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25 YEARS

Water and the Future of the San Joaquin Valley

Technical Appendix A: Updated Assessment of the San Joaquin Valley's Water Balance

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ACRONYMS

af	acre-foot (feet)
BAR	Bear Reservoir
BUC	Eastman Lake
C2VSim	California Central Valley Groundwater Surface Water Simulation Model
CDEC	California Data Exchange Center
CMN	Camanche Reservoir
CVHM	Central Valley Hydrologic Model
CVP	Central Valley Project
CWP	California Water Plan
DNP	Don Pedro Reservoir
DWR	California Department of Water Resources
EBMUD	East Bay Municipal Utility District
EXC	Lake McClure
GIS	geographic information system
HR	hydrologic region
ISB	Lake Isabella
KDWCD	Kaweah Delta Water Conservation District
maf	millions of acre-feet
MAR	Mariposa Reservoir
MIL	Millerton Lake
NASA JPL	National Aeronautics and Space Administration, Jet Propulsion Laboratory
NHG	New Hogan Lake
NML	New Melones Reservoir
NOAA	National Oceanic and Atmospheric Administration
PNF	Pine Flat Dam
SCC	Success Dam
SFPUC	San Francisco Public Utilities Commission
SJV	San Joaquin Valley
SWP	State Water Project
taf	thousands of acre-feet
TRM	Kaweah Lake
USBR	United States Bureau of Reclamation

Introduction

This appendix provides information on data sources and methods used to assess the annual water balances in the San Joaquin Valley for water years 1988–2017.[1] It also details the assumptions of groundwater overdraft, estimated at the subregional scale. The annual regional water balance data are included in *PPIC San Joaquin Valley Water Balance 1988–2017*.

The water balance presented here is a high-level overview of major water sources and uses. For the San Joaquin Valley, a particular interest is understanding the extent of long-term groundwater overdraft, or long-term depletions of water stored in aquifers. This practice will need to end as water users implement the state's 2014 Sustainable Groundwater Management Act. Ending overdraft can be achieved by augmenting other usable sources and reducing net water uses.

Estimating regional water balances is challenging in California. Official estimates of flows and uses often are not available over a time period that is both sufficiently long and up-to-date for long-term planning purposes. In addition, many of the flows needed are not available in a comprehensive and consistent manner. In particular, groundwater withdrawals and use are not tracked in a comprehensive way within the valley, and there are no systematic, long-term estimates of net water use. For these reasons, water balance estimation requires numerous intermediate calculations and assumptions.

This water balance updates previous versions found in Technical Appendix A of the 2017 PPIC report *Water Stress and a Changing San Joaquin Valley* and Technical Appendix A of the 2018 PPIC report *Replenishing Groundwater in the San Joaquin Valley*. The update addresses three issues. First, the previous version did not properly estimate wet years and the recharge associated with them. Second, we excluded lands in the vicinity of the Sacramento–San Joaquin Delta that generally rely on direct diversions from the Delta, where assumptions about water diversions and use added unnecessary uncertainties to the overall estimates. Third, we updated the balance to account only for those years where data is consistent.

In the following sections, we first define the region's boundaries and then describe the updates made in this version. We then present estimates of inflows, outflows, and changes in water stored. Then we summarize the overall water balance for the valley and compare our results with other estimates for overlapping years. Finally, we describe the assumptions about how the valley's long-term groundwater overdraft is broken down at the subregional scale.

Despite the inherent uncertainties, we believe our estimates provide a good big picture representation of the valley's water balance and the sub-regional overdraft for the past three decades.

Definition of the Region's Boundaries

The San Joaquin Valley includes two hydrologic regions (HRs): the San Joaquin River Basin and the Tulare Lake Basin. Together, these two regions have a clear physical limit as an external boundary—the Sierra Nevada in the east, the Tehachapi Mountains in the south, the Coastal Range in the west, and the Delta in the North—with considerable internal hydrological connectivity. Flows from the San Joaquin River are conveyed to the Tulare Lake region through the Central Valley Project's (CVP) Friant–Kern Canal. Flows from the Kings River in the Tulare Basin run to the San Joaquin River during flood periods. Both hydrologic regions receive water imported

[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 it ends and which includes 9 of the 12 months.

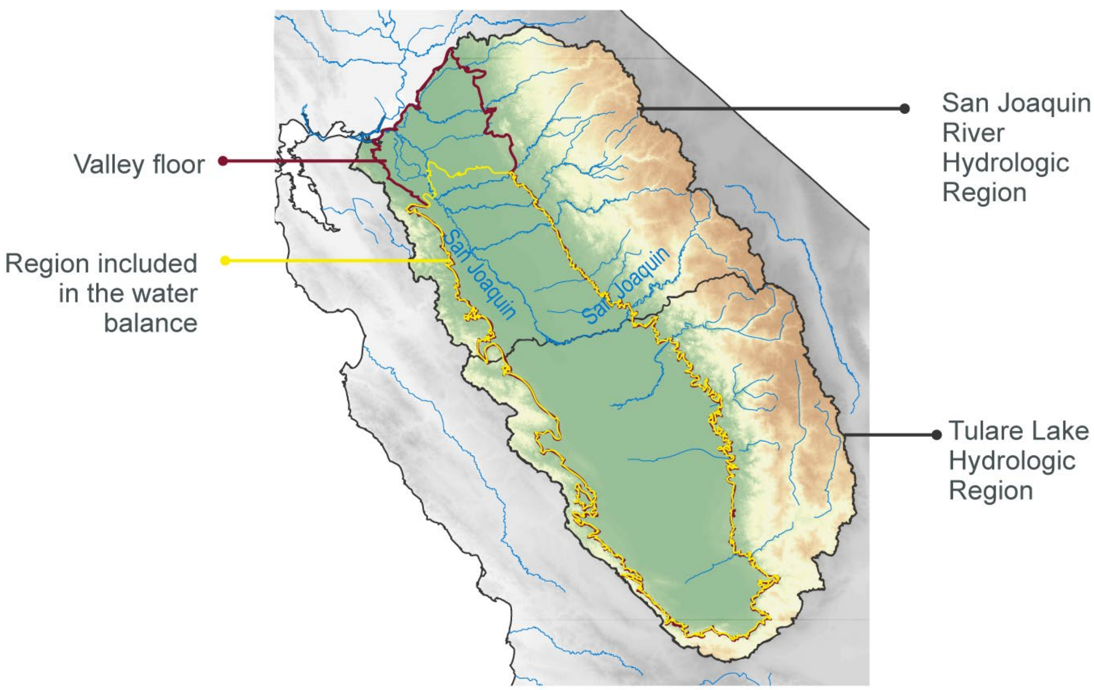
from Northern California through the Delta, and there is also significant joint water management and water trading across the combined region using local, state, and federal infrastructure.

We calculate the water balance for the two regions combined—the commonly accepted definition of the greater San Joaquin Valley. We exclude the lands in the vicinity of the Delta, where estimates of water diversions and use are less reliable.[2]

To assess the water balance, we focus on the valley floor. Most water available in the San Joaquin Valley is either native to the Central and Southern Sierra Nevada or imported from the Sacramento hydrologic region through the Delta. The valley floor is where most net or consumptive uses occur—especially from irrigated agriculture, but also from urban and environmental evapotranspiration and natural landscapes. The objective is to assess the annual net balance of inflows, outflows, and changes in water stored in surface reservoirs and aquifers.

We define the valley floor as the intersection of the Department of Water Resources (DWR) Planning Areas 602, 603, 606, 607, 608, 609, 702, 703, 704, 705, 706, 708, 709, and 710. For the water balance we exclude Delta regions 602 and 603 (Figure A1).

FIGURE A1
San Joaquin River and Tulare Lake watersheds



SOURCE: Developed by the authors using information from the Department of Water Resources.
NOTE: The water balance excludes DWR planning regions in the Delta (602 and 603).

[2] These areas rely heavily on direct diversions from the Delta. Although overdraft is a cause for concern (especially in the Eastern San Joaquin groundwater basin), we exclude them from our valley-wide water balance. Estimates of overdraft in these regions are less reliable due to uncertainties in water diversions and use, and the complexities of accounting for surface-groundwater interactions with Delta water. While the effects of excess pumping are significant locally—for example, declining groundwater levels in the Eastern San Joaquin Basin has caused saltwater intrusion from the Delta, which degrades water quality—the size of overdraft in these regions does not significantly affect the valley-wide numbers.

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, 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. It also illustrates 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 demands.

As noted above, this balance has been updated to address the following three issues:

- **Improving recharge and overdraft estimates:** Previous versions of this water balance showed very few years with net recharge in the valley—even in some very wet years. This was a result of the way we treated precipitation and evapotranspiration. We assumed—as is common in hydrologic studies in arid regions—that most precipitation (in this case, a constant rate of 85%) returns quickly to the atmosphere as evaporation from soils and other surfaces, and is not available for other uses. While on average it is valid to assume large evaporative losses, we realized that this method did not adequately account for the variability between dry and wet years in the valley. Therefore, this version of the water balance includes the full amount of precipitation. We used a more comprehensive measure of evapotranspiration, which does a better job of capturing evaporation from soils and other surfaces as well as transpiration from natural vegetation.
- **Redefining the region's boundaries to avoid unnecessary uncertainties:** Previous versions of this balance included lands in the vicinity of the Delta. These regions directly divert Delta water from many locations. There are no reliable measures of the amount diverted, so we had to estimate based on evapotranspiration. Although some of these lands experience excess pumping (especially in the Eastern San Joaquin groundwater basin), the amount of overdraft in these regions does not significantly affect the valley-wide numbers (see footnote 2).

