

Climate-Resilient Groundwater Management

*Metrics to Ensure Sustainable Groundwater
Management for Current and Future
Californians*

Juliet Christian-Smith

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Juliet Christian-Smith is a Climate Scientist in the UCS California and Western States Office.

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Two Brattle Square
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Summary

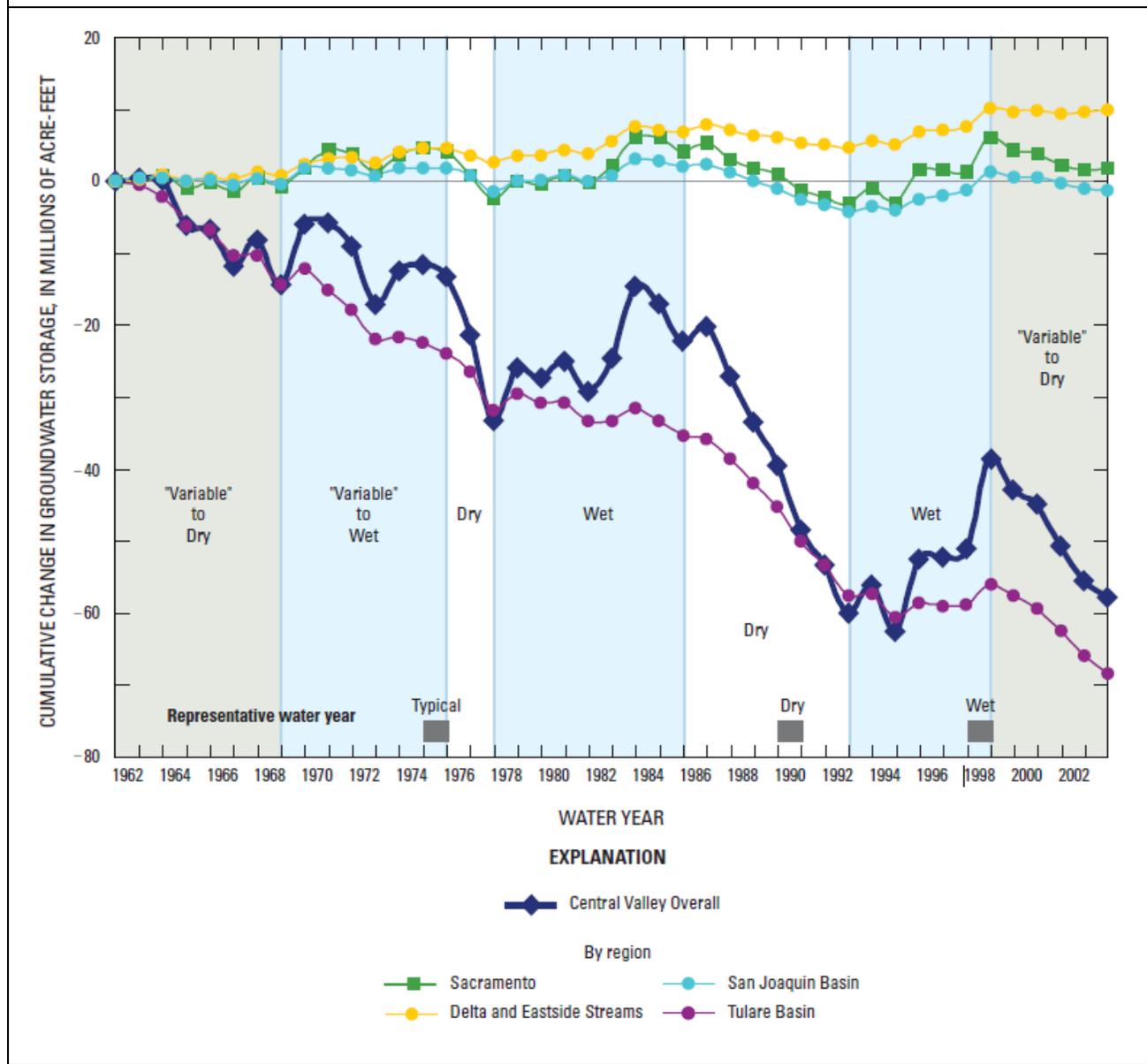
California is the only state in the nation with no statewide groundwater regulation. It is clear that for California to address current and future water challenges, the state must adopt a more comprehensive approach to groundwater management. California has recently taken bold steps to re-think its approach to groundwater. Yet, a commitment to sustainable groundwater management is only as good as the metrics that will be used to assess progress. Further, climate change is already altering the timing and reliability of California's water supplies. Groundwater management must incorporate the state's changing hydrology and its impact on groundwater recharge and use. This paper reviews a number of approaches to groundwater management. California's groundwater policy can benefit from the lessons learned elsewhere. Specifically, California's groundwater policy should provide clear metrics to define and measure sustainable yield, explicitly incorporating climate change.

