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Special Issue:

The Sustainable Groundwater Management Act

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SPECIAL ISSUE

JANUARY–MARCH 2018 • VOLUME 72, NUMBER 1

The Sustainable Groundwater Management Act

News and opinion

COVER: Map adapted from Figure 2 in Bulletin 118 Interim Update 2016, California DWR. Areas highlighted in yellow, orange and red are, respectively, the medium-priority, high-priority and critically overdrafted groundwater basins subject to regulation under California's Sustainable Groundwater Management Act of 2014.

Research and review articles

INTRODUCTION

Special Issue: The Sustainable Groundwater Management Act

This special issue of *California Agriculture* focuses on the implications of the Sustainable Groundwater Management Act, or SGMA, the package of bills signed into law by California Gov. Jerry Brown in September 2014.

The legislation puts California on a path to the sustainable management of a resource that accounts for between one-third (in wet years) and two-thirds (in dry years) of the state's water use. In dry years, statewide overdraft is in the range of 3 to 7 million acre-feet. Some of that is recharged in wet years, but in many basins, including some of the state's top-producing agricultural regions, the long-term trend has been falling water tables (see groundwater.ucdavis.edu for links to UC video introductions to groundwater in California and SGMA).

Sustainable management under the act is defined as the avoidance of "significant and unreasonable" levels of six impacts: (1) lowering of groundwater levels, (2) reduction in groundwater storage, (3) seawater intrusion, (4) water quality degradation, (5) land subsidence and (6) impacts on beneficial uses of interconnected surface waters.

Regulation of groundwater in California was long in coming. The state has often been a national leader in environmental policy, for instance on air quality and greenhouse gas emissions. But it was the last state to adopt statewide groundwater regulations (Cannon Leahy 2016). In most basins, groundwater use was unrestricted beyond the basic requirement in the state constitution that all water use be reasonable and beneficial.

Of the state's 515 groundwater basins, SGMA applies to the 127 judged to be high- or medium-priority based on a combination of factors related to current and future groundwater demand and the consequences of overdraft. These 127 basins account for 96% of the state's groundwater extraction (CASGEM 2018). Twenty-seven of these basins have previously been adjudicated — meaning that they are under a court order to limit overdraft.

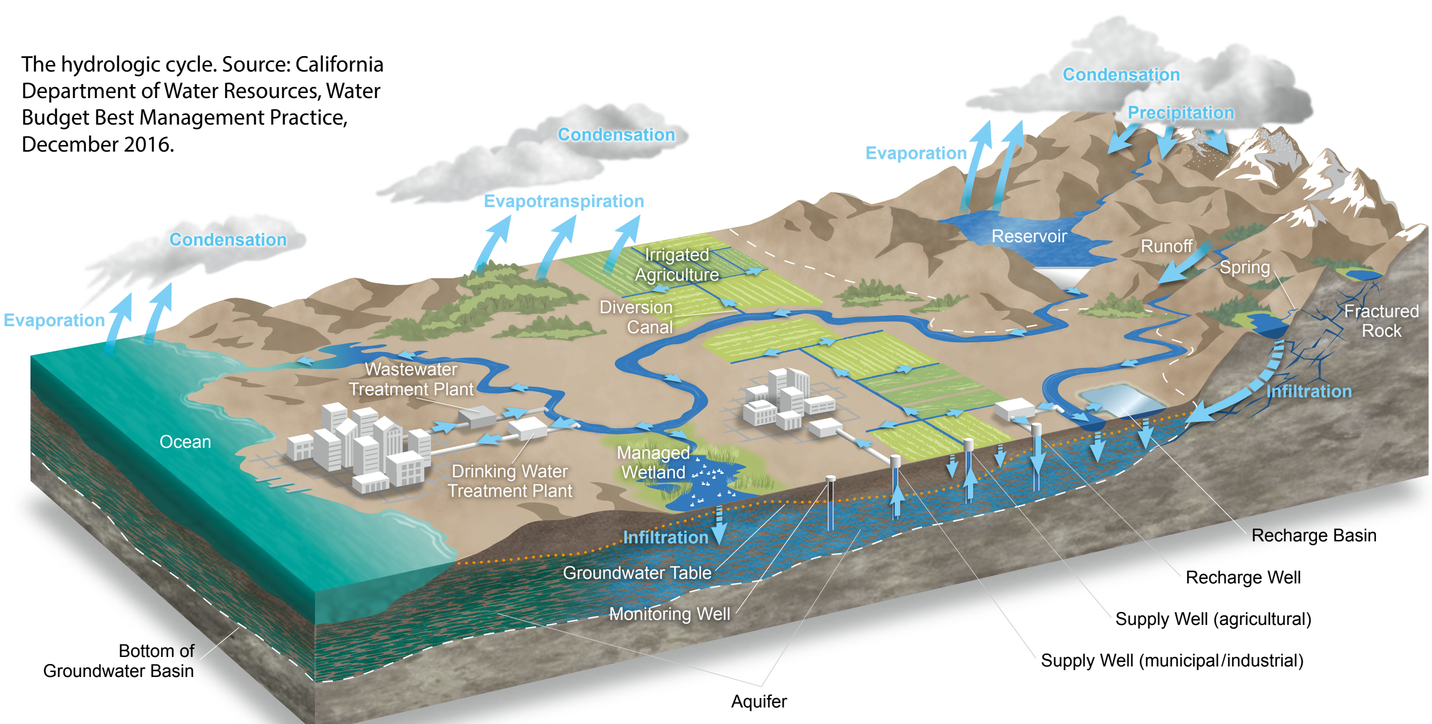
The act mandated the creation, by June 30, 2017, of a new set of local agencies, groundwater sustainability agencies (GSAs), responsible for complying with SGMA's directives. To date, 266 groundwater sustainability agencies have been formed, accounting for 378 areas in 141 basins statewide (in many cases there is more than one GSA in a basin; also, GSAs may be formed in low-priority basins even though the law does not require it).

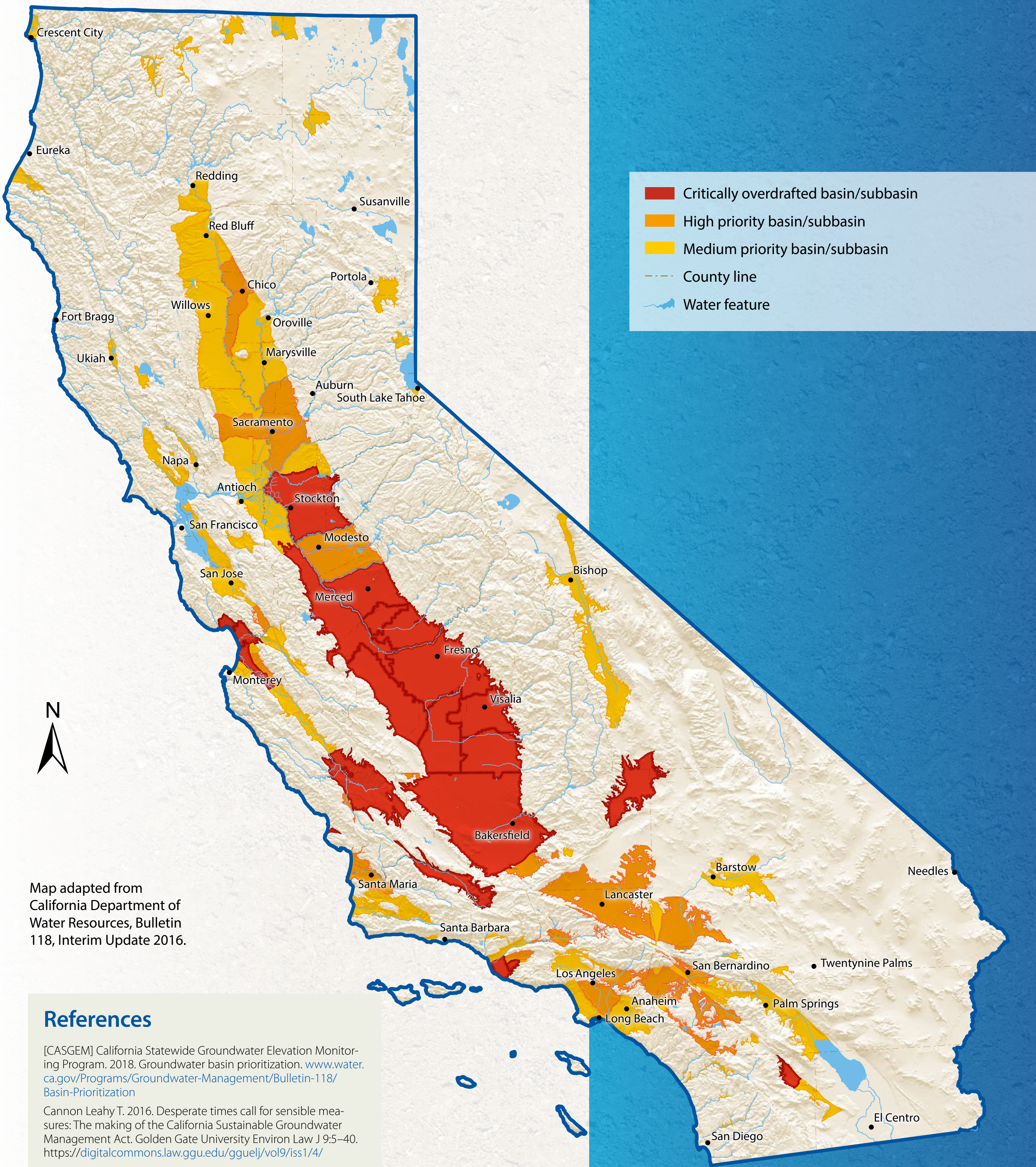
The next step is the preparation of groundwater sustainability plans. These plans must put the basin on a path that will lead to sustainable management within 20 years, with interim milestones subject to state review every 5 years. Critically overdrafted basins (map) must submit plans by January 31, 2020; other basins must submit by January 31, 2022.

Two state agencies have primary responsibility for supporting the implementation of SGMA. The Department of Water Resources acts as facilitator and evaluator, while the State Water Resources Control Board has an enforcement role, ensuring compliance with the law (see article page 18).

California Agriculture thanks the guest editors of this special issue: Faith Kearns and Doug Parker (California Institute for Water Resources, UC Agriculture and Natural Resources), Meredith Niles (University of Vermont) and Kurt Schwabe (UC Riverside). The journal also thanks the Stockholm Environment Institute for supporting a portion of the printing costs of the issue. CA

The hydrologic cycle. Source: California Department of Water Resources, Water Budget Best Management Practice, December 2016.





Map adapted from California Department of Water Resources, Bulletin 118, Interim Update 2016.

References

[CASGEM] California Statewide Groundwater Elevation Monitoring Program. 2018. Groundwater basin prioritization. www.water.ca.gov/Programs/Groundwater-Management/Bulletin-118/Basin-Prioritization

Cannon Leahy T. 2016. Desperate times call for sensible measures: The making of the California Sustainable Groundwater Management Act. Golden Gate University Environ Law J 9:5–40. https://digitalcommons.law.ggu.edu/gguelj/vol9/iss1/4/

EDITORIAL

Supporting sustainable groundwater management

by Faith Kearns and Doug Parker

Implementation of the 2014 Sustainable Groundwater Management Act is on schedule. The first phase, completed in 2017, created a new layer of local government — groundwater sustainability agencies (see Conrad et al. research article, page 44).

Now, these new agencies must prepare groundwater sustainability plans (see Mehta et al. research article, page 54). These plans will lay out a basic reckoning for every overdrafted basin: without additional water to replace groundwater pumping or to recharge aquifers, there will be less available to produce food, supply homes and businesses, and ensure there is enough water for the environment.

UC Agriculture and Natural Resources (UC ANR) is working to develop one of the most promising groundwater recharge approaches — replenishing aquifers by spreading wintertime river flood flows onto farm lands and other open spaces. It's an effort that illustrates the core strengths of UC ANR and UC Cooperative Extension — research and partnerships.

UC ANR researchers have mapped recharge-relevant soil conditions across the state to identify the most promising sites for deliberate recharge (O'Geen et al. 2015). Demonstration projects with private-sector partners (Bachand 2016) have begun to illuminate the costs and operational considerations for farm-based recharge projects. And in this issue of *California Agriculture*, Dahlke et al. (page 65) report the results of field trials suggesting that alfalfa — already one of the most promising crop candidates for farm-field recharge — tolerates cool-season flooding well.

On-farm groundwater recharge takes advantage of the water capture, filtration and storage services provided by natural and working landscapes — water is held by plants and absorbed by the soil (rather than running off), cleaned as it percolates through the soil profile, and stored underground. Wintertime flood flows are being targeted because they may provide water that is essentially "surplus" — not claimed by another user, not needed to maintain the health of downstream ecosystems, and beyond what can be stored in the state's surface water reservoirs.

The potential of this type of recharge is vast. Available aquifer storage capacity far exceeds the total capacity of all the state's surface-water reservoirs, and studies suggest that new groundwater storage can be developed at about one-sixth the cost of new surface water storage (Perrone and Rohde 2014).

Realizing that potential is another matter. One major obstacle is that implementing such projects requires a great deal of cooperation and coordination. Farms and groundwater sustainability agencies can't fully implement recharge projects on their own. They will need to work in partnership with surface water suppliers, flood control agencies, water regulators, wildlife conservation agencies and organizations, local land use planners, water rights attorneys and many others.

To address the collaborative aspect of this challenge, UC ANR Vice President Glenda Humiston, in partnership with the California Economic Summit, has brought together experts and decision-makers

Flooding an alfalfa field for a groundwater recharge research project.

from around the state — hydrologists, land-use planners, engineers, agency leaders, attorneys, local officials, and more — to build a strategy. At a meeting in Davis hosted by UC ANR, the group developed a series of actions, policies and funding mechanisms (see box) to promote the development of groundwater recharge projects, ideas that were then presented at the California Economic Summit in San Diego in November. The group's work is continuing in 2018.

There are reasons for optimism. In Fresno, for instance, city officials have partnered with the local flood control district to use flood control basins for recharge, sending 50,000 acre-feet of water into underground storage annually. The city has also adopted plans to preserve open space suitable for recharge, and to lease or purchase vacant parcels for use as recharge basins. The adoption of similar actions and policies in other cities around the state, especially in agricultural regions, could substantially increase annual recharge.

The need to increase recharge, of course, is just one piece of California's groundwater puzzle.

As this special issue illustrates, UC ANR and its partners are working in a variety of other ways to support sustainable groundwater management. In San Luis Obispo County, UCCE Farm Advisor Mark Battany's work (page 76) has helped to efficiently estimate recent rates of groundwater pumping for vineyards, generating data now being used in the development of the region's groundwater sustainability plans. In the Scott Valley in Siskiyou County, the work of Laura Foglia and Thomas Harter of UC Davis, the late UCCE Farm Advisor Steve Orloff, and their collaborators (page 84) illuminates interactions between surface water and groundwater. UC Davis Ph.D. Meredith Niles (now a professor at the University of Vermont) and her collaborators are working to improve our understanding of farmers' perspectives on SGMA and its implementation (page 38). The review paper by UC Davis Agricultural and Resource Economics Professor Emeritus Richard Howitt and his collaborators (page 28) provides lessons from the experiences of 18 adjudicated or otherwise regulated groundwater basins across the western states. And the research news section of this issue provides a roundup of many more projects under way across the UC system.

All of these perspectives will be important as California moves toward sustainable management of its groundwater resources while also seeking to maintain the health of its rural communities and agricultural economy. CA

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References

Bachand P, Roy S, Stern N, et al. 2016. On-farm flood capture could reduce groundwater overdraft in Kings River Basin. Calif Agr 70:200–7. https://doi.org/10.3733/ca.2016a0018

O'Geen AT, Saal M, Dahlke H, et al. 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. Calif Agr 69:75–84. https://doi.org/10.3733/ca.v069n02p75

Perrone D, Rohde M. 2014. Storing water in California: What can $2.7 billion buy us? Research Brief. Water in the West program, Stanford University. http://waterinthewest.stanford.edu/sites/default/files/Storing_Water_in_CA.pdf

Promoting groundwater recharge on working lands and open space

Recommendations from a multidisciplinary group of experts convened by UC ANR and the California Economic Summit. More at: https://goo.gl/onAE1T

- Prioritize multi-agency partnerships through decisions on state funding of groundwater recharge projects.
- Establish a state task force to identify barriers to new groundwater recharge projects.
- Require the consideration of groundwater recharge sites in General Plan updates (the primary planning documents produced by local governments).
- Support continuous improvement in publicly available spatial data on suitable groundwater recharge locations.
- Make groundwater recharge a standard part of local land use planning and local and regional water planning.
- Align policies to support groundwater recharge on agricultural lands, including those governing water rights, water quality standards, permitting, habitat conservation, and landowner assurances against damage. Streamline permitting and planning requirements.
- Make groundwater recharge a part of climate adaptation plans (which local governments are required to produce under the state's climate legislation).
- Publicize broadly the benefits of groundwater recharge on agricultural lands.
- Make state water bond funding available, explicitly, for such projects.
- Provide a property tax benefit for keeping land in a state that facilitates groundwater recharge, through a mechanism similar to that used to incentivize conservation of agricultural land under the Williamson Act.

Joe Proudman, UC Davis

UC groundwater research: A survey

As California implements the Sustainable Groundwater Management Act (SGMA), UC research is building knowledge and supporting innovation in groundwater recharge, groundwater accounting, groundwater quality, groundwater governance and more. Here's a sample of work from across the UC system.

Whole-watershed accounting

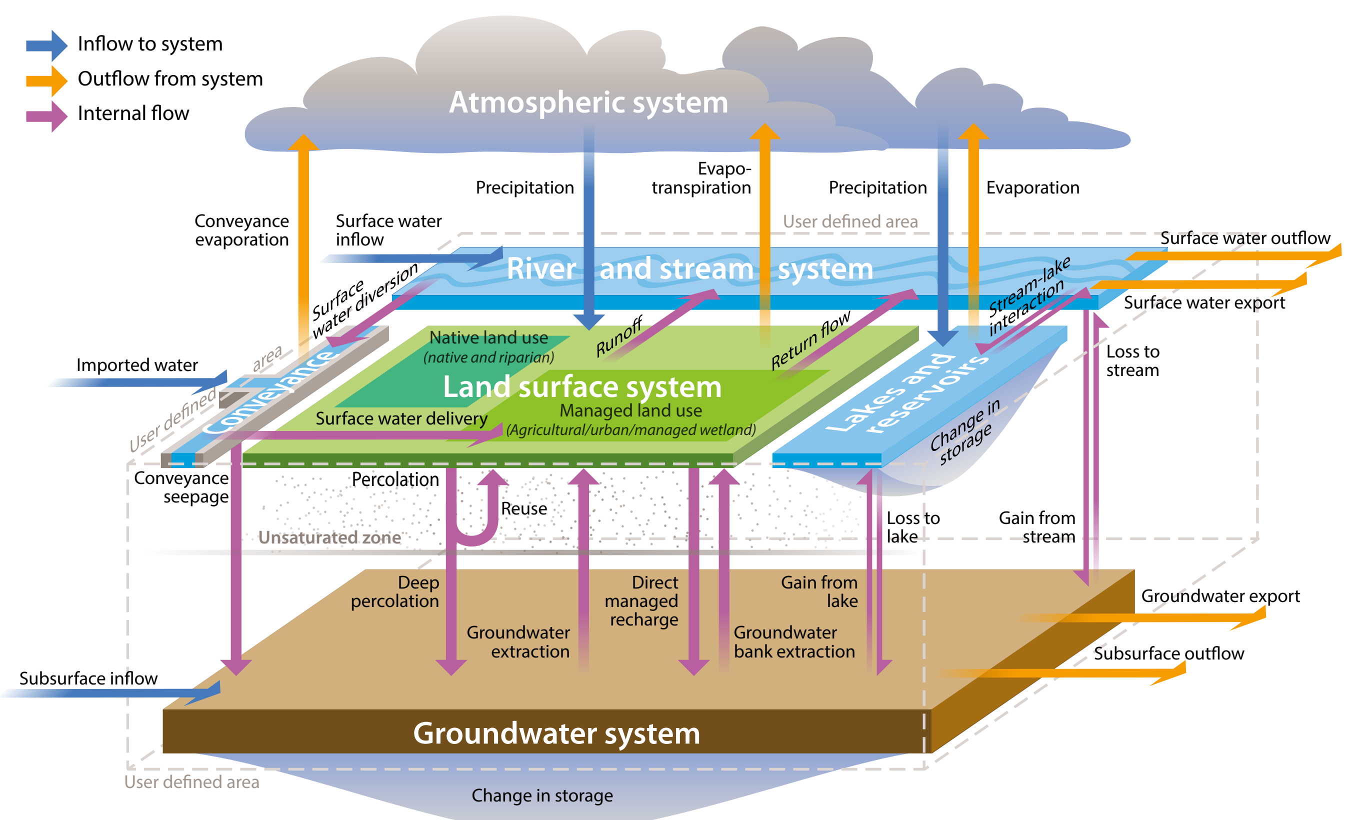
Whole-watershed accounting assesses all surface and groundwater flows and storage over a large area. The idea is to account for all the major sources of water at once, rather than focusing on only a portion of them, such as what's stored in surface water reservoirs. This work can reveal how joint management of surface and groundwater flows and storage could increase the overall amount of water available on decadal time scales.

Graham Fogg, professor of hydrogeology at UC Davis, leads a group conducting this type of analysis on a region that spans the American River and Cosumnes River watersheds — a project being conducted through the UC Water Security and Sustainability Research Initiative. Using data and models on historical conditions, combined with information about the available storage space in the region's aquifers and the availability of geologically suitable groundwater recharge sites, the researchers are finding that optimizing the use of all available storage space — above as well as below ground — could have increased net water storage on the order of hundreds of thousands of acre-feet per year, on average.

"Imagine all of your money is in two bank accounts, but you only manage one of them. With water, we've been managing the surface water bank account, but not the groundwater account," Fogg said. "They need to be managed together. Furthermore, we also need to better track and manage the snow account."

Water availability for recharge

On a larger scale, Helen Dahlke, professor of hydrology at UC Davis, and Thomas Harter, professor of water management and policy and UC Cooperative Extension (UCCE) specialist at UC Davis and director of the UCCE groundwater program (groundwater.ucdavis.edu), are modeling the impact



Relationships among potential water budget components and the water systems that comprise the hydrologic cycle. Source: California Department of Water Resources, Water Budget Best Management Practice, December 2016.

of large-scale groundwater recharge across the entire Central Valley. Using historical flow records, they assess the magnitude, frequency and duration of high-magnitude streamflows (e.g., flood flows) in watersheds around the valley (Kocis and Dahlke 2017), and simulate the impact that recharge of these "excess" streamflows could have on Central Valley groundwater resources using the C2VSIM groundwater–surface water model.

"It wouldn't be the panacea that some think," said Harter. "But we're finding that if we do this consistently, we'll gain some water storage, and — in some cases — we'll also gain some downstream summer and fall streamflow due to a higher water table near some streams."

Precision data on snowmelt

At UC Merced, Mohammad Safeeq, research scientist at the Sierra Nevada Research Institute, Martha Conklin, professor of engineering, and Roger Bales, professor of engineering, are leading several projects across the Sierra Nevada headwaters to gather and utilize higher-resolution in-situ information on the magnitude and timing of snowmelt (Bales et al. 2018; Zhang et al. 2017a; Zhang et al. 2017b)

These projects, a collaboration with Steven Glaser, systems engineering professor at UC Berkeley, use distributed wireless sensor networks technology, in which hundreds of sensors are placed strategically in clusters to develop a picture of snow water content in a watershed.

The use of many sensors enables the capture of data reflecting the wide variability in snow conditions in a watershed — snow cover along an elevation gradient, beneath tree canopies as well as in open areas, on hillsides with a range of slopes and aspects, and so on. These sensors also gather information on other key hydrologic variables such as soil moisture and air and soil temperatures. The approach is a significant improvement over traditional systems that are limited to a handful of easily accessible measurement stations scattered throughout a basin.

The data can then be combined with numerical models to estimate, in near-real-time, how much water is in the Sierras, and when water from snowmelt will arrive in streams and reservoirs. That information, in turn, can inform the planning and operation of groundwater recharge projects as well as surface water reservoirs. This unique dataset is also helping to inform forest management — researchers are working towards evaluating the impacts of different forest management prescriptions on water balance and forest health and resilience.

The distributed snow sensor networks along with numerical modeling have been or are being deployed in portions of several Sierra watersheds, in the Feather, American, Stanislaus, Merced and Kings river basins.

Spatial data on well vulnerability

At UC Santa Barbara (UCSB), Debra Perrone, professor of environmental studies, is leading a study to map the locations of the millions of groundwater wells in the United States, as well as their vulnerability to falling groundwater levels and water quality problems.

In earlier work, Perrone and collaborator Scott Jasechko, professor in the Bren School of Environmental Science and Management at UCSB, used well-construction records as well as data on groundwater levels to map the locations of likely dry wells across California and other western states (Perrone and Jasechko 2017). Their current project expands the geographic scope to the entire continental United States, and adds additional data on water quality impairment. For example, Perrone and Jasechko have also used the groundwater well data to evaluate the proximity of hydraulic fracturing operations to domestic groundwater wells to identify hotspots that may be used to target further water-quality monitoring (Jasechko and Perrone 2017).

Large-scale groundwater recharge and agricultural systems

Dahlke and Sam Sandoval, professor and UCCE specialist in water management at UC Davis, recently launched a 3-year project with the U.S. Department of Agriculture Economic Research Service to assess the economic costs and benefits of different managed aquifer recharge methods (e.g., on-farm recharge, infiltration basins, recharge of recycled or treated wastewater, and in lieu recharge) in the Central Valley to determine which economic incentives are needed to increase groundwater recharge efforts statewide.

To do this, they will integrate existing large-scale groundwater–surface water hydrologic models with economic models — developed by the Economic Research Service and by Ariel Dinar, professor of environmental economics and policy at UC Riverside (UCR) — that incorporate crop production practices, land and water policies, land values, production and capital costs and other factors.

The project will focus on California's Central Valley as well as the lower Mississippi River region — another agricultural region with high groundwater use — and will include collaborations with researchers at UCR and the University of Arkansas.

Groundwater–surface water interactions

SGMA requires groundwater sustainability agencies (GSAs) to manage groundwater such that significant and unreasonable impacts on beneficial uses of interconnected surface waters are avoided.

More on UC groundwater work:

UC Cooperative Extension groundwater (groundwater.ucdavis.edu)

California Institute for Water Resources (ciwr.ucanr.edu)

UC Water: The UC Water Security and Sustainability Research Initiative (ucwater.org)

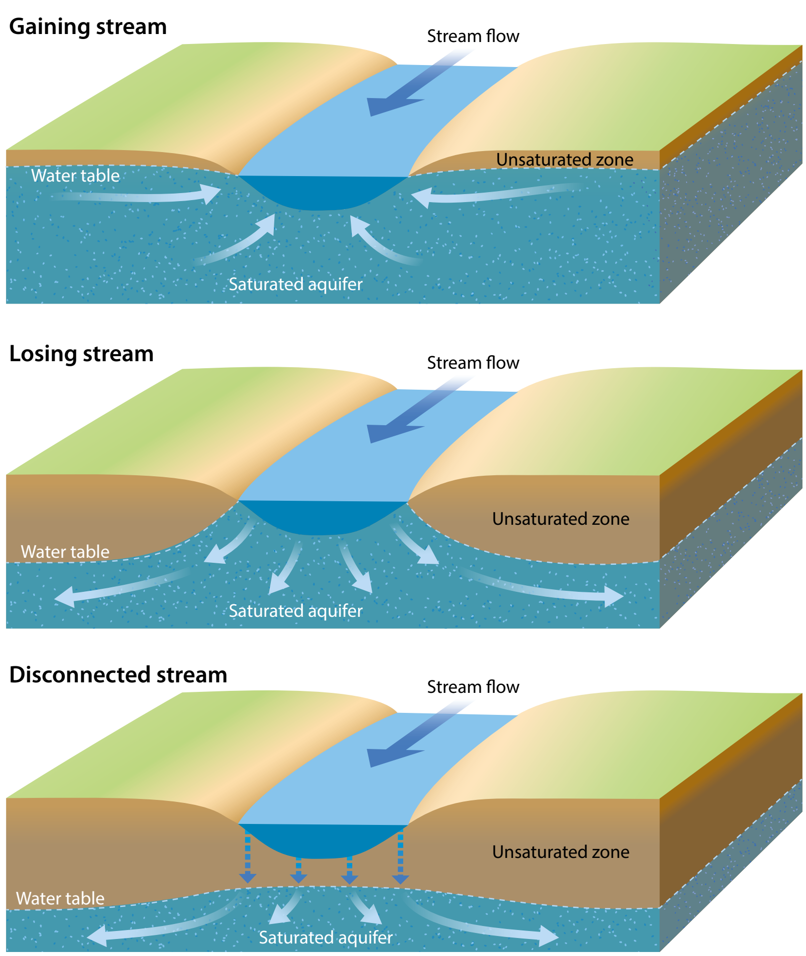
Wheeler Water Institute (law.berkeley.edu/research/clee/research/wheeler/)

Harter leads several projects to model groundwater–surface water interactions at the local level. An article in this issue (page 84) models these relationships in the Scott Valley, an agricultural region in Siskiyou County where groundwater levels have a strong influence on streamflows and salmon habitat in the Scott River.

The management of groundwater–surface water interactions raises legal and policy questions in addition to scientific ones. In an upcoming paper from the Wheeler Water Institute at UC Berkeley and the UC Water initiative, Harter, Wheeler Water Institute Director Michael Kiparsky and collaborators report on discussions on these topics at a series of expert workshops hosted in 2017 that brought together thought leaders in hydrogeology, law and policy (Cantor, Owen et al. 2018).

Topics covered include: examples of conflicts between groundwater and surface water users and how conflicts have been resolved; how SGMA alters or should alter legal relationships between groundwater and surface water users; the tools needed to identify and address potential conflicts between groundwater and surface water uses; and the interactions between SGMA and other laws governing water use and environmental protection.

The report synthesizes content from the workshops, legal analysis, and technical and legal literature review, and identifies key themes, with the objective of providing guidance and practical advice for practitioners, including groundwater managers and state agency staff.



Groundwater–surface water interactions. Source: California Department of Water Resources, Water Budget Best Management Practice, December 2016.

Groundwater quality and salinity

SGMA and other state regulations also require that groundwater management not degrade water quality (see Harter 2015 for an overview of the multiple regulatory programs concerning groundwater quality).

In agricultural regions, nitrate contamination of drinking-water aquifers and long-term salinization of groundwater for all uses are generally the major concerns.

Much of Harter's work focuses on nitrate. He and Jay Lund, professor of civil and environmental engineering at UC Davis, led the development of a major statewide assessment of nitrate contamination of drinking water wells in agricultural regions. The report was released in 2012, with a significant update in 2017 (groundwaternitrate.ucdavis.edu/).

Harter's work investigates a variety of aspects of nitrate in groundwater — major nitrate sources, subsurface transport and transformation of nitrate, and interactions of nitrate flows with wells, surface water streams and aquifer recharge projects.

A broad lesson of this research, Harter said, is the need for an integrated collection of changes in farming and water management practices: More-efficient application of water and fertilizer during the growing season, combined with increased application of clean water in winter. That combination of practices would reduce in absolute terms the amount of nitrate applied to farmlands, and replace flows of nitrate-contaminated water into aquifers with flows of cleaner water that may help to dilute existing contamination and refill depleted groundwater basins.

Salinization is a separate but related groundwater quality issue, particularly in the Tulare Basin — roughly the southern third of the Central Valley — which depends heavily on groundwater for irrigation.

Irrigation water — whether sourced from a river, from the Delta via canal, or from a groundwater well — contains salts. As groundwater is extracted and used to irrigate crops, water leaves the system through evapotranspiration, but salts are left behind. These salts percolate steadily downward, eventually reaching the aquifers that supply agricultural wells.

Because of the intensity of groundwater use in the Tulare Basin, the area's groundwater system has effectively become a closed hydrological basin, akin to Mono Lake or the Salton Sea. In the past, groundwater in the basin had outlets, through connections with surface water and horizontal flows beneath the surface, and hence the groundwater stayed fresh. But now, due to groundwater depletion, the dominant way that groundwater leaves the basin is via pumping and evapotranspiration on farmland. As a result, the groundwater in the basin can only become more saline.

This is also true of other parts of the Central Valley and the world, where even moderate groundwater development, together with irrigation, has converted groundwater basins from being open, with water and salts exiting via natural pathways, to closed basins in which the salts accumulate in the groundwater.

Fogg's research group is modeling the salinization rate of groundwater in the Tulare Basin. If current practices continue, in the foreseeable future — within about 50 years for shallow aquifers and 100 years for deeper aquifers — much of the groundwater will become too saline to irrigate most crops. The salinization could be slowed by reducing groundwater extraction or increasing recharge with low-salinity water, Fogg said. Fogg's group is creating groundwater quality management models for determining how land and water management could be changed in order to put groundwater quality on a more sustainable path.

Water supply, land use and rural communities

UC Davis' Dahlke is leading a $1.6M project funded by the National Science Foundation (NSF) to analyze the relationships between surface water and groundwater supply, agricultural land use and the economic well-being of rural communities.

The team will incorporate survey data with economics and hydrology expertise to develop models to help guide decision-making around water management and land use in the state.

The project is one of nine funded nationwide under the NSF's Dynamics of Coupled Natural and Human Systems program. While Dahlke's team will focus on the Tulare Basin, the work is expected to provide insights applicable to other regions of the United States facing similar issues involving economic and water security.

The project also seeks to help local disadvantaged communities participate in the governance of water resources, including through the creation of "water schools" and engaging K-12 students in science and policy issues. The Visalia-based Community Water Center (see article page 20) is a co-principal investigator on the project.

Data on water use and water rights

UC researchers are also working to address the broad problem of a lack of centralized, well-indexed, accessible data relevant to water management in California. Legislation passed in 2016 — AB 1755, the Open and Transparent Water Data Act — charges state agencies to make such data available for a range of water management challenges including SGMA implementation.

It's a major information challenge, covering hundreds of data sets from state, federal, university and private sources that cover water as well as ecology, agriculture, infrastructure, geology, soils, climate and socioeconomics.

UC Berkeley's Kiparsky, UC Merced's Bales and a multi-institutional group of collaborators are working with the California Department of Water Resources to support the development of information systems that can effectively support water management.

The effort approaches the water data challenge from a software design perspective — starting by working to understand how people use (or would like to use) the data to make decisions or inform management, and then building systems to serve those needs (Kiparsky and Bales 2017). With their collaborators, they convened a series of three stakeholder workshops to develop the concept of use cases for water data, along with a method for generating them. They generated a collection of 20 use cases that illustrate the data needs for a range of water-related decisions, such as planning a groundwater recharge project or developing a groundwater basin water budget (available at http://law.berkeley.edu/datafordecisions).

Based on these data, the group published a policy paper with recommendations in January (Cantor, Kiparsky et al. 2018), which has helped directly inform DWR's efforts on AB 1755 implementation.

Along with water attorney Richard Roos-Collins, Kiparsky is also leading a pilot project to tackle another major data gap in California water management — water rights.

Surface water rights documents in California currently are stored as millions of pieces of paper at the offices of the State Water Resources Control Board in Sacramento, in county courthouses around the state, and in other repositories. Digitizing and making these documents accessible could increase transparency, and remove a barrier to management tools such as water markets and as-yet-unimagined innovations for water management where groundwater and surface water intersect under SGMA.

Last year, the Kiparsky and Roos-Collins team won the California Water Policy Challenge competition held by the water technology accelerator Imagine H2O, for a proposal to begin building a water rights database for California. They are engaging state agencies and stakeholders in a process to develop robust standards for such a database, along with a pilot project in the Mono Basin, in partnership with the Los Angeles Department of Water and Power.

Managed aquifer recharge on farmland

Managed aquifer recharge is the deliberate recharge of groundwater with surface water through infiltration basins or injection wells. Using wintertime stream diversions as a water source and orchards and fields as infiltration basins is a promising approach to increase overall recharge in many of California's agricultural regions. A number of UC research groups are working

Lawrence Berkeley National Laboratory researchers (left to right: Yuxin Wu, Craig Ulrich, Peter Nico) collect electrical resistance tomography data in an almond orchard as part of a project to develop a detailed picture of soil structure between the surface and the groundwater table. The information will help to illuminate the effects of groundwater recharge in an agricultural setting.

to address some of the questions it raises — impacts on crops, leaching of nitrate and other chemicals into aquifers, and the effects of much-increased flows of water through subsurface soils.

Dahlke is leading a series of field trials in alfalfa (see article page 65) and in almonds, in collaboration with UC alfalfa and almond experts. The projects are assessing the amount of groundwater that can be recharged in areas with a variety of soil types; effects of heavy wintertime water application (irrigating 2 feet or more in addition to winter rainfall) on crop health and yield; and, for almonds, the effects of winter recharge on root health and soil nitrate concentrations in the soil profile.

Initial findings suggest that, given soil conditions that allow for deep percolation, yields of both alfalfa and almonds are little affected by wintertime flooding (and may even benefit from flooding under certain conditions). The flooding had a wide range of impacts on soil nitrate, depending mainly on soil types.

On some of Dahlke's almond study plots, Peter Nico, staff scientist at Lawrence Berkeley National Laboratory (LBNL), and team are using advanced two- and three-dimensional geophysical imaging and modeling techniques to develop a more detailed picture of the soil structure between the surface and the groundwater table than soil core data alone can provide. The goal is a more nuanced understanding of how water added for recharge moves down through the soil, and how recharge may affect the soil structure and the transport of nitrate and salts to an underlying aquifer.

Soil suitability for recharge

Toby O'Geen, UCCE soil resource specialist based at UC Davis, led the development of the Soil Agricultural Groundwater Banking Index (SAGBI) dataset for California, which provides an initial assessment of the suitability for managed aquifer recharge of the soils in every agricultural region (O'Geen et al. 2015). It considers five factors: deep percolation, root zone residence time, topography, chemical limitations and soil surface condition.

An online map interface (https://casoilresource.lawr.ucdavis.edu/sagbi/) makes it easy to see the SAGBI rating for any location in the state. O'Geen's group has also shared the full dataset with dozens of organizations, including many GSAs as well as the California Department of Water Resources, which has created a geographic information system layer from the data to inform land-use planning.

Distributed stormwater collection

In the Pajaro Valley of central coastal California, Andrew Fisher, UC Santa Cruz (UCSC) professor of earth and planetary sciences, is collaborating with a team of students, researchers, agency staff and regional stakeholders. This group is exploring the potential for distributed stormwater collection for groundwater recharge, as well as the viability of an innovative net metering program designed to provide landowners a financial incentive to develop recharge projects.

The Pajaro Valley is a small but extremely productive agricultural region, with annual farm revenues of roughly $1 billion from a cultivated area of less than 30,000 acres. With no imported water and no significant local surface water storage, farms in the area depend heavily on groundwater for irrigation. The Pajaro Valley Water Management Agency, which manages groundwater in the area, in 2014 (before the passage of SGMA) set a target of reducing net groundwater overdraft by 12,000 acre-feet per year.

Distributed stormwater collection works by collecting runoff from relatively small drainage areas using simple infrastructure like small berms and culverts, then infiltrating this water using a variety of techniques.

As the climate continues to change, high-intensity storms — which produce lots of runoff — are expected to become more common, though overall precipitation is not expected to increase. As a result, collecting and recharging runoff is likely to become increasingly important.

UCSC doctoral candidate Sarah Beganskas has been modeling the Pajaro River watershed to identify good sites for distributed stormwater collection projects, based on information including topography, vegetation cover, soil type, aquifer locations and groundwater levels.

Collecting and infiltrating just a few percent of a watershed's total runoff during heavy rainfall events can increase groundwater recharge substantially. A pilot project on a 172-acre property in the Pajaro Valley infiltrated more than 100 acre-feet annually even in the dry 2015–2016 winter (Beganskas and Fisher 2017).

Net metering for groundwater

A significant hurdle to the expansion of distributed stormwater collection projects — and for groundwater recharge project on farmland in general — is the need to provide an incentive for individual landowners to put projects on their land. Recharge projects have initial and ongoing expenses, and involve some loss of land use and local impact — for instance by adding fine sediment, which can impair soil drainage. In addition, recharged water flows into a general subsurface pool, rather than all being available for withdrawal by the landowner who went through the trouble to recharge it (that is, it's not like a bank, where all deposits are available for withdrawal).

Recharge net metering is an institutional innovation designed to provide a clear financial incentive to develop individual recharge projects. Fisher and colleagues at UCSC, along with the Resource Conservation District-Santa Cruz County, are leading a 5-year pilot of the concept in the Pajaro Valley, in collaboration with the Pajaro Valley Water Management Agency (Kiparsky et al. 2018).

The concept is modeled on net metering in electricity, which is used widely to incentivize home-scale rooftop solar panels: When panels produce more electricity than a home is using, the excess flows into the power grid, and the homeowner receives a credit on her electricity bill to offset power drawn from the grid at other times.

In the Pajaro Valley, agricultural water users currently pay a fee of $217 or more per acre-foot of water pumped (most agricultural pumpers around the state don't pay a water extraction fee now, but it's likely that it will become more common as groundwater sustainability plans (GSPs) are implemented under SGMA). Under the net metering pilot project, the owner of a groundwater recharge project receives a credit against that fee based on the amount of water infiltrated as a result of the project. The rebate is set at half of the value of the additional water infiltrated, to account for uncertainties associated with recharge and the fate of infiltrated water.

The pilot program is targeting roughly 1,000 acre-feet per year of new groundwater recharge, through perhaps 10 projects. It is designed to clarify various issues associated with administering a net metering system, such as financial sustainability, the economics of small recharge projects, and accuracy in water accounting.

Fisher is collaborating with Kiparsky and Michael Hanemann, professor of agriculture and resource economics at UC Berkeley, who are leading a related project, funded by the U.S. Department of Agriculture and the UC Office of the President, to examine the institutional and economic elements of the recharge net metering concept to evaluate prospects for scaling and broad adoption.

Geophysical imaging

Fogg's group has for a number of years been using data from well-drilling logs to map locations where sandy soils extend from the surface to the underlying aquifer — such sites indicate a prime location for groundwater recharge. The information is complementary to the SAGBI map (O'Geen et al. 2015), which is based on several sources of data about near-surface soil conditions. It's limited, however, by the availability of well-drilling logs. Advanced geophysical remote sensing tools now make it possible to generate a more complete map of these surface–aquifer connections, but they are costly. A helicopter-based airborne electromagnetic method, Fogg said, could be deployed to map the Central Valley, as shown in a recent demonstration project in the Tulare Lake Basin (Knight et al. in press).

Separately, LBNL's Nico and team are evaluating the use of satellite-based sensing of ground elevation as a way to detect changes in groundwater storage. The technology, known as interferometric synthetic aperture radar, or InSAR, can detect millimeter-scale changes in soil elevation. Because ground elevation rises or falls slightly in response to aquifer recharge or depletion, the technique may prove useful in quickly assessing groundwater storage over large areas.

Groundwater governance

Researchers at the UC Davis Center for Environmental Policy and Behavior are using social science approaches to study a range of issues regarding SGMA processes and implementation. The research team includes Professor Mark Lubell, and graduate students Linda Esteli Mendez-Barrientos, Jessica Rudnick, Kristin Dobbin, Amanda Fencl, Sean Maxson, and Mackenzie Johnson.

Their research has focused on four main questions: What is the structure and diversity of institutional arrangements for groundwater sustainability agencies and plans? How do different policy actors participate and cooperate in SGMA governance processes? How do political leaders and facilitators influence the evolution of governance institutions within and across groundwater basins? How does the process of institutional change reflect differential access to water resources and power, and the consequences for procedural and distributional equity? All of these questions reflect core theoretical issues in social science, but have direct practical implications for SGMA implementation.

While many of the research projects are in the early stages, some intriguing initial findings have emerged. Qualitative research on GSA development suggests that facilitation services, information and knowledge sharing, small agency sizes, common 'adversarial' conditions and participation in other water policy processes have contributed to the emergence of collaborative GSAs — those that include at least nominal representation from stakeholders beyond counties and water districts such as private pumpers and disadvantaged communities. However, even within these GSAs, power asymmetries among participants are shaping institutional outcomes (Méndez-Barrientos, in review). For example, initial findings indicate limited representation of disadvantaged communities and involvement in the SGMA process. About 10% of groundwater-dependent disadvantaged communities analyzed thus far are represented on their respective GSAs. Likewise, Rudnick et al. (2016) created a diversity index for agriculture that predicts which basins will face steeper challenges in equitably addressing the needs of their diverse agricultural stakeholders.

Doctoral student Linda Esteli Méndez-Barrientos noted that the sort of decentralized water resources management framework created by SGMA has been enacted in a number of other countries, such as South Africa. That body of experience creates a rich opportunity for comparative study, and helps to inform the questions that the group is asking about the institutions created under SGMA. "Around the world, there's a lot of idealistic legislation, but there's a huge gap between what's envisioned and what's implemented. My job is to understand that gap," said Méndez-Barrientos.

In February, Lubell's group along with other UC Davis researchers working on SGMA convened a conference at UC Davis that brought together SGMA researchers from across the country with SGMA practitioners and government agencies. The goal of the conference was to synthesize current knowledge about SGMA governance challenges and establish a policy-engaged research agenda that connects governance theory with SGMA practice. A synthesis of conference proceedings will be available in spring 2018.

Lessons on groundwater permitting from around the West

Many GSPs developed under SGMA are likely to include the implementation of a permitting system for groundwater extraction.

To support that process, UCSB's Perrone is leading a project to build a publicly accessible database of permitting systems used by groundwater management agencies from the western 17 states. The database will include details on metering, monitoring, reporting and other requirements (e.g., Nelson and Perrone 2016).

The information will be published this spring via an interactive online dashboard hosted by Stanford University's Water in the West program, where Perrone was a postdoctoral researcher prior to joining the UCSB faculty in 2017.

Next steps in the project include an analysis of the data to identify successful approaches to groundwater management that may be applicable to GSAs as the agencies develop their GSPs. As part of this work, Perrone and colleague Rebecca Nelson will survey groundwater managers to identify which aspects of permitting authority groundwater managers exercise most frequently and find most useful.

Supporting GSP development

Under SGMA, a key piece in generating a local GSP is the development of a groundwater basin diagnosis, called a *water budget*, that incorporates data on current aquifer conditions, sources of recharge, extraction via wells, and water flows within the aquifer. With this information, a basin's sustainable yield can be calculated — and from that, the net rate of extraction that the basin can support sustainably.

The work of UC researchers is informing and supporting this process in a number of basins. In Mendocino County, for instance, a team of UC ANR academics and graduate students led by Sandoval conducted a water budget project in the Ukiah Valley, which is classified as a medium-priority subbasin under SGMA. The work determined the current status of the basin and informed this result to stakeholders during the formation of the GSA in the area, and is informing the development of the basin's GSP.

Important findings include that the basin is not in overdraft, and that the Russian River gains water from the aquifer and tributaries from November to June and loses water into the aquifer from July to October (Marquez et al. 2017).

The economics of sustainable groundwater management

SGMA calls for sustainable management, but leaves much leeway to local stakeholders — through the groundwater sustainability agencies — to define what sustainability means in their basin.

Economic modeling can provide insights about what constitutes long-term sustainability, and the relationships among the many variables that influence groundwater management. Kurt Schwabe, professor of environmental economics and policy at UCR, oversees multiple projects in this area.

One, led by recent UCR Ph.D. graduate Brad Franklin (now at the Gulf of Maine Research Institute) with collaborators from UCR and the University of Minnesota, models the effects of perennial crop irrigation on future groundwater levels.

The recent extreme drought in California has led to significant changes in land and water use by the state's agricultural sector. Market pressures have encouraged a further shift from annual crops to lucrative perennial crops such as almonds, which had already exacerbated the high dependence of irrigation on groundwater pumping to meet the crop's high water requirements and protect investments in new perennial crops. Yet there has been no formal economic modeling of the potential effects of perennial crop irrigation on future groundwater levels.

The project develops an integrated economic model of groundwater use and perennial crop production in Kern County that captures both groundwater and perennial crop dynamics. The research identifies the degree to which shifting acreage into perennial crop production along with climate change influence both the costs of groundwater management and the difficulties in meeting particular groundwater sustainability goals. It also highlights the added vulnerability growers confront from such shifting cultivation under different climate change scenarios, and the implications on both the elasticity of demand for water and role of water markets.

Another project, led by Keith Knapp, professor of resource economics at UCR, and Franklin, extends the standard groundwater model typically used for economic optimization of groundwater management. Their model adds consideration of household consumption, investments in manufacturing capital, and budget constraints, and adjusts optimization criteria to ensure equity over time.

The result is a model that better reflects sustainable management and that leads to several qualitative conclusions about what that entails. First, declining resource stocks are not necessarily indicators of non-sustainability — and they may in fact be necessary for sustainability since they tend to drive investment. Second, unregulated usage is not the only — or even necessarily the main — cause of non-sustainability. Sustainability is driven more by how rents from groundwater are invested in other sectors (e.g., manufacturing or finance) rather than resource management.

Considerations for groundwater markets

SGMA authorizes GSAs to assign groundwater extraction allocations to pumpers and provide for trading of those allocations — thus creating the basis for the development of local groundwater markets.

Economic theory suggests that such markets could, under certain conditions, promote more efficient allocation of groundwater resources. But markets can also have negative effects, or externalities — for instance, if a groundwater trade between two parties harms a third party or the environment.

To help GSAs as they consider whether and how to implement a trading system, a report from the Wheeler Water Institute at the UC Berkeley School of Law (Green Nylen et al. 2017) presents a (long) list of considerations for the development of groundwater markets: from foundational aspects like how groundwater extraction will be measured; to market-specific issues such as interactions between groundwater extraction allocations and existing groundwater rights, and the various potential impacts of trades; to general considerations like monitoring, enforcement and public engagement.

The role of cooperation and markets

In order to leverage local knowledge and honor pumpers' unique circumstances, SGMA foresees groundwater users themselves crafting plans to meet its requirements. However, pumpers often disagree about how to allocate access to groundwater, especially when some stand to lose economically from restricting pumping. Such users fight institutional change, thereby creating obstacles to addressing overextraction. These obstacles increase the economic costs of negotiating agreement, termed "contracting costs." Regulators and SGMA stakeholders alike can benefit from better understanding how rules for accessing groundwater pay dividends, and how contracting costs block collective action.

