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RESEARCH

Water Budgets for the Delta Watershed: Putting Together the Many Disparate Pieces

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ABSTRACT

Water budgets integrate and summarize the water inputs and outputs that are essential for effective water resources management. Using water data collected from different sources, we constructed three water budgets (a 12-year annual average, a wet year, and a critically dry year) for the Sacramento–San Joaquin Delta (Delta), the Sacramento River (SR) watershed, and the San Joaquin River (SJR) watershed. Although multiple water budgets for the Delta exist, the water budgets presented here are the first to provide all three of the following: (1) water budgets for the entire Delta watershed, divided into management-relevant components, (2) comparisons between wet and dry years and between different regions of the watershed, and (3) discussion of major gaps and uncertainties in the available water data to guide and inform future data collection and water management. Results show that, from 1998 to 2009, the Delta received 24.2 million acre feet (maf) of water each year on average, which primarily exited the Delta as river outflow (71%), water exports (22%), and evapotranspiration (ET; 6%). The SR watershed received 56.9 maf of water (95% as precipitation). The major outputs from the SR watershed were ET (63%) and flows to the Delta (34%). In the SJR watershed, total water input was 28.7 maf composed of precipitation (74%), water imported from the Delta (18%), and storage depletion (7%). The major outputs from the SJR watershed were ET (65%), water exports (19%), and flows to the Delta (14%). Most values varied greatly from year to year. Although streamflows, water exports, and valley precipitation are relatively well measured and estimated, uncertainties are higher for groundwater storage change as well as for ET and precipitation in montane regions. Improvement in data collection and synthesis in these components is necessary to build a more detailed and accurate water budget.

KEY WORDS

Water budget, precipitation, evapotranspiration, streamflow, groundwater, Delta, Sacramento River, San Joaquin River

INTRODUCTION

Water and environmental management in the Sacramento–San Joaquin Delta (Delta) faces immense challenges from the Delta's hydrologic, hydrodynamic, ecological, economic, and institutional complexities (Luoma et al. 2015). The Delta is the hub for California's water distribution system: water from the Delta is distributed to roughly two-thirds of California's population and 3 million acres of farmland (CDWR 2014a). Ecologically, the Delta provides habitat for many native and commercially important species, and functions as a major migratory corridor for waterfowl (Luoma et al. 2015). However, the Delta ecosystem and Delta-dependent water users are subject to variable and unreliable water supplies as a result of: (1) highly variable inter-annual precipitation patterns, and 2) the geographic imbalance between water supply (precipitation) and demand (Dettinger et al. 2011; Luoma et al. 2015; Lund 2016). Climate change (Hanak and Lund 2012; Dettinger et al. 2015), sea-level rise, population growth (Vörösmarty et al. 2000; Jiménez Cisneros et al. 2014), land use change (Wilson et al. 2016), and ecosystem protection requirements (Lund 2016) will add increasing complexity to the reliability of water supplies from the Delta. The existence of current stressors and the advent of future stressors will require water resource managers to better understand and manage multi-faceted and complicated water supply systems.

Understanding the water budget—including its major storage compartments, location of water use, and rates of flow between these compartments—is key to managing limited water supplies in California (Escriva–Bou et al. 2016). A water budget is a quantitative accounting of the rates of water movement and change in storage (surface and subsurface) in a hydrologic system (Healy et al. 2007). Constructing a water budget provides an opportunity to look at the water supply system holistically, and to identify the linkages where management actions could be implemented (Vardon et al. 2007; Ryu et al. 2012; Escriva–Bou et al. 2016). Knowledge gained through developing water budgets helps basin-wide water cycles and dynamics to be understood, as well as the potential sources of error and uncertainties associated with using different methods of measuring water (S. Wang et al. 2014). The Delta watershed is highly managed, with complex systems of pumps, reservoirs, and canals constantly redistributing water within the watershed, importing water from other areas, or exporting water outside of the watershed (Lund 2016). Therefore, a thorough understanding of water flow and storage is vital to managing this complex system and planning for future water needs. Water resources data and synthesized information contained in water budgets are essential components of water accounting[1] and can help address key water management problems (e.g., surface water allocation, groundwater use, determining environmental water needs, drought preparedness, and water trading) in California (Escriva–Bou et al. 2016).

