Replenishing Groundwater in the San Joaquin Valley

Technical Appendices

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Appendix A: Update of the San Joaquin Valley's Water Balance and Estimate of Water Available for Recharge in 2017

Summary

This appendix is divided in two main sections. The first updates each component of the San Joaquin Water balance (published in the Technical Appendix A of the 2017 PPIC report *Water Stress and a Changing San Joaquin Valley*) to include 2016 and 2017 and provides estimates of how groundwater overdraft is distributed across subregions of the valley. The second estimates how much water was available for recharge in 2017 replicating the approaches presented by two recently released studies (DWR 2017a and 2018a, and Kocis and Dahlke 2017).

From the San Joaquin water balance update, we find that 2017 was an extraordinarily wet year when compared to the 1986-2017 series. With high levels of imports and the highest local inflows in more than three decades, water availability was at peak levels. Although San Joaquin River outflows were also the highest in the series, there was a net increase in storage of 7.8 maf (4.6 maf in surface reservoirs and 3.2 maf in aquifers). Considering the 1.75 maf of overdraft over the long-term, the 3.2 maf net recharge in the aquifers is roughly 5 maf more total recharge than the 32-year average, and 8 maf more than annual total recharge during the 2012-16 drought.

To obtain the subregional differences in overdraft in the valley we use data from the two hydrological models that have been independently applied in the Central Valley to estimate historical groundwater budgets: CVHM (Faunt et al., 2009) and C2VSim (Brush et al. 2013). We find that the overdraft estimates are much more significant in the Tulare Lake hydrologic region, and especially in Kern County.

Finally we obtain different estimates for how much water was available for recharge in the San Joaquin Valley in 2017. The approaches used by DWR and Kocis and Dahlke result in a wide range of additional volumes of water that could have been captured in 2017: from a high of 6.3 maf (DWR's unadjusted "maximum project estimate" under our assumptions) to 3.7 maf (Kocis and Dahlke), to 0.88 maf (DWR's unadjusted "best estimate"). These levels are substantially higher than the long-term averages estimated by these two studies (1.2 and 0.55 maf for DWR's unadjusted and adjusted "maximum project estimate"; 0.46 maf for Kocis and Dahlke's post-1989 "impaired period," and 0.43 maf and 0.19 maf for DWR's unadjusted and adjusted "best estimate"), reflecting the fact that 2017 was an extraordinary year.

Introduction

After a multi-year drought, 2017 was one of California's wettest years since record-keeping began in the 1890s. In the San Joaquin Valley high runoff, in conjunction with initial work on sustainable groundwater management plans mandated by the 2014 Sustainable Groundwater Management Act (SGMA), triggered an unprecedented interest in groundwater recharge. In this appendix we seek to answer two questions that are crucial to understanding the potential for groundwater recharge in the San Joaquin Valley over the long term: how did 2017 compare to other years? And how much additional water could have been available for recharge?

This appendix provides information on data sources and methods used to 1) assess the annual water balances in the San Joaquin Valley for water years 1986-2017, including estimates of groundwater recharge and overdraft at the subregional scale, and 2) estimate water available for recharge in 2017.[1]

[1] In this technical appendix we always refer to water years: the 12-month period between October 1st and September 30th of the following year. The water year is designated by the calendar year in which ends and which includes 9 of the 12 months.

For the annual water balances, this report provides an update of Technical Appendix A of the 2017 PPIC report *Water Stress and a Changing San Joaquin Valley*, with an expanded analysis for water years 2016 and 2017. For that reason we only include here the sources of information used to update the numbers and the results. Readers should consult the earlier document for a more detailed explanation of methods and results.

This appendix is divided into two main sections. The first updates each component of the San Joaquin Water balance to include 2016 and 2017 and provides estimates of how groundwater overdraft is distributed across subregions of the valley. The second estimates how much water was available for recharge in 2017, replicating the approaches presented by two recently released studies (DWR 2017a and 2018a, and Kocis and Dahlke 2017).

Updating the San Joaquin Valley's Water Balance

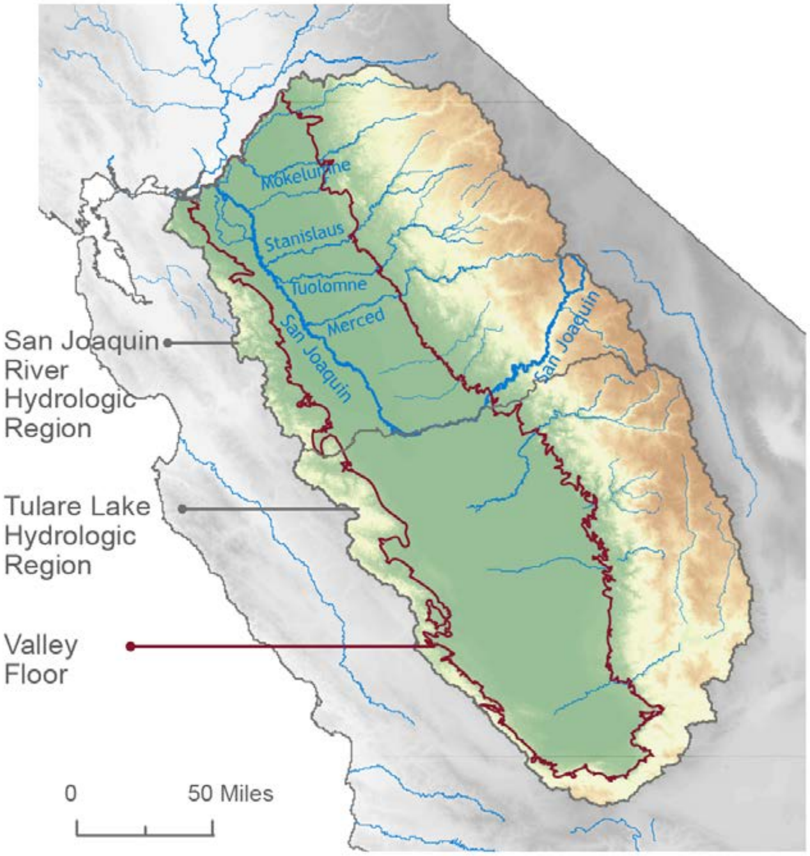
A water balance is an accounting statement that estimates water inflows (including precipitation and other water flowing into the area), outflows (including net or consumptive water used locally and water flowing out of the area), and changes in water stored in surface reservoirs and aquifers. As with any mass balance, the sum of inflows, outflows, and changes in storage has to be zero every year, as shown in the following equation:

$$Inflows - Outflows = \Delta\, Storage$$

By presenting inputs and outputs in an understandable way—and accounting for their variability—a water balance depicts the water uses and availability in a region. Water balances also illustrate how change in a water system—such as new policies, new infrastructure, or climate change—affects water availability and the system's ability to meet water demands.

The San Joaquin Valley includes two hydrologic regions (HRs): the San Joaquin River Basin and the Tulare Lake Basin (Figure A1). In the following sections, we present estimates of inflows, outflows, and changes in water stored. We then summarize the overall water balance for the valley. Finally we estimate the groundwater overdraft at the subregional scale using data from the two main Central Valley hydrological models: C2VSim (Brush et al. 2013) and CVHM (Faunt et al. 2009).

FIGURE A1
San Joaquin River and Tulare Lake watersheds



Inflows

Four types of water inflows are considered here: flows into the valley from local watersheds (including the Central and Southern Sierra Nevada and the Coast Range), water from net precipitation on the valley floor, direct diversions from the Delta, and water imported from other regions—especially through the Sacramento-San Joaquin Delta, but also much smaller imports through the Folsom South Canal.

These inflows can be either used the same year or stored in surface reservoirs or aquifers for later use. Conversely, some of the water used in a given year can be obtained from withdrawals from surface and groundwater storage.

Inflows from local watersheds

To assess inflows into the valley floor from local watersheds we used estimates of full natural or "unimpaired" flows for the main rivers and creeks in the region.[2]

We obtained full natural flows (monthly volume) for the period of study from California Data Exchange Center (CDEC) for the major rivers in the valley. For some minor local watersheds where CDEC data were insufficient or inconsistent we used 1986–2003 data from DWR (2007). For these minor watersheds we estimated the data

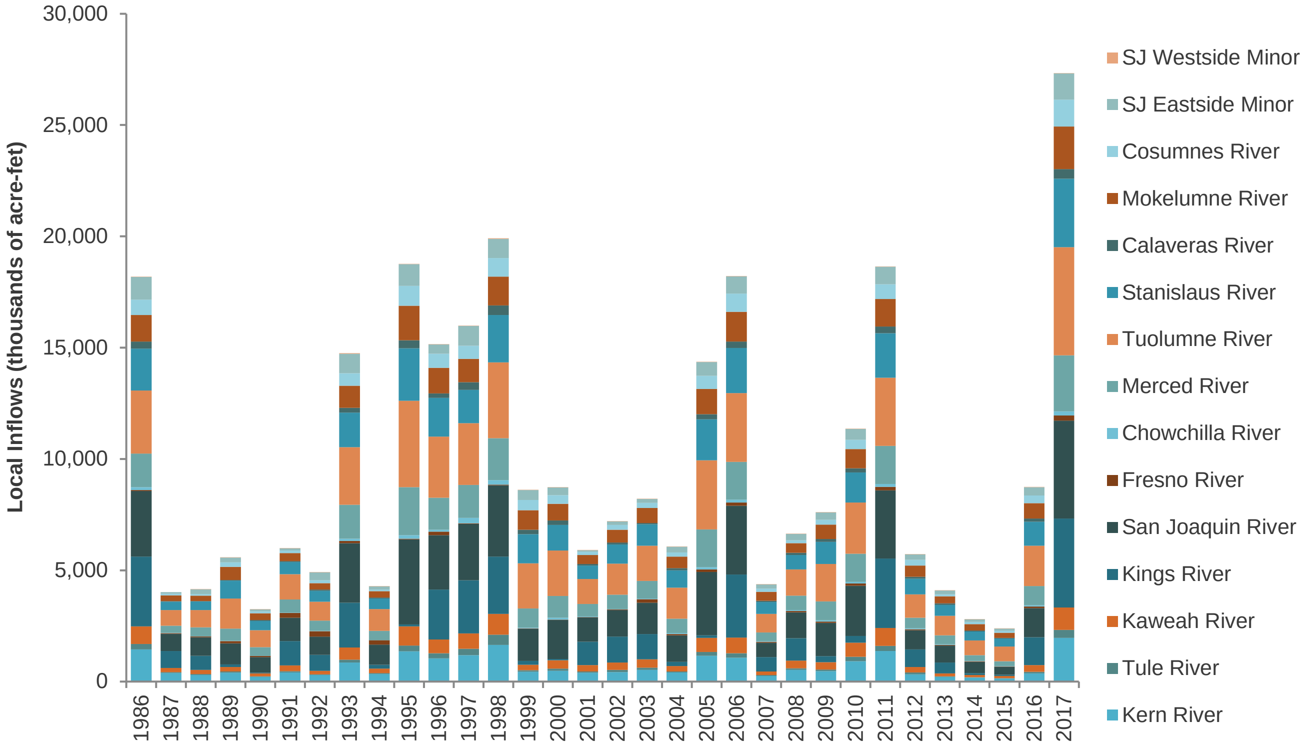
[2] Unimpaired flow is the natural runoff of a watershed in the absence of storage regulation and stream diversions. Full natural flow is the natural runoff of a watershed that would have occurred prior to human influences on the watershed, such as storage, diversions, or land use changes. In this report we used full natural flows from CDEC stations where available, and unimpaired flows from DWR (2007) for the remaining watersheds.

after 2003 calibrating a simplified rainfall-runoff model that mimics the runoff response to rainfall in the gaged catchments.

Figure A2 shows total annual inflow volumes from each watershed, with 2017 the highest in the period analyzed.[3] Although there are inflows from 15 local watersheds, five rivers account for nearly 70 percent of the average total: Tuolumne (19%), San Joaquin (17%), Stanislaus (11%), Kings (11%), and Merced (10%).

FIGURE A2

Inflows from local watersheds



NOTES: The rivers shown in the bar chart are ordered geographically from south to north. The Kern, Tule, Kaweah, and Kings drain into the Tulare Lake Basin, and the remaining rivers drain into San Joaquin River Basin. The Tulare Lake Basin is a closed basin in most years, with all inflows remaining within the basin. The exception is very wet years, when excess flows drain into the San Joaquin River through the James bypass (Fresno slough).

Net valley floor precipitation

Total monthly precipitation on the valley floor has been obtained by clipping the gridded datasets from PRISM Climate Group, Oregon State University, using a GIS layer of the study area. We assume that 15 percent of total monthly precipitation becomes net precipitation—the precipitation that does not evaporate and remains in the Valley, where it is used by plants, flows into streams, or percolates into an aquifer. This estimate is based on the water balances from DWR's *California Water Plan* (DWR 2013) for the entire Central Valley, and in the Central Valley water balance of the C2VSim model (Brush et al. 2013). Relative to inflow from the Sierra (shown in Figure A2), net precipitation on the valley floor is less variable across dry and wet years (Figure A3) and does not always mirror differences in runoff.

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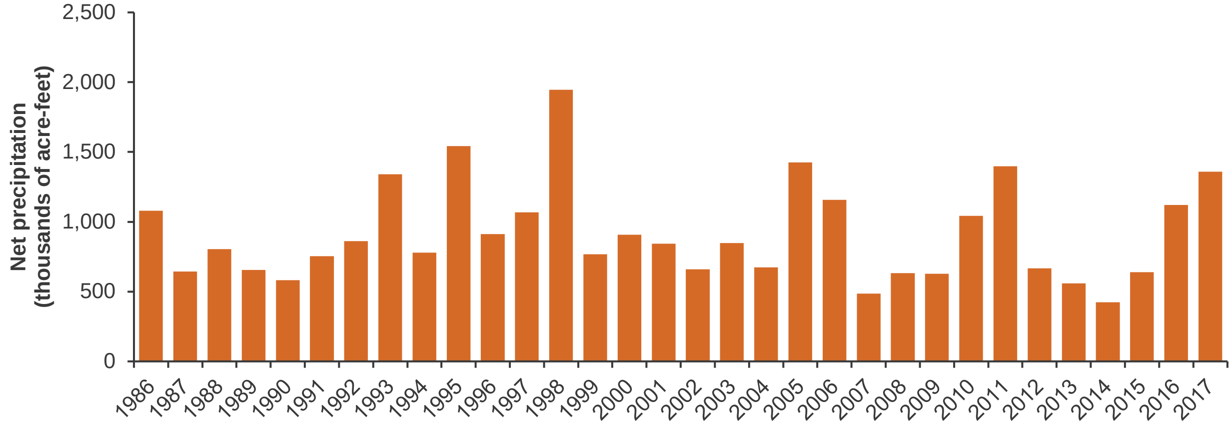
[3] Water year 1983 was the wettest year on record in the region in terms of both runoff and precipitation. Water year 2017 was the second wettest for runoff (using CDEC data for full natural flows), and the sixth wettest for precipitation (using NOAA data).