  We now confine our analysis to the San Joaquin Valley floor region upstream (or south of) of Vernalis, where inflow and outflow data is more precise. Figure A1 shows the San Joaquin Valley, including the San Joaquin River Basin and the Tulare Lake Basin hydrologic regions, and the updated boundary of the valley floor analyzed in this study.
- **Using consistent data for surface storage:** In previous versions of this balance, we started our analysis in 1986. But the reliability of data for the 1986 and 1987 water years was lower because there were more gaps in the series. To reduce the uncertainties associated with these years, we now assess the balance for the period 1988-2017, for which data is more consistent.

Inflows

Three 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 precipitation on the valley floor, and water imported from other regions—especially through the Sacramento–San Joaquin Delta.

These inflows can either be 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.[3]

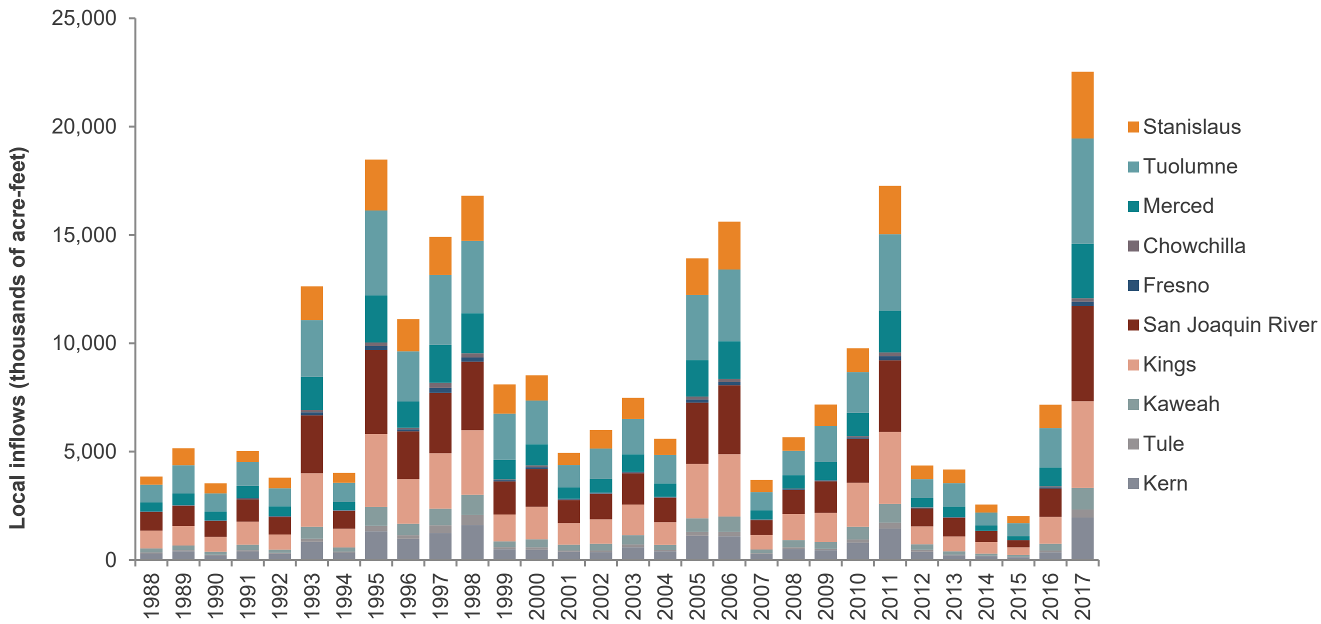
Inflows from local watersheds

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.[4]

For the years 1988–2015 in the San Joaquin River hydrologic region we obtained unimpaired monthly flow estimates from DWR (2016). For the full period of study in the Tulare Lake hydrologic region and for 2016 and 2017 in the San Joaquin River hydrologic region we used estimates for full natural flows from the California Data Exchange Center (CDEC). Note that we are not including any of the rivers and streams that do not flow into Vernalis (i.e., north of the Stanislaus River).

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).

Figure A2 shows total annual inflow volumes from each watershed, with 2017 the highest in the period analyzed.[5] Although there are inflows from 10 local watersheds, five rivers account for nearly 85 percent of the average total: Tuolumne (22%), San Joaquin (20%), Kings (19%), Stanislaus (13%), and Merced (11%).

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[3] In practice, some of this water is also stored in soils. However, the year-to-year changes in the volume stored in soils are small relative to changes in water in aquifers. So our approach assumes that all changes in water stored in the ground occur in aquifers.

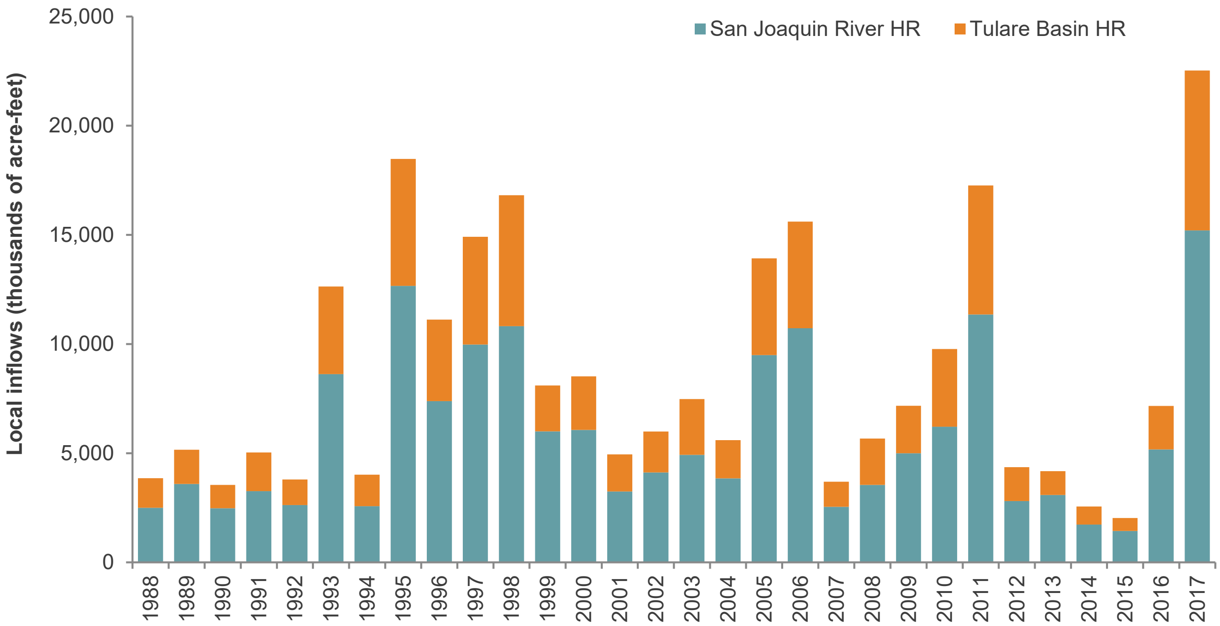
[4] Unimpaired flow is a watershed's natural runoff in the absence of storage regulation and stream diversions. Full natural flow is a watershed's natural runoff that would have occurred prior to human influences, such as storage, diversions, or land use changes.

[5] 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).

The inflows from local watersheds represent most of the flows that could be captured in surface reservoirs or used for recharging aquifers. Inflows not captured or used within the valley flow out to the Delta. Figure A3 demonstrates that roughly two-thirds of these flows come from the San Joaquin River hydrological region (68% of total inflows), whereas just one-third (32%) come from the Tulare Basin.

FIGURE A3

Inflows into the valley from local rivers by hydrologic region

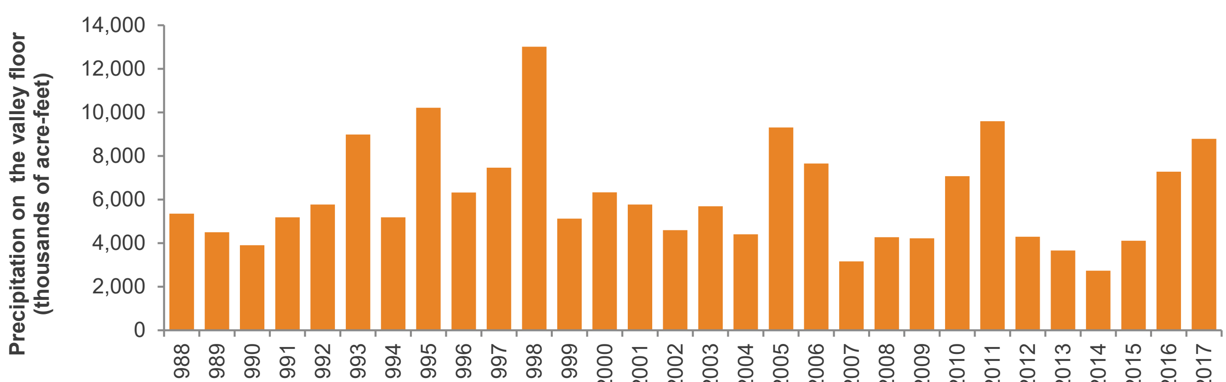


Precipitation on the valley floor

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, and is shown in Figure A4.