Currently, several peer-reviewed and non-peer-reviewed works include water budgets for various portions of the Delta watershed (e.g., CDWR 2014a; Lund 2016; Hanak et al. 2017; Mount et al. 2018). Lund (2016) and Mount et al. (2018) provide excellent information about variations in Delta inflows and outflows in recent wet and dry years, but do not connect these variations explicitly to the entire Delta watershed. Hanak et al. (2017) give detailed long-term averages for inflows and outflows to the San Joaquin Valley, but not the entire Delta watershed or the water balance components in montane regions (except for their final outflow to the San Joaquin Valley). CDWR (2014a) gives detailed water balances for the Sacramento and San Joaquin River watersheds, and a more simplified water balance for the legal Delta over a similar time-period as that covered in this paper. However, CDWR (2014a) does not explicitly present the relationships among these three sub-areas or specifically separate natural landscapes' evapotranspiration (ET) from other types of consumptive use. All these water budgets are useful for their intended purposes, but our analysis is the first to provide a clear view of the connections among different parts of the Delta watershed (separated by sub-watershed and by land use) accompanied by a discussion of data uncertainties for all water budget components. The aim of preparing water budgets in this way is to provide data appropriate for high-level, long-term

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[1] Water accounting is a method of organizing and presenting information relating to the physical volumes of water in the environment and economy as well as the economic aspects of water supply and use (Vardon et al. 2007).

planning by showing the big-picture view of how the Delta connects to its larger watershed, and to demonstrate the annual variability in wet and dry years. In addition, the analysis of data uncertainties allows us to provide future recommendations for data collection, improved accuracy, and more comprehensive water budget construction. The degree of uncertainty of the inputs and outputs affects acceptance of the results, analysis, and recommendations by decision-makers (Batchelor et al. 2016). Therefore, clearly communicating and reducing the uncertainty in water budgets will facilitate more effective policy-making for and management of water resources.

As further described in Appendix A, multiple sources of water data for the Delta and its watershed are available as direct measurements, model estimates, and remote sensing data. In this paper, to construct annual water budgets for the Delta, Sacramento River (SR) watershed, and San Joaquin River (SJR) watershed, we collect and synthesize these disparate water data for different water budget components. When possible, we compare multiple data sources for each water budget component, and use that which appears the least uncertain. To the best of our knowledge, this is the first published water budget to use this combination of data sources.

This document aims to provide three types of information that are not all covered in any single pre-existing document:

1. A quantitative water budget for the entire Delta watershed, including its montane regions, using data from a variety of sources
2. A comparison of water budgets
   - between wet and dry years (to demonstrate the wide range in water availability and consumption patterns across years, and how this variation affects management decisions)
   - between different regions of the watershed (both between different sub-watersheds and different types of land use/land cover, which have different management strategies and thus are useful to view separately)
3. Identification of major data gaps and uncertainties in the available water data to guide and inform future data collection and water management.

This paper is intended to facilitate a comprehensive understanding of water inputs, consumption, and flows in this important watershed, as well as illustrate where further research is needed to quantify certain components of the water budget with greater certainty. Appendix A provides further details that are useful for understanding trends in the water budget, bur are not necessary for high-level understanding of this topic.

METHODS

Geographic Scope

The Delta watershed was divided into three regions: the Delta, the SR watershed, and the SJR watershed (Figure 1). The SR and SJR watersheds were further separated into the Central Valley floor region and the montane region (the western slope of the Sierra Nevada and eastern slope of the Coast Range), based on elevation and vegetation. In general, the Delta watershed has a Mediterranean climate with hot, dry summers and mild, wet winters. The amount of annual precipitation and ensuing streamflow depend on the frequency and intensity of storms that produce intense precipitation, which vary widely year-to-year (Dettinger et al. 2011; Dettinger 2016).

The Delta as described in this paper is consistent with the legal Delta (per the Delta Reform Act of 2009: California Water Code Sections 85000–85350). It covers an area of approximately 3,000 km^2 (1,160 mi^2) encompassing portions of five counties (Sacramento, San Joaquin, Contra Costa, Solano, and Yolo). The Delta includes more than 70 islands and tracts that are protected from flooding by over 1,600 km (1,000 mi) of levees (Lund et al. 2007). Many islands in the central Delta are 3 to 8 meters (10 to 25 feet) below sea level (Ingebritsen et al. 2000). Agriculture (> 60%) was the predominant land use in the Delta, although there were small areas of urban (9%), open water (9%), and natural lands (16%; but some of this area was used as rangeland) as of 2016 (Medellín–Azuara et al. 2018). Total population in the area was approximately 570,000 in the 2010 census (CDWR 2014a; Table A7).

Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 1 Geographic extent of the legal Delta, as well as the Sacramento River (SR) and San Joaquin River (SJR) watersheds, for which water budgets were developed (Source: CDWR 2014a)

The SR watershed is the Sacramento River Hydrologic Region as defined in the 2013 California Water Plan (CDWR 2014a) excluding those portions that fall within the legal Delta. The SR watershed drains approximately 70,000 km^2 (27,000 mi^2) and is the largest river system in the state (CDWR 2014a). The SR watershed lies between the Coast Range to the west and the Sierra Nevada to the east, and extends from the Delta in the south to the Goose Lake drainage area in Oregon to the north. The SR watershed's total reservoir capacity is 16.1 million acre feet (maf; CDWR 2014a). It contains ~7,900 km^2 (3,050 mi^2) of irrigated agriculture mostly on the valley floor (6,400 km^2 (2,500 mi^2), and 2,800 km^2 (1080 mi^2) of urban areas. It had a population of ~3 million people according to the 2010 census (Table A7).