FIGURE A3

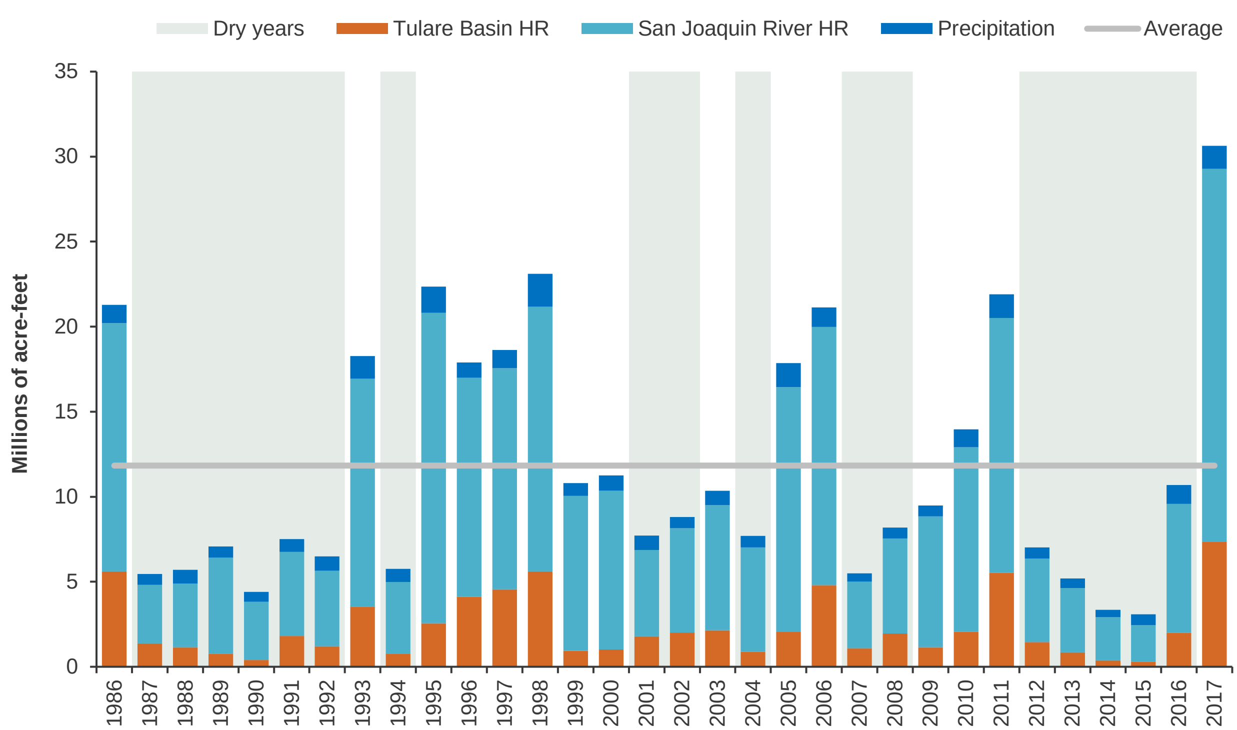
Net precipitation on the valley floor



The inflows from local watersheds and the precipitation on the valley floor are the flows that could be captured in surface reservoirs or used for recharging aquifers. Figure A4 demonstrates that most of these flows come from the San Joaquin River hydrologic region (73% of total inflows), whereas nearly a fifth (19%) comes from the Tulare Basin watersheds, and just 8 percent from precipitation on the valley floor. This is important because is an indicator of the amount of water available for recharge (as we show later in this report).

FIGURE A4

Inflows into the valley from local rivers and precipitation on the valley floor



Direct Delta diversions

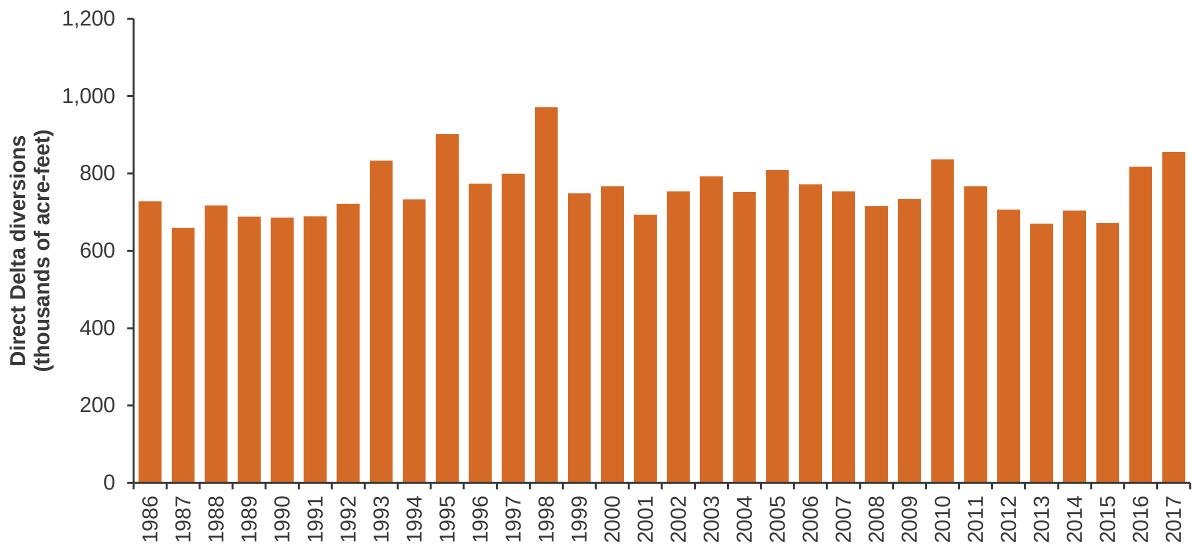
Central and southern Delta agricultural lands—which are considered part of the San Joaquin Valley—use water diverted directly from the Delta. Most of this water flows into the Delta, with lesser volumes from the San Joaquin River and other Delta tributaries.

To account for this inflow we assume that all agricultural water use in the area of the Delta that is included in the San Joaquin Valley is directly diverted from the Delta and is estimated as the net or consumptive water use of these agricultural lands.

The methods to obtain net or consumptive water use are described in a section below. We use the same methodology to obtain the direct Delta diversions, but just for the area of the Delta that is in the San Joaquin Valley floor. Diversions average roughly 750 thousand acre-feet per year (Figure A5).

FIGURE A5

Direct Delta diversions



Imports from other regions

Water is imported into the valley from Northern California through pumps in the south Delta. A small volume is also imported from the American River through the Folsom South Canal.

Delta imports

Delta imports are primarily from the Sacramento River with a small share from the San Joaquin River. These sources mix as they enter the Delta. Daily data for Delta imports from State Water Project (SWP) facilities (Banks Pumping Plant or Clifton Court Intake), the Central Valley Project (CVP) facilities (C.W. "Bill" Jones Pumping Plant at Tracy), and the Contra Costa Canal are obtained from Dayflow—a program that estimates daily average

Delta outflows (DWR, 2016)—for the period 1986-2015. The water years 2016 and 2017 were provided by DWR.[4]

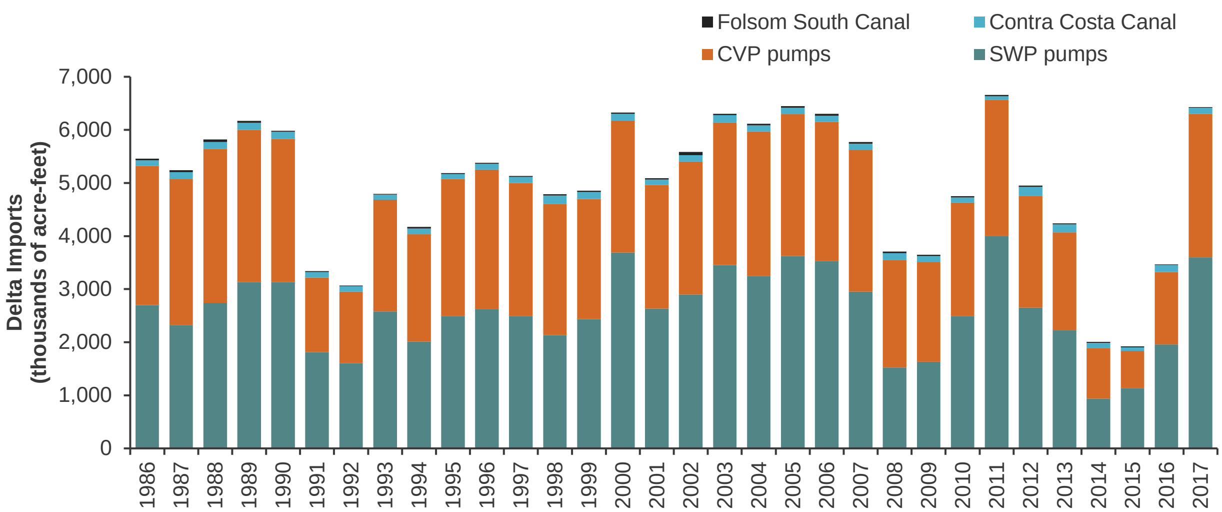
Imports through the Folsom South Canal

The Folsom South Canal imports a small volume of water from the American River into the northeastern side of the San Joaquin Valley. Data on water imported through the South Folsom Canal is obtained from the US Bureau of Reclamation Central Valley Operations Annual Delivery Reports (Table 21).

Figure A6 shows annual imports from the CVP and SWP pumps in the south Delta (Jones and Banks, respectively), the Contra Costa Canal, and Folsom South Canal. Total imports averaged 4.9 million acre-feet/year (53% from SWP and 47% from CVP), but in dry years imports from the Delta fall below 2 million acre-feet, as occurred in 2015. In 2017 the Delta imports were 6.4 maf, only a little less than the 2011 record of 6.6 maf. Imports through the South Folsom Canal averaged around 26,000 acre-feet/year.

FIGURE A6

Imports from other regions



Outflows

Four types of water outflows are considered: consumptive water use from evapotranspiration (water consumed by plants, and other evaporation to the atmosphere from the valley floor), San Joaquin Valley outflows to the Delta, exports from San Joaquin River tributaries to Bay Area water users, and exports of imported water that enters the valley.[5]

Consumptive water use

Similar to precipitation, monthly consumptive water use was obtained by clipping evapotranspiration gridded datasets from the operational Simplified Surface Energy Balance model (Senay et al. 2013) using a GIS layer. This dataset provides high-resolution estimates of evapotranspiration, but only covers the period from 2000 to the

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[4] CVP deliveries under the Friant Division are not included in these totals—this water is diverted from the San Joaquin River at Millerton Lake to the Friant-Kern Canal, which delivers water to users on the east side of the Tulare Basin. For the purposes of this regional water balance, these are considered local flows. Contra Costa Canal imports are included because the pumps are inside the San Joaquin Valley floor, but as the Contra Costa Water District is entirely outside of the valley floor, these imports are later considered as exports to the Bay Area.

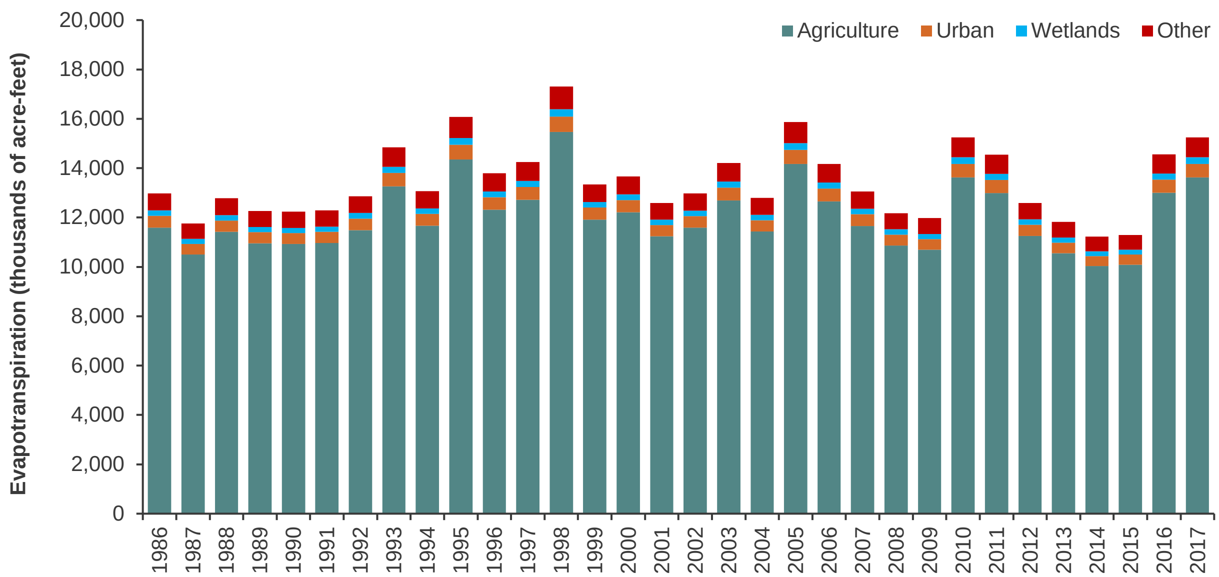
[5] This may slightly understate total net water use insofar as it does not include water embodied in manufactured goods produced in the valley.

present. To obtain earlier values, we employed multiple regression analysis, using temperature, precipitation, and potential evapotranspiration from crops as independent variables (see Arnold and Escriva-Bou 2017 for more details). The values for 2016 and 2017 were 14.6 and 15.3 maf respectively, at the higher end of the distribution—reflecting the greater volume of water available to evaporate from soils and transpire through vegetation in wetter years.

To break down the consumptive use by end users (i.e., agriculture, urban, environmental, and natural landscapes) we obtained the average share of consumptive uses by end use from the California Water Plan (DWR 2013), and then applied these shares to the estimates of evapotranspiration for the entire 32-year period (Figure A7).

FIGURE A7

Annual evapotranspiration by end use



NOTE: The category "other" includes evapotranspiration from natural landscapes not categorized as wetlands.

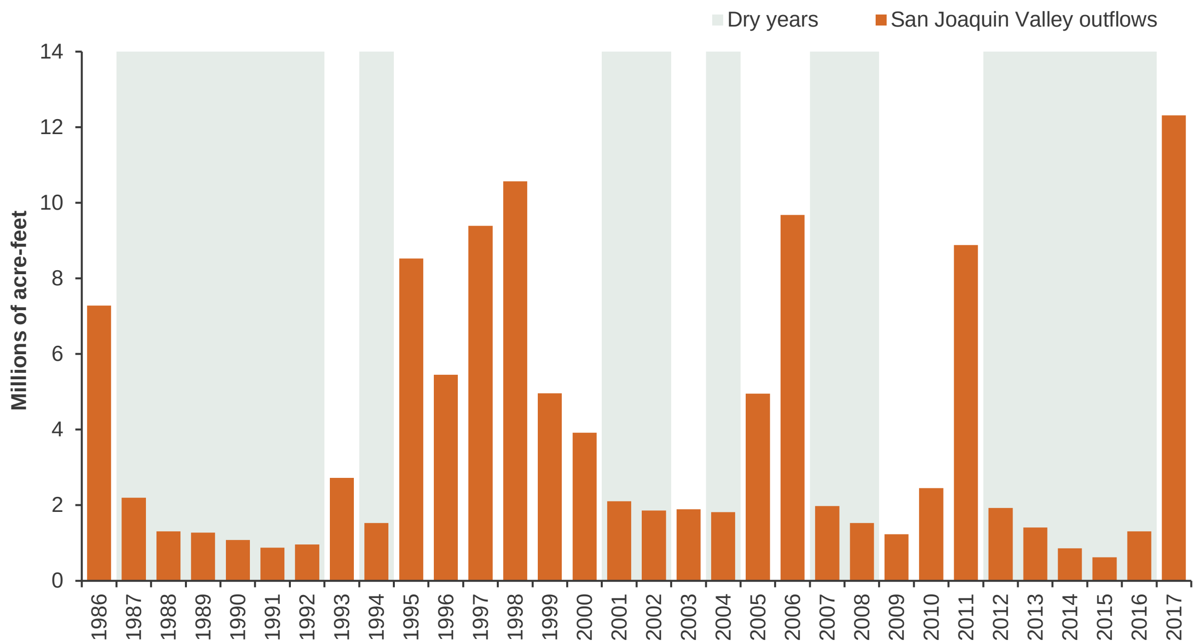
San Joaquin Valley outflows

San Joaquin River and other minor Delta tributaries outflows (Figure A8) were obtained from Dayflow and CDEC. These flows are reported as Delta inflows from the San Joaquin River (measured at the Vernalis gage) and eastern Delta inflow (including the Cosumnes and Mokelumne rivers and other minor creeks).[6] The magnitude of the outflows in the San Joaquin Valley are highly influenced by the storage capacity within the basin, whereas minimum outflows in the river and the Delta are required by water quality and other environmental regulations. In 2017, the outflows were 12.3 maf, the highest level in the past 32 years.

