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Replenishing Groundwater in the San Joaquin Valley

Cover photo: Jonathan Parker, Kern Water Bank Authority

SUMMARY

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The San Joaquin Valley—which has the biggest imbalance between groundwater pumping and replenishment in the state—is ground zero for implementing the 2014 Sustainable Groundwater Management Act (SGMA). Expanding groundwater recharge could help local water users bring their basins into balance and make a dent in the long-term deficit of nearly 2 million acre-feet per year. The experience with recharge in 2017—the first wet year since the enactment of SGMA—offers valuable insights in how to expand recharge. A survey of valley water districts' current recharge efforts revealed strong interest in the practice, and a number of constraints. The following actions are needed to better capitalize on future opportunities:

- **Clarify rules on water available for recharge.** The State Water Board needs to develop an expeditious process for enabling water users to capture surface water when it is available. Beyond the legal aspects of establishing rights for diversion and storage, an essential part of this process is technical: developing a simple, rapid way to determine when river flows exceed water required for environmental purposes and downstream users.
- **Evaluate infrastructure capacity.** One of the key challenges for expanding recharge is that most available flows are in the northern part of the valley, while most of the overdraft—and best recharge lands—are in the south. In addition, these flows are mainly available for just a few months. A top priority is to evaluate opportunities for improving the use of existing infrastructure (conveyance facilities, surface reservoirs, and recharge basins) and determine where additional investments are warranted. A big bottleneck is likely to be regional conveyance, which is inadequate for capturing and moving high flows to suitable recharge locations.
- **Improve recharge on farmland.** Active recharge on farmland may be one of the most promising ways to capture water cost-effectively in wetter years, but it is low relative to its potential. Significantly ramping up this practice will require addressing a suite of technical issues and establishing incentives.
- **Address regulatory barriers.** State and federal agencies need to improve processes for approving construction of new recharge projects, moving recharge water through their conveyance facilities, and enabling more flexibility in where water is stored. Water managers and growers also need guidelines from the state for implementing on-farm recharge in ways that are consistent with water quality rules.

- **Strengthen groundwater accounting.** Better accounting of water going into and out of groundwater basins is key to sustainable management. It is also needed for developing incentives for growers to recharge, encouraging recharge partnerships, and informing decisions on new investments.

Making the most of recharge opportunities will require high levels of cooperation among a wide variety of stakeholders. Local and regional partnerships—for capturing and moving water efficiently, making new investments, and devising projects that bring multiple benefits—are key to helping the region manage this critical resource over the long-term.

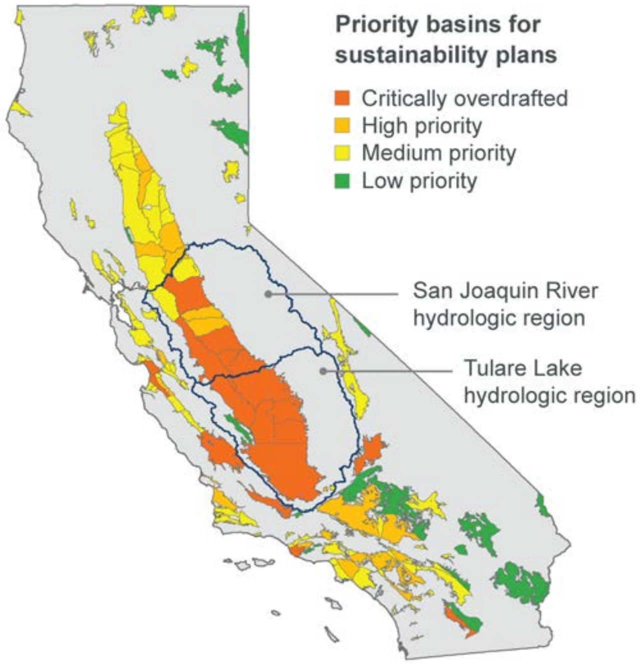
Introduction

The San Joaquin Valley is home to more than 4 million people, half of California's agricultural output, and most of its critically overdrafted groundwater basins, where pumping exceeds replenishment. Although the pace of groundwater pumping accelerated during the 2012–16 drought, overdraft has been a challenge in the region for many decades (Faunt et al. 2016, Brush et al. 2013). A March 2017 study by the PPIC Water Policy Center estimated that since the mid-1980s, the valley's average annual overdraft was nearly 2 million acre-feet (maf), or 13 percent of net water use (Hanak et al. 2017). The consequences include dry wells, damage to local infrastructure from sinking lands, and reduced water supplies to weather future droughts.

The 2014 Sustainable Groundwater Management Act (SGMA) requires California's groundwater users to develop and implement plans to bring their basins into long-term balance. In the San Joaquin Valley, 11 groundwater basins are considered to be critically overdrafted and must launch their groundwater sustainability plans by 2020 (Figure 1). Four other high- and medium-priority basins, all located in the northern valley, have until 2022 to begin implementing their plans. More than 120 groundwater sustainability agencies (GSAs)—which can include water suppliers, city and county governments, and other stakeholders—have been formed in the valley to develop and implement these plans.[1]

FIGURE 1

Most of the San Joaquin Valley's groundwater basins are critically overdrafted



SOURCE: Department of Water Resources (2014 and 2016a).

NOTE: One relatively saline basin on the valley's west side is considered a low priority basin and is not required to comply with SGMA.

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[1] Only local public agencies can form a GSA. By agreement, mutual water companies and private water corporations regulated by the California Public Utilities Commission may join a GSA (Department of Water Resources 2016). The law does not authorize other private organizations, such as environmental and community rights organizations, to formally participate (i.e., have voting rights) in a GSA, but there are options for involving them, for instance as associate members (Kincaid and Stager 2015). Many of the valley's GSAs consist of individual special districts, cities, or counties, while others include multiple entities. In basins with more than one GSA, the GSAs are required to coordinate on the development of a single sustainability plan or a set of plans that jointly achieve sustainability goals for the basin. See Escriva-Bou and Jezdimirovic (2017) for a map showing GSAs by size and location as of summer 2017.

In overdrafted basins, attaining balance will require augmenting water supplies, reducing water use, or some combination of these supply- and demand-side approaches.[2] On the supply side, there are growing efforts to capture and store unused surface flows in groundwater basins. California's warming winters have also heightened interest in this strategy as a way to help mitigate anticipated losses in snowpack, which historically has been an important component of seasonal water storage (Niraula et al. 2017, Li et al. 2017).

Aquifer recharge can be a relatively cost-effective way to store water for later use (Perrone and Merri Rohde 2016). It has been a water management tool in some parts of the valley for decades, and some recent studies have explored how much water could be available for expanding this practice (Department of Water Resources 2017a and 2018a, Kocis and Dahlke 2017). In deciding whether to expand recharge activities, water districts consider numerous factors, including the availability of additional surface water, the ability to get regulatory approvals for diverting and storing it, and the capacity to capture it on-site. With the advent of SGMA, interest in expanding recharge programs has clearly increased. The very wet conditions in 2017 provided a useful test of both the opportunities and challenges of capturing more water with the current system.

As part of an ongoing project to explore practical and effective solutions to the San Joaquin Valley's water challenges, the PPIC Water Policy Center surveyed local water districts in the fall of 2017 about their groundwater recharge efforts.[3] The survey sought information about the types and extent of recharge activities, as well as opportunities for and constraints to expansion. It also provided a good opportunity to get real-time, field-level insights about recharge practices and potential because 2017 was the first wet year since 2011, and the first since the enactment of SGMA.

This report draws on these local insights as well as analyses of potential water availability to assess the opportunities and barriers to expanding recharge in the valley. We find that interest in expanding recharge in the valley is widespread, as evidenced by local efforts during the banner year of 2017, when approximately 6.5 million acre-feet of water was actively recharged. Yet even in this very wet year, there were missed opportunities for capturing more water from local rivers. How much water is available for recharge over the long-term—after accounting for water that must remain in rivers to meet downstream water rights and environmental needs—is still uncertain. Recent studies find that up to a quarter of the valley's supply deficit of close to 2 million acre-feet could be filled by capturing more water from local rivers, and our analysis suggests that even more might be available.

One important caveat is that this additional water is mainly available over a short period of time during high-flow events. For this reason, it will be essential to determine how much could be captured cost-effectively with existing or enhanced infrastructure. A central issue is the capacity to move more water from the wetter northern half of the valley to the drier southern half, where overdraft is more pronounced and recharge conditions are more favorable. Conveyance capacity has fallen since the latest drought because extra groundwater pumping caused lands to sink around the Friant-Kern Canal—the key infrastructure for moving San Joaquin River flows to the southern valley. Expanding recharge will also require local, state, and federal entities to address a range of regulatory and institutional barriers for recharge.

This report is organized as follows. We first describe some background on our survey. We then provide an overview of how recharge works in the valley—types of practices used now, and local managers' views on which practices they might use more in the future. Next we look how much water was recharged in 2017—the wettest year in more than three decades. The following two sections look at the potential to expand recharge. The first

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[2] Hanak et al. (2017) provide a detailed list of various supply- and demand-side options to bring the valley's basins into balance (pp. 30-32).

[3] This report is part of a larger study on water and the future of the San Joaquin Valley. The first report, *Water Stress and a Changing San Joaquin Valley* (Hanak et al. 2017) highlights the importance of water in the valley's economy and describes a range of water-related challenges and potential solutions. The next report, to be published later in 2018, will explore a suite of policy and management solutions in greater detail.

examines how much more water might be available for recharge, and outlines some of the physical constraints to capturing it. The second looks at managers' perspectives on barriers and opportunities for expanding recharge in their districts. Finally, we identify key takeaways for policy and management actions by local, state, and federal entities.

Two appendices provide background information and analysis. Technical Appendix A presents the details of our analysis of hydrological conditions, including an updated water balance for the valley from 1986 through 2017 and estimates of water available for recharge over this timeframe. Technical Appendix B provides further details on the survey.

Some Background on the Survey

Regional Characteristics

Our survey region is the valley floor of the San Joaquin River and Tulare Lake hydrologic regions, stretching from San Joaquin County in the north to Kern County in the south. This is the area within these two hydrologic regions that includes the valley's priority groundwater basins under SGMA (Figure 1).

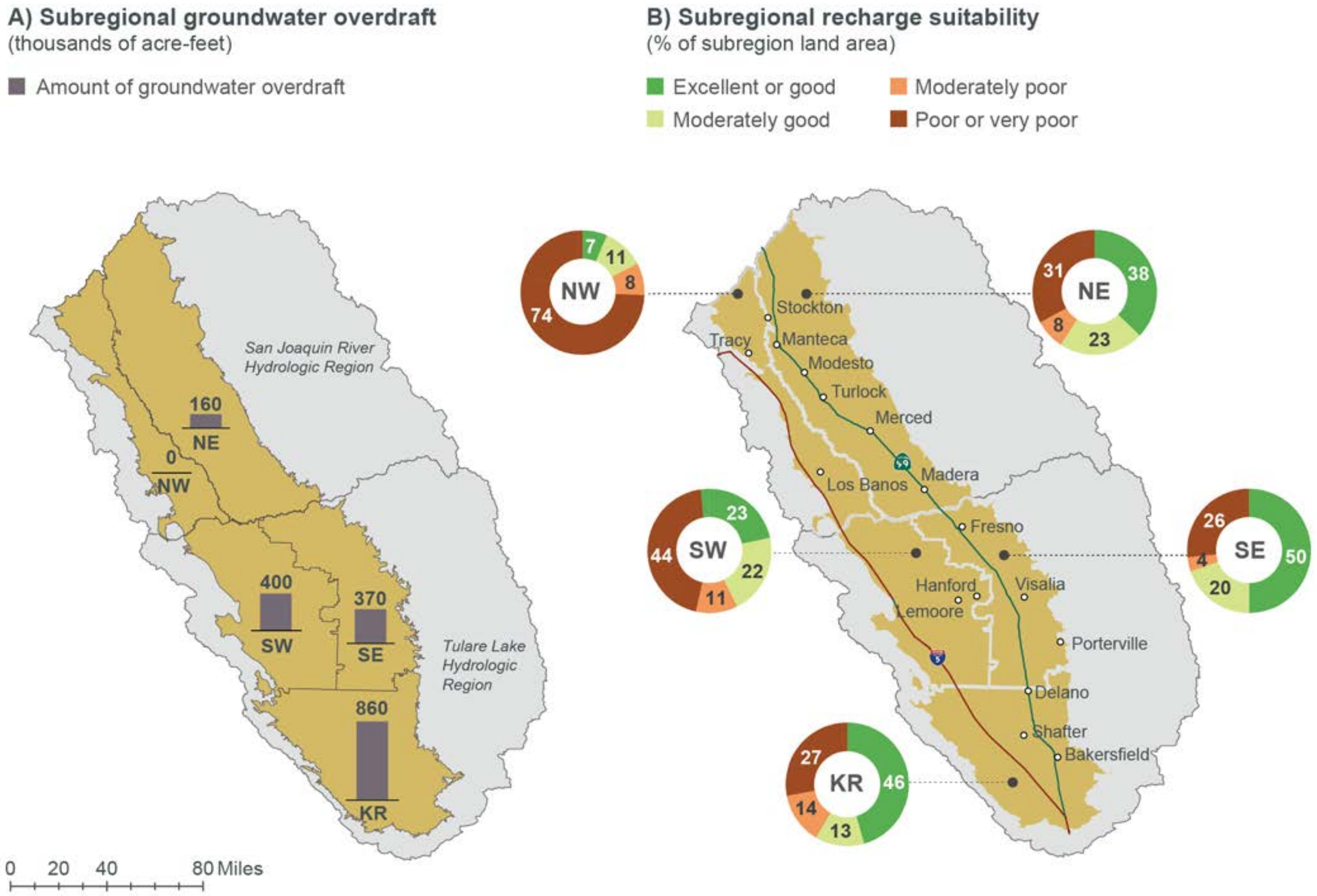
Both the extent of overdraft and the suitability of lands for recharge vary considerably across the valley. When describing survey results, we consider five subregions that broadly capture these differences: two in the San Joaquin River hydrologic region (northwest and northeast), and three within the Tulare Lake hydrologic region (southwest, southeast, and Kern basin) (Figure 2).