Background

A growing body of scientific research concludes that increased temperatures along with changing precipitation patterns are altering the timing and availability of water resources in the Western United States (DWR 2009, IPCC 2013, Walsh et al. 2014). Over the last several decades, remote satellite data shows that groundwater use has substantially increased during dry periods (Figure 1). For instance, during the 2007-2009 drought period in California, more than 1 million acre-feet of groundwater storage was lost (Famiglietti et al. 2011). With longer and more severe droughts projected for the Western U.S. (Seager et al. 2007, Sheffield and Wood 2008, Karl et al. 2009), groundwater will play an increasingly important role in both climate change mitigation and adaptation efforts. Up until now, however, California has been the only state without statewide groundwater management.

The current drought conditions in California are increasing reliance on the state's aquifers and groundwater tables are dropping significantly (California Water Foundation 2014). These challenges highlight the inadequacies of 20th century approaches to water planning and management in the 21st century. While there are increasingly urgent calls for better groundwater management in the state, there is little discussion of how this would be measured despite the common recognition that you can't manage what you don't measure. This white paper briefly reviews a number of technical approaches to quantifying sustainable groundwater management, including *safe* yield and *sustainable* yield. There are some important lessons to be learned from the successes and challenges associated with the application of these approaches in different contexts. Specifically, California should consider setting a quantifiable *sustainable* yield policy. Such a policy should explicitly incorporate climate change and address managed recharge.

FIGURE 1. SIMULATED CUMULATIVE ANNUAL CHANGES IN AQUIFER STORAGE BETWEEN WATER YEARS 1962 AND 2003 FOR THE CENTRAL VALLEY, CALIFORNIA



DATA SOURCES (FAUNT ET AL. 2009).

NOTE: THE CENTRAL VALLEY HYDROLOGICAL MODEL WAS USED TO SIMULATE CHANGES IN GROUNDWATER STORAGE. DETAILS OF THE MODEL ARE EXPLAINED IN THE USGS PUBLICATION GROUNDWATER AVAILABILITY OF THE CENTRAL VALLEY AQUIFER, CALIFORNIA (FAUNT ET AL. 2009). THE MODEL DEMONSTRATES THAT, GENERALLY, GROUNDWATER STORAGE DECREASES DURING DRY PERIODS (INDICATED BY A GREY OR WHITE BACKGROUND) AND INCREASES DURING WET PERIODS (INDICATED BY A BLUE BACKGROUND).