FIGURE A4

Precipitation on the valley floor

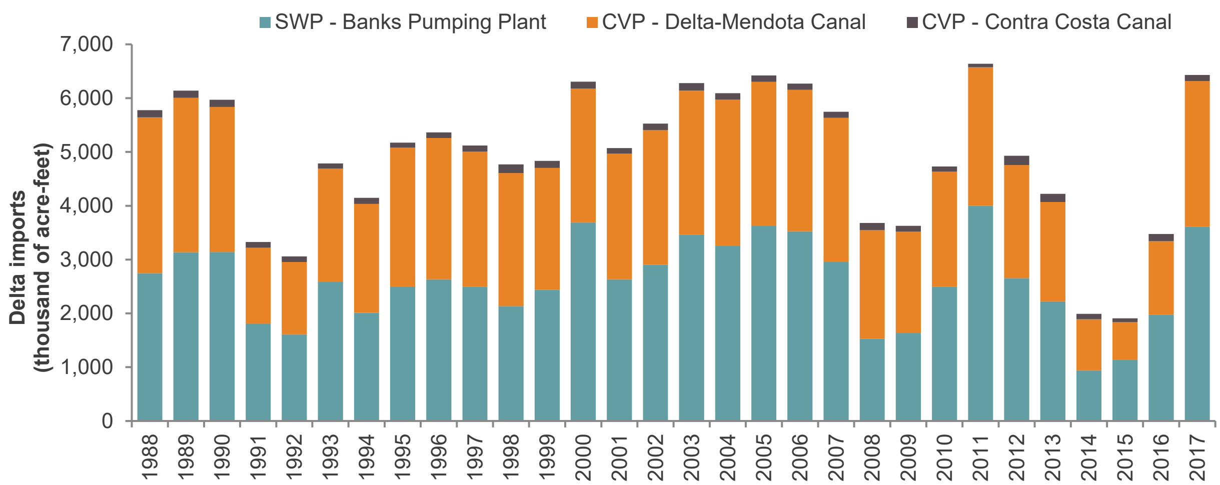


Imports from other regions

Water is imported into the valley from Northern California through pumps in the south Delta.[6] 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 2016a)—for the period 1986-2015. The water years 2016 and 2017 were provided by DWR.[7] Figure A5 shows the imports from the different facilities.

FIGURE A5

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.[8]

Evapotranspiration (consumptive water use)

Evapotranspiration on the valley floor has been obtained from the beta version of the C2VSim model (DWR 2018c) for the period 1988–2015 and estimated afterwards (Figure A6).[9] The model includes evapotranspiration from agricultural lands, urban landscapes, and vegetation in natural landscapes (referred to in C2VSim as "native and riparian vegetation").

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[6] The previous version of this water balance also considered a small volume imported from the American River through the Folsom South Canal. In this version we do not account for this amount given because it is used in the eastern Delta region.

[7] 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.

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

[9] We estimated the evapotranspiration for the years 2016 and 2017 using the most similar years (in terms of precipitation and temperature) of the 1988–2015 series. For 2016 we used the average of 1996, 2000, and 2003, whereas for 2017 we used 1996, 1998, and 2011.

As Figure A7 shows, agriculture represents most of the total consumptive use in the valley (87%) urban landscapes 3 percent, and native and riparian vegetation roughly 10 percent. Although agricultural evapotranspiration remains fairly stable at around 14 million acre-feet (maf) per year, evapotranspiration from native and riparian vegetation varies with precipitation. The minimum amount of evapotranspiration from native and riparian vegetation was 763 thousand acre-feet (taf) in 2015, and the maximum amount was slightly over 3 maf in 1998 (Figure A6).

FIGURE A6

Annual evapotranspiration by end use

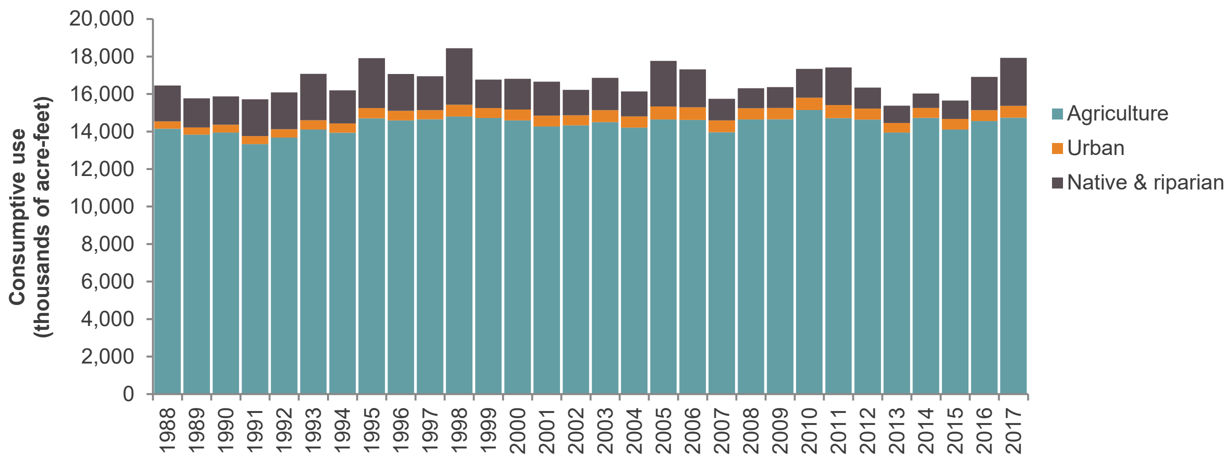
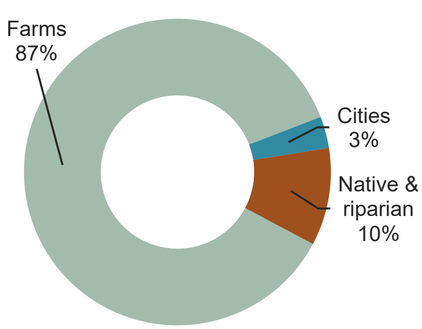


FIGURE A7

Average evapotranspiration by end use, 1988–2017



NOTE: Total evapotranspiration averages 16.65 maf over the 1988–2017 period, with evapotranspiration from farms averaging 14.4 maf, 0.6 maf from cities, and 2.2 maf from native and riparian landscapes.

San Joaquin Valley outflows

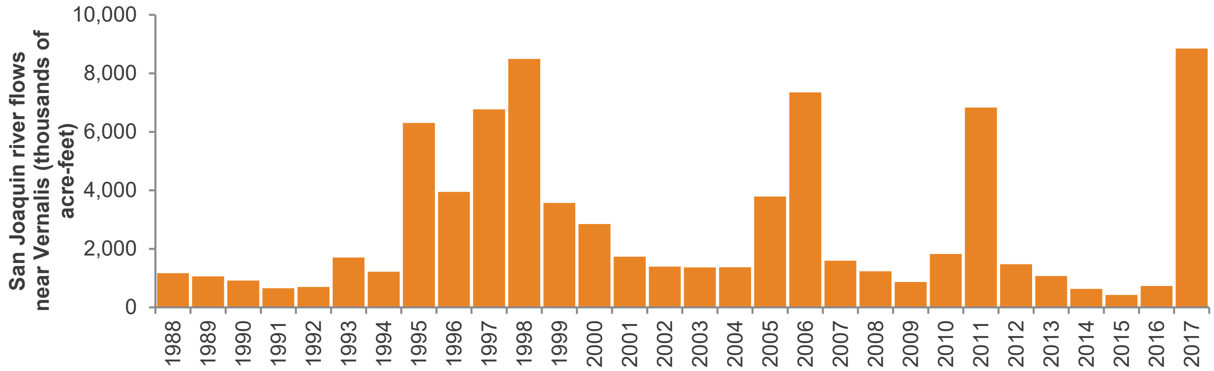
San Joaquin River flows at Vernalis (Figure A8) provide a measure of most outflows from the valley's local rivers. These flows were obtained from Dayflow and CDEC.[10] The volumes of these outflows are highly variable. Minimum outflows are required by environmental and water quality regulations within the river system and in the Delta. But in wet years, outflows can be much higher than these regulatory requirements, reflecting limitations in

[10] A previous version of this water balance also included eastern Delta inflow (including the Cosumnes and Mokelumne Rivers and other minor creeks).

storage capacity within the region. In 2017, the outflows in Vernalis were 8.9 maf, the highest level in the past 32 years.

FIGURE A8

San Joaquin River outflows near Vernalis

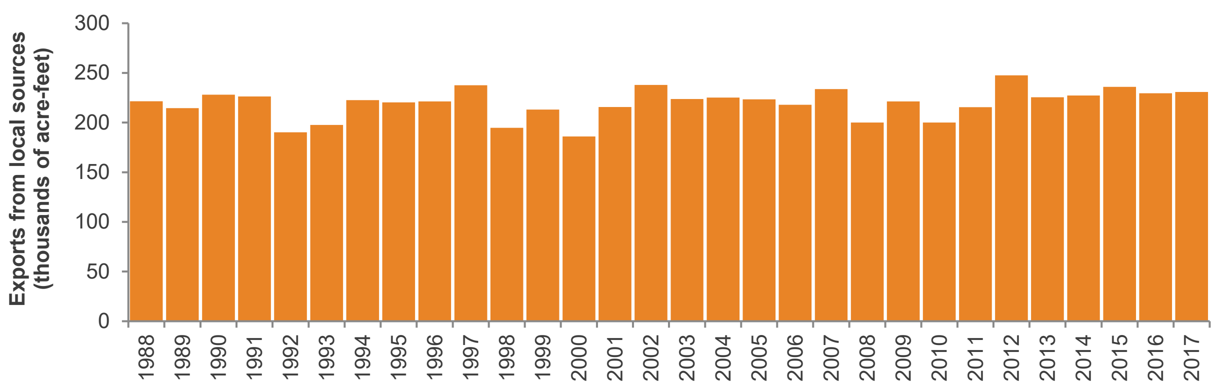


Exports from San Joaquin River tributaries

The San Joaquin Valley also exports more than 200 thousand acre-feet of water annually from the Tuolumne River to the San Francisco Bay Area (Figure A9). The amount of exported 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.[11]

FIGURE A9

Water exports from the Tuolumne River (a San Joaquin River tributary)



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

[11] In this version of the water balance, we do not account for water exported from the Mokelumne River, which is stored in Pardee and Camanche Reservoirs and conveyed to the East Bay Municipal Utility District (EBMUD) service area. The Mokelumne River is downstream of Vernalis.

shares of the diverted data with respect to the unimpaired flows for the 1998–2010 dataset. Average annual exports for 1988–2017 are 0.22 maf/year.