To answer these questions, researchers from UC Santa Barbara are analyzing historical changes in groundwater access institutions in basins across California. Andrew Ayres, previously a Ph.D. candidate at UCSB and now an economist with Environmental Defense Fund, Kyle Meng, assistant professor at the Bren School of Environmental Science & Management, and Andrew Plantinga, professor at the Bren School, are assessing the economic returns to addressing overextraction by clarifying the definition of rights to the resource. Defining groundwater rights entails setting a cap on the groundwater volume that can be pumped annually and allocating tradable permits among users. This process improves long-term resource availability and allows flexible reallocation of water use. In statistically comparing land parcels with well-defined and poorly defined rights to the Mojave groundwater aquifer, Ayres and colleagues find that more clearly defining property rights caused land values to increase by over 50%, on average; this reflects an increase in the value of water rights held on each parcel. Aggregate gains exceeded $60 million (Ayres et al., 2018 working paper).

Despite the promise of gains, many basins where more restrictive access rules are needed remain in critical overdraft. High contracting costs that obstruct collective action are one explanation. Ayres, Eric Edwards, assistant professor at North Carolina State University, and Gary Libecap, professor at UCSB's Bren School, are examining systematically how these costs vary across basins. The researchers statistically compare basins that have adopted effective institutions with otherwise similar basins where institutions are fragmented or nonexistent and document a critical role of contracting costs in explaining the inability to adopt management. These costs increase with basin size, the number of users, dispersion in water uses and valuations, and spatial variance in recharge within a basin (Ayres et al., in press).

How can pumpers and regulators facilitate agreement? Tradable pumping rights are advantageous in cases where allocating these rights to otherwise recalcitrant landowners is important for overcoming opposition. Additionally, different institutional rules entail different levels of costs, so stakeholders should remain open to approaches that economize on contracting costs by addressing relevant issues without defining pumping allocations or including all potential actors; for example, pumpers have historically adopted spatially restricted management rules to address local overdraft and written contracts to share imported water in order to avoid costly bargaining over cutbacks. CA

References

Ayres A, Edwards E, Libecap G. In press. How transaction costs obstruct collective action: Evidence from California's groundwater. J Environ Econ Manag.

Ayres A, Meng K, Plantinga A. 2018. The economic value of secure water: Landowner returns to defining groundwater property rights. Working paper, available upon request.

Bales RC, Goulden ML, Hunsaker CT, et al. 2018. Mechanisms controlling the impact of multi-year drought on mountain hydrology. Sci Rep 8:690. https://doi.org/10.1038/s41598-017-19007-0

Beganskas S, Fisher AT. 2017. Coupling distributed stormwater collection and managed aquifer recharge: Field application and implications. J Environ Manage 200:366–79. https://doi.org/10.1016/j.jenvman.2017.05.058

Cantor A, Kiparsky M, Kennedy R, et al. 2018. Data for water decision making: Informing the implementation of California's open and transparent water data act through research and engagement. Center for Law, Energy & the Environment, UC Berkeley School of Law. https://doi.org/10.15779/J28H01

Cantor A, Owen D, Harter T, et al. 2018. Navigating groundwater-surface water interactions under the Sustainable Groundwater Management Act. Center for Law, Energy & the Environment, UC Berkeley School of Law. https://doi.org/10.15779/J23P87

Green Nylen N, Kiparsky M, Acher K, et al. 2017. Trading sustainably: Critical considerations for local groundwater markets under the sustainable groundwater management act. Center for Law, Energy & the Environment, UC Berkeley School of Law. law.berkeley.edu/trading-sustainably

Harter T. 2015. California's agricultural regions gear up to actively manage groundwater use and protection. Calif Agr 69:193–201. https://doi.org/10.3733/ca.E.v069n03p193

Jasechko S, Perrone D. 2017. Hydraulic fracturing near domestic groundwater wells. P Natl Acad Sci 114:13138–43. http://doi.org/10.1073/pnas.1701682114

Kiparsky M, Bales R. 2017. Advanced data would improve how California manages water. Sacramento Bee. February 9, 2017. www.sacbee.com/opinion/op-ed/soapbox/article131528914.html

Kiparsky M, Fisher AT, Hanemann WM, et al. 2018 (in press). Recharge net metering to enhance groundwater sustainability. Issue brief. Center for Law, Energy & the Environment, UC Berkeley School of Law.

Knight R, Smith R, Asch T, et al. In press. Mapping aquifer systems with airborne electromagnetics in the Central Valley of California. Ground Water.

Kocis TN, Dahlke HE. 2017. Availability of high-magnitude streamflow for groundwater banking in the Central Valley, California. Environ Res Lett 12:084009. https://doi.org/10.1088/1748-9326/aa7b1b

Marquez MF, Sandoval-Solis S, DeVicentis AJ, et al. 2017. Water budget development for SGMA compliance, case study: Ukiah Valley Groundwater Basin. J Cont Water Res Educ 162:112–27. https://doi.org/10.1111/j.1936-704X.2017.03263.x

Méndez-Barrientos LE. (in review). The influence of power asymmetries in institutional development. An empirical view of groundwater institutional reform in Northern California. (submitted to special issue of Water Alternatives on "Local and national-level politics of groundwater overexploitation")

Nelson R, Perrone D. 2016. Local groundwater withdrawal permitting laws in the south-west US: California in comparative context. Ground Water 54:747–53. http://doi.org/10.1111/gwat.12469

O'Geen AT, Saal M, Dahlke H, et al. 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. Calif Agr 69:75–84. https://doi.org/10.3733/ca.v069n02p75

Perrone D, Jasechko S. 2017. Dry groundwater wells in the western United States. Environ Res Lett 12:104002. https://doi.org/10.1088/1748-9326/aa8ac0

Rudnick J, DeVincentis A, Méndez-Barrientos LE. 2016. The Sustainable Groundwater Management Act challenges the diversity of California farms. Calif Agr 70:169–73. https://doi.org/10.3733/ca.2016a0015

Zhang Z, Glaser SD, Bales RC, et al. 2017a. Technical report: The design and evaluation of a basin-scale wireless sensor network for mountain hydrology. Water Resour Res 53:4487–98. https://doi.org/10.1002/2016WR019619

Zhang Z, Glaser S, Bales R, et al. 2017b. Insights into mountain precipitation and snowpack from a basin-scale wireless-sensor network. Water Resour Res 53:6626–41. https://doi.org/10.1002/2016WR018825

CONVERSATION

Four decades of sustainable groundwater management

An interview with Peter Kavounas, General Manager, Chino Basin Watermaster

Peter Kavounas

Peter Kavounas is the General Manager of Chino Basin Watermaster, the nine-person entity created in 1978 by a state Superior Court adjudication judgment. The Watermaster is charged by the Court to sustainably manage groundwater in the 235-square-mile Chino Basin in San Bernardino, Riverside and Los Angeles counties.

Under the oversight of a board that represents the basin's groundwater users, Watermaster monitors groundwater extraction so that it does not exceed the basin's safe yield. In some ways, the roles and responsibilities of the Watermaster are similar to those of the groundwater sustainability agencies (GSAs) formed recently around the state under the Sustainable Groundwater Management Act.

California Agriculture spoke with Kavounas about the challenges that the Chino Basin Watermaster has faced and potential lessons that the agency's experience may offer for GSAs around the state as they prepare and implement groundwater sustainability plans (GSPs).

What have been the key elements to making sustainable groundwater management work in the Chino Basin?

I would say that the most important element has been willingness and commitment to cooperate on the part of the stakeholders, starting with the 1978 judgment, which was a stipulation, an agreement by all, that was ordered by the Court. The basin experienced overdraft, and everybody recognized that some kind of allocation of water rights made more sense.

The second element is continuously getting everybody to the point of awareness and agreement about the issues — that takes political leadership. It is essential for long-term success that the stakeholders stay engaged. You have to have management and oversight systems that adapt and evolve over time.

One of the most interesting things about the Chino Basin judgment was that it looked at what was likely to happen in the future, which was that agricultural use was likely to decrease and urban development was likely to expand, and provided for an orderly transfer of unused rights from agriculture to appropriators. So, it needs to be more than "let's just manage for what's happening to today." We have to ask whether and how cities and agriculture are likely to change, and plan for that.

How has the management of the basin changed over the years to respond to changing conditions?

The first step was to determine the safe yield in 1978 and adjust as the land use has changed. Also, the judgment ordered Watermaster to create an optimum basin management plan that drives data collection, better understanding of hydrology and water budget, development of water supply plans, storage management, and subsidence management. This plan was adopted in the year 2000 and has been actively implemented since.

In round numbers, the safe yield was originally set at 140,000 acre-feet per year; the overlying land owners' (agricultural and nonagricultural users) share is 90,000, and the appropriators' share is 50,000. Since then, because the basin has been so closely monitored and studied, our understanding has improved, particularly with respect to surface water–groundwater interactions. So, we are in the process of adopting a new safe yield of 135,000 acre-feet per year. That will mean that the appropriators' share drops from 50,000 to 45,000 acre-feet per year.

One of the reasons the safe yield has dropped is that, in the Chino Basin, land use has completely reversed. In 1978, more than 70% of the land overlying the groundwater basin was actively farmed. Now more than 70% of it is developed. Land has been paved over, stream channels have been lined with concrete — so we have less recharge from percolation. Because we have the advantage of decades of extensive data collection and very robust computer simulations, we can model how various scenarios of future land-use changes would affect recharge rates and the safe yield.

However, communicating this reduction in the safe yield has been hard — why it is happening, what methods we used to determine what the new safe yield should be. Our lesson learned is that it can be hard to communicate about groundwater models and other technical tools. We have decided that we are going to re-evaluate the safe yield every 10 years — and to address the issue of communication, we have already made clear to the basin water users exactly which methods are going to be used.

How are conflicts among water users resolved in the Chino Basin?

Traditionally, conflicts among users are resolved through discussion and negotiation, and on occasion litigation. In case there is a difference of opinion among users or with Watermaster about the judgment, the user can be in front of the judge within 30 days. There's a very appealing cleanliness to that. The Court is not affected by politics, and the procedures that have to be followed are clear.

What are the most important lessons you've learned about governing a groundwater management agency?

When I've been invited to speak on panels about SGMA implementation, the point I've made is that GSAs will be called on to produce GSPs, and many GSAs will hire staff to do that, as well as technical and legal consultants. Two points about that:

It's really critical for the governing members of the agency (the board members, the people empowered to make decisions) to be actively engaged in the issues and decisions. It shouldn't be treated as just another committee assignment. Also, the issues — technical, legal and political — are so complex that it can take a year or two for a new board member to get up to speed. So the people appointed to GSA boards should be given some stability — for instance, 5-year terms that are renewable.

Second, is the relationship between the GSA board and GSA management and staff. Inevitably, the staff are going to have to come back and say to the board members, "you can't pump as much as you used to." The staff can't be worried about the politics of that — simply giving the GSA unwelcome news should not be an offense. Groundwater management is a complicated problem — it has money, politics, all the dimensions. So it just has to be approached from a higher perspective.

What are some innovative engineering solutions the Watermaster has implemented?

Chino Basin has had one engineer for 30 years. His understanding of the basin has become almost supernatural, and he's been able to come up with great solutions — for instance for salinity management.

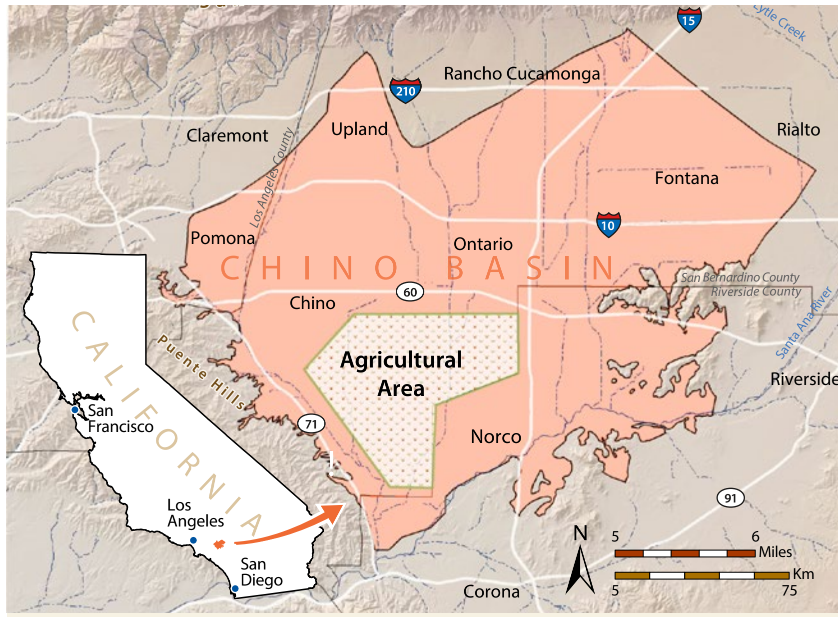
Our basin is a tilted, flow-through basin. The basin naturally empties into its southwest corner, where it connects with the Santa Ana River. We have a lot of high-salinity groundwater in that part of the basin, and as that infiltrated in the river it was increasing the salinity for downstream users of Santa Ana River water — like the Orange County Water District.

We have implemented a groundwater desalination system in that portion of the basin. Two treatment plants — capacity of 40,000 acre-feet per year — remove the salts, and the water goes into the municipal supply systems of water providers in our basin.

The [Santa Ana] Regional Water Quality Control Board was so satisfied with that as an overall salinity control plan that it allowed using recycled water upstream for direct use in farming or groundwater recharge. Flows in the Santa Ana River have remained above the levels required in the adjudication of that river (an adjudication separate from the Chino Basin adjudication). And Orange County is grateful for the reduced salinity.

Any closing thoughts?

In the Chino Basin, we have a plan that we call the Optimum Basin Management Program. It really corresponds to a GSP — and, having seen it work, I'm a believer in SGMA. It will help the state advance to better groundwater management. Having said that, the ultimate goal is having the state look at water — surface water as well as groundwater — as a singular resource. There's a disconnect now. The existing projects — the State Water Project and the Central Valley Project — are magnificent surface water projects. In the future, their operation will have to be very much integrated with sustainable groundwater management. We'll have to shift from sustainable groundwater management in every basin to sustainable water management statewide. CA



The Chino Basin

One of the largest groundwater basins in Southern California, the Chino Basin has a total storage capacity of roughly 6 million acre-feet. It currently holds about 5 million acre-feet of water. A substantial fraction of the basin's land area has shifted from agricultural to urban uses in recent decades, and the population continues to grow rapidly.

In the 1960s and '70s, the basin was being overpumped by more than 50,000 acre-feet per year, and water levels were dropping rapidly, as much as 7 feet per year in some areas. This chronic overdraft, combined with disagreements about groundwater allocation, led to adjudication hearings in San Bernardino Superior Court. The adjudication judgment issued in January 1978 established a safe yield of 140,000 acre-feet per year, allocated among overlying agricultural users (82,800 acre-feet per year); overlying nonagricultural users, mainly industry (7,366 acre-feet per year); and appropriative users, mainly municipal water suppliers (49,834 acre-feet per year).

Today, multiple approaches are used in the basin to increase the amount of water available without exceeding the safe yield — including extensive groundwater recharge, water recycling (an increasingly important source of water for aquifer recharge), and desalination of groundwater (see article).

CONVERSATION

Enforcing the Sustainable Groundwater Management Act

An interview with Sam Boland-Brien, Groundwater Management Program Chief, California State Water Resources Control Board

Sam Boland-Brien

The State Water Resources Control Board (SWRCB) and the California Department of Water Resources (DWR) are the two state agencies overseeing the Sustainable Groundwater Management Act (SGMA). They have distinct roles. In general, DWR acts as a facilitator and evaluator — for instance, assisting with groundwater data management, helping local groundwater sustainability agencies (GSAs) to develop and follow plans that will lead to sustainable management, and evaluating plans once they are developed. SWRCB, by contrast, has more of an enforcement role. It is the agency authorized and empowered to ensure that basins comply with the law's requirements. Sam Boland-Brien leads these efforts as chief of the SWRCB Groundwater Management Program.

To start with, tell us about SWRCB's role in implementing SGMA, and what work you're doing leading up to the first deadline for groundwater sustainability plan submission in January 2020.

The legislation gives us the broad layout of what we're supposed to do, and our task has been to turn those general authorities into specific actions. We've been preparing the tools and processes that need to be in place so that we can act when needed. Day-to-day, we're answering the many specific questions that come up about SGMA. We're working with DWR, to make sure that we are in sync, for instance with managing groundwater data, and in developing systems for pumpers and GSAs to conveniently submit data. We're also exploring satellite-based monitoring approaches where possible, so we don't have to have as many staff in the field. And we're focusing on developing scalable processes, so that, if it turns out that we suddenly need to manage multiple basins in the future, we'll be able to adapt and expand quickly.

In a lot of areas, county involvement has been really helpful. That's one of the nice elements of SGMA — that it's bringing more counties into the groundwater management process. There was already the recognition that land use planning is an important aspect of water resource planning, and now SGMA calls out explicitly that the county can be a first backstop, before state regulators get involved. Counties, for instance, are managing areas that weren't covered by a GSA. I think there are many interesting future opportunities for creative local solutions that involve actions by counties — actions that could possibly demonstrate to the state that intervention isn't necessary.

Give us some more detail about how SWRCB's enforcement role is likely to play out.

First, it's important to remember that enforcement starts at the local level, with the GSAs. One of the big things that SGMA does is to give a lot of authority to GSAs. They can levy fees, they can order a pumper to stop pumping, and infractions are linked to civil penalties. The legislation gave them a bunch of tools — though we still have to see how the GSAs will settle into using them.

It's only when DWR finds that a groundwater sustainability plan (GSP) — or its implementation — is inadequate, and sees that the issues aren't getting fixed, that the Board becomes involved. With each plan, DWR will be evaluating whether it is it likely to achieve sustainability: does it lay out projects and actions that are going to bring the basin into balance in 20 years. Each plan also needs to set milestones every 5 years, and DWR will be evaluating whether those are adequate, and whether the GSAs are doing what they said they were going to do.

Basins run the risk of state intervention if they miss the deadline for plans or don't have a plan that DWR thinks will be sustainable. Say a GSA fails to adopt a GSP in time. The GSA would go before the Board (the five board members of the SWRCB), and the Board would issue a decision on whether or not to proceed with enforcement action. The Board could designate the basin probationary and lay out the deficiencies, with the consequence being that if those deficiencies are not remedied, the Board will proceed with its own plan until the issues are fixed. While a basin was probationary, all of the pumpers in the basin would be required to submit their groundwater pumping data directly to the SWRCB. The SWRCB would use the data to develop an interim plan and would provide the data publically as a resource for stakeholders in the basin.

That kind of interim plan wouldn't have much flexibility: we'd require monitoring, collect pumping data, and set a schedule for certain corrective actions — likely reduced pumping. SGMA gives us that blunt instrument — reducing pumping — and we would probably use it.

I have been told that no one wants to be first through the Board's enforcement process. Folks understand that the first time through, we are probably going to need to be firm so that it is clear the Board is serious about the prospect of state intervention.

What are some of the pros and cons of SGMA's prescriptions being somewhat flexible, with sustainability defined as the avoidance of six types of impacts (see page 4) to a "significant and unreasonable" degree?

I appreciate that SGMA is outcome-based. It establishes a framework for local agencies to set targets and then the state holds them to those targets. It would be hard for us at the state level to be that flexible. The local-level implementation gives local agencies some flexibility about how to get to the finish line, and also about what the finish line is. Under SGMA, the GSAs define what "significant and unreasonable" impacts look like. Those impacts do have to be quantified — the law says that there need to be clear "minimum thresholds" and "measurable objectives" — and they are subject to review by DWR, as a reasonableness check. But there's still a lot of flexibility, and SWRCB is kept at a distance from those processes.

As for the cons: At the end of the day, there's still going to be, in many cases, the core issue of determining how much individuals can pump. At the state level, SGMA doesn't want us to presume that pumping restrictions are necessarily going to be required in any given basin. But we wouldn't want a GSA to get so wrapped up in trying to figure out what is "sustainable" that it delays dealing with the fact that you still need to divide the pie.

Closing thoughts?

With your audience being significantly in agriculture, I think another important part of SGMA is the need for having a broad buy-in and consensus as GSAs move through the GSP process. There's going to have to be really serious engagement with the various groundwater users in each basin, including growers and dairy operators. Folks need to be part of the decision-making process, and to buy in to the implementation process. That's why we've been working a lot on outreach and think GSAs need to emphasize outreach if they want to move to implementation successfully. We've been trying to work with the county Farm Bureau offices, and we'd like to do more with UC Cooperative Extension to help those in agriculture understand SGMA. CA

Groundwater irrigates a rice field in Yuba County.

A seat at the table for rural drinking water

An interview with Adriana Renteria, Regional Water Management Coordinator, Community Water Center

Adriana Renteria

The Community Water Center (www.communitywatercenter.org) is a nonprofit organization that works through education, organizing and advocacy to increase access to clean water. Founded in 2006, it has offices in Visalia and Sacramento and focuses on domestic water issues in California's rural agricultural areas. Adriana Renteria is the Community Water Center's regional water management coordinator. She leads the group's involvement in the implementation of the Sustainable Groundwater Management Act (SGMA), working in particular to increase public participation in groundwater planning and management.

Tell us about CWC's involvement in the GSA/GSP processes at the local level.

We have been involved since the early stages of the development of the legislation, and helped to advocate for the inclusion of drinking water seats on several groundwater sustainability agency (GSA) boards and committees. We try to make the groundwater planning and management processes accessible to more people and to increase public participation.

We have held a series of groundwater workshops, and we helped the Union of Concerned Scientists develop a guide to participation in the SGMA process (https://goo.gl/Agxy3U). There are statutory requirements in SGMA that require stakeholder engagement. Through our workshops we've shared information about how to get involved in the GSA processes and the development of groundwater sustainability plans (GSPs) — so that all stakeholders know what SGMA means for their community, what a water budget is, what sorts of questions to ask the consultants that are preparing the GSPs, and what questions to ask in GSA board and committee meetings. Generally, it's about sharing tools and resources that demystify the technical components of groundwater planning in order to lessen this barrier of participation.

A sprinkler line in the southern San Joaquin Valley.

John Chacon, California Department of Water Resources

Florence Low, California Department of Water Resources

Over 95% of drinking water supply systems in the San Joaquin Valley rely on groundwater as a primary source.

We also, as an organization, are members of various GSA technical advisory committees and stakeholder advisory committees. These stakeholder advisory committees are one way that many GSAs are trying to incorporate stakeholder interests, and drinking water interests in particular. Some GSAs also have drinking water interests represented on their governing board. Where we are on stakeholder advisory committees we work with the drinking water districts in the area to ensure they are knowledgeable on important GSA information and can share their feedback and concerns. The GSAs we are most involved in are located in Tulare, Fresno and Kings counties. CWC has prioritized these GSAs because many communities in these areas rely on groundwater as a primary drinking water source. Many small, rural communities are vulnerable to groundwater depletion and oftentimes do not have the financial means to drill new wells or seek new sources of water if they find themselves facing water quantity or quality concerns. For these reasons, it's important for representatives from drinking water districts to participate in the management of their local groundwater resources.

What are your main concerns with respect to the representation of all groundwater users the groundwater management?

The main thing is that, in developing GSPs, GSAs have to come together to set the criteria for each of the six "undesirable impacts" of SGMA (see page 4). For example, what is the minimum threshold for groundwater depletion that each GSA will allow. For different stakeholders, the acceptable level of depletion may be very different. Agriculture, large municipal water districts, and industry stakeholders generally have the capacity to drill deeper wells, and are not as vulnerable to groundwater depletion as small community service districts that have shallower wells and limited financial capacity to address water shortage and water quality concerns.

Groundwater quality is another issue. GSAs have to set minimum thresholds for how much degradation of groundwater quality they are going to allow (though aquifers used for drinking water still have to abide by state and federal drinking water standards and irrigators have to comply with state regulatory programs). Input from stakeholders dealing with water quality concerns is important to get a better understanding of the overall water quality state of the basin. As GSAs develop proposed projects to reach sustainability, it's important for them to identify multi-benefit water projects that can address both water supply and quality concerns.

How well are state efforts to support inclusive groundwater management working? What needs improvement?

Over 95% of the drinking water supply systems in the San Joaquin Valley rely on groundwater as a primary source. Yet the majority of representation is the agricultural industry. So, we are concerned.

The Department of Water Resources (DWR) has released documents on best management practices (available at https://goo.gl/e1CPmV and https://goo.gl/1nido6) for the stakeholder engagement that is required under SGMA. DWR is also offering facilitation support services, where a third-party professional would come in to facilitate discussions and meetings and help coordinate outreach to different stakeholders. And there is a DWR SGMA point person in every region, and then also a DWR point of contact at an even more local level.

But DWR has also stated several times that its role is not to enforce how GSAs should develop their GSPs. SGMA is very rooted in the concept that local decision-makers should be the ones making the decisions about managing their resources.

While some GSAs in Kern and Kings counties used the DWR's facilitation service during the GSA formation process, currently no GSAs in the southern San Joaquin Valley are using the services as part of the GSP development process. Not every subbasin is interested in third-party facilitation.

We think facilitation support for stakeholder engagement is something that subbasins would greatly benefit from and should be taking advantage of. We feel that it would be helpful for DWR to do more targeted outreach during the GSP development process — and the DWR's coordinator of facilitation and support services has definitely been very understanding and responsive to suggestions when we have met.

Also, because it's early, there is still a lot of uncertainty around many topics. One of the big uncertainties has been how the SGMA requirements interact with and complement the existing regulatory and planning programs — like the Irrigated Lands Regulatory Program and CV-SALTS program (which concerns water quality). DWR is still working on providing GSAs additional guidance on that. Another issue is how the GSAs are going to address how depletion of interconnected surface waters impacts groundwater-dependent ecosystems.

Closing thoughts?

I'd just point to some challenges, some reasons why public participation might not be as inclusive as it could be.

One thing is that the timeline for GSP development is definitely quick. Because of that, the GSAs should reflect on how they are doing outreach to share updates, to make sure that all beneficial users of water, including domestic well users, are aware of meetings and plan updates. GSAs should be, or should start, working with schools, community-based organizations, nonprofits, and local bilingual media stations to make sure the general public is knowledgeable about SGMA and aware of opportunities to engage in local groundwater planning. This is statutorily required — inviting a diverse group of people to participate means that you have to communicate in a diverse way.

Another barrier is that GSA meetings tend to take place during the day, when irrigation district and other city and county staff are at work — so they can attend the meetings on the clock. But many other people are not able to attend meetings during regular working hours.

In addition, the technical and stakeholder advisory committees must present technical information in an accessible way that allows for questions from the public, for working through uncertainty, for really having an understanding of what's happening in the basin. You can't just present something and then approve it the next week without giving stakeholders enough time to understand the impacts the policy will have on their community. It is up to the GSA chairs and subbasin facilitators to work with consultants to make sure information presented is understood and that their GSP development timeline is transparent and clearly defined.

I just think that, across the board, inclusion could be improved. GSAs really should be taking the lead from those GSAs who are taking their stakeholder communication and engagement plans seriously and are using this step of the GSP development process as an opportunity to engage their communities in groundwater management.

The Community Water Center offers resources about SGMA for stakeholders at www.communitywatercenter.org/sgma_engagement. CA

CONVERSATION

Advocating for growers as SGMA moves forward

An interview with Christina Beckstead, Executive Director, Madera County Farm Bureau

Christina Beckstead

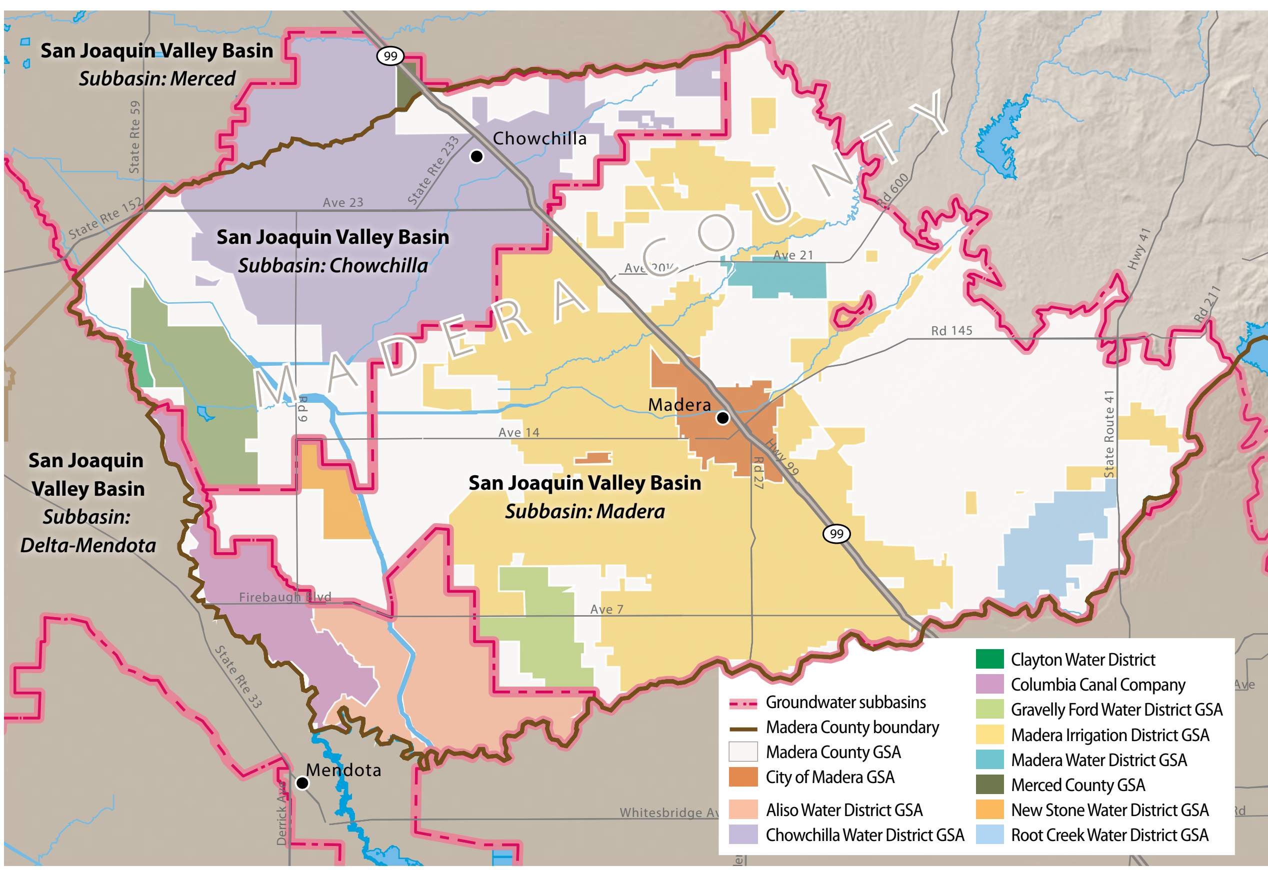
Christina Beckstead is executive director of Madera County Farm Bureau. As an advocate for growers in her county, she has been closely involved in the formation of groundwater sustainability agencies (GSAs) in Madera County and the steps towards the development of groundwater sustainability plans (GSPs). There are three subbasins in Madera County — the Madera subbasin, the Chowchilla subbasin and a small portion of the Delta-Mendota subbasin. All are classified by the state as critically overdrafted.

Tell us about the groundwater landscape in Madera County and where things stand with SGMA implementation.

The Madera subbasin has just under 400,000 irrigated acres, about half of which is supplied with surface water by irrigation or water districts. Each of the districts and municipalities has formed a GSA, creating seven GSAs with boundaries roughly matching each service area. The Chowchilla subbasin has roughly 145,000 irrigated acres, with about 100,000 acres receiving surface water from three water districts, each of which has formed a GSA. We have about 1,200 irrigated acres that are part of the Delta-Mendota subbasin and that don't receive surface water.

The irrigated areas that are outside the water district or irrigation district service areas are called "white areas." They have no access to surface water and depend entirely on groundwater. In the white areas, the county serves as the GSA, which makes the Board of Supervisors the governing body. One thing that is unique about Madera County is that all the white areas are managed by the county — in other counties, at least some of those areas are covered by water-district GSAs.

My role in the SGMA process is to advocate for farmers and agricultural landowners, to make sure that their interests are taken into consideration and adequately represented. The subbasins have regular coordination meetings of the GSAs in their boundaries. The GSAs, including the county GSA, generally schedule their GSA board meetings to coincide with their



Groundwater basins and water and irrigation districts in Madera County. Irrigated areas outside of water district or irrigation district service areas are shown in white and depend entirely on groundwater. Madera County is unique in that all such areas are part of a county-managed groundwater sustainability agency. Map source: Madera County groundwater sustainability agencies.

regular board meetings, saving some time, but still, it's a lot of water meetings.

The GSAs and the county are now working on developing GSPs. An analysis of the data gaps has been done, and consultants have been hired to determine what the sustainable yield is in each basin and create GSPs that take into account drought, average and wet years. There is still a lot of work to do.

As far as support from the state — I think they've been really good. You go and you have questions — and maybe they don't have everything in place, and there aren't defined responses yet, but they've tried very hard to lead me in the right direction or provide me with as much information as they can. The biggest hurdle for everyone is that SGMA implementation is an ongoing thing — it's been building, with the rules and guidance coming out slowly but surely.

Irrigation in an almond orchard. Almonds are the leading crop in Madera County, with the 2016 harvest valued at $593 million.

Do you feel agriculture's interests are being considered fairly in the SGMA implementation process in your region?

Overall, I would say yes. In Madera County, agriculture is the driving force of the economy, and all of the water districts that have formed GSAs are primarily agricultural water suppliers.

My main concern in Madera County is the white areas that don't receive surface water and are governed by the Board of Supervisors.

There has been a history of conflict over water for agriculture versus water for urban development in the county. On the east side of the county in particular, there's a lot of planned development. One case that people often bring up, is when the county Board of Supervisors approved a plan for 3,000 new homes that would be entirely dependent on groundwater, and then at their next meeting they proposed a moratorium on new agricultural wells. That moratorium didn't pass (and the housing developer later agreed to limits on groundwater extraction), but there's generally just a concern that the county may not represent the farmers well when those issues come up again. Unfortunately, ag will always be outvoted at election time, as municipal water users significantly outnumber ag land owners. Though I will say that currently we have a good board, all of whom are pretty mindful of agriculture.

Do you think growers in Madera County are really confronting what a future with less groundwater extraction will look like?

The conversations are definitely happening, though there hasn't really been any movement yet.

In the Chowchilla subbasin, the GSAs have said that the last thing they want to do is take land out of production, which I think is a common goal throughout the entire county. Everyone is looking for solutions, trying to be creative. In a lot of areas, landowners went above and beyond last winter to recharge as much groundwater as they possibly could. Conversations are also happening about ways to set up some sort of water credit or exchange system.

But, it's in the back of everyone's mind that some land is going to have to be fallowed. There's going to be an allocation set, and there's not going to be enough water to go around.

Closing thoughts?

I think it's just important that stakeholders remain engaged, and for the governing bodies to understand the importance of listening to stakeholders. We've had a lot of bumps in the road to get to where the county, the GSA governing body for much of the county, hears our voice. At the end of the day, municipal users will always outvote ag water users. Being engaged, having a voice, is still so important.

Also, I still get some farmers that tell me they're just now hearing about SGMA, or that they don't understand it. The other day somebody told me that they were thinking about putting in a permanent crop, and I asked about their source of water, and they said, "We have wells, we're OK." But those are the first people that are going to be subject to the regulations! So, I can't stress enough the importance of being engaged and asking questions. CA

CONVERSATION

Can we speed this up?

A perspective on SGMA from outside California

Ronald C. Griffin, Professor Emeritus, Texas A&M University, and WaterEcon.com

Ronald C. Griffin

Academic economists such as myself are lucky to live during a time when we can witness a major resource — in this case, water — evolving from state or common property forms to private ones. It's interesting to us! In other resource settings, we have learned that scarcity drives institutional (policy) reform in particular directions. Heightened scarcity reveals the failures of old resource regimes and calls for refinements. According to economic doctrine, the resource management tragedies of nonmarket policies — such as California groundwater law — become so severe that these policies are cast off in favor of private property policy. So, the contested resource is eventually partitioned among its users as a tradable commodity. Because users experience a much fuller slate of their actions' benefits and costs under private property, they practice more efficient stewardship. Absent private property, it is more difficult to achieve various good behaviors in the right amounts (e.g., conservation, investment, technology selection, production, consumption and reallocation).

With groundwater, a move to private property requires the severing of water rights from land rights, quantification (adjudication) of the resultant groundwater rights, and enforcement. Thus, a landowner with a newly created groundwater permit will now own two different things, forever transferrable independently. Good design of water rights, no-trespass enforcement, and efficient oversight of water markets are additionally important elements if things are to progress well.

Where does SGMA point?

So, what has the 2014 Sustainable Groundwater Management Act (SGMA) done to accelerate this evolution? Let's see. New local groundwater sustainability agencies must develop sustainability plans, and sustainability is defined as the avoidance of six things if any are "significant and unreasonable": lowered groundwater levels, reduced groundwater storage, seawater intrusion, degraded water quality, land subsidence, and depleted surface water. Obviously, all six can accompany groundwater use (two regularly), so what then is reasonable sustainability? One cannot tell by reading the Act. Nice dodge, Legislature. Haven't we learned by now that the political attractiveness of sustainability is its feel-good vagueness, and that reasonable means "let's argue this forever"? What has been achieved by SGMA other than to shift the crucial questions to lower jurisdictions, thus multiplying the burden rather than confronting it and inviting disrespect of the outside-of-jurisdiction effects of depletion?

Of course, this excess employment act for water professionals is welcome in some quarters, and some will speak highly of roles for "stakeholders" and "governance". Water users should always wince when they hear words such as these exulted. Their pockets are being picked by a process that is focused on the process, not the outcome. With regard to moving away from the management failures of state/common property, it would seem that the velocimeter for California groundwater reform is still set on "glacial." The new law allows groundwater sustainability agencies to consider adjudication, to allow transfers of "allocations", and even to allow carryovers of unused allocations (all good!), but

Kelly M. Grow, California Department of Water Resources

there are no compulsions or expectations for agencies to uniformly evolve in these directions. Undeveloped funding for these sustainability agencies adds to the inertia.

What would the czar say?

Considering all this costly "progress", one longs for the czarist state water engineer of the early western states. In California, this dictator would think, "people are pumping too much groundwater", and would think this before things got out of control. The state engineer would have a team study the hydrologies of the various aquifers, and would fund external studies to firm up this knowledge. The czar would set pumping limits at the aquifer level and reject new permit applications that would broach these limits. Initial uncertainties might instill some socially attractive precautions in the announced limits. One hundred percent metering of wells would commence, and the state's demand for compliance would initiate stronger bookkeeping.

The state engineer would know that water supply varies from year to year, so limits and permits would be designed accordingly (for decades now, surface water reservoirs have had successful operating rules to handle variations). Using a seniority system based on prior use (appropriative rights) might make sense to the engineer because it interfaces well with surface water rules, and early pumpers have made respectable investments that should not be wastefully stranded. A correlative shares system would be an acceptable alternative. In this system, each permit represents a stated proportion of each year's varying groundwater availability.

The state engineer would be highly concerned about the surface water interactions of groundwater rulings, including required environmental flows, so attention here would be instrumental in framing groundwater limits. Clearly, the engineer's pivotal problem would be whether to set pumping limits at estimated levels of aquifer recharge or at levels involving long-run depletion. For those aquifers with a high degree of surface water interaction and recharge, targeting "no long-run depletion" might be feasible. Otherwise, groundwater use must entail a degree of depletion, and the engineer would be forced to decide on an acceptable rate of depletion for these aquifers. Somewhere in the depths of the SGMA processes these same questions must be answered.

Regardless of the overall limits, trade of groundwater permits would seem sensible to the state engineer. Why not? It's working for surface water and contributes to regional welfare and resilience. The state's compliance division would administer this. Use in excess of one's permit would be seen as a trespass upon other permit holders, and would therefore be penalized at greater than market value. The engineer would know that hydrological knowledge is the weak link in this or any groundwater rule system, so prioritized studies

Groundwater irrigates a rice field in Yuba County.

Dale Kolke, California Department of Water Resources would be continued, limits and permits might be revised over time, and data collection would be a mainstay.

Slow reform has real costs

But I'm just dreaming. That's because I cannot stop thinking about the enormous costs of water policy reform and poor water policy in California. The cost of the state's water-focused news coverage alone and the reporter time it takes to compile it might exceed Rhode Island's GDP. Just kidding . . . perhaps. More disappointing is that all of this news is correlated with the psychological costs felt by a water-worried public saddled with the uncertainty of how badly this will come out and what it is costing them monthly. These are real costs, although they remain unmeasured. Then there's all the political gaming and influence peddling that must be supported. Can the inequities of this political power be any less worrisome than those of economic power accompanying water marketing? Political power is certainly more covert. Even if a city or water district doesn't want to take advantage of its neighbors, it is compelled to hire protection (attorneys, lobbyists, public relations) against other sectors and pumpers. And consider all the miscellaneous consultants, including the new ones needed to wander through the SGMA process. And consider all the effort, from statewide agencies to the local groundwater sustainability agencies that must implement this incomplete Act. All the meetings. All the debates and discussions. Again and again. This will continue because SGMA focused on designing a process rather than directing and guiding an adjudication of groundwater rights.

When legislation such as SGMA is written in California, using malleable PC terms like sustainability and reasonability, are the authors aware that they're fertilizing a water sector of the economy that barely exists in other states? But all government-created jobs are good jobs, right? Never mind that these jobs are siphoning off rewards that water users were supposed to be getting from their state's water resource base. Never mind the diffused tax costs and the injuries to competitiveness. Never mind that the slow pace of reform is another factor failing to signal overpopulation in a state burdened by climate change.

Lest it be forgotten in the mist of implementation, let's try to keep our eyes on an achievable end game. As compared to an idealized water czar or some other expedient path to transferrable groundwater rights, we might try to improve things using nonmarket policies such as nontransferable use regulations (including Governor Jerry Brown's recent conservation edicts), education programs, technology subsidies, and oddly tinkered water rates, but these are partial measures reflecting the limits of individual instruments and the political aims and water acumen of their designers. These nonmarket policies are not commonly robust in the face of drought cycles, unintended consequences, unforeseen options, and other changes. And continuing "change" is the crucial feature of the water scarcity problem. Private property and consequent markets is a more promising strategy.

Private property has been useful

Westerners are quite familiar with private property in land and even surface water. We have managed developed and developing land this way for a long time, while setting aside large tracts as parks, forests, and other public areas and keeping these tracts out of private hands. Complex economic doctrine formalizes the good sense of this division and is applicable to water. Recall that land has not always been managed this way, and that private property in land was troublesome to achieve. Major U.S. homestead policy of the 1800s converted public land into private land, thereby clarifying stewardship responsibilities and unlocking private investments and labor. More famously during earlier centuries, thousands of Enclosure Acts in England converted open and shared agricultural lands into private holdings that could support wiser cropping choices and practices. Of course, privately owned land is not locked into agriculture, so it can be shifted to new pursuits as conditions change. Private property in land has been an essential human invention for addressing change.

So too has it recently become useful to move to private property in surface water. The transition of surface water into a private property character is strongly with us now (finally). It has a several-decade jump on similar (hopefully) transformations for groundwater. Major surface water transactions and contracts are crucial tools in the California policy portfolio, as most people know. These tools are predicated on some incarnation (especially quantified shares or prioritized quantities) of enforced, no-trespass, exclusive ownership. Problems such as weak enforcement and organizational ownership of California water, especially by irrigation districts, rather than ownership by individual agents has limited market achievements, but surface water markets have been important.

Can we get there from here?

With ingenuity, some locales might achieve admirable reform, working within SGMA's messy parameters. The window has closed for installing top-down centralized management à la Idaho and New Mexico, and we cannot wait on a revised SGMA. My outsider's view is that the Act left important opportunities on the table and perpetuated the glacial pace of policy advance.

Maybe groundwater sustainability agencies can struggle forward by emphasizing adjudication and transferability, but shrinking permits down to physical sustainability (zero depletion forever) can be costly, thereby impinging on our social vision of "reasonable sustainability" and adding more delay. CA

RESEARCH ARTICLE

How are Western water districts managing groundwater basins?

A study of 18 districts finds that common groundwater management approaches that minimize economic impacts to agricultural users include low-cost monitoring and a flexible combination of supply augmentation and demand management.

by Claire Newman, Richard Howitt and Duncan MacEwan

Abstract

Making the transition from open-access groundwater rights to sustainable groundwater management is a formidable task for newly formed groundwater sustainability agencies in California. As agencies begin to decide how to make equitable water allocations, how to monitor groundwater use and what mix of supply- and demand-side mechanisms to adopt to satisfy sustainability criteria, the groundwater management strategies in place across other basins in the western United States are worth studying. We surveyed 18 groundwater districts in California and other Western states to identify the management approaches and practices they have instituted. The conclusions we draw suggest a correlative rights framework of water allocation with phase-ins for heavy users; metered pumping; flexible arrangements for trading and carrying over allocations for multiple years; and incentivizing groundwater recharge, including recharge from deep percolation from crops. Rigid formulas for significantly reducing groundwater use in medium- and high-priority basins are likely to have significant negative effects on the regional economy.

California's Sustainable Groundwater Management Act of 2014 (SGMA) overhauls groundwater management in California. Currently, most California groundwater basins are unmanaged and extractions from basins are unmeasured. SGMA requires the formation of local groundwater agencies (GSAs) to provide management (DWR 2016a) for all basins designed by the state as medium- or high-priority. The GSAs have the unenviable task of unifying and managing a set of water users, many of whom have different objectives. The law also requires medium- and high-priority groundwater basins in a state of critical overdraft to adopt a groundwater sustainability plan (GSP) by Jan. 31, 2020, and medium- and high-priority basins not in a state of critical overdraft to adopt GSPs by Jan. 31, 2022.

If GSAs fail to meet these deadlines (or a GSA has not been formed), the law has provisions to designate a basin as probationary and subject to regulation by

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An engineering geologist with the California Department of Water Resources measures the water depth at an agricultural well in Colusa County. Periodic measurements at wells around the state feed into databases that track changes in groundwater levels.

Kelly M. Grow, California Department of Water Resources

the State Water Resources Control Board (SWRCB). Successfully navigating the complicated regulatory process will require GSAs to balance demands across water users with different preferences and water values. With tight deadlines, often competing interests among different water users, and strict sustainability requirements, GSAs face a difficult transition.

Most of the initial focus on sustainable groundwater management has been on navigating the political process of forming GSAs. Because of differing hydrologic and agronomic conditions, groundwater management usually requires the detailed definition of groundwater sub-basins. Currently, 127 of the 515 sub-basins in the state are classified as medium- or high-priority (DWR 2016b). As of January 8, 2018, 266 unique local agencies have formed GSAs that account for 378 areas (GSAs may encompass more than one sub-basin, and there may be multiple GSAs within a sub-basin). Figure 1 illustrates the boundaries of the 43 medium- and high-priority groundwater basins in the Central Valley as defined by Department of Water Resources Bulletin 118.

Moving forward, GSAs must work to adopt GSPs that are acceptable to the parties they represent and that result in demonstrable progress toward sustainable management. Specifically, GSPs must avoid the six sins of groundwater overdraft, defined by SGMA as the "significant and unreasonable" lowering of groundwater elevations, reduction in groundwater storage, salt water intrusion, water quality degradation, land subsidence and negative effects on beneficial uses of interconnected surface water.

California has implemented groundwater management in a few basins under AB 3030 plans and SB 1938; however, under these bills there is no statewide mandate to implement management as there is under SGMA. Since groundwater management is a new process in nearly every basin, it seemed useful to identify what has worked elsewhere and why.

Survey of 18 water districts

We surveyed 18 districts in the western United States that have already implemented sustainable groundwater management to compare their practices, identify commonalities and highlight themes in the survey responses. The districts selected were in California, as far north as Washington and as far east as Kansas and Texas

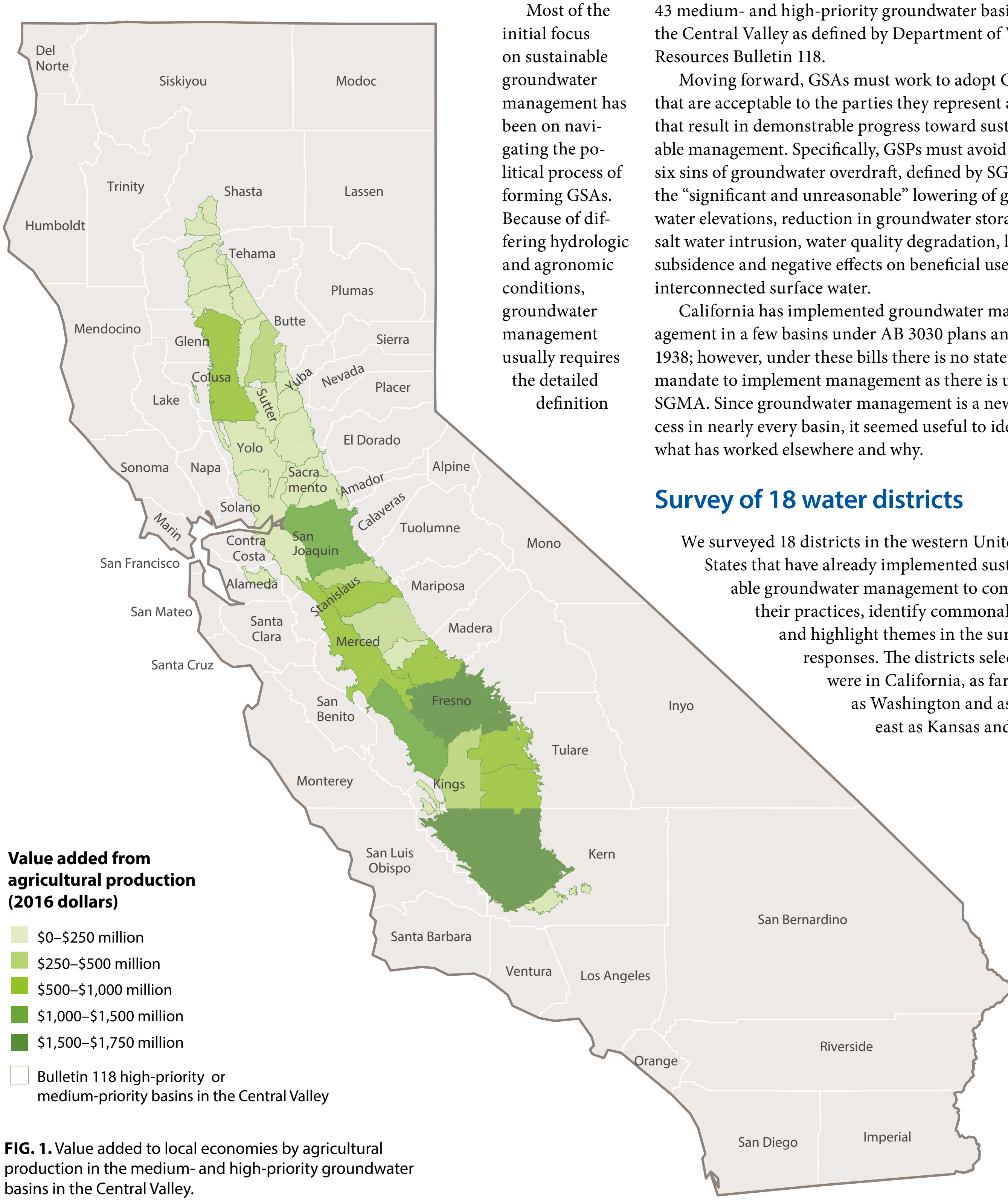

FIG. 1. Value added to local economies by agricultural production in the medium- and high-priority groundwater basins in the Central Valley.