GROUNDWATER IS CRITICAL FOR CLIMATE CHANGE ADAPTATION AND MITIGATION

As the California Department of Water Resources (DWR 2009) points out, “For California water managers, the future is now. Climate change is already having a profound impact on water resources as evidenced by changes in snowpack, river flows and sea levels.” While more is known about the potential impacts on surface water, climate change also influences groundwater systems both directly through changes in recharge (or how much precipitation and surface water percolates into groundwater over a specified time period) and indirectly through changes in groundwater use patterns (or where and how much groundwater is pumped over a specified time period). Studies show that California is already experiencing the impacts of climate change. Average early spring snowpack in the Sierra Nevada decreased by about 10 percent during the last century, a loss of 1.5 million acre-feet of snowpack storage (one acre-foot of water is enough for one to two families for one year) (DWR 2009). If global warming emissions remain at today’s levels, snowpack is expected to decrease by approximately 80 percent by the end of the century (Cayan et al. 2007), drastically reducing the state’s surface water supplies. Groundwater is clearly critical for climate change adaptation: “Groundwater can provide a buffer against climate extremes and is consequently essential to global food security...The value of groundwater is expected to increase in coming decades as temporal variabilities in precipitation, soil moisture and surface water are projected to increase under more frequent and intense climate extremes associated with climate change” (Taylor et al. 2013).

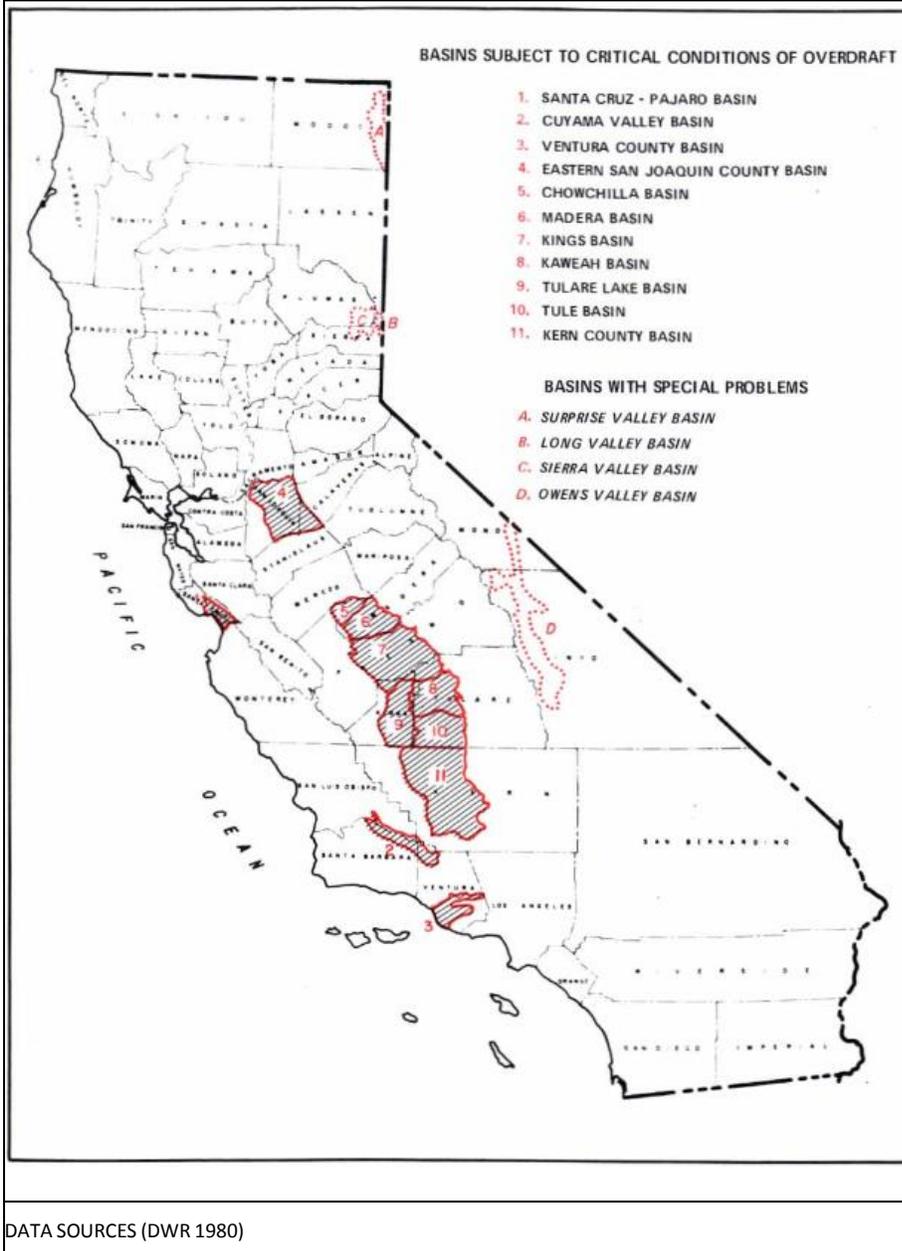
The role of groundwater in climate change mitigation is less well understood. Growing attention to the water-energy nexus is bringing to light the significant amount of energy embedded in water, and the water required for energy generation. For instance, water is required for much of the state’s electricity generation (e.g., hydropower and thermoelectric cooling) and moving and treating water consumes a great deal of energy. According to the California Energy Commission (2005), water-related energy use in California (e.g., pumping, transporting, treating, and heating water) consumes approximately 20 percent of the state’s electricity, and 30 percent of the state’s non-power plant natural gas.