Similarly, the SJR watershed represents the San Joaquin River Hydrologic Region as defined in the 2013 California Water Plan (CDWR 2014a) excluding the legal Delta. It drains approximately 39,000 km^2 (15,050 mi^2) of the northern portion of the San Joaquin Valley. The watershed is bordered on the east by the Sierra Nevada Mountains and on the west by the coastal mountains of the Diablo Range, and extends from the headwaters of the San Joaquin River in Madera County—and its southern drainage in Fresno County—north to the southern end of the Delta. (CDWR 2014a). It is hydrologically separated from the Tulare Lake basin by a low broad ridge that spans the San Joaquin Valley between the San Joaquin and Kings rivers. The SJR watershed's total reservoir storage capacity is ~11.5 maf (CDWR 2014a). It contains ~8,800 km^2 (3400 mi^2) of irrigated agriculture and 1,600 km^2 (617 mi^2) of urban areas. It had a population of over 2 million people according to the 2010 census (Table A7).

Our subdivision of the Delta watershed is different from other reported approaches. For example, CDWR (2014a) includes portions of the Delta in its Sacramento River and San Joaquin River watershed water budgets, whereas our analysis removes the legal Delta from the Sacramento and San Joaquin River sub-watersheds. This approach allows the three sub-regions to be more clearly compared with no overlap (and thus no double-counting across sub-regions). We separated the Delta watershed into as few regions as possible for ease of interpretation, while keeping separate those regions that involve very different land use and/or management types (e.g., separating the Delta, valley floor, and montane regions, as well as separating urban, agricultural, and natural lands).

Water Budget

A water budget accounts for all water fluxes in a watershed by balancing the difference between water inputs and outputs with changes in water storage. The basic water budget equation used for this study was:

$$P + Inflows = ET + \Delta S + Outflows$$

where P is precipitation, ET is evapotranspiration, and ΔS is change in water storage (e.g., surface reservoirs, groundwater). In this study, inflows include stream and subsurface inflows plus water imports, and outflows include stream and subsurface outflows plus water exports. We obtained the data for these components from multiple sources (e.g., government agency reports and websites) that have collected water data through direct measurements as well as indirect calculations and model estimations. Therefore, when combined, the available data do not necessarily lead to a perfectly balanced water budget. We also calculated runoff coefficients (outflow as a fraction of precipitation: Q/P) to assess how different water-supply conditions affected water use within each basin.

This analysis is meant to inform land and water management at a watershed scale. Therefore, the water budgets we present do not describe water withdrawals that are then applied within the same watershed. Confusion between such applied use and consumptive use (water exiting the watershed as ET) has confounded efforts to conserve water resources in various regions (Perry and Steduto 2017). Water diverted from streams or pumped from groundwater is sometimes included in water budgets, but such water can remain in the watershed by contributing to groundwater recharge, or being discharged into surface water and then re-used downstream. As shown in CDWR 2014a, consumptive use can be much smaller than applied use. Therefore, the values here account only for water entering or leaving each defined region. Of course, all diversions can have important effects on local water use and the sub-annual timing of water availability, so they should be considered when appropriate, but such effects are outside our current scope.

Evapotranspiration in these analyses is further separated into four categories: agricultural, urban, natural lands in the valley floor, and all montane areas. This separation is partially a result of differences in data availability between valley and mountain areas. More important, though, discriminating between different sources of ET allows for analysis of water volumes that could be affected by different types of management decisions for these four different types of land.

We created annual average water budgets using data from water years (WYs) 1998 to 2009 (a water year is defined as being from October 1 of the previous year to September 30 of the current year; USGS c2017). We selected WYs 1998 to 2009 because it was the longest series of consecutive years having the most data available for all three regions (Table A6). Water years 1998 to 2009 represent the period of the two major data sources: (1) water portfolios (CDWR c2018a) starting from 1998 provided data for precipitation, groundwater storage, reservoir storage, imports and exports, and lake and reservoir evaporation; and (2) California Central Valley Groundwater–Surface Water Simulation Model (C2VSim; CDWR c2014b) data ending in 2009 provided values for ET and subsurface flows. For each watershed, we constructed an annual average water budget using the average values of the 12-year period. In addition, we developed single-year water budgets for WYs 2006 (a wet year) and 2008 (a critically dry year) to provide examples of how key water budget components respond to annual differences in water input from precipitation. We used water year-type definitions from the California Data Exchange Center (CDWR c2017a). One benefit of selecting the study period of 1998 to 2009 is the balanced number of wet and dry years. During the 12 water years analyzed (1998–2009), the SR watershed experienced 3 wet, 3 above-normal, 1 below-normal, 4 dry, and 1 critically dry years; the SJR watershed experienced 3 wet, 2 above-normal, 2 below-normal, 3 dry, and 2 critically dry years.