FIG. 2. Locations of the 18 surveyed water districts.

(fig. 2). Table 1 shows the relevant characteristics of the 18 districts.

We interviewed district managers and reviewed groundwater management plans, agricultural water management plans and other district documents. We focused on five themes that we think are central to the operation of GSPs: (1) allocating the sustainable yield of the basin, (2) measuring and monitoring individual pumping, (3) setting the level and type of management fees charged, (4) setting the degree to which intertemporal and interspatial trading of pumping rights is permitted and (5) designing incentives to improve both distributed and concentrated recharge.

Allocating basin sustainable yield

The first important component of effective groundwater management is allocating the sustainable yield of the basin. This involves three tasks: (1) defining the sustainable yield and how it relates to the safe yield of the basin, (2) quantifying the basin sustainable yield and (3) allocating the sustainable yield across groundwater users.

Definition of sustainable yield

Before defining a basin's sustainable yield, we need to distinguish the subtle difference between sustainable and safe yield of a basin. The basin safe yield balances extraction with all sources of recharge; it's a simple measure of quantities. The basin sustainable yield is

TABLE 1. Characteristics and current practices of the 18 surveyed water districts

Water district	Groundwater rights	Metering	Fee structure	Trading permitted	Carryover permitted
Arizona Active Management Areas	Beneficial use	Varies	Varies by AMA	Yes	No
Big Bend Groundwater District #5: Central Kansas Water Banking Agency	Appropriation	Annual	Land and water assessment	Yes	Yes
Coachella Valley Water District	Beneficial use	Annual	Assessment surcharge	No	No
Deschutes Groundwater Mitigation Program	Appropriation	Annual	Mitigation costs	Yes	No
Edwards Aquifer Authority	Appropriation	Annual	User type fees	Yes	No
Fox Canyon Groundwater Management Agency	Irrigation allowance	Semiannual	Extraction and overallocation surcharge	No	Yes
Mojave Water Agency	Adjudicated	Quarterly	Overallocation fee	Yes	No
Monterey County Water Resources Agency	Beneficial use	Annual	N/A	No	No
Orange County Water District	Beneficial use	Monthly	Overallocation surcharge	No	No
Pajaro Valley Water Management Agency	Beneficial use	Annual	Varies by zone	No	No
Republican River Basin	Appropriation	Annual	Varies by district	Yes	Yes
Santa Clara Valley Water District	Beneficial use	Varies	Varies by zone	No	No
Twin Platte Natural Resources District	Appropriation	Annual	Per acre	Yes	Yes
United Water Conservation District	Beneficial use	Semiannual	Varies by zone	No	No
Upper Klamath Basin	Adjudicated	Annual	Per acre	No	No
Upper Republican Natural Resources District	Allocation per acre	Semiannual	N/A	Yes	Yes
Yakima Water Basin	Beneficial use	Annual	Per acre	No	No

Source: Primary survey by ERA Economics LLC.

defined in terms of the SGMA legislation (and corresponding regulations) as a yield from the basin that does not impose long-term economic or environmental costs to overlying basin residents. It may consider the rate of groundwater extraction, for example, if it might result in land subsidence or reductions of hydrologically associated stream flows or vernal pools. Both safe and sustainable yields are usually measured as the average over a 5- to 10-year period. In some situations, sustainable and safe yields will be the same, but in others sustainable yield will be lower than safe yield. All the 18 districts surveyed needed to define and allocate the basin sustainable yield.

Defining the sustainable yield of a basin is a hydrologic question that requires agreement on a water balance accounting based on a groundwater model that is accepted by a majority of a district's stakeholders. For example, in the Chino Basin the water balance is quantified by using a calibrated model of developed yield (net inflow into the basin) over 50 years that incorporates the Santa Ana River Underflow New Yield (SARUNY) to determine the net recharge to the basin (Wildermuth Environmental 2013). The groundwater model is used to make projections of currently developed yield and the future sustainable yield through production and replenishment based on expected hydrology. Getting all parties to agree to the water balance accounting is essential. In many basins in California, such as those in Kern County, which covers a large area and has multiple GSAs, achieving consensus will be a difficult task.

Sustainable yield can be defined for a single objective (e.g., to limit groundwater extraction) or for multiple objectives (e.g., to limit groundwater extraction, prevent saline water intrusion into the aquifer and maintain river flows, vernal pools or wetlands). For basins with multiple objectives and complicated hydrologic linkages between the environmental and economic components of groundwater management, the optimal rate of groundwater extraction is often dominated by environmental constraints; and more nuanced pumping rules are usually required, varying by time and location. For example, management of the basin in the Upper Republican Natural Resources District in Nebraska requires surveys of aquifer levels, water flows and interbasin transfers and conserving wildlife habitats across streams, reservoirs and wetlands.

Most of the critically overdrafted basins in California have deep groundwater tables, typically several hundred feet below the surface. Essentially this decouples the groundwater level from environmental outcomes (e.g., surface waters), except for subsidence. For basins without subsidence and environmental concerns, optimal groundwater management simplifies into an economic decision of the optimal depth at which to stabilize the aquifer. In these cases, the management usually requires matching the average pumping to the sustainable yield of the basin, which is approximately equal to the safe yield.

Quantification of sustainable yield

Quantification of a basin's sustainable yield is usually an iterative process over time. Nine of the 18 basin management agencies surveyed for this study have mechanisms for adjusting the sustainable yield. For example, the Chino Basin Watermaster reevaluates sustainable yield annually. The sustainable yield of a basin cannot be a static value because it is influenced by the recharge that is, in turn, changed by the overlying irrigated acreage, the crops grown and the irrigation technology. If water district managers are required to manage groundwater basins by reducing irrigation on the overlying land, the quantity of recharge from deep percolation will also be reduced, and thus the sustainable yield of the basin will decrease. That is, even without factoring in the effects of climate change, the sustainable yield of a basin is a moving target that must be adjusted over time. It follows that management rules should be designed to be equitable — and perceived as such — but also be subject to tuning as managers see how the biophysical system evolves.

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DWR staff members measure groundwater elevations using a handheld computer and electronic sounder at a well in Sutter County.

Another reason why sustainable yield cannot be a fixed value is that groundwater in the western United States acts as a reserve water supply for the inevitable dry years that characterize the regional climate. It is extremely valuable to have the capacity to overdraft groundwater during dry years. However, overusing groundwater in this way can lead to reduced pumping or an increased need for recharge in years with above-average rainfall. Effective management strategies allow for this trade-off over time, and for the sustainable yield of a basin to change over time.

Allocation of sustainable yield

Groundwater property rights affect the allocation of the basin sustainable yield. Our survey shows that eight of the 18 districts have groundwater rights based on beneficial use, five have appropriative groundwater rights, three are adjudicated and two use a per-irrigated acre allocation rule. The more complex allocation rules are found in parts of Nebraska and Colorado where the linkage of groundwater pumping to river flows must be clearly defined so that river flow standards are met over different water year types and locations. For example, on Colorado's Front Range, groundwater pumping linked to river flows is constrained by a time-varying criterion known as the run of the river.

Some basins have already defined extraction allocations in the form of adjudicated pumping quotas and pumping rules. If these allocations are not consistent with the sustainable yield standard established by SGMA, they will need to be modified accordingly. For basins with rights based on prior allocation, reductions in pumping to meet the sustainable yield are based on seniority of rights. However, this raises the question of whether prior appropriators have an absolute priority whereby adjustment costs to meet sustainable yield are inflicted on the lowest-priority pumpers first. An alternative method is to view the adjustments of groundwater appropriations as changes in shares of the sustainable yield, and assign the reduced pumping yield in proportion to the priority level so that the burden of adjustment is shared in proportion to the established priority levels.

Most of California's groundwater basin extractions are defined by the correlative rights doctrine, which allocates groundwater in proportion to the overlying land area regardless of prior use. For the surveyed basins that have groundwater pumping defined by beneficial use, groundwater rights are similar to correlative rights. Adaptation to a limited sustainable yield from the basin based on correlative rights seems to be the most equitable allocation in the long run. However, the allocation of correlative rights in California is complicated by those groundwater users who are extracting substantially more on average than their share of the basin sustainable yield, for example, agricultural users with recently developed permanent crop plantings that have inflexible water needs, and cities that rely on groundwater.

Given the per-acre water requirements of urban development in the Central Valley, cities are likely extracting more than their share of the sustainable yield based on the urban land area. Furthermore, they have often gone beyond their boundaries to seek groundwater extraction sites. Since cities do not have the same flexibility for use changes as agriculture, fair-share negotiations will be tense, with cities probably claiming a higher beneficial use and health and safety concerns for their extraction patterns. A rigid application of correlative rights under SGMA to cities and current over-appropriators is likely to invite strong opposition and excessive adjustment costs to some parties. These pumpers should be managed by a phase-in period under which their short-run grandfathered excess pumping allowances and long-run extraction quantities are clearly defined.

Monitoring groundwater extraction

The strongest common theme running through the survey is that every basin management district monitors groundwater pumping. The adage that you cannot manage what you cannot measure seems to hold true for groundwater management. Two methods of measuring extractions dominated the survey responses. Districts either use well meters or they estimate groundwater use based on the standard applied water requirements for crops grown in the region. Meters provide the best accuracy, and offer the possibility of wireless reporting, but the devices and installation are costly and direct metering can raise privacy objections from landowners. Crop-based groundwater

Drilling for groundwater in Yuba County. The authors' survey results suggest that a correlative rights approach, which assigns water shares by overlying land area, is the most equitable approach to allocate groundwater.

Kelly M. Grow, California Department of Water Resources

use estimates by zone, such as used in the Santa Clara basin, are less accurate and remove any incentives for improved water use technology. Groundwater use estimates based on aggregate basin measures are even less precise than those based on zones.

The frequency of monitoring reported from the surveyed districts varied over a range from annual, semiannual, quarterly and monthly. The decision on how frequently to monitor pumping is driven by the costs of using imprecise data. In Orange County, where saline intrusion is controlled by maintaining a freshwater mound, the cost of monthly monitoring is justified. The same precise monitoring would be required in basins where domestic water supplies, subsidence or linked river flows are of concern. In basins with low lateral conductivity rates, annual monitoring is sufficient.

Direct monitoring of groundwater extraction is potentially contentious. During the debate over SGMA in the Legislature, the requirement for compulsory groundwater management was supported by several groups, such as the Association of California Water Agencies and the California Water Foundation. However, farmers were united in their opposition to it, and the legislators from rural districts urged Governor Brown to veto it (Austin 2014). In our survey, we found that, because direct monitoring is unpalatable, some basin management districts provide exemptions to agriculture.

If the monitoring stays reasonably local and pumping measurements can be aggregated before they are transmitted to oversight agencies assessing regional compliance, so they don't reveal individual performance, monitoring may be less of a concern for most users. Even with local control, the perception, correctly, is that SGMA requires a shift from individual to collective decision making. Conflict resolution programs may ease the introduction of a GSP, but pushback over voluntary and mandatory groundwater well monitoring is to be expected (Theesfeld 2011).

One emerging option to estimate groundwater use at a low cost and on a consistent basis is to use satellite data on energy spectra reflected by a crop to estimate net evapotranspiration. Combining that information with data on applied surface water, type of irrigation system, and crop, the net use of groundwater can be calculated more precisely, removing human measurement error and self-reporting issues that are common to other approaches. Another advantage of remotely sensed metering is that it avoids the high capital cost of well meters and the implicit intrusion on private land.

For example, the Fox Canyon Groundwater Management Agency includes in its annual budget consultant contracts for meter and well inspections ($100,000), online support services ($43,000) and additional equipment ($2,000) to maintain the monitoring of wells. Additionally, a remotely sensed system, because it is automated, cannot discriminate across farms. Clearly, a satellite is both impartial and equitable in its measurements.

In Idaho, the satellite-based Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) system has been widely adopted; for example, it has been used to generate monthly and seasonal evapotranspiration (ET) maps predicting irrigation flows and basin recharge for the Snake Plain Aquifer (Allen et al. 2005). It is also being increasingly used in California and other states (Allen et al. 2005). However, none of the districts surveyed use remote sensing for estimating groundwater use.

Management approaches

As GSAs formulate their GSPs, the critical action will be how to select and implement one among the many groundwater management approaches. Our survey revealed supply-side management approaches and demand-side management approaches that include water trading and fees.

Supply-side mechanisms

Managing groundwater supply is the most popular approach, probably because it appeals to our past "build first and ask questions later" engineering traditions. Supply management is a command and control approach in which growers are forced to use less groundwater, additional recharge is supplied through imports of surface water, and changes in management approaches occur, such as stress irrigation and crop switching. However, there are limits to the effectiveness of this approach: for example, importing surface water may be possible, but it is typically expensive. In practice, there are limited opportunities for additional surface storage in California, thus limiting the effectiveness of stabilizing a basin through increased supplies.

Applying water to agricultural lands outside production seasons may provide additional basin percolation (O'Geen et al. 2015). However, it remains to be seen how much additional recharge can be achieved from flooding cropland in winter (Nelson 2015), and whether this strategy will cause negative agricultural production or environmental externalities. Browne and Micretich (1988) demonstrate the link between long flood durations and the development of crown rot for apples, and a recent article by Bostock et al. (2014) explores the susceptibility of plants to diseases after abiotic stresses including extended flooding.

The key questions for supply management approaches in California are the availability of additional surface water, and whether the benefits of supply augmentation justify the costs. The value of a distributed recharge source of water under SGMA may be high enough to challenge the profitability of field crops on coarse soils, which are prime soils for effective percolation. O'Geen et al. (2015) identify those areas in the Central Valley that have soils with hydraulic conductivities of over 300 millimeters per hour. Many of them are in continuity with underlying groundwater,

Coachella Valley Water District's Thomas E. Levy Groundwater Replenishment Facility percolates imported Colorado River water into the eastern subbasin of the Coachella Valley's aquifer, replenishing 40,000 acre-feet of water annually.

for example, the sandy-bottomed recharge basins in the Consolidated Irrigation District near Selma. The Kern Water Bank is similarly located on the alluvial fan soils of that river that were taken out of production. Of course, these high conductivity soil properties need to be combined with adequate surface supplies to result in effective and commercially viable artificial recharge systems.

Demand-side mechanisms

Demand management approaches may be a cheaper way to achieve a sustainable groundwater balance. They include water trading and other market programs and fee structures to incentivize growers to use water efficiently. Reallocating annual pumping allocations among users in the form of exchanges or trading pumping allocations within the basin takes place in seven of the 18 districts surveyed. The flexibility introduced from users being able to trade pumping allocations is particularly important during dry cycles.

Other districts, for example, the Coachella Valley Water District, charge large fees to disincentivize users from overpumping. The fees are applied not only to the amount that exceeds the entitlement, but to the entire quantity pumped for that reporting period, thus creating a significant incentive to remain within pumping allotments. Table 1 shows the very wide range of fee structures the districts use to manage groundwater. They can be summarized as flat use fees levied to offset the costs of running the district, fees based on the mitigation costs of supplementing groundwater recharge, and fees for different zones that reflect the differential impact on river flows or environmental systems.

A district may impose only fees for the administrative costs of running the district. They are substantial and can be divided into start-up and operating costs. Start-up costs fluctuate depending on administrative needs, the operation costs of the monitoring system, legal considerations, and any additional infrastructure. The operating costs for groundwater management include metering, monitoring, and establishing the annual sustainable yield.

Alternatively, fees can be used as a management tool for the mitigation of impacts, or replenishment of groundwater stocks by recharge or conservation. Eight of the 18 districts surveyed impose surcharge fees for overpumping or fees to cover replenishment costs. For California basins that are heavily overdrafted, replenishment fees to augment surface supplies or recharge groundwater aquifers will be critical.

Replenishment fees have been a successful and long-lasting management tool for the Orange County Water District. Early threats of seawater intrusion there stimulated heavy investment of these fees in water recycling systems and additional sources of surface water supplies for recharge purposes. Future management by replenishment fees is less likely in basins in the southern San Joaquin Valley. In these regions access to alternative surface water supplies to offset overdraft will be more limited in the future, given the flow modifications on the Lower San Joaquin River and its three eastside tributaries proposed by the California Water Resources Control Board (SWRCB 2012).

We anticipate that the fee structure necessary for California sustainable groundwater management will include a fixed fee for basin administration and fees for replenishment when pumping above the sustainable yield occurs. The replenishment fees will vary by year and location, but they should be consistent with California's Proposition 218 that requires that additional fees must reflect the cost of providing additional service.

Table 2 summarizes the fees levied by the 18 surveyed districts. Pajaro Valley Water Management Agency, Santa Clara Valley Water District and United Water Conservation District charge growers according to the volumetric amount of water they pump. Fox Canyon Groundwater Management Agency and other districts focus on incentivizing growers to stay within their allocation by levying minimal extraction and administration fees and expensive surcharges for exceeding allocations. The relative costs to the growers in these 18 districts are highly variable, based on district priorities, management system and enforcement policies.

Economic stability, trading and carryovers

SGMA regulations are vague in defining groundwater sustainability objectives, and what constitutes a "significant and undesirable" outcome is left largely up to the GSAs to determine. Our observation is that, so far, most water managers and experts are focusing on environmental criteria and stabilizing pumping around a historical average as the way to avoid the six sins of SGMA. An economist might convincingly argue that socioeconomic outcomes for affected parties, such as agriculture, should be factored into sustainability criteria.

Groundwater and the economy

Agriculture is a dominant share of the economy in many regions causing employment, income growth, and local taxes to be directly linked with the value of agricultural output. We estimate the gross value of agricultural production in each basin by combining statewide cropping data within basin boundaries and 2014 U.S. Department of Agriculture National Agricultural Statistics Service prices and yields in a basin-level economic model. We then applied a value-added multiplier from the Impacts from Planning Analysis (IMPLAN v3.1) model to identify the total value added (total change from benefits and costs) in each basin from the agriculture industry. Figure 1 shows that irrigated agriculture is a dominant share of the local economy across the medium- and high-priority Central Valley basins, generating $250 million to $1.75 billion of value added.

In total, agricultural production in these basins, excluding processing and manufacturing, contributes

TABLE 2. The 18 surveyed water districts, main crops, and fee structures

District	Crops	Administrative fee	Water fee	Replenishment fee
Arizona Active Management Areas	Cattle, cotton, vegetables	Phoenix: $45/AF Pinal: $45/AF Tucson: $45/AF	Phoenix: $294/AF Pinal: $294/AF Tucson: $294/AF	Phoenix: $246/AF Pinal: $225/AF Tucson: $276/AF
Big Bend Groundwater District #5: Central Kansas Water Banking Agency	Wheat, corn, cattle	Land assessment: $0.05/acre	Water assessment: $0.67/AF	N/A
Chino Basin Watermaster	Ornamentals, root vegetables, bedding plants	Appropriative: $41.96/AF Agriculture: $22.04/AF	Appropriative: $15.59/AF Agriculture: $8.19/AF	$519–$611/AF
Coachella Valley Water District	Grapes, bell peppers, lemons	Included in water fee	Water rate: $33.48/AF	West Whitewater River Subbasin: $128.8/AF Mission Creek Subbasin: $123.3/AF East Whitewater River Subbasin: $66.00/AF
Deschutes Groundwater Mitigation Program	Potatoes, seed crops, alfalfa	Water right: $280	Per acre of land: $2 Surface water substitution: $725	Temporary mitigation credit: $70–$150/acre Permanent mitigation credit: $2,000:5.000/acre
Edwards Aquifer Authority	Livestock, sorghum wheat	Included in water fee	Agricultural: $2/AF M&I: $36–$116/AF	Overallocation surcharge: $84/AF
Fox Canyon Groundwater Management Agency	Strawberries, celery, raspberries	Sustainability fee: $4/AF	Extraction fee: $6/AF Unmetered extraction fee: $12/AF	Exceeding allocation surcharge: Tier 1: $1,315/AF Tier 2: $1,565/AF Tier 3: $1,815 AF
Mojave Water Agency	Alfalfa, pasture, orchards	N/A	N/A	Overallocation fee: $484/AF
Monterey County Water Resources Agency	Strawberries, broccoli, celery	Administrative fee: $2.23–$8.98/acre	N/A	N/A
Orange County Water District	Strawberries, oranges, ornamentals	Included in water fee	Basin equity assessment: $80/AF	Overallocation fee: $322/AF
Pajaro Valley Water Management Agency	Strawberries, artichokes, broccoli	Included in water fee	Outside delivered water zone (DWZ): $203/AF Inside DWZ: $258/AF Unmetered: $184/AF Delivered water charge: $359/AF	N/A
Republican River Basin	Corn, wheat, soybeans	Varies by district	Varies by district	Varies by district
Santa Clara Valley Water District	Nursery crops, mushrooms, wine grapes	Included in water fee	Zone W:2 agricultural use: $21.36/AF nonagricultural use: $894/AF Zone W:5 agricultural use: $21.36/AF nonagricultural use: $356/AF	N/A
Twin Platte Natural Resources District	Alfalfa, beans, corn, wheat	Included in water fee	Levy taxes up to $100/acre	N/A
United Water Conservation District	Alfalfa, pasture, orchards	Included in water fee	$40–$150/AF	N/A
Upper Klamath Basin	Cereal grains, alfalfa, potatoes	Included in water fee	Operational fee: $66–$100/acre	N/A
Upper Republican Natural Resources District	Cattle, grain, wheat	Levied in taxes	N/A	N/A
Yakima Water District	Hops, pears, cherries	New permit: $50–$25,000	N/A	N/A

over $14 billion in value added to the regional economy. Note that value added is a measure of net economic activity and is consequently less than the gross value of production in these regions. Groundwater represents a significant share of the total water use that supports the industry. Rigid groundwater management approaches that significantly reduce irrigation water supply in these areas will result in significant and undesirable economic outcomes for these regions, violating a fundamental rule of sustainable groundwater management.

Implementation of SGMA will substantially increase the value of recharged groundwater, and that value should be credited to the irrigator responsible. For example, growers of flood-irrigated alfalfa, which can generate substantial deep percolation without any nitrate leaching, should be allocated recharge credits.

Trading allocations

Many basins limit trading of groundwater pumping allocations among users to prevent the concentration of pumping in one location. Excessive pumping in an area may cause a significant cone of depression, imposing additional costs on nearby wells, and potentially increasing subsidence or other environmental damage. Pfeiffer and Lin (2012), in their empirical analysis of groundwater spatial interdependencies in Kansas, found evidence of spatial externalities between local pumpers, where the cost of dropping groundwater levels caused by an individual is spread across many neighbors in the basin. Since an individual pumper gains all of the benefits of overdrafting but bears only a fraction of the cost, pumpers rationally overextract water compared to the optimal basinwide extraction rate. The sensitivity of a given groundwater basin to this effect is a function of several different hydrologic parameters.

Hydrologic considerations, however, are unlikely to dominate over the political and equity considerations of allowing trading among users. Orange County Water District, for instance, has good replenishment supplies and an effective, but unusual, groundwater management approach. There are no restrictions on groundwater pumping, however fees vary and are based on the current cost of replenishing the groundwater supply. Replenishment fees also differ spatially with discounts to surface water costs in regions near the coast. This provides an incentive to maintain the freshwater mound that prevents sea water intrusion that would degrade water quality in the basin.

Carryover rights

An important role of groundwater in California agriculture is to offset the hydrologic cycles of our Mediterranean climate and provide some stability in irrigation water supply during dry years. Allowing individual pumpers to carry over groundwater pumping rights between years is a natural way of providing this flexibility of water supply that is required for growing perennial crops in the California climate. However, 13 of the 18 districts surveyed did not allow any carryover of pumping rights between years, primarily to avoid excessive pumping in drought years. One district, the Twin Platte Natural Resources District, does not restrict carryover trades. The reason may be that this district has deployed an automated trading program that reduces trading costs and facilitates trades among willing farmers. Four districts allowed carryover for a limited number of years (usually 1 to 3). These short carryover periods may not work as a drought compensation mechanism in California. Major California droughts seem to occur about every seven years so a longer carryover period may be required to enable the use of groundwater as an effective drought reserve.

Initial studies show that in the San Joaquin Valley, current average annual overdraft represents between 0% and 24% of total water supplies, depending on location (Howitt et al. 2015). Clearly, the ability to recharge the existing groundwater basins is integral to the successful management of the basins.

Incentivizing recharge credits

In California, deep percolation from irrigated agriculture is an important part of the natural recharge of groundwater, and in some cases it equals or exceeds the natural recharge from other precipitation and subsurface flows. In many cases, then, a successful GSP will need to incentivize optimal recharge, whether it occurs from artificial spreading ponds or from deep percolation as a byproduct of existing irrigated agriculture.

The need to maintain a distributed source of recharge from irrigated agriculture may result in reassessing the concept of irrigation efficiency. Irrigation efficiency is measured as the ratio of water evapotranspired by the plant to the applied irrigation water. This definition ignores the value of deep percolated water and encourages its reduction. Ward and Pulido-Velazquez (2008) and Qureshi et al. (2010) have analyzed the negative effects of water conservation on the amount of water available downstream in the Rio Grande and in Australia's Murray–Darling Basin, respectively.

Implementation of SGMA will substantially increase the value of recharged groundwater, and that added value should be credited to the irrigator responsible. For example, growers of flood-irrigated alfalfa, which can generate substantial deep percolation without any nitrate leaching, should be allocated recharge credits. Rather than being stigmatized as inefficient irrigation, flood irrigation could be credited as an efficient source of recharge.

In addition, water banking systems for the intentional recharge of imported surface water are not part of the natural hydrology of the basin, and therefore should not be included in the sustainable yield calculations or the annual allocations. In some locations, the natural recharge is practically nil due to soils and geology (e.g., in confined aquifers where horizontal flow is the dominant source of extractable groundwater). GSAs in such areas would need to partner with GSAs with recharge credits. For the GSAs with credits, some of their water would be assigned to meet their portion of annual natural recharge and any excess, net of losses, would become transferable to other GSAs on an annual basis. The accounting and management systems required would be complex.

In our survey of 18 districts, we found no formal requirements for measuring an individual user's contribution to recharge and no examples of incentives for an individual user to increase or maintain high levels of recharge to the groundwater basin. We envisage that effective recharge incentives for individual users would be provided by a system of net metering of groundwater use similar to the system that incentivizes individual solar energy generation. Using information on irrigation technology and crops grown, recharge credits could be calculated as part of net metering. The GSA would maintain for each user a groundwater escrow account that considered both withdrawals from and contributions to the groundwater basin.

Our conclusions, what applies in California

The most contentious decision for each GSA contemplating a GSP is likely to be the method used to allocate the basin sustainable yield among members. Phase-in periods will be important, but in the long-run a correlative rights approach that allocates water share by overlying land area seems to be the most equitable.

The second conclusion we draw from the survey is that pumping must be metered — either directly with meters and crop coefficients, or indirectly through remote sensing — for effective groundwater management. It is not possible to manage groundwater without knowing how much is used.

The third conclusion focuses on the important role groundwater plays in California in balancing inherently variable surface water supplies. Due to climate and crop differences, it follows that groundwater management rules in California should have more flexibility over both time and space than the rules adopted by most established Western water systems. Finally, because of the importance of deep percolation from crops as a source of groundwater recharge, we need a management system that will incentivize recharge on a distributed basis.

Given the common property nature of groundwater, where the costs of an individual's overpumping are spread across all pumpers in the basin, it is natural to find that unmanaged basins are overexploited. Since the primary goal of groundwater management is to end this overexploitation and stabilize the average depth of each basin, assessing how groundwater management has been addressed in other regions will provide a background of approaches that can help GSAs form their GSPs. CA

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References

Allen RG, Tasumi M, Morse A, Trezza R. 2005. A Landsat-based energy balance and evapotranspiration model in Western US water rights regulation and planning. Irrig Drain Syst 19(3–4):251–68.

Austin C. 2014. Reactions: Legislators and organizations respond to the passage of groundwater legislation. August 30, 2014. Maven's Notebook. http://mavensnotebook.com/2014/08/30/reactions-legislators-and-organizations-respond-to-the-passage-of-groundwater-legislation/.

Bostock RM, Pye MF, Roubtsova TV. 2014. Predisposition in plant disease: Exploiting the nexus in abiotic and biotic stress perception and response. Annu Rev Phytopathol 52:517–49.

Browne GT, Micretich M. 1988. Effects of flood duration on the development of Phytophthora and crown rots of apples. Phytopathology 78(6):846–51.

[DWR] California Department of Water Resources. 2016a. Groundwater Information Center. Key legislation. www.water.ca.gov/groundwater/groundwater_management/legislation.cfm (accessed July 15, 2016).

DWR. 2016b. California Statewide Groundwater Elevation Monitoring (CASGEM). www.water.ca.gov/groundwater/casgem/overview.cfm (accessed Nov. 10, 2016).

Howitt RE, MacEwan DM, Medellín-Azuara J, et al. 2015. Economic Analysis of the 2015 Drought for California Agriculture. Center for Watershed Sciences, University of California, Davis. 31 p.

Nelson D. 2015. Flooding farms in the winter may help replenish groundwater. UC Davis News & Information. www.ucdavis.edu/news/flooding-farms-winter-may-help-replenish-groundwater/ (accessed April 10, 2017).

O'Geen AT, Saal M, Dahlke H, et al. 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. Calif Agr 69(2):75–84. https://doi.org/10.3733/ca.v069n02p75 (accessed April 10, 2017).

Pfeiffer L, Lin C-YC. 2012. Groundwater pumping and spatial externalities in agriculture. J Environ Econ Manag 64(1):16–30.

Qureshi MEM, Whittem A, Kirby M. 2010. A multi-period positive mathematical programming approach for assessing economic impact of drought in the Murray Darling Basin, Australia. 56th AARES Annual Conference, Feb. 7-11, 2012. Fremantle, WA.

[SWRCB] California State Water Resources Control Board. 2012. Evaluation of San Joaquin River Flow and Southern Delta Water Quality Objectives and Implementation. Appendix F.2. In: Substitute Environmental Document in Support of Potential Changes to the Water Quality Control Plan for the San Francisco Bay-Sacramento/San Joaquin Delta Estuary: San Joaquin River Flows and Southern Delta Water Quality. December 2012. ICF 00427.11.

Theesfeld I. 2011. Perceived power resources in situations of collective action. Water Altern 4(1): 86–103.

Ward F, Pulido-Velazquez M. 2008. Water conservation in irrigation can increase water use. P Natl Acad Sci USA105(47):18215–20.

Wildermuth Environmental. 2013. 2013 Chino Basin Groundwater Model Update and Analysis of Safe yield. www.cbwm.org/FTP/Safe%20Yield%20Reset/20130829%20Workshop%20%232/20130829%20Safe%20Yield%20Recalculation%20Workshop%20No.%202%20Presentation%20(WEI).pdf (accessed April 3, 2016). Lake Forest, CA: Wildermuth Environmental, Inc. 74 p.

RESEARCH ARTICLE

Farmers share their perspectives on California water management and the Sustainable Groundwater Management Act

Focus groups with Yolo County farmers demonstrate that farmers' perceptions of and responses to the regulation are important to its success.

by Meredith T. Niles and Courtney Hammond Wagner

Abstract

Agriculture is the largest human use of water in California, which gives farmers a critical role in managing water to meet the goals of the Sustainable Groundwater Management Act (SGMA). To explore farmers' perspectives on SGMA, we held focus groups with 20 farmers in Yolo County, where the groundwater basin has been given a high/medium priority under SGMA. The farmers had varying perspectives about the factors that led to SGMA and varying responses to the regulation. They suggested that drought, competing agricultural and urban uses, and an increase in perennial crops were factors in recent water use, resulting in changes to water quality and quantity. Impacts of those changes included variable well levels, increased infrastructure costs, and ecosystem impacts, which farmers had responded to by implementing multiple management strategies. Additional research in other regions is imperative to provide farmers' viewpoints and strategies to policymakers, irrigation districts, farmer cooperatives, and the agricultural industry and give farmers a voice at the table.

In 2014, the California legislature passed the Sustainable Groundwater Management Act (SGMA), the state's effort to achieve the sustainable use and management of groundwater by 2040. The act requires the establishment of local and regional governance structures, known as groundwater sustainability agencies (GSAs), to develop and implement groundwater sustainability plans (GSPs) by 2022. The legislation sent into action a process in which, basin by basin, local communities are identifying who they would like to govern groundwater (GSA formation) and how they would like groundwater to be governed (GSP development).

The role of farmers is critical in achieving water sustainability because agriculture is the largest human use of water in the state, especially of groundwater in

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Groundwater pump and filtration equipment sit adjacent to a tomato field in Yolo County.

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dry years (CA DWR 2014). Agricultural production in California surpassed $20 billion in 2016, with California farmers producing more than 400 commodities (CDFA 2016). Much of the state's agricultural production feeds a global population, with 44% exported out of the state, representing 15.6% of total U.S. agricultural exports (CDFA 2016). Agricultural production relies on both surface water and groundwater, depending on farm location and water access.

At this early stage, much remains to be seen in terms of how the SGMA will be interpreted and implemented locally. Thus far, the process has primarily revolved around the forming of the GSAs. The deadline for that was June 30, 2017, for the 127 medium- and high-priority basins; low- and very-low priority basins are encouraged, though not required, to form a GSA and write a GSP (Water Education Foundation 2015). Recent research from Conrad et al. (2016) highlights through case studies, based on interviews with regional stakeholders, that GSA formation looked very different from region to region.

Kiparsky (2016) suggests that a number of the unanswered questions on SGMA implementation revolve around the social acceptance of policy definitions and mechanisms by different groundwater users. Social acceptance issues involve users' perceptions of fairness, efficacy and other value-based dimensions that can raise tensions and lack clear, unambiguous solutions. Social acceptance is likely to become increasingly important as the emphasis now shifts to writing GSPs, which must include measurable objectives and detailed planning for achieving sustainable groundwater use within 20 years. The deadline for completing the GSPs is Jan. 31, 2020, for critically overdrafted basins and Jan. 31, 2022, for the remaining medium- and high-priority basins (Water Education Foundation 2015).

Despite the significance of farmers in the SGMA process, only a little empirical research has examined their perceptions of SGMA implementation, which may be of critical importance for the functioning of GSAs and the implementation of GSPs. In a snapshot of three farmers' perspectives on SGMA, Rudnick et al. (2016) brought attention to the burden different farm sizes and systems may face under the new regulation and called for better understanding of stakeholder needs to facilitate the SGMA process.

To help fill the gap in empirical literature, we collected the perspectives of farmers in Yolo County, California. Our work presents an early view of their perspectives on the factors that influence water availability and management and of the approaches they propose for SGMA implementation. With a groundwater basin that has been categorized under SGMA as high/medium priority, Yolo County provides an opportunity to examine the GSA process in context. Located on alluvial plains in the Sacramento Valley region of the Northern Central Valley, it supports vibrant and diverse agricultural production, including rice, cattle grazed in summer-dry grasslands and savannas, and perennial, vegetable, and row crops (Jackson et al. 2012; Niles et al. 2013). In 2015, the top 10 commodities in Yolo County (by dollar amount) were processing tomatoes, almonds, wine grapes, organic production, walnuts, sunflower seed, rice, alfalfa hay, cattle and nursery products. The county had more than 90 direct export partners, indicating its importance in a global agricultural system (Yolo County 2016). Of the 653,449 acres in the county, 531,902 (81%) are agricultural land, including grazing land (CA DOC 2015).

To explore farmers' perceptions, we used the drivers, pressures, states, impacts and responses (DPSIR) framework (Kristensen 2004). In particular, we asked for farmers' perspectives on (1) drivers of recent water use, (2) pressures current water users faced, (3) changes in the state of water, (4) impacts of these changes and (5) responses they had implemented and how they wanted SGMA implementation to be designed.


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The Sustainable Groundwater Management Act mandates the formation of basin-level agencies charged with achieving sustainable groundwater management by 2040.

Focus groups

Focus groups took place in October 2016 in Yolo County. With assistance from the Yolo County Flood Control and Conservation District, we used an organizational recruitment strategy, relying on the district as a key stakeholder in the GSA process with significant local connections to identify and recruit farmer participants (Krueger and Casey 2015). Farmers were selected to represent a diversity of different farm systems (conventional, organic, small, medium and large, different irrigation technologies, mix of surface water and groundwater) and agricultural products (diversified vegetable production, tree nuts, fruit, olives, row crops such as corn and alfalfa, rice, animal production).

We designed 10 questions (see technical appendix, ucanr.edu/u.cfm?id=184) for the focus groups and recruited 20 farmers into four focus groups (four to six farmers per group). Focus groups were audio recorded, and the recordings were professionally transcribed to facilitate analysis. Using the framework approach for qualitative research (Ritchie and Lewis 2003), we drew upon the DPSIR framework (Kristensen 2004) and coded using NVivo qualitative data analysis software (version 10, QSR International Pty Ltd, Melbourne, Australia). We organized a set of codes (see technical appendix) into emergent categories. Then, using a systematic approach, we double-coded transcripts using the framework categories and assessed coding agreement. Overall coding agreement for all categories and all focus groups was 95%; researchers discussed coding disagreements and recategorized as necessary. Results presented here represent dominant themes in the analysis, grouped by DPSIR codes and subcodes (table 1).

Drivers of water use

Farmers stated that both agricultural and nonagricultural uses are important drivers of water use in Yolo County and California. Agricultural water uses stem from a diversity of farm sizes, cropping patterns and livestock types. Despite agriculture's long history in the region, many farmers reported that new drivers are changing the landscape, including an increase in permanent crops, urbanization and new agricultural development of previously uncultivated areas.

Most farmers reported using a mix of surface water and groundwater, although in certain parts of the region (e.g., Zamora) farmers have access to only groundwater. Farmers expressed that there had been an increasing reliance on groundwater irrigation, driven by drought in the past several years and new agricultural development, which was served by new wells and the lowering of existing wells. As one farmer said,

> *We have a classic tragedy of the commons when you have groundwater down there, and we can't all pump, pump and pump forever.*

Pressures water users face

Most farmers expressed that land-use change and irrigation technologies were exerting pressure on groundwater. In particular, farmers felt that the price of almonds was driving agricultural development in Yolo County, and developers with access to capital were planting permanent crops in new areas and drilling deep wells. One farmer said,

> *I actually call this California's second gold rush, because everyone is so driven by that shining gold — that in this case is a nut.*

Some farmers said that developers were in many cases developing marginal land with highly erodible soil, which might result in unexpected development impacts. Some farmers who had been in Yolo County prior to the recent agricultural development stated they did not believe they could compete with the rising costs of land and with developers. There was a sense amongst many focus group participants that nonlocals did not have the same sense of stewardship or responsibility.

Many farmers expressed that the increase in orchards had put drip irrigation on lands that were previously unirrigated. Some of these farmers felt that drip might not be decreasing overall water use as expected, because it had facilitated this new development and did not allow for the capture and reuse of tailwater. However, other farmers acknowledged that drip was increasing yields, which meant that less water was producing more food overall, though the systems were expensive. Farmers are also using furrow and flood irrigation technology in the county.

TABLE 1. Drivers, pressures, states, impacts and responses identified by Yolo County farmers for sustainable groundwater management

Drivers	Pressures	States	Impacts	Responses
Agricultural • Diverse land uses • Drilling new wells, new irrigated lands • Permanent crops in new areas **Nonagricultural** • Urban areas and domestic use **Water source** • Mix of surface water and groundwater (only groundwater in some areas) • Reduced surface water allocations, typically from drought, increasing reliance on groundwater	**Development** • Outside developers converting land and drilling deep wells • Irrigation and perennial crops on highly erodible ground **Irrigation technologies** • Drip increasingly common • Furrow and flood still used	**Water quantity** • Less water leaves fields now • Even if reservoirs are full, farmers may not get water • Uncertainty in groundwater levels and flow **Water quality** • Salts • Boron **Soil quality** • Subsidence • Boron and salts in soil	**Access to water** • Well levels have varied, but generally held up • Drip irrigation has allowed for agricultural expansion • Wells positively affected when surface water is available **Economic** • Costly to pump • Significant investment in water infrastructure • Land values increasing **Ecosystem** • Efficient irrigation is decreasing water for habitat • Competition for water between fish, farms and waterfowl	**Farm management** • Crop insurance • Fallowing land • Changing crops • Purchasing water • Monitoring wells • Digging new wells **Regulation** • Competing regulations from different agencies • Support for Yolo County Flood Control and Water Conservation District

State of water quality and quantity

Farmers perceived these drivers and pressures to be affecting the state of water quality and quantity. New development of orchards and wells were taking place in erodible areas and subsidence was evident in regions that relied exclusively on groundwater for irrigation. Because of the transition by many to drip irrigation, farmers felt that less water leaves their fields now for use by downstream users or groundwater recharge. Also, farmers said that soil salts (i.e., increased soil salinity) and boron in the irrigation water were quality issues. Boron in the water was an issue in parts of the county, especially because of its toxicity in trees (Nable et al. 1997).

Farmers expressed that surface water was often challenging to pump and filter because of sediments and algae; they suggested cleaner surface water might alleviate pressures on groundwater. Surface water availability in the county ebbed and flowed, and farmers acknowledged that one rain event could change a whole season. However, sometimes even when lakes and dams were full, farmers, especially those near the Sacramento River, couldn't get access to surface water, which might occur when water was prioritized for environmental use and became unavailable to agriculture.

Impacts of water changes

Farmers reported the impact of the water quantity and quality changes on access to water, economic returns and the functioning of local ecosystems. Farmers felt that increases in irrigation efficiency with drip irrigation had allowed for agricultural expansion in the county. With respect to water quantity, recent good rain years had led to better water availability; however, some farmers felt surface water availability for agriculture was inconsistent even in wet years. When surface water was available, farmers reported that groundwater wells were positively affected. Most farmers expressed the opinion that groundwater use should be second to surface water use. While some farmers had dug deeper wells in recent years, others reflected that many wells had remained productive. New and deeper wells had also negatively affected some domestic wells. Given recent changes to water availability and shortages statewide, a small number of farmers were pumping groundwater to send south or trade out of the county.

According to farmers, water quantity changes had also had economic and ecosystem impacts. Water was very expensive to pump, and too costly to let run off their fields, so farmers have been making significant investments in water infrastructure. Land was becoming a new limited resource in the county due to rising costs, which resulted in increasing land values. If farmers fallowed land because of lack of water, they believed the economic impacts to farming would reverberate across the county through dwindling income in support industries and other businesses and less demand for farmworkers. In terms of ecosystem impacts, many farmers mentioned that the lack of water had negative effects on habitat, fish and waterfowl (particularly because farmers had less access to water to create habitat) and that springs in the county were drying up. Farmers reported that increases in irrigation efficiency also result in less water for habitat.

Farmers' responses, strategies

Farmers said that a number of strategies had been used to respond to a lack of water, including buying crop insurance, fallowing land, growing crops that used less water, purchasing water, cover cropping, monitoring wells and digging new wells. Farmers mentioned that they were also responding to a range of other policy demands that affect agriculture.

Many expressed the perception that regulations were often a greater challenge than drought. Agencies had competing issues, which, according to farmers, resulted in heavy regulatory burdens for managing water, species and other environmental resources. One farmer said,

> *Well, I've become a resource manager, that's really what my job has boiled down to. So now I'm just a resource manager. I manage land resources, and water, and that's what I really do now.*

While farmers voiced frustration at heavy regulatory burdens, they also expressed support for the work and initiative taken by Yolo County Flood Control and Water Conservation District in working with them to manage water quantity and quality challenges.

Perspectives on SGMA

Farmers expressed a range of perspectives on the SGMA process (table 2). We grouped their opinions

Some farmers in the study expressed concern about an increase in high-value orchard crops in previously uncultivated areas, which they felt had increased overall water application in the region and contributed to increases in the price of agricultural land.

Phil Hogan, USDA NRCS

TABLE 2. Yolo County farmers' perspectives on SGMA

SGMA regulatory design	Definition of sustainability	Potential policy mechanisms	Farmer involvement
• Common sense • Locally relevant • Farmer involvement • Solutions oriented • Science of groundwater informed by farmer experience	• Capture and reuse • Transfers • Reasonable use	• Prioritize surface water over groundwater use • Drilling moratorium • Limit development • Incentives for farmers • Water trading • Investment in infrastructure	• Opportunity through districts • Involvement is critical • Lack representation in decisions

into four categories: regulatory design, defining sustainability, potential policy mechanisms, and farmer involvement.

Regulatory design

At the time of the focus groups, a GSA was forming in Yolo County. Farmers said that they would like to see a common sense design for SMGA, meaning that SGMA needed to make sense on the ground, not just on paper, with a long-term perspective for sustainable water use and a sustainable agricultural industry. One farmer reflected on the SGMA process and the future:

> *I would say, I have both hope and fear of SGMA. My hope is that some logic and common sense prevails in coming up with how things work and that the result of that will … produce [a] sustainable environment that enhances farming in Yolo County for decades to come. My fear is that the result will not be that! And my fear is that farming in California could be severally impacted in ways that will change the state as we really know it.*

Farmers also mentioned that they would prefer to see bottom-up processes, but they already felt written out of the process because they could not officially be part of the GSA. They suggested that there was not a one-size-fits-all solution to groundwater management in the state, so a focus on local context and needs was important.

Farmers expressed that they would like SGMA to take a solutions-oriented approach, integrating development and efficiency improvements. However, they acknowledged that the success of SGMA might be a challenge because it was difficult to regulate stewardship. Farmers also mentioned that SGMA success might require a new paradigm of water rights and water-use priorities. Finally, many said that sustainable management of groundwater required a better understanding of the groundwater systems in the county, which should include farmer intuition and experience combined with science.

Defining sustainability

SGMA seeks to create sustainable groundwater management for California. For farmers, sustainability has multiple meanings. As one farmer stated,

> *It's present. It's real. And whether we address it ourselves or — it will get addressed somehow. I mean, if we don't come up with something sustainable, then someone will for us. And we may like that even less.*

Farmers expressed that sustainable groundwater use involved thinking beyond single use to water capture, reuse, and transfer between users, and it involved emphasizing reasonable use and water balance. This could mean, as some suggested, a recognition that not all water uses are equal — for example, water use for food production and water use for lawns. Most farmers also suggested that the current planting of perennial crops on previously nonirrigated land in the county was most likely unsustainable and would be more so in the long term as trees matured. Finally, some farmers felt that sustainable groundwater use needed to be achieved much sooner than 2040.

Potential policy mechanisms

Farmers suggested a number of potential mechanisms for GSPs under SGMA. The sustainable groundwater plans could encourage the use of surface water over groundwater. The availability of cleaner surface water for irrigation use was one change farmers suggested could aid in facilitating the prioritization of surface water use over groundwater. Some farmers also mentioned that a change in electricity contracts, such as removing the contractual obligation to pump groundwater when surface water was available, could help farmers transition away from groundwater reliance.

Some farmers mentioned the potential of a drilling moratorium, but opinions on that were mixed. Some farmers saw it as a threat to their farm business; others saw it as a necessity to control developers from outside the county who were coming in and drilling new wells on marginal lands:

> *I'm not sitting here saying I want government in my life. I don't. But I also want water in the long term. And if it takes a little government regulation to force everyone to participate, as they well should … (then) it might take some of that.*

An alternative option was control mechanisms for overdrafting wells. Additionally, some farmers expressed that there could be restrictions on new acreage in water-intensive crops like almonds. Similarly, some farmers mentioned that new developments could require some type of cost-benefit analysis or environmental impact assessment.

Farmers suggested that payments to farmers for saving water or some other acknowledgment of farmers' efforts to conserve groundwater, such as signs that identify a farm as a "good steward", as potential policy mechanisms. Some farmers also mentioned intra-county water exchange and trading. With water trading, there was fear expressed that cap and trade could turn into pay-to-play, with larger developers controlling water.

Finally, farmers enthusiastically supported infrastructure solutions to groundwater management. These included upgrades to existing infrastructure and new dams, pipes, winter storage and increased gate automation. Farmers wanted to see funding for local infrastructure projects through SGMA. However, farmers expressed that funding in the past for infrastructure improvements had been difficult to acquire because of regulatory red tape. One farmer said,

> *I think we can engineer our way out of a lot of problems, but then it becomes a money problem.*

Farmer involvement

Farmers saw themselves as important participants in the sustainable management of water. They anticipated that the transition to countywide sustainable use would be a painful process for farmers. They also expressed that it was imperative to be proactive and involved. One farmer said,

> *I don't want to get the state involved. I think that's why we need to be very proactive as locals to make it happen and to bring all the parts together.*

Farmers felt they were able to participate in the SGMA process through irrigation districts and with Farm Bureau representation. However, they felt outnumbered in the decision-making process. Most representatives were from cities or boards of irrigation districts that did not have a lot of farmer representation. They saw that as a real concern with consequences for their businesses. They suggested if someone was going to create a policy, farmers should be a key part of the process.

Agriculture's voice at the table

Our results demonstrate that farmers, even within one county in California, have varying perspectives about the factors that led to SGMA and varying responses to the regulation. Nevertheless, some key themes emerged — farmers acknowledged the role of agriculture in sustainable surface water and groundwater management and recognized that many strategies may be necessary across different actors to achieve sustainable water management. To our knowledge, this study is the first to detail farmer perceptions of sustainable water management and SGMA policy preferences and implementation using empirical research. As such, it is an important contribution to understanding farmer viewpoints necessary for policymakers, irrigation districts, farmer cooperatives, and the agricultural industry.