Overdraft—and hence demand for replenishment water—is much more significant in the Tulare Lake region, which is drier and more heavily dependent on surface water deliveries imported from elsewhere (Figure 2, panel A). On the east side, these imported water sources include San Joaquin River water conveyed through the Central Valley Project's (CVP) Friant-Kern Canal; and on the west side, imports from the Sacramento–San Joaquin Delta through the CVP's Delta Mendota Canal and the State Water Project's (SWP) California Aqueduct.

Recharge conditions are generally less favorable on the valley's west side due to poor soil permeability, salinity, and the presence of deep clay layers that limit water percolation (Figure 2, panel B). Some of the most favorable recharge conditions are clustered in alluvial fans in the northeast, southeast, and the Kern basin. As described below, districts in the latter two subregions have the most active recharge programs.

FIGURE 2

Overdraft is most pronounced in the south, and recharge suitability is best in the east and in the Kern basin



A) Subregional groundwater overdraft (thousands of acre-feet)

B) Subregional recharge suitability (% of subregion land area)

SOURCES: Recharge suitability: University of California, Davis Soil Resource Lab, Soil Agricultural Groundwater Banking Index (modified version). Sub-regional overdraft: author estimates (Technical Appendix A).

NOTES: NE is northeast, NW is northwest, SE is southeast, SW is southwest, and KR is Kern basin. Our rough estimates of overdraft in panel A were developed by averaging results from two valley-wide models (C2VSIM and CVHM), adjusted for our estimates of the 1986-2015 valley-wide water balance. For details, see Technical Appendix A. The measure of recharge suitability in panel B shows the suitability of soils for recharge if all soils with restrictive layers that would inhibit recharge were modified by deep tillage, a practice common for some crops. Based on land use breakdowns for 2014 from the Department of Water Resources Land Use Viewer, these estimates include roughly 5 million acres of irrigated cropland, 460,000 acres of urbanized lands, 240,000 acres of wetlands, and 2.5 million acres of rangeland and other underdeveloped lands. Valley-wide, 36 percent of all lands have excellent or good conditions, 20 percent moderately good, 8 percent moderately poor, and 36 percent poor or very poor. Cropland shares are similar to the overall shares.

Entities Surveyed

Over time, the region's groundwater sustainability agencies will likely take on activities to track, invest in, and incentivize groundwater recharge. But because the GSAs are so new, we directed our survey to the 202 public and private entities already charged with delivering and managing water supply within the valley floor. This included 151 agricultural and 51 urban water suppliers. All of these entities will be playing important roles in the GSAs' sustainability planning.

The survey received strong participation from across the valley, with responses from 81 of the 202 entities contacted (40%). All five subregions shown in Figure 2 are well-represented. Response rates were somewhat higher from agricultural than urban suppliers (42% versus 33%), larger urban suppliers, and suppliers with more access to surface water. Respondents were also more likely to have dedicated recharge basins. For these reasons, the sample likely over-represents districts that engage in active groundwater recharge, and particularly districts that have large, formal recharge programs. (For greater detail on the survey, see Technical Appendix B.)

In the presentation of results, we also break down responses by agricultural and urban districts, by levels of surface water availability, and by subregion—three factors that reflect differences in recharge activity.

Survey Questions

We developed the survey with input from water managers, farmers, and other experts from across the valley. We fielded the survey in September 2017, and held a workshop with some survey participants to discuss results in October 2017. Survey questions focused on recharge practices currently in use or with potential for expansion; recharge volumes, tools, and water sources in 2017; and barriers and priorities for action to expand recharge.

To provide context for understanding what was accomplished in 2017—and the opportunities and challenges on the horizon—we next provide an overview of recharge practices in the valley, drawing on survey findings.

How Recharge Works in the Valley

Groundwater recharge spans a spectrum of approaches, from passive to active (see "Aquifer Recharge Methods," page 10). On the most passive end of the spectrum, some surface water seeps into the ground every year—even during droughts—as a natural by-product of water moving through rivers and unlined canals and the irrigation of fields and urban landscapes. On the most active end, some districts have invested in dedicated infrastructure, such as recharge basins on lands with good permeability. Many districts operate somewhere in the middle—taking advantage of opportunities to recharge extra water in unlined canals and riverbeds and on irrigated lands when it is available. Historically, such relatively informal methods were most common, and often encouraged by water districts through price incentives that made surface water cheaper than groundwater pumping (Hanak et al. 2011). In the past two decades, districts in some areas have adopted more formal programs and accounting systems.[4] At the same time, investments in canal lining and more efficient drip irrigation systems have restricted the use of the more traditional approaches in some areas.

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[4] For instance, formal groundwater banking programs got underway in Kern County in the mid-1990s (Hanak and Stryjewski 2012).

Aquifer Recharge Methods

Applying extra irrigation water to cropland. Irrigation almost always results in some passive recharge because crops do not use all the water applied to fields. But recharge can be actively increased by applying extra irrigation water during the spring and summer growing season. Recent efforts have also experimented with flooding cropland during the winter months—a time before annual crops are planted and when deciduous perennial crops are dormant. Flood irrigation systems are most suitable for cropland recharge because they make it possible to get extra water onto the land quickly, but sprinkler and drip irrigation systems can also be used to increase recharge in a more limited way.

Irrigating or spreading water on fallowed fields. In contrast to cropland recharge, which can be passive, this method is only used for active recharge.

Spreading water on open space lands. Unlike recharge on cropland and fallowed farmland, natural landscapes lack irrigation systems, which can limit this practice. Open space that lies within floodplains can be well suited for recharge.

Using extra surface water instead of groundwater ("in-lieu recharge"). Because this practice leaves more groundwater in place, it can mimic the effects of recharge even where the soils are not permeable. Although this method can be a passive by-product of having access to more surface water than usual, the term is typically employed where districts deliberately encourage it through water pricing or other incentives.

Directing extra water to unlined canals and riverbeds. Some passive recharge happens naturally when water moves through riverbeds and earthen canals. When excess surface water is available, it can be directed to these canals to increase recharge. Some districts also direct excess water to dry creeks or riverbeds for this purpose.

Using dedicated recharge basins. Suitable areas have highly permeable soils. In some urban areas, basins that capture and percolate stormwater can double as recharge basins.

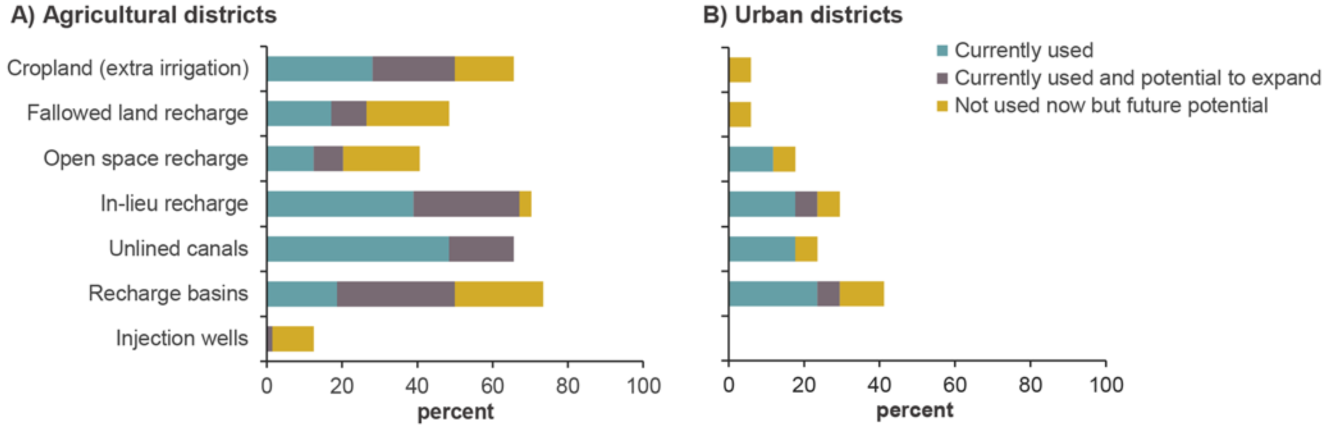
Directly injecting water into the aquifer through wells. The injection well method—sometimes called "aquifer storage and recovery" or ASR— may be attractive in areas lacking good soil permeability. Water quality can be a concern, however, because the recharged water mingles directly with the water in the aquifer, potentially causing chemical interactions that may compromise water quality. Untreated surface water—which often contains a lot of sediment—can be unsuitable because it can clog the underground passageways to the aquifer from the well.

Active Recharge Methods Now Used or Envisaged

We asked managers to indicate which active recharge methods their organization currently uses, and which they envisage adopting or expanding in the future. The patterns look quite different for agricultural and urban districts (Figure 3). Agricultural districts are already employing a broad mix of recharge tools, and many see potential for growth. Urban districts in the valley—most of which rely heavily on groundwater—are much less active and see less potential.

FIGURE 3

Agricultural districts use a wider range of recharge methods than urban districts, and see more potential for expansion



SOURCE: PPIC San Joaquin Valley recharge survey.

NOTES: The sample includes 64 agricultural districts and 17 urban districts. Additional approaches offered by some survey respondents were grouped with similar categories (e.g., use of stormwater basins was grouped with recharge basins, and use of dry streambeds was grouped with unlined canals). The share of districts with recharge basins from the survey is higher than the share we identified through publicly available sources (technical appendix Figure B3). This reflects both more recent investment in new facilities and the fact that some districts reported using basins operated by neighboring districts.

The most widespread methods—used by two-thirds of agricultural districts surveyed—include two traditional practices: allowing water to seep through unlined canals and streambeds, and "in-lieu" recharge (using surface water instead of groundwater), which reduces pumping and allows natural recharge processes to replenish the aquifer. Other popular options—used by half of agricultural districts surveyed—include directing water to dedicated recharge basins and applying extra water on irrigated cropland. For most districts, active recharge on cropland is done by augmenting water applied during the growing season, but a few are also experimenting with spreading water during the winter on fields planted to some crops (notably alfalfa and deciduous perennials such as almonds and grapes). Some districts also spread water on fallowed lands and open space. The one method nearly absent in this region is directly injecting water into aquifers through dedicated wells, which have faced regulatory hurdles over water quality concerns. Such wells are more common in urban Southern California.

