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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).

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 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.

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.

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).

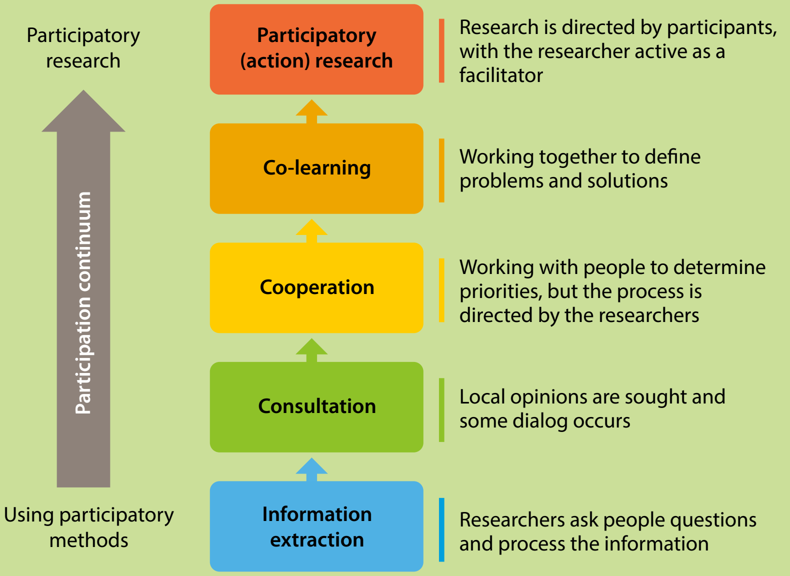


FIG. 1. Levels of engagement in participatory methods (Source: Forrester et al. 2008).

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.

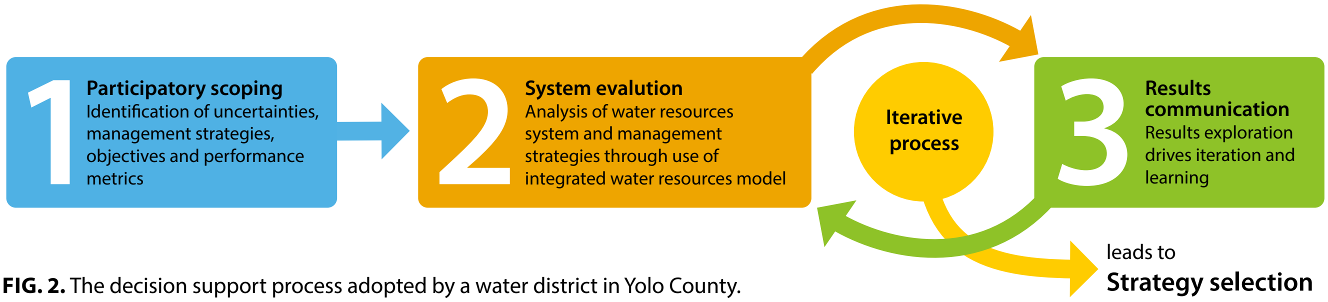


FIG. 2. The decision support process adopted by a water district in Yolo County.