Yet, the energy intensity of groundwater pumping remains unknown as there is no statewide reporting of groundwater use. And the energy intensity of groundwater pumping is changing as groundwater levels continue to decline throughout much of the Central Valley (Famiglietti et al. 2011), requiring more energy to pump from greater depths. Thus, groundwater pumping may be an increasing source of global warming emissions with longer and more frequent droughts expected in the future and, therefore, may be important when considering how to reduce statewide carbon emissions.

As of this writing, California is unique in that it is the only state in the nation without comprehensive statewide groundwater regulation. However, there is reason for optimism: a number of policy documents and pieces of draft legislation have been released recently acknowledging the critical role of groundwater in climate-resilient water management. For example, the California Water Action Plan points to current unsustainable groundwater uses and their consequences, concluding that better groundwater management is an important element of climate change adaptation.

“Groundwater accounts for more than one-third of the water used by cities and farms—much more in dry years, when other sources are cut back. Unfortunately, much of California’s groundwater is not sustainably managed. Climate change is exacerbating ongoing problems with groundwater resources in California, including overdraft, seawater intrusion, land subsidence, and water quality degradation. Taking more than is returned lowers groundwater levels which makes pumping more expensive and energy intensive...Well-managed groundwater has the potential to buffer against the impacts of climate change on our water resources.” (California Water Action Plan 2013).

FIGURE 2. IN 1980, 11 GROUNDWATER BASINS WERE SUBJECT TO CRITICAL OVERDRAFT



GROUNDWATER PLANNING IS FRAGMENTED AND LACKS STATEWIDE STANDARDS

Despite the importance of groundwater in climate change adaptation and mitigation, groundwater management is currently highly fragmented in California. Authority over groundwater has been largely left to local entities with the intent of avoiding one-size-fits-all solutions. Today, groundwater management plans cover about 130 of more than 400 groundwater basins in the state. In addition, there are about 30 counties with groundwater ordinances, 22 adjudicated basins, and 13 special districts with groundwater management authority (Table 1).

While local groundwater management plans are the most common form of governance, they vary widely in their authority, implementation and effectiveness. Numerous studies have concluded that groundwater management plan

requirements are out of date, do not match modern principles of groundwater planning, and do not compel action even in the most extreme cases of groundwater overdraft (Nelson 2011). The last comprehensive assessment of groundwater overdraft (Bulletin 118) was conducted in 1980 and found 11 groundwater basins subject to critical overdraft (Figure 2). Existing legislation allowing groundwater management planning lacks clear measures of success to ensure that groundwater management meets certain state requirements such as the prohibition against the waste and unreasonable use of water (California Constitution, Article X, Section II) and the state has not played a significant role in providing oversight of groundwater planning efforts to date (Nelson 2011).