Off-Site Partnerships

We also asked managers to indicate whether they are involved in any recharge partnerships with off-site parties—either storing water for their own customers elsewhere or storing water for others within their districts. This collaborative practice—sometimes referred to as groundwater banking—enables cost-effective recharge in the most suitable areas, and can be particularly useful for districts with poor local recharge conditions. Off-site recharge is usually done with recharge basins, and sometimes with in-lieu recharge. The process generally requires the two parties to have a physical connection through a shared aquifer or shared conveyance.[5]

These partnerships have been growing since the mid-1990s, but they are not yet widespread. Overall, just 10 percent of all districts surveyed reported recharging for off-site parties on their lands, and roughly double that number said they store some water in off-site basins. Districts in Kern have been most active on both sides of these partnerships, followed by districts in the southeast (Figure 4). Interest in expanding off-site storage is

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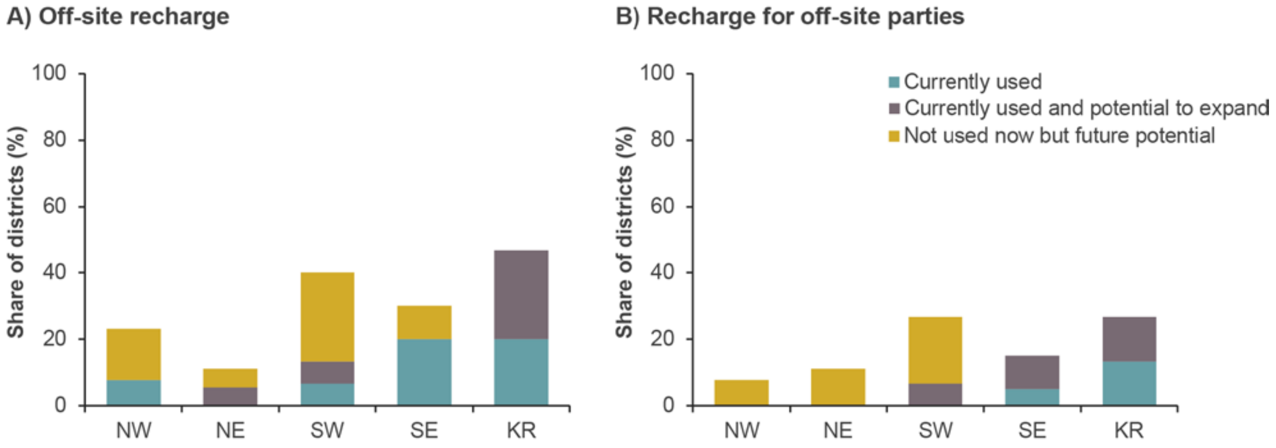
[5] Exchanges are typically used to retrieve stored water by parties located upstream. For instance, an off-site party located to the north of a groundwater bank along the California Aqueduct will take deliveries of the water banker's surface water, and in exchange the banker will use the off-site party's groundwater. Exchanges also make it possible to connect districts that do not directly share conveyance, if they both share conveyance with another district that serves as an intermediary.

highest in the southwest—reflecting the combination of water scarcity and more limited local recharge opportunities in that subregion.

FIGURE 4

Off-site recharge through partnerships is still relatively limited, with Kern basin districts leading the way



SOURCE: PPIC San Joaquin Valley recharge survey.
NOTES: The sample includes 13 districts in the northwest, 18 in the northeast, 15 in the southwest, 20 in the southeast, and 15 in Kern. NW is northwest, NE is northeast, SW is southwest, SE is southeast, and KR is Kern basin.

Recharging in a Very Wet Year

The 2017 water year was the San Joaquin Valley's wettest in more than three decades, and one of the wettest on record.[6] Wet conditions in the Sacramento River hydrologic region also enabled high levels of water imports through the Delta—an important source of surface water for the valley.[7] While this abundance of surface water brought ample opportunities for recharging groundwater basins, the sheer volume of water in some months also created problems of plenty, with managers scrambling to avoid harmful flooding.

Here we briefly review the hydrologic context for 2017 and examine survey findings on recharge activity.

The Hydrologic Context

To put 2017 into perspective, we looked at inflows from local rivers originating in the Sierra Nevada and precipitation on the valley floor across years and by month. Water year 2017 (October 2016 to September 2017) had more than 30 million acre-feet (maf) of local inflows. This was more than double the average, and 40 percent higher than other wet years in the past three decades (Figure 5).

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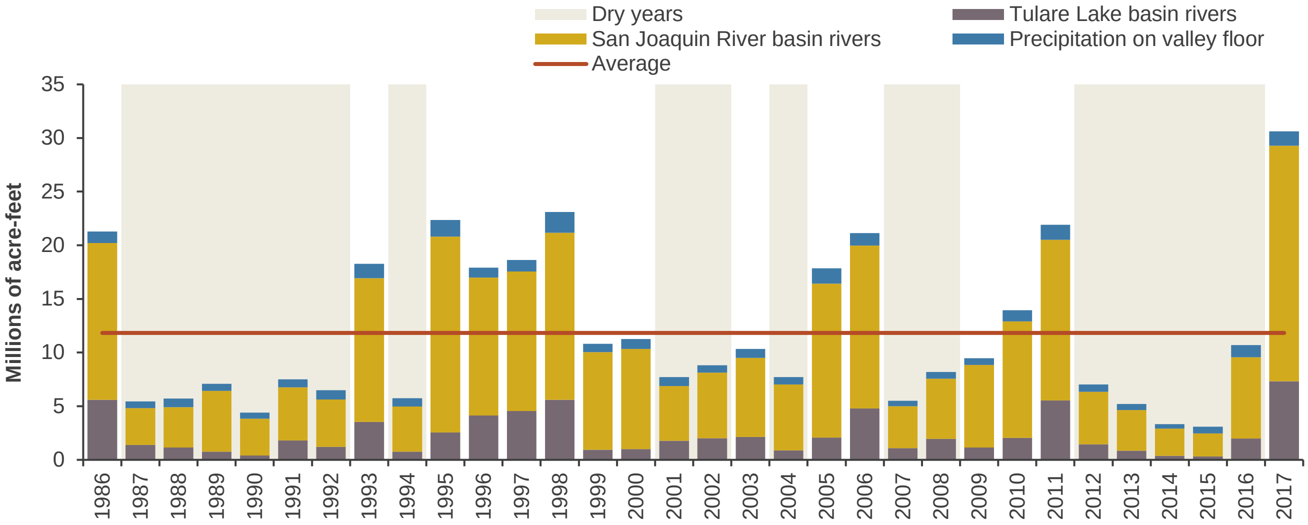
[6] Water year 1983 was the wettest year on record in the region in terms of both runoff and precipitation. Water year 2017 was the second wettest for runoff (using CDEC data for full natural flows), and the sixth wettest for precipitation (using NOAA data).

[7] Total Delta imports from the CVP and SWP pumps were 6.4 maf, just a little below the 2011 record of 6.6 maf (technical appendix Figure A6). Net imports to the valley (subtracting volumes that went to the San Francisco Bay Area, the Central Coast, and Southern California) were more than 4.2 maf, trailing only 2011 (4.6 maf), 2005 (4.4 maf), and 1989 (4.3 maf) (technical appendix Figure A12A).

FIGURE 5

Dry years outnumber wetter ones, and very wet years like 2017 are rare



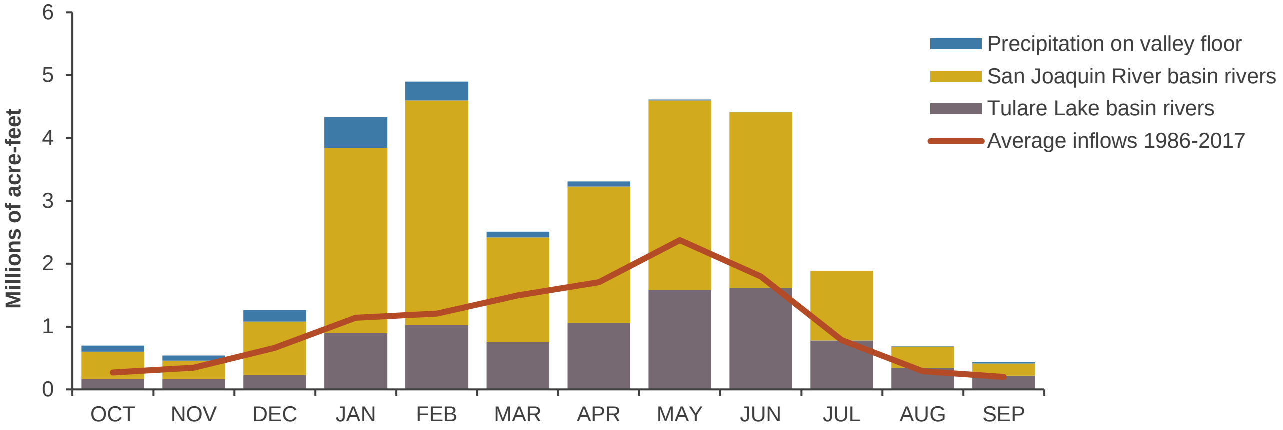
SOURCE: Technical Appendix A.

NOTES: The figure shows inflows from rivers in the Tulare Lake and San Joaquin River hydrologic regions and precipitation on the valley floor. The data are reported in water years (from October 1 of the preceding year to September 30 of the year shown). Dry years are those classified as dry or critically dry for the San Joaquin Valley by the Department of Water Resources.

Total inflows were above average in every month, but particularly in January and February, when they were four times higher than average (Figure 6). The concentration of high flows in a few winter and spring months can pose challenges for two overlapping management objectives: avoiding harmful flooding and capturing extra water for recharge.

FIGURE 6

High flows in 2017 were concentrated in a few winter and spring months, posing management challenges



SOURCE: Technical Appendix A.

NOTE: The figure shows inflows from rivers in the Tulare Lake and San Joaquin River hydrologic regions and precipitation on the valley floor during the 2017 water year.

As usual, river inflows were higher in the wetter northern half of the valley. But rivers in the Tulare Lake hydrologic region were flowing so high in the first half of 2017 that local managers took a lot of river water to help prevent local flooding. This also reduced demand for deliveries of excess flows of San Joaquin River water and Delta imports into the region in these months.

Efforts on the Ground

We asked managers to indicate whether their districts engaged in active aquifer recharge in calendar year 2017, along with the volumes recharged, the methods used, the sources of water, and how recharge activity compared with the last very wet year (2011) and with their current recharge capacity.[8]

Volumes, Methods, and Sources

Roughly 75 percent of the districts surveyed reported active recharge programs in 2017, and 75 percent of this group provided estimates of the volumes recharged.[9] The missing volume data reflects the fact that districts using some popular methods (extra irrigation of cropland, in-lieu recharge) are less likely to formally track how much recharge occurs.[10]

Volumes recharged and implications for the valley's water balance

On-site active recharge reported for 2017 was 4.1 maf. Districts also reported that they banked 0.5 maf of water off-site through partnerships within the valley. About 80 percent of the water was already recharged by September, with the remainder expected to occur in the fall. Most districts recharged as much or more than in 2011, reflecting both the wetter conditions in 2017 and the heightened interest in recharge since the drought and the passage of SGMA.

Based on the characteristics of the districts that responded to the survey, we estimate that total active on-site recharge valley-wide was about 6.5 maf.[11] Of this total, about 0.9 maf was stored for other districts within the valley.[12] Although we asked districts to report active recharge, the on-site estimates likely include some recharge that would have occurred anyway—e.g., through unlined canals. But our estimates do not include some passive recharge—perhaps as much as 4 maf—that occurs every year through seepage from river channels and regular irrigation practices.[13]

Together, active and passive recharge—on the order of 10–11 maf—contributed to a positive groundwater balance in the valley for the first time since 2011. We estimate that the valley's net groundwater balance—the amount recharged minus the amount of groundwater used—was on the order of 3.2 maf for water year 2017. This

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[8] We focused on the calendar year (January to December), rather than the water year (October to September), because this corresponds better to the timing of surface water deliveries from annual winter and spring runoff. Particularly in wet years, recharge often extends into the autumn months of the next water year.

[9] Seven districts that reported no active recharge indicated the presence of in-lieu recharge and/or unlined canals in an earlier survey question (Figure 3). Based on other answers, we considered these to be entirely passive programs.