Delta Water Data

We obtained river inflow data to the Delta from the SR and SJR from the Dayflow website (CDWR c2015) maintained by the California Department of Water Resources (CDWR). We obtained precipitation data for the Delta from the CDWR's Bay–Delta Office (CDWR, unpublished data), which estimates the volume of water added to the Delta as a result of precipitation (mainly rainfall) using the Theissen polygon method based on seven rain gauges in and near the Delta (Mahadevan 1995).

Major water outputs from the Delta are river outflow to San Francisco Bay, water exports from the Delta, and in-Delta ET (or consumptive use). Dayflow (CDWR c2015) provides the data for Delta outflow as a Net Delta Outflow Index (NDOI; CDWR c2017b) and for daily water exports from the Delta (Table A2). The CDWR's Bay–Delta Office provided water depletion data calculated from the Delta Island Consumptive Use (DICU) model. Since DICU does not provide ET from different land cover categories, we used C2VSim data to estimate ET from individual land cover categories (agriculture, urban, and natural lands). C2VSim also provided estimates for subsurface flow and groundwater storage change in the Delta (CDWR c2014b). The water portfolios (CDWR c2018a, originally published in 2014, but updated in 2018) database used to develop the California Water Plan Update 2013 (CDWR 2014a) provided additional groundwater storage change data. There is no large surface storage reservoir in the Delta. See Tables A2 and A6 for details on data sources for the Delta.

Sacramento River Watershed Water Data

The water portfolios (CDWR c2018a) provided watershed-wide precipitation data for the SR watershed. We estimated these precipitation values by combining spatially interpolated precipitation developed from gauge data and the Parameter-elevation Relationships on Independent Slopes Model (PRISM; NACSE c2018). We also obtained water import data, mainly from the Trinity River watershed, from the water portfolios (CDWR c2018a). We used the C2VSim model ouputs to obtain subsurface flow data in the SR watershed. Water outputs from the SR watershed include river flows to the Delta, ET from the Central Valley floor and the montane regions (above the valley floor), evaporation from water surfaces (reservoirs, lakes, streams, and rivers), water exports, and subsurface flows. We obtained river flows to the Delta from Dayflow (CDWR c2015). We obtained data on water exports to other watersheds and water surface evaporation from lakes and reservoirs from the water portfolios (CDWR c2018a). Evaporation estimates from stream and river surfaces were obtained from Meyers and Nordenson (1962), which measured the rates from 1946 to 1955 for the SR watershed. We assumed that the evaporation values from the water surfaces reported in the earlier research remained about the same for the current study period (1998 to 2009). We obtained ET rates from the Central Valley floor region from C2VSim (CDWR c2014b). C2VSim provided ET estimates from different land use/land cover categories (agriculture, urban, and natural lands) in the valley floor region. Comprehensive measurements of total ET from forests on the eastern slope of the Coast Range and the western slope of the Sierra Nevada Range, collectively labelled as the montane region, are not currently available. We thus estimated this montane region ET by closing the water budget within each watershed:

$$\begin{gathered}\textit{Montane region ET} = \textit{Inputs} - \textit{Outputs other} \\ \textit{than montane ET} - \textit{Change in storage}\end{gathered}$$

Data for storage change, both surface reservoirs and groundwater storage, were obtained from the water portfolios (CDWR c2018a). We estimated the surface storage change by using the differences in the reservoir volumes at the beginning and end of each water year. The major reservoirs in the SR watershed are Shasta Lake, Folsom Lake, Lake Oroville, Lake Berryessa, and New Bullards Bar Reservoir. We estimated changes in groundwater storage using the difference between water extracted from and water recharged into groundwater basins (CDWR c2018a). We counted changes in combined surface and groundwater storage as a part of input (when change < 0) or output (when change > 0). See Tables A4 and A6 for details on data sources for the SR Watershed.

San Joaquin River Watershed Water Data

The water portfolios (CDWR c2018a) provided watershed-wide precipitation inputs for the SJR watershed. Dayflow provided water import data from the Delta through the Central Valley Project (CVP) and State Water Project (SWP) to the SJR (CDWR c2015). The SJR watershed also imports small amounts of water from the SR watershed upstream of the Delta (American River through Folsom South Canal) and receives occasional overflows from the Tulare Basin. The water portfolios (CDWR c2018a) provided the data for these minor imports, and these are included in the water budget as "other" imports. C2VSim model results provided subsurface inflows to the SJR watershed.

Flows to the Delta from the SJR system are available in Dayflow (CDWR c2015). Many reservoir–aqueduct or reservoir–canal systems export water from various locations in the SJR watershed to other watersheds. We collected data for these water exports from various state, federal and local agencies' websites and reports (Table A1). C2VSim model results provided the ET data for the valley floor region in the SJR watershed. We estimated ET from the montane region of the SJR watershed by closing the water budget as we did for the SR watershed, since a comprehensive estimate of ET for this region was not available. Evaporation from lakes and reservoirs in the SJR watershed is available in the water portfolios (CDWR c2018a). We derived evaporation from stream and river surfaces from estimates by Meyers and Nordenson (1962), after adjusting for the total river or stream lengths to include only waters within the SJR watershed. The water portfolios (CDWR c2018a) provided changes in reservoir storage and groundwater storage. Major reservoirs in the SJR watershed are New Melones Reservoir, Don Pedro Reservoir, Lake McClure, and San Luis Reservoir. See Tables A5 and A6 for details on data sources for the SJR Watershed.