[6] San Joaquin Valley outflows that are subsequently recaptured as either Delta imports or direct Delta diversions are counted as inflows to the region, and included in the Delta import measures presented below.

FIGURE A8

San Joaquin Valley outflows

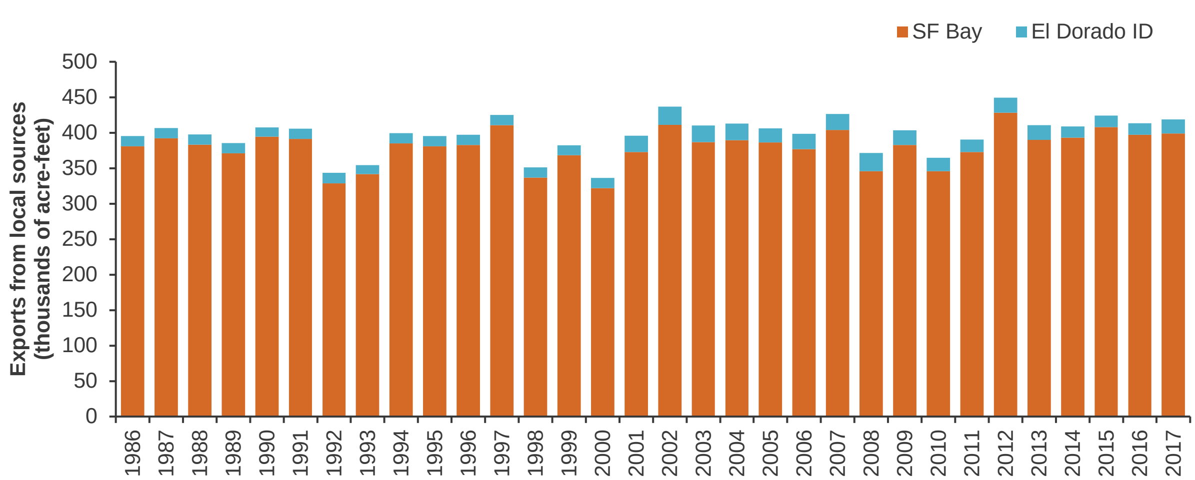


Exports from San Joaquin River tributaries

The San Joaquin Valley exports several hundred thousand acre-feet of water annually from local sources to the San Francisco Bay Area (Figure A9). The amount of export water does not vary significantly from year to year. Water from the Tuolumne River is stored in Hetch Hetchy Reservoir and then conveyed to the San Francisco Public Utilities Commission (SFPUC) service area, while water from the Mokelumne River is stored in Pardee and Camanche Reservoirs and conveyed to the East Bay Municipal Utility District (EBMUD) service area.[7]

FIGURE A9

Water exports from San Joaquin River tributaries



[7] EBMUD also has a contract with USBR to divert 100 million gallons a day at Freeport on the Sacramento River in an emergency; this is not included here.

Data from 1998-2010 was obtained from the California Water Plan (DWR 2013), using the series "imports to the San Francisco Bay Hydrologic Region." The remaining years have been estimated with a regression analysis using the unimpaired flows of the rivers for the entire series as an independent variable, and extrapolating the shares of the diverted data with respect to the unimpaired flows for the 1998-2010 dataset.[8] Average annual exports for 1986-2015 are 0.38 maf/year.

Figure A9 also includes a small volume of exports to the El Dorado Irrigation District in the Sacramento River hydrologic region. This water is diverted from Jenkinson Lake on Sly Park Creek, a tributary of the Cosumnes River, and averages 18,000 af per year. Diversion data is from CDEC (station CCN).

Note the low variability of water exports from the San Joaquin Valley tributaries compared with the high variability of inflows to these tributaries shown in Figure A2.

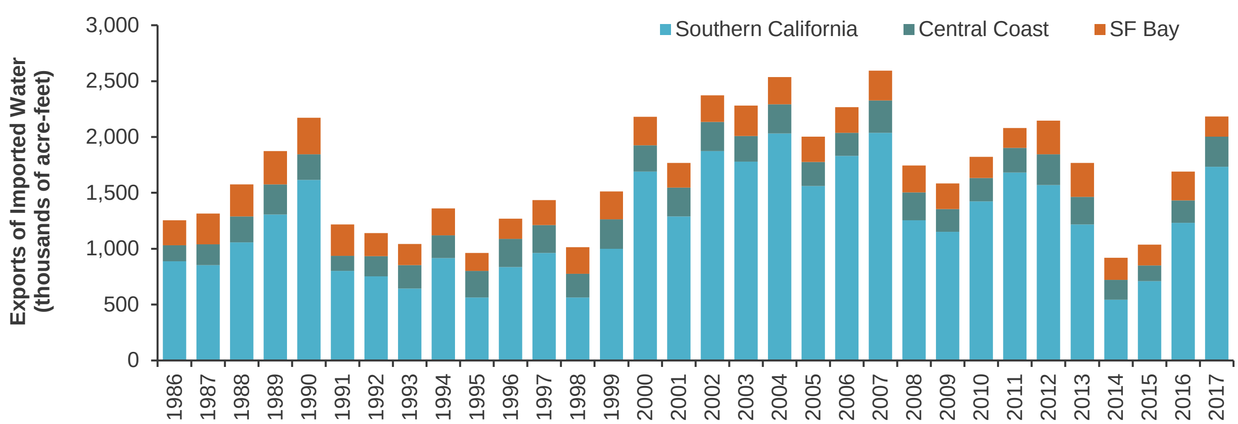
Exports of Delta imports

Some Delta imports that enter the Valley through the CVP and SWP pumps are delivered to the San Francisco Bay area, the Central Coast, and Southern California (Figure A10).

- **Exports to the San Francisco Bay Region:** This includes water from two points of diversion: (1) through the South Bay Aqueduct from the South Bay Pumping Plant (data are from the SWP Annual Reports of Operations), and (2) through the Contra Costa Canal (data are from USBR Central Valley Project Annual Reports of Operations, Table 21).
- **Exports to the Central Coast:** This includes water from two points of diversion: (1) through Las Perillas Pumping Plant on the California Aqueduct (from the State Water Project Annual Reports of Operations: Table 1); and (2) through the Pacheco Tunnel.[9]
- **Exports to Southern California:** This includes water delivered through the A.D. Edmonston Pumping Plant on the California Aqueduct (from DWR SWP Annual Reports of Ops: Table 1 Totals).

FIGURE A10

Exports of Delta imports



[8] Note that for this update we did not get actual data for these exports, so 2016 and 2017 values were estimated using a regression analysis.

[9] San Luis Reservoir Operations, from DWR SWP Annual Reports of Operations: post-2000 Reports, Table 15 Annual San Luis Joint-Use Facility Total, and pre-2000 Reports, Table 13 San Luis Reservoir Operations Total Outflow (Pacheco Tunnel). 2015 data obtained from Santa Clara Valley Water District urban water supply data and data for years 2016 and 2017 was obtained directly from DWR. Some water going through the Pacheco Tunnel goes to the Santa Clara Valley Water District and could be included in the exports to the San Francisco Region. As we do not have access to sufficient data to separate the flows that remain in the Central Coast and those that go to the San Francisco Bay hydrologic region, we include them as exports to the Central Coast.

Changes in Storage

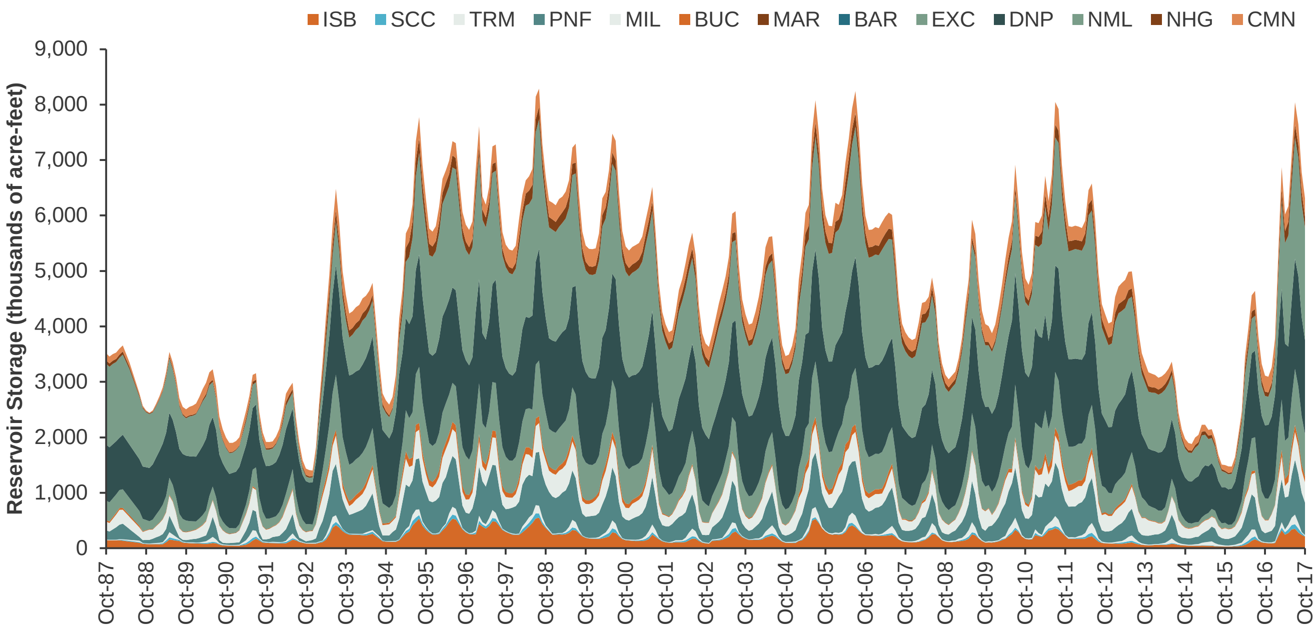
Two main storage types are considered: surface reservoirs and water stored in aquifers. Data exist for water stored in surface reservoirs. Changes in aquifer storage are estimated as the volume required to close the water balance for the valley.

Changes in reservoir storage

From CDEC, we obtained data for monthly storage for 13 major reservoirs in the San Joaquin Valley (Figure A11). Annual storage change is the water stored at the beginning of the prior water year minus the storage at the beginning of a new water year (October 1). The reliability of data for the 1986 and 1987 water years is lower because there were more gaps in the series.[10]

FIGURE A11

Water stored in the 13 major reservoirs in the San Joaquin Valley



NOTE: The 13 major reservoirs are: New Melones (NML), Don Pedro (DNP), Lake McClure (EXC), Pine Flat (PNF), Lake Isabella (ISB), Success Dam (SCC), Kaweah Lake (TRM), Millerton Lake (MIL), Eastman Lake (BUC), Mariposa Reservoir (MAR), Bear Reservoir (BAR), New Hogan Lake (NHG), and Camanche Reservoir (CMN). TAF is thousand acre-feet.

To include water stored in other minor reservoirs, we obtained the change in total water stored from the California Water Plan (DWR 2013) for the two hydrologic regions and extrapolated the other years using a linear relationship between total changes in storage and changes in the storage in the 13 major reservoirs (see details in Arnold and Escriva-Bou, 2017).

Total net changes in annual surface storage are shown below in Figure A12B. The long-term average change in surface water stored is roughly zero.

Changes in water stored in aquifers

Finally, we determine the change in water stored in aquifers as the residual that closes the water balance for the valley. In short, the net available water supply (from inflow, precipitation, and changes in storage) must equal the

[10] As discussed below, the estimates for 1986 appear low relative to precipitation and runoff year, which may in turn result in an overestimate of the level of aquifer storage in that year.

net volume of water used within the valley (consumptive use) or exported. The mass balance equation can be formulated as:

$$\Delta\, AquiferStorage =$$

$$Inflows\ from\ Local\ Watersheds + Direct\ Delta\ Diversions + Net\ Precipitation + Imports\ from\ Other\ Regions - Consumptive\ Use - SJV\ Outflows - Exports\ from\ SJ\ River\ Tributaries - Exports\ of\ Delta\ Imports - \Delta\, Surface\ Storage$$

Changes in annual aquifer storage are shown below in Figure A12C. As discussed in Arnold and Escriva-Bou (2017), these estimates are in the neighborhood of estimates of groundwater depletion found by others. Arnold and Escriva-Bou (2017) found that the long-term overdraft of San Joaquin Valley aquifers for the period 1986-2015 is roughly 1.8 maf/year. With the addition of the two most recent years (including one very wet year), the long-term overdraft is slightly lower, 1.75 maf/year.

San Joaquin Valley Water Balance

Once all annual inflows, outflows, and changes in storage are estimated, the balance for each year is calculated (Figure A12). Although consumptive water use remains fairly constant (averaging more than 13 million acre feet over 1986-2017), inflows from local supplies and net imports into the valley are highly variable depending on annual precipitation.[11, 12] The difference between annual water supply and consumptive use—shown in Figure A12A—is reflected in changes in surface and groundwater storage. In wet years, when annual supplies exceed consumptive use, there is net recharge. In other years, there is net withdrawal.

This highlights that water storage is essential in managing water in the San Joaquin Valley because of the high variability in annual precipitation and between drought and wet years. Figures A12A and A12B show that water storage is increased only in a few very wet years. Most years have a net withdrawal from surface and groundwater storage. Average change in surface storage is close to zero over the 1986-2017 period because all the water that enters a reservoir has to be discharged eventually. However, on average roughly 1.75 million acre-feet per year was withdrawn from aquifers over this period.[13]

Surface storage capacity is much less than underground storage capacity.[14] Figure A12B shows that surface reservoirs help greatly in the first years of a drought, but if the drought persists and reservoir levels are dropping, much more water is pumped from aquifers. This pattern has worsened in the last decade, when reduced Delta imports have coincided with dry years—2007-09 and 2012-15—resulting in an average aquifer overdraft of 2.4 million acre-feet per year during 2006-15 (Figure A12B).[15]

In summary, 2017 was an extraordinarily wet year when compared to the 1986-2017 series. With high levels of imports and the highest local inflows in the last 32 years, water availability was at peak levels. Although San Joaquin River outflows were also the highest in the series, there was a net increase in storage of 7.8 maf (4.6 maf in surface reservoirs and 3.2 maf in aquifers). Considering the 1.75 maf of overdraft over the long-term, the 3.2 maf net recharge in the aquifers is roughly 5 maf more total recharge than the 32-year average, and 8 maf more than annual total recharge during the 2012-16 drought.