TABLE 1. A summary of groundwater-related state planning efforts and associated actions or funding		
Management Approach	Approximate Count	Authority
Groundwater management plan	130	AB 3030 (1992), Section 10750-10756 of the California Water Code
County groundwater ordinances	30	County Police Powers (Baldwin v. Tehama County, 31 Cal. App. 4th 166, 1994)
Legal adjudications	22	California Constitution, Article X, Section II (Katz v. Walkinshaw, 114 Cal. 116, 1903)
Special district laws to manage groundwater	13	Numerous parts of the California Water Code allow the establishment of Special Districts
DATA SOURCES (DWR 2003, NELSON 2011)		

In some areas with rapidly declining water tables, counties have recently used their police powers to halt additional groundwater extraction temporarily. For example, San Luis Obispo County is in the process of developing a cap-and-trade approach to groundwater pumping. The San Luis Obispo County Board of Supervisors approved a 45-day emergency groundwater ordinance in 2013 — later extended to two years — that prohibits new pumping from the basin unless it is offset by an equal amount of conservation. The emergency ordinance states that all new water use in the basin must be offset using a 1:1 ratio (with several supervisors arguing for a 2:1 offset ratio). In addition, any new irrigation wells must be metered and monitored to track water use (Sneed 2013). However, county boundaries do not line up with basin boundaries and it is unclear if these new rules will be effective basinwide.

Recently, there has been growing interest in determining the proper role of the state in encouraging more sustainable groundwater management in California. Several different proposals have been made in policy documents over the last year. For instance, the Governor’s proposed budget for fiscal year 2014-2015 recommends allocating \$7.8 million to sustainable groundwater management and monitoring efforts along with \$472.5 million for integrated regional water management programs, which can include groundwater-related efforts.

“The administration will take steps, including sponsoring legislation, if necessary, to define local responsibilities and to give local agencies the authority necessary to manage groundwater sustainably and ensure no groundwater basin is in danger of being permanently damaged by over drafting. When a basin is at risk of permanent damage, and local and regional entities have not made sufficient progress to correct the problem, the state should protect the basin and its users until an adequate local program is in place.” (California Water Action Plan 2013).

The interagency Water Action Plan recommends updating Bulletin 118, including anticipated impacts of climate change on surface water and groundwater resources. In addition, the Water Action Plan commits the state to a more proactive role in protecting groundwater from overdraft. In addition, the State Water Resources Control Board's draft groundwater work plan assesses existing state authorities to compel better groundwater management and how these authorities could be expanded or strengthened. And, finally, proposed legislation would require local groundwater planning with a role for the state if basins do not set up groundwater management plans within a specified timeframe or are unable to sustainably manage the resource (SB 1168 and AB 1739).

Sustainable Groundwater Management Metrics

While it is widely acknowledged that groundwater management must be improved, there is less clarity around what constitutes sustainable groundwater management (Rudestam and Langridge 2014). The remainder of this paper focuses on different metrics used to measure and monitor sustainable groundwater management. Groundwater management has progressed in many countries over the latter half of the last century, concurrent with a change in emphasis from resource exploitation to resource management (Kalf and Woolley 2005). California can benefit from these experiences in setting its own sustainable groundwater management policies.

There are two prominent concepts in groundwater management: *safe* yield and *sustainable* yield. Both concepts, generally, proscribe a relationship between groundwater withdrawal (outputs) and groundwater recharge (inputs). *Safe* yield was originally defined as the quantity of water that can be withdrawn regularly and permanently without dangerous depletion of the storage reserve (Lee 1915). Safe yield is, therefore, focused primarily on groundwater storage and levels, and does not fully consider the multiple benefits that groundwater provides. Often the objective of safe yield has been to match groundwater withdrawal to groundwater recharge (USGS 1999). However, this was found to overly simplify the complex hydrological, ecological, and social context of groundwater management (see the case study of Kansas).

In the late 1980s, the concept of sustainable development — meeting the needs of the present without compromising the ability of future generations to meet their own needs — informed a shift to the concept of *sustainable* yield. The concept of sustainable yield is an attempt to determine a metric that can ensure the long-term resilience of a groundwater system (Rudestam and Langridge 2014). Sophocleous (1997) defines sustainable yield as groundwater withdrawal that allows for environmental sustainability. Sustainable yield protects not just groundwater levels but the multiple ecological and social benefits that groundwater provides such as contributing to stream baseflow (Maimone 2004), maintaining groundwater dependent ecosystems, and serving as a protection against land subsidence and seawater intrusion. Therefore, sustainable yield typically allows only a portion of groundwater recharge to be withdrawn.