However, this study is limited in its geographic scope, which means it may not be representative of other California regions or all farmers. Given the potential for SGMA to transform water management in California, and the implications that such transformations could have for the agriculture industry, we think it is imperative that additional research — including interviews, focus groups and large-scale surveys — across multiple California regions explore the role of farmers in the GSA and GSP process, and document their behaviors and perspectives. This research could help ensure that one of the key players for water management — California agriculture — has a role in the process and a voice at the table. CA

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References

[CA DOC] California Department of Conservation. 2015. Farmland Mapping and Monitoring Program: Yolo County Important Farmland Data Availability. www.conservation.ca.gov/dlrp/fmmp/Pages/Yolo.aspx

[CA DWR] California Department of Water Resources. 2014. California Water Plan Update 2013. Sacramento, CA. www.water.ca.gov/waterplan/cwpu2013/final/index.cfm

[CDFA] California Department of Food and Agriculture. 2016. California Agricultural Statistics Review 2015-2016. Sacramento, CA. www.cdfa.ca.gov/statistics/PDFs/2016Report.pdf

Conrad E, Martinez J, Moran T, et al. 2016. To Consolidate or Coordinate? Status of the Formation of Groundwater Sustainability Agencies in California. Stanford University. http://waterinthewest.stanford.edu/sites/default/files/GSA-Formation-Report_1.pdf

Jackson L, Haden VR, Hollander AD, et al. 2012. Agricultural Mitigation and Adaptation to Climate Change in Yolo County, CA. California Energy Commission Project 500-09-009, p 26–9.

Kiparsky M. 2016. Unanswered questions for implementation of the Sustainable Groundwater Management Act. Calif Agr 70(4):165–8. https://doi.org/10.3733/ca.2016a0014

Kristensen P. 2004. The DPSIR Framework: Comprehensive/Detailed Assessment of the Vulnerability of Water Resources to Environmental Change in Africa Using River Basin Approach. UNEP, Nairobi, Kenya.

Krueger RA, Casey MA. 2015. *Focus Groups: A Practical Guide for Applied Research*. Thousand Oaks, CA: Sage Publishing.

Nable RO, Bañuelos GS, Paull JG. 1997. Boron toxicity. Plant Soil 193(1–2):181–98.

Niles MT, Lubell M, Van R. Haden. 2013. Perceptions and responses to climate policy risks among California farmers. Global Environ Chang 23:1752–60.

Ritchie J, Lewis J. 2003. *Qualitative Research Practice: A Guide for Social Science Students and Researchers*. London: Sage Publishing.

Rudnick J, DeVincentis A, Méndez-Barrientos L. 2016. The Sustainable Groundwater Management Act challenges the diversity of California farms. Calif Agr 70(4):169–73.

Water Education Foundation. 2015. The 2014 Sustainable Groundwater Management Act: A Handbook to Understanding and Implementing the Law. Sacramento, CA. www.watereducation.org

[Yolo County] Yolo County Department of Agriculture and Weights and Measures. 2016. Yolo County Agricultural Crop Report 2015. www.yolocounty.org/home/showdocument?id=37378

RESEARCH ARTICLE

Diverse stakeholders create collaborative, multilevel basin governance for groundwater sustainability

Groundwater sustainability agencies recently formed in three large groundwater basins in the Central Valley have developed innovative ways to incorporate farmers' voices and respect local autonomy.

by Esther Conrad, Tara Moran, Marcelle E. DuPraw, David Ceppos, Janet Martinez and William Blomquist

Abstract

The Sustainable Groundwater Management Act (SGMA) is introducing significant changes in the way groundwater is governed for agricultural use. It requires the formation of groundwater sustainability agencies (GSAs) to manage groundwater basins for sustainability with the engagement of all users. That presents opportunities for collaboration, as well as challenges, particularly in basins with large numbers of agricultural water users who have longstanding private pumping rights. The GSA formation process has resulted in the creation of multiple GSAs in many such basins, particularly in the Central Valley. In case studies of three basins, we examine agricultural stakeholders' concerns about SGMA, and how these are being addressed in collaborative approaches to groundwater basin governance. We find that many water districts and private pumpers share a strong interest in maintaining local autonomy, but they have distinct concerns and different options for forming and participating in GSAs. Multilevel collaborative governance structures may help meet SGMA's requirements for broad stakeholder engagement, our studies suggest, while also addressing concerns about autonomy and including agricultural water users in decision-making.

Groundwater is a critical resource for California's agricultural sector, accounting for almost 40% of agricultural water use, and far more in drought years (DWR 2015). Many groundwater basins, particularly in the Central Valley, have experienced significant declines in groundwater levels over the past several decades, and the recent drought heightened concerns over these declines and associated impacts. In 2014, the California Legislature passed the Sustainable Groundwater Management Act (SGMA), introducing for the first time a requirement that local agencies manage groundwater sustainably or face state intervention.

SGMA grants broad authority for groundwater management to locally formed groundwater sustainability agencies (GSAs). Local agencies were given until June 30, 2017, to establish GSAs and until 2020 or 2022

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The Sustainable Groundwater Management Act mandates the formation of groundwater sustainability agencies (GSAs) to manage groundwater basins, and requires broad stakeholder participation in these agencies. This research finds that multilevel collaborative governance structures — those that include nongovernmental entities such as nonprofits, landowners and farmers — can help ensure that agricultural users' interests are represented adequately in GSA decision-making.

Bruce Conrad

(depending on basin conditions) to adopt groundwater sustainability plans (GSPs), which must consider all "beneficial uses and users" (California Water Code [CWC] § 10723.2, California State Legislature, 2014). In groundwater basins where agriculture plays an important role, the number of beneficial users can be large, in some cases including thousands of landowners who have long exercised their overlying pumping rights.

Collaborative governance

In recent decades, collaborative governance has gained attention as an effective approach to managing common pool resources, including groundwater (Megdal et al. 2017; Ostrom 1990). Collaborative governance has been defined as "the processes and structures of public policy decision-making and management that engage people constructively across the boundaries of public agencies, levels of government, and/or the public, private and civic spheres in order to carry out a public purpose that could not otherwise be accomplished" (Emerson et al. 2012, 2).

Collaborative governance typically involves engaging nongovernmental entities in public policy decision-making, which is expected to help develop shared knowledge, trust and buy-in among diverse interests (Ansell and Gash 2008; Innes and Booher 2010). In the context of groundwater governance, such nongovernmental entities would include individual landowners and farmers as well as private or nonprofit organizations representing agricultural interests, among others. While public agencies hold authority deriving from legislative mandates, the influence of nongovernmental entities in a collaborative process is grounded in their authentic representation of key interests and widely accepted values, referred to as discursive legitimacy (Purdy 2012).

Organizing successful collaborations at large scales can be challenging, requiring special efforts to design and track meaningful participation and representation (Ansell and Torfing 2015; DuPraw 2014). Multilevel governance structures featuring collaboration among entities at different scales may be one way to achieve meaningful engagement (Newig and Fritsch 2009). For example, in a river basin, instead of forming a single, basinwide governing body, local agencies and stakeholders work together at smaller scales, but coordinate their efforts across the basin. However, we still have much to learn about how multilevel structures work in practice (Huitema et al. 2009).

In California, collaborative governance in water management has been encouraged in recent decades (Hughes and Pincetl 2014). It has played an important role in the success of certain groundwater adjudications and special act districts in reducing overdraft, but most of these examples are in urban areas or relatively small basins (Blomquist 1992). Across much of the state — including the Central Valley, where basins are large, overdraft is severe, agricultural use is high and overlying rights holders are numerous — collaborative plans to manage groundwater prior to SGMA were voluntary, lacking binding commitments to address groundwater depletion and its impacts (Nelson 2011). By contrast, SGMA requires that in over 125 designated medium- or high-priority basins local management must achieve groundwater sustainability within 20 years of GSP adoption or be subject to state intervention. GSPs must avoid "significant and unreasonable" reductions in groundwater levels and five other "undesirable results."

SGMA effectively requires collaborative governance at the basin scale in the context of developing and implementing GSPs, as distinct from the discretion it allows in GSA formation. If there are multiple GSAs within a groundwater basin, they must either work together to develop a single GSP or sign a coordination agreement ensuring that their multiple GSPs are based on common data and assumptions (CWC § 10727.6) (alternatively, local agencies could collaborate to form a single GSA covering the entire basin, and develop a single GSP). In addition, per statutory language, GSAs must encourage the "active involvement" of all "beneficial users" of groundwater in the development of a GSP (CWC § 10727.8).


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Landowners and other stakeholders participate in a public meeting about the formation of a GSA in Yolo County. The resulting GSA covers the vast majority of the Yolo basin; it has a multilevel governance structure that includes the Yolo County Farm Bureau as a voting member.

In forming GSAs, on the other hand, SGMA required public involvement but not necessarily collaborative governance. All beneficial users of groundwater had to be consulted in GSA formation (CWC § 10723.2), but they were not required to be included in decision-making structures. Public agencies had the authority to form GSAs individually and at any scale. Private pumpers and nonprofit entities such as the Farm Bureau, however, could not. Local agencies could take a collaborative approach to the GSA formation process by including representatives of beneficial users in GSA and basinwide governance structures. Alternatively, agencies could provide beneficial users with opportunities for public input but not a role in

FIG. 1. Case study groundwater basins.

decision-making within the GSA or in coordination at the basin scale.

Case studies in three basins

Agriculture has long been a critical driver of water management in California, and SGMA has significant implications for how agricultural water is managed. To examine how collaborative governance structures are emerging at the basin scale, we undertook case studies of three groundwater basins in California's Central Valley that have followed a collaborative governance approach, and we reviewed data about GSA formation statewide. We address two questions in our case studies: What are agricultural stakeholders' primary concerns in designing groundwater governance under SGMA, and how were those concerns represented in GSA formation. Our aims are to deepen our understanding of how collaborative processes can be structured to manage resources at large scales and to lay the groundwork for future research regarding the effectiveness of those governance arrangements in accommodating diverse stakeholder interests.

Our case studies include the Colusa and Yolo subbasins of the Sacramento Valley groundwater basin and the Eastern San Joaquin subbasin of the San Joaquin Valley basin (fig. 1). Under SGMA, subbasins are treated as groundwater basins, so for simplicity we use the term "basin" for both. These basins were selected because they are relatively large, agriculture plays a significant role in each one, and stakeholders in each of these areas took a collaborative approach to GSA formation at the basin scale.

In all three basins, farmers generally use surface water for irrigation but switch to groundwater when surface supplies are curtailed. Tree crops are important in all three basins, with a particularly significant expansion in Yolo County, where almond acreage has more than doubled since 2010. This expansion is placing additional demand on groundwater, since much of this land was previously unirrigated (Morain 2015). Agricultural production and groundwater dependence are greatest in the Eastern San Joaquin basin, which is critically overdrafted and must complete its GSP by 2020 instead of 2022. Farms are on average smaller in this basin, and more farmland is under irrigation. Table 1 summarizes key features of the three basins.

In all three cases, discussions about a collaborative approach to GSA formation at the basin scale began early and lasted for more than a year. A convening entity played a key role, seeking to include stakeholders across the basin in a group decision-making process (in the Colusa basin, Glenn and Colusa counties conducted

TABLE 1. Overview of case studies in three basins

	Yolo	Colusa	Eastern San Joaquin
Land area (sq miles)	788	1,099	1,202
Population (2010)*	194,158	48,369	582,662
No. of counties†	2	2	3
Agricultural production value (2015)‡	$510 million	$752 million	$2.26 billion
Top three crops (by value, 2015)§	Tomatoes, almonds, grapes	Almonds, rice, walnuts	Almonds, grapes, walnuts
Average farm size (acres, 2012)§	456	545	220
Percentage of farmland under irrigation§	50%	47%	62%
Groundwater basin priority (2014)*	High	Medium	High, critically overdrafted
Percentage of water use accounted for by groundwater*	25%	10%	43%
No. of GSAs¶	2	2	17
No. of GSA-eligible entities	33	47	24
Length of GSA formation process (months)	19	16 (Colusa County); 13 (Glenn County)	20

Sources: 2016 basin boundaries shapefile (DWR 2015; California Statewide Groundwater Elevation Monitoring Program prioritization data (DWR 2014), California Agricultural Statistics Review 2015–2016 (CDFA 2016), 2012 Census of Agriculture (USDA 2014), and GSA formation meeting notes.

* Estimates based on 2003 groundwater basin boundaries.

† A very small area of the Yolo subbasin falls within neighboring Solano County.

‡ Estimates based on county-level data and percentage of county area within each basin.

§ Estimates based on county data (Yolo and San Joaquin counties for Yolo and Eastern San Joaquin basins, and average of Glenn and Colusa counties for Colusa basin).

¶ 900 acres of the Yolo basin fall within a reclamation district that formed a separate GSA. This GSA plans to join in a single GSP for the Yolo subbasin.

separate processes but communicated regularly). In the Colusa and Eastern San Joaquin basins, county governments convened these meetings; in the Yolo basin, a nonprofit water association and the Yolo County Farm Bureau led the process. Professional facilitation services were used in all three basins, supported by funding from the California Department of Water Resources (DWR).

Although not representative of all groundwater basins in California, these cases offer insight into the interests of agricultural communities under SGMA, and how these interests have influenced GSA governance structures. Data was gathered from governance documents and meeting notes, as well as from observations of GSA formation meetings during 2016 and 2017, as described in the online technical appendix. In addition, two co-authors served as facilitators for GSA formation in the Yolo and Colusa basins and contributed their knowledge of stakeholder concerns and decisions there.

GSA formation study

SGMA allows local public agencies with water supply, water management or land use responsibilities to form GSAs. They may do so as single agencies, or join with other local agencies to form a multi-agency GSA through a joint powers agreement (JPA) or memorandum of agreement (MOA). Each proposed GSA was required to send a notice to DWR, indicating its boundaries, the local agencies involved and a description of how it would engage 10 types of beneficial users of groundwater (CWC § 10723.2, and listed in the technical appendix).

We reviewed GSA formation notices submitted to DWR via its online SGMA portal as of June 30, 2017 (agencies could still revise or submit new notices after that date). We compiled data regarding GSA type (single or multi-agency), beneficial users identified and agricultural interests in GSA governance. We also recorded the number of GSAs declared in each high- and medium-priority basin and evaluated basin coverage by GSAs. The technical appendix provides additional detail on methods.

Agriculture represented in most GSAs

A diverse array of interests is present within most GSAs in California. Our analysis of GSA formation notices indicates that at least five of the 10 SGMA-identified beneficial users are present in over 80% of all GSAs. Agricultural interests are present in nearly all GSAs; 87% of GSAs reported the presence of overlying rights for agricultural use.

Beneficial users have been represented in the GSA formation process through a mix of public and private entities. Table 2 shows the types of entities that participated in GSA formation meetings in our three case studies. Most have direct or indirect interests in agriculture. Local irrigation, reclamation and water districts, and some mutual water companies represent landowners who have access to surface water but often rely in part upon groundwater. Private pumpers are landowners who are not part of a district, and usually rely solely upon groundwater for irrigation, domestic use, or both. Municipalities deliver water for domestic use, but many residents of these cities have ties to agriculture. Agricultural interests were also represented through nonprofit associations, particularly by the Farm Bureau in each county.

Agricultural interests, concerns

GSA formation represents a significant change for many agricultural users, who in most of California have historically faced few constraints in exercising their overlying rights to pump groundwater. Although SGMA explicitly states that it does not alter property rights, it grants substantial authority to GSAs, including to establish fees, limit extractions and require metering in some instances. In our case studies, local agencies and private pumpers who participated in GSA formation expressed a strong preference to establish GSAs rather than to allow the state to intervene. However, many were concerned about the prospect of larger-scale public agencies such as counties

TABLE 2. Local entities with groundwater interests involved in GSA formation in the three basins

	Yolo	Colusa	Eastern San Joaquin
Local agencies (GSA-eligible)			
Water districts	✔	✔	✔
Irrigation districts	✔	✔	✔
Reclamation districts	✔	✔	✔
Cities	✔	✔	✔
Counties	✔	✔	✔
Community service districts	✔	✔	✔
Drainage districts	✔	✔	
Levee districts		✔	
Resource conservation districts	✔	✔	
Water management–related JPAs	✔		✔
Private water companies	✔	✔	✔
Landowners/private pumpers	✔	✔	
County farm bureau	✔	✔	✔
Nonprofit water user associations	✔		
Environmental or other nongovernmental agencies		✔	✔
Tribes	✔		

Sources: participant lists in GSA formation meeting notes (Colusa and eastern San Joaquin basins) and meeting observations (Yolo basin).

establishing GSAs, because of the potentially limited familiarity with local water conditions and agricultural needs.

Local water districts and private pumpers had distinct interests and options with respect to their participation in GSA formation. In our case studies — as is true across much of the state — most local irrigation, water and reclamation districts have access to surface water, which provides an alternative water source to groundwater and can be used for direct or in-lieu groundwater recharge. During the GSA formation processes that we observed, many of these districts were concerned about retaining control of surface water deliveries and receiving credit for groundwater recharge in the basinwide water budget that must be included in GSPs. Some sought to protect their interests by forming their own GSAs, as local agencies with water management responsibilities have the right to do under SGMA.

In the Colusa basin, as many as 15 GSA notices were submitted to DWR. Once Glenn and Colusa counties began to convene discussions toward collaboratively forming multi-agency GSAs, districts agreed to participate but developed a set of "districts' principles" to convey their common interests. A few mutual water companies shared interests similar to those of the local districts and participated in developing these principles (under SGMA, water companies cannot form their own GSAs but can be invited by public agencies to be a member of a multi-agency GSA.)

In contrast to the districts' situation, most private pumpers in our case study basins are entirely reliant upon groundwater for irrigation and domestic purposes and have invested significant personal funds in their well systems. In addition, their areas have often experienced the most significant declines in groundwater levels and require more substantial management actions under SGMA.

In these areas — often called "white areas" because they are not covered by other local districts — SGMA presumes that the county will serve as the GSA. In our case studies, many private pumpers did not believe that their county would adequately represent their interests; they were particularly concerned about the potential fees and pumping restrictions that could be imposed. They sought to establish avenues to represent their interests in the GSA formation process, and ultimately in GSA governance. Their ability to do this rested upon the widely recognized legitimacy of their interests, leading the convening entities to take steps toward meaningfully including the voices of private pumpers.

In Yolo and Eastern San Joaquin basins, private pumpers looked to their county Farm Bureaus to represent their interests in the GSA formation process. In the Yolo basin, the Water Resources Association (WRA, which is composed of irrigation districts, cities and the county) has for several decades been a trusted forum for discussion of the county's water management issues, even more so than the county itself. Aware of the Farm Bureau's strong relationships with individual landowners, the WRA invited the Farm Bureau to co-convene the GSA formation process. Their high level of credibility among agricultural stakeholders resulted in those stakeholders being included in the process of GSA formation. In particular, the Farm Bureau conducted outreach that resulted in the participation of hundreds of private pumpers in public forums about GSA formation.

In the Colusa basin, private pumper advisory committees were created by each of the two counties (Colusa and Glenn). They were composed of private pumper representatives who attended GSA formation meetings and provided concrete proposals for how the GSA could be structured to ensure their interests were represented.

Multiple GSAs per basin

Numerous water districts in our case studies initially decided to form their own GSAs to retain control over surface and groundwater management activities within their jurisdictions. In the Yolo and Colusa basins, as GSA discussions progressed, many decided to withdraw their notices and join with others to form multi-agency GSAs. However, in the Eastern San Joaquin basin, only a few multi-agency GSAs have formed. Most local agencies have remained single-agency GSAs, resulting in 17 separate GSAs within the basin.

Single agency GSAs are also most common statewide. Agencies may still revise their GSA arrangements but as of the SGMA June 30, 2017, deadline 253 agencies had formed GSAs. The vast majority (70%) are single agencies. Half are involved in managing water for agriculture (e.g., irrigation or reclamation districts). Agricultural interests also appear to be well represented in the governance structures of multi-agency GSAs (see table 3).

As of June 30, 2017, one or more GSAs had been declared in 113 of the high- and medium-priority basins (GSA formation was not required in some basins that were covered by adjudications or alternative plans). Of these basins, 50 (44%) have a single GSA covering the entire basin; 29 of those 50 GSAs are multi-agency

TABLE 3. Types of GSAs declared as of June 30, 3017

GSA type	No. of GSAs declared	Percentage of total GSAs
Single-agency GSAs	**177**	**70%**
Agencies managing water for agriculture	89	35%
Other agencies	88	35%
Multi-agency GSAs (JPAs and MOAs)	**76**	**30%**
Member(s) of board or advisory committee represent agricultural interests	61	24%
No specific agricultural representation	15	6%
Total GSAs declared	**253**	**100%**

Source: GSA formation notices posted in DWR's SGMA portal (DWR 2017). See technical appendix.

GSAs. The remaining 63 basins are covered by between two and 22 GSAs, or coverage is shared between at least one GSA and an adjudicated area. As figure 2 illustrates, nearly all of the basins in the Central Valley are covered by multiple GSAs. A number of these basins have been designated by the state as "critically overdrafted," which under SGMA must complete a GSP by 2020 rather than 2022 in order to avoid state intervention (CWC § 10720.7).

Multilevel collaborative governance

On the face of it, the large number of single-agency GSAs and basins with multiple GSAs suggests that collaboration under SGMA may be limited, particularly in the large agricultural basins of the Central Valley. However, our cases indicated that there had been significant collaboration in at least some of the basins with multiple GSAs.

In the Yolo and Colusa basins, collaborative, multi-agency GSAs were created, reducing the number of GSAs to two per basin. (The Yolo Subbasin Groundwater Agency covers the entire basin except 200 acres that fall within a reclamation district, which plans to work with the agency on a single GSP.) In the Eastern San Joaquin basin, the 17 GSAs have developed a relatively strong collaborative governance structure at the basin scale. In all three basins, multilevel governance arrangements have emerged that allow local agencies to retain some autonomy, and for private pumpers and other interests to have a voice in decision-making. In addition to being reflected in academic literature (Newig and Fritsch 2009), this multilevel approach has been articulated in practical terms as the "local implementing agency" (LIA) model for GSA formation (Ceppos 2016).

Figure 3 illustrates the multilevel governance arrangements that have emerged in our three cases. While the structure and number of GSAs differ, in each basin decision-making and participation are distributed across three levels — basinwide, multi-agency and individual agency — and a distinct set of activities is associated with each.

Basinwide level: GSP development

In all three cases, basin-scale decision-making focuses on coordination of GSP development, including securing grant funds, hiring consultants, data management and monitoring. These basinwide structures emerged in large part to share costs and to ensure compliance with SGMA's coordination requirements. In Yolo, the decision-making body at the basin scale is the

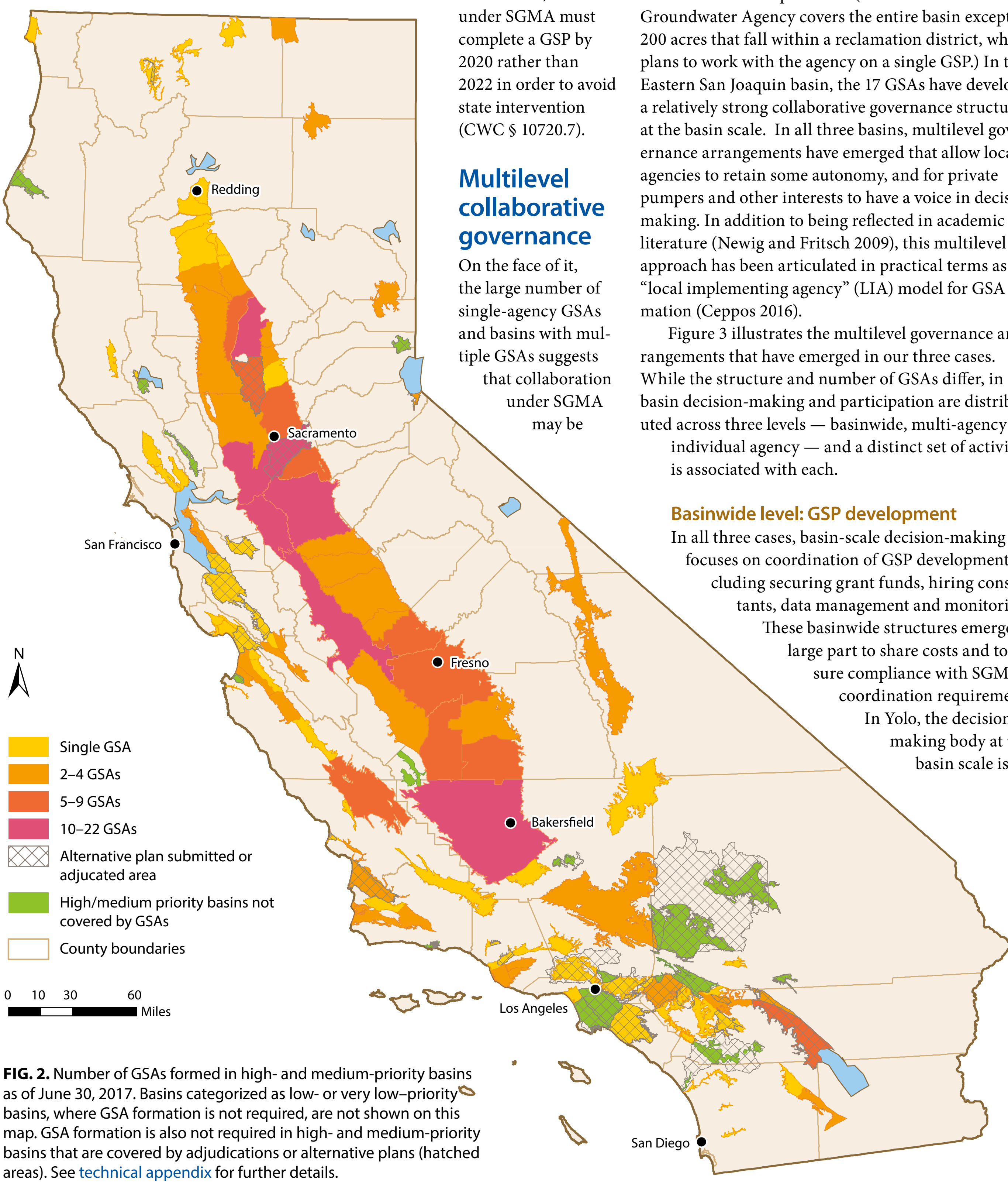

FIG. 2. Number of GSAs formed in high- and medium-priority basins as of June 30, 2017. Basins categorized as low- or very low–priority basins, where GSA formation is not required, are not shown on this map. GSA formation is also not required in high- and medium-priority basins that are covered by adjudications or alternative plans (hatched areas). See technical appendix for further details.

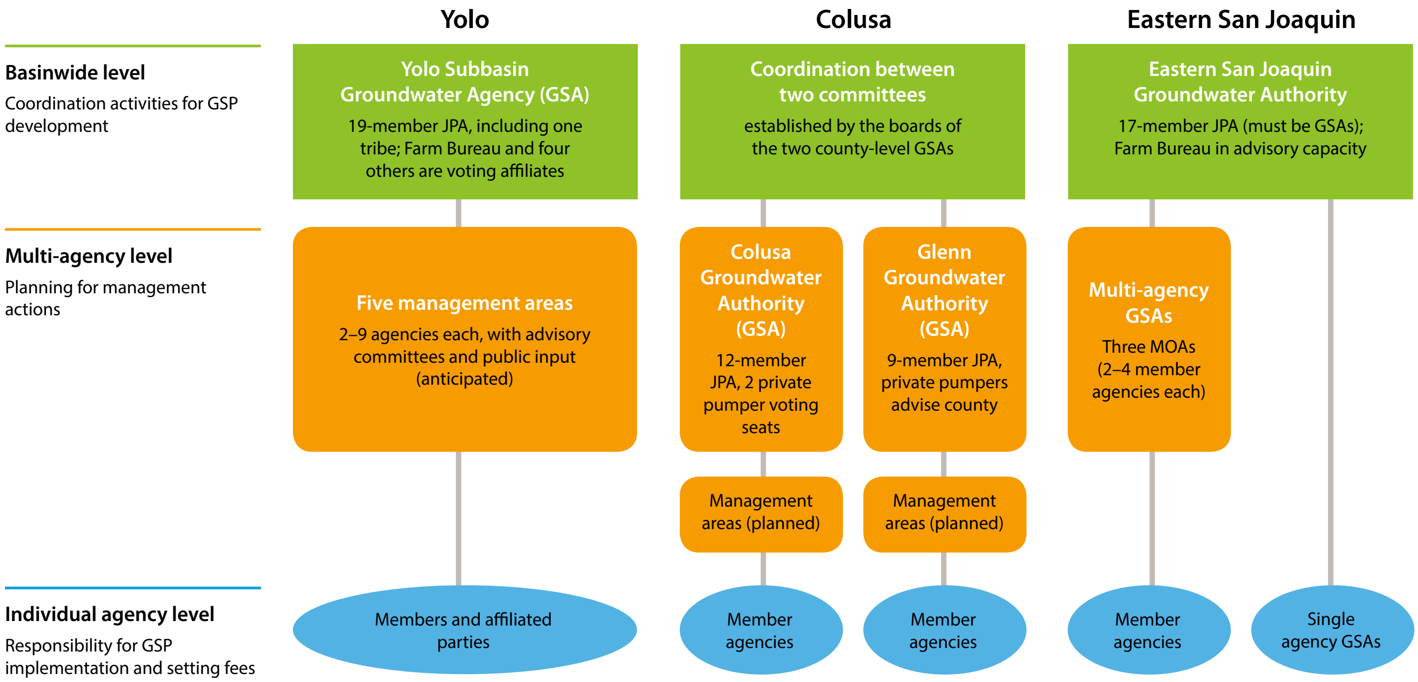

FIG. 3. In each case study, decision-making was distributed across at least three levels. At the basin level, the focus is on coordination and GSP development, while planning for most management actions will occur at the multi-agency level. In keeping with concerns about autonomy, decisions about plan implementation and fees will be undertaken by individual agencies.

GSA; in Eastern San Joaquin, it is a JPA composed of all 17 GSAs. In the Colusa basin, basinwide governance structures are still evolving, but, so far, subcommittees of the boards of the two county-level GSAs are working together on aspects of planning and grant proposal development.

In all three basins, multilevel governance arrangements have emerged that allow local agencies to retain some autonomy, and for private pumpers and other interests to have a voice in decision-making.

The restriction of decision-making powers at the basin level was a frequent topic of discussion in GSA formation meetings. As articulated by an irrigation district board member in Yolo County, "I don't want a city telling us when to turn our water on." During several GSA formation meetings, those involved in convening the process repeatedly acknowledged this concern and emphasized the need to structure the GSA so that as much authority as possible was delegated to local agencies. The JPA establishing the Yolo Subbasin Groundwater Agency reflected this, stating that "the Agency will serve a coordinating and administrative role" without limiting a member's "rights or authority over its own water supply matters," although the GSA retains the right to intervene if sustainability criteria are not being met (Section 8.1, p. 13).

In the Eastern San Joaquin basin, significant portions of several meetings were focused on ensuring that the basinwide JPA, which holds the common powers of its member GSAs, would not usurp the authority of local agencies. The final JPA text restricted the basinwide JPA from undertaking activities "including, without limitation, the restriction or regulation of groundwater extractions," within the service areas of members without their consent (Section 3.6, p. 5).

In the basin-scale governance structures in the Yolo and Eastern San Joaquin basins, private pumper interests are represented by the Farm Bureau. In the Yolo basin, the Farm Bureau serves as one of five affiliated parties who hold voting seats on the GSA board. (Other affiliates include an environmental representative, two mutual water companies and a university.) In the Eastern San Joaquin basin, the Farm Bureau does not have a voting seat but will serve in an advisory capacity to the basinwide JPA, since membership is restricted to GSAs. This arrangement builds upon the Farm Bureau's long history of working with most of the local agencies involved and its experience serving in a nonvoting advisory role to a previous JPA responsible for groundwater management.

Multi-agency level: management actions

Planning for the management actions needed to reach a basin's sustainability goals is largely being conducted by multiple agencies at a scale smaller than a basin (referred to here as the "multi-agency level"). In the Yolo basin, five management areas have been defined within the Yolo Subbasin Groundwater Agency, roughly following groundwater conditions and usage patterns: Capay Valley, North Yolo, Central Yolo, Yolo Zamora, and South Yolo. The specifics of how members and affiliated parties will work together within each management area have not yet been spelled out, but advisory committees and opportunities for public involvement are anticipated.

In the Colusa basin, planning for management actions will be undertaken by the two multi-agency GSAs, which have formed along county lines with each covering approximately half of the basin. The two county-level GSAs also anticipate forming management areas, adding yet another governance level.

Although much of the Eastern San Joaquin basin is covered by single-agency GSAs, three multi-agency GSAs have formed in certain subareas of the basin. For example, the portion of the basin that falls outside of San Joaquin County is being managed by a multi-agency GSA composed of two county governments and two water districts.

Private pumpers are involved at the multi-agency level in several ways. In the Colusa County portion of the Colusa basin, there are two voting seats for private pumpers on the board of this multi-agency GSA, both of whom are representatives from the county's Groundwater Commission. In the Glenn County portion of this basin, private pumpers do not sit directly on the GSA board but instead advise the county — which is a member of the GSA — through the previously established Private Pumpers Advisory Committee. Private pumpers will also likely play a role in the Yolo basin by participating in advisory committees to be established for each management area.

Individual agency level: GSP implementation

Individual agencies represent a third level of decision-making and action, focused on GSP implementation in our case study basins. The delegation of this authority — particularly as related to groundwater use restrictions and fees — to local agencies was critical to reaching agreement to create larger-scale GSAs. For example, one of the Colusa basin's districts' principles, which set out criteria for the districts joining a multi-agency GSA, required that the GSA's governance structure be guided by "respect for each member's discretion, governmental authority, and expertise and knowledge of its groundwater conditions, demands and concerns," as well as an "avoidance of 'top down' planning and implementation" (Districts' principles presentation, Oct. 11, 2016). The JPAs establishing the GSAs in Yolo and Colusa basins, as well as the basinwide JPA of GSAs in Eastern San Joaquin, contain clauses specifying that fee setting and GSP implementation will primarily be undertaken by member agencies.

As of June 30, 2017, the counties in each basin were formally serving as the local agencies representing the interests of private pumpers. However, as described earlier, in all three basins private pumpers have avenues to voice their concerns at the multi-agency or basin levels. In the Yolo basin, private pumpers have expressed a preference to be represented by a water district rather than the county, and efforts are under way by this water district to annex private pumper areas.

The expansion of tree crops in Yolo County, where almond acreage has more than doubled since 2010, has led to increased demand for groundwater. The extent and distribution of tree crops may affect farmers' interests in participating in a GSA and might shape how management areas are formed.


Esther Conrad

Key Case Study Findings

Concerns of agricultural stakeholders:

- Most agricultural stakeholders wanted to preserve some autonomy over decision-making, particularly with regard to setting fees and extraction limits.
- Irrigation, reclamation and other water districts sought to protect their ability to control surface water supplies and to receive credit for groundwater recharge. Under SGMA, these districts had the option to form their own GSAs.
- Private pumpers outside of district boundaries (often called white areas) were concerned about the potential fees and pumping restrictions that a new GSA might impose. Concerned that the county, the default GSA for these areas, would not represent their interests adequately, they sought and gained a voice in decision-making due to the widely recognized legitimacy of their interests.

How these concerns influenced governance:

- Stakeholders ultimately agreed upon collaborative governance arrangements at the basin scale.
- Concerns about autonomy were accommodated by creating multilevel governance structures in which decision-making is distributed across three levels: basinwide, multi-agency and individual agency.
- Counties represent private pumpers in the GSAs of all three basins, but private pumper representatives and the Farm Bureau have voices in decision-making at basinwide and multi-agency levels.

Fair and effective?

SGMA presents significant challenges and opportunities for collaborative governance, particularly in large agricultural basins where beneficial users are numerous and diverse. The GSA formation process has resulted in the creation of multiple GSAs in many such basins, particularly in the Central Valley. As summarized in the sidebar "Key Case Study Findings", our case studies show how multi-level governance structures have helped in such settings to meet SGMA's requirements for collaborative management at the basin scale while also enabling broad participation and addressing local agency concerns about autonomy. They also illustrate how private pumpers have sought and gained a voice in GSA governance arrangements based upon the widely recognized legitimacy of their interests.

Kiparsky et al. (2016) call for ensuring that GSA governance structures are both fair and effective, and identify criteria for evaluating governance options along these two dimensions. Although they have only just started to function, the governance arrangements in our case studies have the potential to meet some of those criteria. For example, the inclusion of private pumpers into decision-making structures enhances representation and participation, two of the criteria related to fairness. One of the criteria for effectiveness — appropriate scale — is addressed through a multilevel structure that operates at the scale of the basin as well as at the scale of distinct subareas of the basin. Multilevel structures may also help meet the effectiveness criterion of capacity by enabling the GSP development process to draw upon the knowledge and resources of local agencies.

Multilevel structures, however, could also pose some challenges for effectiveness. GSP regulations require that plans identify minimum thresholds for each of the six undesirable results, measurable objectives that will result in sustainable management, and 5-year interim milestones (California Code of Regulations, Title 23, Subarticle 3). The regulations allow for measurable objectives and thresholds to be defined differently in each management area, as long as achieving them together will result in sustainability. The Yolo Subbasin Groundwater Agency is taking steps to implement this approach by developing water budgets at all three decision-making scales (individual agency, multi-agency and basinwide). However, since responsibility for implementation has been delegated to the individual agency level, it may prove challenging to ensure that all necessary management actions are undertaken to reach a basinwide sustainability goal. In particular, it may be difficult to encourage local agencies to develop and act upon triggers that provide early warning before thresholds are crossed (Christian-Smith and Abhold 2015). While the Yolo Subbasin Groundwater Agency retains the authority to intervene if sustainability criteria are not being met, such a provision does not exist in the basinwide JPA in the Eastern San Joaquin basin.

Ensuring adequate funding, another criterion for effectiveness identified by Kiparsky et al. (2016), may also be challenging. In our case study basins, responsibility for setting fees is largely allocated to individual agencies. If these agencies prove unwilling or unable to establish new fees when necessary, this could jeopardize timely GSP implementation.

Our case studies do not capture the full range of California's diverse agricultural settings. Each basin's governance arrangements will be influenced by its institutional context, past experiences with collaboration, and even by particular individuals who play significant roles in the process. Differences in agricultural settings may also influence outcomes. For example, in basins with large numbers of small farms, more effort may be needed to find feasible avenues to represent the interests of private pumpers. The extent and distribution of tree crops, which can increase dependence on groundwater, may affect farmers' interests in participating in a GSA and might shape how management areas are formed. Research analyzing a larger number of basins is needed to understand how such factors influence governance arrangements.

While further research is needed to understand factors that influence collaborative governance structures and the effectiveness of multilevel arrangements for SGMA implementation, the experiences of our three case studies may be helpful as GSAs consider how they will work together at a basin scale to prepare one or more GSPs, or if they decide to change their governance structures. In particular, our case studies suggest that if the multiple GSAs in basins across the Central Valley have not already done so, they should begin to consider questions of basin-scale governance, including how they will work together to meet SGMA's basinwide coordination requirements, how responsibilities will be shared across individual agency, multiagency and basinwide levels, and how private pumper interests will be considered in each.

Our case studies, as well as experiences in other basins, show that building collaboration requires extensive dialogue, and significant time and commitment on the part of all participants. For example, the Yolo Subbasin Groundwater Agency's GSA notice documents over 175 meetings between May 2014 and June 2017 at which the GSA formation process was discussed. In addition, a preliminary study of eight GSA formation processes under way in late 2016 suggested that two factors — positive prior experience with collaboration and the presence of trusted leadership at the basin scale — were particularly important in supporting collaboration (Conrad et al. 2016). As stakeholders gain more experience working with one another in the coming years, it is possible that some GSAs may decide to consolidate into a single basinwide GSA.

Much more remains to be understood regarding the effectiveness of different governing arrangements in managing groundwater basins sustainably. Studies that compare different GSA governance models, including collaborative and noncollaborative as well as multi- or single-level governance arrangements, would help to inform SGMA implementation, as well as provide much-needed insight into whether and how collaboration works to manage resources at large scales. CA

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References

Ansell C, Gash A. 2008. Collaborative governance in theory and practice. J Publ Adm Res Theor 18:543–71.

Ansell C, Torfing J. 2015. How does collaborative governance scale? Policy Polit 43:315–29.

Blomquist W. 1992. *Dividing the Waters: Governing Groundwater in Southern California*. San Francisco: ICS Press. 415 p.

California State Legislature. 2014. Sustainable Groundwater Management Act (and related statutory provisions from SB 1168, AB 1739, and SB 1319). Sacramento, CA. http://groundwater.ca.gov/docs/2014%20Sustainable%20Groundwater%20Management%20Legislation%20with%202015%20amends%201-15-2016.pdf

[CDFA] California Department of Food and Agriculture. 2016. California Agricultural Statistics Review 2015-16. Sacramento, CA. 124 p. www.cdfa.ca.gov/statistics/PDFs/2016Report.pdf

Ceppos D. 2016. Local Implementing Agencies: A Localized Governance Alternative for the Sustainable Groundwater Management Act. Sacramento: Center for Collaborative Policy, California State University, Sacramento. www.csus.edu/ccp/documents/publications/lia_white_paper_final.pdf

Christian-Smith J, Abhold K. 2015. Measuring What Matters: Setting Measurable Objectives to Achieve Sustainable Groundwater Management in California. Union of Concerned Scientists, Oakland, CA. 37 p. www.ucsusa.org/measuring-whatmatters

Conrad E, Martinez J, Moran T, et al. 2016. To Consolidate or Coordinate? Status of the Formation of Groundwater Sustainability Agencies in California. Water in the West Program, Stanford University, CA. 44 p. http://waterinthewest.stanford.edu/sites/default/files/GSA-Formation-Report_1.pdf

DuPraw ME. 2014. Illuminating Capacity-Building Strategies for Landscape-Scale Collaborative Forest Management Through Constructivist Grounded Theory. Dissertation, Graduate School of Humanities and Social Sciences, Nova Southeastern University, Ft. Lauderdale.

[DWR] California Department of Water Resources. 2017. SGMA Portal. http://sgma.water.ca.gov/portal/

DWR. 2016. Final 2016 Bulletin 118 Groundwater Basin Boundaries. GIS shapefiles. Sacramento, CA. http://water.ca.gov/groundwater/sgm/basin_boundaries.cfm

DWR. 2015. California's Groundwater, Update 2013. Sacramento, CA. 90 p. www.water.ca.gov/waterplan/topics/groundwater/index.cfm

DWR. 2014. California Statewide Groundwater Elevation Monitoring (CASGEM) and Groundwater Sustainability Basin Prioritization. Sacramento, CA. www.water.ca.gov/groundwater/casgem/pdfs/lists/PubRel_BasinRank_by_HR_5-18-15.pdf

Emerson K, Nabatchi T, Balogh S. 2012. An integrative framework for collaborative governance. J Publ Adm Res Theor 22:1–29.

Hughes S, Pincetl S. 2014. Evaluating collaborative institutions in context: The case of regional water management in southern California. Environ Plann C 32:20–38.

Huitema D, Mostert E, Egas W, et al. 2009. Adaptive water governance: Assessing the institutional prescriptions of adaptive (co-)management from a governance perspective and defining a research agenda. Ecol Soc 14:1.

Innes JE, Booher DE. 2010. *Planning with Complexity: An Introduction to Collaborative Rationality for Public Policy*. New York, NY: Routledge. 256 p.

Kiparsky M, Owen D, Nylen NG, et al. 2016. Designing Effective Groundwater Sustainability Agencies: Criteria for Evaluation of Local Governance Options. Center for Law, Energy and the Environment, UC Berkeley School of Law. 63 p. www.law.berkeley.edu/groundwater-governance-criteria

Megdal SB, Gerlak AK, Huang L, et al. 2017. Innovative approaches to collaborative groundwater governance in the United States: Case studies from three high-growth regions in the Sun Belt. Environ Manage 59:718–35.

Morain D. 2015. Drought transforms Valley, right in our own backyards. Sacramento Bee, October 30.

Nelson R. 2011. Uncommon Innovation: Developments in Groundwater Management Planning in California. Water in the West Working Paper 1. Stanford University, CA. 38 p. http://waterinthewest.stanford.edu/sites/default/files/UncommonInnovationMarch_2011.pdf

Newig J, Fritsch O. 2009. Environmental governance: Participatory, multi-level — and effective? Environ Policy Gov 19:197–214.

Ostrom E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press. 298 p.

Purdy JM. 2012. A framework for assessing power in collaborative governance processes. Public Admin Rev 72:409–17.

[USDA] United States Department of Agriculture. 2014. 2012 Census of Agriculture: California State and County Data. Vol. 1, Part 5. Washington, DC. 550 p. www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_2_County_Level/California/cav1.pdf

RESEARCH ARTICLE

How can we support the development of robust groundwater sustainability plans?

A decision support process helped stakeholders in Yolo County understand the vulnerabilities of their groundwater situation and evaluate strategies to overcome them.

by Vishal K. Mehta, Charles Young, Susan R. Bresney, Daniel S. Spivak and Jonathan M. Winter

Abstract

Three years after California passed the Sustainable Groundwater Management Act (SMGA), groundwater sustainability agencies (GSAs) are now preparing to develop their groundwater sustainability plans (GSPs), the blueprints that will outline each basin's road to sustainability. Successful GSPs will require an effective participatory decision-making process. We tested a participatory process with the Yolo County Flood Control and Water Conservation District, a water-limited irrigation district in the Central Valley. First, we worked with district stakeholders to outline the parts of the plan and set measureable objectives for sustainability. The district defined seven management strategies, which the research team evaluated against climate, land use and regulatory uncertainties using a water resources model. Together, we explored model results using customized interactive graphics. We found that the business-as-usual strategy was the most unlikely to meet sustainability objectives; and that a conjunctive use strategy, with winter groundwater recharge and periphery ponds storage, achieved acceptable measures of sustainability under multiple uncertainties, including a hypothetical pumping curtailment. The process developed a shared understanding of the vulnerabilities of the local groundwater situation and proved valuable in evaluating strategies to overcome them.

Groundwater is an important water supply source in California. On average, it provides 38% of California's total water supply (DWR 2015) and supports a $46 billion agricultural economy (USDA 2015). While the extent of groundwater use varies across the state, overall it has been increasing, from an estimated 9 million acre-feet in 1947 to 20.9 million acre-feet per year from 2005 to 2009 (DWR 2015). Groundwater contributes to farmers' economic stability by providing a buffer to water supply variability. However, over-reliance on groundwater has led to overdraft, which threatens its long-term sustainability.

Until recently, groundwater use in California was mainly unregulated by the state and left largely to local management. With a few exceptions in adjudicated basins, groundwater could be pumped without restriction for beneficial use on the overlying land area. This has led to a "tragedy of the commons" (Hardin 1968), with individual groundwater pumpers rationally overusing the shared resource.

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As required by the 2014 Sustainable Groundwater Management Act, groundwater agencies throughout California are beginning to develop plans for achieving groundwater sustainability. Research suggests that enabling effective stakeholder engagement and utilizing a water resources model are key to a successful planning process.

Kelly M. Grow, California Department of Water Resources

First comprehensive law on groundwater

In the fall of 2014, as a fourth consecutive year of drought was imminent, California lawmakers passed the state's first comprehensive law on groundwater, the Sustainable Groundwater Management Act (SGMA). It required local (typically county to subcounty scale) agencies in designated medium- and high-priority basins to self-organize by June 30, 2017, to form local governing bodies, called groundwater sustainability agencies (GSAs) (DWR 2014).

GSA formation rules

Each basin may have different variations of governing bodies, ranging from one GSA for the entire basin to many GSAs that coordinate (Conrad et al. 2016). GSAs can be made up only of public entities within the basin that already have water supply, water management or land use responsibilities (California Water Code [CWC] § 10721(n)). This means that farmers and private landowners, the biggest water users in many basins, cannot form a GSA. It is up to the GSAs to decide whether and how to include them through legal agreements (CWC § 10726.6), such as a memorandum of agreement, or by establishing a joint powers authority (see Kincaid and Stager 2015 for details on various other legal options for forming GSAs).

GSP development framework

Each basin must develop a groundwater sustainability plan (GSP) by 2020 (for critically overdrafted basins) or 2022 (for other high- or medium-priority basins). The plan must present the ways in which the GSAs will measure and achieve sustainability within the basin. Basins have 20 years to achieve groundwater sustainability. If the GSAs cannot sufficiently develop and implement a GSP, the state will step in to enforce groundwater management. Part 2.74, chapter six of SGMA and the GSP Emergency Regulations describe in detail what the GSP should contain, including GSP components, methodologies, assumptions and evaluation criteria. The sidebar "Required contents of GSPs" summarizes these requirements.

Stakeholders' involvement is required

GSAs are required to consider "all interests of all beneficial uses and users of groundwater" (CWC § 10723.2) in developing the GSP. CWC § 10723.2 includes a (nonexclusive) list of beneficial users who must be considered, including agricultural users, domestic well owners, operators of public and municipal water systems, land use planning agencies, federal government, California American Indian tribes, disadvantaged communities, environmental users, and surface water users if the surface water and groundwater are connected hydrologically. Before beginning GSP development, the GSA must make public the procedures for how interested parties can participate (CWC § 10727.8), with the intention of including a diverse population in the stakeholder group that is representative of the basin population.

Questions GSAs are facing

Our research was motivated by three key questions that GSAs are facing as they enter the GSP development phase.

The first is, what kind of planning process can effectively support GSA decision-making? The focus of water managers, practitioners and researchers so far has understandably been on GSA formation (e.g., Kincaid and Stager 2015; Kiparsky 2016; Kiparsky et al. 2016; Moran and Cravens 2015; Water Education Foundation 2015). However, GSAs are now facing many challenging decisions as they develop their GSPs, including how to articulate their sustainability goal and related minimum thresholds, measureable objectives, sustainability indicators and management actions (see the Glossary for definitions of these terms). Beyond guidance on SGMA's statutory requirements, there exists little information on how local GSAs can design a planning process that can successfully develop these key components of the GSP.

The second question is, how can the design of the planning process enable effective stakeholder engagement? There are statutory requirements for stakeholder

Required contents of GSPs

The following elements are required in GSPs.