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[11] Inflows from local supplies can be used directly as surface diversions but also indirectly by replenishing aquifers and pumped later as sustainable groundwater use. According to C2VSim groundwater budgets at the subregional scale (Brush et al. 2013), rivers in the San Joaquin Valley contribute to roughly 0.5 maf of groundwater recharge on average for the period 1973-2009. Also there is water recharged from unlined canals and percolation of excess irrigation water on agricultural lands.

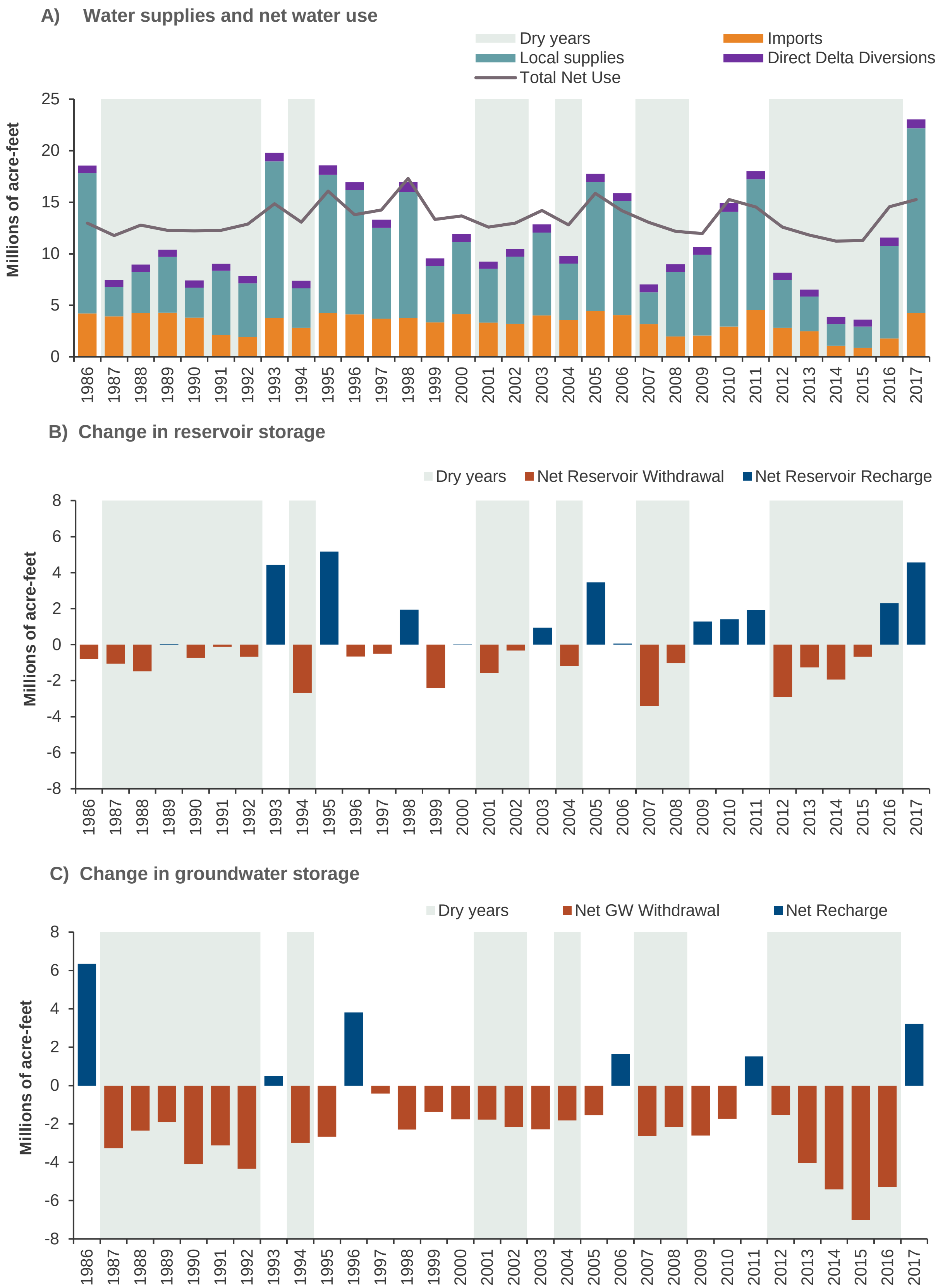
[12] Net imports into the valley are the total water imported from other regions minus the water that is exported to other regions.

[13] As mentioned above, reservoir data for the years 1986 and 1987 had low reliability. This could explain why in 1986, a wet year, our model is not reporting an increase in reservoir storage, but an unusually large increase in water stored in aquifers, relative to the volume of runoff and imported water deliveries. If the balance between surface and groundwater storage in 1986 was in line with more recent wet years, average overdraft for the entire period would be closer to 1.9 maf/year.

[14] California has approximately 850 maf to 1.3 billion acre-feet of groundwater in storage (DWR, 1994), and about 45 maf of surface storage (PPIC, 2017)

[15] More information about the different changes in temporal patterns can be found in Hanak *et al*., 2017.

FIGURE A12
Components of the San Joaquin Valley's annual water balance

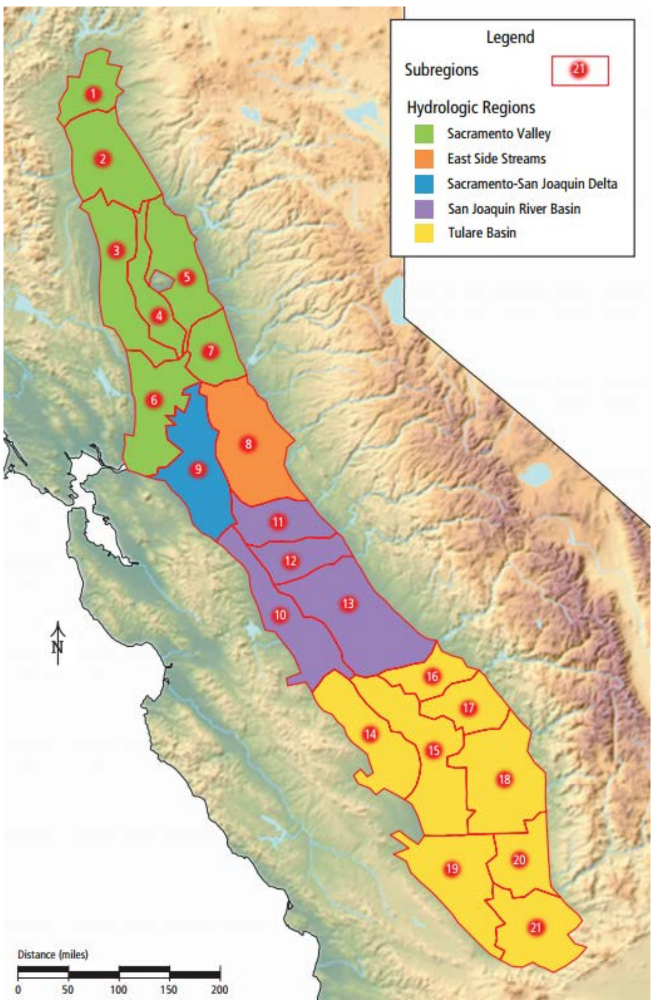


Estimating Groundwater Overdraft at the Subregional Level in the San Joaquin Valley

Two hydrological models have been independently applied in the Central Valley to estimate historical groundwater budgets: CVHM (Faunt et al., 2009) and C2VSim (Brush et al. 2013). The models use precipitation, surface-water inflows, and surface-water diversion input data that is either similar or identical (Dogrul et al., 2011) to estimate subregional water budgets, with a focus on assessing agricultural groundwater pumping.

Using C2VSim and CVHM models we determined the groundwater overdraft for 14 subregions of the San Joaquin Valley by assessing the decrease in groundwater storage over the long term (Figure A13). Table A1 shows the results for both models for the 14 subregions within the San Joaquin Valley for the period 1975-2003, and also an average of both models.

FIGURE A13
Hydrologic regions and model subregions used by both C2VSim and CVHM models



SOURCE: Brush et al. (2013).
NOTE: The numbers refer to analysis subregions commonly used in hydrologic and economic modeling in the Central Valley.

The results of Table A1 show that the models are in fairly close agreement at the regional scale (plus or minus 20%), but with some significant discrepancies for individual subregions (note for instance the discrepancies in regions 9 and 18).

TABLE A1

Change in groundwater storage at the subregional scale (1975-2003)

Subregion	Change in groundwater storage (in taf/year)		
	C2VSim	CVHM	Average
8*	-52	-3	-28
9*	-17	96	39
10	-8	1	-4
11	-11	-5	-8
12	5	32	19
13	-97	-134	-116
14	-271	-177	-224
15	-59	-170	-115
16	-14	-140	-77
17	-124	-107	-116
18	156	-408	-126
19	-210	-192	-201
20	-232	-159	-195
21	-411	-255	-333
Total	-1,345	-1,622	-1,483

SOURCE: C2VSim results at the subregional scale were obtained directly from model outputs, while CVHM results were provided by Stephen Maples.
NOTES: *The actual change in groundwater storage in regions 8 and 9 is twice the value we show in this table. We made this adjustment because only a part of regions 8 and 9 are in the San Joaquin River hydrological region.

To provide a rough estimate of the distribution of overdraft across different parts of the valley, we aggregated the results, combining the 14 modeling subregions into five (Table A2). The San Joaquin River hydrologic region includes the northwest (subregions 9 and 10) and northeast (subregions 8, 11, 12, and 13), and the Tulare Lake hydrologic region includes the southwest (subregions 14 and 15), the southeast (subregions 16, 17, and 18), and the Kern basin (subregions 19, 20, and 21). This aggregation reinforces the discrepancy between the two models in the southeast: whereas the C2VSim model estimates a positive change of groundwater storage over the long-term, CVHM estimates overdraft of more than 650 taf/year. This subregion includes the Kings, Kaweah, and Tule basins, all of which DWR considers to be "critically overdrafted." Moreover, parts of these regions are experiencing significant subsidence.[16] It therefore appears that C2VSim is underestimating pumping and/or overestimating recharge in this part of the valley.

Finally, we also made a simple adjustment to include years after 2003, which were drier. For the northwest, where the average change in groundwater storage from the two models is positive, we assumed that there is no contribution to overdraft at the subregional scale (although there could still be local issues). For the areas with overdraft, we multiplied the 1975-2003 average by a factor that accounts for the additional overdraft for the San Joaquin Valley from our 1986-2015 water balance. Using this procedure we are implicitly assuming that overdraft increased at a similar pace after 2003 across affected areas. This rough approximation is supported by the widespread decline in groundwater tables since the mid-2000s shown in DWR's Groundwater Information Center Interactive Map Application (DWR 2018b).

[16] See DWR's identification of Critically Overdrafted Basins and NASA JPL report on Subsidence in the Central Valley

TABLE A2

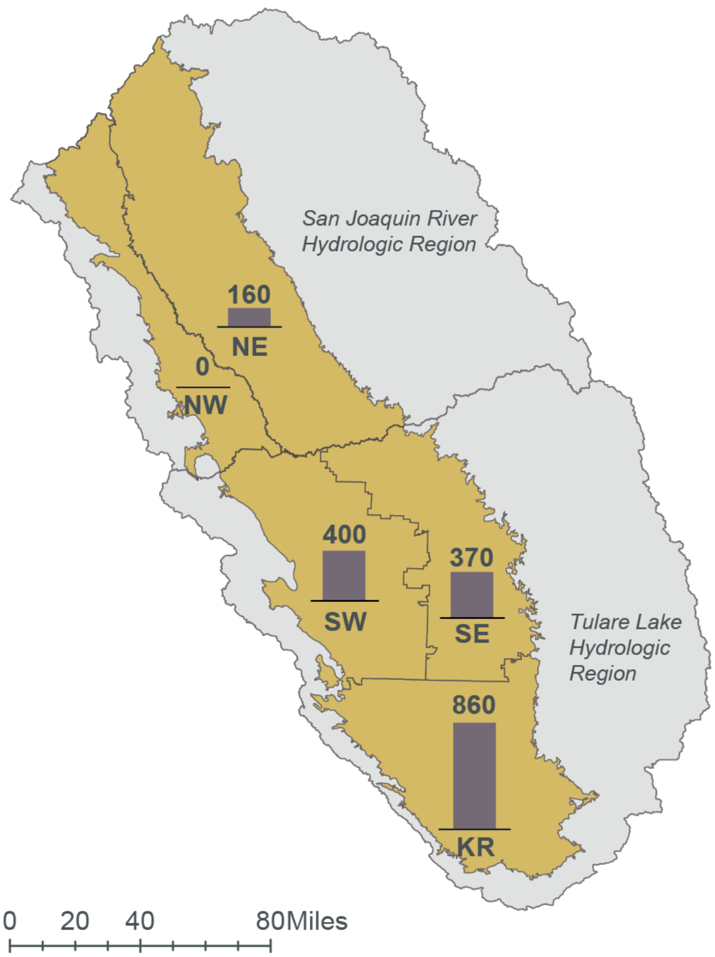
Change in groundwater storage for the five aggregated subregions

Subregion	Change in groundwater storage (in taf/year)			
	C2VSim 1975-2003	CVHM 1975-2003	Average 1975-2003	Adjusted long-term average*
Northwest	-25	96	16	0
Northeast	-155	-110	-133	-156
Southwest	-330	-347	-339	-397
Southeast	18	-655	-318	-374
Kern	-853	-606	-729	-856
Total	-1,345	-1,622	-1,483	-1,783
Total in overdrafted subregions*	-1320	-1,718	-1,519	-1,783

NOTES: *The adjusted long-term average allocates the additional overdraft we find in our 1986-2015 water balance relative to the 1975-2003 total for the four subregions experiencing average overdraft (1,783 – 1,519 = 264 acre-feet) in proportion to their overdraft in 1975-2003. We assume that the northwest is in average long-term balance.

FIGURE A14

Groundwater overdraft at the subregional scale (in thousands of acre-feet per year)



NOTE: Given the uncertainties of the estimations, this figure shows results rounded to the nearest 10 taf.

Estimating Water Available for Recharge in 2017

This section explains estimates of how much water was available for recharge in the San Joaquin Valley in 2017. We first describe two different approaches from studies that estimated how much water is available to replenish aquifers in California. Then we try to reproduce each approach with the available data from the San Joaquin Valley for 2017 and the other years examined in our water balance. Finally, we discuss the results.

DWR's Approach

In January 2017, the Department of Water Resources released *Water Available for Replenishment Report Draft* (DWR 2017a).[17] The study estimated water available for replenishment for each of the state's 10 hydrologic regions and 56 planning areas. Basically, the methodology defines a minimum streamflow requirement that accounts for environmental needs and is not available for recharge. The remaining outflow can be diverted for recharge if there is infrastructure capacity for doing so.[18] To account for uncertainties in its estimates, DWR shows a range of values based upon a range of instream flows and project capacity. These include a "best estimate" that uses the instream flow requirement and an estimate of the existing project capacity, a "sensitivity range," and a "maximum project estimate" that illustrates the maximum potential diversion for recharge.

DWR's approach caps the maximum amount of water that can be diverted above the minimum instream flow requirement based on the infrastructure needed to divert this water. To do this they define a conceptual "project diversion capacity" which is the total capacity of the diversions that would be used to recharge groundwater. To obtain the "best estimate" they define as project diversion capacity the "existing project diversion capacity", which is sized based on the water right with the largest single point of diversion capacity on a given river/stream. The sensitivity ranges are obtained by using two and half times the "existing project capacity." Finally they obtain the "maximum project estimate" by assuming that there is no infrastructure constraint in the amount of water that can be diverted.