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

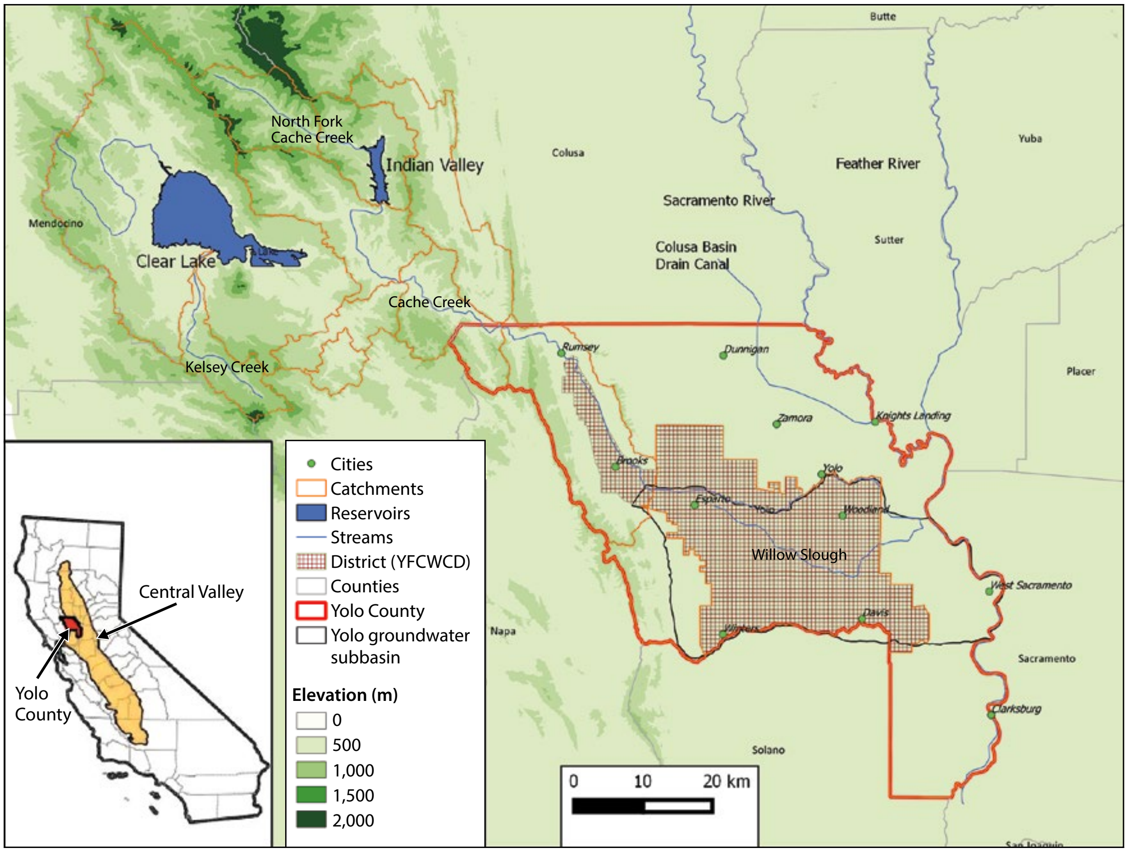


FIG. 3. Study area showing modeled catchments, county and district boundaries, reservoirs and rivers.

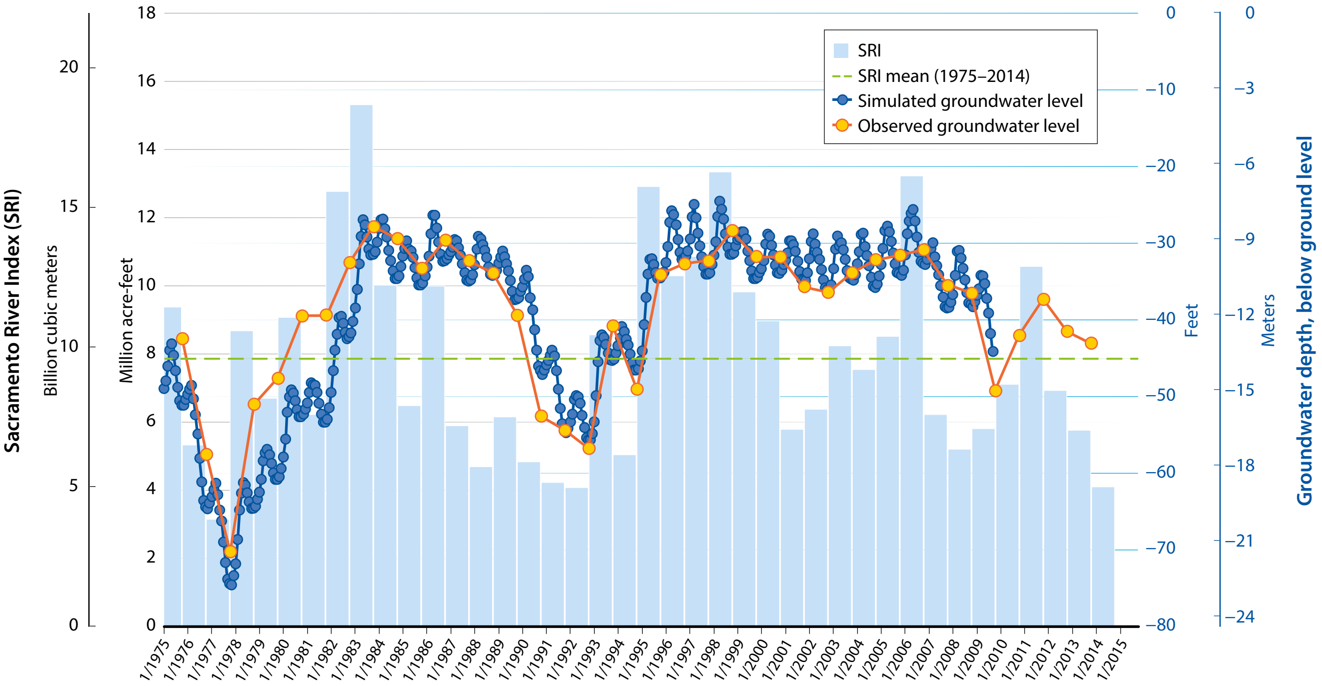


FIG. 4. Observed (water year [WY] 1975–WY2014) and modeled (WY1975–WY2009) groundwater depths in the case study area. The SRI (Sacramento River Index) is a sum of unimpaired flow from four points throughout the Sacramento basin. Observed values are from fall and represent the average of up to 99 wells. 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 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

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.