- Administrative information about the GSA, GSP and the plan area (CCR Article 5, Subarticle 1).
- An explanation of the basin setting, including maps, a hydrogeologic conceptual model, and current, future (50 years ahead) and historical (at least 10 years into the past) water budget information, which may be developed using a numerical groundwater and surface water model or "an equally effective method, tool or analytical model" (CCR Article 5, Subarticle 2).
- Sustainable management criteria, which define the basin's sustainability goal, describe the six undesirable results and how they pertain to the basin and describe the minimum thresholds and measureable objectives for identified sustainability indicators (CCR Article 5, Subarticle 3)*.
- A description of the monitoring network and network objectives, along with an explanation of how the monitoring network adequately covers the basin, and detailed information on procedures and protocols associated with monitoring (CCR Article 5, Subarticle 4).
- An explanation of project and management actions and how these actions maintain the minimum thresholds, meet measureable objectives and therefore achieve the sustainability goal (CCR Article 5, Subarticle 5)*.
- Interagency coordination agreements if there are multiple GSAs in a basin and more than one GSP (CCR Article 8).

* These are the requirements that the planning process addresses most directly.

inclusion during both GSA formation and GSP development and implementation. These requirements include public hearings, meetings and disseminating information to interested individuals (e.g., CWC §§ 10723(b), 10723.4, 10723.8(a)(4) and 10728.4). "Active involvement of diverse social, cultural and economic elements of the population" is required (CWC § 10727.8(b)), but how do GSAs ensure this involvement is effective and leads to the development of a plan that is well received?

Effective engagement is important especially because, as with any new policy, local stakeholders may resist new regulations that are perceived to negatively impact current modes of operation (Arbuckle et al. 2015; Haden et al. 2012; Niles et al. 2013). Surveys show that farmers perceive greater risk from potential climate change policies than they do from climate change itself (Haden et al. 2012; Haden et al. 2013; Niles et al. 2013). If similar perceptions about SGMA exist, implementation of local groundwater policy will be more likely to succeed if an inclusive policy development process is used, one in which major water users (farmers) are involved in policy development even if not officially part of the GSA. In the case of SGMA, farmers already fear they will have to inequitably bear substantial additional costs, with expectations that the relative burden will be higher for smaller growers (Rudnick et al. 2016).

The third question is, how can models inform the planning process? While models are not strictly required by SGMA, given the complexity of human-biophysical connections in these basins, and the requirement that GSPs use a 50-year planning horizon, GSAs are likely to need models and related technical support to develop GSPs (Christian-Smith and Alvord 2016; Kiparsky 2016; Moran 2016). Not least among the model's uses will be the handling of uncertainties into the future.

To address these three questions, we designed a case study to apply a decision support process in a water district in the Central Valley, the Yolo County Flood Control and Water Conservation District (henceforth, District). The study was conducted with District management staff in 2014–2015 through quarterly workshops and monthly meetings. This was after the passing of SGMA but before the June 2017 formation of the Yolo GSA, which is called the Yolo Subbasin Groundwater Agency (YSGA). YSGA had 19 signatories to a joint powers authority, including the District. Our objective was to gain experience from this study and be able to guide GSAs, their partnering consultants and researchers on how to develop key requirements of GSPs in a comprehensive and collaborative manner that meets the statute's requirements while receiving broad support from diverse water users.

Glossary

Measurable objectives: Specific, quantifiable goals for the maintenance or improvement of specified groundwater conditions that have been included in an adopted plan to achieve the sustainability goal for the basin (California Code of Regulations [CCR] § 351(s)).

Minimum threshold: A numeric value for each sustainability indicator used to define undesirable results (CCR § 351(t)).

Sustainability goal: The existence and implementation of one or more groundwater sustainability plans that achieve sustainable groundwater management by identifying and causing the implementation of measures targeted to ensure that the applicable basin is operated within its sustainable yield (Water Code § 10721(u)).

Sustainability indicator: Any of the effects caused by groundwater conditions occurring throughout the basin that, when significant and unreasonable, cause undesirable results, as described in Water Code § 10721(x) (CCR § 351(ah)).

Uncertainty: A lack of understanding of the basin setting that significantly affects an agency's ability to develop sustainable management criteria and appropriate projects and management actions in a plan, or to evaluate the efficacy of plan implementation, and therefore may limit the ability to assess whether a basin is being sustainably managed (CCR § 351(ai)).

Undesirable result: Any 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 if continued over the planning and implementation horizon.
- Significant and unreasonable reduction of groundwater storage.
- Significant and unreasonable seawater intrusion.
- Significant and unreasonable degraded water quality, including the migration of contaminant plumes that impair water supplies.
- Significant and unreasonable land subsidence that substantially interferes with surface land uses.
- Depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water (Water Code § 10721(x)).

The decision support process

Findings from the literature (see the sidebar "Elements of a decision support process for GSAs" and fig. 1, next page) suggest that an appropriate decision support process for GSAs should include three key elements: (1) a formal problem-structuring approach, capable of incorporating uncertainties, defining shared objectives and evaluating alternatives and trade-offs, (2) deep levels of stakeholder participation that facilitate collective learning through iteration and (3) model development and use with appropriate analytics that are driven by (1).

The decision support process we used in our study, developed in 2012 by the Stockholm Environment Institute (SEI) and its research partners (Bresney et al. 2017), aligns well with these elements. It is related to and informed by robust decision-making (e.g., Groves and Bloom 2013; Kalra et al. 2015; Kasprzyk et al. 2013) but places a greater emphasis on

Elements of a decision support process for GSAs

The literature suggests that a decision support process should include three key elements:

A formal problem-structuring approach: People can be quite poor at making complex decisions without assistance (Slovic 2000; Slovic et al. 1977), which points to the critical importance of providing formal structure to a decision at hand, even if that structure simply follows common sense. A structured decision-making approach helps by splitting a difficult decision into its parts (Gregory and Keeney 2002) and addressing five fundamental tasks: framing the decision, defining objectives, establishing alternatives, identifying consequences and clarifying trade-offs (Gregory 2000). In the absence of a structured process, people in a stakeholder group are more likely to make decisions that do not address their concerns (Russo and Schoemaker 1989).

Deep levels of stakeholder participation: Stakeholder involvement can occur at various levels (Avison et al. 1999), from information extraction at the lowest level of engagement to participatory action research at the most engaged level, where research is iteratively directed by participants with the researcher acting only as the facilitator (fig. 1) (Forrester et al. 2008). The most appropriate level of engagement is context-specific; it should not be assumed that the highest level of engagement is always successful (Stern and Fineberg 1996).

As Dobbin et al. (2015) state, the benefits of effective and inclusive stakeholder engagement can include "improved outcomes, resource optimization, building support and reducing conflict," which are especially valuable benefits in the context of a shared resource like groundwater. However, as these authors go on to point out, exactly how to effectively engage stakeholders remains a question left to the GSAs to answer.

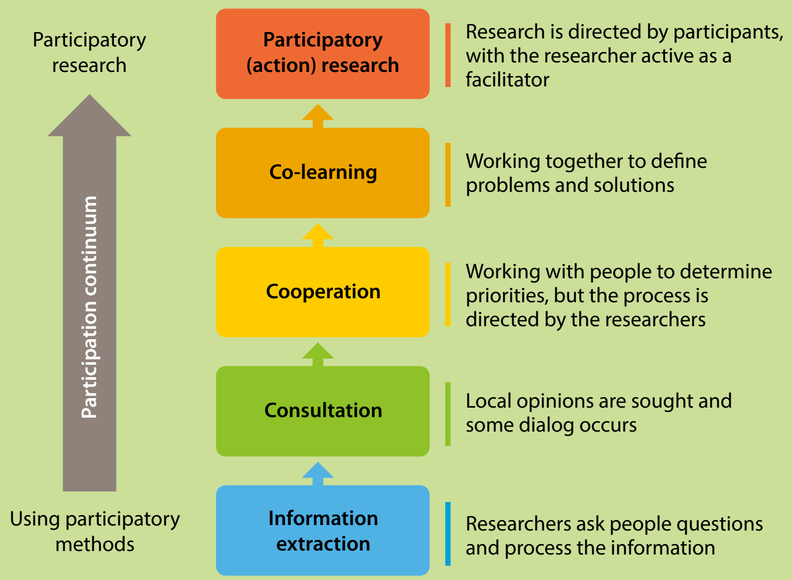

FIG. 1. Levels of engagement in participatory methods (Source: Forrester et al. 2008).

Most of SGMA's statutory requirements (e.g., concerning public hearings and meetings) are at the consultative end of the spectrum of stakeholder involvement (fig. 1). However, effective stakeholder engagement (i.e., engagement that leads to the potential benefits stated earlier) will depend on collective action being developed through a process that develops shared meaning and values (Pahl-Wostl et al. 2007) among stakeholders who have individual values, preferences and data. This will likely require deep levels of engagement that allow for collective learning to occur through iteration (Heikkila and Gerlak 2013; Pahl-Wostl et al. 2007). Collective learning leads to collective action through the development of new ideas (or the re-enforcement of existing ones) as well as through changes in more fundamental aspects like rules, policies or organizational structure (Argyris 1976; Heikkila and Gerlak 2013).

Model development and use: Quantitative computer modeling can aid decision-making using simulation or optimization approaches, with some organization of preferences when multiple objectives are involved. It can improve the quality of individual and group choices in the face of uncertainty (Keeney and Raiffa 1993; Lempert et al. 2003). Classical (utility theory-based) decision analysis, traditional scenario planning, robust decision-making, multicriteria decision analysis (MCDA), and real options and portfolio planning are some examples of analytical models and methods from the decision analysis literature. As with the level of stakeholder engagement, the type and extent of decision analytics used should be specific to the problem at hand.

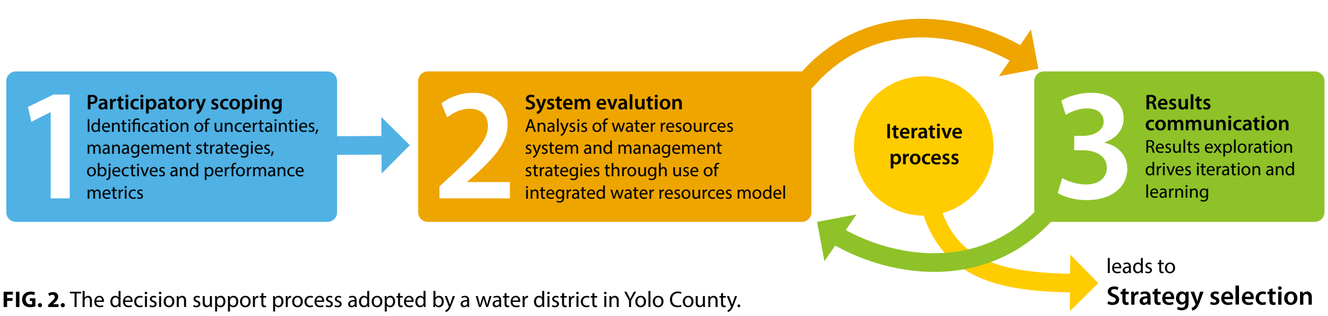

FIG. 2. The decision support process adopted by a water district in Yolo County.

stakeholder engagement. We have applied its three steps (fig. 2) effectively in various water resources planning contexts, in both single- and multi-stakeholder situations. Recent examples of its application include supporting integrated regional water management (IRWM) planning in Yuba County, California (Forni et al. 2016), urban water planning in Bolivia (Forni et al. 2016), water and power sector planning in seven African river basins (Cervigni et al. 2015), and river basin planning in Colombia and Peru (Bresney et al. 2017).

Study area

The focus of this study was in the management area of the Yolo County Flood Control and Water Conservation District (District) in Yolo County in California's Central Valley (fig. 3). The county's main land use is agriculture, and irrigation accounts for close to 95% of human water use (Borcalli and Associates 2000). Farmers in this region respond to water shortages by using more groundwater, adopting low-volume irrigation technology and fallowing low-value crops (Haden et al. 2012).

The District covers 41% of Yolo County's irrigated area and has provided its agricultural customers with surface water from Cache Creek via Clear Lake since the District was established in 1951 and from Indian Valley Reservoir since it was built in 1976. Water availability from Clear Lake is constrained by the Solano Decree, which sets limits on water releases (CA Superior Court 1978; CA Superior Court 1995). Despite the flexibility offered by the District-owned Indian Valley Reservoir, there have been 3 years of severe drought in the past 40 years when the District could not supply any water to its customers: 1977, 1990 and 2014.

Total irrigation demand exceeds what the District can supply, even in a wet year. Groundwater use (all through private means since the District does not supply groundwater) makes up the shortfall and has been estimated to account for 49% of total water demand on average between 1971 and 2000 (Mehta et al. 2013), ranging from a high of 100% in dry years to a low of 36% in wet years. The groundwater basin experienced some depletion of storage in the 1970s but recovered in wet years (fig. 4). Increased storage and provision of surface water by Indian Valley Reservoir has helped recovery of groundwater levels in Yolo County in recent decades (Borcalli and Associates 2000). Further details of the area managed by the District are provided in Mehta et al. (2013).

Step 1: participatory scoping

Participatory scoping, the first step (fig. 2) of the process we tested with the District, involves formal problem structuring. Discussion of the collective objectives, measures of success (or failure), key uncertainties and management strategies takes place in this step, at

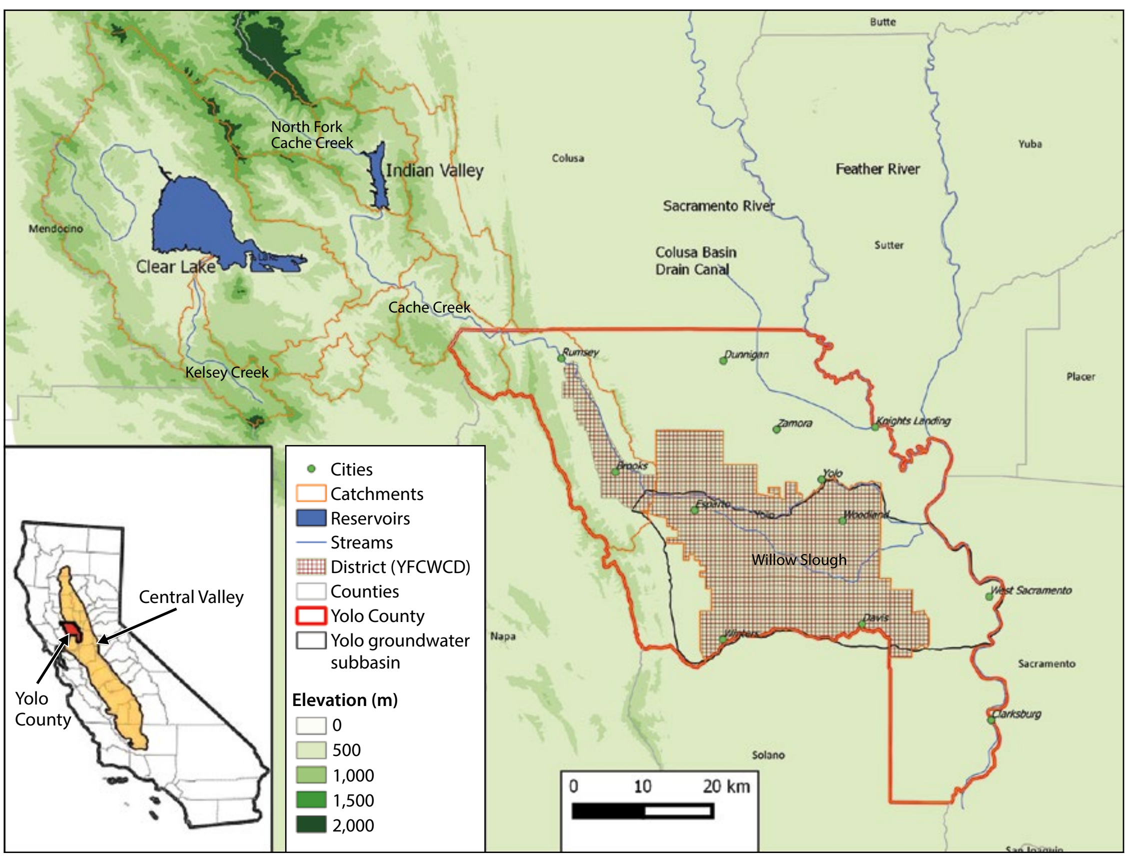

FIG. 3. Study area showing modeled catchments, county and district boundaries, reservoirs and rivers.

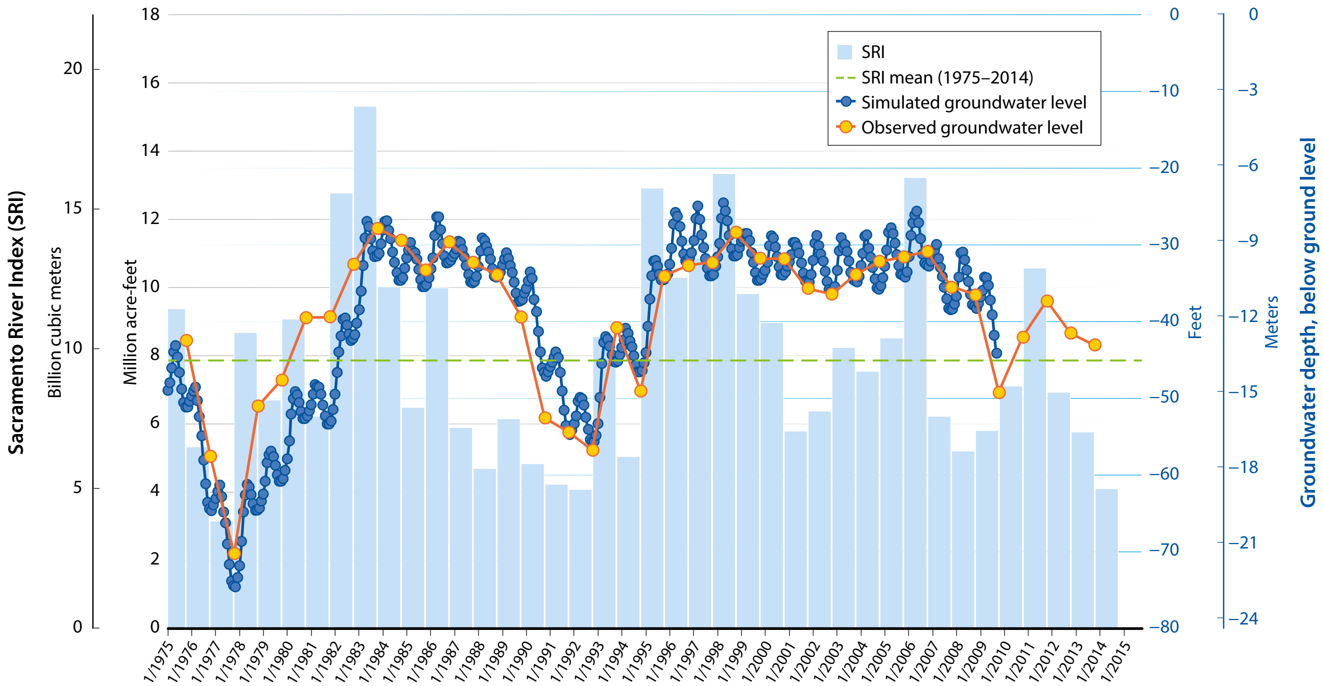

FIG. 4. Observed (water year [WY] 1975–WY2014) and modeled (WY1975–WY2009) groundwater depths in the case study area. The SRI (Sacramento River Index) is a sum of unimpaired flow from four points throughout the Sacramento basin. Observed values are from fall and represent the average of up to 99 wells. Observations show well drawdowns in the major droughts of 1976–1977, the late 1980s and the last few years. They also show recovery after drought.

a deep level of engagement between stakeholders and their technical support. This is where GSAs starting the process of developing a GSP would identify minimum thresholds, measureable objectives, sustainability indicators and management actions, possibly with the help of trained facilitators.

Participatory scoping exercises were carried out using the XLRM problem elicitation method. We used this method because we have had positive experiences with it, and because it is a well-tested method for problem structuring at the California statewide water planning scale (Groves and Bloom 2013) as well as in environmental decision-making elsewhere (e.g., Groves et al. 2014; Isley et al. 2015; Kalra et al. 2015; Kasprzyk et al. 2013; Murray et al. 2012; Ocampo Melgar et al. 2015). The XLRM method has stakeholders identify four aspects of the problem — exogenous factors, levers, relationships and metrics (table 1).

Exogenous factors (X)

Exogenous factors, or uncertainties, that are outside the control of water managers, must be considered in GSPs. The District defined three categories of uncertainties important to them and their management goals: climate, land use, and groundwater pumping curtailment (table 1).

Climate. Dry climates were of particular interest to the District staff because of the 3 years when the Solano Decree stipulations resulted in no available water supply. Discussions led to the District requesting climate projections for a 30-year future based on three different climate regimes: recent climate, severe drought climate and average climate. The methods used to develop these 30-year sequences (30 years corresponds to their planning horizon) based on paleoclimatic reconstructions are outlined in supporting information S1 online.

Land use. Cropping patterns have been dynamic in Yolo County, reflecting spatial heterogeneity, changes in water availability over decades and responses to agricultural markets. The District's main concern was their observation of increased planting of new orchards, despite the fourth consecutive drought year. This change, also observed over five decades from the County Agricultural Crop Statistics data, has imposed a hardening of demand for water, because unlike annual crops, orchard crops cannot be fallowed. This implies that farmers will ensure reliable water supply even in a dry year by pumping groundwater.

Two projections of land use in the model captured the District's concern: we calculated groundwater use based on (1) the existing demand, keeping land use at 2014 levels and (2) on a hardening of demand over 25 years, from 14,400 acres (58.3 square kilometers) of unirrigated pasture and rangeland and 12,000 acres (48.6 square kilometers) of field crops being converted to new orchards. Within both projections, the growers'

TABLE 1. XLRM problem formulation

X (exogenous factors, uncertainties)	L (levers, management strategies)
Climate Land use Groundwater pumping curtailment	1. Business as usual (current management) 2, 3, 4. District pumping with 2, 10 and 20 pumps, respectively 5. Winter recharge 6. Periphery pond storage 7. Combination of Strategies 3, 5 and 6
R (relationships, system model)	**M (metrics of performance)**
Cache Creek model (in WEAP)	Water supply reliability Financial viability Groundwater sustainability

response to drought was included by converting 10% of tomatoes to less water-consuming safflower and idling 4,000 acres (16.2 square kilometers) of rice within the District. These were realistic short-term coping strategies identified by District management based on their knowledge of farmer practices and the land area that can be serviced by their existing canal system.

Pumping curtailment. In this case study, we implemented a hypothetical pumping curtailment that the Yolo GSA might consider in its GSP. This hypothetical curtailment would restrict groundwater pumping whenever groundwater levels fell below a threshold. We tested curtailment of pumping for purposes of illustration only; it may not be one of the actions that the Yolo basin GSA considers in its final GSP. We chose a threshold informed by the lowest observed groundwater levels, which occurred during the 1977 drought, when the average of 99 well observations reached 77 feet (23.5 meters) below ground level (BGL). We constructed two projections: one without any curtailment, and the other with a curtailment stipulating that no groundwater pumping can occur when the average groundwater level falls below 80 feet at any time step.

The District preferred to address pumping curtailment as an uncertainty (X) because, at the time of our case study, before the GSA was formed, potential implications of SGMA were outside of the District's control. However, curtailment would likely be cast as a strategy (an L in the XLRM method) if adopted now by the GSA.

Levers (L)

Levers are management strategies such as infrastructure enhancements or changes in operations rules that can be implemented by water managers. A lever is the equivalent of a management action in the GSP. Table 2 summarizes the seven strategies that were elicited from the District and investigated in the model. Strategy 1, business as usual (BAU), assumes current management into the future, with no changes in water supply. Strategies 2, 3 and 4 explore three levels of pumping, based on an exploratory study commissioned by the District (YCFCWCD 2009). They reflect the District's interest in investing in its own groundwater pumping infrastructure to stabilize its revenue and provide water in years when surface water is unavailable. The last three strategies involve implementing winter recharge (Strategy 5), periphery pond storage (Strategy 6) and a combination of the strategies (Strategy 7).

TABLE 2. District management strategies investigated

Strategy	Description
1. Business as usual (BAU)	Current management into the future.
2, 3, 4. District pumping with 2, 10 and 20 pumps, respectively	Groundwater infrastructure operated by the District. The 2, 10 and 20 pumps would extract approximately 2,000, 10,000 and 20,000 acre-feet per year for summer irrigation. Capital costs of $225,000/pumps. Loan payment at 1.7% interest over 15 years.
5. Winter recharge	The unlined canal network is a substantial source of groundwater recharge (Borcalli and Associates 2000; YCFCWCD 2012). Winter runoff directed (November to February) into the canal network, recharging up to 150 cubic feet per second (cfs) when Cache Creek flows are greater than 100 cfs. Existing infrastructure would be used.
6. Periphery pond storage	Storage of up to 20,000 acre-feet in four ponds that would be filled in the winter and used in the summer. Some of the directed flows would percolate (up to 50 cfs); the rest (up to 150 cfs) would be available to fill the ponds from November to February. Estimated investment of $20 million, financed at 1.7% interest over 15 years. Water supplied by this source would be priced higher, at $100 per acre-feet.
7. Combined strategies	District pumping at 10,000 acre-feet per year (Strategy 3), with winter recharge (Strategy 5) and periphery pond storage (Strategy 6).

Relationships (R)

The relationships between identified uncertainties and levers inform the development of a system model. Creating that model fulfills the GSP requirement of an effective method, tool or analytical model for assessing management actions. For the District, we evaluated scenarios of combined uncertainties and management strategies using an integrated water resources model for the Cache Creek system. The model was previously built in collaboration with the District to evaluate irrigation demand and supply under land use and climate change (Mehta et al. 2013). Developed using the Water Evaluation and Planning (WEAP) platform (Yates et al. 2005), it simulates the climate-driven water balance of each catchment shown in figure 3, along with municipal and irrigation demand, water resources infrastructure operation and allocation.

While WEAP was determined to be the best tool for this analysis, other modeling software and tools may be used to deploy this decision support process. Details of model development and calibration across multiple dimensions (hydrologic flows, reservoir operations, and applied irrigation water for 17 crops) are in Mehta et al. (2013) and summarized in supporting information S2 online.

For this study, the Cache Creek model was enhanced in four ways: WEAP's financial routines were used to evaluate the financial outcomes and metrics of performance. Since groundwater depth was an important metric of performance, we included WEAP's groundwater–surface water interaction routines described in Yates et al. (2005), calibrating the lumped groundwater model output to the average fall (deepest) groundwater depths of 99 monitoring wells in the area (fig. 4). We extended the hydroclimatic database to include water years 1950 to 2009. And we included model enhancements so that each of our seven strategies could be evaluated.

Metrics of performance (M)

Metrics of performance (e.g., supply reliability and reservoir storage levels) are used to evaluate the success or failure of various management strategies. They encompass the required sustainability indicators, minimum thresholds and measureable objectives. Table 3 describes the objectives and related metrics articulated by the District. These are measureable outcomes that evaluate the success of the management strategies under various uncertainty scenarios.

The metrics demonstrate how the scoping process allowed stakeholders to create a multifaceted articulation of sustainability, what sustainability meant to them, rather than limiting themselves to only avoiding the six undesirable results mentioned in SGMA. If, for example, the emphasis were simply to avoid the undesirable results, GSP actions could lower groundwater levels, as required, but fail to be financially viable for farmers and water districts.

Step 2: system evaluation

In the second step of our decision support process (fig. 2), quantitative tasks (often involving computer models of the basin) are undertaken that are driven by the first step. With the District, we automated model runs using Visual Basic (VB) scripts and the WEAP Application Programming Interface (API). The ensemble covered 84 combinations of the seven identified strategies, two demand projections, three climate projections and two groundwater pumping curtailment projections.

We extracted key outputs from each run that included (but were not limited to) the metrics of performance listed in table 3. We processed and analyzed the data in R (R Development Core Team 2016) and created customized, interactive graphics in Tableau software (Tableau Software 2010) to communicate the results to the District.

Step 3: results communication, decisions

The third step of our process (fig. 2) involved collective learning (for both stakeholders and us, their technical support) about the basin, as we quantitatively explored the basin's vulnerabilities and opportunities through studying the data interactively. It's at this step that GSAs can evaluate whether the management actions are likely to achieve the measureable objectives and overall sustainability goal under different types and degrees of uncertainty. The process of iteration involves the search for new and innovative strategies based on the learnings from previous rounds of results exploration. It may result in a GSA revising its management actions or developing new actions with stakeholders.

In the sixth and seventh workshop with the District, in 2015, we presented the results of model runs that incorporated the information created by the XLRM exercise. We explored the results together, which led to model refinements as well as refinements of management strategies; table 2 presents the final product of our iterative process. The interactive visualizations of key

TABLE 3. Objectives and related metrics

Objective	Performance metric/ sustainability indicator	Description
Water supply reliability	April 1 Clear Lake level (feet)	Indicator of the District's water availability from Clear Lake. No water is available for irrigation at lake levels below 3.22 feet (0.98 meter).
	Total April 1 water supply (acre-feet)	Clear Lake allocation plus Indian Valley Reservoir storage.
	Irrigation water demand (acre-feet)	Annual irrigation demand.
	Water supply reliability (%)*	Percentage of years when 100% of water demand is met. Less than 100% reliability can occur when groundwater regulation is enforced and pumping is curtailed.
Financial viability	Net present value (NPV) ($)	Net present value of annual District net revenue values over period of simulation.
	Financial viability (%)	Zero when NPV is negative in any scenario, 100% when NPV is positive. Sets a threshold of performance requiring NPV to be positive.
Groundwater sustainability	Groundwater depth (feet)	Average groundwater depth in the District.
	Groundwater reliability (%)	Percentage of years when maximum groundwater depth exceeds the threshold of 80 feet BGL, which is the groundwater regulation that is illustrated here.

* Italics indicate the selected metrics used to quantify the corresponding objectives for assessment of strategies in the final step of the process.

system objectives and performance metrics involved several customized graphics: figure 5 shows one example. For each graphic, we toggled uncertainties and strategies in real time to enhance group exploration and learning.

The District confirmed that interactive visualizing of results allowed them to better understand the system and feel more comfortable about the effect of their decisions. However, even with the graphics, it was challenging to weigh decisions and actions against each other, so, using Tableau, we developed a summary graphic with information from all 84 model simulations (fig. 6). It summarized the seven strategies (and 84 scenarios) against the three key metrics of performance: groundwater sustainability, water supply reliability and financial viability, showing the percentage of time within the simulation period of 30 years during which desired levels of performance were achieved (i.e., groundwater depth above the threshold of 80 feet BGL and unrestricted irrigation water).

The summary graphic communicated the following messages: (1) Except under severe drought, the District's outlook is positive in all scenarios irrespective of strategy. And (2) should severe drought (as severe as the paleoclimate reconstruction suggests) occur, groundwater sustainability of the Yolo subbasin (at the threshold defined) is seriously undermined unless regulation occurs; there is a trade-off in protecting groundwater against securing water supply reliability for farmers; and financial viability of the District is at risk and can only be mitigated by Strategies 6 (periphery ponds) and 7 (combined strategies).

Another view of the trade-offs is provided by table 4, which ranks the strategies using the data in figure 6, except the financial viability ranking is based on estimated net present values (NPVs), not a binary transformation. We saw that no one strategy performs best across all performance metrics. A selection based only on financial viability would lead to a preference

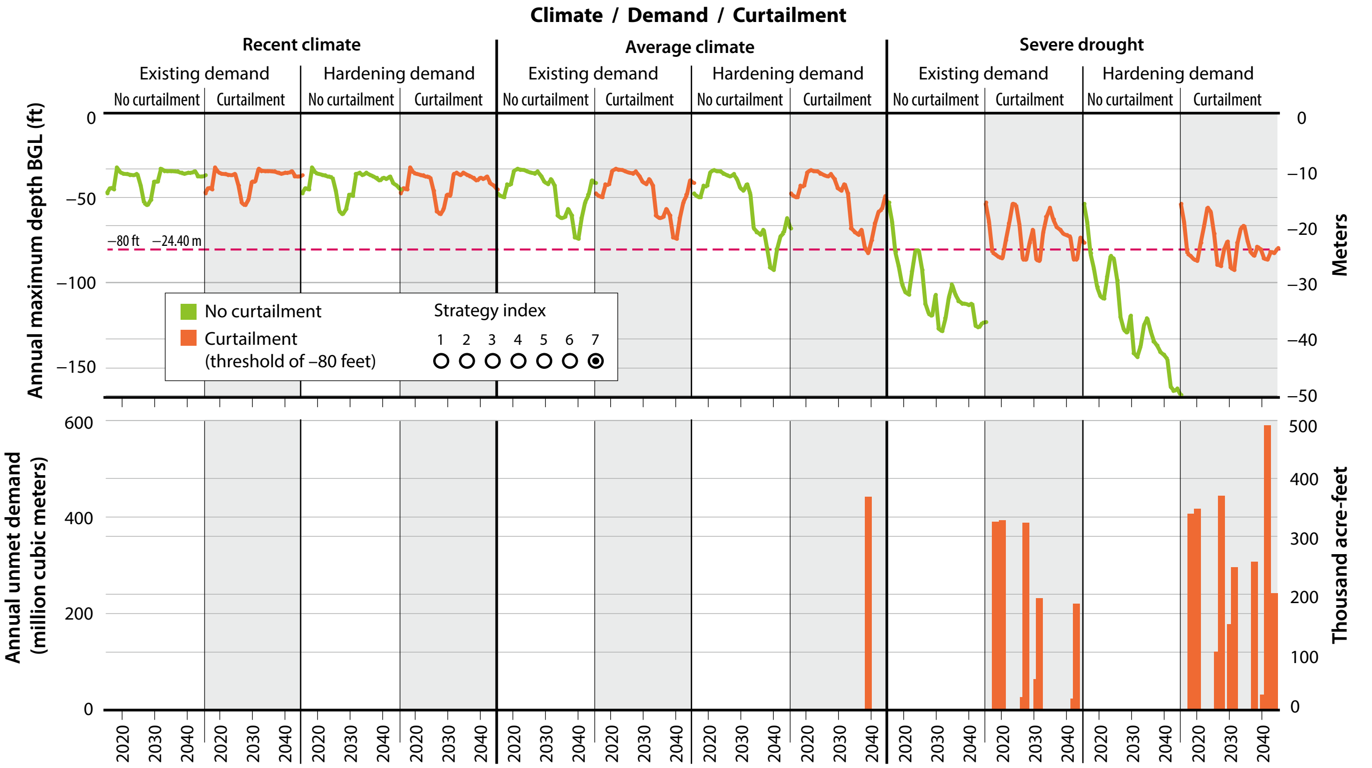

FIG. 5. Modeled maximum annual depths of groundwater below ground level (BGL) (top panel) and unmet irrigation demand (bottom panel) for each climate and demand scenario corresponding to Strategy 7. Groundwater depths recover to existing levels in the nondrought climates and stay above the 80-foot threshold (dotted line, top panel) except in one year, under the hardening demand scenario. In the two severe drought scenarios without groundwater use curtailments, groundwater levels fall, reaching about 125 to 164 feet. When groundwater pumping is curtailed, levels remain close to the 80-foot threshold. In the worst-case scenario (bottom right panel) under Strategy 7, there are 12 years with irrigation water shortages (unmet demand > 0). The largest shortage occurred in a year when there was little surface water available and the groundwater level exceeded the threshold for pumping curtailment. We toggled through strategies to gauge the response of these two metrics of performance (unmet demand and groundwater depth) to each management action.

Climate, demand and curtailment scenarios, and strategy number

Scale: 0 – 100

Recent climate — Existing demand

	No curtailment							Curtailment						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Groundwater sustainability	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Water supply reliability	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Financial visibility	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Average climate — Existing demand

	No curtailment							Curtailment						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Groundwater sustainability	100	97	97	97	100	100	100	100	97	97	97	100	100	100
Water supply reliability	100	100	100	100	100	100	100	93	93	93	93	100	100	100
Financial visibility	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Severe drought — Existing demand

	No curtailment							Curtailment						
	1	2	3	4	5	6	7	1	2	3	4	5	6	7
Groundwater sustainability	7	7	7	7	13	7	7	60	60	53	57	67	67	67
Water supply reliability	100	100	100	100	100	100	100	60	60	60	60	70	67	67
Financial visibility	0	0	0	0	0	100	100	0	0	0	0	0	100	100

FIG. 6. Trade-offs visualization. The three chosen sustainability metrics are shown here on a common scale of 0% to 100% for all 84 model runs. Financial viability is on a binary scale (0% if the net present value (NPV) of the annual net benefits is negative, 100% if NPV is positive). Groundwater sustainability and water supply reliability are on a continuous scale from 0% to 100%. A cell value of 100% means that the threshold for that scenario was met in all 30 years of the model run.

for Strategy 6, with its highest average NPV of $35.4 million. However, this strategy ranks third for groundwater sustainability and water supply reliability.

Limitations, power dynamics

A limitation of our process is that it cannot by itself produce the entire GSP, which includes many statutory requirements, for example, on monitoring and on interagency coordination; these items are beyond the direct scope of a decision support process. In terms of the levels of engagement in figure 1, our work with the District was at the co-learning level. We anticipate that most GSAs will need at least this level of engagement for successful GSPs.

As in any planning process, the effectiveness of a GSP is contingent on the nature of stakeholder interaction. Our process has been proven successful to promote cooperation between agencies formerly unlikely to cooperate, once they agree to participate (Forni et al. 2016), and therefore would likely be successful in developing many key parts of a GSP (the articulation of sustainability goals, indicators, thresholds and management actions, the use of models and stakeholder engagement) in a robust and inclusive way. However, the process cannot ensure that all necessary parties will participate. Here, power dynamics and the existing (non)inclusiveness of the GSA will influence the overall robustness of the plan, especially in dimensions concerning fairness of its decisions (Kiparsky et al. 2016).

Of particular concern are basins where historically the power dynamics have been against the many rural, unincorporated communities (there are more than 400 in the Central Valley) whose challenges in securing domestic water are well documented (e.g., Balazs and Ray 2014; Pannu 2012). In noninclusive, inequitable settings, oversight by California Department of Water Resources (DWR) and the larger community of SGMA practitioners in the state should ensure that these communities' interests are included in the GSP through decision-making power in the GSA. This could ensure that the process we describe here does not end up further serving the interests of only a few, at the possible detriment of communities that have historically been marginalized. The recent guidance documents provided by DWR on stakeholder engagement (DWR 2017a; DWR 2017b) as well as DWR's funding support for professional facilitator services could be put to good use in these circumstances.

As mentioned earlier, the Yolo Subbasin Groundwater Agency (YSGA) was formed, after our case study, with many stakeholders. Our case study was limited to a single stakeholder, the District, but our other experiences with this decision support process in multistakeholder settings provide confidence in its value for multistakeholder GSA settings. We have seen how the process allows stakeholders to go beyond the double-negative definition of sustainability (avoiding the undesirable results) and engage in more aspirational work (what can be gained from better collaboration?). In doing so, creative, mutually beneficial solutions across different sectors are created, "innovative" solutions that Kiparsky (2016) points out are necessary for SGMA to be successful.

TABLE 4. Ranking of strategies*

Strategy	Financial viability†	Water supply reliability	Groundwater sustainability
1	5 ($14.7M)	4	4
2	4 ($15.0M)	4	5
3	6 ($14.3M)	7	7
4	7 ($14.2M)	4	6
5	3 ($15.1M)	1	1
6	1 ($35.4M)	3	3
7	2 ($30.1M)	1	2

* Ranking is based on average performance over the 12 scenarios of uncertainty (three climate × two land use × two regulatory).

† Numbers in parentheses are average net present value (NPV) in $ millions, calculated over the 12 scenarios.

Ongoing work with YSGA

At the time of this writing, we are supporting the YSGA in developing its GSP using the process described here. Some of the creative solutions that it might consider have been detailed in this study. Deliberations might also include conjunctive use management strategies that deploy winter runoff on fields, which has been explored in Kings County (Bachand et al. 2014).

Recently completed focus group interviews with Yolo County farmers point to additional management strategies and local policy that the YSGA might investigate: water trading, prioritizing surface water use, a drilling moratorium, new infrastructure, and providing incentives for farmers such as credits for recharge or water conservation (Niles and Hammond Wagner 2017, page 38 in this issue). We will also be incorporating insights from an ongoing farmer survey within a hydroeconomic model to investigate the economic impacts of potential management strategies. CA

We have seen how the process allows stakeholders to go beyond the double-negative definition of sustainability (avoiding the undesirable results) and engage in more aspirational work (what can be gained from better collaboration?).

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References

Arbuckle JG, Morton LW, Hobbs J. 2015. Understanding farmer perspectives on climate change adaptation and mitigation: The roles of trust in sources of climate information, climate change beliefs, and perceived risk. Environ Behav 47:205–34. doi:10.1177/0013916513503832

Argyris C. 1976. Single-loop and double-loop models in research on decision making. Admin Sci Quart 21:363. doi:10.2307/2391848

Avison DE, Lau F, Myers MD, et al. 1999. Action research. Commun ACM 42:94–7.

Bachand PAM, Roy SB, Choperena J, et al. 2014. Implications of using on-farm flood flow capture to recharge groundwater and mitigate flood risks along the Kings River, CA. Environ Sci Technol 48:13601–9. doi:10.1021/es501115c

Balazs CL, Ray I. 2014. The drinking water disparities framework: On the origins and persistence of inequities in exposure. Am J Public Health 104:603–11. doi:10.2105/AJPH.2013.301664

Borcalli and Associates I. 2000. Water Management Plan, Yolo County Flood Control and Water Conservation District. 118 p.

Bresney S, Moncada Aguirre AM, Escobar M. 2017. How Governance Affects Participation: Insights from Water Resources Planning Projects in Colombia and Peru. Stockholm Environment Institute, Stockholm, Sweden. 8 p. www.sei-international.org/publications?pid=3115 (accessed Sep 26, 2017).

Cervigni R, Liden R, Neumann JE, Strzepek KM (eds.). 2015. Enhancing the Climate Resilience of Africa's Infrastructure. Africa Development Forum series. World Bank, Washington DC. 178 p. doi:10.1596/978-1-4648-0466-3

Christian-Smith J, Alvord A. 2016. The devil is in the data: The role of science, data, and models in California's historic Sustainable Groundwater Management Act. Calif J Polit Policy 8(3):1–6. doi:10.5070/P2cjpp8331696

Conrad E, Martinez J, Moran T, et al. 2016. To Consolidate or Coordinate? Status of the Formation of Groundwater Sustainability Agencies in California. Stanford University, Stanford, CA. 44 p.

Dobbin KJ, Clary LF, Christian-Smith J. 2015. Collaborating for Success: Stakeholder Engagement for Sustainable Groundwater Management Act Implementation. Community Water Center, Sacramento, CA. 41 p.

[DWR] California Department of Water Resources. 2014. California Groundwater Elevation Monitoring: Basin Prioritization Process. Sacramento, CA. 28 p.

DWR. 2015. California's Groundwater Update 2013: A Compilation of Enhanced Content for California Water Plan Update 2013. Sacramento, CA. 98 p.

DWR. 2017a. Guidance Document for the Sustainable Management of Groundwater: Engagement with Tribal Governments. Sacramento, CA. 9 p.

DWR. 2017b. Guidance Document for Groundwater Sustainability Plan: Stakeholder Communication and Engagement. Sacramento, CA. 15 p.

Forni LG, Galaitsi SE, Mehta VK, et al. 2016. Exploring scientific information for policy making under deep uncertainty. Environ Modell Softw 86:232–47. doi:10.1016/j.envsoft.2016.09.021

Forrester J, Swartling G, Lonsdale K. 2008. Stakeholder Engagement and the Work of SEI: An Empirical Study. Stockholm Environment Institute, Stockholm. 42 p. ISBN: 978-91-86125-09-7.

Gregory R. 2000. Using stakeholder values to make smarter environmental decisions. Environ Sci Policy Sustain Dev 42:34–44. doi:10.1080/00139150009604888

Gregory RS, Keeney RL. 2002. Making smarter environmental management decisions. JAWRA J Am Water Resour As 38:1601–12. doi:10.1111/j.1752-1688.2002.tb04367.x

Groves DG, Bloom E. 2013. Robust Water-Management Strategies for the California Water Plan Update 2013. RAND Corporation, Santa Monica, CA. 70 p.

Groves DG, Bloom E, Lempert RJ, et al. 2014. Developing key indicators for adaptive water planning. J Water Res Plan Man 141(7):05014008. doi:10.1061/(ASCE)WR.1943-5452.0000471

Haden VR, Dempsey M, Wheeler S, et al. 2013. Use of local greenhouse gas inventories to prioritise opportunities for climate action planning and voluntary mitigation by agricultural stakeholders in California. J Environ Plann Man 56:553–71. doi:10.1080/09640568.2012.689616

Haden VR, Niles MT, Lubell M, et al. 2012. Global and local concerns: What attitudes and beliefs motivate farmers to mitigate and adapt to climate change? PLoS ONE 7:e52882. doi:10.1371/journal.pone.0052882

Hardin G. 1968. The tragedy of the commons. Science 162:1243–8. doi:10.1126/science.162.3859.1243

Heikkila T, Gerlak AK. 2013. Building a conceptual approach to collective learning: Lessons for public policy scholars. Policy Stud J 41:484–512. doi:10.1111/psj.12026

Isley SC, Lempert RJ, Popper SW, et al. 2015. The effect of near-term policy choices on long-term greenhouse gas transformation pathways. Glob Environ Chang 34:147–58.

Kalra N, Groves DG, Bonzanigo L, et al. 2015. Robust Decision-Making in the Water Sector: A Strategy for Implementing Lima's Long-Term Water Resources Master Plan. Policy Research Working Paper 7439. World Bank, Washington, D.C. 43 p.

Kasprzyk JR, Nataraj S, Reed PM, et al. 2013. Many objective robust decision making for complex environmental systems undergoing change. Environ Modell Softw 42:55–71.

Keeney RL, Raiffa H. 1993. *Decisions with Multiple Objectives: Preferences and Value Trade-Offs*. Cambridge, UK: Cambridge Univ Pr. 573 p.

Kincaid V, Stager R. 2015. Know Your Options: A Guide to Forming Groundwater Sustainability Agencies. California Water Foundation, Sacramento, CA. 41 p.

Kiparsky M. 2016. Unanswered questions for implementation of the Sustainable Groundwater Management Act. Calif Agr 70:165–8. doi:10.3733/ca.2016a0014

Kiparsky M, Owen D, Green Nylen N, et al. 2016. Designing Effective Groundwater Sustainability Agencies: Criteria for Evaluation of Local Governance Options. Center for Law, Energy and the Environment, Berkeley, CA. 63 p.

Lempert RJ, Popper SW, Bankes SC. 2003. Shaping the Next One Hundred Years. RAND Corporation. 210 p.

Mehta VK, Haden VR, Joyce BA, et al. 2013. Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California. Agr Water Manage 117:70–82. doi:10.1016/j.agwat.2012.10.021

Moran T. 2016. Projecting Forward: A Framework for Groundwater Model Development under the Sustainable Groundwater Management Act. Stanford Woods Institute for the Environment, Stanford, CA. 30 p.

Moran T, Cravens A. 2015. California's Sustainable Groundwater Management Act of 2014: Recommendations for Preventing and Resolving Groundwater Conflicts. Stanford Woods Institute for the Environment, Stanford, CA. 49 p.

Murray AT, Gober P, Anselin L, et al. 2012. Spatial optimization models for water supply allocation. Water Resour Manag 26:2243–57.

Niles M, Hammond Wagner C. 2017. Farmers share their perspectives on California water management and the Sustainable Groundwater Management Act. Calif Agr 72(1):38–44. https://doi.org/10.3733/ca.2017a0040

Niles MT, Lubell M, Haden VR. 2013. Perceptions and responses to climate policy risks among California farmers. Glob Environ Chang 23:1752–60. doi:10.1016/j.gloenvcha.2013.08.005

Ocampo Melgar A, Vicuña S, Gironás J. 2015. Science-society collaboration for robust adaptation planning in water management — The Maipo River Basin in Chile. EGU General Assembly Conference Abstracts 17:1286.

Pahl-Wostl C, Craps M, Dewulf A, et al. 2007. Ecology and society: Social learning and water resources management. Ecol Soc 12. doi:10.5751/ES-02037-120205

Pannu C. 2012. Drinking water and exclusion: A case study from California's Central Valley. Calif Law Rev 100:223. doi:10.15779/Z38B133

R Development Core Team. 2016. R: A Language and Environment for Statistical Computing. Foundation for Statistical Computing, Vienna, Austria. www.r-project.org

Rudnick J, DeVincentis A, Méndez-Barrientos LE. 2016. The Sustainable Groundwater Management Act challenges the diversity of California farms. Calif Agr 70:169–73. http://doi.org/10.3733/ca.2016a0015

Russo JE, Schoemaker PJH. 1989. *Decision Traps: Ten Barriers to Brilliant Decision-Making and How to Overcome Them*. New York: Doubleday. 304 p. ISBN: 978-0-385-24835-8.

Slovic PE. 2000. *The Perception of Risk*. London: Earthscan Publications. 473 p. ISBN: 1-85383-528-5.

Slovic P, Fischhoff B, Lichtenstein S. 1977. Behavioral decision theory. Annu Rev Psychol 28:1–39.

Stern PC, Fineberg HV. 1996. *Understanding Risk: Informing Decisions in a Democratic Society*. Washington, D.C.: National Academies Press. 249 p.

[CA Superior Court] Superior Court of the State of California — County of Solano. 1978. Stipulation and consent to entry of judgement and decree: The County of Lake vs Yolo County Flood Control and Water Conservation District, et al.

CA Superior Court. 1995. Order amending April 21, 1978 judgement and decree: The County of Lake vs Yolo County Flood Control and Water Conservation District, et al.

Tableau Software. 2010. Tableau Visual Guidebook: Simple Techniques for Making Visualization Useful and Beautiful. Tableau Software, Inc. 20 p.

[USDA] US Department of Agriculture. 2015. California Agricultural Statistics: Agricultural Overview, Crop Year 2013. Pacific Regional Field Office, CA. 101 p.

Water Education Foundation. 2015. The 2014 Sustainable Groundwater Management Act: A Handbook to Understanding and Implementing the Law. Sacramento, CA. 49 p.