The methodology uses historical daily gage data (1930 through 2015 for the San Joaquin River) to develop an initial set of estimates of available water. It then adjusts these using a simulation model (Water Evaluation and Planning [WEAP]) to account for changes in outflows reflecting current water demands and operations. In our analysis, we refer to the results based on the historical gage data as the "unadjusted" estimates, and those adjusted using WEAP as the "adjusted" estimates.[19] For the San Joaquin Valley, the WEAP adjustment reduces the volume available for recharge significantly—to 45 percent of the unadjusted volumes.

In Figure A15 we show a conceptual depiction of DWR's "best estimate" and "maximum project estimate." In this illustration, which uses actual outflow from Vernalis for the water year 2016, a minimum instream flow requirement of 1,000 cfs is defined for any day of the year, and an existing project diversion capacity is 500 cfs. The shaded region in yellow would be the "best estimate" of water available for replenishment. When there is no upper limit assumed for project diversion capacity, we use the "maximum project estimate."

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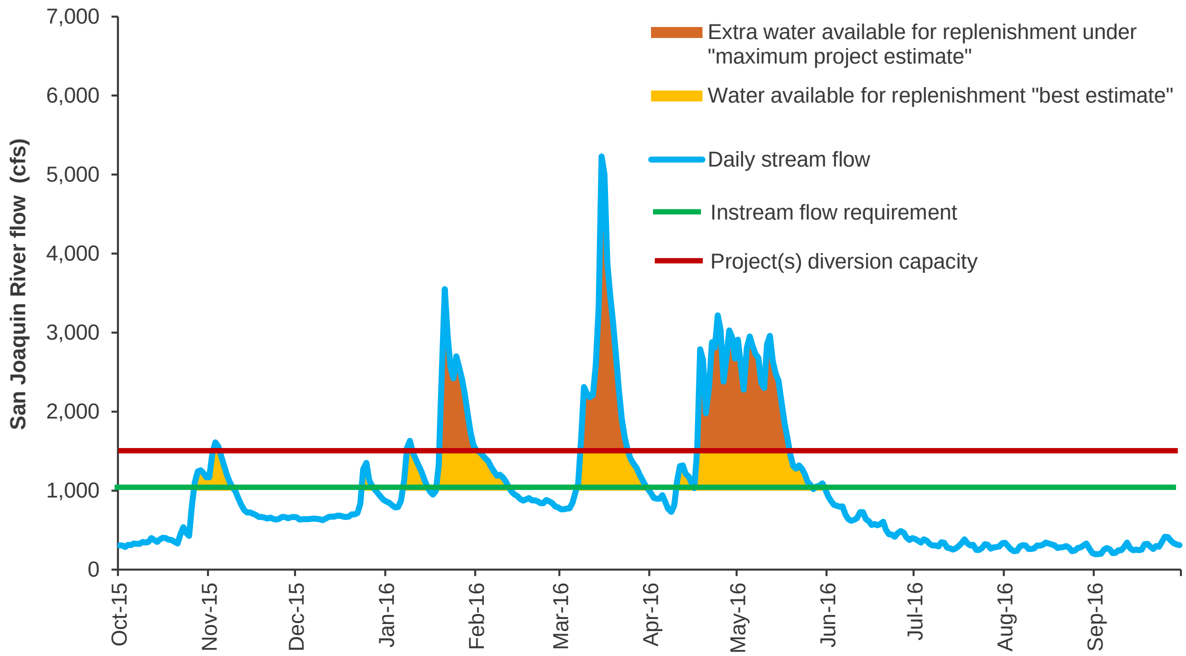
[17] The final report is expected to be released in 2018. Its appendices have already been updated and published, and we use the estimates in updated appendix A in our analysis (DWR 2018a).

[18] DWR's *Water Available for Replenishment Report Draft* does not explicitly identify instream flow requirements nor the existing project capacity data, so to replicate that study's approach we developed rough estimates below that result in comparable levels of water available for recharge.

[19] DWR refers to the estimates based on the historical gage data as the "gage data outflow" and the estimates using the WEAP adjustment as "water available for replenishment." WEAP results are only available at a monthly—not daily—timescale.

FIGURE A15
Conceptual depiction of DWR's water available for replenishment



For the San Joaquin River hydrological region, DWR's "best estimate" of water available for replenishment is 190 taf/year and the "maximum project estimate", which includes also the water captured under the best estimate assumptions, is 550 taf/year. These totals include water in the Tulare Lake region (47 taf/year in the "best estimate" and 213 taf/year in the "maximum project estimate") because excess surface water from the Tulare Lake region flows into the San Joaquin River.

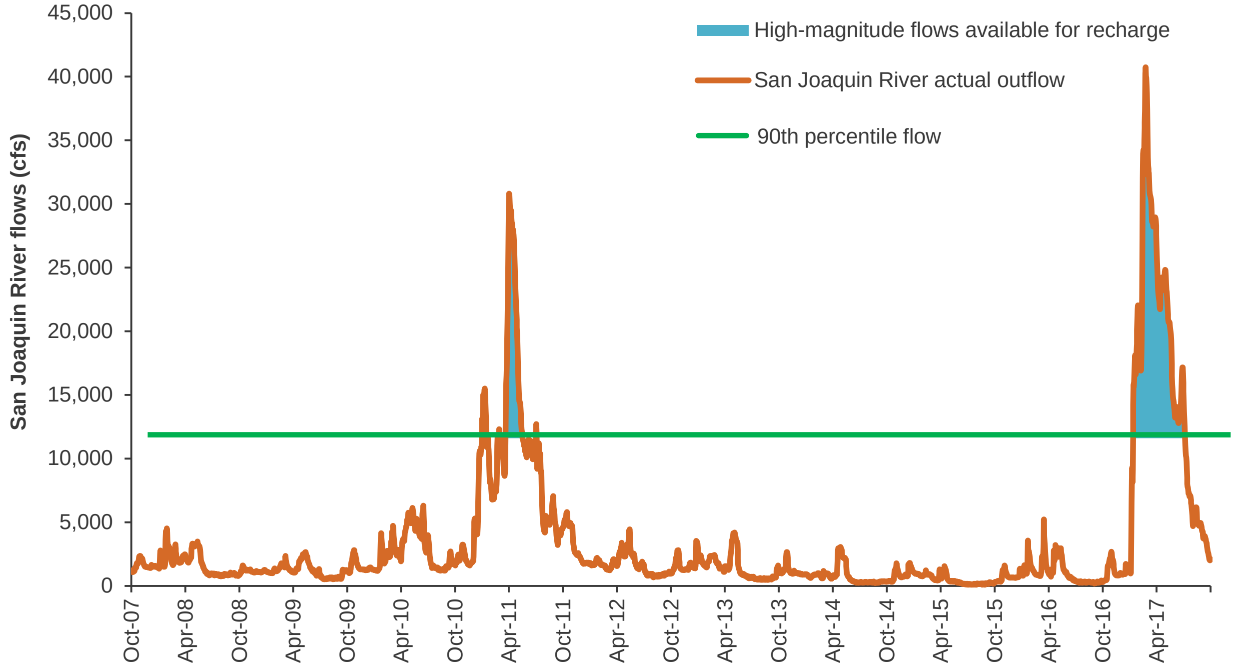
The Kocis and Dahlke Approach: High-Magnitude Streamflow

Also in 2017, Tiffany N. Kocis and Helen E. Dahlke, two scientists at UC Davis, published a paper estimating the availability of high-magnitude streamflow for recharge in the Central Valley (Kocis and Dahlke 2017). Their approach is different from DWR's. Using historic daily streamflow records available from USGS, they assume that the days on which outflows are within the highest 10 percent (or above the 90th percentile) over a 90-year period exceed both environmental flow requirements and current surface water allocations under California water rights, and could therefore be used to recharge aquifers.

Using USGS data for the San Joaquin River at Vernalis for the period October 1923 through September 2014, Kocis and Dahlke obtained a 90th percentile flow of 11,600 cfs. Figure A16 depicts the high-magnitude flows for the past 10 years using their approach, which assumes that the volume in excess of the 90th percentile could be taken on days with higher outflow.

FIGURE A16

Water available for recharge in the San Joaquin Valley in 2008-17 using the Kocis and Dahlke approach



For the period 1989-2014—a subset of years included in this analysis that better reflects current water demand and operations in the valley—Kocis and Dahlke estimate that an average of 1.3 maf would be available for recharge in years with high-magnitude flows. Because these flows only occur in 36 percent of all years (9 out of 25), this translates to a long-term average across all years of 455 taf/year.[20]

Water Available for Recharge in 2017

In the water balance analysis above, we estimate that there was 3.2 maf net groundwater recharge in the valley in water year 2017, roughly 5 maf more recharge than the 32-year average and 8 maf more than annual recharge during the 2012-16 drought. To estimate how much additional water was available for recharge in 2017, we try to reproduce both approaches using data for 2017.

DWR's approach

DWR's *Water Available for Replenishment Report Draft* does not explicitly report the underlying assumptions for instream flow requirements to meet environmental needs and downstream water rights, nor the assumptions on existing project capacity to divert additional flows for recharge. Also, the authors used a complex modeling approach at the planning area scale that would be difficult to replicate precisely.

In an effort to provide a rough replication of DWR's approach, we made some simplifying assumptions. We treated the entire San Joaquin Valley as a single basin, with a unique outlet: the San Joaquin River at Vernalis.[21] This facilitates a comparison with the results of Kocis and Dahlke, who also used the Vernalis gage to estimate high-magnitude flows.[22] We selected values for instream flow requirements and existing project capacity that

[20] The study refers to 1989-2014 as the "post-impairment" period. For the entire 1923-2014 period of analysis, they estimate an average of 1.46 maf is available in years with high magnitude flows, which occur in 47 percent of years, translating to a long-term average across all years of 686 taf/year.

[21] The gage near Vernalis is the point commonly used to measure flows leaving the San Joaquin River and Tulare Lake regions for the Delta. Vernalis flow does not include the northernmost San Joaquin hydrologic region tributaries: the Calaveras, the Mokelumne, and the Cosumnes Rivers. As a result, these outflow values differ somewhat from the totals shown in the valley-wide water balance, shown in Figure A8.

[22] Kocis and Dahlke (2017) also provide estimates for some gages upstream of Vernalis (for interactive maps and graphics, see recharge.ucdavis.edu/starr).

result in a similar long-term average level of water available for recharge for the region under DWR's best estimate and maximum project estimate scenarios. Because these assumptions may differ from what DWR used, we cannot ensure that the annual and seasonal hydrographs we obtain are the same as those obtained by DWR, even though our estimates of the long-term average annual volumes available for recharge are similar.

We define the minimum instream flow requirement based on Delta conditions, which is also the focus of DWR's approach for the San Joaquin hydrologic region (DWR 2018a).[23] First, we assume that water is available only when the Delta is in "excess conditions."[24] Then we define a minimum daily Delta outflow requirement—as a parameter to calibrate—to meet water quality standards and other environmental regulations in the Delta. The water above this threshold is the uncaptured water—flows that exceed the capacity of existing storage and diversion facilities and regulatory demands.[25] Because this water comes from both the Sacramento and the San Joaquin hydrologic regions, we distribute the total amount based on the share of total inflow from each river on a daily basis using Dayflow data.

With this approach, and without capping the amount that can be diverted, we are reproducing DWR's unadjusted "maximum project estimate." Calibrating the minimum Delta outflow parameter to 10,000 cfs, we determine that the water available for recharge over the long term (using data for 1986-2015) is 1.216 taf/year, just 0.3 percent lower than DWR's unadjusted "maximum project estimate."[26]

To reach DWR's unadjusted "best estimate" we had to cap the amount of water that can be diverted through the "existing project"—i.e., available conveyance infrastructure. Using a cap of 2,250 cfs we get a best estimate of 421 taf/year, just 2.1% lower than DWR's unadjusted best estimate. Figure A17 shows how this approach performs from 2000 to 2010. The adjusted best estimate and maximum project estimate—adjusting outflows based on the WEAP model simulations—are 190 and 550 taf/year respectively.

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[23] Water availability in the Central Valley depends on meeting environmental conditions downstream in the Sacramento-San Joaquin Delta. DWR's approach for the Sacramento River and San Joaquin River hydrologic regions takes this into account (DWR 2018).

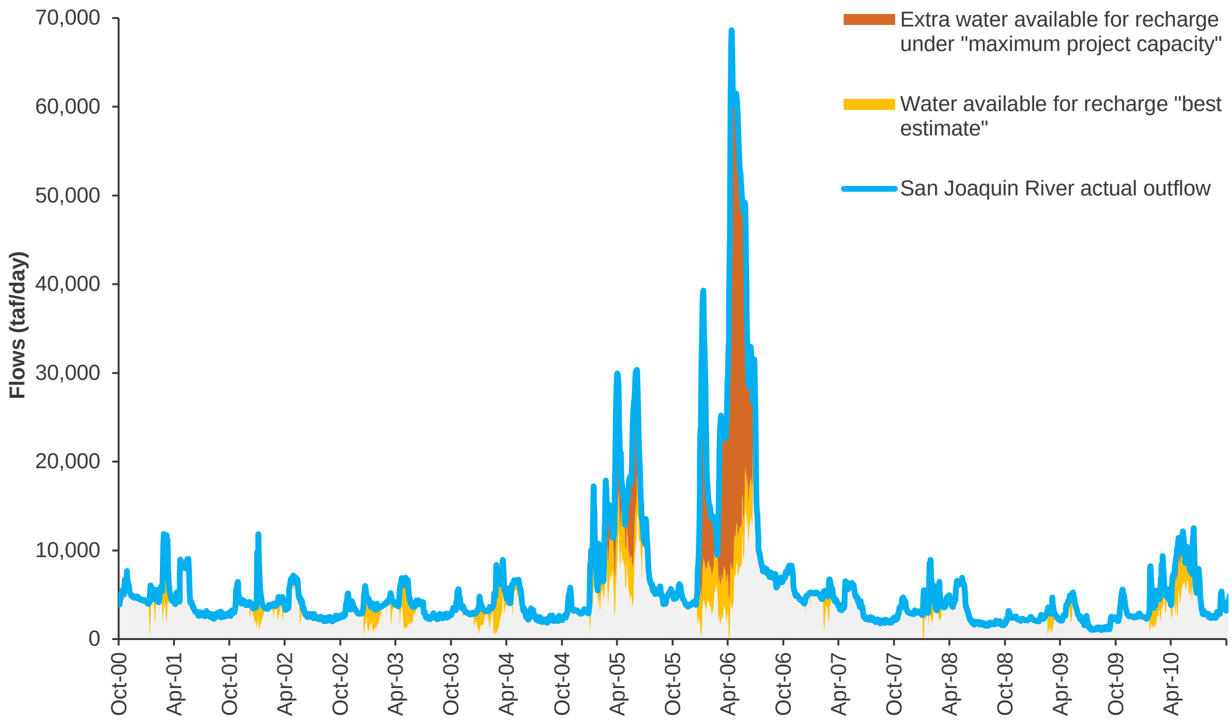
[24] Excess water conditions occur in periods when releases from upstream reservoirs plus unregulated flows exceed Sacramento Valley in-basin uses plus exports (USDOI 2004).

[25] See Gartrell et al. (2017) for a detailed explanation of uncaptured water. Note that this method of determining water available for recharge assumes that upstream environmental flow regulations do not require additional water to reach the Delta, beyond that needed to meet regulations in the Delta and downstream water demands.

[26] On average, this calibration results in just a slightly higher estimate of uncaptured outflow (+11%), with a similar temporal distribution, to estimates of uncaptured Delta outflow by Gartrell et al. (2017).