[10] A few districts with formal programs also declined to provide volume information. Most of the districts that did not provide volume data also were unsure how their recharge in 2017 compared with 2011—another sign that these programs are more informal.

[11] We used multiple regression analysis to arrive at these estimates. The analysis controlled for subregion, average surface water deliveries, whether the district is agricultural or urban, and whether the district has recharge basins—all factors associated with differences in recharge activity. We applied the regression coefficients to all districts that did not provide recharge volumes (including survey non-respondents). While these estimates are rough, the equations are a good fit for cross-sectional regressions (for details, see Technical Appendix B). And as discussed below, the volumes are reasonable relative to our estimates of a positive net groundwater balance valley-wide for the 2017 water year. Because surface reservoir levels were somewhat higher in September 2017 than the year before, fall recharge in 2017 may also have been higher than the year prior—making our calendar year estimates for 2017 slightly higher than what occurred in the 2017 water year.

[12] The within-valley estimate is based on our regression analysis. In addition, banks in Kern County store water for cities in the San Francisco Bay Area and Southern California, which temporarily improves the regional groundwater balance (Hanak and Stryjewski 2012).

[13] Annual recharge from rivers in this region is estimated to be about 0.5 maf/year, and recharge from crop and urban landscape irrigation about 3.5 maf per year (Brush et al. 2013). These values are fairly stable across year types.

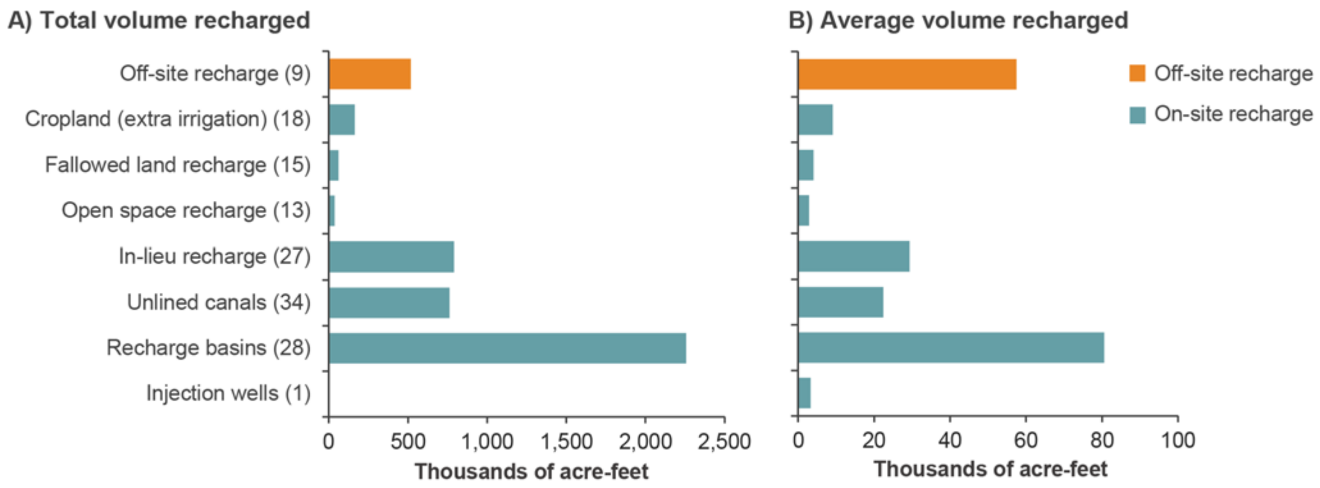
is 5 maf more than the long-term average, and 8 maf more than the average during the 2012–16 drought.[14] This highlights the fact that in a region where significant groundwater pumping occurs every year, recharge efforts need to exceed the volumes pumped to reduce the long-term imbalance.

Dedicated recharge basins stored the most water

Three active recharge methods were used to store more than 90 percent of all on-site recharge reported by survey participants (Figure 7). Dedicated basins topped the list (55%), followed by unlined canals and in-lieu recharge (19% each).[15] These methods were also used more intensively. For instance, 28 districts reported volumes stored in dedicated basins, and they stored 80,000 acre-feet on average.[16] Fewer districts reported how much water they stored by spreading it on the land (cropland, fallowed land, or open space), and the average volumes stored were less than 10,000 acre-feet per method.

FIGURE 7

Among recharge methods, dedicated recharge basins stored the most water



SOURCE: PPIC San Joaquin Valley recharge survey.

NOTES: In all, 46 districts reported volumes recharged. The numbers in parentheses show districts reporting volumes for each method. Off-site recharge can use any of the on-site methods shown to store water, but most commonly uses recharge basins and in some cases in-lieu recharge methods.

Finally, although just a fraction of districts currently bank off-site, those that did recharged a lot of water this way (on average, nearly 60,000 acre-feet). This demonstrates the potential of such partnerships to help bring basins into balance, particularly when local conditions are not favorable for on-site recharge.

Districts tapped a variety of surface water sources

Water from local rivers and streams was the most commonly used source for recharge, but districts also tapped a variety of other sources, including CVP and SWP deliveries, urban stormwater, and in a few cases recycled municipal wastewater (Figure 8). Some also purchased water for recharge from other parties. Districts that stored

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[14] For details on the water balance, see technical appendix Figure A12 and related discussion.

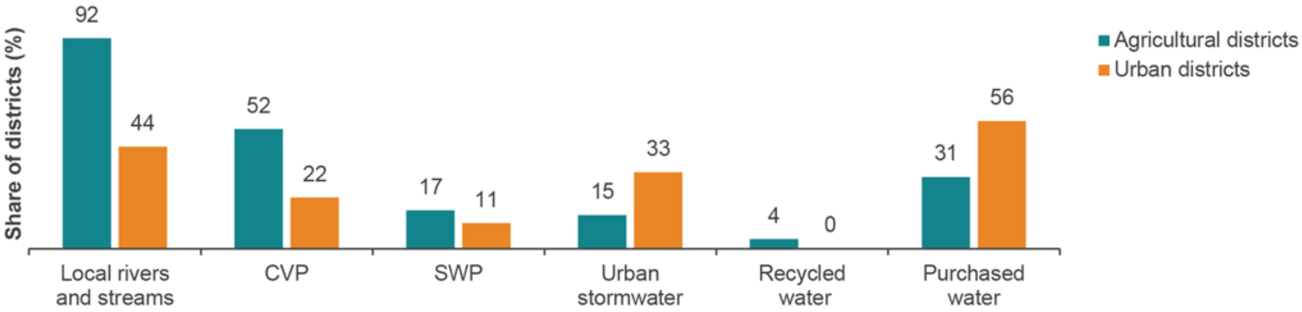
[15] These shares are for the volumes reported by survey participants. They may differ for the recharge conducted by districts that did not report volumes recharged or did not participate in the survey. The survey likely undercounts the water stored through extra cropland irrigation and in-lieu recharge, because districts using these methods were less likely to report recharge volumes.

[16] More than half of these districts stored more than 10,000 acre-feet in recharge basins, and more than a quarter stored more than 100,000 acre-feet.

more water drew on more sources. Those storing 100,000 acre-feet or more of water used an average of three sources, while those storing less than 10,000 acre-feet typically used just one source.

FIGURE 8

Water from local rivers and streams was the most common source for recharge



SOURCE: PPIC San Joaquin Valley recharge survey.

NOTES: The figure shows the share of districts that used each source for recharge. In all, 57 districts reported recharge sources, including 48 agricultural districts and 9 urban districts. CVP, SWP, and local river water includes surplus or flood flows (Article 21 water from the SWP and Section 215 and Recovered Water Account for the CVP) in addition to regular contract deliveries.

Who Recharged?

Several characteristics were associated with more active recharge: agricultural districts recharged more often than cities; districts with more surface water recharged more than those with less; and districts in the southern half of the valley—and particularly in the Kern basin—recharged more than those in other areas.

Cities are lagging

That cities are lagging was already apparent in their more limited use of recharge methods (Figure 3). Fewer cities reported any recharge activity (60%, versus 80% of agricultural districts), and of those that did, fewer could report volumes stored. In large part, this reflects the more limited availability of surface water for many urban utilities in the valley. With less unpaved acreage, cities also have fewer direct opportunities to spread water on the land than agricultural districts.[17] However, some communities are creatively using open space areas to spread water, and directing extra surface water to stormwater basins for recharge. Cities also have the ability to mobilize funds to support partnerships with agricultural districts that have more extensive recharge capabilities. For example, the cities of Fresno and Clovis engage in a range of recharge practices, including use of stormwater basins and a partnership with a local irrigation district.[18] As water users work to bring basins into balance under SGMA, cities will have more incentives to participate in active recharge programs.

Surface-water access confers a big advantage

As might be expected, districts with greater access to surface water recharged more (Figure 9A). Survey respondents were fairly evenly distributed among four categories of surface water availability: no regular surface water (i.e., groundwater only), limited regular deliveries (less than 10,000 acre-feet per year), moderate deliveries

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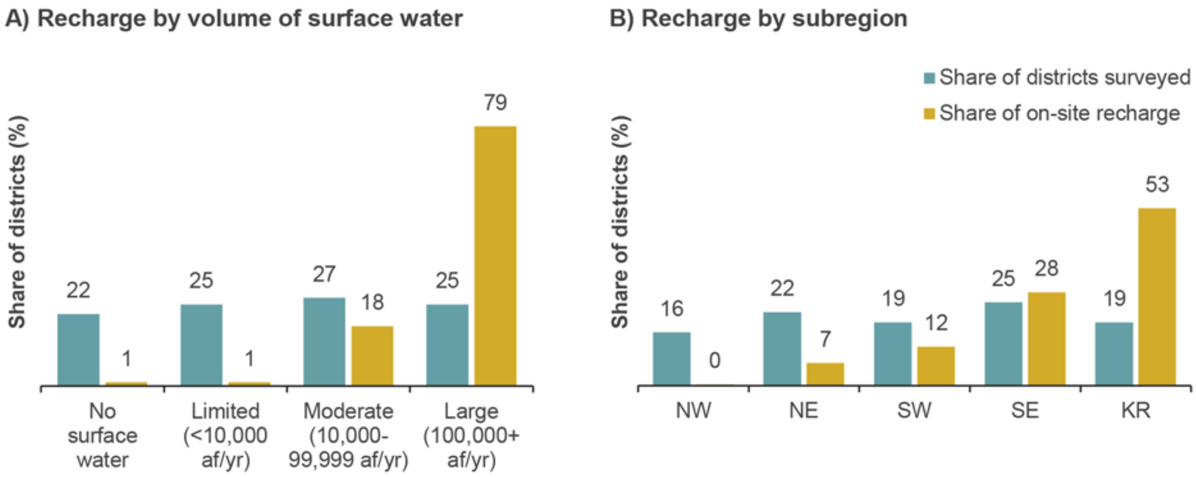
[17] The valley's total urban footprint is roughly 460,000 acres, and much of this area is hardscape unsuitable for recharge. By comparison, irrigated cropland covers roughly 5 million acres, and many agricultural districts also have some additional undeveloped, unirrigated area. (See notes to Figure 2.)

[18] See the City of Fresno's Recharge Fresno website and the Fresno Flood Control District's groundwater recharge fact sheet.

(under 100,000 acre-feet per year), and large deliveries (100,000 acre-feet or more per year). Yet almost all recharge was stored by the largest districts (79%) or those with moderate surface water access (18%).

FIGURE 9

Recharge is concentrated in districts with more surface water and in the southern part of the valley



SOURCE: PPIC San Joaquin Valley recharge survey.

NOTES: In all, 81 districts responded to the survey, and 46 districts reported positive volumes recharged. The figure shows the share of total on-site recharge reported (4.1 maf), to avoid double-counting off-site recharge, which could be reported by both partners. The volume of surface water is the annual average of water deliveries to the district from 2005–08 (see Technical Appendix B for details). Af/yr is acre-feet per year. NW is northwest, NE is northeast, SW is southwest, SE is southeast, and KR is Kern basin.

During wet years like 2017, ample additional surface water for recharge—above and beyond the regular delivery volumes—is available. But districts' ability to take it depends on their existing physical capacity—for instance, having conveyance channels that connect them to rivers and large aqueducts—as well as their existing institutional arrangements with federal, state, and local surface water projects that deliver the water. Districts that regularly use more surface water are more likely to have this capacity, as well as greater managerial, financial, and planning capacity to invest in recharge projects and capitalize on opportunities that arise.