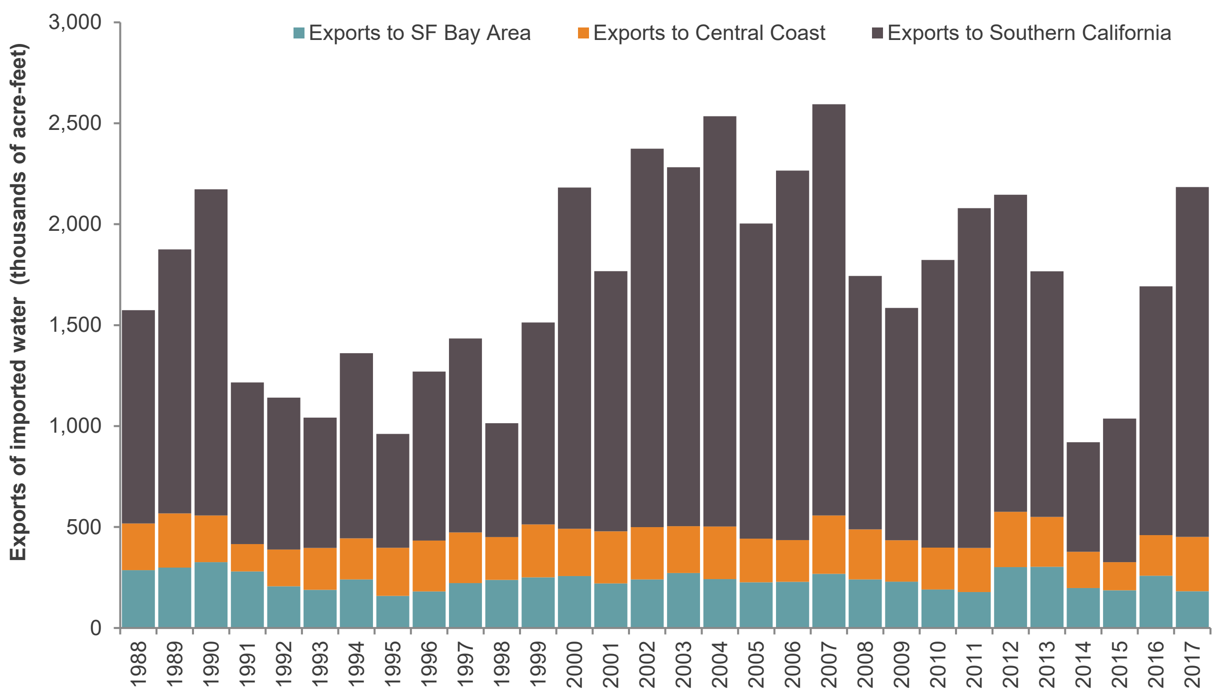
Exports of Delta imports

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 Area:** 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).[12]
- **Exports to the Central Coast:** This includes water from two points of diversion: through Las Perillas Pumping Plant on the California Aqueduct (from the State Water Project Annual Reports of Operations: Table 1); and through the Pacheco Tunnel.[13]
- **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



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[12] Earlier versions of this balance also included water exported from the Mokelumne River to EBMUD's Bay Area service area. As we are no longer including rivers flowing north of Vernalis, we also excluded exports from these rivers.

[13] 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

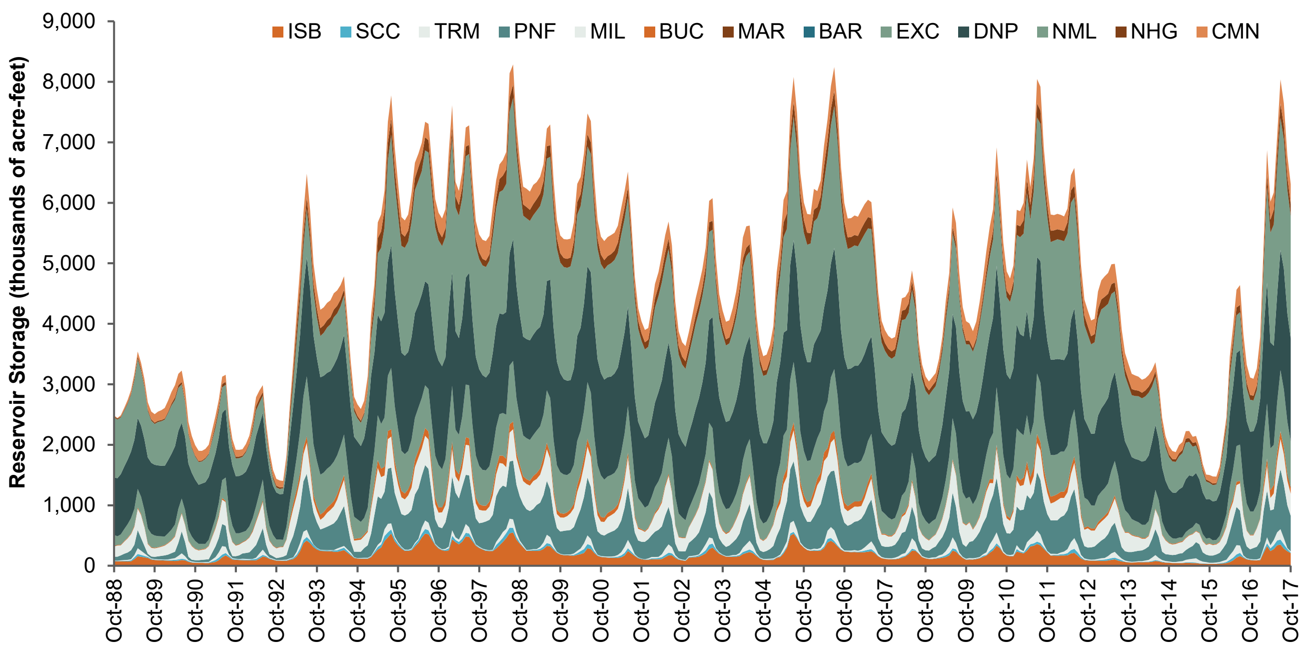
Two main storage types are considered: surface reservoirs and water stored in aquifers. Data exist for water stored in surface reservoirs. Changes in aquifer storage are estimated as the volume required to close the water balance for the valley.

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 the new water year (October 1).

FIGURE A11

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

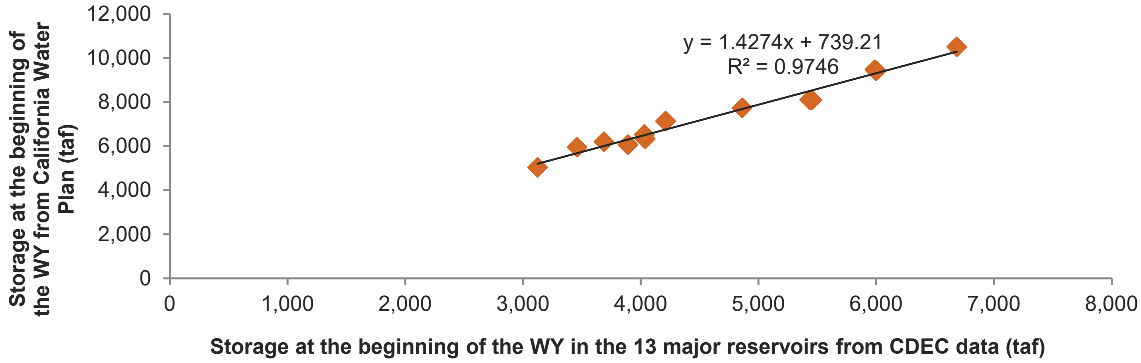


NOTES: The 13 major reservoirs are: New Melones (NML), Don Pedro (DNP), Lake McClure (EXC), Pine Flat (PNF), Lake Isabella (ISB), Success Dam (SCC), Kaweah Lake (TRM), Millerton Lake (MIL), Eastman Lake (BUC), Mariposa Reservoir (MAR), Bear Reservoir (BAR), New Hogan Lake (NHG), and Camanche Reservoir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

To include water stored in other smaller 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 storage changes and those in the 13 major reservoirs (Figure A12). Finally, to confine the analysis to the updated boundaries, which exclude rivers that do not flow into Vernalis, we adjusted the total storage by a factor of 92 percent, representing the amount of storage in the water-balance region with respect to total storage in the San Joaquin Valley.[14]

[14] This factor was calculated as the monthly average of the total water stored in the 11 major reservoirs in the updated region's boundaries (we excluded New Hogan Lake and Camanche which don't flow into Vernalis), over the total water stored in all 13 major reservoirs.