RESULTS

Data Limitations

Any analysis of the water budgets presented below should take into account the limitations of the data used because levels of uncertainty varied among water balance components.

Streamflows, imports and exports of water, and reservoir storage can all be measured fairly directly, and thus these values have low uncertainty. Precipitation is also measured directly at individual points, but interpolated total precipitation can have

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high uncertainties in mountainous regions, including those which provide much of the Delta watershed's water (Henn et al. 2018). In-Delta consumptive use matched well (within 13%) between the C2VSim and DICU data (Table A2), suggesting low uncertainty, but similar data were not available for comparison for ET from other valley floor areas.

In the water budgets presented below, we calculated ET estimates from the montane regions by closing the water budgets for the SR and SJR watersheds, because ET estimates for the montane regions in our study area were not available. The residual represents the estimated montane ET. An alternative approach for calculating montane region ET involves calculating the montane region ET as a water balance between precipitation in the uplands and unimpaired flows ($P-Q$) from the watersheds upstream of the Central Valley. We tested this approach by summing precipitation from the Plan Areas (defined in CDWR 2014a, sub-regions in each hydrologic region) located in the montane regions, and using unimpaired flows (Huang 2016) from the upland watersheds to represent the outflows. This approach resulted in annual average montane ET estimates of 24.7 maf and 10.2 maf (data period: 1998–2009) for the SR and SJR watersheds, respectively (Table A8). These were relatively close (within 10%) to our estimates that used the budget closure method: 26.7 maf and 11.6 maf for the SR and SJR watersheds, respectively (see water budgets below), giving us relatively high confidence in our montane ET estimates.

Groundwater storage change is also difficult to measure. To better understand the uncertainty levels associated with groundwater data, we compared available data from the water portfolios, water balance products from Xiao et al. (2017), and model outputs of C2VSim (Brush et al. 2013) and the Central Valley Hydrologic Model (CVHM; Faunt 2009; Faunt et al. 2016). The water portfolios show very high groundwater depletion rates compared to the other sources (5.8 times higher than C2VSim for the valley floor of the SR and SJR basins; Table 1). Most models agreed that the period 1998–2009 experienced a net loss of groundwater for all spatial coverages studied, except for Xiao et al. (2017), which showed net recharge in the Central Valley from 2003 to 2009 (Table 1). All estimates of mean annual groundwater storage change are relatively small compared to other components of the water budget, so uncertainty in groundwater storage change should not strongly affect the overall water budget. If groundwater depletion is overestimated in the water budgets we present, it would likely mean that montane region ET is actually slightly lower (by up to 7% for SR and 16% for SJR) than shown in our results.

Since groundwater storage change and montane ET had the greatest levels of uncertainty of all water budget components, detailed water budgets in Appendix A provide two potential values for each of these components to illustrate the variation of likely values (Tables A2, A4, A5).

Delta Water Budget

Annual Average (Water Years 1998–2009)

The average annual total inputs and total outputs for the Delta both equaled 24.2 maf for WYs 1998–2009 (Table 2). River inflows from the SR (including the Yolo Bypass) and SJR (including the eastside tributaries) and in-Delta precipitation were the major components of water inputs to the Delta. On average, the SR system contributed more than five times the inflows (81%; 19.5 maf) than the SJR system (16%; 3.9 maf) during this period. Annually, Delta outflow averaged ~17.1 maf, accounting for 71% of the total output from the Delta. Water exports through the CVP (2.6 maf) and SWP (2.9 maf) facilities accounted for ~22% (5.4 maf; Table 2, Figure 2A). Consumptive use (i.e., ET) of water was also a measurable component of water loss, and accounted for ~6% (1.5 maf) of the total water output from the Delta. Consumptive use in the Delta was almost two times greater than in-Delta precipitation, resulting in a net depletion of water (Table 2). The subsurface flow rate was very low (~0.1 maf per year), and the groundwater storage change was negligible (< 0.05 maf per year). The runoff coefficient for the Delta watershed, encompassing the entire SR and SJR watersheds, was 0.23 for the annual average water budget and ranged from 0.11 (2009) to 0.39 (2006; Table 3). A detailed water budget for the Delta is included in Appendix A, with all components provided for each individual year—including the components that we eliminated in the tables in this paper because of their small sizes (Tables A2 and A3, and Figure A1).

Wet Year (2006)

In a wet year (2006), total flows to the Delta were almost double (48.5 maf) the annual average, and the contribution of the SJR system to the total inputs (~20%) was higher (Figure 2A). Water export volume in 2006 (13%; 6.3 maf) increased by 0.9 maf over the annual average. Delta outflow was 84% (~41.6 maf) of the total output, which was much higher than the annual average (71%; ~17.1 maf).