That said, there is considerable interest in recharge among districts that have little or no surface water. Two-thirds of the districts that rely entirely on groundwater reported some recharge activity (though they are often in the very early stages). With the advent of SGMA, such districts view participation in recharge projects as critical to their ability to stay in business. Figuring out the best ways to do this is a challenge, since they may lack both physical infrastructure and institutional arrangements to recharge surface water on their lands. As one manager noted:

> *"We need more of everything: conveyance to areas most conducive to recharge and surface water agreements with neighboring districts…[we are] the canary in the coal mine in our basin."*

The Kern basin is "recharge central"

Districts in the southern part of the valley account for more than 90 percent of reported on-site recharge (Figure 9B). Those in the Kern basin stand out, with more than half of the total. They are followed by the southeast, with more than a quarter of the total. This pattern reflects both the greater demand for recharge where overdraft is more pronounced, and the greater availability of soils suitable for recharge in Kern and the southeast.

These two regions also have more established recharge institutions. Recharge in the southeast is facilitated by long-standing programs within the CVP's Friant system, which is designed to recharge suitable locations in high flow years.[19] Some districts in Kern are part of the Friant system, and formal banking projects are generally more common there. Districts in Kern were also able to draw on more water sources, reflecting greater physical and institutional capacity to move water around. The basin is served by local rivers, the Friant-Kern Canal on the east, and the SWP's California Aqueduct on the west. The Cross-Valley Canal enables east-west water deliveries in both directions. Many districts in Kern have exchange agreements that enable them to share water held under different water rights and contracts, and most water banks are preauthorized to store water for off-site CVP contractors. They routinely purchase water to supplement their recharge programs.[20]

Although the reported volumes are much lower, interest in recharge is also high in the southwest and the northeast, where roughly four-fifths of all districts say they are actively recharging. In the southwest, districts reported constraints related to soil permeability and highlighted the importance of being able to recharge off-site.[21] In the northeast, where local river flows are relatively abundant, districts are more likely to use traditional recharge methods (extra water directed to unlined canals or cropland) and less likely to account for the volumes recharged.

In contrast, only a third of districts in the northwest report any activity—reflecting both the better water balance in that area and more limited suitability of lands for recharge.

Expanding Recharge: How Much More Water Is Available?

Although 2017 was a banner year for recharge in the valley, it should also be seen as a starting point. Since the enactment of SGMA, there has been a growing interest in expanding active recharge to help bring groundwater basins into long-term balance. Several things need to come together to make this possible: adequate physical capacity to cost-effectively capture more water in wet years; enhanced institutions to authorize and manage recharge programs; and clarity about the volume of water available for this purpose (and who may use it). In the next section, we provide some insights from survey respondents on perceived physical and institutional barriers to expanding recharge. But to provide some context, we first explore how much additional water might have been available, and identify some of the capacity constraints that could affect the ability to capture this water.

Estimates of Water Available for Recharge

As of now, there are no definitive answers to the question of how much more water is available for recharge. By law, new water for recharge needs to be in excess of flows required for environmental purposes and to meet claims of existing water-right holders, and the State Water Board is in the early stages of determining what these

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[19] "Class 2" deliveries of Friant water are generally intended for recharge (Friant Water Authority n.d.). Districts with these contracts generally have recharge basins to store this water, and project members use this water. For an early analysis of the economic benefits of this recharge system, see Vaux (1986).

[20] In 2017, *all* survey respondents in Kern engaged in active recharge said they purchased additional water for this purpose. This practice was far less common in other subregions.

[21] Of the roughly half a million acre-feet of off-site storage reported, 13 percent was stored for districts in the southwest, and the remainder for districts in Kern.

volumes might be.[22] However, two recent studies provide some insights for the San Joaquin Valley, using rules of thumb for water that would need to stay in rivers (for details, see Technical Appendix A).

Kocis and Dahlke (2017) assume that water on days with very high flows—above the 90th percentile over a long-term average—are not in competition with any other uses, and therefore could be available for recharge. For the San Joaquin River system, the Department of Water Resources (2017a and 2018a) defines a volume of water that needs to stay instream to meet water quality and other environmental requirements in the Delta; water above that threshold could be available for recharge.[23] Here, we focus on DWR's "maximum" estimate of water available for recharge, which, like Kocis and Dahlke's estimate, does not consider constraints on the capacity to divert water.[24]

These approaches yield somewhat different results for water available from San Joaquin Valley rivers:

- **Water available in 2017.** In this very wet year, the two approaches diverge considerably in their estimates of additional water that could have been available: 3.7 maf for Kocis and Dahlke versus 6.3 maf for DWR's maximum estimate (Figure 10). Recharging all of this water would have entailed 60 to 100 percent more active recharge than our valley-wide estimates of 6.5 maf.
- **Yearly patterns of water availability.** In both approaches, much more water is available for recharge in wet years than in other years. But since the mid-1980s, some water would have been available in most years under DWR's approach (Figure 10). In contrast, the Kocis and Dahlke approach would only have taken water one year in three.
- **Long-term average water availability.** For Kocis and Dalhke, the average is 455 thousand acre-feet (taf) per year.[25] DWR reports a maximum estimate of 550 taf per year, but our analysis suggests that the water potentially available using this approach may be twice that level.[26]

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[22] This process is complicated by the fact that the board is in the midst of updating its Water Quality Control Plan for the Bay–Delta, which proposes increases in ecosystem flow requirements on tributaries to the San Joaquin River and upstream flows in the Sacramento Valley, in addition to changes in outflow from the Delta (State Water Resources Control Board 2016).

[23] We draw on the updated appendix information (2018) for our analysis, which shows lower estimates of water available for recharge in the San Joaquin Valley than the 2017 draft. For this region, DWR focuses on meeting environmental conditions in the Delta, but it does not describe the detailed assumptions. We have sought to replicate DWR's approach. See Technical Appendix A for details.

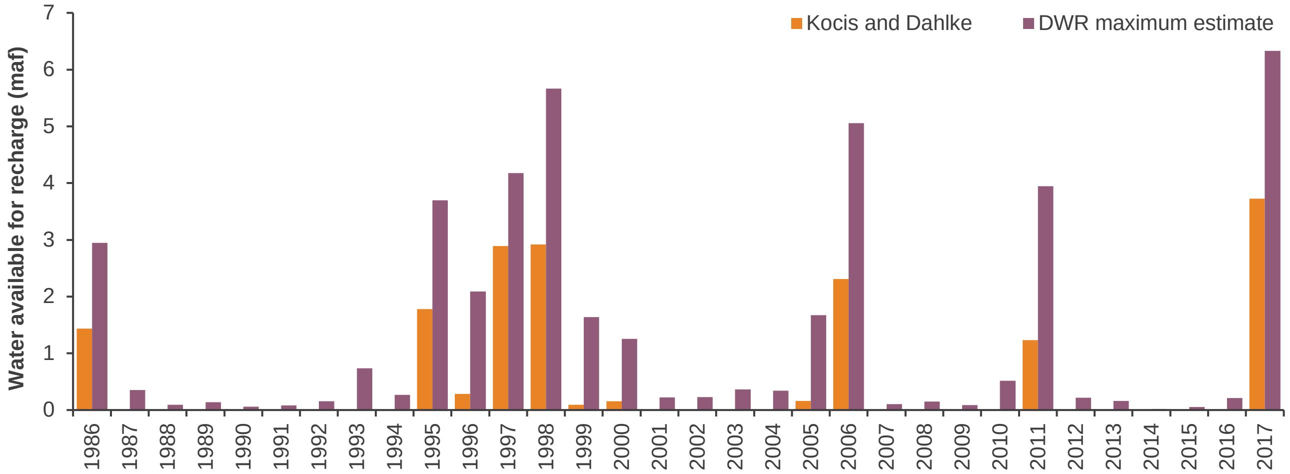
[24] DWR also provides a lower, "best" estimate, by imposing a simple capacity constraint on the ability to divert additional water with existing infrastructure, and obtains a long-term average of water available for recharge of 190 thousand acre-feet per year. We focus on the maximum estimate because more detailed analysis is likely required to determine what is currently feasible, as well as what might be possible with additional cost-effective investments.

[25] This average is for 1989–2014. We consider this period to be more relevant to future planning than the study's longer-term average for 1923–2014, which includes many years when outflows were higher than they would be under current conditions of infrastructure, operations, and demand. The authors report an average of 1.3 maf/year for high magnitude flow years in this period. The annual average of 455 taf reported here reflects the fact that these high flows only occur in 36 percent of all years. See Technical Appendix A for details.

[26] DWR's long-term average for the San Joaquin region is based on stream gage data from 1935–2015. To account for changes in outflow over time from water infrastructure, operations, and demand, DWR adjusts the results with a simulation model. This lowers estimates of water available for recharge to 45 percent of the original values. While such an adjustment is important for the earlier data, it seems less justified for recent decades, when there has been little change in water infrastructure and demands. Using DWR's unadjusted approach for 1986–2015, we estimate that an average of more than 1 maf/year of San Joaquin River flows may have been available at Vernalis after meeting all Delta water quality and ecosystem requirements. See Technical Appendix A for details.

FIGURE 10

Patterns of water potentially available for recharge vary widely



SOURCES: Author estimates using DWR (2017a and 2018a) and Kocis and Dahlke (2017). For details, see Technical Appendix A.

NOTES: The estimates are shown in water years, and based on San Joaquin River flows at Vernalis, which captures water from all San Joaquin River tributaries and flood flows from the Tulare Lake hydrologic region (normally a closed basin with no outflow). Kocis and Dahlke (2017) also provide estimates for some gages upstream of Vernalis (for interactive maps and graphics, see recharge.ucdavis.edu/starr). To replicate the DWR estimate, we made assumptions about instream flow rules consistent with the average estimates from DWR. This may result in different annual and intra-annual patterns than those underlying DWR's estimates. We show results based on stream gage readings, without the adjustment for recent conditions used in DWR's long-term analysis, which reduces average water availability from the San Joaquin River to 45 percent of the original values.

Capacity Constraints Loom Large

A number of capacity issues constrain the amount of water that can be recharged. Even with significant new infrastructure investments, it is probably not feasible to capture all the extra water in high flow years such as 2017. A central challenge is being able to convey the water to suitable storage sites, given the location and timing of available flows. The capacity of Delta conveyance to harness high-flow water is part of this equation—it is a way to move local river flows to the valley's west side, and it also determines the potential for capturing additional flows for recharge from the Sacramento Valley. Another unknown is understanding how surface storage can help smooth out the timing of water availability. Finally, getting more water into the ground depends on a variety of factors at the local level.

Location and Timing Challenges for Moving Water

One of the key challenges for expanding recharge is that most available flows are in the wetter northern half of the valley, while most of the overdraft—and the most suitable recharge lands—are in the drier south.[27] This highlights the need to evaluate the capacity of large, system-level conveyance infrastructure, such as the Friant-Kern Canal and the California Aqueduct, to move water from north to south. The trend is not favorable: capacity in both of these facilities has been reduced in recent years by land subsidence caused by excessive groundwater pumping—significantly in the case of Friant-Kern.