FIGURE A12
Linear relationship between total water stored at the beginning of the water year in the San Joaquin Valley and the valley's 13 major reservoirs



Total net changes in annual surface storage are shown in Figure A13B. 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 net volume of water used within the valley (consumptive use) or exported. The mass balance equation can be formulated as:

$$\Delta\, AquiferStorage =$$

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

Changes in annual aquifer storage are shown below in Figure A13C. As discussed below, these estimates are in the neighborhood of estimates of groundwater depletion found by others. Long-term overdraft of San Joaquin Valley aquifers is roughly 1.85 maf per 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 A13). Although consumptive water use remains fairly stable (averaging more than 16.5 million acre feet over 1988–2017), net volumes of local supplies (from local rivers and precipitation) and Delta imports vary significantly across years.[15] The difference between annual water supply and consumptive use—shown in Figure A13A—is reflected in changes in surface and groundwater storage (Figures A13B and C). In wet years, when annual supplies exceed consumptive use, there is net replenishment of storage. 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. Figure A13 shows 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 1988–2017 period because all the water that enters a

[15] 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. This includes some intentional groundwater recharge efforts, which also use dedicated recharge basins (Hanak et al. 2018).

reservoir has to be discharged eventually. However, on average roughly 1.8 million acre-feet per year was withdrawn from aquifers over this period.

Surface storage capacity is much less than underground storage capacity.[16] Figure A13B 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 (Figure A13C). This pattern has worsened lately, which included two extended droughts (2007–09 and 2012–16). As a result, the valley's overall water balance deteriorated considerably in the second half of this 30-year period. For the first 15 years, overdraft averaged 1.3 maf/year, and for the second 15 years, it averaged 2.4 maf/year (Table A1). For the dry decade from 2007–16, overdraft was even higher, averaging 4.1 maf/year. As described below, the increase in overdraft also reflects changing regulations on Delta imports, as well as a decline in the share of total Delta imports that now remain in the valley.

Figure A14 shows a schematic representation of the average balance for the period 1988–2017.

TABLE A1

The San Joaquin Valley's water balance (1988–2017), millions of acre-feet

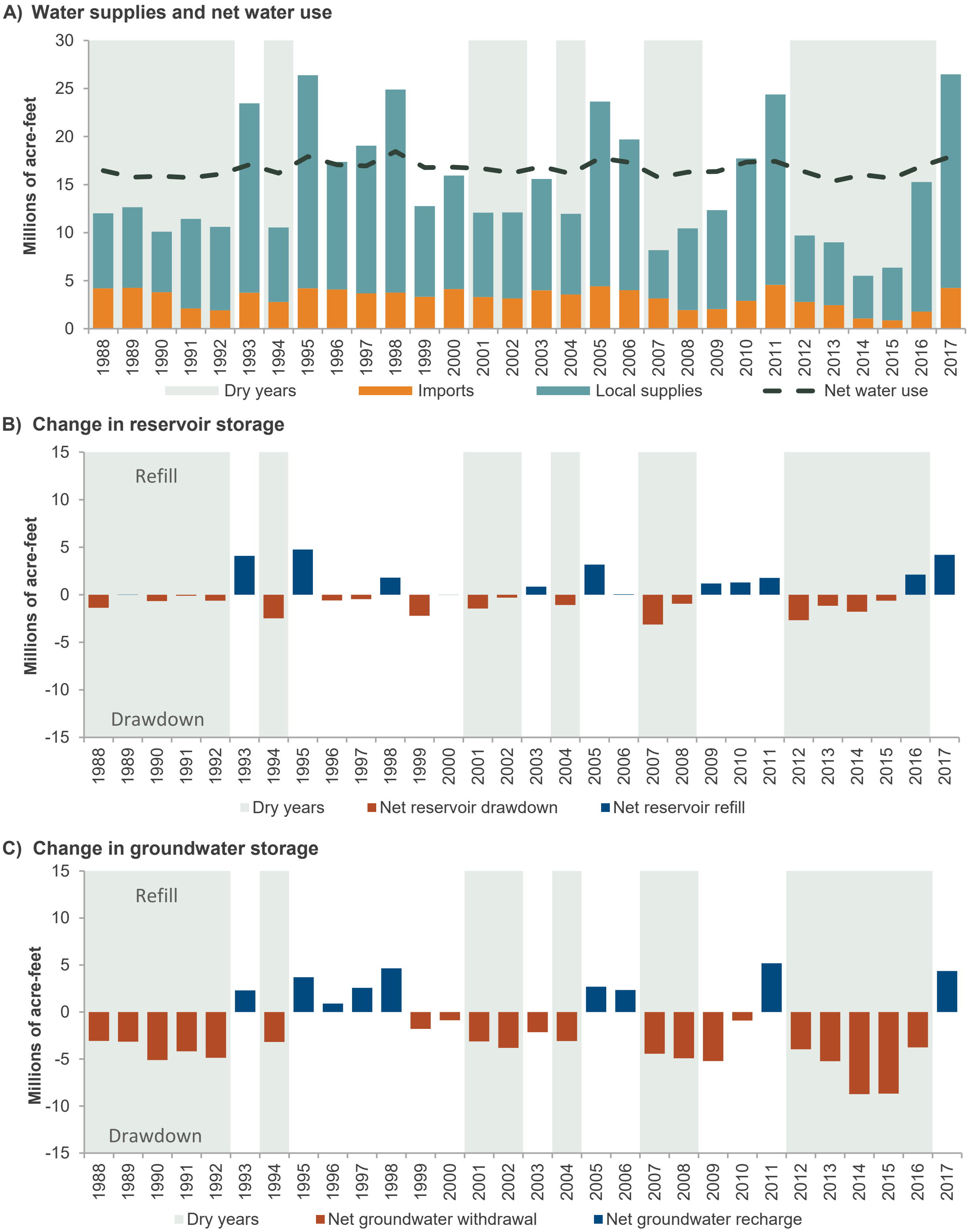
Uses and sources	1988–2002 Average	2003–2017 Average	1988–2017 Average
Net uses	(16,668)	(16,633)	(16,650)
Agriculture	(14,243)	(14,520)	(14,381)
Cities	(497)	(613)	(555)
Native and riparian lands	(1,928)	(1,499)	(1,714)
Net water sources	16,668	16,633	16,650
Local supplies remaining in the valley	11,902	11,283	11,592
Local inflows from the Sierra	8,461	8,600	8,531
Precipitation in the valley floor	6,514	5,750	6,132
San Joaquin River outflow	(2,832)	(2,627)	(2,730)
SJV exports to Bay Area	(215)	(224)	(219)
Local supplies captured in reservoirs	(27)	(217)	(122)
Delta imports remaining in the SJ Valley	3,498	2,919	3,209
Delta imports (total)	5,024	4,830	4,927
Delta imports to Bay Area	(240)	(234)	(237)
Delta imports to Central Coast	(228)	(226)	(227)
Delta imports to Southern California	(1,058)	(1,450)	(1,254)
Groundwater overdraft	1,269	2,431	1,850

NOTE: Outflows from the region are shown in parentheses.

[16] California has approximately 850 maf to 1.3 billion acre-feet of groundwater in storage (DWR 1994), and about 43 maf of surface storage (PPIC 2017).