FIGURE A17

Water available for recharge for 2000-10 using DWR's unadjusted "best estimate" and "maximum project estimate" with our "instream flow requirement" and "existing project capacity" assumptions

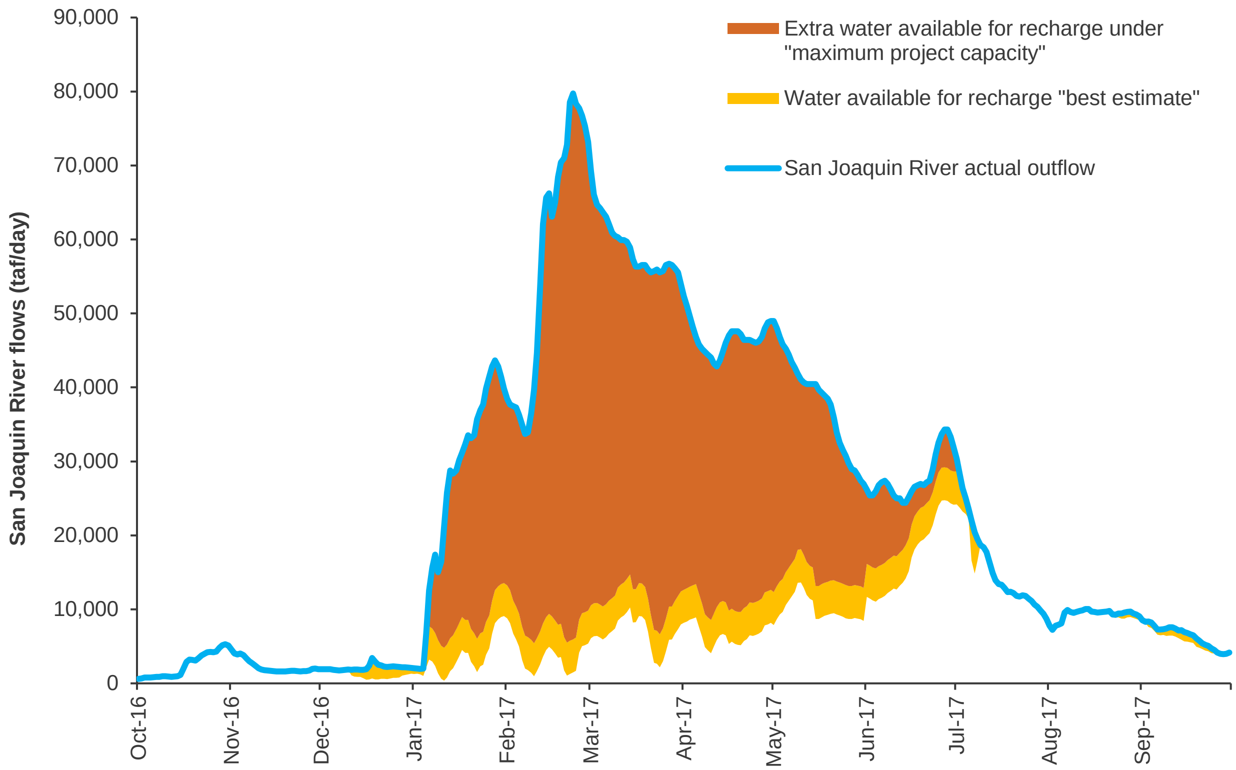


NOTES: Both "best estimate" and "maximum project estimate" are matched to DWR's unadjusted estimates ("gage data outflow") at Vernalis.

Using this same approach for water year 2017, we obtain an unadjusted best estimate of 882 taf and maximum project estimate of 6.3 maf (Figure A18). Using the same WEAP adjustment factor that DWR applied to the long-term averages, the adjusted values are 397 taf and 2.9 maf, respectively. However, the unadjusted values are likely more appropriate for recent years, since actual outflow data already reflect current water use and operations.

FIGURE A18

Water available for recharge for 2017 using DWR's unadjusted "best estimate" and "maximum project estimates" (with our own "instream flow requirement" and "existing project capacity" assumptions)



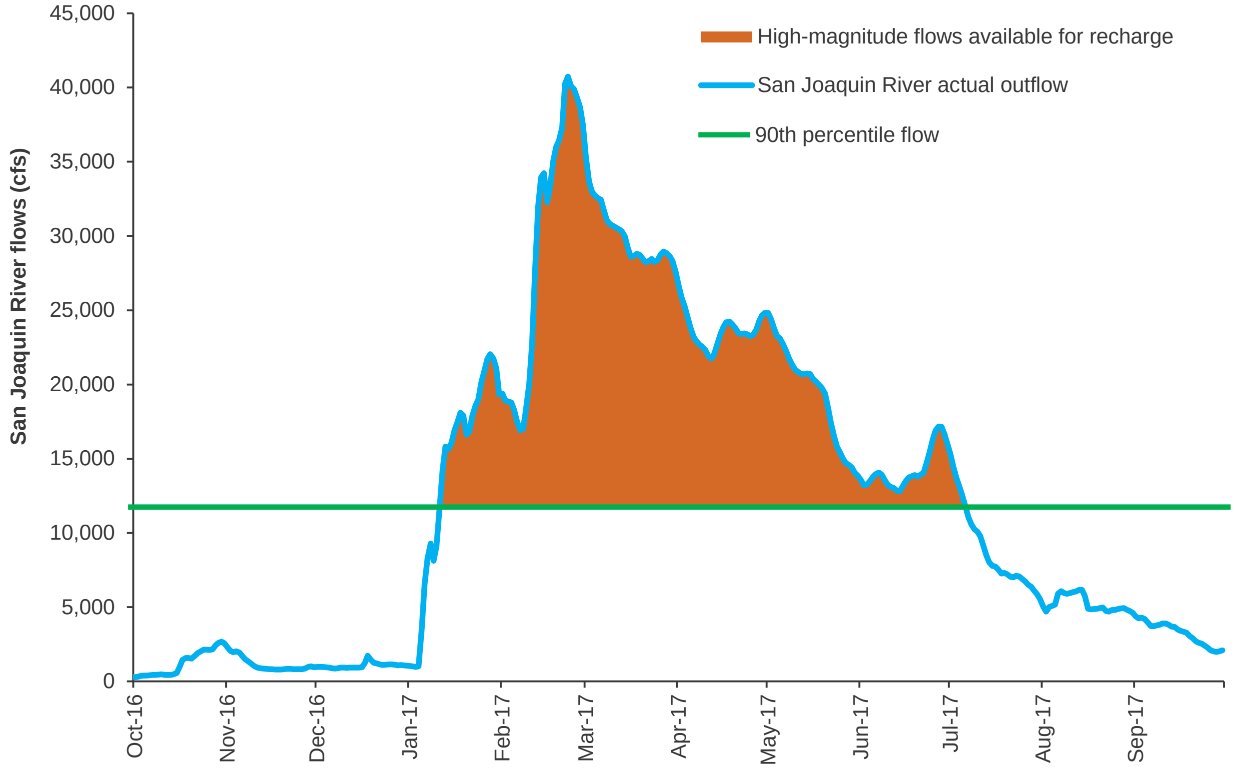
NOTES: Both "best estimate" and "maximum project estimate" are matched to DWR's unadjusted estimates ("gage data outflow") at Vernalis.

The Kocis and Dahlke approach

Once the 90th percentile daily flow is defined, determining high-magnitude flows available for recharge is straightforward. Every flow since January 11, 2017 to July 11, 2017 was above the 90th percentile, so all the water above this threshold (11,600 cfs) would be available: 3.7 maf for the entire water year (Figure A19).

FIGURE A19

Water available for recharge for 2017 using the Kocis and Dahlke approach



Discussion of the Estimates of Water Available for Recharge

Comparison of findings for 2017

The approaches used by DWR and Kocis and Dahlke result in a wide range of additional volumes of water that could have been captured in 2017, from a high of 6.3 maf (DWR's unadjusted "maximum project estimate" under our assumptions) to 3.7 maf (Kocis and Dahlke), to 0.88 maf (DWR's unadjusted "best estimate").[27] These levels are substantially higher than the long-term averages estimated by these two studies (1.2 and 0.55 maf for DWR's unadjusted and adjusted "maximum project estimate"; 0.46 maf for Kocis and Dahlke's post-1989 "impaired period," and 0.43 maf and 0.19 maf for DWR's unadjusted and adjusted "best estimate"), reflecting the fact that 2017 was an extraordinary year.

When comparing the different approaches and the actual monthly outflows in 2017 (Figure A20), it is noteworthy that DWR's maximum project estimate approach takes more flows almost every month than Kocis and Dahlke's approach. This is because in this extremely wet year, the Delta requirements were already satisfied with flows much lower than the 90th percentile used as a cut-off by Kocis and Dahlke.

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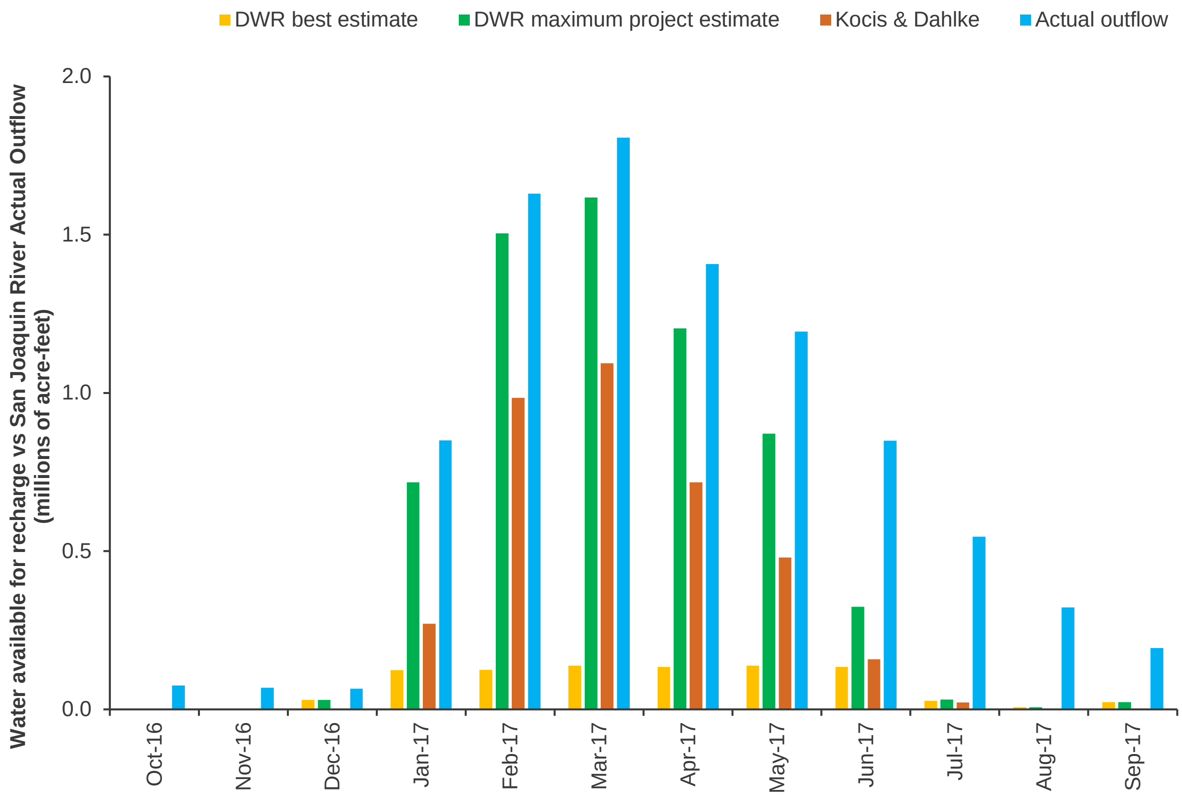
[27] As described further below, we do not include the DWR adjusted estimates here because the 2017 gage data already reflect current demands and operations.

FIGURE A20

Water available for recharge under the different approaches compared to San Joaquin River actual outflow in 2017



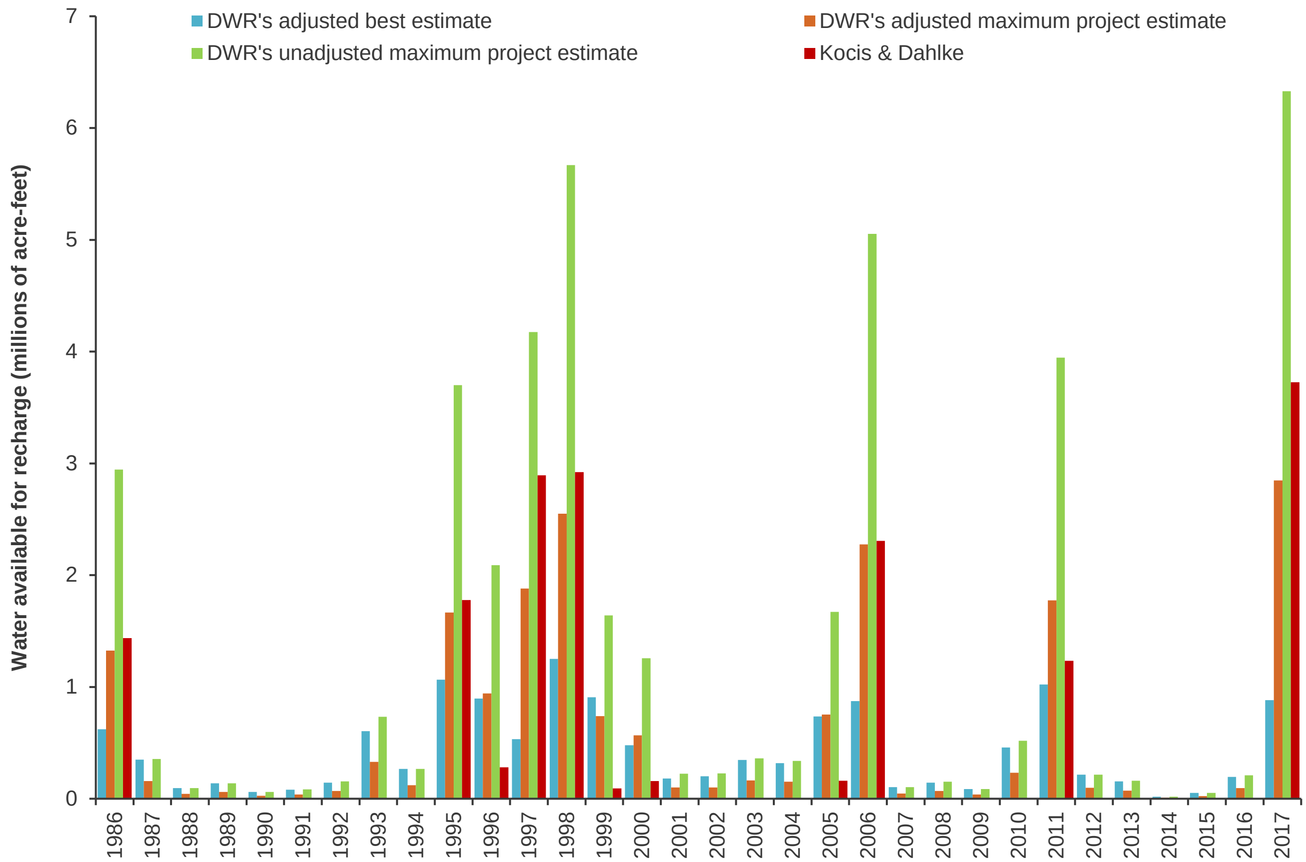
NOTE: Both the "best estimate" and "maximum project estimate" are matched to DWR's unadjusted estimates ("gage data outflow") at Vernalis.