Another central challenge is the timing of water availability in these very flashy watersheds, where storms cause flows to rise quickly. Most of the water is available in a few winter and spring months (Figure 11). To maximize the draw in wet years, very large volumes of water would need to be taken in a short space of time. As an

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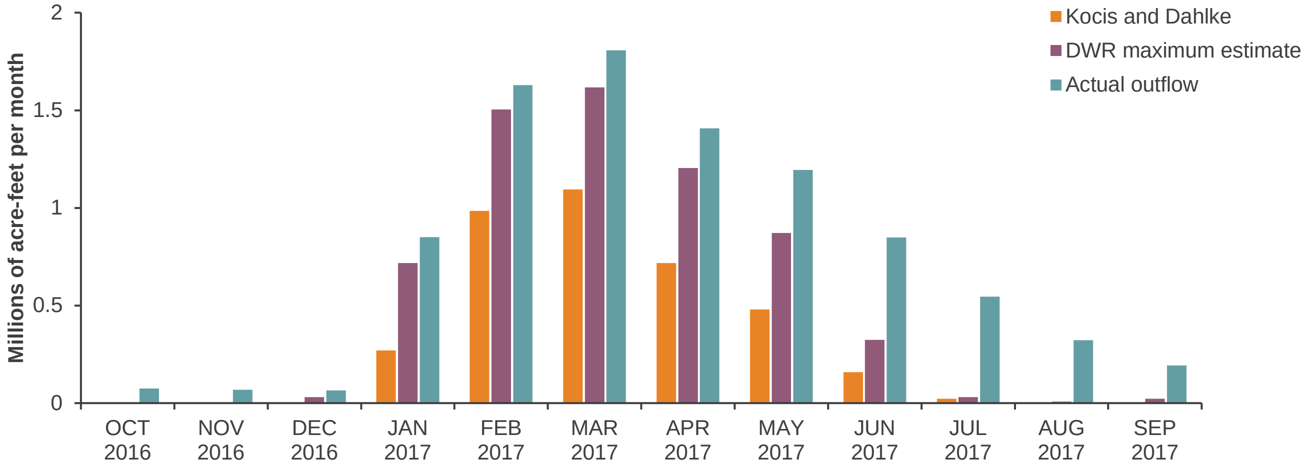
[27] From 1986–2017, 73 percent of local inflows into the valley came from rivers in the San Joaquin River hydrologic region, versus 19 percent from rivers in the Tulare Lake region, and 8 percent from precipitation on the valley floor (technical appendix Figure A3). In DWR's long-term maximum estimate of water available for recharge, 61 percent of the available flows are in the San Joaquin River hydrologic region, and just 39 percent in the Tulare Lake hydrologic region.

example, in 2017 more than half the available water in either Kocis and Dahlke's or DWR's approach would need to be taken in February and March, with diversions above 30,000 acre-feet on most days. While such daily volumes are not excessive relative to the water moved in the valley during the main irrigation season, the water is concentrated in specific locations, where conveyance limits are likely to be a challenge.[28]

FIGURE 11

In wet years like 2017, most additional water would need to be taken in a short space of time



SOURCES: Author estimates using DWR (2017a and 2018) and Kocis and Dahlke (2017). For details, see Technical Appendix A.

NOTES: Actual outflow is measured on the San Joaquin River at Vernalis. Our replication of DWR's maximum estimate is based on stream gage readings, without the adjustment for recent conditions used in DWR's long-term analysis.

We estimate that with 5,000 cubic feet per second of spare capacity—equivalent to roughly 10,000 acre-feet/day—it would have been possible to capture just under half of the available flows under either Kocis and Dahlke's or DWR's approach from 1986–2017.[29] As a frame of reference, design capacity on the Friant-Kern Canal—the key infrastructure to move San Joaquin River flows to the southern valley—is 10,500 acre-feet/day leaving Millerton Lake, dropping to about 8,000 acre-feet/day in southern Tulare County (US Bureau of Reclamation 2017). Subsidence has reduced capacity in that southern reach by 60 percent, to just 3,500 acre-feet/day (Fitchette 2018).[30] And much of the existing capacity is already put to use in wet years.

Delta Conveyance: A Hub for Local Flows and Imports

Conveyance capacity in the Delta is also a consideration, both for local inflows and for imports. High waters from the San Joaquin River system and the Tulare Lake basin flow into the Delta. This makes the Delta an important hub for moving local floodwaters that originate on the valley's east side back into the valley through the California Aqueduct and the Delta Mendota Canal.

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[28] As described in Technical Appendix A, daily deliveries of surface water could reach more than 60,000 acre-feet per day valley-wide during the prime irrigation system—potentially leaving significant spare capacity in the winter and early spring. A key challenge is the much more limited capacity for moving water from the wetter San Joaquin River region to the Tulare Lake region.

[29] Doubling that capacity to 10,000 cubic feet per second would have made it possible to capture another quarter of available flows. See technical appendix Table A2 and related discussion.

[30] Capacity in the southern part of the California Aqueduct, which could bring San Joaquin River flood flows through the Delta to the Tulare Lake region, has fallen from 16,500 acre-feet/day to 13,000 acre-feet/day near Avenal in Kings County (Department of Water Resources 2017b). This limits high flow deliveries to Kern County and Southern California (Fitchette 2017).

And while this analysis focuses on the extra water available for basin replenishment within the San Joaquin Valley, a much greater volume of water has been identified by both DWR and Kocis and Dahlke in the wetter Sacramento Valley—the source of most Delta imports into the San Joaquin Valley.[31] Both SWP and CVP water was used for recharge in 2017, and there is high demand for Delta imports to help redress problems of overdraft in the valley. How much additional Sacramento River water can be harnessed in this region will depend on system capacity issues—including the ability to take water from the Delta in "big gulps" when large excess Sacramento River flows are available—as well as regulatory issues governing Delta outflows and pumping.[32]

Using Surface Storage to Smooth Out Flows

One way to smooth out the peaks is to temporarily store more of the high flows in above-ground storage, so water can be released more gradually. Beyond new storage projects—such as the proposed Temperance Flat reservoir on the upper San Joaquin River or holding ponds on the valley floor—there is potential to expand capacity through more coordinated operation of surface and groundwater storage across the valley.[33]

Moving water stored in reservoirs for dry years into groundwater basins during the fall months can make more room in reservoirs for winter storms.[34] Capitalizing on this potential will require establishing agreements with parties who currently store this water in surface reservoirs, so they are confident they will be made whole when the water moves to groundwater storage. SGMA is likely to facilitate such agreements by ushering in better accounting for water stored underground.

Local Recharge Capacity Constraints

Finally, the capacity to get extra water into the ground can be an issue. This could span a range of considerations—from the size and location of local conveyance channels, to the capacity of recharge basins, to the availability of suitable lands for spreading water, to the willingness of local farmers to recharge on those lands. Our survey provides some insight on the current state of affairs. Most districts said they were "maxed out" in 2017. Less than a quarter indicated that their district could have recharged more water with their existing capacity.[35]

On the other hand, as noted earlier, many districts see potential for expanding their recharge activities by expanding existing methods or adopting new ones (Figures 3 and 4). We next take a look at managers' views of what it would take to make progress on this front.

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[31] The DWR best and maximum estimates for the Sacramento Valley are 0.67 and 4.27 maf per year on average, respectively. Kocis and Dahlke find 1.25 maf per year on average for that region in the "post-impairment" period following the construction of most dams (1970–2014), with fewer gap years where no additional water can be taken.

[32] See Gartrell et al. (2017) for a review of water allocation among exports, in-Delta uses, and outflows from 1980 to 2017. Over this period, the outflow required to keep the Delta fresh enough for farming and urban uses has increased, as has the water required for ecosystem protection. However, in many years there are also large volumes of "uncaptured" outflows in excess of regulatory requirements. Most of this water originates in the Sacramento Valley.

[33] The holding pond concept might include using fields that are not suitable for recharge—such as locations adjacent to rivers that have high groundwater levels or areas with impermeable clay layers—to temporarily store water.

[34] Statewide optimization modelling using the CALVIN model has shown that this type of coordinated management of surface and groundwater storage can substantially improve the ability to capture more winter and spring runoff (Tanaka et al. 2006, Medellín-Azuara et al. 2008). DWR has just begun to explore the scope for operating the surface and groundwater storage systems to capture more flood flows (Department of Water Resources 2017c).

[35] This group included a mix of larger and smaller districts from across the valley, with a range of current recharge levels.

Expanding Recharge: Managers' Views on Barriers and Priorities

We asked managers two questions related to expanding recharge: first, whether they encountered any barriers in 2017; and second, what their top two or three priority actions are for recharging more in the future.

For the first question, we provided a list of 14 potential barriers from which to choose, and managers could elaborate or expand on this list. Table 1 presents their selections, grouped into four broad categories in order of importance: infrastructure capacity, challenges related to on-farm recharge, regulatory constraints, and funding obstacles. In general, agricultural districts perceived about three times as many barriers as urban districts. Since they are also much more active than urban districts, this likely reflects their greater familiarity with recharge and the practical challenges it presents.

TABLE 1

Barriers to recharging groundwater in 2017

Barriers	Share of agricultural districts (%)	Share of urban districts (%)	Share of all districts (%)
Infrastructure capacity	**75**	**25**	**67**
Timing of water availability	58	8	49
Capacity of district recharge basins	47	25	43
Other district capacity (e.g., conveyance to recharge sites)	40	17	36
Capacity of system-wide conveyance (e.g., CVP or SWP canals)	33	8	29
On-farm recharge capacity	**47**	**0**	**39**
Irrigation system (e.g., inability to spread water on fields that use drip irrigation)	42	0	35
Farmer concerns about crop health or yields	26	0	22
Farmer concerns about benefiting adequately from recharge on their lands	12	0	10
Regulatory constraints	**30**	**25**	**29**
Approvals to construct new recharge projects	26	8	23
Water rights or contracts for recharge water	14	8	13
Water quality issues (e.g., waste discharge permits)	9	8	9
Approvals to convey recharge water	9	0	7
Funding constraints	**25**	**42**	**28**
Proposition 218-related difficulties for funding investments	16	0	13
Price of recharge water too high	11	0	9
Concerns about recharge water migrating out of district	0	42	7

SOURCE: PPIC San Joaquin Valley recharge survey

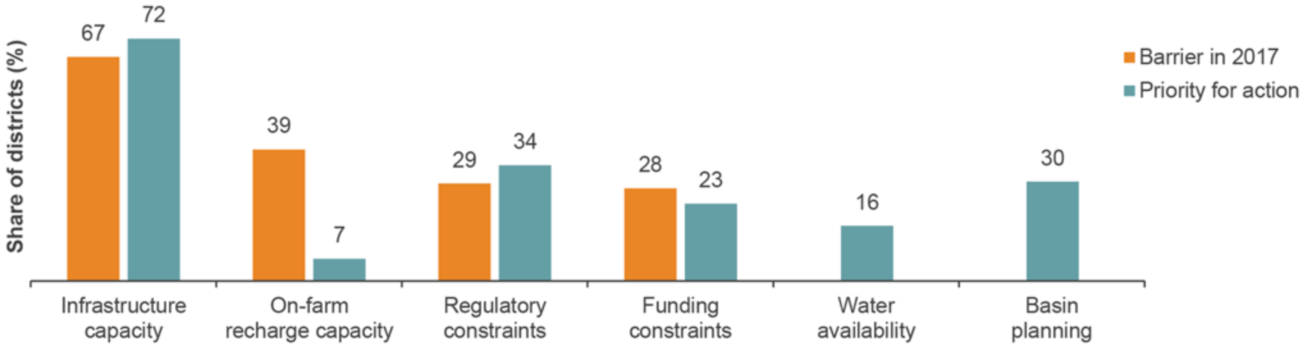
NOTES: In all, 69 districts responded to this question, including 57 agricultural districts and 12 urban districts. We received responses from 45 of the 46 districts that reported recharge volumes, 12 of the 15 districts that recharged but did not report volumes, and 12 of the 20 districts that did not actively recharge in 2017. Seven districts in this last group noted they were limited by poor soil conditions. The overall scores for the categories in bold show the share of districts that picked at least one item in that category. Among districts that actively recharged in 2017, five said they encountered no barriers.

For the second question, we asked managers to describe the top priorities that need to be addressed to expand their district's recharge potential. This question invited open-ended responses, to allow managers to focus on any issues they considered important. Although they emphasized the need to address many of the issues flagged as barriers, some also identified priorities in two additional areas: increasing surface water availability and improving basin planning and management (Figure 12).

It is important to bear in mind that the answers to both questions are shaped by the very wet conditions of 2017. In particular, regulatory issues take a back seat to infrastructure capacity as both a barrier and a priority—something that might be different in a year with average precipitation. That said, these results are instructive. Although opportunities to capture more water exist in many years during short-duration storms, much of the untapped potential lies in expanding the ability to capture more water in wet years.

FIGURE 12

Infrastructure capacity issues topped managers' lists of recharge barriers and priorities



SOURCE: PPIC San Joaquin Valley recharge survey.

NOTES: The figure shows the share of all districts that picked at least one barrier or priority in each category. The samples include 69 districts for barriers (see notes to Table 1) and 61 districts (50 agricultural and 11 urban) for priorities. Response rates for the priorities question were highest among districts recharging the most water (100%), and lowest among districts without active recharge in 2017 (55%).