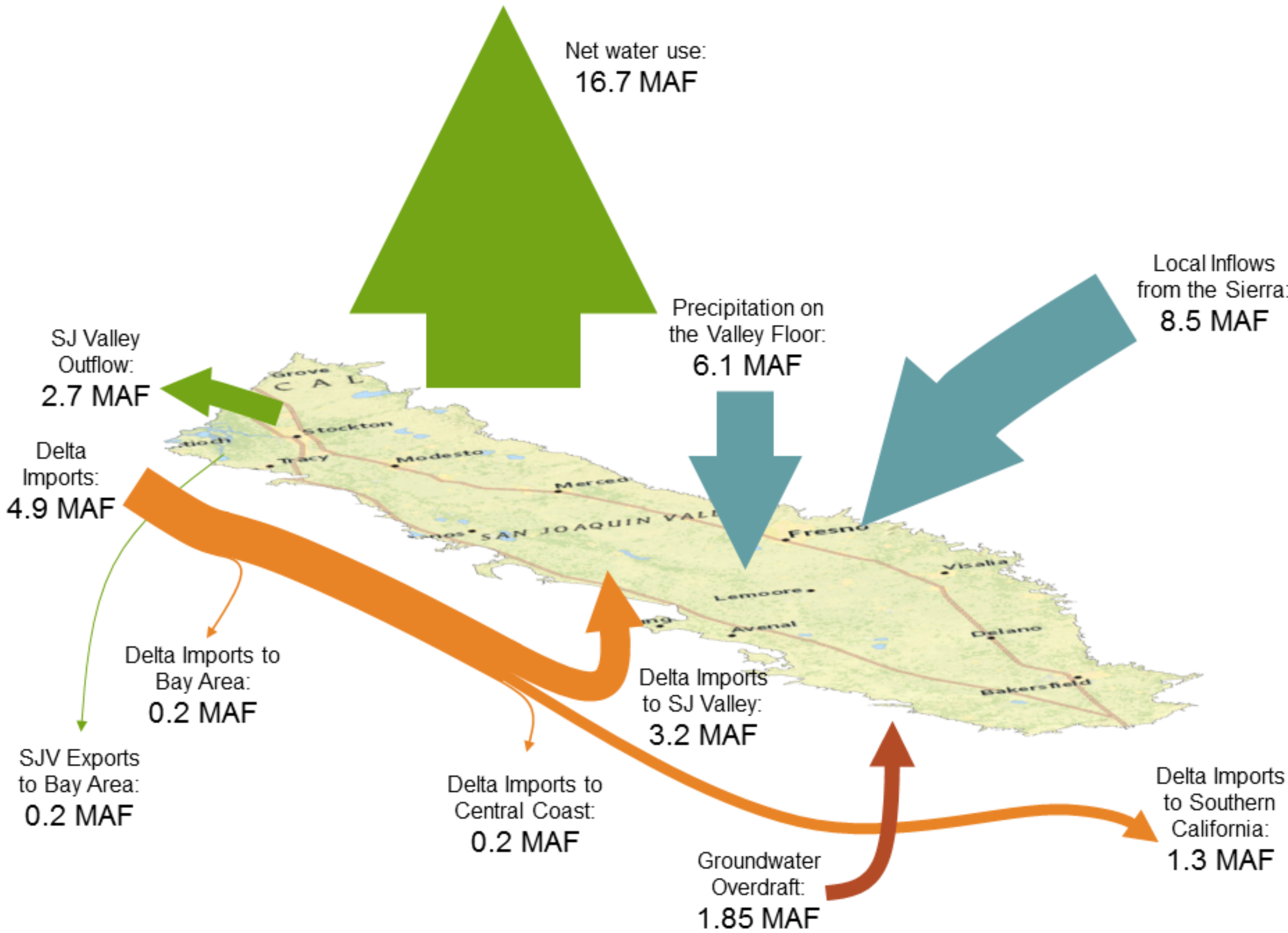
FIGURE A13

Components of the San Joaquin Valley's annual water balance



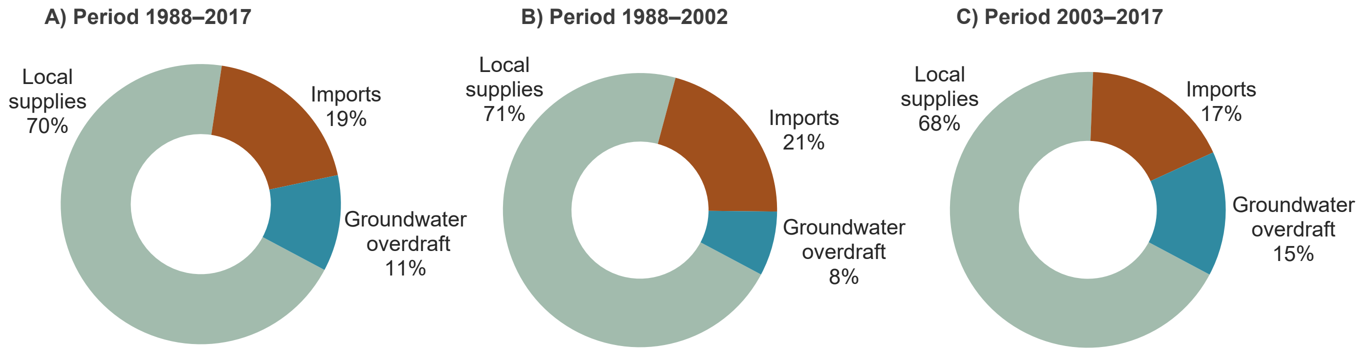
NOTES: To facilitate comparisons, bar heights in all three panels have the same scale. Net imports are the total water imported from other regions minus the water that is exported to other regions. Net local supplies are total inflows from local rivers plus precipitation on the valley floor minus San Joaquin River outflows and exports from San Joaquin River tributaries. "Dry years" are those classified as dry or critically dry for the San Joaquin Valley by the Department of Water Resources. The dry year classification considers precipitation in that year and water available in surface storage from the prior year.

FIGURE A14
Average water balance in the San Joaquin Valley, 1988–2017



Although total average water use remained relatively constant over the first and second half of the 30 years examined here, the shares of different water sources shifted considerably (Table A1 and Figure A15). Local supplies are substantial, averaging 70 percent of the total over the past 30 years. These local supplies can be used directly as surface water and indirectly by replenishing aquifers and pumped later as sustainable groundwater use. The valley also relies significantly on imported water—also used directly as surface water and indirectly as sustainable groundwater use—as well as groundwater overdraft. For the entire 30-year period, imports provided nearly a fifth of supplies, and groundwater overdraft provided 11 percent. These shares have shifted over the second half of the period, marked by prolonged drought and reduced local and imported surface sources. From 2003 to 2018, local supplies were 68 percent of supplies, down from 71 percent in the first half of the period. Imports fell from 21 to 17 percent. And groundwater significantly increased, from 8 to 15 percent of total supplies.

FIGURE A15
Average share of water sources in the San Joaquin Valley over different periods.



Trends in Delta Imports

Beyond the effect of drier hydrology since the turn of the century, net Delta imports to the valley have declined for two other reasons: changing regulatory requirements for imports, and a declining share of imports staying in the valley.

Changing Regulatory Requirements

As detailed in Gartrell et al. (2017), regulations to protect threatened and endangered fish species and to keep Delta waters fresh enough for agricultural and urban uses have increased the volume of required outflow from the Delta since the mid–1990s. Several changes have increased the requirements to protect fish, most notably State Water Board Decision 1641 (since 1995 as part of the update of the Bay-Delta Water Quality Control Plan) and updated Biological Opinions under the federal Endangered Species Act (since 2008). And although the regulations to maintain salinity standards for agricultural and urban uses within the Delta and by importers did not change over this period, it appears that changing conditions in the Delta have also increased the annual volumes of outflow required to maintain these standards since the mid–1990s (Gartrell et al. 2017).

Ascertaining the impact of these changes on Delta imports is not straightforward, because there is not a one-to-one correspondence between the volumes of required outflow and the “cost” in terms of water no longer available for imports by the CVP and SWP. In wetter years, in particular, there is considerable additional water available in the system, so regulatory requirements to maintain certain levels of outflows are less likely to be in direct competition with imports. And even regulations that specifically restrict the operation of the pumps—which were increased significantly in 2008 to protect fish at certain times—do not always lead to import reductions, because project managers sometimes have flexibility to shift the timing of pumping.

With these caveats, we estimate that average net imports to the valley over the 1988–2017 period might have been reduced by as much as 400,000 acre-feet by stricter regulations to protect the ecosystem since the mid-1990s.[17] And net imports to the valley might have been reduced by as much as 100,000 acre-feet because of the projects needed to increase outflows to maintain salinity standards for urban and agricultural water quality since that

[17] This estimate draws on results by water year type from Gartrell et al. (2017), and assumes that increases in required outflow for ecosystems (for water quality and flows) were only binding in critically dry and dry years, and that pumping restrictions were binding in all years. It assumes that the valley’s reductions would be in proportion to its share of total Delta imports in each year. An alternative estimate from MBK Engineers and HDR (2013), based on modeling results for different water year types, finds that net imports to the valley might have been as much as 600,000 acre-feet higher. The MBK estimate does not consider the increase in outflow required to maintain agricultural and urban salinity standards, however.

time.[18] Assuming that higher imports would have displaced additional groundwater pumping—and not increased net water use—the valley's long-term groundwater deficit would have been commensurately lower than the historical average of 1.8 maf per year—as low as 1.3 maf per year.[19]

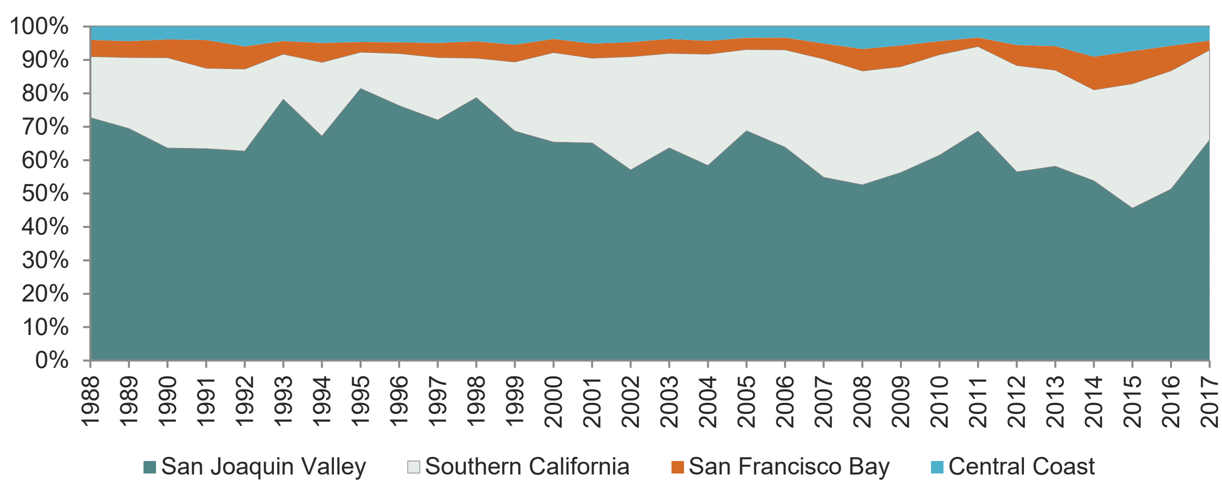
If current ecosystem regulatory standards and salinity outflow requirements for urban and agricultural use had been in effect over the entire 30-year period, the valley's long-term groundwater deficit would have been higher than the 1.8 maf per year historical average—roughly 2.3 maf per year.