Critically Dry Year (2008)

In a critically dry year (2008), total inflow to the Delta (~12 maf) was reduced to almost half the annual average, and the relative contribution from the SJR watershed to the total inflow was reduced to ~13% (~1.5 maf; Figure 2A). The proportion of Delta outflow (~6.7 maf) to total output was reduced to 56% of the annual average, and the water export volume was

Table 1 Comparison of changes in groundwater storage from the water portfolios, GRACE and water balancing methods of Xiao et al. (2017), and model outputs of C2VSim (CDWR c2014b) and CVHM (Faunt et al. 2016). Results for both our study period (1998–2009) and the period of 2003 (beginning of data from Xiao et al.) to 2009 (end of data from C2VSim) are shown whenever possible.

Region		Data source	Mean annual change (maf) 1998–2009	Mean annual change (maf) 2003–2009
Valley floor + montane region	SR + SJR + Tulare	Water portfolios	−6.5	−7 .2
		Xiao et al. – GRACE		Roughly −3.5 [a]
		Xiao et al. – water balance		+1 to −1 [a]
	SR + SJR	Water portfolios	−3.7	−4.0
Montane region only	SR + SJR + Tulare	Water portfolios	−0.2	−0.2
		Xiao et al. – water balance		<1 [a]
	SR + SJR	Water portfolios	−0.2	−0.2
Valley floor only	SR + SJR + Tulare	Water portfolios	−6.3	−7.0
		Xiao et al. – water balance		0 to 1 (net recharge) [a]
		C2VSim	−1.7	−1.9
		CVHM	−2.2	−3.2
	SR + SJR	Water portfolios	−3.4	−3.8
		C2VSim	−0.6	−0.8

a. These values were estimated from charts in Xiao et al. (2017) and supporting information therein.

Table 2 Annual average water budget of the Delta (in maf) for water years 1998–2009

Inputs	Subtotal (maf)	Total (maf)	Outputs	Subtotal (maf)	Total (maf)
Sacramento River system		**19.5**	Exports		**5.4**
Sacramento River	16.9		CVP	2.6	
Yolo Bypass	2.6		SWP	2.9	
San Joaquin River system		**3.9**	Consumptive Use (ET)		**1.6**
San Joaquin River	3.0		Agriculture	1.0	
Eastside tributaries	0.9		Urban	0.1	
Precipitation		**0.8**	Natural land	0.4	
			Subsurface outflow		**0.1**
			Delta outflow		**17.1**
Total inputs		**24.2**	**Total outputs**		**24.2**

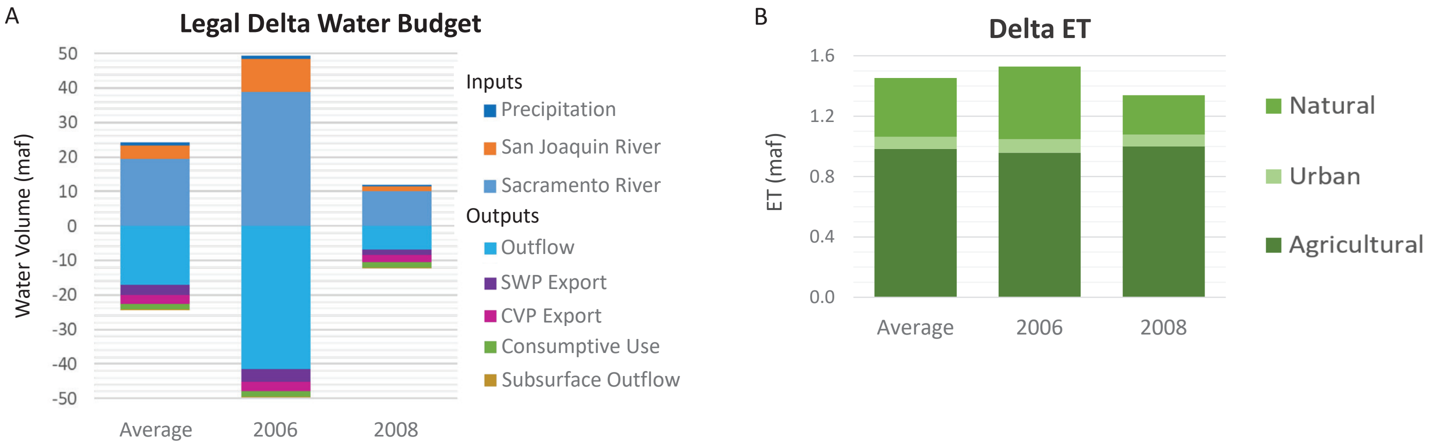

Figure 2 Annual water budgets for the Delta with major water inputs (positive numbers) and outputs (negative numbers) (**A**), and evapotranspiration (ET) in different land use/land cover areas (**B**), for a multi-year annual average (water years 1998–2009), a wet year (2006), and a critically-dry year (2008). Total ET values in (**B**) do not match Table 2 perfectly (1.6 maf versus 1.5 maf) due to differing data sources.

reduced to ~3.8 maf. However, the relative proportion of annual export to total output (33%) was higher than that of the annual average (~22%).