CASE STUDIES

In California, some local groundwater management efforts draw on the earlier concept of safe yield, but fewer have considered how to implement a sustainable yield. Relying on safe yield alone has proven detrimental in some cases, leading to unacceptable environmental outcomes (see case study of Kansas). It is, therefore, useful to consider the experience of other states and countries in setting metrics for the monitoring and measurement of sustainable groundwater management. Below, we review some illustrative groundwater management efforts, starting with Kansas, which was among the first states to adopt safe yield policies and later switched to sustainable yield, and ending with Australia, which launched its Sustainable Yields Project in 2007 to consider how to set sustainable diversion limits for groundwater extraction that incorporate climate variability.

KANSAS: “SAFE YIELD” TO “SUSTAINABLE YIELD”

Kansas is heavily reliant on groundwater and was among the first states to adopt safe yield policies for its groundwater reserves (Sophocleous 2012). Kansas allocates both surface water and groundwater based on the doctrine of prior appropriation, or seniority. By the 1960s, the Kansas Legislature was concerned that too many groundwater rights had been permitted, leading to the depletion of local groundwater reserves. Thus, they passed the Groundwater Management District Act in 1972, requiring that local entities be established to preserve existing groundwater rights. Two of the five districts that were created by the act developed safe yield policies. These

policies required that new groundwater withdrawals not exceed long-term average annual recharge rates. If the sum of existing and new groundwater withdrawals exceeded long-term average annual recharge, the permit would be denied.

Unfortunately, recharge rates were overestimated by not taking into account naturally occurring discharge, such as groundwater that contributes to the baseflow of streams. Thus, the districts modified their *safe* yield policies to *sustainable* yield by incorporating groundwater flows that feed baseflow into the calculation of existing withdrawals. In the 1990s, Groundwater Management District 5 codified a new requirement to include baseflow in the calculation of existing withdrawals in their rules and regulations. This change has led to much lower levels of groundwater extraction in relation to recharge.

EUROPEAN UNION: TESTS TO DETERMINE SUSTAINABILITY

The European Union regulates water under the overarching EU-wide statute: the Water Framework Directive. The Directive sets a series of targets, such as achieving “good” ecological status of all water bodies (including groundwater bodies) by 2018, and provides guidance on how to measure, monitor, and report progress. Each member state has transposed this Directive into its own national law and has some flexibility on how it chooses to meet the Directive’s targets. The Directive’s Common Implementation Strategy suggests a series of tests (see below) to assess the chemical and quantitative status of a groundwater body. If a groundwater body fails any of these tests, then the basin is not considered to be in “good” status. There are criteria specifically related to sustainable yield of groundwater:

- No long-term intrusion of saline (or poor quality) water due to withdrawals,
- No significant harm to groundwater-dependent ecosystems,
- No significant degradation of surface water flows, chemistry, or ecology due to withdrawals, and
- Groundwater withdrawals may not exceed long-term average recharge minus long-term ecological flow needs.

AUSTRALIA: INCORPORATING CLIMATE CHANGE INTO SUSTAINABLE YIELD

Australia began to consider sustainable yield definitions and measures in the late 1990s during the country’s 10-year-long “millennial drought,” which led to a series of significant water policy reforms. The Australian National Groundwater Committee defined sustainable yield as: “The groundwater extraction regime measured over a specified planning time frame that allows acceptable levels of stress and protects dependent economic, social and environmental values.” The National Water Commission is attempting to operationalize this definition through its Sustainable Yields Project. This project represents the world’s largest basin-scale investigation of the impacts of climate variability and climate change on future water availability (Chiew et al. 2008). Results from the project analyses will be used to develop sustainable diversion limits for groundwater, which require that groundwater extraction not compromise the productive base of the groundwater resource, groundwater quality, baseflow to streams or groundwater-dependent ecosystems (CSIRO and SKM 2011). The process of developing sustainable diversion limits that incorporate climate change scenarios is summarized in Table 2.