Changing Regional Patterns of Imported Water Use

The San Joaquin Valley receives the largest share of Delta imports. However, this share has declined over time, as Southern California's share has increased (Figure A16). This shift reflects Southern California's increased ability to take and store water under its long-standing State Water Project contracts, thanks to investments in new surface storage (construction of Diamond Valley Lake, expansion of San Diego's San Vincente dam) and increases in groundwater banking within Southern California and in Kern County. In addition, some San Joaquin Valley irrigation districts have sold project contracts to Southern California urban agencies on a permanent or long-term basis (Hanak and Stryjewski 2012).[20] From 1988 to 2002, the San Joaquin Valley received an average of 69 percent of all Delta imports; that share fell to an average of 60 percent in 2003–2017. Meanwhile, Southern California's share rose from 21 percent to 30 percent. Since 2000, the year when Southern California's imports began to significantly expand, these imports have averaged 560 thousand acre-feet higher than in the 1988–99 period.

FIGURE A16

Share of Delta imports by region



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[18] Gartrell et al. (2017) find that the increase in outflow required to maintain these salinity standards since the mid-1990s is 400,000 to 600,000 acre-feet per year. This estimate of impacts on net valley imports from 1988–2017 assumes that this requirement is binding in below normal, dry, and critically dry years.

[19] Higher imports could also have encouraged water users to expand irrigated acreage, thereby increasing overdraft above this level.

[20] From 1998 to 2009, San Joaquin Valley irrigation districts sold State Water Project contracts with a face value of 110,000 acre-feet to Southern California agencies; long-term transfer agreements for over 12,000 acre-feet were also negotiated. The average annual volume of water transferred through these agreements totaled 83,000 acre-feet from 2003 to 2011 (Hanak and Stryjewski 2012, technical appendix table B6c and B8). During the latest drought, deliveries were lower, commensurate with cuts in SWP deliveries. Southern California also made net withdrawals from Kern County groundwater banks in the 2001–15 period. San Joaquin Valley irrigation districts also permanently transferred 50,000 acre-feet of contracts to San Francisco Bay Area agencies, and agreed to long-term transfers of more than 13,000 acre-feet.

Future Changes in Delta Imports to the Valley

Various factors could affect the availability of Delta imports to the valley in the future. On the one hand, regulatory restrictions in the Delta could increase as part of the pending update of the Bay-Delta Water Quality Control Plan. Sea level rise could also increase the volume of outflow required to maintain current salinity standards.

On the other hand, several changes could increase imports to the valley. This includes the recent renegotiation of the Cooperative Operating Agreement between the CVP and the SWP, which is expected to increase the CVP's share of imports by roughly 100,000 acre-feet per year. This should in turn increase the share of imports that remains within the valley by 60,000–70,000 acre-feet per year.[21] Other regulatory and operational changes could also increase import volumes, including investments in storage and conveyance and changes in the operation of surface and groundwater storage within the Central Valley (see Technical Appendix B), approvals by the State Water Board to capture high-flow run-off from the Sacramento Valley for recharge (Kocis and Dahlke 2017, DWR 2018a), and federal regulatory changes, including implementation of the 2016 WIIN Act and updated Biological Assessments under the federal Endangered Species Act, now underway.

Comparison with Other Water Balance Efforts

Several other efforts have sought to develop water balances for the Central Valley's hydrologic regions for some of the years examined here, using somewhat different approaches. The most comprehensive analyses for the Central Valley are the California Water Plan (DWR 2013), the California Central Valley Groundwater Surface Water Simulation Model (C2VSim), and the Central Valley Hydrologic Model (CVHM).

The California Water Plan (CWP) includes water balances by hydrologic region from 1998–2015. We used CWP data—combining the San Joaquin River and Tulare Lake hydrologic regions—to develop many of our variables, as reported above. Although CWP data are comprehensive, they contain important gaps and inconsistencies. First, the balances omit estimates of natural groundwater recharge, so CWP's estimates of groundwater overdraft are too high. Similarly, the CWP's estimate of consumptive use of water do not include evapotranspiration from native and riparian vegetation, so the reported water use deviates considerably from actual evapotranspiration, especially during wet years.

C2VSim is an integrated numerical model that simulates water movement through the linked systems of land runoff, groundwater, and surface water flow in California's Central Valley. The model contains monthly historical stream inflows, surface water diversions, precipitation, and land use (including crop acreages) from October 1921 through September 2009 (Brush et al. 2013).[22] Groundwater pumping and changes in groundwater storage also can be obtained from the model. The data by hydrologic region is available for download from the C2VSim database.

Finally, the Central Valley Hydrologic Model (CVHM) is an extensive, detailed, three-dimensional (3D) computer model of the hydrologic system of the Central Valley (Faunt et al. 2009 and 2015). The model simulates groundwater and surface-water flow, irrigated agriculture, subsidence, and other key processes in the Central Valley. We obtained the results at the subregional level for the period 1988–2003.[23]

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[21] This change will also shift some water from SWP contractors within the valley to the CVP. Over the entire 1988-2017 period, the share of SWP imports used in the valley was 38 percent; from 2003–2017 this share fell to 31 percent.

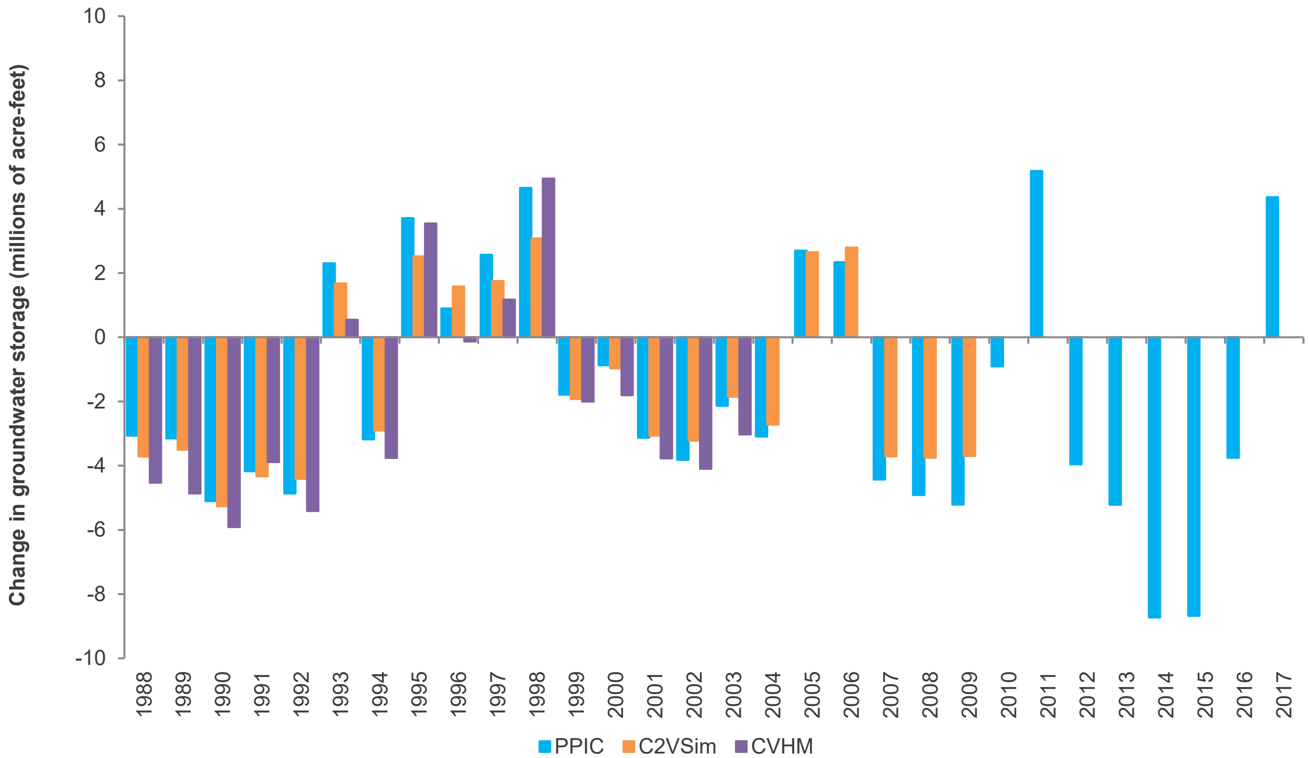
[22] Although there is a new beta version that extends the analysis up to 2015, the results are still not calibrated, so we prefer to just use the calibrated version.

[23] The data was provided by Stephen Maples.

Figure A17 presents a comparison of the change in net groundwater storage for the three sources with comparable estimates—PPIC, C2VSim, and CVHM.[24] For 1988–2003 (years for which estimates are available for three sources), PPIC estimates average annual overdraft of 1.3 maf, versus 1.5 maf for C2VSim and 2.1 for CVHM (note in the figure that the annual overdraft obtained by the CVHM model is consistently larger). For 1998–2009, years for which estimates are available for PPIC and C2VSim, both PPIC and C2VSim estimate an average annual overdraft of 1.5 maf.