Yates D, Sieber J, Purkey D, et al. 2005. WEAP21 — A demand-, priority-, and preference-driven water planning model. Water Int 30:487–500.

[YCFCWCD] Yolo County Flood Control and Water Conservation District. 2009. Drought Protection and Canal Capacity Pump Program Analysis Report. Woodland, CA. 10 p.

YCFCWCD. 2012. Enhanced Canal Recharge Feasibility Report. Woodland, CA. 22 p.

RESEARCH ARTICLE

Managed winter flooding of alfalfa recharges groundwater with minimal crop damage

Over 90% of the water applied to sites in Davis and Scott Valley percolated to recharge groundwater, making this a viable practice on highly permeable soils.

by Helen E. Dahlke, Andrew G. Brown, Steve Orloff, Daniel Putnam and Toby O'Geen

Groundwater is a vital resource in California, providing approximately 38% of the state's water supply in normal years and at least 46% in dry years (DWR 2014). During the recent drought (water years 2011–2012 through 2015–2016), the majority of groundwater wells (90%) experienced a drop in groundwater levels of at least 10–50 ft (3–15 m) while some wells (8%) showed declines in groundwater level of more than 50 ft (>15 m) (DWR 2017). Groundwater overdraft persisted for most of the 20th century but the rate has dramatically increased since 2000 to about 7.2 million acre-feet (ac-ft), or 8.9 cubic kilometers (cu km) per year between 2006 and 2010 (Faunt 2009; Scanlon et al. 2012). State legislation now requires the implementation of groundwater sustainability plans to ensure that all groundwater basins are managed sustainably by 2040 (SWRCB 2014).

Managed groundwater recharge on agricultural lands in winter, when surplus surface water often is available, is one promising strategy for replenishing

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Abstract

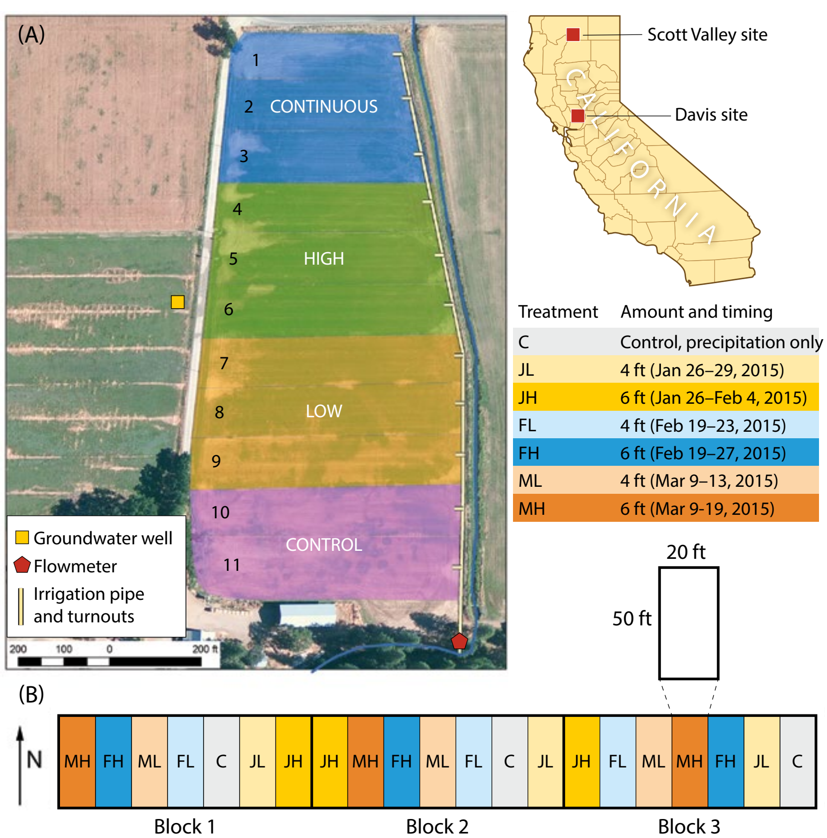
It is well known that California experiences dramatic swings in precipitation that are difficult to predict and challenging to agriculture. In times of drought, groundwater serves as a crucial savings account that is heavily relied upon. However, few tools exist to proactively refill this crucial reserve in wet years. We explored the idea of intentional winter flooding of agricultural land to promote on-farm recharge of the underlying groundwater. Field experiments were conducted on two established alfalfa stands to determine the feasibility of groundwater recharge and test realistic water application amounts and timings and potential crop damage. We studied soils with relatively high percolation rates and found that most of the applied water percolated to the groundwater table, resulting in short-lived saturated conditions in the root zone and minimal yield loss. While caution is appropriate to prevent crop injury, winter recharge in alfalfa fields with highly permeable soils appears to be a viable practice.

An experimental alfalfa plot at the UC Davis Plant Sciences Field Facility is flooded to evaluate crop impacts and groundwater recharge potential. The majority of alfalfa acreage in California is watered with flood irrigation systems capable of conveying large amounts of surface water to fields, many of which likely also have soil and underlying aquifer conditions suitable for recharge.

Andrew Brown

overdrafted aquifers (Bachand et al. 2014). This practice may also be beneficial to agriculture by recharging soil water profiles before an irrigation season. However, challenges and concerns remain regarding the effects of wintertime flooding of fields, particularly in perennial cropping systems such as alfalfa or tree and vine crops. Risks include excessive anaerobic conditions that may damage roots, increased risk of root diseases, excess aboveground humidity affecting insects or diseases, excessively high water tables, nutrient and herbicide leaching, and inability to perform field operations due to wet conditions.

Alfalfa is a promising candidate for groundwater recharge. It is a short-lived perennial that is widely grown in the western United States, with approximately 800,000 ac, or 3,237 square kilometers (sq km) planted in California (USDA NASS 2017). Because alfalfa is a nitrogen-fixing plant, it seldom receives nitrogen fertilizer. Therefore, environmental concerns associated with water application beyond crop needs (i.e., leaching of nitrate to groundwater) are considerably lower than for other crops (Putnam and Lin 2016; Walley et al. 1996).



Treatment	Amount and timing
C	Control, precipitation only
JL	4 ft (Jan 26–29, 2015)
JH	6 ft (Jan 26–Feb 4, 2015)
FL	4 ft (Feb 19–23, 2015)
FH	6 ft (Feb 19–27, 2015)
ML	4 ft (Mar 9–13, 2015)
MH	6 ft (Mar 9-19, 2015)

FIG. 1. Field layout of the experimental sites at (A) Scott Valley, in Siskiyou County (see also Table 1, following page), and (B) Plant Sciences Field Facility, Davis. For the Davis site, a randomized complete block design consisting of seven treatments with three replicates was implemented. The table above summarizes the treatments for the Davis site. C is the control, H and L stand for high and low water amounts of 4 ft and 6 ft, respectively, and J, F and M indicate the month in which the winter recharge was performed (i.e., January, February, March).

Approximately 80% to 85% of the alfalfa acreage in California is irrigated with flood irrigation systems (Schwankl and Pritchard 2003) capable of conveying large amounts of surface water to fields for groundwater recharge. Thus, given the large acreage of alfalfa in the Central Valley with suitable irrigation infrastructure, there are likely to be many fields that also have the soil and underlying aquifer conditions suitable for recharge.

Additionally, on a per-acre basis, average revenue from alfalfa is substantially lower than that for other perennial crops, such as grapes, almonds and walnuts, that are also candidates for managed winter groundwater recharge. For alfalfa, establishment costs are $500 to $600 per ac (Orloff et al. 2012), with average annual yields across the state of 7 tons per ac, or 17.3 tons per hectare (ha), and recent market prices from $140 to $375 per ton (Geisseler and Horwath 2016; USDA AMS 2017). As such, economic incentives designed to offset the risks associated with winter groundwater recharge would be comparatively affordable for alfalfa.

Winter flooding of alfalfa presents risks of crop injury, yield reduction or stand loss under saturated conditions. Alfalfa can be damaged by lack of oxygen in the root zone from prolonged saturation; however, the extent of crop damage is temperature dependent (Barta 1988; Barta and Sulc 2002; Drew and Lynch 1980). Alfalfa is less susceptible to injury when temperatures are cooler, even after prolonged saturation (Barta and Schmitthenner 1986; Cameron 1973; Finn et al. 1961; Heinrichs 1972).

To evaluate the suitability of alfalfa fields for groundwater recharge, we conducted on-farm experiments to measure the amount of groundwater recharge possible and assess crop response to excess winter water applications. Two on-farm experiments were conducted, one at the Plant Science Research Farm at UC Davis (Yolo County) in 2015, and one at Etna, in Scott Valley (Siskiyou County) in 2015 and 2016. In both experiments, the effects of different water amounts, timings and durations of water application were evaluated (fig. 1).

Davis and Scott Valley sites

The Davis site is on a Yolo silty clay loam with an available water capacity of 11 inches (in), or 28.1 centimeters (cm), for a 100 cm pedon, underlain by a sandy substratum within 3 ft of the soil surface. The field was an established alfalfa stand (entering its fifth growing season in 2015) with a fall dormancy rating of 8 (variety WL 550.RR). The depth to groundwater at the site was approximately 15 ft (4.5 m) in January 2015. Total rainfall and mean temperature for the experimental period (January to April) in 2015 were 7.7 in (19.6 cm) and 53.9°F (12.1°C).

The Scott Valley site is in the Klamath Mountains at an elevation of 2,784 ft (848 m). The experiment was conducted on a 15 ac (6 ha) field. The alfalfa variety planted was not known definitively, but was either BlazerXL (fall dormancy rating 3) or Xtra-3 (fall dormancy rating 4). The soil type is a Stoner gravelly sandy loam with an available water capacity of 4.9 in (12.5 cm). The alfalfa stand was entering its ninth growing season in 2015 and depth to groundwater was approximately 24 ft (7.3 m) at the beginning of the experiment (January 2015). Mean temperature during the experiment (February–May in 2015 and 2016) was 47°F (8.3°C); total precipitation over the course of the experiment in both years was 3.3 in (8.5 cm) and 6.8 in (17.3 cm).

Experimental layout

The UC Davis experiment was a replicated study with two winter water application amounts (low = 4 ft (120 cm); high = 6 ft (180 cm)) and three water application timings (January, February, March) and the control (i.e., winter precipitation only). The treatments were replicated three times using a randomized complete block design (fig. 1B) resulting in 21 individual 20 by 50 sq ft (93 sq m) plots.

One irrigation check (435 ft by 50 ft) of a 3 ac field was divided into 21 plots for the experiment (fig. 1B). Plots were separated from one another by berms approximately 1 ft high and 2.5 ft wide, which were established in November 2014. Repeated irrigation events of approximately 1 ft of water per day were used to apply the total treatment quantity. Irrigation treatments began on Jan. 26, 2015, and continued until March 19, 2015 (fig. 1).

At the Scott Valley site, winter recharge experiments were conducted for 2 years (2015 and 2016). The treatments evaluated were (1) a continuous recharge treatment: application of water every day, continuously except for the times when water was being applied to other treatments; (2) a high recharge treatment: three to five water applications per week; (3) a low recharge treatment: one to three water applications per week; and (4) the control, receiving winter precipitation only.

Total amounts applied in each treatment are shown in table 1 for both years. These treatments were each applied to three contiguous irrigation checks (fig. 1A). All treatments received the standard irrigation amount of 3 in before the first cutting and 5 in between the first and the second cutting. Winter recharge treatments lasted from Feb. 17 to April 9 in 2015 and from Feb. 4 to March 21 in 2016.

Water balance modeling

A water balance model based on the Thornthwaite-Mather procedure (Steenhuis and Van der Molen 1986) was set up for each site to estimate the fraction of applied water going to deep percolation (i.e., groundwater recharge) versus to evapotranspiration and to storage in pore space. The model was applied only to the root zone (upper 2 ft), where most evapotranspiration demand takes place.

Attenuation of applied water in the deeper soil profile (transmission zone, 2 to 5 ft) was modeled with a one-dimensional vertical flow model capable of simulating saturated and unsaturated flow (fig. 2). More detailed information on field measurements, statistical analyses and soil water balance measurements are provided in the technical appendix (http://ucanr.edu/u.cfm?id=185).

TABLE 1. Total applied winter water (ft) for groundwater recharge at the Scott Valley site, 2014–2015 and 2015–2016

Treatment	Check	Check size	Applied winter water for recharge							
			2014–2015 (Feb 17–Apr 9, 2015)				2015–2016 (Feb 4–Mar 21, 2016)			
			Total	Feb	Mar	Apr	Total	Feb	Mar	Apr
		ac	*ft*				*ft*			
Continuous	1	0.84	30.74	2.50	22.34	5.90	13.52	6.99	6.52	0.00
	2	1.10	24.87	3.69	16.68	4.51	10.32	5.34	4.98	0.00
	3	1.19	23.38	3.93	15.28	4.17	9.54	4.94	4.61	0.00
High	4	1.18	7.08	2.55	3.70	0.83	4.45	2.83	1.61	0.00
	5	1.35	6.55	2.39	3.48	0.68	3.89	2.48	1.41	0.00
	6	1.44	8.06	3.17	4.06	0.82	3.86	2.54	1.32	0.00
Low	7	1.41	5.10	0.95	1.94	2.21	12.96	1.06	0.68	11.22
	8	1.51	3.54	0.81	2.01	0.72	1.63	0.99	0.64	0.00
	9	1.54	3.26	0.80	1.70	0.76	1.60	0.97	0.62	0.00
Standard	10	1.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	11	1.86	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

* This check received an additional 11.3 ft of water in two irrigation events on April 6–8 and April 21–22, 2016.

Winter rainfall

The winter of 2014–2015 had below average precipitation in both Davis and the Scott Valley. Total November to April precipitation for Davis was 12.3 in (31 cm) — the 1981 to 2010 average was 17.55 in (44.5 cm) — with most rain, 8.2 in (20.8 cm), falling in December (fig. 3A). Total November to April precipitation in the Scott Valley was 16.9 in (43 cm), of which 5.9 in (15 cm) fell in December and January (fig. 4A). At both sites, December rainfall abruptly increased available soil water in the root zone to field capacity, followed by a short dry-out period in January. Volumetric water contents were above 75% of available water capacity at both sites before water applications occurred between January and April.

Davis site percolation amounts

At the Davis site, a small portion of the applied water for each treatment (low: 4 ft; high: 6 ft) was used to fill empty pore space in the soil profile, and as the water application progressed, water-filled pore space increased from field capacity (water retained in soil by gravity) to saturation (freely drainable water) (O'Geen

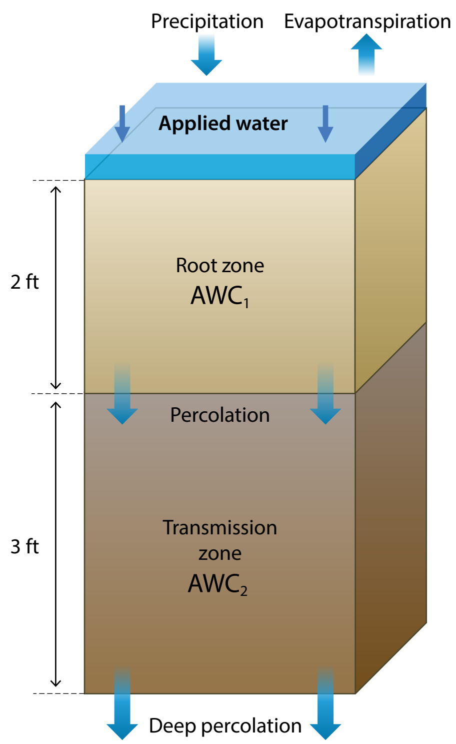


FIG. 2. Conceptual diagram of two-layered soil water balance model. The root zone is modeled with the Thornthwaite-Mather procedure and includes the loss of soil water by evapotranspiration. Saturated and unsaturated flow in the transmission zone is modeled with a one-dimensional vertical flow model receiving only the deep percolation from the root zone as water input. AWC is the soil-specific available water capacity. Variables are explained in the technical appendix.

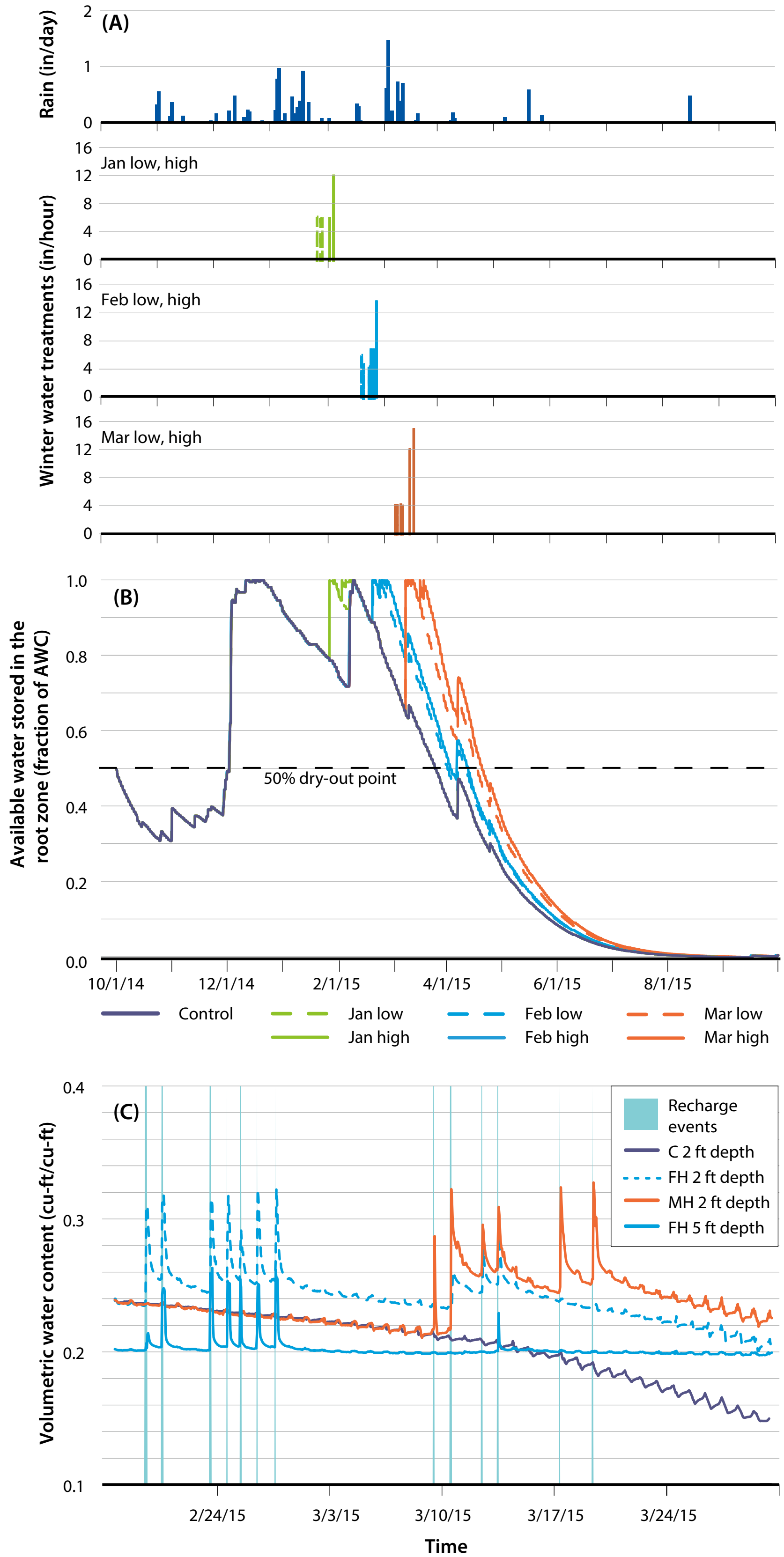


FIG 3. Water balance summary for the Davis site. (A) Daily precipitation and timing of winter water treatments. (B) Change in available soil water in the root zone (0–2 ft) as fraction of the soil-specific available water capacity (AWC). (C) Measured change in soil water content at 2 ft and 5 ft depth. Deep percolation occurred when volumetric soil water content was at a maximum.

2012). Saturated conditions prevailed for up to 12 hours in the loamy root zone (upper 2 ft) and up to 4 hours in the transmission zone.

Total deep percolation amounts (i.e., including recharge from rainfall) for the 5 ft pedon were similar across treatments and ranged from 48.2 to 53.5 in (122 to 136 cm) for the low treatments and from 76.8 to 82.2 in (195 to 209 cm) for the high treatments (table 2). About 95% to 98% of the applied winter water left the root zone (upper 2 ft) as deep percolation, and 92% to 96% left the transition zone as deep percolation, indicating small losses to soil storage and evapotranspiration. Depending on the timing of the winter water application with respect to antecedent rainfall, about 0.9 to 3 in (2.3 to 7.6 cm) of the applied winter water was used to bring the water content in the root zone to field capacity. This contribution to soil storage increased to about 2.7 to 4.7 in (7 to 12 cm) when the transmission zone (2 to 5 ft) was included in the water balance.

Although water application timing had little effect on total deep percolation amounts, it played a vital role for the root zone water balance at the onset of the growing season. In the control plot at Davis, available water in the 2 ft root zone reached field capacity only in December and early February, after which it steadily declined (fig. 3B). It would have reached the wilting point in early June without irrigation. A similar dry-out dynamic was observed for January low and high treatment plots, in which winter water was applied between Jan. 26 and Feb. 4, 2015 (fig. 3B), indicating that applying winter water for recharge 4 to 6 weeks before the onset of the growing season provides little advantage for the growing season water balance because most of the plant-available water is supplied naturally by precipitation in a normal or wet year.

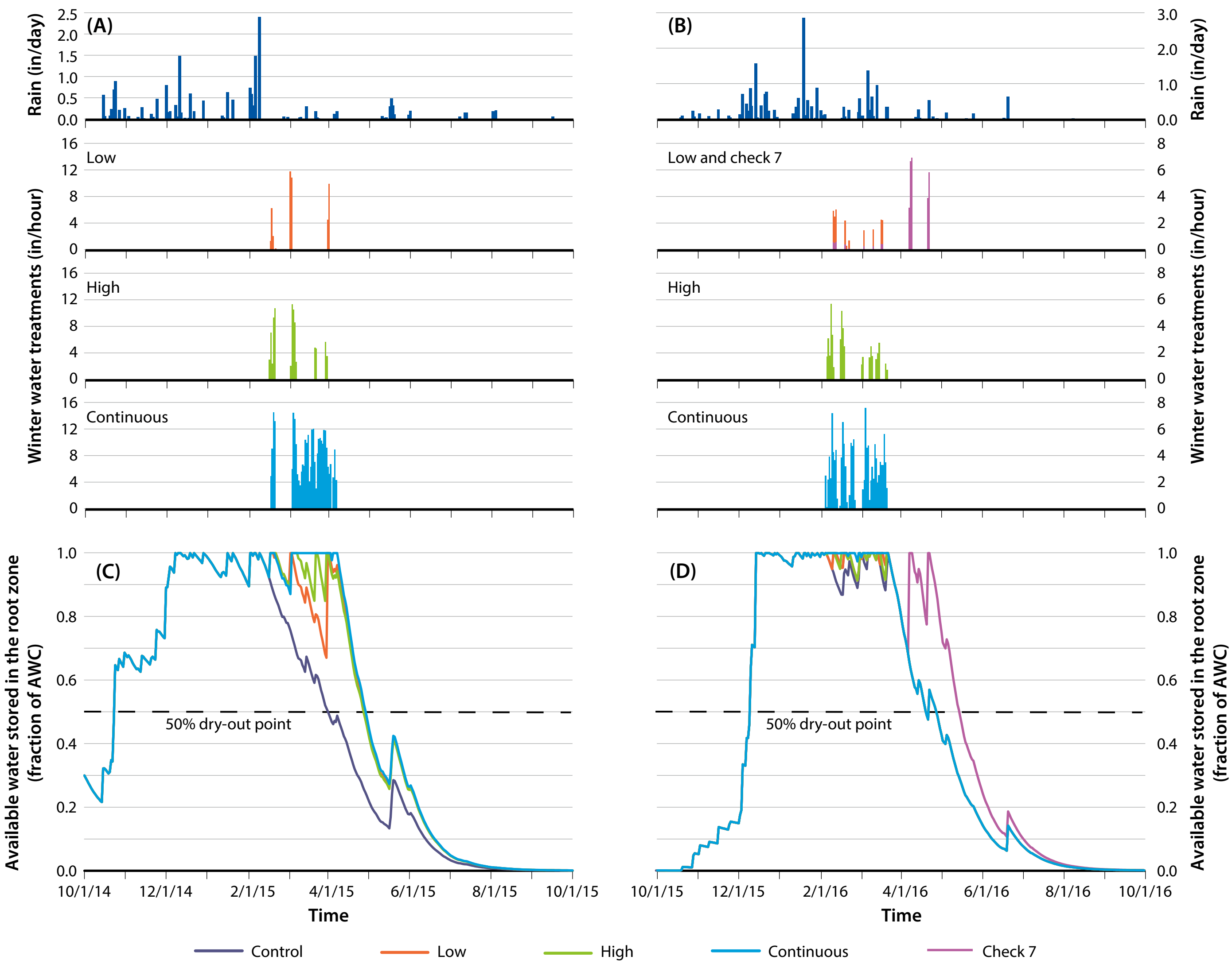


FIG. 4. Daily precipitation and timing of winter water treatments for the Scott Valley site for 2015 (A) and 2016 (B). Change in available soil water in the root zone (0–2 ft) as fraction of the available water capacity (AWC) (C, D).

In both the control and January treatment plots, available water stored in the root zone reached 50% of field capacity on March 23, 2015 (alfalfa irrigation management guidelines, e.g. Orloff and Hanson (2000), recommend maintaining a water content of 80% to 90% of field capacity in the root zone; allowable depletion is 50% of field capacity in the root zone — below that point plants could be damaged) (fig. 3B). In contrast, water applied in February and March resulted in a clear increase of plant-available water during the first month of the growing season (end of March). In February treatments, the root zone stayed saturated between Feb. 19 and Feb. 27, 2015, and then began to lose water, reaching 50% of field capacity on April 1 and 2, 2015. In March treatments, the root zone was saturated from March 9 to March 19, 2015, and dried to 50% of field capacity on April 18, 2015. In contrast to the control, the plots receiving additional water for winter recharge had more plant-available water stored in the soil profile at the beginning of the growing season; it amounted to about 1.3 in and 1.7 in (3.3 to 4.3 cm) in the February low and high treatments and 2.6 in to 3 in (6.6 to 7.6 cm) in the March low and high treatments.

Scott Valley site percolation amounts

At the Scott Valley site, in 2015 and 2016 a total volume of 135 ac-ft (166,520 cu m) and 107 ac-ft (131,982 cu m) of water, respectively, was applied for recharge on the

TABLE 2. Summary of water inputs (precipitation and applied winter water) and estimated deep percolation and soil storage contribution amounts for the two experimental sites

	Precipitation (in‡)	Applied winter water (in)	Total annual deep percolation* (in)	Deep percolation from winter water application (in)	Deep percolation as percentage of applied water (%)	Contribution to soil storage† (in)	Contribution to soil storage† (%)
DAVIS Root zone (0–2 ft)							
Control	14.1	0.0	4.9	—	—	—	—
Jan low	14.1	48.8	53.5	47.1	96%	1.7	3.5%
Jan high	14.1	72.8	77.5	70.6	97%	2.2	3.0%
Feb low	14.1	45.6	49.0	44.6	98%	0.9	2.0%
Feb high	14.1	80.4	83.3	79.0	98%	1.4	1.7%
Mar low	14.1	49.4	51.5	47.1	95%	2.2	4.5%
Mar high	14.1	76.5	77.8	73.5	96%	3.0	3.9%
DAVIS Root zone and deeper soil profile (0–5 ft)							
Control	14.1	0.0	4.9	—	—	—	—
Jan low	14.1	48.8	53.5	45.3	93%	3.5	7.2%
Jan high	14.1	72.8	77.5	70.1	96%	2.8	3.8%
Feb low	14.1	45.6	48.2	42.9	94%	2.7	5.9%
Feb high	14.1	80.4	82.2	76.4	95%	4.0	4.9%
Mar low	14.1	49.4	50.5	45.4	92%	3.9	8.0%
Mar high	14.1	76.5	76.8	71.8	94%	4.7	6.1%
SCOTT VALLEY 2015							
Standard	19.6	0.0	7.8	—	—	—	—
Low	19.6	47.2	51.8	44.0	93%	3.2	6.8%
High	19.6	87.0	91.4	83.6	96%	3.4	3.9%
Continuous	19.6	310.6	314.5	306.8	99%	3.7	1.2%
SCOTT VALLEY 2016							
Standard	23.7	0.0	11.2	—	—	—	—
Low	23.7	19.8	30.9	19.7	99%	0.2	0.8%
High	23.7	48.5	59.6	48.7	100%	0.2	0.3%
Continuous	23.7	130.6	141.7	130.5	100%	0.1	0.1%
Check 7	23.7	155.6	163.8	152.6	98%	3.0	1.9%

* Includes deep percolation from precipitation.
† Amount of applied winter water used to bring soil water content to field capacity.
‡ 1 in = 2.54 cm.

15 ac field. Table 2 summarizes the amounts of applied winter water for each check and treatment for both years.

During the first year, the low, high and continuous treatment plots received a total of 47 in (120 cm), 87 in (221 cm) and 311 in (789 cm) of winter water, of which 44 in (112 cm), 83.6 in (212 cm), and 306.8 in (779 cm) percolated to the water table, respectively (table 2). These winter application amounts translate to about 4, 7.3 and 25.9 ac-ft per ac of water, which is equal to 1.25, 2.4 and 8.6 times the annual growing season water demand of alfalfa in Scott Valley (assuming a water demand of 36 in). Low, high and continuous treatment plots received winter water for a total of 2.7, 6.3 and 31.6 days, respectively. The late-winter water application (mid-February to April) kept soils near field capacity, allowing about 93% to 99% of the applied winter water to go to deep percolation. Roughly 3.2 to 3.7 in (8.1 to 9.5 cm) of the applied water filled empty pore space to bring the water content in the root zone to field capacity.

During the second year (2016), water was applied for 11, 20 and 46 days, respectively, on low, high and continuous treatment plots between Feb. 4 and March 21. The low treatment plot received a total of 20 in (51 cm) of winter water, which is slightly over 50% of the annual growing season water demand of alfalfa in the Scott Valley. The high treatment received 48 in (123 cm) of winter water, which equals about 1.25 times the annual growing season water demand of alfalfa in the Scott Valley. The continuous treatment received 131 in (332 cm) of winter water, or about 3.5 times the growing season demand in 2016 (table 1). In addition, check 7 received 135 in (11.3 ft) of water on April 6–8 and April 21–22, 2016.

These numbers highlight that during one wet winter the growing season's water demand for about 3 years could be recharged. Nearly 100% of the applied water went to deep percolation in 2015–2016, likely because of the wet winter-spring season (table 2). Only 0.15 in (0.4 cm) of the applied water was used to bring the water content of the root zone to field capacity. For irrigation check 7, which received most of the winter water in April, the contribution of applied winter water to soil storage was 3 in (7.5 cm).

Because of the dry winter in 2014–2015, the available water in the root zone of the grower's control plots increased to field capacity only during the winter months (December to February). Dry-out started early in 2015, around mid-February, and progressed rapidly, reaching 50% of field capacity on April 23, 2015 (fig. 4C). Dry-out in the winter water application plots was delayed by about 1 month; all treatment plots remained nearly saturated until mid-April and reached 50% of field capacity either on May 10, 2015 (low and high treatment), or on May 14, 2015 (continuous).

Because of the late-winter water application, low, high and continuous plots had about 2.5 in (6.5 cm) of additional plant-available water stored in the root zone at the beginning of the 2015 growing season (April) compared to the control (fig. 4C). This amount is almost equal to one growing season irrigation event (3 in). In contrast, because of the wet winter and spring in 2015–2016 (total November to April precipitation was 130% of normal: 22.5 in) and the earlier timing of winter water applications, winter recharge did not provide an advantage for the root zone water balance at the onset of the 2016 growing season (fig. 4D). Irrigation check 7 was an exception; it had an additional 2.5 in (6.5 cm) of plant-available water stored at the end of April (fig. 4D). In 2016, dry-out to 50% field capacity of the control occurred about 1 month later than in the drought year of 2014–2015, indicating the generally wetter conditions in 2016.

For the first two winter recharge events conducted in February and March 2015, the groundwater table rose notably within 11 to 18 hours after water application started, indicating that the applied water moved through the 25 ft (7.6 m) vadose zone in less than 24 hours. The applied winter water in conjunction with natural precipitation caused a rise in the groundwater table of approximately 6 ft (1.8 m) in 2015 and 4.5 ft in 2016 (fig. 5). Although surface water was applied nearly continuously at the Scott Valley site, the applied water never created prolonged ponded conditions after water application ceased. Often, the application was supply limited and water moved only two-thirds to three-quarters down each check. Based on the duration

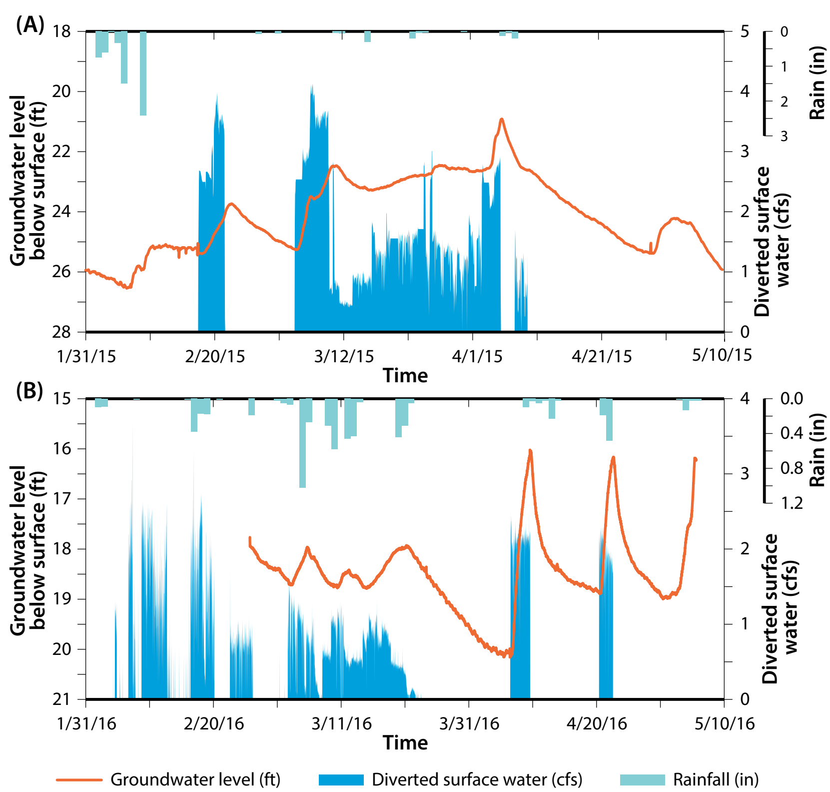
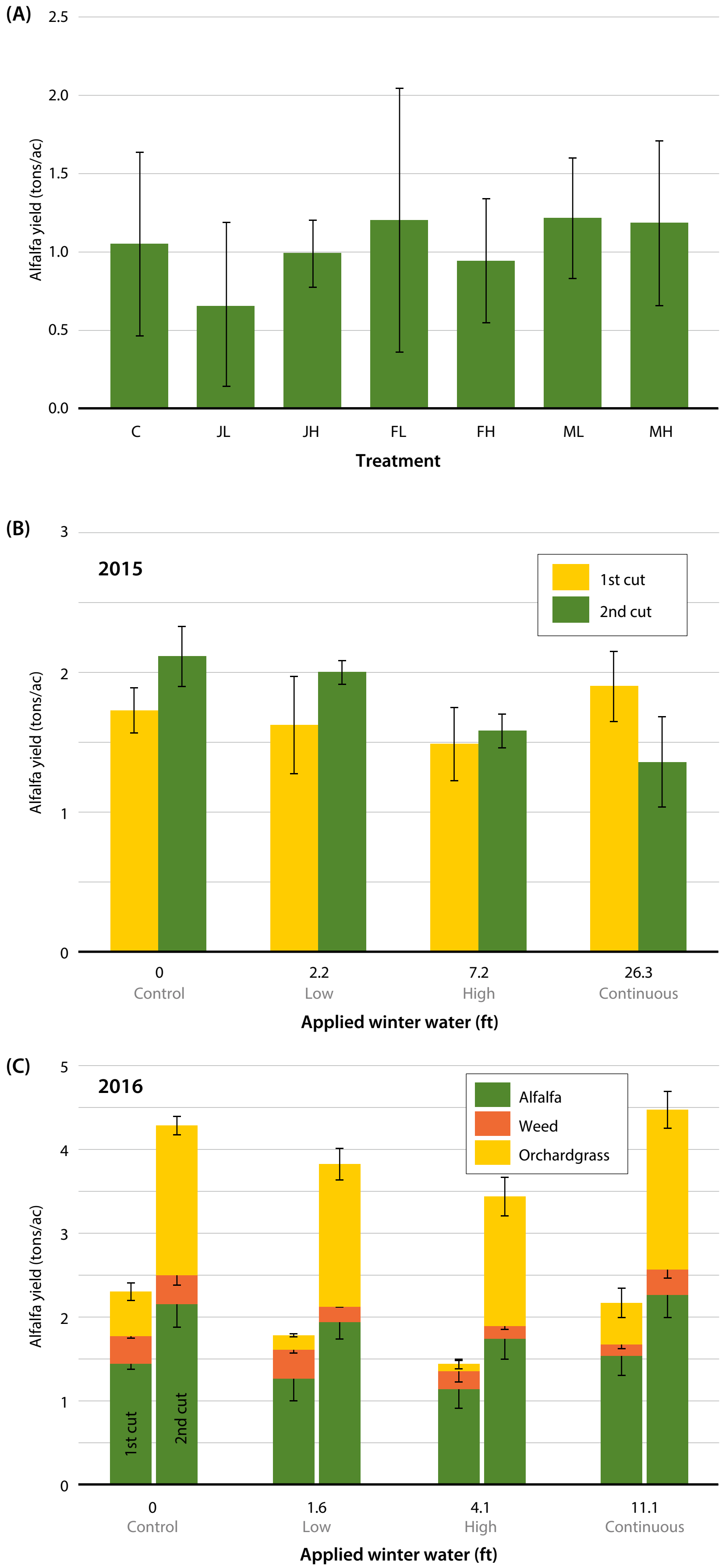


FIG. 5. Amount of winter water applied for recharge (cfs), change in depth to the groundwater table (ft) and rainfall (in per day) measured between January and May in 2015 (A) and 2016 (B) for the Scott Valley site.



and amount of winter water applied at the Scott Valley site, we estimated an infiltration rate of 0.9 ft (27 cm) per day.

Minimal effects on alfalfa

At the Davis site, statistical analysis of the effect of winter water application quantity and timing on alfalfa yield using a mixed-model analysis of covariance (ANCOVA) did not show a significant relationship between alfalfa yield and winter recharge. Overall, alfalfa yield at the Davis site in the first cutting averaged 1 ton per ac (2.47 tons per ha).

Yields were variable (0.7 to 1.2 tons per ac; 1.7 to 3 tons per ha) across the three blocks and the within-plot replicates (fig. 6A). Despite the variability between plots, alfalfa yields were not significantly different across the timing of water applications ($F = 0.98$, $p = 0.4$) and total applied water amounts ($F = 0.07$, p = 0.94) or their interaction (timing amount: $F = 0.74$, $p = 0.5$). Plant counts made prior to the treatments were not significant predictors of yield but explained approximately 15% of the variation in alfalfa yield across treatments. Plant counts were positively correlated with yield ($r = 0.45$), suggesting that low plant density limited yield in some of the observation plots such as the January low plots, but plant counts were not related to the irrigation treatments.

At the Scott Valley site, alfalfa yield did not show a significant correlation to total applied winter water for three out of the four cuttings measured over the 2 years (fig. 6B, C). Similarly, mean weed and orchardgrass biomass in 2016 did not show a significant correlation to total applied winter water (fig. 6C). During the second cutting in spring 2015, alfalfa yield showed a significant negative correlation with increasing amounts of applied winter water ($p = 0.02$) (fig. 6B). Despite this significant correlation, yield in the continuous treatment plot, which received about 26 ac-ft per ac of water, was only 0.76 tons per ac lower than the control.

To our surprise, in 2016, the continuously irrigated checks, which received the largest amount of winter water, showed a slightly higher yield than the control plots during the first and second cutting. A similar pattern was observed during the first cutting in 2015, with yields slightly lower at the center of the field (low and high treatments) than toward either of the edges

FIG. 6. Mean alfalfa yield (tons per ac) for the Davis (A) and Scott Valley (B, C) sites. For the Davis site, yield was estimated from the replicated treatment plots ($n = 3$) on April 23, 2015. C is the grower standard, L and H stand for low and high water amounts of 4 ft and 6 ft, respectively, and J, F and M indicate the month in which the winter recharge was performed (i.e., January, February, March). For the Scott Valley site, yield is shown for the first (end of May) and second (mid-July) cuttings in the control, low, high and continuous treatment plots in 2015 (B) and 2016 (C). Error bars indicate one standard deviation.

(control and continuous treatments). Alfalfa yields for first and second cuttings at the Scott Valley site were comparable between 2014–2015 and 2015–2016 and reached, on average, around 1.7 tons per ac (4.2 tons per ha) per cutting.

The alfalfa yield results show that application of 2 to 26 ft of water for winter recharge did not conclusively result in a significant decline in yield. Neither experiment showed significant declines in alfalfa yield during the first cutting, which would be expected if environmental factors influenced crop health. The yield data together with the deep percolation results suggest that the effect of winter flooding on dormant alfalfa is potentially small for highly permeable soils. However, alfalfa yields were also highly variable among treatments, which complicated the statistical analysis of the water application effect. For the Davis site, results indicated that water application timing and amount were not significant predictors of yield, while initial plant count and variability in soil properties across the field did explain some of the variability in yield observed across the treatments.

Both experimental sites were older alfalfa stands (5-year stand in Davis, 9-year stand in the Scott Valley) with relatively low plant count prior to the recharge experiments, which likely influenced the yield measurements. To more accurately determine the effect of large winter water applications for groundwater recharge on alfalfa health and yield, experiments need to be replicated on younger, high-yielding fields at more sites with varying soil types and drainage characteristics. Further study on susceptibility to root disease, stand survival and long-term productive capability is also needed.

Winter flooding from high rainfall is a known risk for alfalfa production, particularly during early stand establishment (Putnam et al. 2017). Thus, older stands may be preferred for groundwater recharge strategies. Older stands are lower risk since they are usually past peak production.

While there are risks to plant stand and crop productivity with high winter water applications to alfalfa, the risk of economic loss is likely lower than compared to other perennial crops with higher cost structures. Moreover, the risk of crop loss may be low in highly permeable soils, especially when temperatures are low. These risks also may be offset to some degree by benefits from greater early-season moisture in the root zone being available for crop production. The risks also should be weighed against the value of groundwater recharge, which may improve local groundwater resources, making water available during dry summer months or for transfer to other crops.

Application timing, soil oxygen status

We tested the continuous application of winter water over several days and weeks as well as application of winter water in the form of isolated irrigation events. Based on our field observations neither method had a large influence on the amount of the total applied water that went to deep percolation. We attribute this mainly to the highly permeable character of the soil at both sites and the low evapotranspiration rates encountered during the experimental periods.

Soil moisture data collected at both sites further indicated rapid drainage of the soil profile following the end of the recharge events. Since lack of oxygen caused by prolonged flooding is directly related to development of root or plant diseases (Barta and Schmitthenner 1986; Cameron 1973; Heinrichs 1972), free drainage of the applied winter water through the root zone is important and presents one of the main risk factors when applying large amounts of water for winter recharge (Finn et al. 1961).

Oxidation-reduction potential measurements at 4- and 8-in depths at the Scott Valley site revealed close correlation between oxygen status and water content (fig. 7). Reduced oxygen conditions occurred only during the water application events, and returned quickly to aerated conditions after water applications ceased. In addition, both experiments were conducted during the winter period when alfalfa is dormant or growing very slowly. Both findings suggest that pulsed application of water for groundwater recharge is preferred from

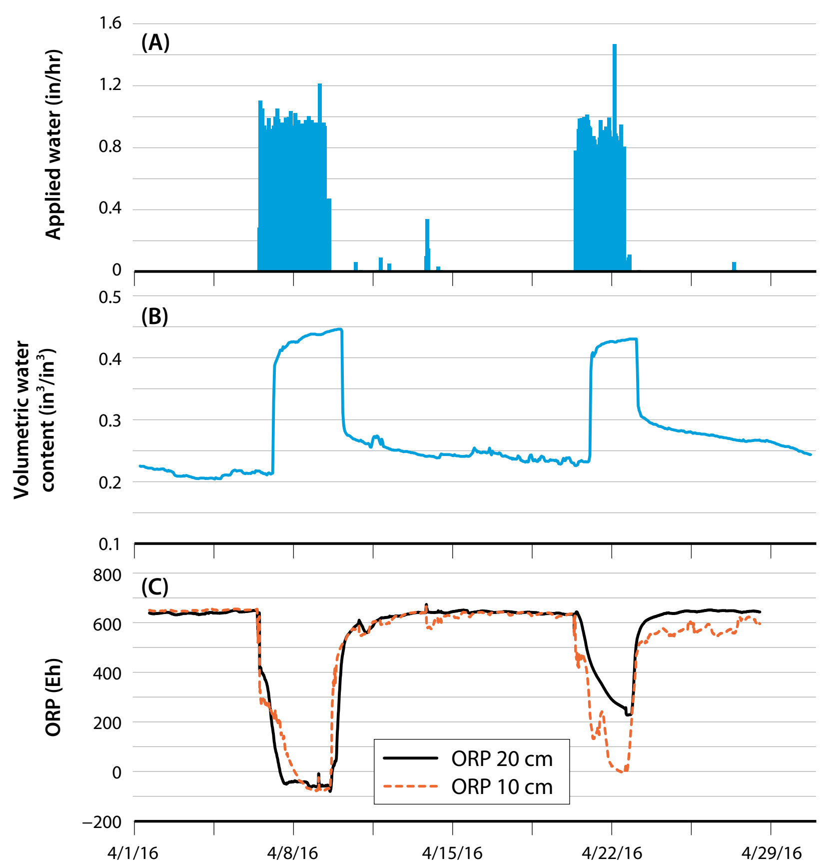


FIG. 7. Precipitation and applied water (A), volumetric water content at 8 in depth (B) and oxidation-reduction potential measured at 10 am (red dots) and 20 cm depth (black line) (C) at the Scott Valley site.

a crop health perspective and that the intensity and frequency of the winter water applications should be tailored to site-specific soil drainage characteristics.

Corroboration of SAGBI

Our field measurements corroborate that the Soil Agricultural Groundwater Banking Index (SAGBI) (O'Geen et al. 2015) may be a reliable predictor of soil suitability for on-farm groundwater recharge. SAGBI (casoilresource.lawr.ucdavis.edu/sagbi/) considers five major factors critical to sustaining crop health and rapid deep percolation of applied water: soil profile percolation rate, root zone residence time, chemical limitations, topography, and soil surface condition. The index ranks soils on a six-class scale ranging from very poor to excellent (O'Geen et al. 2015).

Both of our sites rank in the SAGBI good category. At both sites, recharge is not restricted significantly by chemical limitations (e.g., no accumulation of salts that could result in degradation of water quality), topography or water-restrictive features in the root zone or deeper soil profile, such as hardpan or claypan. For both sites, the root zone residence time and deep percolation ability were the most limiting characteristics due to relatively high clay content. However, as showcased by our field data, both sites nonetheless supported significant amounts of deep percolation.

Potential benefits, need for research

Results from our two on-farm experiments indicate that an astoundingly large fraction of the applied winter water percolated past the root zone toward the groundwater table. Over 90% of the applied water went to deep percolation, ranging between 4 ft (122 cm) and 6.7 ft (204 cm) at the Davis site and 2.6 ft (79 cm) and 26 ft (792 cm) at the Scott Valley site. Less than 10% of the applied water was either evaporated or used to fill up soil pore space to bring the soil to field capacity.

Applying our field observations to the statewide SAGBI map allows a simple approximation of the potential benefit of using alfalfa fields for groundwater recharge for California's groundwater resources. Using a geospatial analysis of crop land data (USDA NASS 2017) and the unmodified SAGBI index, we determined that approximately 300,000 ac (1,214 sq km) of alfalfa in California are planted on soils with a SAGBI rating of moderately good or better. Applying 6 ft of winter water and assuming 90% of it percolates past the root zone, 1.6 million ac-ft (1.9 cu km) of groundwater recharge would be possible if all alfalfa land ranked as suitable for on-farm recharge were used. This is equivalent to 12.8% of the statewide average annual agricultural groundwater use between 2005 and 2010 (DWR 2015). For reference, the Oroville reservoir, second largest in the state, has a storage capacity of 3.5 million ac-ft.

Our study has mainly looked at the physical feasibility of using alfalfa fields for the replenishment of groundwater with winter excess surface water. However, adoption of this practice is locally dependent on many site-specific factors, which influence the overall cost and benefits of this practice to the farmer. On-site factors such as soil suitability; climate (e.g., winter temperature, precipitation); age, health and fall dormancy rating of the alfalfa variety; capacity of the local water conveyance system; and ease at which water can be conveyed onto a field (e.g., involving potential additional labor or electricity cost) influence the rate and total amount of excess water that can be used for recharge and the potential costs, such as from crop damage.

Most landowners will likely have to purchase the surface water they are diverting for recharge (unless it is free-of-charge delivered floodwater), which can cost between $15 per ac-ft (Emil Cavagnolo, General Manager Orland-Artois Water District, personal communication) and $1,456 per ac-ft (CPUC 2016). In addition, most landowners will likely have to expand their existing or obtain a new appropriative surface water right for the diversion of additional surface water outside the growing season. If the state of California decides to adopt the fee structure for the temporary permit for groundwater recharge from Governor Brown's Executive Order B-36-15, the cost for the permit would include a minimum fee of $100 for the application plus $1 per 100 ac-ft in excess of 10,000 ac-ft (based on water actually diverted), but the cost could be as high as $498,665 if a standard permit is pursued (table 3).