TABLE 2. Process followed by Australia’s Sustainable Yields Project

Step of Process	Data Required	Climate Change Considerations
Estimation of groundwater use	Includes all forms of groundwater use, including stock and domestic take. Groundwater use data was obtained from the jurisdictions. This consisted of metered data where available.	Groundwater use changes depending on surface water availability, which is climate-related. Need to estimate how future climate conditions will alter groundwater use patterns.
Estimation of diffuse dryland recharge	Diffuse dryland recharge was calculated across the Basin and formed the primary input into the development of SDLs. Diffuse dryland recharge is recharge that occurs across the broader landscape under non-irrigated land uses. Other forms of recharge include that from rivers, floods, lakes and irrigation. Where available, information on other forms of recharge was incorporated into the total recharge volume.	Groundwater recharge rates are affected by precipitation and runoff. Need to estimate recharge under a range of climate scenarios.
Definition of sustainability factors	Sustainability factors were defined as the fraction of recharge that could be used for extraction without compromising: key environmental assets (based on assessment of the degree of groundwater dependency and sensitivity to groundwater extraction), key ecosystem function (based on assessment of the potential reduction in groundwater discharge to streams), productive base (based on the assessment of the relative volume of aquifer storage and aquifer recharge), and key environmental outcomes (based on assessment of the potential for an increase in groundwater salinity).	Sustainability thresholds may be altered by climate change-related processes, such as increased rates of saltwater intrusion along coastlines due to rising sea levels. Need to consider climate change impacts on sustainability factors.
Calculation of preliminary estimated extraction limits	Calculation of the preliminary estimated extraction limit for high-use areas with a numerical model. A range of scenarios were used to explore the feasible level of extraction while allowing for groundwater levels to stabilize after 50 years.	A number of climate projections can be used to examine the consequences of different groundwater withdrawals under a range of future climate conditions.

DATA SOURCES (CSIRO AND SKM 2011)

Lessons for California

START WITH A QUANTIFIABLE DEFINITION OF SUSTAINABLE YIELD

Despite the diversity of groundwater conditions and management structures, there is a need to be able to manage groundwater in a way that basins can be compared to themselves over time and to each other. Current groundwater policies (SB 1938) in California rely heavily on qualitative measures, such as adopting groundwater plans and basin-specific management objectives. This has led to the proliferation of groundwater management plans that vary widely in their quality and effectiveness, often providing little data to track progress.

Many other countries have chosen to adopt, at least in part, quantifiable yield policies in order to assess whether sustainable groundwater management has, in fact, been achieved. Developing common metrics to assess groundwater management is critical to ensure effective implementation, even while the sustainable level of groundwater withdrawal will vary among basins. Groundwater elevations are often used to report progress; however, elevations can be subject to time lag and geomorphic variations that obscure trends (Kalf and Wooley 2005). One relatively straight-forward approach to setting and tracking groundwater management targets is to set withdrawals as a percent of groundwater recharge over a specified time period (Equation 1).

$$\text{Equation 1: Yield factor} = \frac{\text{Withdrawal}}{\text{Recharge}}$$

For example, a yield factor of 0.5 would indicate that sustainable levels of groundwater withdrawal are estimated to be around 50 percent of recharge; this also implies that the remaining 50 percent of recharge cannot be withdrawn without compromising sustainability such as negatively impacting water quality, land subsidence, groundwater-dependent ecosystems, or saltwater intrusion rates (Smith et al. 2010).