Comparison across the past three decades

The comparison of total water available for recharge across the past three decades further highlights the differences between the approaches (Figure A21). Whereas DWR's approach identifies additional water for recharge in most years, Kocis and Dahlke's approach finds additional water mostly in wet years.[28] This again reflects the different thresholds above which streamflow is considered available. Whereas Kocis and Dahlke only consider flows above the 90th percentile, DWR's approach varies with Delta conditions.

[28] Under this approach, there can also be high magnitude flows during big storm events in other year types, but this results in a very small share of the total water available for recharge: 2 percent of all high magnitude flows at Vernalis for the 1989-2014 "unimpaired period", and 6 percent of all high magnitude flows for the 1971-2017 period.

FIGURE A21
Water available for recharge under the different approaches



Reasons for using DWR's unadjusted estimates for planning purposes

It is also worth noting that while the adjustment DWR makes to account for current demands and operations makes sense when using gage data over a very long timeframe, it might be unnecessary for recent years.[29] As the water balance data presented earlier in this appendix demonstrate (Figures A7 and A12), water use in the San Joaquin Valley has not changed much since the mid-1980s. Nor have there been any significant changes in water infrastructure over this period. For this reason, the unadjusted data may better capture the potential water available for recharge than the adjusted data that DWR presents as final estimates. One caveat is that the method used here to determine water available for recharge—focusing on conditions in the Delta—assumes that upstream environmental flow regulations do not require additional water to reach the Delta beyond that needed to meet regulations in the Delta and downstream water demands.

The method used here also shows how simple accounting rules can help determine when water is available for recharge. Further development of this approach—taking into account the uncaptured water in the Delta as defined in Gartrell et al. (2017) plus some definition of upstream environmental requirements in the San Joaquin River system—would make it possible to estimate water available for groundwater recharge in the San Joaquin Valley. To be useful as a management tool, the flows that need to stay in the river and the amount that can be taken out of the river for recharge purposes would need to be published in a timely manner (maybe weekly). Near-term

[29] Recall that DWR uses daily average Delta outflow from water year 1930 through 2015 to calculate its long-term averages.

forecasts of storm conditions and river flows could be linked to this information to help managers prepare for recharge opportunities, which often need to be acted on quickly. This would be a way to overcome regulatory hurdles that impede the expansion of recharge practices in the valley.

Capacity constraints on capturing additional flows

In 2017, most rivers in the San Joaquin Valley were above flood stage for months, and water managers faced significant capacity constraints in their water storage and conveyance infrastructure. Capturing significant additional flows in wet years like 2017 will likely require new infrastructure investments, in addition to new water rights permits to divert and store the water.

As an example, more than half of the 6.3 maf of water available for recharge in 2017 under DWR's unadjusted "maximum project estimate" would have needed to be taken in two months (February and March), with diversions totaling more than 30,000 af/day (Figure A18). On seven of these days, diversions would have had to exceed 70,000 af per day. The Kocis and Dahlke approach would also require capturing very high daily flows during the peak period: more than half the total would be extracted in 48 successive 30,000-plus acre-foot days between mid-February and the end of March, with a maximum daily withdrawal of 57,776 af/day on February 23, 2017 (Figure A19).

While such volumes are not excessive relative to the water moved during the valley's prime irrigation season, they are concentrated in specific locations where conveyance limits are likely to be a challenge. In this context, it is important to bear in mind that there is a geographic mismatch between the supply of water available for recharge and the demand for this water: most of the available flows are in the San Joaquin River hydrologic region, while most overdraft is in the Tulare Lake region (see Figure A14). [30]

How much additional infrastructure investment is warranted to capture available outflows will depend both on the costs of specific projects and the frequency with which the added capacity can be put to use. As a rough illustration of conveyance capacity requirements, Table A2 summarizes the share of total water available for recharge that could have been captured over the 1986-2017 period with different levels of available diversion capacity for DWR's unadjusted "maximum project estimate" and Kocis' and Dahlke's approach. With 5,000 cfs of capacity—equivalent to roughly 10,000 acre-feet/day—it would have been possible to capture just under half of the available flows under each approach. Doubling that capacity to 10,000 cfs would have made it possible to capture another quarter of available flows. As a frame of reference, design capacity on the Friant-Kern canal—the key infrastructure for moving San Joaquin River flows south—is 10.5 taf/day leaving Millerton Lake, dropping to about 8 taf/day in southern Tulare County (US Bureau of Reclamation 2017). Subsidence has reduced capacity in that southern reach by 60 percent, to just 3.5 taf/day (Fitchette 2018).[31] And as we show in the main report, much of the existing capacity is already put to use in wet years.

[30] To develop a rough estimate of daily surface water use valley-wide, we used data for 1998–2010 from the California Water Plan Update (DWR 2013). Total applied water use for agricultural and urban uses (including surface and groundwater) is about 18.8 maf/year: 16.5 maf for cropland irrigation, 1.3 maf/year for urban uses, and 1 maf/year for conveyance losses. Surface water ranges from 40 to 70 percent of this total between dry and wet years, or 8 to 13 maf/year and 25 to 40 taf/day. But since most agricultural water is delivered in the peak irrigation season (April to September), daily deliveries could reach over 60 taf/day—leaving significant spare capacity valley-wide in the winter and early spring months. A key challenge, however, is the much more limited capacity for moving water from the wetter San Joaquin River region to the Tulare Lake region, as discussed in the text and the next note.

[31] 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 16.5 taf/day to 13 taf/day near Avenal in Kings County (Department of Water Resources 2017). This limits high flow deliveries to Kern County and Southern California (Fitchette 2017).

TABLE A2

Conveyance needs to capture water available for recharge under different approaches

	DWR unadjusted "maximum project estimate" approach		Kocis and Dahlke approach	
Diversion capacity	Share captured (%)	Total captured (maf/year)	Share captured (%)	Total captured (maf/year)
2,500 cfs	37.0	0.45	30.5	0.13
5,000 cfs	49.8	0.67	45.5	0.24
10,000 cfs	71.9	0.97	72.7	0.38
20,000 cfs	92.5	1.24	96.4	0.51
30,000 cfs	99.1	1.33	99.8	0.53

NOTES: Cfs is cubic feet per second. One cfs running over an entire day is approximately 2 acre-feet per day. The table examines flows available for water years 1986–2017, which results in slightly different totals than the long-term averages reported in the text (1986-2015 for DWR's approach, and 1989-2014 for Kocis and Dahlke's approach). We do not report values for DWR's adjusted "maximum project estimate" since we do not have daily estimates for that approach.

The role of surface storage also needs to be part of the infrastructure capacity analysis, because the ability to hold water above ground can make it possible to smooth out the peaks of water available for recharge. In addition to considering new investments in storage—including reservoirs such as Temperance Flat and holding ponds in areas without good recharge capacity—it will be important to consider reoperation of surface reservoirs to fill aquifers. Moving more dry-year storage out of reservoirs and into aquifers during the fall months can increase space in reservoirs during the winter, and reduce the volumes that need to be released as flood flows during peak events. Such a strategy should add some capacity for recharging aquifers with existing conveyance and surface storage infrastructure.[32]

[32] DWR (2017c) has written a white paper and a factsheet on Flood-MAR (Managed Aquifer Recharge) that describes the need to increase this strategy.

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Appendix B: PPIC's Groundwater Recharge Survey

Introduction

The appendix describes the design and deployment of our September 2017 survey of San Joaquin Valley water managers, provides information on the sample characteristics of respondents relative to the overall sample of water districts contacted, and describes our valley-wide estimates of groundwater recharge in 2017. The full survey questionnaire is presented at the end of the appendix.

Survey Design and Deployment

Survey Design

The research team developed the survey questions with input from water managers, farmers, and other experts. This included individual conversations and several group discussions, held in Bakersfield, Madera, and via conference call with members of the Valley Agriculture Water Coalition, whose members include irrigation and water districts across the Valley.

The instrument was developed in Qualtrics, an online survey platform. It included 19 questions, both multiple choice and text entry. The survey took approximately 10 minutes to complete.

The survey was distributed through an email containing individualized links to general managers, engineers, or directors of urban water and agriculture water suppliers, on August 30, 2017. Respondents were required to provide the agency name at the beginning of the survey, but were reminded of the confidentiality of individual responses. Several follow up reminder emails were sent before the survey was officially closed on October 3, 2017.

The survey asked respondents if they wanted to participate in a focus group to discuss initial survey findings. Those who expressed interest were invited to a meeting on the Fresno State campus on October 30, 2017, which was attended by about two dozen water managers.

Sample Design

The overall sample was 202 districts, including 151 agricultural water suppliers and 51 urban water suppliers.

For urban suppliers, we included all water suppliers meeting the state's size threshold for urban water supplier (those required to prepare Urban Water Management Plans, and who were subject to the State Water Board's water conservation mandate during the recent drought).[33] This group generally includes suppliers serving at least 3,000 connections.

Given agriculture's importance in water use in the valley, we cast a wide net to catch as many entities that manage surface and groundwater for agriculture as possible. This required consulting multiple data sources, because no agency maintains a comprehensive list of all entities providing water for agriculture.

We drew on State Controller's Office data for a list of special districts that raise revenues by selling water. To find districts that only have access to groundwater, we reviewed special district municipal service reviews and Integrated Regional Water Management (IRWM) plans. We developed a list of private agricultural water suppliers by compiling information about local rivers and their water rights-holders.[34] We also relied on

[33] For more details on this list, see Mitchell et al. (2017), Building Drought Resilience in California's Cities and Suburbs. Public Policy Institute of California.

[34] Local managers helped us to eliminate some ditch companies from the sample that only providing ditch tending services, not irrigation water supply.

membership lists of the valley's large "umbrella" organizations, like Friant Water Authority, Kaweah and St. Johns Rivers Association, Downstream Kaweah and Tule Rivers Association, Kern County Water Agency, Kings River Water Association, San Joaquin River Exchange Contractors, and San Luis Delta Mendota Water Authority. For additional cross-checking, we consulted Groundwater Sustainability Agency formation notices, State Water Project and Central Valley Project contractor lists, and US Bureau of Reclamation NEPA documentation. To our knowledge, the list that was created is the most comprehensive list of agricultural water providers in the San Joaquin Valley.

Representativeness of Survey Responses

We received a total of 81 survey responses, out of a sample of 202 agencies, a 40 percent overall response rate. We review sample representativeness through the lens of five different categories 1) supplier type classification (agricultural vs. urban), (2) service area size, (3) surface water availability, (4) existence of recharge basins, and (5) subregion.

Response rates were somewhat higher from agricultural than urban suppliers, larger than smaller urban suppliers, suppliers with larger land areas and more access to surface water, and suppliers with 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.

Supplier Type Classification

Response rates were somewhat higher from agricultural than urban suppliers (42% versus 33%). Urban and agricultural entities have quite different patterns of recharge activity, so we sometimes present results separately for these two groups.

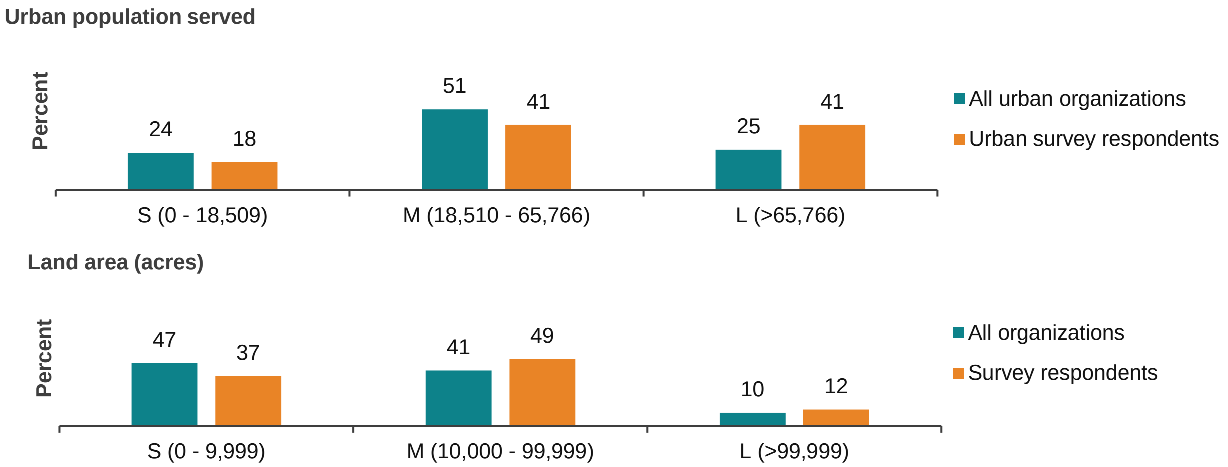
Size

One way of gauging sample representativeness was by service area acreage—a metric we developed for both urban and agricultural suppliers using information from GIS files and district planning documents.[35] For urban entities, we also looked at population served. We find that larger suppliers of both types are overrepresented in the sample (Figure B1). In the analysis, we do not break the data down along these lines, instead focusing on surface water deliveries, a measure of size that is more directly relevant for recharge activities.

[35] Urban district information was collected for use in the study by Mitchell et al. (2017) (see note 1).

FIGURE B1

Comparison of overall sample and survey respondents by size (land area and population)

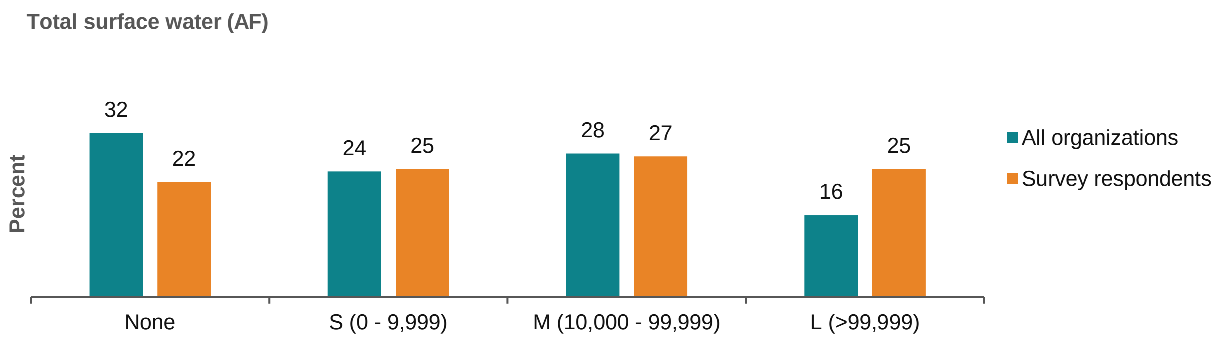


Surface Water Availability

We anticipated that the availability of surface water would be an important factor in the ability to recharge. To provide a general means of comparison among districts, we sought information on average water deliveries during the 2005-08 period, a span including a mix of wet, dry, and normal years. We obtained the information from Central Valley Project, State Water Project, and local water agency and river association records. In a few cases we had to use data from earlier years or make judgment calls about how local river water is apportioned among users within associations. Response rates were higher for districts with greater access to surface water (Figure B2). Our analysis often distinguishes among districts by volume of surface water, which is related to recharge activity.