Infrastructure Capacity: Top Barrier and Top Priority

Barriers

Sixty-seven percent of all districts, and 75 percent of agricultural districts, identified one or more infrastructure-related constraint to recharging water in 2017 (Table 1). The leading challenge was the timing of water availability—the difficulties of capturing flood flows coming through in a short space of time with existing capacity. Two other common constraints were at the district level: inadequate recharge basins and other facilities such as local conveyance. Some managers also noted that system-wide conveyance was inadequate for getting water to their district. The southern part of the valley was particularly affected by this problem, which was made worse by subsidence-related capacity constraints on both the Friant-Kern Canal and the California Aqueduct.

Priorities

The valley's ability to capture significantly more water in wet years will depend on addressing these constraints, something that was clearly top of mind when managers expressed their priorities (Figure 12). Interestingly, however, only a few focused on addressing the timing of water availability—for instance, by building new surface storage or shifting the timing of reservoir operations to improve recharge potential. In discussions, some managers noted their view that it is not realistic to try to capture all the water available in very wet years.

More managers emphasized the need to improve conveyance and especially the capacity to store water in recharge basins. Suggestions included expanding options for off-site partnerships so that districts lacking suitable locations within their boundaries could store water in other locations.

On-Farm Recharge Capacity: A Key Issue for Agricultural Districts

Barriers

One promising alternative to expanding dedicated recharge basins is to spread more water on suitable fields. Indeed, given the large volumes of water available in 2017, it is somewhat surprising how little recharge on cropland and fallowed land took place relative to its potential (Figure 7). The valley has roughly 5 million acres of irrigated cropland—more than half of which has at least moderately good conditions for direct recharge (Figure 2). Constraints in local conveyance capacity—noted above—may have limited this practice in some places. In addition, nearly half of all agricultural water managers flagged one or more farm-level constraints (Table 1).[36]

Top among the barriers was the difficulty of spreading water on fields set up for drip irrigation, which covers more than 40 percent of all fields in the valley.[37] These popular systems produce many important benefits—from better crop quality to reduced chemical runoff. But they can make it difficult or impossible to get a lot of water onto fields quickly—a primary advantage of the (aptly-named) flood irrigation systems they are replacing.

Another barrier was farmer concerns about crop health or yields, something we also heard in focus group discussions. Pilot efforts to flood vineyards and orchards during the winter months when the plants are dormant have been widely publicized in the local press, and managers and growers we spoke with mentioned they had heard about them.[38] But farmers are uncertain about the effects of this practice on their own bottom line, in terms of crop yield and quality. The winter and early spring are also times when farmers undertake field maintenance practices that can be incompatible with high levels of irrigation.

Finally, a few managers noted challenges related to incentives. Recharging on farmland can have costs to those who do the work, whereas the benefits in terms of higher groundwater levels are likely to spread out more widely within the basin. The concern is that farmers may be reluctant to take on the costs of recharging if they find them too high compared to the benefits they might receive. Some did note that SGMA may be starting to change the paradigm, with farmers requesting to recharge groundwater on their lands in exchange for a “SGMA credit”—i.e., the ability to pump some of this water in the future. This kind of crediting system requires more formal accounting systems and groundwater budgets.

Priorities

Surprisingly few managers emphasized addressing barriers to on-farm recharge in their list of top priorities (Figure 12). This may reflect the view that there is little to be done about the top-ranked barrier—the fact that modern low-flow irrigation systems are ill-adapted to flooding fields. The few who did stress action in this area emphasized the importance of research and farmer outreach on the effects of recharge on crop health and yields.

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[36] Districts that currently recharge on cropland and fallowed land were three times more likely to flag on-farm constraints than those not using these methods.

[37] Methods have been shifting rapidly towards the low-water systems. In 2010, 46 percent of fields in the valley had gravity/flood irrigation (down from 55% in 2001), 42 percent used low-volume/drip methods (up from 36% in 2001), 8 percent used sprinklers (7% in 2001), and 4 percent used subsurface irrigation (2% in 2001) (Department of Water Resources Statewide Irrigation Systems Methods Survey). From 2010–17, the US Department of Agriculture has funded the transition of an additional 150,000 acres (about 3% of irrigated cropland) to drip irrigation in the eight valley counties (author estimates using data from the Natural Resources Conservation Service). Some state grants have also been available for this purpose, and some farmers fully fund the transition on their own.

[38] Bachand et al. (2014, 2016) describe some of the experiments that took place in 2011 to flood vineyards on the Terranova Ranch in the Kings River basin. In 2016 and 2017 winter flooding pilots were run on almond orchards and some other crops.

As one manager noted:

> *“Farmers have concerns about the impacts of flood water applied to permanent crops in the off season. Current studies of flood water applied to almonds should help shed light on some of these topics.”*

Regulatory Issues: Less Pervasive, at Least in a Wet Year

Barriers

From our discussions with water managers and growers before administering the survey, we expected regulatory barriers to loom larger than they did in 2017. On their advice, we included a range of potential regulatory hurdles to expanding recharge—acquiring permits or contracts to divert and store water, getting approvals to construct new recharge projects or to convey available water, and running afoul of water quality regulations. Yet in all, fewer than a third of respondents had any issues of this nature (Table 1).

Challenges related to getting approvals for recharge activities—permits for new projects, rights or contracts to access recharge water, or approvals to convey this water—were flagged primarily by the districts that had excess recharge capacity in 2017. For other districts, the fact that so much water was available relative to their own capacity to use it appears to have limited concerns about these issues. Such concerns could increase with the rising demand for recharge projects—especially in years when extra supplies are not so abundant and there is both more competition for the water and more regulatory scrutiny over its use.

Just a few managers identified water quality regulations as a challenge. This may change, however, if more farmers begin to spread recharge water on active or fallowed cropland. At issue is conditions under which recharge accelerates the migration of agricultural chemicals in the soil (especially nitrate) that can impair drinking water quality.

Priorities

Managers’ regulatory priorities focused on addressing these barriers. The following quotes are illustrative of issues related to speeding up the approval process:

> *“Some [groundwater] banking facilities that should have been approved … are still in process, causing issues.”*

> *“Approvals to access water can take months, when the high-flow supply is only available for a short duration (days/weeks). This results in missed opportunities!”*

On the issue of storing water for which they do not already have water rights, some managers recommended the State Water Board define recharge as a “beneficial use” to reduce uncertainties about the legality of its use. As one manager explained:

> *“Under the California Water Code, recharge is not a ‘reasonable and beneficial use’ of water. Our water right is limited to water for irrigation only. To engage in a practice that is not permitted under our water right would jeopardize our water right. That needs to be addressed.”*

In this view, defining recharge as a beneficial use of water under state law could forgo the need to acquire a water right to capture and store this water. Both board staff and some water users have taken a different view, noting that rechargers will generally need to establish water rights to store water underground, just as they do for above-ground storage.[39] As described below, finding ways to expedite this permitting process is essential to developing a coherent recharge strategy for the valley.

Finally, a few managers highlighted priorities related to water quality regulations. Several agricultural districts in areas with unfavorable soils emphasized the importance of making it "less complicated to obtain approvals" to use injection wells—something not widely authorized in the Central Valley—to recharge directly into deeper layers beneath the clay. Some cities emphasized an easier approval process for using recycled water for recharge on their lands.

Funding Concerns: Not Yet Widespread

Barriers

Just over a quarter of managers noted one or more funding obstacles (Table 1). For some agricultural districts, concerns included difficulties in raising funds from their customers for investments in recharge projects, given constraints imposed by Proposition 218. This constitutional amendment, adopted in 1995, set a number of substantive and procedural requirements for water rate increases by public agencies that can be challenging to implement.[40] Rural districts with relatively few ratepayers are more prone to concerns that ratepayers will not approve new rates, or overturn rate structures adopted by elected boards. This issue could become more pronounced with the implementation of SGMA because groundwater sustainability agencies will also be subject to Proposition 218, and they will need funds to implement sustainability plans, including expanding recharge where feasible.

A few agricultural districts also reported that the price of water was too high. This could seem surprising in a year when ample flood flows were available from local rivers at minimal cost.[41] But not all districts had ready access to cheap local supplies. We also heard complaints that floodwaters from the CVP Friant project were costly this year, because prices were set to help recover costs incurred during the drought, when water sales were very low.

Finally, some urban districts expressed reluctance to pay for recharge efforts because of concern that the water might get used by someone else—for instance, neighboring farmers.

Priorities

Noting concerns about costs for new recharge infrastructure, including land for new recharge basins, some managers emphasized the importance of state and federal support for funding expanded recharge capacity. In focus group discussions, some also stressed the need for funding to support the development of groundwater sustainability plans.

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[39] For a clear discussion of this issue, see the video of the panel on "Legal, Policy, and Regulatory Opportunities and Constraints for Managed Recharge" from the public forum on Managed Groundwater Recharge to Support Sustainable Water Management, hosted by the California Department of Food and Agriculture and the Department of Water Resources in Sacramento on November 8, 2018 (the panel starts at 3 hours, 21 minutes, 50 seconds on the event video). For a helpful guide on the steps involved in establishing new rights, see Department of Water Resources (2018b).

[40] See Hanak et al. (2014) for a detailed discussion of this law and its implications for water rate setting. Substantive requirements include setting charges proportional to the services provided to property owners. Procedural requirements include notifying all ratepayers of any proposed changes, which can be overturned if more than half protest the changes.

[41] As an example, Kern River water was available at $5/acre-foot.

Additional Priorities

When identifying their priorities for expanding recharge, managers were encouraged to think beyond tackling the barriers mentioned in the survey. Two additional priority areas came to the fore: increasing surface water availability and improving basin planning and management (Figure 12).

Surface Water Availability: Other Improvements Wanted

Beyond the regulatory issues relating to accessing high-volume flows, some managers emphasized the importance of improving the general availability of water that districts might use—including water for which they already have rights or contracts.

One concern was environmental restrictions that can reduce those supplies. Several districts that use CVP and SWP water said the federal and state governments should ease environmental flow requirements to make it easier to move water through the Delta, which has faced tightening restrictions on exports in the past two decades.[42] Districts in the northeast are concerned that proposed increases in required environmental flows on tributaries of the San Joaquin River—as part of the State Water Board's update of the Bay–Delta Water Quality Control Plan—would be at odds with efforts to achieve balance in local aquifers (see footnote 22).

Another concern was the management of large water projects, which are considered too inflexible for the needs of recharge efforts. Suggestions to help with planning included facilitating water transfers and making earlier announcements of the volumes of water that will be delivered.

Basin Planning and Management: A Priority for Newcomers

Finally, a top priority—particularly for districts that do not have large, formal recharge programs—was improving planning and management at the basin scale. Issues emphasized included expanding partnerships to jointly fund projects and store water off-site. As one manager noted:

> *"SGMA has blurred the distinction of service area. Water delivered to others in the same GSA…creates the potential for virtual groundwater banking."*

Another manager noted that successful partnerships will require:

> *"….accounting for recharge, who gets credit..."*

This emphasis on the opportunities for SGMA to foster new cooperative approaches in water management is promising. One issue that came up in focus group discussion was the distinction between off-site banking within and across the valley's 15 groundwater basins. Today, both types of banking occur. In Kern and in the southeast, multiple local parties within the same basin store water in shared groundwater banking projects. But some of these banks—particularly those in Kern—also store water for parties in other basins where storage conditions are less favorable.

Some managers interpret SGMA as encouraging—perhaps even requiring—recharge partnerships to stay within the same basin. In this view, water stored in another basin does not contribute to improving the local groundwater balance. But this perspective on recharge could limit opportunities. If water stored elsewhere enables local water users to pump less groundwater, it can also help bring basins into balance. Given the disparities in recharge suitability across the valley—reflecting soil and geologic conditions, physical capacity to access water, and institutional capacity to manage large recharge projects—it will likely continue to be advantageous to expand off-site partnerships that extend beyond basins, even as local partnerships grow.

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[42] See Gartrell et al. (2017) for a discussion of these changes and their effects on water assigned to the environment in the Delta.

This review of managers' views on barriers and priorities suggests a range of measures that can be taken to improve understanding of the potential for recharge and to facilitate its practice where appropriate. We now turn to our overall assessment of the areas where policy and management actions are needed to advance groundwater recharge—taking into account the insights from the survey and our assessment of the hydrologic opportunities and constraints.