To capitalize on the recharge rates that some of the most suitable soils promote, landowners may want to consider expanding the capacity of their water conveyance system. For example, to recharge 200 ac-ft in 10 days on an 80 ac field (assuming an infiltration capacity of 3 in per day), the conveyance system would need to have a minimum capacity of 10 cu ft per second (cfs). For soils that can infiltrate water at higher rates (e.g., 1 ft per day), such as the Stoner gravelly loam in the Scott Valley site, a diversion capacity of 40 cfs would be needed for an 80 ac field. The least cost-extensive

TABLE 3. Application filing fees for water permits with the State Water Resources Control Board (SWRCB), 2017

Application	Minimum fee	Fee structure	Maximum
Standard permit	$1,000	$1,000 + $15 per ac-ft in excess of 10 ac-ft	$498,665
Standard temporary permit	$2,000	Half the fee for an equivalent standard permit or $2,000, whichever is greater	$249,333
Temporary permit for recharge	$100	$100 + $1 per 100 ac-ft in excess of 10,000 ac-ft (based on water actually diverted)	N/A

Source: www.waterboards.ca.gov/waterrights/water_issues/programs/applications/groundwater_recharge/docs/staffpresentation.pdf.

method would be to divert water using the existing conveyance capacity and apply the water using the same method as during the growing season (i.e., irrigation of individual checks); alternatively, if the conveyance capacity does not support the infiltration capacity of the soil, the area to which the water is applied could be reduced to match the water delivery rate of the conveyance system.

Recharged water would provide several benefits to landowners and associated water districts, including increased water supply and water security, achievement of sustainable groundwater management goals, flood protection, improved water quality, reduction in imported water use, mitigation of land subsidence and seawater intrusion, and long-term benefits for nearby groundwater-dependent ecosystems (e.g., rivers, wetlands). The recharged water would also provide indirect benefits to the conjunctive use of surface and groundwater resources and might stimulate statewide trading of water, which, considering an average market price of $650 per ac-ft of water in 2015 (Howitt et al. 2015), might provide a supplemental source of income for alfalfa growers. These tradeoffs and economic incentives could inform and motivate agricultural groundwater banking programs statewide. Hence, the risks and value of groundwater recharge strategies for agricultural fields including alfalfa should be considered as California attempts to balance its groundwater demand with the sustainability of water resources available on a seasonal basis.

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References

Ayars JE, Fulton A, Taylor B. 2015. Subsurface drip irrigation in California — here to stay? Agr Water Manage 157:39–47.

Bachand PAM, Roy SB, Choperena J, et al. 2014. Implications of using on-farm flood flow capture to recharge groundwater and mitigate flood risks along the Kings River, CA. Environ Sci Tech 48(23):13601–9.

Barta AL. 1988. Response of alfalfa and birdsfoot trefoil to shoot removal and root anoxia. Crop Sci 28(2):275–8.

Barta AL, Schmitthenner AF. 1986. Interaction between flooding stress and Phytophthora root rot among alfalfa cultivars. Plant Dis 70(4):310–3.

Barta AL, Sulc RM. 2002. Interaction between waterlogging injury and irradiance level in alfalfa. Crop Sci 42(5):1529–34.

Burt CM, Howes DJ, Freeman B. 2011. Agricultural Water Energy Efficiency. ITRC Report No. R 11-007. Irrigation Training & Research Center, California Polytechnic State University, San Luis Obispo, California. 248 p.

Cameron DG. 1973. Lucerne in wet soils — the effect of stage of regrowth, cultivar, air temperature and root temperature. Crop Pasture Sci 24(6):851–61.

[CNRA] California Natural Resources Agency. 2009. *2009 California Climate Adaptation Strategy, A Report to the Governor of the State of California in Response to Executive Order S-13-2008*. 200 p.

[CPUC] California Public Utilities Commission. 2016. What Will Be the Cost of Future Sources of Water for California? www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/About_Us/Organization/Divisions/Policy_and_Planning/PPD_Work/PPD_Work_Products_(2014_forward)/PPD%20-%20Production%20costs%20for%20new%20water.pdf. 16 p.

Dettinger M. 2011. Climate change, atmospheric rivers, and floods in California — a multimodel analysis of storm frequency and magnitude changes. J Am Water Res Assoc 47(3):514–23.

Drew MC, Lynch J. 1980. Soil anaerobiosis, microorganisms, and root function. Annu Rev Phytopathol 18(1):37–66.

[DWR] Department of Water Resources. 2014. California Water Plan, Update 2013. Investing in Innovation & Infrastructure. Bulletin 160-13. www.water.ca.gov/waterplan/cwpu2013/final/index.cfm

DWR. 2015. California's Groundwater Update 2013. A Compilation of Enhanced Content for the California Water Plan Update. www.water.ca.gov/waterplan/topics/groundwater/index.cfm

DWR. 2016. SGM Sustainable Groundwater Management, Critically Overdrafted Basins. www.water.ca.gov/groundwater/sgm/cod.cfm (accessed Aug. 17, 2017).

DWR. 2017. Groundwater Level Change* - Fall 2011 to Fall 2016. www.water.ca.gov/waterconditions/docs/2017/DROUGHT_DOTMAP_F1611_50ft.pdf (accessed Aug. 29, 2017).

Faunt CC (ed). 2009, Groundwater Availability of the Central Valley Aquifer, California: US Geological Survey Professional Paper 1766. 225 p.

Finn BJ, Bourget SJ, Nielsen KF, Dow BK. 1961. Effects of different soil moisture tensions on grass and legume species. Can J Soil Sci 41(1):16–23.

Geisseler D, Horwath WR. 2016. Alfalfa production in California. https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Alfalfa_Production_CA.pdf (accessed Jan. 18, 2017).

Hanak E, Lund JR. 2012. Adapting California's water management to climate change. Climatic Change 111(1):17–44.

Harter T, Dahlke H. 2014. Out of sight but not out of mind: California refocuses on groundwater. Calif Agr 68(3):54–5.

Heinrichs DH. 1972. Root-zone temperature effects on flooding tolerance of legumes. Can J Plant Sci 52(6):985–90.

Howitt R, Medellín-Azuara J, MacEwan D, et al. 2015. Economic Analysis of the 2015 Drought for California Agriculture. UC Davis Center for Watershed Sciences.

O'Geen AT. 2012. Soil water dynamics. Nat Educ Knowledge 3(6):12.

O'Geen A, Saal M, Dahlke H, et al. 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. Calif Agr 69(2):75–84.

Orloff SB, Hanson B. 2000. Monitoring alfalfa water use with soil moisture sensors. In: Proceedings of the 30th California Alfalfa Symposium, Dec. 11-12, 2000. Las Vegas, NV. University of California. http://alfalfa.ucdavis.edu/+symposium/proceedings/2000/00-111.pdf

Orloff SB, Klonsky KM, Tumber KP. 2012. Sample costs to establish and produce alfalfa hay. Intermountain Region - Siskiyou County, Scott Valley - mixed irrigation. UC Cooperative Extension. 18 p. https://coststudyfiles.ucdavis.edu/uploads/cs_public/a6/b3/a6b35d9d-bd82-495c-86b1-1987dd6154ae/alfalfa_im_scott2012.pdf

Putnam DH, Gull U, Perez B, et al. 2017. Flooding and waterlogging damage in alfalfa – what to do? Alfalfa & Forage News, UC Cooperative Extension. Jan. 17, 2017. http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=22996 (accessed Jan. 31, 2017).

Putnam DH, Lin E. 2016. Nitrogen dynamics in cropping systems — why alfalfa is important. In: Proc 2016 Cal Plant and Soil Conf Amer Soc of Agron, Cal Chapter, Feb. 2–3, 2016. Visalia, CA. http://calasa.ucdavis.edu/files/250178.pdf (accessed Jan. 31, 2017).

Scanlon BR, Longuevergne L, Long D. 2012. Ground referencing GRACE satellite estimates of groundwater storage changes in the California Central Valley, USA. Water Resour Res 48(4).

Schwankl L, Prichard T. 2003. Improving irrigation water management of alfalfa. In: Proc 33rd Cal Alfalfa and Forage Symp, Dec. 17–19, 2003. Monterey, CA. http://alfalfa.ucdavis.edu

[SWRCB] State Water Resources Control Board. 2014. Sustainable Groundwater Management Act. §§ 346-1-10, §§ 347-1-23, §§ 348-1-3. State of California. www.water.ca.gov/cagroundwater/docs/2014%20Sustainable%20Groundwater%20Management%20Legislation%20with%202015%20amends%201-15-2016.pdf

Steenhuis TS, Van der Molen WH. 1986. The Thornthwaite-Mather procedure as a simple engineering method to predict recharge. J Hydrol 84(3-4):221–9.

[USDA AMS] US Department of Agriculture Agricultural Marketing Service. 2017. National Hay, Feed & Seed Weekly Summary. Jan. 13, 2017. www.ams.usda.gov/mnreports/lswfeedseed.pdf (accessed on Jan. 18, 2017).

[USDA NASS] USDA National Agricultural Statistics Service. 2017. https://quickstats.nass.usda.gov/ (accessed Jan. 31, 2017).

Walley FL, Tomm GO, Matus A, et al. 1996. Allocation and cycling of nitrogen in an alfalfa-bromegrass sward. Agron J 88:834–43.

RESEARCH ARTICLE

Paso Robles vineyard irrigation study provides benchmark data to assist future area groundwater management

Researchers have identified baseline irrigation application data that can help groundwater sustainability agencies estimate regional irrigation usage for wine grape crops.

by Mark C. Battany and Gwen N. Tindula

Abstract

Accurate information on irrigation water usage does not exist in many areas where groundwater is the primary water source. This lack of information will hinder efforts to manage these groundwater basins sustainably according to current and future water regulations and policies. Using a low-cost methodology of irrigation-line pressure sensors connected to data loggers, we estimated irrigation applications at 84 vineyard sites in the Paso Robles Groundwater Basin over 4 years (2010–2013). We compared irrigation amounts with the preceding winter's rainfall and with the growing season reference evapotranspiration (ET_o). Over the study period, the average annual irrigation application was 11.46 inches (291 millimeters). The average annual application correlated inversely to the preceding winter's rainfall, while the irrigation over the growing season (April–October) correlated directly with the ET_o over this same period. This study provides an initial data framework that can be used by groundwater sustainability agencies to help manage groundwater in the Paso Robles area. The methodology also could be utilized in other regions to estimate regional irrigation usage while maintaining anonymity for participants.

The recent passage of the Sustainable Groundwater Management Act (SGMA) in California obligates increased levels of management in high- and medium-priority groundwater basins in the near future in order to achieve long-term sustainable groundwater conditions (DWR 2014). An immediate challenge for effective management in many agricultural areas reliant upon groundwater is that little or no information currently exists on the amount of water extracted for irrigation at the individual farm level. Unlike users of developed surface water, growers who pump groundwater have generally never had to measure or report how much water they extract unless they are located in an adjudicated or actively managed basin.

This lack of information on how much water is extracted can become a major handicap for any agency tasked with managing the groundwater supply in the near future, before metering becomes more widespread. Accurate information on extraction amounts and how these amounts can vary from year to year as a function of rainfall conditions will be critical in order

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In many agricultural areas reliant upon groundwater, such as the Paso Robles Groundwater Basin, there is little or no information on how much water is extracted for irrigation at the individual farm level, which makes it challenging for groundwater sustainability agencies to effectively manage groundwater supply. The authors present a low-cost monitoring approach that employs irrigation-line pressure sensors and data loggers.

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to create effective, sensible and fair groundwater management strategies. Having accurate water usage information will also ensure that groundwater modeling efforts will produce the most reliable output possible and thus serve as reliable tools for improving groundwater basin management.

The Paso Robles Groundwater Basin in San Luis Obispo County is classified as a high priority, critically overdrafted basin under SGMA, and is required to adopt a groundwater sustainability plan by January 2020 (DWR 2017) (a critically overdrafted basin is one in which continuing current management practices is likely to result in adverse environmental, social or economic impacts). The basin supports an important irrigated agricultural economy currently dominated by wine grape production. Earlier attempts to grow non-irrigated fruit crops in the region over a century ago largely failed, highlighting the importance of a reliable water supply (Shinn 1902). After the discovery of seemingly abundant groundwater, local crop production shifted to irrigated crops, including forage, alfalfa and sugar beets. In recent decades, the advent of pressure-compensating drip irrigation systems has enabled vineyard cultivation to occur on steeper terrain that was unsuited to earlier irrigation methods.

The region is relatively dry, with an average annual rainfall of 14.1 inches (in) (358 millimeters [mm]) in the city of Paso Robles since 1942 (Paso Robles Water Division 2014). Precipitation diminishes heading east from Paso Robles towards Shandon (Fugro West and Cleath 2002). Groundwater is virtually the only source of irrigation water for the basin area, as the developed surface water in the region is mostly devoted to local municipal use or for groundwater recharge in Monterey County to the north. Across the study region, the depth to groundwater below the surface is roughly several hundred feet. Even prior to the recent 5-year drought beginning in 2012, groundwater levels were observed to be declining in parts of the basin, suggesting that water extraction was exceeding recharge (City of Paso Robles 2011).

The lack of accurate information on agricultural pumping of groundwater has been a serious impediment to understanding the basin and predicting future trends. Vineyards are the dominant crop in the region and represent the largest single water extraction from the basin (Geoscience and Todd Groundwater 2014), and as such, errors in the estimate of annual vineyard irrigation applications may have large impacts on the accuracy of modeling efforts. Previous groundwater studies of the Paso Robles Groundwater Basin used theoretical estimates of vineyard irrigation, but no measured data was available to verify these estimates. A 2010 peer review of the previous studies indicated that improving the accuracy of the vineyard irrigation component was a major priority to improving the modeling results (Yates 2010).

The generic irrigation application values ascribed to vineyards in California had been utilized in the initial studies of groundwater conditions in the area, but it was unknown how representative these values were for local conditions. It was suspected that these values likely overestimated actual vineyard irrigation application, but no data was available to improve upon them. The 2012 San Luis Obispo County Master Water Report indicated an annual irrigation application of 1.7 feet (518 mm) as a "medium" value for the study region, but this type of theoretical estimate unavoidably makes many assumptions on irrigation management such as applied leaching fractions or levels of deficit irrigation; these may not hold true in actual practice (San Luis Obispo County 2012).

Another challenge in estimating annual irrigation applications in the region is that the style of wine grape production has evolved over time and irrigation technology has improved; both have implications for applied irrigation amounts. In the 1990s, the region was producing relatively high tonnages of fruit per acre; since that time there has been a steady decline in average production per acre, in part due to a shift in focus to producing higher quality crops at lower tonnages per acre (Battany 2015). This shift has generally been accompanied by a reduction in applied irrigation, as this is the main tool that growers have to control vineyard vegetative growth, and a reduced level of production requires less area of foliage. The increasing use of pressure-compensating drip emitters and tools such as soil moisture monitoring has likely increased application efficiencies over time as well. Thus, earlier estimations of applied irrigation may not address current wine grape production conditions and irrigation practices in the region.


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Different production styles and goals — producing high tonnages of fruit per acre versus higher quality crops at lower tonnages per acre — result in vineyards that have very different canopy sizes and, therefore, different irrigation water requirements. The block on the left, for example, has a large amount of foliage and will need more irrigation than the block on the right.

The purpose of this study was to develop a representative value of the annual vineyard irrigation water application in this region, and to determine how this amount varied in relation to the amount of rainfall that occurred in the preceding winter and to the reference evapotranspiration (ET_o) during the current growing season. To our knowledge, the resulting dataset is the only large-scale collection to date of direct measurements of agricultural groundwater use in this region; as such, it provides important baseline information for groundwater management under SGMA.

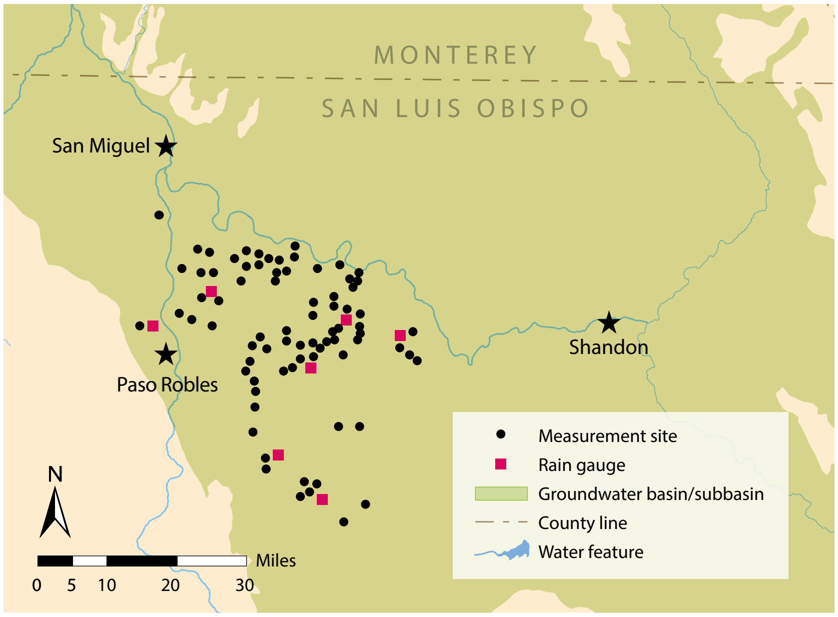

FIG. 1. The 84 study sites at vineyards across the Paso Robles Groundwater Basin. Source: DWR Bulletin 118 (DWR 2016).

The study approach

Measurements were made at 84 vineyard blocks in the western portion of the basin (fig. 1). At the time that we initiated the study, this specific area was considered to be the primary region of declining groundwater levels in the basin, based on groundwater level changes between 1997 and 2009 (City of Paso Robles 2011). We chose sampled vineyard blocks at random from all of the blocks on a participating property, with one block chosen for each 100 acres (40 hectares) of planted vineyard area on that property. All sampled blocks were mature and producing fruit; one block was grafted over during the study period, and none were removed.

In each sampled block a pressure switch with a 4 psi (28 kPa) activation pressure (5000 series switch, part number 76575, Honeywell Corporation, Morristown, NJ) was plumbed into the irrigation drip line with a separate spaghetti line. This sensor was read continuously with a small Hobo State data logger (Onset Computer Corporation, Bourne, MA) to record the irrigation system run time. This run time information, multiplied by the value of the design flow of the

A pressure sensor and data logger in the field. The sensor is plumbed via the spaghetti line into the drip line, and the data logger is housed inside a waterproof container covered in aluminum foil.

Twenty-two of the 84 sites had sprinkler systems in addition to drip lines. To determine water applied over time for these systems separately, a second pressure sensor and data logger were attached to a sprinkler riser or cleanout line, as shown above.

corresponding block, produced an estimate of the volume of water applied over time. At sites with sprinklers in addition to drip lines, we installed a second data logger and pressure switch unit and used a similar calculation method to determine water applied over time for this system separately. Twenty-two of the 84 locations had sprinklers; some were utilized for springtime frost protection, while others had been installed solely to provide supplemental irrigation in the winter.

The measurement devices were installed in the fall of 2009 and irrigation data was collected over four complete calendar years from 2010 through 2013. A set of seven recording rain gauges was also installed throughout the study area before the winter rainfall period began in late 2009, and these seven gauges were operated over the same time period. The ET_o values are from the California Department of Water Resources Spatial CIMIS program, calculated for the Paso Robles Airport location; the nearest CIMIS weather station (#163) is located approximately 16 miles (27 km) to the south in Atascadero.

The fundamental assumption with this method — measuring the duration for which the irrigation system is pressurized and then multiplying this time by the design flow — is that the actual flow rate that occurs with the system is the same as the design flow rate (e.g., the rate indicated on the emitters). There are many reasons why the actual flow rate may differ from the design flow rate: inadequate or excessive system pressure, clogging, wear, broken or missing components, or leaks. However, the assumption that the actual flow and design flow are very similar in the aggregate for larger sample sizes is supported by long-term drip irrigation system test data. For example, in 113 evaluations between 1995 and 2008 of drip irrigation systems using nominal 0.5 gallon (1.89 liters) per hour emitters, the mean measured flow rate was 0.504 gallons (1.91 liters) per hour (Cal Poly ITRC 2010). The alternative of installing flow meters at the pumping wells that did not already have them would have been prohibitively expensive and itself also subject to considerable potential errors (Hanson and Schwankl 1998). It also would have required the measurement of irrigation applications in all of the vineyard blocks served by that well in order to be able to correlate flow meter readings to the particular block of interest in this study. Additionally, among potential cooperators there was very strong hesitation to allow measurements of pump flow meters, while the measurements of single vineyard blocks were more acceptable.

A major challenge with this type of research project, which needs to be conducted on private property, is that some growers simply do not want their water usage measured for any reason. Growers in the area have had concerns about potential groundwater basin adjudication that might limit their future access to water; as a result, they have been hesitant to divulge any information about pumping that might somehow be used against them in the future. To make participation in this project as palatable as possible in order to achieve a sufficient number of participating growers, we devised a data management method that ensured anonymity of the irrigation application information. This was accomplished by using random site codes that were destroyed each year after a previous calendar year's data was downloaded in early January and the necessary calculations were performed. This assurance of data privacy was a key factor in achieving a broad level of participation in this study. Because the goal of the project was to generate an understanding of how the regional industry as a whole utilized irrigation water rather than what individual users themselves did, this was a very worthwhile concession to make in order to secure broad voluntary participation.

The findings

Wine grape production in this region is dominated by the variety cabernet sauvignon, which accounted for over half of the study sites selected (table 1). Other major varieties included merlot, zinfandel and syrah, and a number of minor varieties were also included.

A variety of vine training (trellis) systems are utilized in the area, and these were represented in the study sites (table 2); for a description of trellis types see Christensen et al. 2003. The vertically shoot positioned (VSP) system predominated at the study sites. The distinction between a VSP and hybrid-VSP system can be somewhat arbitrary, as there is a continuum of management styles with this basic trellis system that involves positioning a varying percentage of the shoots in different manners. The summary vineyard planting

TABLE 1. Wine grape varieties for all of the measurement sites in the Paso Robles Groundwater Basin

Variety	Number of sites	Percentage
Cabernet sauvignon	47	56%
Merlot	11	13%
Zinfandel	8	10%
Syrah	5	6%
Other*	13	15%

* Cabernet franc, chardonnay, grenache, petite sirah, petit verdot, sangiovese, sauvignon blanc, and tempranillo.

TABLE 2. Training systems at the measurement sites in the Paso Robles Groundwater Basin

Training system	Number of sites	Percentage
Vertically shoot positioned (VSP)	40	48%
Sprawl	20	24%
Hybrid VSP-sprawl*	12	14%
Quadrilateral	11	13%
Lyre	1	1%

* Only a portion of the shoots are positioned under the foliage wires, generally on the side of the trellis with lower risk of sunburn.

TABLE 3. Vineyard planting dimensions

Parameter	Mean	Standard deviation	Maximum	Minimum
Row spacing, ft (m)	9.5 (2.9)	1.2 (0.37)	11.5 (3.5)	6.0 (1.8)
Vine spacing, ft (m)	6.3 (1.9)	0.7 (0.21)	8.0 (2.4)	4.0 (1.2)

TABLE 4. Annual average irrigation applications and rainfall, 2010–2013

	Irrigation				
	Annual average	Standard deviation	Maximum	Minimum	Preceding winter rainfall
Year	*in (mm)*				
2010	10.35 (263)	5.39 (137)	27.01 (686)	3.07 (78)	16.30 (414)
2011	8.43 (214)	4.76 (121)	24.76 (629)	2.13 (54)	21.61 (549)
2012	12.05 (306)	4.84 (123)	28.15 (715)	2.72 (69)	8.31 (211)
2013	14.96 (380)	5.47 (139)	32.01 (813)	5.43 (138)	5.51 (140)
Overall average	11.46 (291)				12.91 (328)

dimensions represent moderate-density plantings typical of the region (table 3).

The four study years encompassed two seasons of above-average rainfall and two seasons of below-average rainfall (table 4). The average annual irrigation application over the 4 years was 11.46 in (291 mm). The variation in the total amount of annual irrigation that is applied at different vineyards in the region in a given year is quite large, as indicated by the large standard deviation relative to the mean value. The maximum values each year are more than twice the average, and the minimum values are less than half the average. Numerous factors determine how much irrigation is applied to a given vineyard; this includes the amount of winter rainfall at that specific site, the soil water holding capacity, the management of cover crops, the particular rootstock and its rooting depth, the salinity conditions, the row spacing and type of trellis (which both influence the total amount of vegetative growth), and the fruit production goals, among others. Considering the wide range of these factors, there is no single strategy for managing irrigation or no single amount of irrigation that will suit all sites equally well; this variability in irrigation application creates an additional challenge for groundwater sustainability agencies (GSAs), which the SGMA has tasked with managing groundwater usage.

The relationship between the total rainfall during the preceding winter (average of the seven rain gauges) and the total applied irrigation in the calendar year shows a trend of diminishing irrigation applications following winters with higher precipitation (fig. 2). Each additional unit of rainfall in the preceding winter reduces the subsequent irrigation in the calendar year by 0.36 units. While this may seem like a very intuitive finding, having an equation to precisely describe this relationship is very useful because it can be used as a tool by management agencies that need to predict and potentially allocate pumping amounts as early as possible in the growing season.

The typical growing season for grapes in this area encompasses the months of April through October. The ET_o and applied irrigation during this period varied by year (table 4). In addition to the rainfall during the winter prior to the growing season, the ET_o conditions also influenced the amount of irrigation applied during the growing season, with larger amounts of irrigation applied as ET_o increased (fig. 3).

Annual cumulative applied irrigation, expressed as the average of all sites over the calendar year, indicates how the wet and dry years differed in the timing of irrigation applications over the year (fig. 4). The two drier years (2012, 2013) stand out for the amount of irrigation applied during January, February and March, before bud break; growers were making up for the lack of rainfall with this winter irrigation. When winter rainfall was more abundant (2010, 2011), little to no winter irrigation was applied. The slopes of the curves

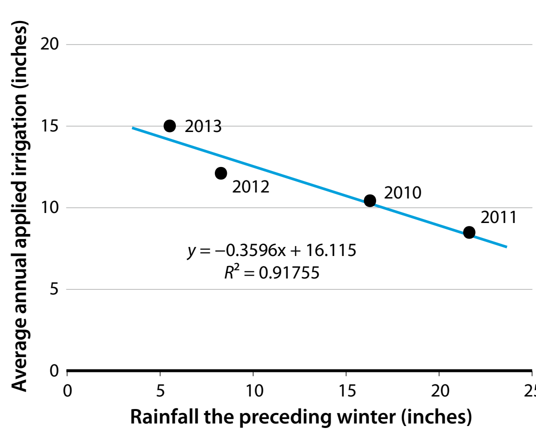

FIG. 2. Relationship between the amounts of rainfall the preceding winter and the total irrigation applied in the calendar year. The rainfall is the average of the seven gauges over the study area.

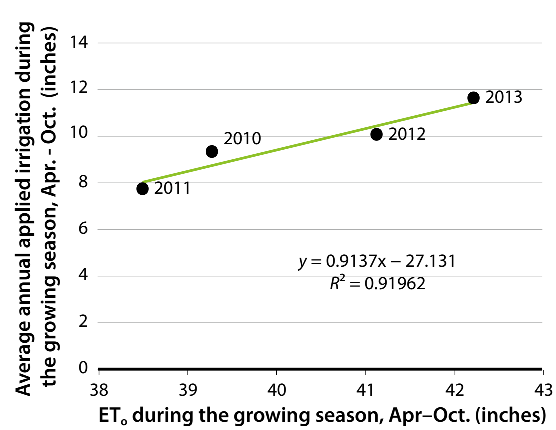

FIG. 3. Relationship between growing season (April–October) ET_o and irrigation applied during the growing season.

from May through September are very similar for 2010, 2012 and 2013 with an average value of 1.68 in/month (43 mm/month), indicating that once irrigation applications begin in earnest, the average monthly application amount does not vary much from year to year. An exception was observed for 2011, which had a shallower slope (1.28 in/month [32 mm/month]), indicating less application of irrigation over the May–September period. The 2011 season had both the greatest amount of preceding winter rainfall (table 4) and the lowest ET_o value during the growing season (table 5).

The amount of irrigation applied relative to the ET_o throughout the growing season is not constant (fig. 5). The leaf canopy will be essentially fully grown by June, and thus vine water requirements from June through October are in theory a constant percentage of the ET_o. In practice, however, less irrigation is applied in June and July relative to ET_o, as compared to August and September. Two reasons help explain this: after fruit set in late May or early June, more severe deficit irrigation is used to help slow down foliage growth and to keep developing berry sizes small; and deeper soil moisture from winter rainfall is often still available to the vines. By August and September, the deeper soil moisture from earlier rainfall is becoming depleted, and the deficit irrigation is eased up to help maintain functional leaf canopies. This pattern is reflected in the lower values of "Irrigation/ET_o" for June and July as compared to August and September (fig. 5).

Implications

The average annual irrigation application identified in this study is lower than the estimates that had been previously used in the region. The relatively low irrigation application demonstrates the suitability of wine grapes as a crop in areas with limited water availability, as the historical irrigated field crops in the region required far more irrigation water per acre and produced much lower value crops. The current relatively low average application of irrigation per acre suggests that there is not much room to save water by cutting back on applications without experiencing some level of yield loss as a result (Williams et al. 2010). The economic conditions of wine grape production in the region have not been favorable for many growers over the past decade, so reducing production levels without a commensurate increase in crop value would be unpopular (Battany 2015).

One reason why previous estimates of irrigation usage in the region may have been considerably higher than what was observed in this study was the assumption that leaching fractions were used to help remove accumulated salts from the root zone. Groundwater in the region varies widely in quality; an earlier study evaluating water quality from 16 wells in the study region observed electrical conductivity (EC_e) ranging from 0.52 to 2.38 deciSiemens per meter (dS/m) (Fugro West and Cleath 2000). In order to save water or reduce

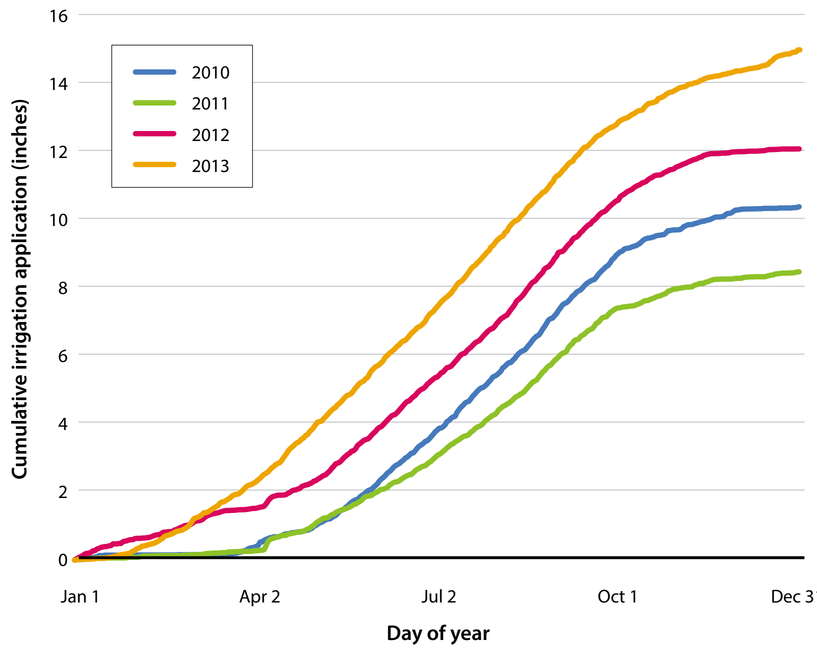

FIG. 4. Average cumulative irrigation application for each calendar year.

TABLE 5. Growing season (Apr–Oct) ET_o and applied irrigation during the growing season

Year	ET_o	Irrigation	Irrigation/ET_o
		in (mm)	
2010	39.3 (998)	9.3 (237)	0.24
2011	38.5 (978)	7.7 (196)	0.20
2012	41.1 (1045)	10.0 (255)	0.24
2013	42.2 (1072)	11.6 (295)	0.28

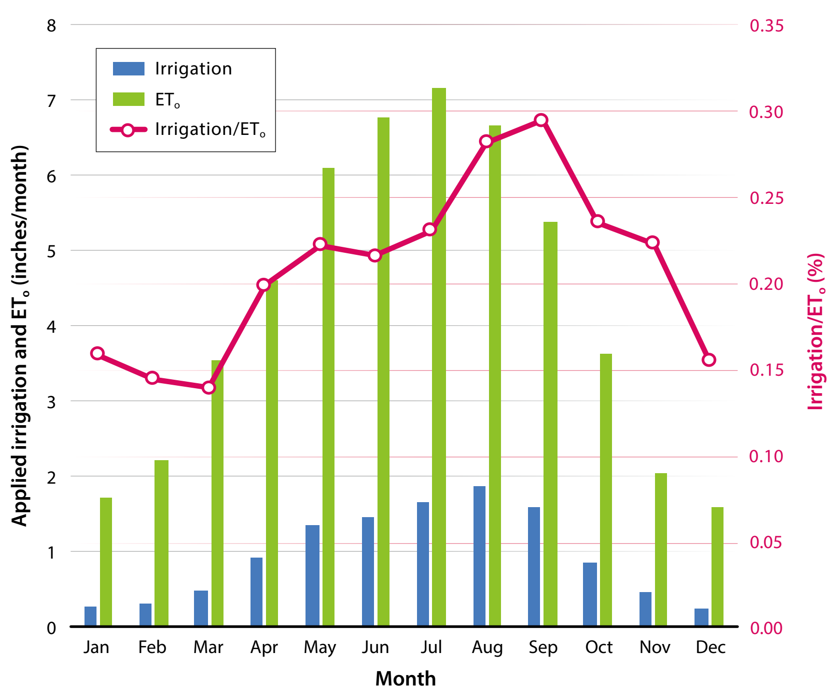

FIG. 5. The average monthly irrigation compared to the average monthly ET_o over the 4-year period.

The relatively low average application of irrigation per acre identified in the study was lower than the estimates that had been used previously in the region. This demonstrates the importance of generating more accurate estimates of irrigation applications based on comprehensive field measurements whenever possible.

The relatively low irrigation application demonstrates the suitability of wine grapes as a crop in areas with limited water availability, as the historical irrigated field crops in the region required far more irrigation water per acre and produced much lower value crops.

costs, some growers may not be applying sufficient leaching fractions, and as a result may be experiencing increased salt accumulation in their soils; this pattern of increasing salt accumulations has been observed in the region (Battany 2011). Excessive soil salinity is an issue at numerous sites in the area, particularly those that were planted in past decades before the more salt-tolerant rootstocks became available. Wine grapes (*Vitis vinifera*) are classed as moderately sensitive to soil salinity, having a threshold soil EC_e of 1.5 dS/m; soil salinity levels greater than this value will result in diminishing productivity (Grieve et al. 2012). Rootstocks with greater salt tolerance such as 1103 Paulsen have higher threshold EC_e values and are now being widely planted. One reason why some growers have added supplemental sprinkler irrigation to their vineyards in the region is to have another tool for helping manage soil salinity.

Data utilization for modeling

Past modeling efforts of the Paso Robles Groundwater Basin have been hampered by the lack of accurate information on agricultural pumping from the basin. As this is the largest single discharge of water from the basin, errors in the estimates can lead to significant errors in the overall modeling results. In 2014, an update to the Paso Robles Groundwater Basin model was prepared for San Luis Obispo County as a refinement over the previous 2005 model (Fugro West et al. 2005; Geoscience and Todd Groundwater 2014). The daily values of average vineyard irrigation applications from this research project were utilized in the calibration of the vineyard irrigation portion of this model, providing valuable feedback to further refine the accuracy of the model parameters. Accurate groundwater basin models will be a key tool for future management of the basins; thus, having accurate data to construct them will be a high priority in many areas.

Potential for real-time management

As GSAs are formed in areas of high- and medium-priority basins, one of the first steps that these agencies will likely take is to require the installation of flow meters on all irrigation wells. If these flow meters are equipped with an automated data delivery system that allows the GSA to have real-time pumping information, this in turn can be expressed as irrigation amounts per acre, and this information may be very useful for irrigation management. Irrigators all make challenging decisions as to how much water to apply and when, but it is unlikely that anyone gets this exactly right every season. The collective information sourced from a large community of growers all facing similar growing conditions may benefit from the phenomenon of the "wisdom of crowds," in which collective knowledge may sometimes be better than any single individual's knowledge (Surowiecki 2005). Thus, the types of curves shown in figure 4, if shared in real time during a growing season, may have value as an irrigation index that growers could refer to for guidance on their own irrigation decisions. This could have particular value for smaller growers with limited management resources or for those with very limited experience in the region.

Conclusions

The GSAs that are being formed in California face a big challenge in developing programs that lead to sustainable groundwater management. A key tool for any GSA will be to have comprehensive data on representative irrigation water applications for key crops, and how this application amount responds to varying rainfall and evapotranspiration conditions from year to year. This project has produced such baseline irrigation application data for the wine grape crops grown in the area east of Paso Robles; these results can now be used by the area GSAs as a benchmark in their decision-making processes. The approach and methodology used in this study may have applications for developing estimates of typical irrigation applications over multiple years in other regions to help create benchmarks for groundwater management in those regions as well. CA

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References

Battany MC. 2011. Evaluations of soil salinity conditions in California Central Coast winegrape vineyards. In: Proceedings of the Western Nutrient Management Conference, March 3–4, 2011. Reno, NV. 9:10–5.

Battany MC. 2015. Production and economic trends for SLO County vineyards. Grape Notes Blog. http://ucanr.edu/blogs/blogcore/postdetail.cfm?postnum=18590 (accessed Sept. 26, 2017).

[Cal Poly ITRC] Cal Poly Irrigation Training & Research Center. 2010. Irrigation Evaluation Data, Drip/Micro. www.itrc.org/irrevaldata/index.php (accessed Sept. 26, 2017).

Christensen LP, Dokoozlian NK, Walker MA, Wolpert JA. 2003. *Wine Grape Varieties in California*. UC Agriculture and Natural Resources Publication 3419.

City of Paso Robles. 2011. Annual Monitoring Report for Calendar Year 2009. http://pasobasin.org/technical-studies/ (accessed Sept. 26, 2017).

[DWR] California Department of Water Resources. 2014. Sustainable Groundwater Management. http://groundwater.ca.gov/ (accessed Sept. 26, 2017).

DWR. 2016. Bulletin 118, Interim Update 2016. California's Groundwater: Working Toward Sustainability. www.water.ca.gov/groundwater/bulletin118/docs/Bulletin_118_Interim_Update_2016.pdf (accessed Sept. 26, 2017).

DWR. 2017. Sustainable Groundwater Management: Critically Overdrafted Basins. www.water.ca.gov/groundwater/sgm/cod.cfm (accessed Sept. 26, 2017).

Fugro West Inc. and Cleath & Associates. 2002. Final Report, Paso Robles Groundwater Basin Study. www.slocountywater.org/site/Water%20Resources/Water%20Forum/pdf/Paso%20Robles%20Groundwater%20Basin%20Study,%20Phase%20I.pdf (accessed Sept. 26, 2017).

Geoscience and Todd Groundwater. 2014. Paso Robles Groundwater Basin Model Update. www.slocountywater.org/site/Water%20Resources/Water%20Forum/Computer%20Modeling/ (accessed Sept. 26, 2017).

Grieve CM, Grattan SR, Maas EV. 2012. Plant salt tolerance. In: Wallender WW, Tanji KK (eds.). *Agricultural Salinity Assessment and Management* (2nd ed.). ASCE Manual and Reports on Engineering Practice No. 71. Reston, VA: ASCE.

Hanson BR, Schwankl LJ. 1998. Water turbulence disrupts accuracy of some flow meters. Calif Agr 52(1):25–30. https://doi.org/10.3733/ca.v052n01p25

Paso Robles Water Division. 2014. Rainfall totals, 1942-2014. www.prcity.com/government/departments/publicworks/water/rainfall.asp (accessed Sept. 26, 2017).

San Luis Obispo County. 2012. Master Water Report Volume III, May 2012. www.slocountywater.org/site/Frequent Downloads/Master Water Plan/pdf/Vol_III_MWR final.pdf

Shinn CH. 1902. Experiments with Deciduous Fruits at and Near the Southern Coast Range Sub-Station, Paso Robles from 1889 to 1902. University of California Bulletin No. 141.

Surowieki J. 2005. *The Wisdom of Crowds*. New York, NY: Anchor Books. 336 p.

Williams LE, Grimes DW, Phene CJ. 2010. The effects of applied water at various fractions of measured evapotranspiration on reproductive growth and water productivity of Thompson Seedless grapevines. Irrigation Sci 28:233–43.

Yates G. 2010. Peer Review of Paso Robles Groundwater Studies. Executive Summary. www.slocountywater.org/site/Water%20Resources/Water%20Forum/pdf/GW%20Basin%20Peer%20Review%20Final%20Sec.pdf

Modeling guides groundwater management in a basin with river–aquifer interactions

A Scott Valley study shows gains in understanding seasonal dynamics of groundwater–surface water fluxes as model tools address more complex natural phenomena.

by Laura Foglia, Jakob Neumann, Douglas G. Tolley, Steve B. Orloff, Richard L. Snyder and Thomas Harter

Abstract

The Sustainable Groundwater Management Act (SGMA) of 2014 seeks to maintain groundwater discharge to streams to support environmental goals. In Scott Valley, in Siskiyou County, the Scott River and its tributaries are an important salmonid spawning habitat, and about 10% of average annual Scott River stream flow comes from groundwater. The local groundwater advisory committee is developing groundwater management alternatives that would increase summer and early fall stream flows. We developed a model to provide a framework to evaluate those alternatives. We first created a water budget for the Scott Valley groundwater basin and integrated the detailed, spatiotemporally distributed water budget results into a computer model of the basin that simultaneously accounted for groundwater flow, stream flow and landscape water fluxes. Different conceptual representations (using the MODFLOW RIV package and MODFLOW SFR package) of the stream–aquifer boundary provided significantly different results in the seasonal dynamics of groundwater–surface water fluxes. As groundwater sustainability agencies draw up plans to meet SGMA requirements, they must choose and test simulation tools carefully.

Management of California's water supplies serves diverse goals. Securing the needs of urban and agricultural water customers is a key goal. Meeting environmental health, ecosystem services and stream water quality goals has also been an integral part of many California water management systems. To meet this range of goals, groundwater, soil water and surface water will need to be managed conjunctively, management will likely become more tightly linked with land use and land resources planning and management, and modelling will play a key role in the development of successful and useful management plans.

The 2014 California Sustainable Groundwater Management Act (SGMA) and recent salt- and nitrate-related regulations to protect groundwater quality have put a focus on groundwater resources management, both quality and quantity, particularly in agricultural regions (Harter 2015). They mandate that local agencies pursue groundwater sustainability goals: avoiding long-term groundwater storage depletion, land subsidence,

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The Scott River is an important salmonid spawning habitat that depends on groundwater to maintain stream flow during the summer. A hydrologic model developed by UC researchers can help predict the impact of different groundwater and surface water management scenarios on stream flow.

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seawater intrusion, groundwater management–related water quality degradation, and deterioration of groundwater–surface water interactions.

Particularly important under the SGMA regulations is the interaction between groundwater and surface water: how do groundwater management decisions — by individual landowners or by groundwater sustainability agencies (GSAs) — impact not only beneficial users, but also streams (Zume and Tarhule 2011) and groundwater-dependent ecosystems (GDEs) (Boulton and Hancock 2006; Hatton 1998). Prominent California examples of areas where groundwater–surface water interactions are already addressed include the Napa River in Napa County and the Scott River in Siskiyou County. Both feature important salmonid fish habitat and therefore temperature is a critical issue (Brown et al. 1994; Moyle and Israel 2005); and low or decreased late-summer stream flow over the last half-century has impacted the quantity and quality of fish habitat (Kim and Jain 2010; NCRWQCB 2005; Nehlsen et al. 1991). During drought, portions of these rivers may temporarily dry up. In intermontane Scott Valley, dry sections disconnect lower sections of the stream from tributaries in the headwaters. Summer stream temperatures in the Scott River are affected by groundwater discharge into the streambed and by riparian shading and were being addressed under the federal Clean Water Act (NCRWQCB 2005) before SGMA.

Some measurements can be collected in the field to evaluate groundwater–surface water interactions, but computer models are needed to fully understand groundwater basin flow dynamics and assess impacts to stream flow under future groundwater management scenarios. For example, computer models can show the response of integrated water systems to management decisions such as pumping and intentional recharge. They are expected to play a key role in the implementation of SGMA and regulatory efforts.

Various modeling approaches have been developed for groundwater–surface water interactions (Furman 2008; Harter and Seytoux 2013). These range from analytical or spreadsheet tools (Foglia, McNally, Harter 2013) and coupled or iteratively coupled numerical model codes for computer simulations, such as the MODFLOW river (RIV) package (Harbaugh et al. 2000) and the MODFLOW stream flow routing SFR1 package (Prudic et al. 2004) and SFR2 package (Harbaugh 2005; Niswonger and Prudic 2005), to fully coupled models such as ParFlow (Ashby and Falgout 1996; Kollet and Maxwell 2006) and Hydrogeosphere (Brunner and Simmons 2012).

Fully coupled models provide the physically and mathematically most consistent and complete integration of groundwater, surface water and soil water systems. But they are computationally more expensive and require more parameterization (data input) than iteratively coupled models. In coupled or iteratively coupled models, multiple models are coupled such that one model provides input to the other model and vice versa, sometimes iteratively. Full coupling may not always yield better results (Furman 2008). For some applications, statistical models or analytical tools, which are based on highly simplified concepts and therefore have the least data input requirements and are computationally much less demanding, may be appropriate.

Almost 70% of Scott Valley is used for agricultural production, with a nearly even split between alfalfa/grain and pasture.

In Scott Valley, groundwater–surface water interactions are analyzed as part of an action plan to meet temperature TMDL (Total Maximum Daily Load) requirements for the Scott River. Climate change and groundwater pumping for irrigation in the valley have impacted late-summer and early fall stream flows in the Scott River (Drake et al. 2000; Kirk and Naman 2008). The local groundwater advisory committee is developing potential groundwater management scenarios that would increase summer and early fall stream flows. To evaluate those scenarios, we explored three levels of conceptual complexity at which information can be obtained about groundwater–surface water interactions: a water budget approach, a groundwater model with a conceptually simplified stream model (RIV) and a fully coupled groundwater–surface water model (SFR).

Scott Valley study area

Our study area was Scott Valley in northern California. Almost 70% of the valley is used for agricultural production, with a nearly even split between alfalfa/grain and pasture.

Geography and climate

Scott Valley is an intermontane 220-square-kilometer agricultural groundwater basin at an elevation of 2,600 to 3,100 feet in Siskiyou County (fig. 1). The Scott River

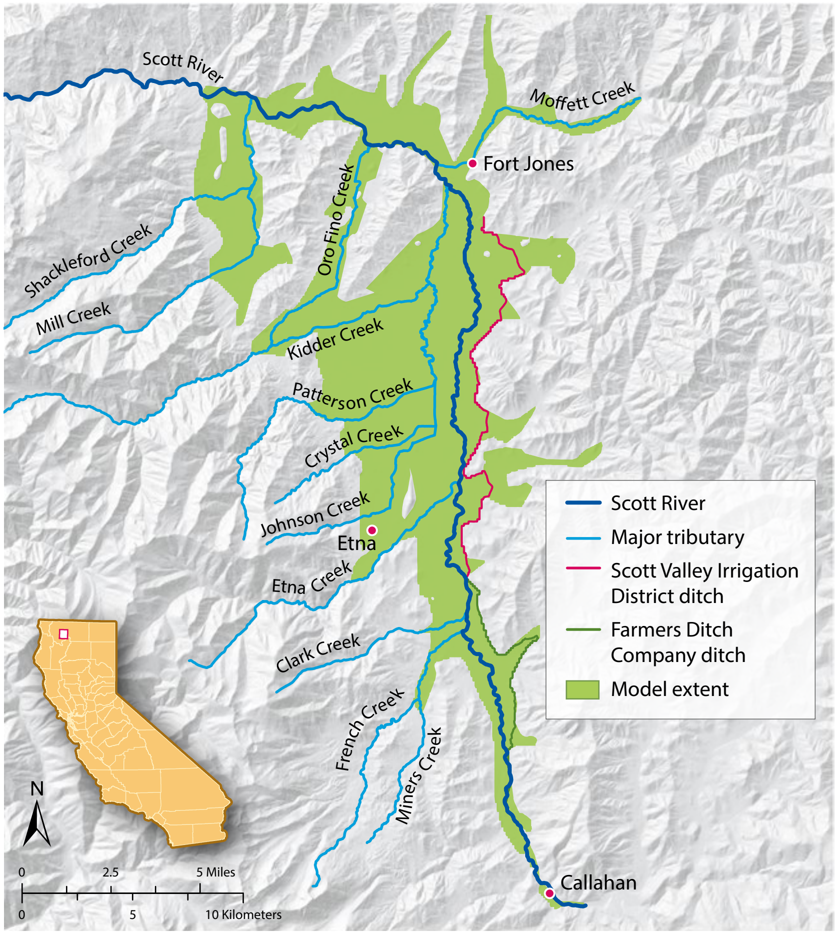

FIG. 1. The boundaries of the groundwater model study in Scott Valley, and its surface waters. The Scott River and its tributaries are an important salmonid spawning habitat, home to native populations of the threatened coho. Source: Model extent derived from Mack (1958) and Soil Survey Geographic Database (SSURGO) data. Projection: North American Datum 1983, UTM Zone 10.

flows from south to north along the east-central and northern portion of the valley. At the valley's northwest corner, the river descends into a gorge before joining the Klamath River several miles below Scott Valley. The Scott River watershed above Scott Valley extends into the surrounding Klamath Mountains to elevations of over 8,500 feet. The river and its tributaries are an important salmonid spawning habitat, home to native populations of the threatened *Oncorhynchus kisutch* (coho).

Scott Valley formed primarily due to movement along an eastward dipping normal fault, with unconsolidated, highly heterogeneous fluvial and alluvial fan deposits forming an alluvial groundwater basin (Mack 1958). Surrounding the valley, the geology is comprised of relatively impermeable bedrock composed of metamorphic and volcanic units, although fractures do yield some water in the form of springs at the margins of the valley and in surrounding upland areas.

Aquifer thickness may be as much as 400 feet in the wide central part of the valley (Mack 1958). However, there is no evidence of sufficiently coarse material to support agricultural groundwater pumping below 250 feet (Foglia, McNally, Harter 2013). The aquifer pinches out at the valley margin.