A review of groundwater yield policies across numerous countries found that safe yield policies tend to allow a yield factor of 1, or withdrawal of 100 percent of recharge, while sustainable yield policies typically limit withdrawals to 15 percent to 85 percent of recharge (Smith et al. 2010). Criteria that were used to constrain withdrawals include: climate change; maximum reduction of baseflow to streams and rivers; maximum allowable drawdown of hydraulic head or minimum aquifer water level; maximum allowable seawater intrusion; maximum groundwater withdrawal rate; and maximum allowable land subsidence (Smith et al. 2010). While setting the thresholds for these criteria requires a detailed basin water balance, the yield factor approach offers a clear way of tracking and reporting on groundwater management efforts in a manner that can be easily-understood and compared between time periods. In addition, it requires that groundwater management entities determine the criteria by which they will limit withdrawals and explain the thresholds that have been chosen to preserve particular ecological and social benefits. Finally, the yield factor approach is dynamic and integrates climatic changes by being proportional to recharge. Conversely, a single volumetric measure of sustainable yield may become outdated quickly.

INCORPORATE CLIMATE CHANGE

Climate change is already altering the timing and quantity of both surface water and groundwater supplies. Thus, it will be critical to model the changes in surface water availability, groundwater recharge rates, and groundwater use under a range of future climate scenarios to inform sustainable groundwater management. Much of the data needed to run such analyses are already available; for instance, the Cal-Adapt website has downscaled climate projections (cal-adapt.org), the California Department of Water Resources' Draft Reliability Report (2013) estimates of the reduction in State Water Project deliveries under a range of future climate conditions, and there is a variety of remotely sensed data on groundwater fluxes (see below).

Australia's process for using climate modeling to set sustainable diversion limits can be seen as a template for how climate change can be incorporated into sustainable yield policies (see Table 2). For groundwater management entities that do not have the ability to conduct modeling using climate projections, they can still employ the yield factor approach highlighted above, using recharge from representative dry periods to ensure policies will be protective of social and natural resources in future dry years (Equation 2). For example, rather than allowing withdrawals of 50 percent of normal recharge, a management entity could limit withdrawals to 50 percent of the average annual recharge during the 2007-2009 water years. Finally, it will be necessary to require adaptive management and comprehensive monitoring efforts to ensure that sustainable groundwater management is incorporating new climatic information.

$$\text{Equation 2: } \textit{Withdrawal} = \textit{Yield factor} \times \textit{Recharge during a dry period}$$

TAKE ADVANTAGE OF EXISTING REMOTE SENSING DATA

Collecting groundwater data has often been cited as a key obstacle to better groundwater management. Tracking numerous monitoring wells can be expensive and time-consuming. However, scientists are increasingly using remote sensing data to monitor groundwater flux. For example, scientists at Stanford recently used Interferometric

Synthetic Aperture Radar (InSAR) to measure groundwater levels in Colorado's San Luis Valley, finding that measurements from InSAR matched locally collected well data (Reeves et al. 2014). Despite the range of currently available remote sensing data for soil moisture, precipitation and other components of a water budget, "very few, if any, groundwater managers are tapping into any of the data" according to one of the InSAR study's co-authors (Dr. Knight quoted in Jordan 2014). In addition, scientists have been using the Gravity Recovery and Climate Experiment (GRACE) satellite data for several years to remotely monitor groundwater storage variations in the Central Valley (Famiglietti et al. 2011, Scanlon et al. 2012).

ADDRESS MANAGED RECHARGE

Managed recharge, as opposed to natural recharge, requires human intervention. It can be direct in terms of injecting or percolating water into aquifer storage for later recovery or it can be indirect in terms of allowing "in lieu" recharge or trading surface water use for groundwater use. Managed recharge is, for the most part, unregulated in California, but will be a key part of many regional approaches to sustainable groundwater management (Nelson and Casey 2013). Sustainable groundwater management will need to consider how to count managed recharge in a way that does not lead to perverse incentives. For example, in areas with active groundwater banking projects, recharge rates may be high, but much of the water in the bank may be the property of interests outside of the basin where the groundwater is banked and, therefore, should not be "counted" as part of the recharge that benefits the basin. This creates another potential problem, which is that some basins may not be able to achieve a sustainable yield within their basin if much of the underground storage space is occupied by water for out-of-basin interests. Additional legislation may be needed to allow managed recharge to become part of sustainable groundwater management.

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