Key Takeaways for Policy and Management

Groundwater recharge has potential to help water users in the San Joaquin Valley bring their groundwater basins into balance and make a dent in the long-term deficit of nearly 2 million acre-feet per year. While 2017 was exceptional, the experience with recharge in this first wet year since the enactment of SGMA offers valuable insights into the work that lies ahead to expand this practice.

One encouraging starting point is that interest in recharge is widespread. Most districts we surveyed reported some type of active recharge in 2017, and they recharged more than in 2011—the last opportunity for significant recharge. Recharge volumes were highly concentrated in agricultural districts in the southern end of the valley with large surface supplies and formal recharge programs, often including dedicated basins. But interest in expanding the practice is much broader—including among those who rely solely on groundwater, and those who have principally relied on more passive, informal methods of recharge.

Looking ahead, the potential for expansion raises two key questions. First, how much surface water is available for recharge, after accounting for the water that needs to remain instream for the environment and surface water-right holders? And second, how much of this water could be captured cost effectively? Answering these questions is essential to understanding how much groundwater recharge can contribute to reducing the valley's long-term water imbalance.

Although there are no firm answers yet, two recent studies find that up to a quarter of the valley's supply deficit could be filled by capturing more water from local rivers, and our analysis suggests that even more might be available. However, realizing this annual average would require recharging much more in wet years than is currently possible. As an example, an additional 4 to 6 million acre-feet might have been available in 2017, and most districts we surveyed said they could not have recharged more with their current capacity. Although it seems clear that there is potential to do more, it is probably not economically feasible to capture all the extra water in high flow years such as 2017. Understanding how existing infrastructure can be leveraged to expand recharge on suitable lands, and where new investments would pay off, is key to taking advantage of this opportunity to help balance supply and demand in the valley.

Improving the capacity to recharge will require concerted actions on a number of fronts, involving a range of local, state, and federal partners. Our analysis points to six priorities.

Clarify Rules on Water Available for Recharge

The State Water Board—the agency that oversees surface water rights—needs to develop a straightforward, expeditious process for enabling water users to capture surface water when it is available. Board staff have indicated that establishing new water rights for diversion and storage will generally be required for water that is not already held under existing rights and contracts (see footnote 39). But they have also indicated their intent to make this process easier. Beyond the legal aspects of establishing new rights, an essential part of this process is technical: developing a simple, rapid way to determine when flows on local rivers exceed water required for the environment and downstream users. Having the ability to make these decisions quickly is critical, given the flashy nature of these river systems.

Evaluate the Capacity to Get Available Water to Recharge Locations

It's not surprising that infrastructure constraints loomed so large among the barriers and priorities water managers identified in 2017—the valley's wettest year in more than three decades. Going forward, it will be crucial to understand the opportunities for improving the use of existing infrastructure and where additional investments may be warranted. The decision to make large new investments will depend not only on how much additional water may be available, but also how often, since it is harder to justify investments that are used very infrequently.

One key issue is system conveyance capacity—and the ability to move available water from the wetter northern part of the valley to the drier south, where the demand for recharge water is highest and the conditions for recharge are most suitable. In particular, the subsidence-constrained capacity in the Friant-Kern Canal significantly limits the ability to transfer high volumes of flood flows to the south. Exploring opportunities to stretch out the timing of these flows—for instance, by moving water stored in reservoirs into groundwater basins in the fall to free up storage space for winter and spring flood flows—is another priority. Analysis of new surface storage opportunities—including temporary holding ponds on the valley floor as well as upstream reservoirs—should be considered in this light.

State, federal, and regional entities that own and operate storage and conveyance infrastructure can play a critical role in helping to assess system capacity issues and potential. Local managers will also need to evaluate which augmentations of their own capacity—including recharge basins, conveyance, and other tools—are warranted.

Improve the Ability to Actively Recharge on Farmland

Some recharge nearly always occurs when fields are irrigated with surface water, and some farmers in half of the agricultural districts we surveyed applied extra water in 2017. This happened mainly during the regular irrigation season, and in some pilot cases by irrigating cropland in the winter. In addition, a third of farm districts applied recharge water to fallowed fields. But active recharge of farmland seems low relative to its potential, given the vast expanse of irrigated lands in the valley (5 million acres, more than half of which have at least moderately good potential for recharge). Indeed, this may be one of the most promising ways to cost-effectively capture water in wetter years, rather than investing in dedicated recharge basins that would often sit empty. Based on a pilot study in the Kings River basin, Bachand et al. (2016) estimate that cropland recharge can cost just $36 per acre-foot stored, whereas using recharge basins can cost from $90–$1,100 per acre-foot.

Significantly ramping up this practice will require addressing a suite of technical and institutional issues:

- **Identify which subset of farmland is suitable for active recharge.** This requires both good recharge potential and a connection to surface water infrastructure. In addition, only some crops are suitable for spreading large volumes of water during the winter.[43]

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[43] Sustainable Conservation's Groundwater Recharge Assessment Tool (GRAT) can combine many relevant factors for individual water districts to help determine the best opportunities for on-farm recharge. It includes spatial data on soil suitability and cropping patterns for the entire valley. In cooperation with local districts, it can be used to incorporate district-specific information on local conveyance availability and scenarios of water availability. It was piloted in 2017 by two districts interested in exploring winter recharge.

- **Overcome constraints to spreading water on drip- or sprinkler-irrigated fields.** Fields equipped with drip irrigation—now more than 40 percent of the total and growing—may be unable to recharge large amounts quickly. The design of "dual" systems that allow both drip and flood irrigation would be beneficial in the areas most suitable for on-farm recharge. Another option to explore is expanding recharge on fields irrigated with drip or sprinkler systems, by enrolling a large number of farmers willing to use extra irrigation when water becomes available.
- **Improve understanding of the seasonal availability of water.** In 2017, roughly a third of the water identified as potentially available came in April or later, in the midst of the cropping season (Figure 11). On-farm recharge poses different management issues during this time compared with winter flooding.
- **Improve information on the impacts on crop yields and water quality.** This has implications for farm profits and compliance with water quality regulations, and it can vary by crop, location, and timing.[44]
- **Explore the implications for farming operations.** For winter recharge, this includes finding ways to avoid interference with field maintenance practices that normally take place when fields are dormant.
- **Develop incentive systems (in water or in cash) to encourage farmers to participate in practices that could reduce profits.** Such crediting systems for farmers who recharge are likely to be necessary to significantly scale up farmland enrollment.[45] Pre-enrolling farmers in advance of the rainy season, so they are ready to take water quickly when it becomes available, will be another important element in this package.

Finally, it will be important to communicate evolving information on all of these issues with farmers, and to encourage their involvement in experiments to make the most of this high-potential tool.

Address Other Regulatory Barriers to Recharge Projects

Clarifying rules on how much water is available for recharge—the first priority noted above—is a central regulatory issue for expanding recharge. But it is not the only regulatory impediment.

State and federal agencies also need to improve the process for approving construction of new recharge projects, moving recharge water through their conveyance facilities, and enabling more flexibility in the location of water stored under different water rights and contracts. This problem arises because different water rights have different places of use assigned to them under state law, and federal rules limit the ability to use CVP water on non-CVP lands. This can make it difficult to bank water outside of the place of use, even if that is a more suitable location.

To encourage more wet-year recharge, the federal and state projects may also need different pricing formulas for flood flows. As an example, CVP Friant flood water was relatively expensive in 2017 because the prices were set to help recover costs incurred during the drought, when water sales were very low.

Locals, for their part, can do more up-front work to prepare for wet years by seeking longer-term permits in advance. A good example is the work done by some districts in the Kern basin, which have obtained pre-authorizations to store water for off-site CVP contractors.

Another area requiring regulatory attention is water quality. Water managers and growers need guidelines for implementing on-farm recharge of cropland and fallowed land in ways that are consistent with water quality rules. The Regional Water Quality Control Board may want to consider introducing some flexibility in the administration of these rules in cases where recharge may cause temporary worsening of groundwater quality.

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[44] Pilot projects are investigating how to manage water quality and plant health in flooded fields (Mohan 2016, Dahlke et al. 2018). Sustainable Conservation has also developed a preliminary field guide for growers on managing the timing of extra irrigation of cropland, using information from a study of nitrate leaching (Bachand et al. 2017). There appears to be potential to improve groundwater quality with recharge on fields that use little or no nitrogen (e.g., grapes and alfalfa, respectively) (Mayzelle et al. 2015).

[45] One interesting approach being piloted in the Central Coast is the concept of net metering, borrowed from the electricity sector's practice with solar installations. Farmers would be credited with water when they incur costs for recharging efforts that benefit the basin (Fisher 2016). See also Pottinger (2018) for an example of crediting being developed in Kern County.

Information on the potential for using injection wells in the valley would also be very helpful: right now, parties on the ground do not appear to have a good understanding about when this might be a useful approach.

Strengthen Groundwater Accounting

Better accounting of the water that goes into and out of groundwater basins will be key to successful implementation of SGMA. It will also support efforts to expand recharge activities, such as developing incentives for farmers to recharge water on their lands, and providing a sound basis for making decisions to invest in more capacity. Solid accounting will also be key to GSA efforts to raise funds for recharge activities, given the transparency and accountability requirements of Proposition 218. And good accounting is necessary to enable water banking partnerships, so that all parties know who has claims to banked water.

Develop Recharge Partnerships

SGMA is forging new local partnerships for managing groundwater. The GSAs charged with developing and implementing groundwater sustainability plans often consist of multiple parties, and in most of the valley's groundwater basins several GSAs will also need to coordinate to ensure that their plans are consistent.

Our survey highlights the opportunities for these partnerships to expand the recharge pie. Joint programs between surface and groundwater districts and between cities and farms can help align water, funding, and suitable recharge areas in ways that benefit individual partners and the water balance for the basin. Urban districts will have a growing interest in participating in such projects, and they can bring funds to the table to support them if they get credit for the water they help store. Recharge projects can also improve drinking water quality and provide intermittent wetland habitat, which brings potential to engage additional community and environmental partners.[46]

As parties move forward with such efforts, they should be open to partnerships beyond their basin's borders. Off-site recharge in basins with particularly good conditions offers potential to cost-effectively store water for dry years and improve the local groundwater balance in basins lacking good local conditions. This requires developing good accounting systems, creatively leveraging storage and conveyance infrastructure, and putting in place a package of federal, state, and local agreements to enable water to be stored in places other than its intended place of use. Experience shows that this can be done successfully: it is already helping parties in some of the most overdrafted areas to manage their scarce water resources more effectively, and it holds promise for doing more.

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[46] Mayzelle et al. 2015 show how on-farm recharge projects and land planted to crops using little or no nitrogen fertilizer can help clean up drinking water supplies. The Kern Water Bank is an example of a groundwater banking project where the recharge basins provide thousands of acres of wildlife habitat.

Conclusion

Bringing the San Joaquin Valley's overdrafted groundwater basins into balance will require a portfolio of approaches to augment water supplies and manage demands. On the supply side, groundwater recharge is a significant and growing element in this portfolio. Recent studies find that up to a quarter of the valley's supply deficit of close to 2 million acre-feet could be filled by capturing more water from local rivers, and our analysis suggests that even more might be available. Logistical and economic constraints will limit how much of this water can be captured, because it is mainly available over a short period of time during high-flow events. Thus while the potential to increase recharge is high, it will not be a panacea.

That said, recharge will be an important element of many groundwater sustainability plans. Lessons from local recharge efforts after the very wet winter and spring of 2017 showed strong and widespread activity, and also revealed hurdles that must be overcome—including limitations in infrastructure capacity, a lack of clear rules to govern recharge, and a need for improved groundwater accounting. To take recharge to the next level, three critical questions must be answered: How much water is legally available for recharge? What share of this can be captured cost-effectively with existing or enhanced infrastructure? And which methods will be most effective in recharging aquifers?

Finding the right mix of policies, regulations, and incentives to encourage more active groundwater recharge is still a work in progress. One thing is clear: cooperative efforts hold great promise. As water districts and water users develop basin-wide sustainability plans, cooperative approaches—forming partnerships that pair cities with farming areas and surface water "haves" with "have nots," and encouraging partnerships to expand off-site recharge—can help ease the path and increase chances of success.

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