Delta Evapotranspiration (ET)

ET from different land use/land cover areas in the Delta illustrated an interesting annual water-use pattern (Figure 2B). On average, agricultural lands in the Delta consumptively used the largest amount of water (~1.0 maf), as would be expected, given that agriculture is the dominant land-use type. Urban areas in the Delta consumed a much smaller volume of water (~0.1 maf) than agricultural areas. Consumptive use by natural lands (annual average: 0.4 maf) responded the most strongly to the changing precipitation patterns in a wet year (0.5 maf in 2006) and a critically dry year (0.3 maf in 2008).

Table 3 Runoff coefficients (total annual outflow divided by precipitation) for the full Delta watershed as well as its two sub-basins, the Sacramento River and San Joaquin River watersheds

	Delta watershed	**Sacramento River watershed**	**San Joaquin River watershed**
1998–2009 average	0.23	0.36	0.18
2006 (wet year)	0.39	0.51	0.34
2008 (critically dry year)	0.13	0.27	0.10
2009[a] (dry/below normal year)	0.11	0.23	0.07

a. The minimum runoff coefficients from 1998 to 2009 were observed in 2009 rather than 2008 for all regions, while the maximum runoff coefficients were observed in 2006 for all regions.

Sacramento River Watershed Water Budget

Annual Average (Water Years 1998–2009)

The annual average (1998–2009) water inputs and outputs in the SR watershed equaled 56.9 maf each (Table 4). The average annual storage change combined for surface reservoirs and groundwater was 2.0 maf, showing a net depletion. Precipitation was the major annual water input (95%; 54 maf) to the SR watershed; a small amount of water was imported annually from the Trinity River (1.5%; 0.8 maf); and reduction of stored water in reservoirs and groundwater accounted for 3.5% (2.0 maf) of water input. The major outputs in the SR watershed were ET from the montane (47%; 26.7 maf) and valley floor (16%; 9.0 maf) regions, and streamflows to the Delta (34%; 19.5 maf; Figure 3A). The runoff coefficient for the annual average water budget was 0.36 and ranged from 0.23 (2009) to 0.51 (2006) in the SR watershed. A detailed water budget for the SR watershed is included in Appendix A (Table A4).

Table 4 Annual average water budget of the Sacramento River watershed (in maf) for water years 1998–2009

Inputs	Total (maf)	Outputs	Subtotal (maf)	Total (maf)	Change in storage	Total (maf)
Precipitation	**54.0**	Flow to Delta		**19.5**	Groundwater	**–1.8**
		Sacramento River	16.9			
Imports from	**0.8**	Yolo Bypass	2.6		Surface	**–0.2**
Other watersheds		Valley floor evapotranspiration (ET)		**9.0**	Reservoirs	
		Agriculture	6.0			
		Urban	0.6			
		Natural land	2.5			
		Water surface evaporation (E)		**1.4**		
		Reservoir E	1.1			
		Stream E	0.3			
		Montane ET[b]		**26.7**		
		Exports		**0.2**		
Total inputs	**54.9**	**Total outputs**		**56.9**	**Total change**	**–2.0**

b. ET from the montane region was estimated by closing the water budget (see "Methods").

