limited. The occurrence of more severe storm events under climate change will exacerbate the basin's inability to capture the maximum amount of stormwater runoff. The basin's first priority is to develop the infrastructure to capture high volumes of stormwater runoff for recharge (Lyles 2017).

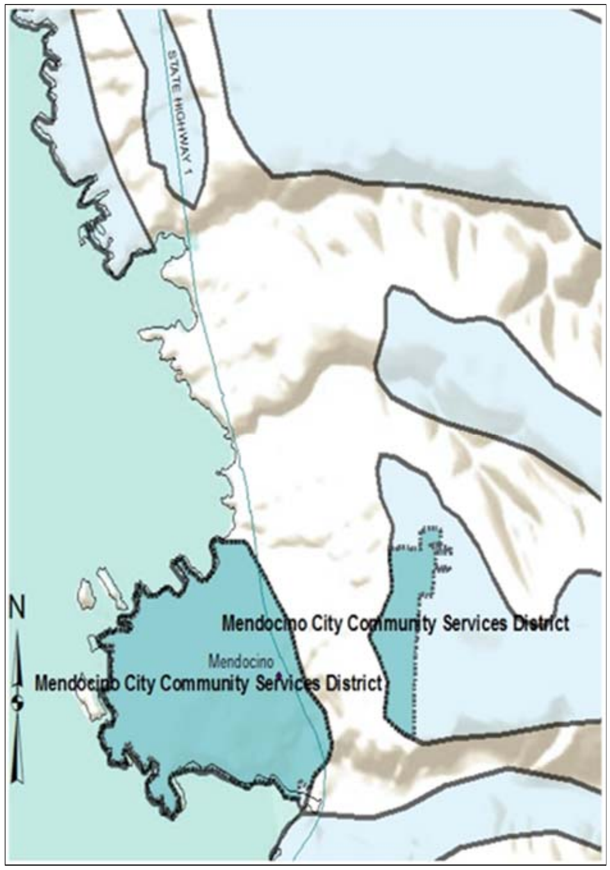
Figure 11: Six Basins Adjudicated Groundwater Basin

This priority does not remove the likelihood of future droughts for the Six Basins due to high temperatures (and thus high evapotranspiration) and increasing human demand. Moreover, most Six Basins Parties purchase imported surface water from several local water districts, who in turn receive imported surface water supplies from MWD. MWD's sources of water include both the Colorado River and the SWP, and projections are that both of these sources will be reduced under climate change, particularly during drought periods. The Six Basins Watermaster has expressed concern that drought would increase the salinity of Colorado River supplies, thus requiring imported surface water be mixed with other higher quality sources in order to meet potable standards (WEI, 2015, sec. 3.1.6). Additionally, the basin Watermaster notes that many of the best strategies for lower residential demand are already in place, so opportunities to reduce demand will be difficult (Langridge et al. 2016b, Lyles 2017). The twin challenges of both droughts and floods, which were significant factors in the history of Six Basins' management, will likely become even more formidable as inter-annual variability increases in the future.

4.2 Mendocino City Community Services District

In some basins, strict demand control strategies at all times is possibly the only drought adaptation response to local hydro-geologic conditions. Due to the geology of the small Mendocino

Headlands Aquifer on California's North Coast, each year most groundwater flows through springs in the rock formation and into the Pacific Ocean on a seasonable basis rather than remaining in storage. The groundwater is the primary source of water for the small town of Mendocino, with the exception of tanker truck imports that occur in the dry months of drier years.



Source: SWRCB

Figure 12: Mendocino Community Services District

The Mendocino City Community Services District (MCCSD) (Figure 12), a Special Act District, has full responsibility for managing the town's groundwater (Mendocino County Community Services District 2012). Approximately 400 privately owned and operated wells supply groundwater for residential and commercial purposes within MCCSD boundaries. The sparse population of the town, its severely limited natural water resources, and its relative geographic isolation from larger population centers make importing water from elsewhere in the state cost-prohibitive.

Two major strategies for managing the groundwater resources are the implementation of groundwater extraction permitting regulations and mandatory water conservation requirements at all times (Langridge et al. 2016b). The cumulative effects of a continued drought are not yet well known, making it uncertain how MCCSD will weather an extreme drought under climate change.

5: Conclusions and Future Directions

Groundwater is one of the most critical natural resources for California communities and an essential source of supply during the state's periodic droughts when surface supplies are reduced. During the 1976 drought, it was primarily the state's groundwater resources that prevented a potential disaster (ACE 1993). The conundrum is that overdraft and associated impacts continue to increase and are significant in many groundwater basins. Climate change, including projections of more extreme droughts, will exacerbate these groundwater storage declines. Many scholars and practitioners point to the need for proactive drought mitigation strategies and the importance of groundwater as a supply source during drought, yet most drought mitigation strategies are focused on general supply reliability. There are fewer examples of strategies to manage groundwater that are specifically focused on reducing drought vulnerability, and very few examples of managing groundwater to account for the extreme droughts projected under climate change.

To fill that gap, our paper discussed:

> **1) How groundwater management agencies are planning for drought, and**
>
> **2) What new approaches are currently being used that show promise for addressing the more extreme droughts projected under climate change?**

The paper first provided a review of the research on drought and groundwater management in California including strategies currently being used to address drought. We then provided seven case studies to illustrate the varied approaches agencies are using to plan for drought, strategies that are important first steps to adapt to the future more extreme droughts projected under climate change.