Climate in the valley is Mediterranean, with 89% of the nearly 500-millimeter average annual precipitation falling between October and April. Daily mean temperatures range from 70°F in July to 32°F in January. Precipitation depths in the surrounding mountains are much higher, and snowmelt is a major source for ephemeral tributaries feeding the Scott River and recharging into the aquifer. Snowmelt dominates Scott River flows through June. During the summer months, flows in the Scott River immediately below the montane valley (USGS gage 11519500 Ft. Jones) can drop to 4 cubic feet per second (cfs), while maximum flows during winter can reach 40,000 cfs. After snowpack storage has been depleted, the Scott River is dependent on discharge from the Scott Valley aquifer to support base flow. In dry years, sections of the Scott River overlying the valley floor become ephemeral.

Land use and irrigation

Land use was surveyed in 2000 (DWR 2000) and further refined using aerial photo analysis and on-the-ground verification through interviews with landowners. A total of 2,119 land use parcels overlie the Scott Valley groundwater basin (fig. 2): 710 parcels (17,400 acres) are alfalfa/grain (an 8-year rotation with, on average, 1 year of grain crop followed by 7 years of alfalfa), 541 parcels (16,600 acres) are pasture, 451 parcels (20,400 acres) belong to land use categories with significant evapotranspiration but no irrigation (e.g., cemeteries, lawns, natural vegetation) and 417 parcels (1,700 acres) represent land uses with no evapotranspiration or irrigation (e.g., residential areas, parking lots, roads, and — most significantly — historic mine tailings).

The year 2000 land use survey by DWR (DWR 2000) also identified the irrigation type associated with each land parcel. About 6,200 acres of cropland were identified as nonirrigated, dry or subirrigated. In Scott Valley, flood, center-pivot sprinkler and wheel-line sprinkler irrigation are used almost exclusively. Over the past 25 years, significant conversion from wheel-line sprinkler (but also from flood irrigation) to center-pivot sprinkler has occurred. For our study, we mapped the location (extent) and year of such irrigation-type conversions to land parcels by reviewing 1990 to 2011 aerial photos.

The beginning of the irrigation season is determined by soil moisture depletion but also by grower peer behavior. Earliest irrigation dates reported by local growers were March 15, March 24 and April 15 for grains, alfalfa and pasture, respectively. Growers irrigate based on soil moisture data, experience, peer behavior and established irrigation practices. The irrigation season typically ends on July 10, Sept. 1 and Oct. 15 for grain, alfalfa and pasture, respectively.

Water sources (identified for each land parcel by the DWR 2000 land use survey and updated through landowner survey) include groundwater, surface water, subirrigated (shallow groundwater table, not actually irrigated), mixed groundwater–surface water, and nonirrigated (dryland farming). Land parcels are distributed across nine subwatersheds associated with the major tributaries and the main stem Scott River. Discharge on these streams into the Scott Valley defines available maximum diversion rates for surface water irrigations. Where surface water is the only source of irrigation, lack of surface water will terminate the irrigation season. Groundwater pumping for a land parcel is from nearby or on-site irrigation wells. Well locations and type for the study area were obtained from DWR well permit records (fig. 2).

Hydrogeology

Within the alluvial groundwater basin of the Scott Valley, Mack (1958) distinguished six subareas (fig. 3). In our work, we also included the mine tailings at the southern end of the alluvial basin, an important hydrogeologic area consisting almost exclusively of reworked boulders from mine dredging operations (Foglia, McNally, Harter 2013).

Aquifer pumping tests were performed to determine hydraulic properties in the main subarea of the valley, along the Scott River corridor. The tests showed that even within hydrogeologic subareas, hydraulic property values vary greatly. Estimates of hydraulic property values were also obtained from literature available for the region (DWR 2000; Mack 1958; SSPA 2012). The ratio of vertical hydraulic conductivity to horizontal hydraulic conductivity was estimated to be 1:10, a relatively high value representing relatively strong vertical connectivity of the coarser sediments.

The aquifer receives recharge from excess rainfall and irrigation but also from streams entering the basin on highly permeable alluvial fans. Groundwater discharge generally occurs through groundwater-dependent wetlands and riparian vegetation, pumping (primarily for irrigation) and discharge to streams, mostly along the valley thalweg.

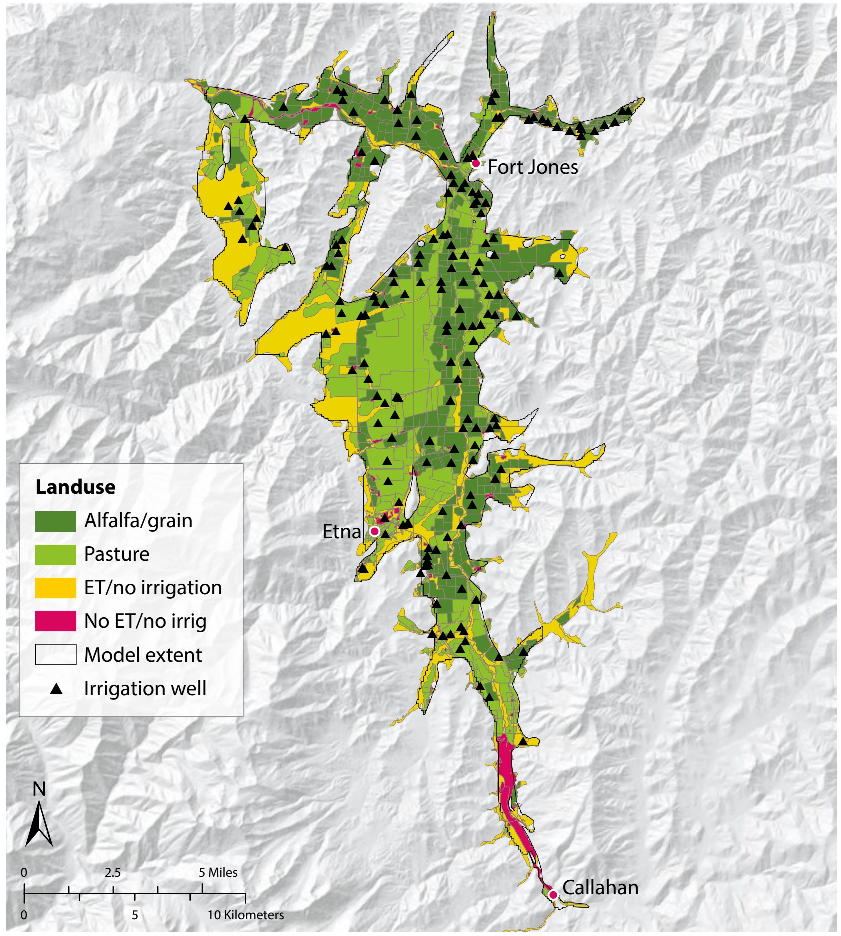

FIG. 2. Land use information and well locations in Scott Valley. ET/no irrigation reflects nonirrigated vegetation, e.g., lawns and riparian vegetation. No ET/no irrigation represents nonvegetated land surfaces including the mine tailings near Callahan. Well location information was obtained from well logs filed with the Department of Water Resources and verified in the field. Source: Model extent derived from Mack (1958) and SSURGO data. Land use polygon data source: DWR (2000). Revised to reflect 2011 land use patterns (GWAC, Groundwater Advisory Committee). Projection: North American Datum 1983, UTM Zone 10.

Modeling tools

We developed the Scott Valley Integrated Hydrologic Model (SVIHM) to (1) provide a tool that integrates a diverse set of data and information within a consistent physical, hydrological framework; (2) estimate water budget components and their seasonal and interannual dynamics in the groundwater, stream and landscape–soil system; (3) better understand the relationship between land use, irrigation, groundwater pumping and stream flow; (4) provide a tool to predict potential impacts on stream flow from future groundwater and surface water management scenarios; and (5) provide an educational and decision-making tool for local stakeholders, regulators and policy- and decision-makers engaged in developing solutions to support and protect groundwater-dependent salmon habitat in the Scott Valley watershed.

For the simulation, we considered the period from October 1991 through September 2011, a period that includes the transformation of the Scott Valley landscape from predominantly sprinkler to significant center-pivot irrigation, a series of wet periods (1996 to 1999, 2006) and dry periods (1991, 2001, 2007 to 2009) and a series of years with potentially higher temperature. We developed several distinct model elements, representing the 1991 to 2011 period of the different hydrologic system components at varying levels of complexity that meet the modeling objectives. These were linked together into the SVIHM:

The upper watershed was represented by a statistical regression model to simulate incoming stream flows in the Scott River and its tributaries from the upper watershed to the valley, which are also used for irrigation. The Scott Valley landscape overlying the groundwater basin was represented by a tipping-bucket-type soil water budget model (SWBM) that simulates daily and monthly landscape-related water fluxes at the land parcel scale (see description above), including irrigation from diversions of surface water inflows to the valley and by groundwater pumping, evapotranspiration and groundwater recharge. Valley groundwater and surface water were simulated using a numerical model capable of simulating groundwater flow dynamics and the groundwater–surface water interface at sufficient detail to guide future data collection and simulate future water management scenarios.

Upper watershed stream flows

Surface water inflows to Scott Valley from the upper watershed are an important source of irrigation water. During the summer, incoming low flows may limit or terminate surface water diversions for irrigation. This in turn affects groundwater pumping in some crop parcels equipped for dual irrigation (surface and groundwater). Quantitative estimates of surface water inflows are also an important input to simulation of stream flow dynamics (including tributaries) within the valley, where streams are in direct connection with groundwater (the groundwater–surface water interface).

Since only limited stream gauging data were available on inflowing streams, a stream flow regression model was developed (Foglia, McNally, Hall 2013). Several factors were considered in developing the regression model, including precipitation, precipitation history, snowpack, and stream flows at the valley outlet, where the USGS Ft. Jones gage has provided nearly continuous records since the early 1940s. Foglia, McNally, Hall (2013) showed that the latter was the most critical factor to predict available monthly total incoming stream flow measured near the valley margins.

Soil water budget model, SWBM

In California, no water rights permits are issued for groundwater pumping, and wells, including wells in the study area, are largely unmetered. The primary purpose of the soil water budget model (SWBM) was therefore to estimate spatially and temporally varying recharge and pumping across the groundwater basin. A second goal was to quantify crop evapotranspiration (crop ET) and irrigation water use from surface water and from groundwater, and to understand the role of soil water storage. Conceptually, the soil water budget model encompasses the managed and unmanaged landscape including its vegetation and soil root zone and also the managed components of the surface water system (diversions) and of the groundwater system (well pumping).

SWBM does not account for fluxes at the groundwater–stream interface (stream recharge, groundwater discharge to streams) or for evapotranspiration due to root water uptake directly from groundwater by nonirrigated crops or in natural landscapes with a shallow water table. These processes were instead accounted for by the groundwater–surface water models MODFLOW RIV or MODFLOW SFR.

SWBM provided daily estimates of groundwater pumping, groundwater recharge, and evapotranspiration from Oct. 1, 1991, to Sept. 30, 2011, for each of the 2,115 parcels delineated in the land use survey of Scott Valley. Storage routing and mass balance were calculated for each land parcel as

$$\theta_i = \max\,(0, \theta_{i-1} + Padj_i + AW_i + actualET_i - Recharge_i) \quad (1)$$

$$actualET_i = \min(ET_i, \theta_{i-1} + Padj_i + AW_i) \quad (2)$$

$$Recharge_i = \max(0, \theta_{i-1} + Padj_i + AW_i - actualET_i - WC4_i) \quad (3)$$

where θ_i is the water content at the end of day *i*; $Padj_i$ is the precipitation that infiltrates into the soil and is available for recharge or evapotranspiration on day *i*; AW_i is the applied water (irrigation) amount on day *i;* ET_i is the evapotranspiration on day *i* (computed as the product of the crop coefficient Kc and measured reference ET); $Recharge_i$ is deep percolation to the groundwater below the 1.22 meter (4 foot) deep root zone; and $WC4_i$ is the soil-dependent water holding capacity of the 1.22 meter (4 foot) root zone (Foglia, McNally, Harter 2013).

SWBM approximated growers' irrigation decisions in a simplified fashion: In the model, daily irrigation depths, AW_i, were controlled by crop evapotranspiration depth and effective precipitation, which in turn were computed from daily climate data, using appropriate crop coefficients:

$$AW_i = \frac{(actualET_i - Padj_i)}{\frac{AE}{100}}$$

where *AE* is the water application efficiency, which was assumed to be constant over the growing season. The *AE* values were based on published values (Canessa et al. 2011) adjusted for local conditions: 90% for center-pivot sprinkler, 75% for wheel-line sprinkler and 70% for flood irrigation. The model accounted for the strong relationship between crop evapotranspiration and irrigation, but it did not represent temporal details of the actual irrigation schedule or alfalfa cuttings, as these have negligible impact on variations in groundwater conditions. The model also did not account for delivery losses.

Within the alluvial groundwater basin of the Scott Valley, there are six subareas. In this work, the authors also included the mine tailings at the southern end of the alluvial basin, an important hydrogeologic area consisting almost exclusively of reworked boulders from mine dredging operations.

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MODFLOW simulations

A water budget model accounts for water fluxes into and out of a groundwater basin, the associated landscape and streams, and it provides some insight into large-scale, regional groundwater–surface water interactions. But integrated groundwater–surface water computer models, such as the MODFLOW packages, are more useful to fully assess and understand groundwater–surface water dynamics that are also driven by human impacts (e.g., pumping).

We used the MODFLOW-2005 code to build the groundwater–surface water model element of SVIHM (Harbaugh 2005). MODFLOW-2005 is a computer-based groundwater–surface water model that simulates groundwater flows and surface water flows by representing the aquifer basin and overlying stream system through discretized blocks (much like the way pixels on a TV screen are a representation of a continuous image). Aquifer and stream properties were defined for each block, which allowed the model to not only take on the actual shape of a groundwater–surface water system but also to represent the internal variability in aquifer and streambed properties that best reflects that actual system.

At the core, the model code solved the equations governing groundwater flow and stream flow, one time step after another. The entire Scott Valley groundwater basin (fig. 1) was discretized into 50-meter-by-50-meter cells, and it was divided into two vertical layers to better capture vertical fluxes associated with groundwater–surface water interactions. Due to the basin geometry, the bottom layer is not laterally expanding as much as the top layer (see supporting information S1 online).

Figure 3 summarizes the boundary conditions used to develop the groundwater model. The model simulates groundwater–surface water interactions along the Scott River, along major tributary streams (Shackleford, Mill, Kidder, Oro Fino, Moffett, Patterson, Etna, Crystal, Johnson, Clark Miner's and French Creeks) and along two major irrigation ditches (Farmers Ditch Company and Scott Valley Irrigation District). These features were simulated using different combinations of the river, stream flow routing (SFR1) and drain (DRN) packages of MODFLOW.

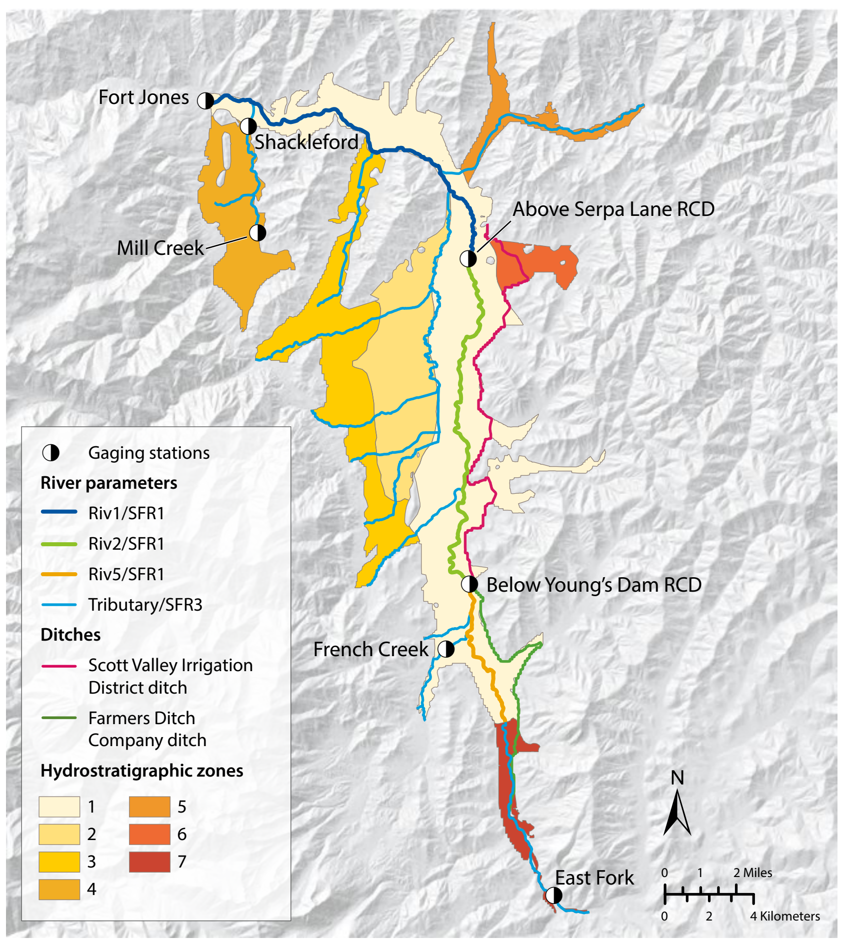
In our study, we developed two versions of SVIHM to represent two levels of conceptual complexities in the simulation of the groundwater–surface water interface. Both used the same algorithm to determine groundwater–surface water exchanges based on water level differences between the stream and groundwater, and as a function of streambed hydraulic conductivity.

In SVIHM-RIV, using the MODFLOW RIV package (Harbaugh 2005), stream water levels were user assigned and might vary in time and space. The advantage of SVIHM-RIV is that it is computationally much less expensive (has a much lower simulation run time) than SVIHM-SFR, since it does not simulate the stream flow system. The computational efficiency is advantageous in model calibration. In Scott Valley, only sparse data were available on stream water levels. As an initial modeling design step, we chose a simple approximation of stream water levels using a constant, average stream depth uniform across the valley at all times.

In SVIHM-SFR, using the MODFLOW SFR package (Prudic et al. 2004), inflows from the upper watershed (obtained from the statistical model of watershed inflows), after irrigation diversions (obtained from SWBM), were physically routed by simulation through the valley's stream system. The simulation computed stream water level as a function of flow rate, stream slope, streambed morphology and stream roughness (Manning's equation). Detailed streambed morphology was available from two LIDAR surveys (SSPA 2012). With SFR, stream flow varied from stream cell to stream cell due to diversions, tributary inflows or groundwater–surface water exchanges. In this way, MODFLOW SFR tracked stream water depth variations in time and along the stream system. It could also estimate the timing and location of stream sections that fell dry.

The land parcel–based output results of SWBM — agricultural groundwater pumping, groundwater recharge and irrigation — were used as input to the MODFLOW RIV and MODFLOW SFR versions of

FIG. 3. Representation of the main characteristic of the modelled area, including boundary conditions, hydraulic conductivity and specific storage as defined by hydrostratigraphic zone, irrigation ditches, stream flow gaging stations and river segments (represented as Riv1, Riv2 and Riv5). Source: Model extent derived from Mack (1958) and Soil Survey Geographic Database (SSURGO) data. Projection: North American Datum 1983, UTM Zone 10.



SVIHM, which simulated the 21-year period using monthly variable boundary conditions (monthly stress periods). Recharge was applied to the top of the highest active cell in the model using the recharge (RCH) package. Evapotranspiration rates were calculated using SWBM for irrigated and for nonirrigated vegetated areas. In addition, in vegetated areas where irrigation water was not applied, additional evapotranspiration from shallow groundwater was calculated within MODFLOW using the evapotranspiration segments (ETS) package (Banta et al. 2000).

Groundwater pumping rates for individual land parcels were assigned to the nearest irrigation well. The sum of groundwater pumping assigned in a given month to a well by SWBM was the input for the MODFLOW well (WEL) package. Surface water irrigations estimated by SWBM were subtracted from the incoming tributary stream flows prior to routing surface water through Scott Valley with MODFLOW. Hydraulic parameters and other relatively uncertain components of the conceptual model were separately evaluated with the numerical model using sensitivity analysis and calibration (Tolley et al., unpublished data).

For SVIHM-RIV, groundwater level measurements across the valley and the net gain or loss in stream flow for three stream reaches along the Scott River were used as calibration targets. For SVIHM-SFR, the same valleywide groundwater level measurements have been included, but flow discharges were calibrated against the time series in the four locations used in the SVIHM-RIV and in the Fort Jones station gaging station, since SVIHM-SFR tracks stream gains and losses for computing stream flows.

Soil water budget calibrated collaboratively

The results of the initial version of SWBM (Foglia, McNally, Harter 2013) were vetted with the Scott Valley Groundwater Advisory Committee, local growers and the UC Cooperative Extension (UCCE) farm advisor. The initial SWBM estimated an average applied irrigation on (mostly sprinkler-) irrigated alfalfa of about 33 inches per year. However, landowners in the valley reported irrigation equipment to be set up for only about 20 to 24 inches per year.
To understand the origin of the discrepancy between simulated and grower-reported irrigation depths, a manual sensitivity analysis was performed with SWBM. SWBM was implemented with varying parameter combinations to quantify the effect these parameters had on water budget results.

To account for the possibility of deficit irrigation and deep soil moisture depletion during the irrigation season, the irrigation model in SWBM (Foglia, McNally, Harter 2013) was modified: Under deficit irrigation, application efficiency is assumed to be 100%, evapotranspiration is assumed to be met by precipitation and applied water but also by soil moisture depletion, where applied water demand is computed from

$$AW_i = \frac{(actualET_i - Padj_i)}{1 + \dfrac{SMDF}{100}}$$

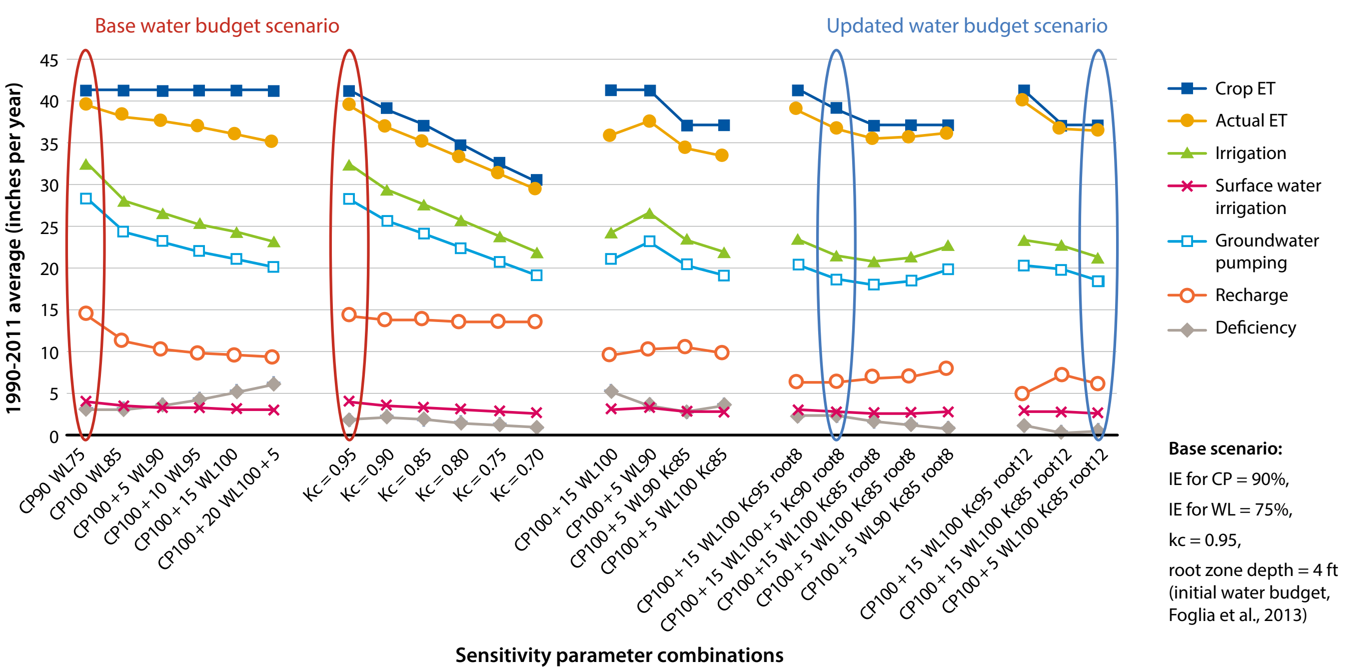


FIG. 4. Sensitivity of the simulated soil water fluxes to application efficiency, soil moisture depletion, root zone depth, and crop evapotranspiration (represented as crop coefficient Kc). For the soil water budget model sensitivity analysis, we adjusted root zone depth, from 4 feet (base value) to 8 feet (root8) and 12 feet (root12); alfalfa crop coefficient, from 0.95 (base value, Kc95) to 0.7; application efficiency for center-pivot from 90% (base value, CP90) to 100% + 20% SMDF (CP100 + 20), and for wheel-line from 75% (base value, WL75) to 100% + 5% SMDF (WL100 + 5); and (for deficit irrigation) the soil moisture depletion fraction (SMDF).

and *SMDF* is the soil moisture depletion fraction, defined as the ratio of soil moisture depletion to applied water during the irrigation season:

$$SMDF = \frac{\Sigma(\textit{soil moisture depletion})\ \textit{during the irrigation season}}{\Sigma(AW)\ \textit{during the irrigation season}} \times 100\%$$

For the sensitivity analysis, root zone depth, alfalfa crop coefficient (Kc), application efficiency and (for deficit irrigation) SMDF were adjusted (fig. 4).

The scenarios offered several combinations of these parameters that resulted in irrigation amounts of 24 inches or less: Reducing the Kc value led to lower irrigation needs but conflicted with previously measured Kc values (0.95). Increasing application efficiency, increasing the soil moisture depletion fraction for deficit irrigation and increasing root zone depth all led to significant reductions in simulated irrigation without significantly affecting simulated evapotranspiration. It remained unclear which parameter option to choose.

A 3-year field research project was launched in cooperation with local growers to measure evapotranspiration, irrigation water applications and deep soil moisture profiles in eight alfalfa fields distributed across representative locations in Scott Valley. The study established a new, slightly lower Kc value of 0.9. For alfalfa, the soil water profile from 5 feet to 8 feet was found to generally decline in soil water content throughout the irrigation season. Thus, alfalfa was found to be effectively deficit irrigated, that is, the application efficiency was 100%. Experimental results better constrained input choices in SWBM. Using an 8-foot root zone for alfalfa, the new Kc = 0.9 value and soil moisture depletion fractions of 5% for wheel-line irrigation and 15% for center-pivot irrigation (on both alfalfa and grain), the total annual simulated irrigation depth on alfalfa, computed by the adjusted SWBM, averaged 22 inches per year instead of 33 inches per year, corresponding with measured irrigation rates (blue oval in fig. 4).

Aggregated water budget results from this calibrated SWBM provided some important insights into understanding the groundwater–surface water interface dynamics (table 1): The total amount of groundwater pumping (an output from the groundwater account) was equal to about two-thirds of the estimated total landscape recharge (an input to the groundwater account). Since long-term groundwater levels were balanced, the surplus in recharge relative to pumping, 14,000 acre-feet per year, was the net contribution of the landscape to base flow, that is, to the groundwater discharge to the Scott River.

A small portion of the 14,000 acre-feet per year may also contribute to evapotranspiration from groundwater (e.g., riparian vegetation). Note that actual net groundwater discharge to the Scott River is higher, as SWBM does not account for about 44,000 acre-feet per year of mountain-front recharge from tributaries and leakage to groundwater from irrigation ditches (a result obtained from the groundwater–surface water modeling, below). The total amount of net groundwater discharge to streams is only about one-tenth of the much larger Scott River total annual flow, most of which originates from the upper watershed. However, during the low flow period (July/August through September/October) the Scott River outflow from the basin is mostly groundwater dependent, particularly in dry years. Over that period, total stream outflow from the

TABLE 1. Aggregated average annual water budget model results over the 21-year simulation period by land use

	Crop ET*	Actual ET†	Irrigation‡	SW irrigation	GW pumping	Recharge	Area
	Inches per year						*Acres*
Alfalfa	39.2	36.8	21.5	2.8	18.7	6.3	13,893
Grain	16.1	16.1	10.3	1.6	8.7	10.6	1,985
Pasture	38.2	34.8	26.0	20.5	5.5	11.6	11,909
ET/no irrigation	14.0	11.0	0.0	0.0	0.0	10.8	20,383
No ET/no irrigation	0.0	0.0	0.0	0.0	0.0	21.6	1,695
	Acre-feet per year						*Acres*
Alfalfa	45,384	42,065	24,871	3,207	21,665	7,294	13,893
Grain	2,663	2,663	1,707	263	1,444	1,753	1,985
Pasture	37,910	34,536	25,791	20,351	5,440	11,512	11,909
ET/no irrigation	23,780	18,684	—	—	—	18,345	20,383
No ET/no irrigation	—	—	—	—	—	3,051	1,695

Note: All calculations assume that the water table is below the root zone.

* Annual evapotranspiration rate if optimal irrigation was applied year-round.

† May be less than crop evapotranspiration due to discontinued irrigation in late summer (lack of surface water) or fall (no irrigation is typically applied after August).

‡ Includes irrigation with surface water and irrigation with groundwater.

SW = surface water, GW = groundwater.

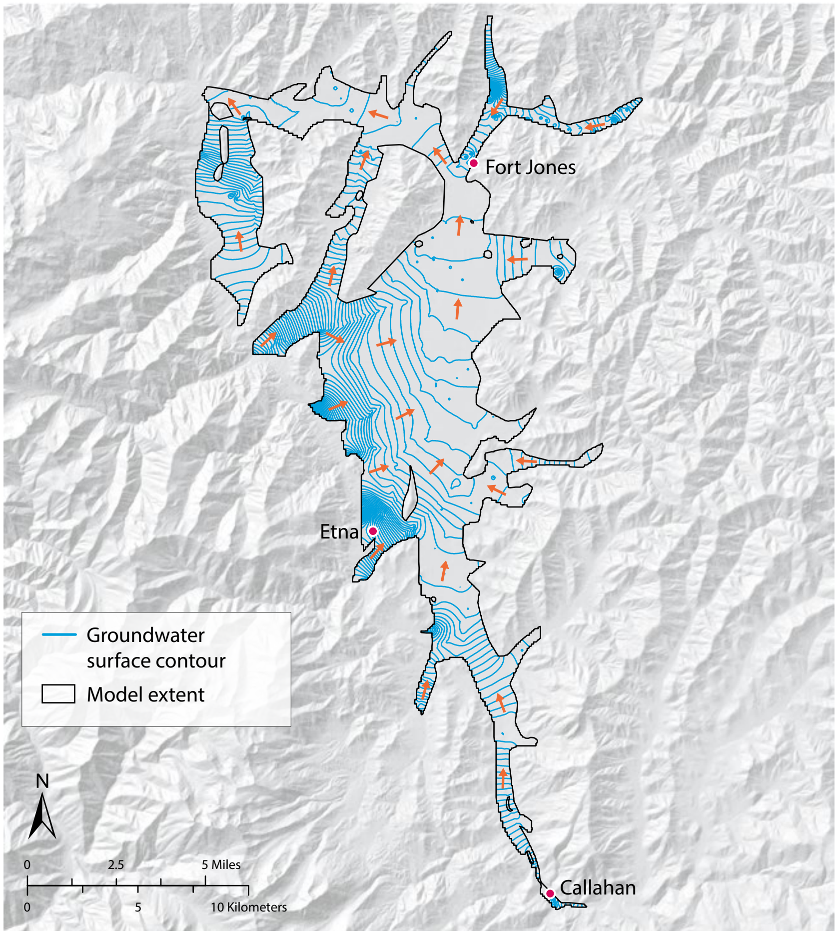


FIG. 5. Groundwater levels and flow direction in August 2001. This is one of the results from the groundwater–surface water model. Other output from the groundwater–surface water model included monthly water levels, groundwater flow directions and amounts, and groundwater–surface water exchanges for water years 1991 to 2011. Arrows indicate the flow direction but are not scaled to groundwater flow velocity. See supporting information S1 for comparison of simulated water levels and flow rates to measured water levels and flow rates. Source: Model extent derived from Mack (1958) and SSURGO data. Projection: North American Datum 1983, UTM Zone 10.

During the low flow period (July/August through September/October) the Scott River outflow from the basin is mostly groundwater dependent, particularly in dry years.

valley may amount to less than 10,000 acre-feet, and in exceptionally dry years (e.g., 2001, 2014, 2015) to less than 2,000 acre-feet. Relative to these flows, landscape recharge contribution to base flow was significant.

SWBM did not account for recharge contributions to groundwater from streams or for the dynamics of groundwater discharge to streams. SWBM also did not provide insight in how those may be affected by groundwater pumping and recharge or by intentional groundwater storage in the basin (a potential future project). For these additional analyses, SWBM must be coupled to a more complex groundwater–surface water model.

Importantly, SWBM was an important tool for outreach and education. That outreach led to initiation of the new field research, results from which improved model development. Refinement of SWBM was made possible through regular interactions between local stakeholders and growers on the groundwater advisory committee, the local UCCE farm advisor, the modeling team and the new field research. The collaboration on the SWBM increased the community's trust of the groundwater–surface water (MODFLOW) model component of SVIHM. (SWBM drives the pumping and recharge condition in the MODFLOW component, which in turn drives the dynamics at the groundwater–surface water interface.)

Water fluxes: RIV versus SFR representations

The groundwater–surface water model component of SVIHM, represented using both the RIV and SFR packages, simulated 21 years of groundwater and stream flow dynamics driven by monthly data of the statistically simulated stream inflows at each tributary from the upper watershed, by pumping in nearly 200 wells and by recharge from over 2,000 land parcels. Output included monthly water levels, groundwater flow directions and amounts, and groundwater–surface water exchanges at the 50-meter scale throughout Scott Valley for water years 1991 to 2011 (fig. 5).

Sensitivity analysis and calibration of the numerical MODFLOW-based groundwater–surface water simulation model were completed to assess model performances and to fine-tune model parameters (supporting information S1 and Tolley et al., unpublished data). These steps were taken to ensure that SVIHM's input and structure yielded simulation results that were consistent with 1991 to 2011 measured water level and long-term stream gauging information on the Scott River.

Groundwater budgets, including groundwater–surface water fluxes, will be one of the critical components evaluated and discussed by groundwater sustainability agencies. It's important to understand how to read the groundwater budget outputs from the conceptually very different RIV and SFR models and how the difference in the model can affect predictions of future scenarios.

SVIHM-RIV and SVIHM-SFR fundamentally differ in the representation of the elevation of the stream's water surface (stream state) — one user defined, one based on a streamflow model. In all other aspects, they are identical. The RIV representation, which lets the user specify stream stage (water level elevation) at each river cell, is an excellent option where water depth in the stream does not vary significantly in time or measurements are available about changes in stream stage at high spatial resolution and where these are not impacted or impacted in known ways under future scenarios of interest. Our very simplified RIV representation (constant, uniform stream water depth) was developed as a simplified conceptual approach to generate a first-order approximation of the groundwater–surface water interface, and we had no stream depth data.

In contrast, in the SFR representation, stream stage is simulated by a stream flow routing model that internally computes stream water levels while preserving water balance within the stream system dynamically. Stream stage at each grid cell is a function of stream flow into the cell, of physical characteristics of the stream available from detailed surveys and of groundwater–surface water fluxes at each grid cell. The SFR representation also accounts for the confluence of streams and for diversions to surface water users, which in turn affect local stream flow rates. When flow is insufficient to support stream flow, the streambed falls dry until either upstream inflow becomes available or groundwater begins to emerge into the streambed due to a higher water table. Given data available for Scott Valley and the dynamics of its stream system, MODFLOW SFR provided a physically more accurate, if computationally more expensive, model representation.

Aquifer water budgets for both the irrigation season (summer) and the nonirrigation season (winter) (fig. 6) showed that exchange of water between surface water and groundwater was about three times larger in SVIHM-RIV than SVIMH-SFR. All other boundary fluxes were identical due to both models having otherwise identical boundary conditions. In figure 6, the exchange between surface water and groundwater is represented in green and labeled "Stream". For all the terms in figure 6, the flow "in" represents the amount of water entering into the aquifer from various sources, while the flow "out" is the flow leaving the aquifer.

The difference between stream recharge (input to the water budget) and groundwater discharge (output from the budget), however, is the same in both models — a net groundwater discharge to the stream of 80 cfs (58,000 acre-feet per year), when averaged over the entire year. This is not coincidental: The net groundwater discharge of 58,000 acre-feet per year is independent from the groundwater–stream connectivity. It is instead entirely driven by the average annual difference between mountain-front recharge (determined by the upper watershed model), ditch losses to groundwater (user input based on measured data) and landscape recharge (SWBM result) on the one hand and groundwater pumping (SWBM result) and evapotranspiration losses from groundwater (MODFLOW result) on the other hand, none of which is a function of the choice of RIV or SFR package. The exception was the MODFLOW simulated evapotranspiration losses from groundwater near streams, which may be affected by the model choice (RIV or SFR).

With SVIHM-SFR, net groundwater discharge (fig. 6, difference between the Stream "in" and the Stream "out") was only slightly smaller over the summer months than over the winter months (about 60 cfs in both seasons). In contrast, with SVIHM-RIV, the net discharge to streams was about 50 cfs in summer but almost 140 cfs in winter. This large seasonal variation was driven by seasonal variations in groundwater storage that operate differently in the SVIHM-RIV model than in the SVIHM-SFR model: Groundwater storage during winter increased in SVIHM-RIV by just 40 cfs, or 15,000 acre-feet per 6 months, half the increase in SVIHM-SFR (80 cfs, or 29,000 acre-feet per 6 months), due to the larger winter net groundwater-to-stream discharge in SVIHM-RIV. By the same token, groundwater storage during summer decreased in SVIHM-RIV by just half of that in SVIHM-SFR due to the much lower net groundwater-to-stream discharge in SVIHM-RIV in summer.

The difference between the simulated fluxes was caused by differences in the stream stage between SVIHM-RIV and SVIHM-SFR. The SVIHM-SFR model relied on measured and estimated stream flow entering the valley, which in turn drove the local and seasonal dynamics of stream stage and the magnitude of groundwater–surface water interaction. Inflows to the valley are highly dynamic and vary strongly between winter and summer. The SVIHM-RIV model with its uniform, constant stream water depth that we chose did not sufficiently capture the spatial and temporal changes in stream flow dynamics. In this simplified representation, the stream became an artificial buffer to groundwater level changes. SVIHM-RIV added recharge from streams during the low flow periods when no exchange occurred in SVIHM-SFR simulations.

When using SVIHM-RIV, it would therefore be important that dry stream sections are properly characterized a priori for simulating future management projects. Also, even in flowing sections of the stream, characterization could be improved by providing

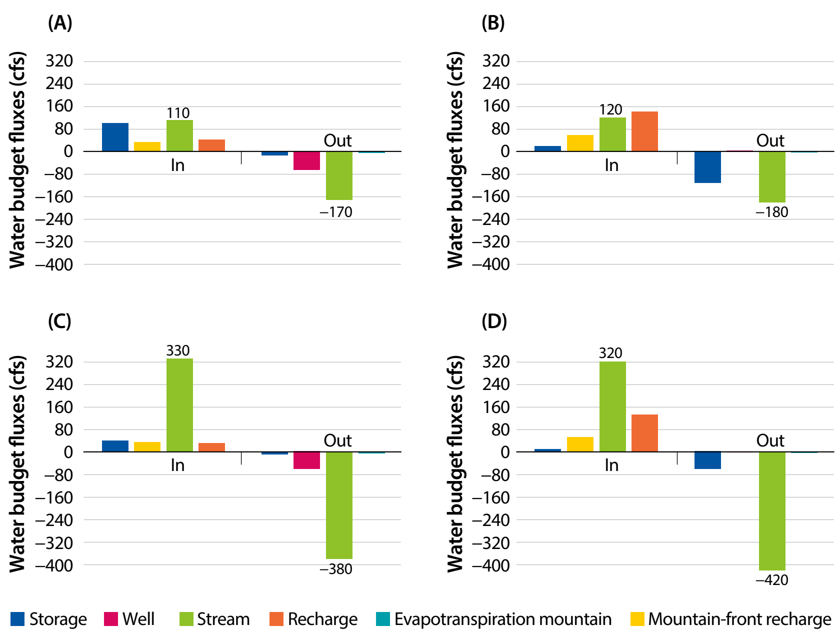


FIG. 6. Water budget results for various seasons and stream models. Markedly different groundwater–surface water fluxes were evident in the results of SFR and RIV models: (A) SFR during summer (the irrigation season, April to Sept), (B) SFR during winter (the nonirrigation season, October to March), (C) RIV during summer and (D) RIV during winter.

Scott Valley Irrigation District diversion and fish ladder. The river and its tributaries are an important salmonid spawning habitat, home to native populations of the threatened *Oncorhynchus kisutch* (coho).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spatially more detailed, seasonally varying water level depth within the stream network as part of the RIV representation. In Scott Valley, however, one of the future scenario modeling goals for which the model will be used is to predict the change in the timing and extent of dry stream sections in response to groundwater management actions. For that purpose, only the SVIHM-SFR approach can be used.

Our Scott Valley study suggests that knowledge of stream stage at high spatial and temporal detail is critical when representing the groundwater–surface water boundary with a RIV approach. More detailed calibration that has been carried out for the SVIHM-SFR model (Tolley et al., unpublished data) demonstrated that the presence of river reaches that become dry during a certain time in the summer was a critical observation to calibrate or validate SVIHM-SFR.

Models for SGMA implementation

Under California's new groundwater governance, groundwater sustainability agencies across the state have to consider the potential impact of new groundwater management measures on groundwater–surface water interaction and specifically on estimating the effect of groundwater management on surface water depletion. Only a groundwater model that also has some representation of streams can provide the spatially and temporally more detailed information on groundwater–surface water exchange that may be required when evaluating individual groundwater management projects and their impacts to stream flow.

Irrigation well in Scott Valley.


Thomas Harter

As shown in our Scott Valley study, the choice of stream representation will depend on availability of data, data density in space, and data continuity in time for stream flow and stream stage. Depending on implementation, significantly different results may be obtained. The value of the model outcome will increase with better physical representation of the integrated hydrologic system, which in turn is driven by good data availability.

Integrated numerical modeling tools represent and link upper watersheds, the basin soil–landscape systems, the groundwater system and the basin surface water system. These tools will be useful to evaluate groundwater conditions (in SGMA referred to as sustainability indicators) and the benefits of management actions to address undesirable results. Some of these conditions, such as depletion of surface water by groundwater pumping, are otherwise difficult to measure from field data alone.

For the broader audience among groundwater agency stakeholder groups, the important take-away from our work is that numerical groundwater modeling tools are all based on the same mathematical representation of groundwater flow. But other elements of the hydrologic cycle to which a groundwater model must inevitably be linked — for example, the soil–landscape system, including the ways in which urban and agricultural water demands operate; the stream system; and the upper watershed system — are subject to more varied model representations. This variability affects the simulation of groundwater–surface water interface, pumping, recharge from various sources, and flows of surface water and groundwater at the basin boundaries.

As we demonstrated, an integrated model is not only a platform for a unifying, scientifically defensible framework to connect spatially and temporally distributed data of many different kinds and to represent a range of groundwater (and surface water) sustainability indicators. It is also a tool to explore conceptual uncertainties and initiate additional research and data collection to improve representation of the driving elements of groundwater–surface water interactions and other drivers of groundwater dynamics. The integration of various model components also (1) allows representation of fluxes within the basin and between different basins, (2) allows evaluation of the sensitivity of the integrated model to different parameters and observations, (3) facilitates an estimate of the uncertainty in the results (Tolley et al., unpublished data) and (4) supports the design of future management scenarios (not yet implemented here).

Our Scott Valley study shows that models of various complexity (regression model, mass balance model, and numerical dynamic model) can be successfully integrated and provide a useful interface to communicate with and successfully engage stakeholders in developing groundwater sustainability plans. Our results demonstrate the importance for stakeholders to fully understand the conceptual implications of the different assumptions of model development and how these can impact water budgets and management of fluxes between basins. This understanding is fundamental for the successful development of groundwater sustainability plans as required by SGMA. CA

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References

Ashby SF, Falgout RD. 1996. A parallel multigrid preconditioned conjugate gradient algorithm for groundwater flow simulations. Nucl Sci Eng 124:145–59. (Also available as LLNL Technical Report UCRL-JC-122359.)

Banta ER. 2000. MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model - Documentation of Packages for Simulating Evapotranspiration with a Segmented Function (ETS1) and Drains with Return Flow (DRT1). U.S. Geological Survey Open-File Report 00-466. 127 p.

Boulton AJ, Hancock PJ. 2006. Rivers as groundwater-dependent ecosystems: A review of degrees of dependency, riverine processes and management implications, Aust J Bot 54:133–44.

Brown LR, Moyle PB, Yoshiyama RM. 1994. Historical decline and current status of Coho salmon (*Oncorhynchus kisutch*) in California. N Am J Fisheries Manage 14(2):237–61. doi:10.1577/1548-8675(1994)014<0237

Brunner P, Simmons CT. 2012. HydroGeoSphere: A fully integrated, physically based hydrological model. Ground Water 50:170–6. doi:10.1111/j.1745-6584.2011.00882.x

Canessa P, Green S, Zoldoske D. 2011. Agricultural Water Use in California: A 2011 Update. Staff Report, Center for Irrigation Technology, California State University, Fresno, CA. 80 p. www.waterboards.ca.gov/waterrights/water_issues/programs/hearings/cachuma/exbhts_2012feir/cachuma_feir_mu289.pdf

Drake D, Tate K, Carlson H. 2000. Analysis shows climate-caused decreases in Scott River fall flows. Calif Agr 54(6):46–9. https://doi.org/10.3733/ca.v054n06p46

[DWR] California Department of Water Resources. 2000. Siskiyou County Land Use Survey 2000, Division of Planning and Local Assistance. www.water.ca.gov/landwateruse/lusrvymain.cfm

Foglia L, McNally A, Hall C, et al. 2013. Scott Valley Integrated Hydrologic Model: Data Collection, Analysis, and Water Budget, Final Report, April 2013. UC Davis. http://groundwater.ucdavis.edu. 101 p.

Foglia L, McNally A, Harter T. 2013. Coupling a spatiotemporally distributed soil water budget with stream-depletion functions to inform stakeholder-driven management of groundwater-dependent ecosystems. Water Resour Res 49:7292–310. doi:10.1002/wrcr.20555

Furman A. 2008. Modeling coupled surface–subsurface flow processes: A review. Vadose Zone J 7(2):741. doi:10.2136/vzj2007.0065

Harbaugh AW. 2005. *MODFLOW-2005, The US Geological Survey Modular Ground-Water Model — the Ground-Water Flow Process*. US Geological Survey Techniques and Methods. 253 p.

Harbaugh A, Banta E, Hill M, McDonald M. 2000. *MODFLOW-2000, The US Geological Survey Modular Ground-Water Model – Users Guide to Modularization Concepts and the Ground-Water Flow Process*. US Geological Survey Open-File Report 00-92.

Harter T. 2015. California's agricultural regions gear up to actively manage groundwater use and protection. Calif Agr 69(3):193–201. https://doi.org/10.3733/ca.E.v069n03p193

Harter T, Morel-Seytoux H. 2013. *Peer Review of the IWFM, MODFLOW and HGS Model Codes: Potential for Water Management Applications in California's Central Valley and Other Irrigated Groundwater Basins*. California Water and Environmental Modeling Forum, Sacramento, August 2013. 121 p.

Hatton TJ. 1998. *The Basics of Recharge and Discharge, Part 4: Catchment Scale Recharge Modeling*. CSIRO: Commonwealth Scientific and Industrial Research Organization, Collingwood, Victoria, Australia.

Kim JS, Jain S. 2010. High-resolution streamflow trend analysis applicable to annual decision calendars: A western United States case study. Climatic Change 102(3):699–707. doi:10.1007/s10584-010-9933-3

Kollet SJ, Maxwell RM. 2006. Integrated surface-groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. Adv Water Res 29:945–58.

Mack S. 1958. Geology and Ground-Water Features of Scott Valley Siskiyou County, California. US Geological Survey Water-Supply Paper 1462. Washington DC.

Moyle PB, Israel JA. 2005. Untested assumptions: Effectiveness of screening diversions for conservation of fish populations. Fisheries 30(5):20–8. doi:10.1577/1548-8446(2005)30[20:UA]2.0.CO;2

NCRWQCB. 2005. Staff Report for the Action Plan for the Scott River Watershed Sediment and Temperature Total Maximum Daily Loads. www.waterboards.ca.gov/water_issues/programs/tmdl/records/region_1/2010/ref3872.pdf

Nehlsen W, Williams JE, Lichatowich JA. 1991. Pacific salmon at the crossroads: Stocks at risk from California, Oregon, Idaho, and Washington. Fisheries 16(2):4–21. doi:10.1577/1548-8446(1991)016<0004:PSATCS>2.0.CO;2

Niswonger RG, Prudic DE. 2005. Documentation of the Streamflow-Routing (SFR2) Package to Include Unsaturated Flow beneath Streams—A modification to SFR1. US Geological Survey Techniques and Methods 6-A13. 50 p.

Prudic DE, Konikow LF, Banta ER. 2004. A New Stream-Flow Routing (SFR1) Package to Simulate Stream-Aquifer Interaction with MODFLOW-2000. US Geological Survey Open-File Report 2004-1042. 95 p.

[SSPA] SS Papadopulos & Associates. 2012. Groundwater Conditions in Scott Valley. Report prepared for the Karuk Tribe, March 2012.

Zume JT, Tarhule AA. 2011. Modeling the response of an alluvial aquifer to anthropogenic and recharge stresses in the United States Southern Great Plains. J Earth Syst Sci 120(4):557–72.

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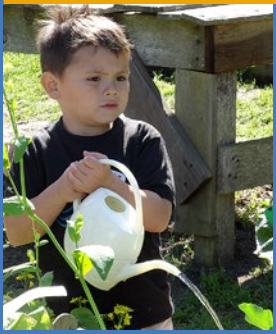
Contact: DeAnn Tenhunfeld dtenhunfeld@ucanr.edu



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Date: March 22–23, 2018
Time: 10:00 a.m. to 2:00 p.m.
Location: UC Elkus Ranch Environmental Education Center, Half Moon Bay
Contact: Leslie Jensen elkusranch@ucanr.edu