FIGURE A17

Model results comparison of annual change in groundwater storage in the San Joaquin Valley

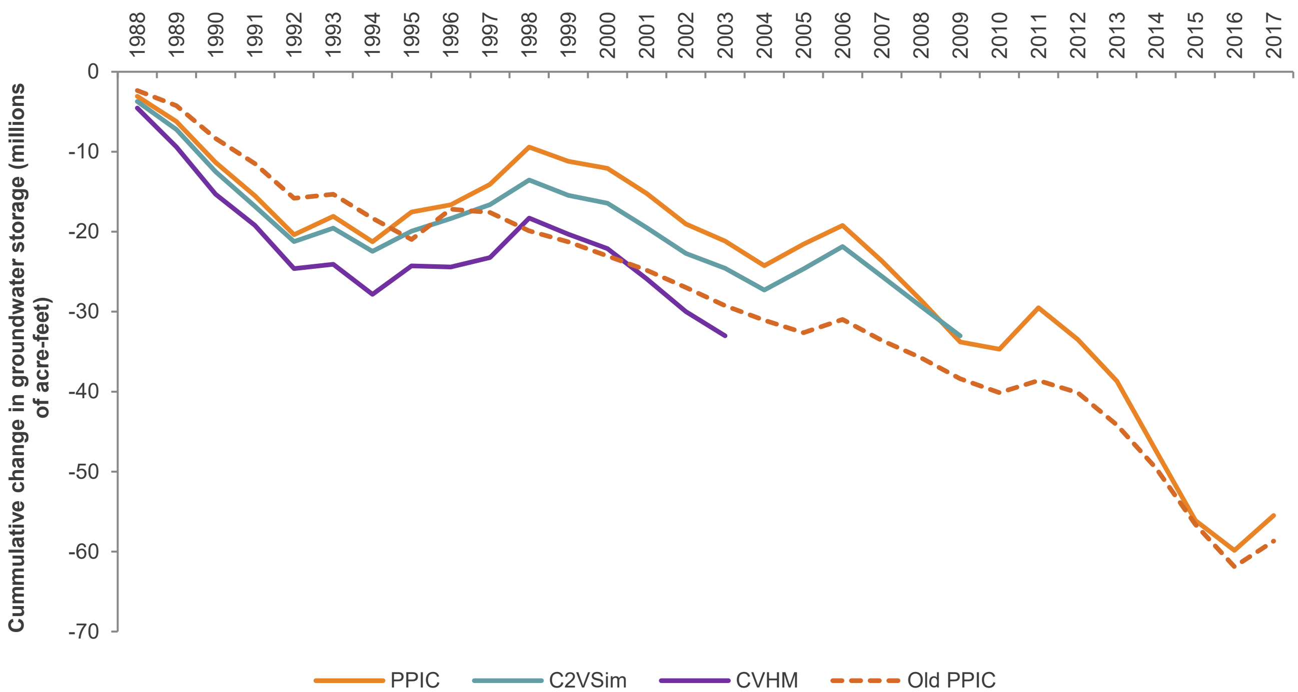


[24] We did not include the California Water Plan estimates because the results are not fully comparable given the omissions mentioned earlier.

Figure A18 presents a comparison of the cumulative change in groundwater storage for the same three models, including the results of the previous version of the PPIC water balance. Beyond the confirmation that CVHM estimates a larger overdraft than PPIC and C2VSim models, this figure also shows how the old version of our PPIC water balance did not adequately capture recharge during wet years. The new version of our balance is closer during dry and wet years to C2VSim and CVHM results.

FIGURE A18

Model results comparison of cumulative change in groundwater storage in the San Joaquin Valley



These comparisons make us reasonably confident that our 30-year regional estimates of groundwater overdraft—the "balancing" element in our San Joaquin Valley's water balance—are in the ballpark. We are also confident that the updated version of our water balance more accurately captures the difference in changes in groundwater storage during dry and wet cycles. Moreover, this exercise underscores the importance of improving estimates of key elements of the water balance for detailed planning purposes, including the development of groundwater sustainability plans. Although there is value in understanding the regional picture of water sources and uses, it will be essential to understand these balances at the sub-regional scale, where management actions and planning occur.

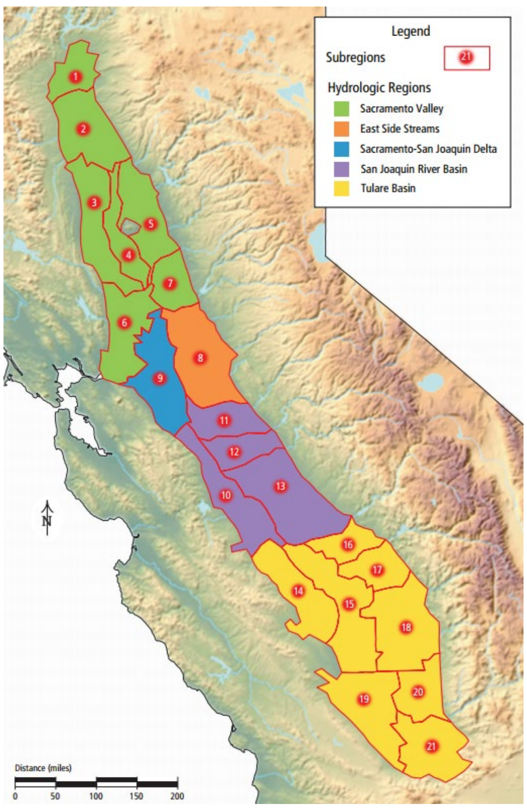
Estimating Groundwater Overdraft at the Subregional Level

Both CVHM and C2VSim have been applied to estimate historical groundwater budgets at the subregional level. 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 A19). Table A2 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 A19

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 A2 show that the models are in fairly close agreement at the regional scale for this period (plus or minus 20%), but with some significant discrepancies for individual subregions (note for instance the discrepancies in regions 9 and 18).

TABLE A2

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

Subregion	Change in groundwater storage (in taf/year)		
	C2VSim	CVHM	Average
8*	-88	-3	-46
9*	-21	120	50
10	-8	2	-3
11	-11	-4	-8
12	5	34	19
13	-97	-133	-115
14	-271	-186	-228
15	-59	-169	-114
16	-14	-140	-77
17	-124	-105	-114
18	156	-408	-126
19	-210	-194	-202
20	-232	-159	-196
21	-411	-255	-333
Total	-1,385	-1,599	-1,492

SOURCES: C2VSim results at the subregional scale were obtained directly from model outputs; CVHM results were provided by Stephen Maples.
NOTES: *Only a part of regions 8 and 9 are in the San Joaquin River hydrological region. Given that, the value shown for regions 8 and 9 represents a proportion of the total amount obtained from the models based on the area included in the San Joaquin Valley (85% for region 8 and 61% for region 9).

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 A3). The San Joaquin River hydrologic region includes the northwest (part of subregion 9 and subregion 10) and northeast (part of subregion 8 and subregions 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 nearly 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.[25] It therefore appears that C2VSim is underestimating pumping and/or overestimating recharge in this part of the valley.[26]

Finally, we made a simple adjustment to include years after 2003, which were drier. Given the inconsistent results of the C2VSim model for some parts of the valley, we decided to use the CVHM subregional results and then multiply them by a factor that accounts for the additional overdraft for the San Joaquin Valley from our 1988–2017 water balance. Using this procedure we are implicitly assuming that the pumping behavior after 2003 was the same everywhere. This assumption is supported by the widespread decline in groundwater tables since the

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[25] See DWR's identification of Critically Overdrafted Basins (DWR 2016b) and NASA JPL report on Subsidence in the Central Valley (Farr et al. 2017)

[26] The C2VSim results in some parts of the valley are also in conflict with some of the published water budgets, especially in the southeastern part of the San Joaquin Valley. See for instance the Kaweah Delta Water Conservation District Groundwater Management Plan (KDWCD 2015).

mid-2000s shown in DWR's Groundwater Information Center Interactive Map Application (DWR 2018b). Results for this adjustment are shown in Table A3 and in Figure A20.

TABLE A3

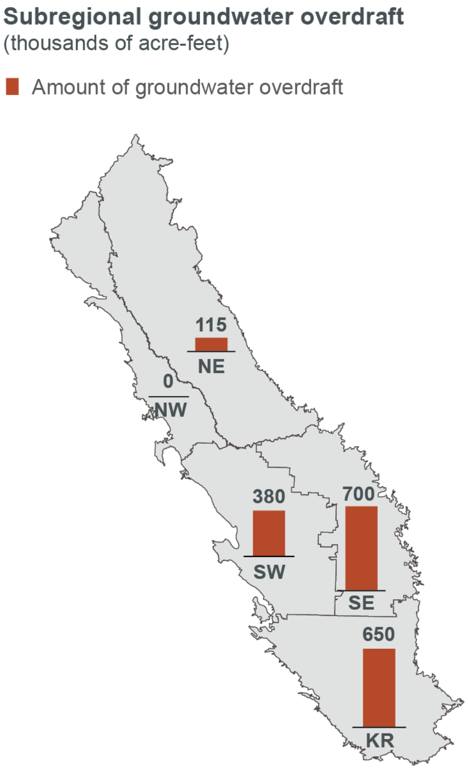
Change in groundwater storage for the five aggregated subregions

Subregion	Change in groundwater storage (in taf/year)		
	C2VSim 1975-2003	CVHM 1975-2003	Adjusted long-term average*
Northwest	-25	122	0
Northeast	-155	-106	-114
Southwest	-330	-355	-381
Southeast	18	-653	-701
Kern	-853	-608	-653
Total	-1,345	-1599	-1850
Total in overdrafted regions*	-1320	-1,722	-1,850

NOTES: *The adjusted long-term average allocates the additional overdraft we find in our 1988-2017 water balance relative to the 1975–2003 total for the four subregions experiencing average overdraft (1,722 – 1,599 = 122 acre-feet for the CVHM model) in proportion to their overdraft in 1975–2003 based on the CVHM model. We assume that the northwest is in average long-term balance.

FIGURE A20

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



NOTE: NE is northeast, NW is northwest, SE is southeast, SW is southwest, and KR is Kern basin. Given the uncertainties of the estimates, this figure shows results rounded to the nearest 5 taf.

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