Notable points from our review relevant to how the state and groundwater agencies are currently planning for drought, including what is known and what remains understudied, are listed below

- The concept of snow drought is significant in California where higher temperatures under climate change will reduce the amount of snowmelt and change the timing of runoff, both critical for the state's imported water supplies.
- Imported surface water is a major water supply source, but under climate change it is projected to be less reliable and more expensive in the future. Some basins are moving to diversify their sources, and the use of recycled water in particular has increased since 1976, but for the most part local water supply sources are still not sufficient to compensate for potentially reduced imported water.
- Drought planning and groundwater management plans rarely intersect. Drought plans give limited attention to sustaining groundwater over the long term, while groundwater plans provide limited attention to drought. This is despite groundwater's role as a critical supply source for the state and, importantly, a backstop during drought.
- The 2014 Sustainable Groundwater Management Act requires the management and use of groundwater to prevent undesirable effects but has no explicit incentives to manage groundwater with pro-active long-term strategies that account for future droughts including the extreme droughts projected under climate change.
- Strategies to regulate withdrawals are generally modest in scope and often contested.

- Approaches to recharging aquifers have increased including taking advantage of the anticipated increase in storm events to flood fields for both irrigation and recharge.

Case studies highlight more innovative practices that have the potential to increase drought resilience to future extreme droughts.

- **Orange County Water District** management researched and then defined an acceptable range for its groundwater levels to ensure limited negative impacts, which is aligned with SGMA's approach. This reduces groundwater declines that usually occur during drought and that are frequently not recoverable during normal and wet years. Managing so as to sustain levels within this range can potentially provide increased resilience in future extreme droughts under climate change.

Four approaches emphasize not only increasing storage but also establishing groundwater levels that incorporate a reserve to be primarily used under defined drought conditions. One basin management, GWD, established a reserve in 1991 and the reserve has been a significant factor in reducing the region's drought impacts. In three of the basins, this approach is recent. Establishing and sustaining a drought buffer strategy is one important management tool that can assist in reducing the impacts from extreme droughts projected under climate change and increase the state's resilience to future droughts.

- **The Main San Gabriel Basin Watermaster** held the Operating Safe Yield (OSY) low to encourage decreased groundwater pumping. This **incentivizes decreased groundwater pumping to meet demand because any water pumped over the OSY requires users to pay a replenishment fee.** They established a Resource Development Assessment - Stormwater Augmentation Program to help manage the basin's water supplies under "worst case" drought conditions (defined as 15 years under the same condition as the 2012-2016 drought). Their goal is to purchase 100,000 AF of water within ten years and store it as a reserve for future needs during dry periods, and to use untreated imported replenishment water for stormwater augmentation to maintain the Key Well at an elevation where there are limited negative impacts.

- **Tehachapi Basin Watermaster** adopted a new M & I Agreement that established a recharge component for imported surface water that requires water purveyors to put a 5-year water supply into the basin, which would be equal to a 5-year imported water requirement, to serve as a drought reserve. This can be accumulated over a 10-year period

- **The Monterey Peninsula Water Management District** a) uses a coastal distribution system to provide growers with recycled water in-lieu of pumping groundwater, b) invested in a new major recycling facility, and of particular note c) negotiated with growers for an agreement that resulted in a groundwater reserve supply for their use during drought.

- **The Goleta Water District** has been at the forefront of proactive drought management with the establishment of a groundwater drought reserve in 1991 that provided an important buffer through the 2012-2016 drought that was particularly severe for that part of the Central Coast, and that extended into 2018. They were an early proponent of recycled water and have a strong conservation program. They were one of the few management districts to continue conservation rules mandated by the state in 2015 drought after the rules were rescinded in 2016.

Two case studies demonstrate the limits of a drought reserve and indicate that more needs to be done to address the range of individual groundwater basin conditions and the varied needs of the communities reliant on the groundwater.

It is notable that some strategies being used by the state's groundwater districts to adapt to drought have evolved since the 1976 drought. We point to a few trends in Table 13 that, if continued, can assist in better preparing the state to cope with future extreme droughts under climate change.

Table 13: Drought Management Trends

1976 Drought	1987-1992 Drought	2001-2009 Drought	2011-2016 Drought
Voluntary Conservation	Voluntary Conservation	Mandated Conservation SBX-7-20x20x20	EOB-29-15: Mandatory Conservation-25% reduction for urban users
Recycled water use ~190,000 AF	Recycled water use ~279,000 AF	Recycled water use ~669,000 AF	Recycled water use ~714, 000 AF
	Sustainable groundwater management – voluntary plans		2014 Sustainable Groundwater Management Act (SGMA) – mandatory requirements
	Goleta Basin establishes a local groundwater drought reserve		Increasing use of local groundwater drought reserves

Areas to be considered in future research include:

- What are the impacts, benefits and challenges of long-term proactive strategies to manage groundwater under drought and climate change?
- Under what conditions (social, economic, legal) do basins adopt more sustainable drought management practices?

Drought periods in California frequently end with periods of heavy rain and concomitant floods. Research exploring how to incorporate this climate variability into management strategies that can increase groundwater storage and potentially reduce vulnerability to future extreme droughts under climate change is promising but still limited, and it is an area for further research.

According to the IPCC (2007b), the array of potential adaptive responses available to human societies is very large, including technological, behavioral and managerial strategies. While traditional drought adaptation strategies are known and developed, the effectiveness of various options to fully reduce risks for vulnerable water-stressed areas during extended and intense drought periods remain understudied. Research on what practices implemented during past California droughts were effective in reducing drought vulnerability in subsequent droughts would be beneficial.

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