FIGURE B2

Comparison of overall sample and survey respondents by surface water deliveries

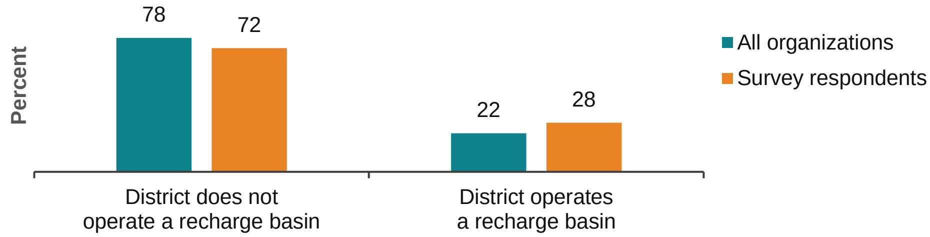


Existence of Recharge Basins

The existence of a formal recharge program also plays a role in determining how entities responded to the very wet conditions in 2017. As an indicator of a formal recharge program, we collected publicly available information on which districts operate recharge basins. Although districts can operate recharge programs using other methods, the presence of basins signals dedicated investment in recharge activities. We find that survey response rates were somewhat higher for districts that operate recharge basins (Figure B3).

FIGURE B3

Comparison of overall sample and survey respondents by existence of recharge basins

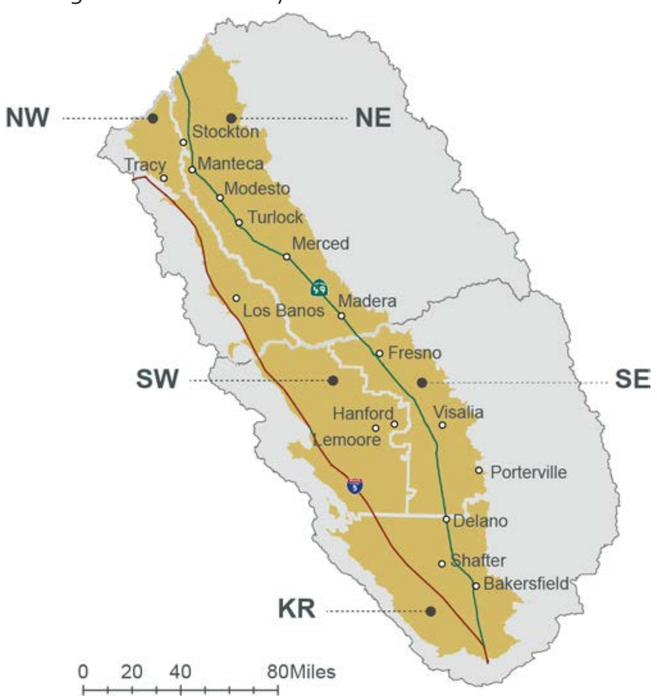


Subregion

Another useful distinction is geography, because both the extent of overdraft and the suitability of lands for recharge vary considerably across the valley. 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 B3).[36]

FIGURE B4

Subregions used for analysis

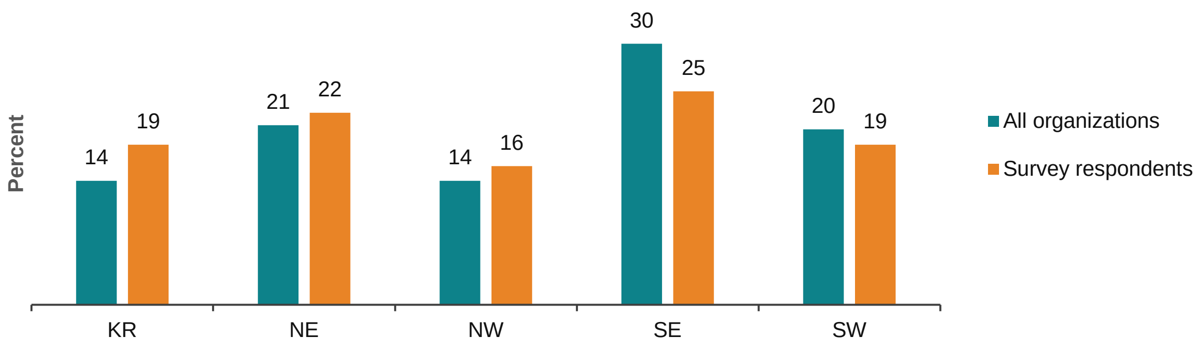


Survey respondents are well-represented across all five subregions, but with districts in the Kern basin slightly over-represented, and districts in the southeast slightly underrepresented (Figure B4).

[36] Technical Appendix A describes how we formed these sub-regions from analysis regions for hydrologic models (Figure A13 and related discussion).

FIGURE B5

Comparison of overall sample and survey respondents by subregion



Estimates of Valley-wide Recharge Volumes in 2017

To get a sense of how much water was recharged in calendar year 2017, we asked water managers to provide us with estimates of the total volume their district recharged and the methods used. We received valid responses from 66 districts (including 46 that recharged water and 20 that did not). 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. To provide a rough estimate of the total volumes of active on-site recharge in the valley (6.5maf) and the proportion of this recharge stored for off-site parties (0.9 maf), we applied the results of a regression analysis for districts that supplied volume data to estimate volumes for the 136 districts that either did not report recharge volumes, or did not respond to our survey. This section provides details on data and methods used in the analysis.

Data, Variables, and Methods

Our analysis was based on the districts that provided volumes of recharge in their survey response, or indicated that they did not actively recharge in 2017. Using that sample, we ran multivariate regressions with two dependent variables: (1) the natural log (ln) of total recharge volume, and (2) the natural log of on-site recharge volume. Off-site banking is calculated as the difference between these two values. Both models controlled for subregion, average surface water deliveries (in natural logs), whether the district is agricultural or urban, and whether the district has recharge basins—all variables we could obtain for the entire sample, and which are associated with differences in recharge activity (Table B1). We set zero levels of recharge and surface water availability to 1 acre-foot for compatibility with the natural log format of these variables. Table B2 reports descriptive statistics for all variables used in the analysis.

TABLE B1

Independent variables used in regression analysis

Variable	Description
Average surface water supply	Natural log of average annual surface water supply available to district from all sources
District has recharge basin(s)	Binary variable that equals 1 if the district owns and operates recharge basin
Type of water supplier	Binary variable indicating if district is an urban supplier (1) or agricultural supplier (0)
Subregion	Binary variables for four of the five subregions: Southeast, Southwest, Northeast, Northwest (with Kern as the omitted category)

TABLE B2

Regression sample descriptive statistics

	Observations	Mean	Standard deviation	Min	Max
Recharge volume (acre-feet)	66	69,509	129,848	1	570,000
Ln of recharge volume	66	7.0	4.9	0	13.3
On-site recharge volume (acre-feet)	66	61,679	129,897	1	570,000
Ln of on-site recharge volume	66	6.2	5.0	0	13.3
Average surface water supply (acre-feet)	66	72,379	139,944	1	920,332
Ln of average surface water supply	66	8.2	4.4	0	13.7
District has recharge basin(s)	66	0.3	0.5	0	1
Urban water supplier	66	0.2	0.4	0	1
Kern basin (omitted subregion)	66	0.21	0.41	0	1
Southeast	66	0.21	0.41	0	1
Southwest	66	0.21	0.41	0	1
Northeast	66	0.20	0.40	0	1
Northwest	66	0.17	0.37	0	1

Results

Table B3 presents the results of the regression analysis. Higher volumes of recharge are associated with having a recharge basin, being an agricultural supplier, having more access to surface water supply, and being located in regions with good recharge suitability. The equations have a good fit for cross-sectional regressions (adjusted R^2 of 0.57 for total recharge and 0.51 for on-site recharge).

TABLE B3

Regression analysis estimating the total volume of recharge, and the volume of on-site recharge

	Regression estimating total volume of recharge	Regression estimating on-site recharge
Ln of average surface water supply	0.344**	0.102
	(0.119)	(0.131)
District has recharge basin(s)	3.015**	6.102**
	(1.137)	(1.250)
Urban water supplier	-4.871**	-3.59*
	(1.263)	(1.387)
Southeast	-1.539	1.209
	(1.250)	(1.374)
Southwest	-1.749	1.407
	(1.362)	(1.497)
Northeast	-0.597	2.176
	(1.365)	(1.500)
Northwest	-7.166**	-2.407
	(1.499)	(1.6469)
Constant	5.978**	3.500*
	(1.459)	(1.602)
Observations	66	66
Adjusted R-squared	0.57	0.51

NOTES: The table reports regression coefficients for each variable, with standard errors in parentheses. Statistical significance at the 99 and 95 percent levels are represented by ** and *, respectively. The total volume of recharge by district includes off-site recharge by other districts within the valley.

We applied coefficients from Table B3 to the 136 districts that did not respond to our survey, or did not provide volumes of recharge. Table B4 provides descriptive statistics for that sample. Aggregating the reported recharge and the estimates for non-respondents, our calculations provide rough estimates of total valley-wide on-site recharge (6.5 maf) and the proportion of this recharge that is banked for off-site parties within the valley (0.9 maf) in 2017.

TABLE B4

Extrapolation sample descriptive statistics

	Observations	Mean	Standard deviation	Min	Max
Average surface water supply	136	37,451	87,892	1	580,958
Ln of average surface water supply	136	6	5	0	13
District has recharge basin(s)	136	0.2	0.4	0	1
Urban water supplier	136	0.3	0.5	0	1
Region	136	1.9	1.2	0	4
Kern basin (omitted subregion)	136	0.11	0.31	0	1
Southeast	136	0.35	0.48	0	1
Southwest	136	0.20	0.40	0	1
Northeast	136	0.21	0.41	0	1
Northwest	136	0.13	0.34	0	1

Survey Questionnaire

SAN JOAQUIN VALLEY GROUNDWATER RECHARGE SURVEY

Thank you for agreeing to participate in this survey, which aims to obtain first-hand input from San Joaquin Valley water managers regarding groundwater recharge challenges, practices, and opportunities. The results will inform a public document that identifies policies, regulations, and funding tools to support groundwater recharge activities in the region. We have developed the questions in consultation with water managers from across the Valley.

The survey is designed to take about 10 minutes to complete, and it covers the following topics:

1. Current and potential groundwater recharge methods in your service area,
2. Groundwater recharge activities this year,
3. Barriers to groundwater recharge (e.g., infrastructure, regulatory, financial issues), and
4. Priorities for expanding your system's potential to engage in groundwater recharge.

At the end of the survey, we also ask you to indicate if you would be interested in participating in a focus group discussions of preliminary results, to inform conclusions and recommendations in our report. **We will maintain confidentiality of individual responses, and present results such that no organization-specific identifiers will be publicly available.**

If you choose to complete the survey on this form instead of completing the online version, please:

- Send a scanned copy to jezdimirovic@ppic.org **OR**
- Mail a paper copy to Jelena Jezdimirovic, PPIC; 500 Washington St., Suite 600; San Francisco CA 94111

Before we start, we'd like to confirm your organization's name:

CURRENT AND POTENTIAL GROUNDWATER RECHARGE METHODS

[Q1] What methods of active groundwater recharge does your organization currently practice—or envisage using or expanding in the future? (Please check all that apply.)

	Currently used	**Potential to expand**
Dedicated recharge basins	☐	☐
Injection wells / ASR (aquifer storage and recovery)	☐	☐
Recharging via unlined canals	☐	☐
In-lieu recharge (i.e., using surface water instead of groundwater in wetter years)	☐	☐
Recharge on cropland (e.g., extra irrigation, winter flooding)	☐	☐
Recharge on fallowed farmland	☐	☐
Recharge on open space lands	☐	☐
Banking groundwater for my customers off-site in other districts	☐	☐
Banking groundwater within my district on behalf of off-site parties	☐	☐
Other (specify): ______________________________	☐	☐
Other (specify): ______________________________	☐	☐
None	☐	☐

[Q1.1] Please feel free to list other recharge methods we've overlooked, and/or elaborate on any of the answers above.

ACTIVE GROUNDWATER RECHARGE THIS YEAR

[Q2] Has your organization actively recharged groundwater this calendar year (2017)?

- ○ Yes
- ○ No

[Q3] Please provide the estimated volume of water recharged to date and additional recharge expected this calendar year (by the end of 2017):

Recharged to date: ____ *(acre-feet)*

Additional recharge expected: _____________________________________ (*acre-feet)*

[Q4] Please provide the approximate percentage of total recharge by type:

Dedicated recharge basins	%
Injection wells / ASR (aquifer storage and recovery)	%
Recharging via unlined canals	%
In-lieu recharge (i.e., using surface water instead of groundwater in wetter years)	%
Recharge on cropland (e.g., extra irrigation, winter flooding)	%
Recharge on fallowed farmland	%
Recharge on open space lands	%
Banking groundwater for my customers off-site in other districts	%
Other (specify): ________________________________	%
Other (specify): ________________________________	%
Total	100%

[Q5] How does the total expected volume of recharge this year compare with the amount you were able to recharge in 2011, which was also a wet year?

- ○ Much more this year
- ○ About the same
- ○ Much less this year
- ○ Unsure
- ○ Not applicable: We did not recharge at all in 2011

[Q5.1] Please feel free to comment on how your recharge activity this year compares with 2011.

[Q6] What were the sources of water for recharge this year?

	Please check all that apply
CVP water (including Section 215 and Recovered Water Account)	☐
SWP water (including Article 21 water)	☐
Water from local rivers or streams (including flood flows)	☐
Urban stormwater runoff	☐
Recycled wastewater	☐
Water purchased from another party	☐
Other (specify): ____________	☐
Other (specify): ____________	☐

[Q6.1] Please feel free to elaborate on any of the answers above regarding water sources.

[Q7] Which of the following statements is most accurate for your system this year:

- ◯ We could have recharged more water with our existing recharge capacity
- ◯ We will have used all of our existing recharge capacity.
- ◯ Unsure.

BARRIERS TO GROUNDWATER RECHARGE THIS YEAR

[Q8] Did you encounter any barriers to recharging groundwater this year?

	Please check all that apply
Capacity constraints in system-wide conveyance (e.g., CVP or SWP canals)	☐
Capacity constraints in district-level recharge basins	☐
Other district-level capacity issues (e.g., conveyance to recharge locations)	☐
Irrigation constraints (e.g., inability to spread water on fields that use drip irrigation)	☐
Timing of water availability (e.g., too much water available at some times)	☐
Regulatory issues related to project construction (e.g., obtaining permits)	☐
Water rights or contracts for recharge water (e.g., SWRCB, CVP, SWP approvals)	☐
Permitting and approvals to convey recharge water	☐
Issues related to groundwater quality (e.g., waste discharge permits)	☐
Proposition 218-related difficulties raising funds to support recharge investments	☐
Price of recharge water too high	☐
District-level concerns about water migrating to neighboring areas	☐
Farmer concerns about benefiting adequately from on-farm recharge on their lands	☐
Farmer concerns about on-farm recharge because of crop health or yields	☐
None - we did not encounter any barriers	☐

[Q8.1] Please feel free to list other barriers to recharge we've overlooked, and/or elaborate on any of the answers above.

PRIORITIES FOR EXPANDING GROUNDWATER RECHARGE

[Q9] In your opinion, what are the top two to three priorities that need to be addressed to expand the potential of your organization to engage in groundwater recharge activities in the future? (You can refer to barriers listed above or other issues.)

1.____

2.____

3.____

CONTACT INFORMATION

Thank you very much for your participation.

So that we can contact you for follow-up questions or clarifications, please provide your name and contact information. **This information is optional and will remain confidential.**

Name:

Position:

Phone:

Email:

Would you be interested in participating in a focus group discussion of preliminary survey results with other water managers?

- Yes
- No

We welcome your comments on these topics, as well as comments regarding the questionnaire itself or clarifications of your responses. You may include any written comments in the space below.

Thank you for taking the time to fill out this survey. We greatly appreciate your input, and will send you a copy of the final report when it is released.

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