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

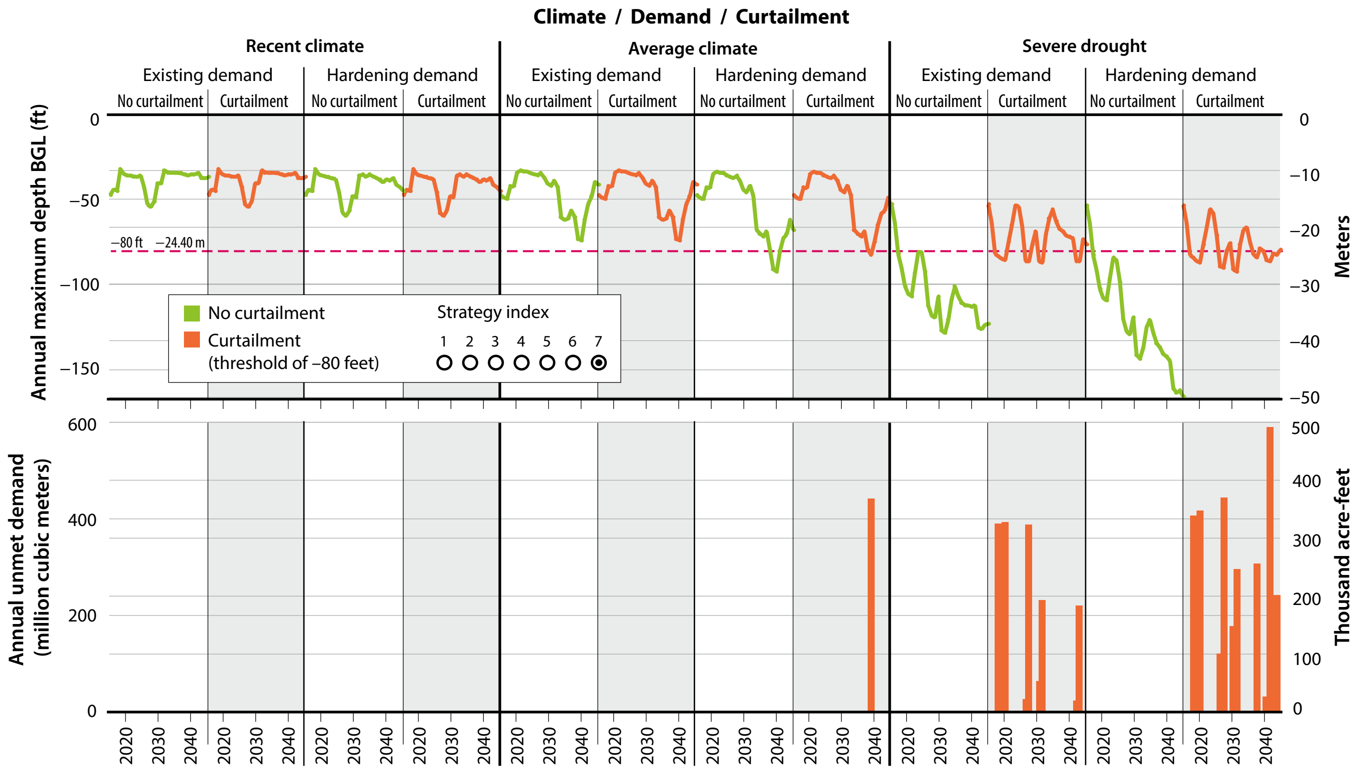
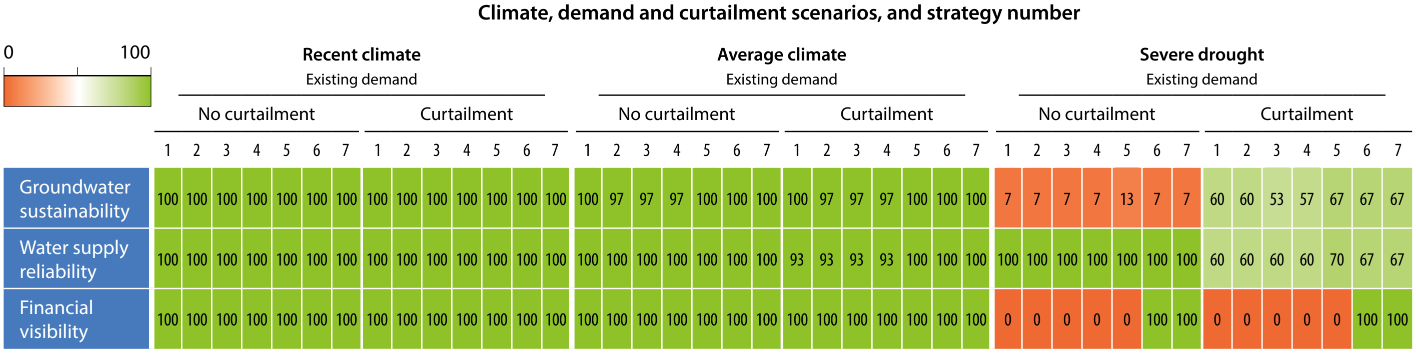


FIG. 5. Modeled maximum annual depths of groundwater below ground level (BGL) (top panel) and unmet irrigation demand (bottom panel) for each climate and demand scenario corresponding to Strategy 7. Groundwater depths recover to existing levels in the nondrought climates and stay above the 80-foot threshold (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.



	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.

> 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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