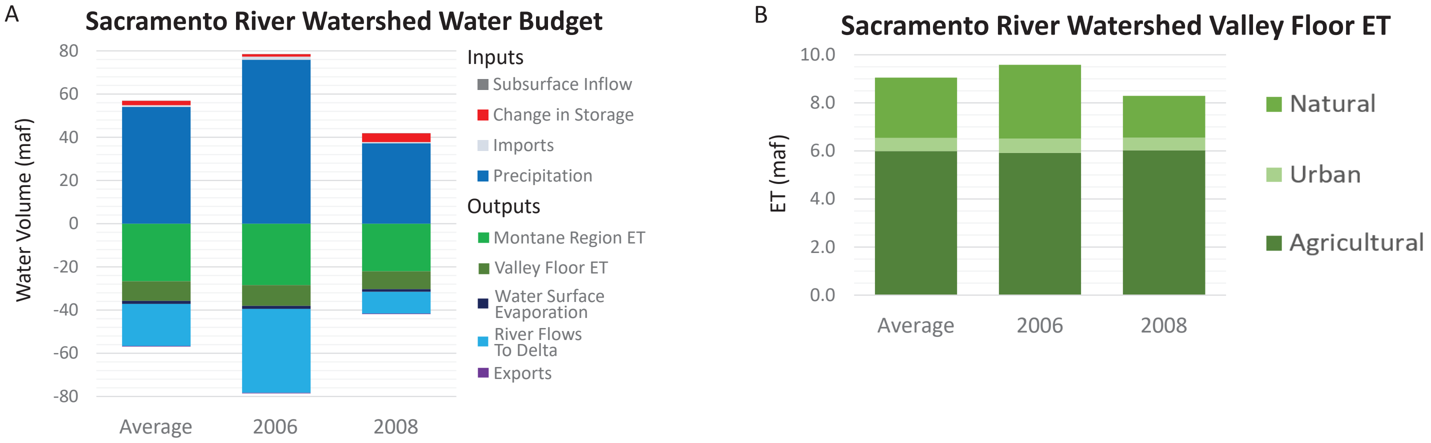

Figure 3 Annual water budgets for the Sacramento River watershed with major water inputs (positive numbers) and outputs (negative numbers) (**A**), and ET in different land use/land cover areas in the valley floor region (**B**), for a multi-year annual average (water years 1998–2009), a wet year (2006), and a critically dry year (2008). Change in storage (red section of the bar) represents a net withdrawal of stored water thus contributing to the water input.

Wet Year (2006)

In a wet water year, the SR watershed had a total water input of 77.3 maf that resulted from much higher precipitation (75.9 maf) and a larger volume of water imported from the Trinity River system (1.4 maf) than the annual average (Figure 3A). River outflows to the Delta through the SR and Yolo Bypass were the largest annual output components, accounting for almost 50% (38.8 maf) of the total output. We estimated ET from the montane region in the SR watershed to be approximately 28.5 maf (36%). The amount of ET in the valley floor region during a wet year (9.6 maf) was similar to the annual average but constituted a smaller proportion (12%) of the total output. Water storage change showed a net depletion (1.2 maf) during the wet year when groundwater depletion (1.6 maf) exceeded reservoir storage gains (0.3 maf). The runoff coefficient was 0.51 (Table 3).

Critically Dry Year (2008)

In a critically dry year, total water input (37.8 maf) was substantially reduced as a result of much smaller amounts of precipitation (37.2 maf; Figure 3A). River outflow (10 maf; 24% of the total) in 2008 was reduced to almost half of the annual average (19.5 maf; accounting for 34% of the total). The valley floor ET (8.3 maf) during the critically dry year was similar to the annual average, but its proportion (22%) to the total annual output was much larger. Water storage lost a combined 4.1 maf during the critically dry year as a result of reservoir storage decreases (2.1 maf) and groundwater overdraft (2.0 maf). The runoff coefficient for the critically dry water year was 0.27 (Table 3).

Valley Floor Evapotranspiration (ET)

Annual ET in the valley floor region of the SR watershed ranged from 8.3 maf (2008) to 10.3 maf (1998). ET from agricultural lands accounted for 66% (6.0 maf) of the total valley floor ET, followed by ET from natural lands (28%; 2.5 maf) and urban areas (6%; 0.6 maf) during the study period (Figure 3B). Agricultural land is the major area of net water depletion because annual ET (6 maf) exceeds annual precipitation (2.8 maf; CDWR 2014) by 3.2 maf in the valley floor region of the SR watershed. ET estimates from agricultural lands (6 maf) and urban areas (0.6 maf) were relatively constant regardless of water-year types (Figure A4A). However, ET estimates from natural lands fluctuated a great deal, ranging from 1.7 maf in a critically dry year to 3.1 maf in a wet year (Figures 3B, A4A).

San Joaquin River Watershed Water Budget

Annual Average (Water Years 1998–2009)

The average annual inputs and outputs for the SJR watershed were 28.7 maf each for the period from 1998 to 2009 (Table 5, Figure 4A). Water storage loss averaged 1.9 maf per year. Precipitation (74%; 21.1 maf) and water imports from the Delta (18%; 5.3 maf) were the major sources of water inputs. Major output components were montane-region ET (41%; 11.6 maf), valley floor ET (24%; 6.9 maf), water exports to other watersheds (19%; 5.6 maf), and streamflows to the Delta (14%; 3.9 maf; Figure 4A). Though the SJR watershed received a large quantity of water from the Delta (5.3 maf), its overall exports (5.6 maf) exceeded its imports (Table 5). The runoff coefficient for the annual average water budget was 0.18 and ranged from 0.07 (2009) to 0.34 (2006). A detailed water budget for the SJR watershed is included in Appendix A (Table A5).

Wet Year (2006)

In a wet year, total water input to the SJR watershed was 34.5 maf as a result of the high precipitation (28.7 maf) and high amount of water imported from the Delta (6.2 maf; Figure 4A). Water output as ET from the montane region (30%; 12.5 maf) was slightly larger than the annual average. River outflows (26%; 9.7 maf), on the other hand, were much higher in the wet year than the annual average. The total water export volume from the SJR watershed in the wet year (6.9 maf) was higher than the annual average (5.5 maf), but its proportion to the total output (19%) was lower. The amount of ET in the valley floor region (7.2 maf) was similar to the annual average but constituted a smaller proportion (19%) in the wet year. The combined water storage change showed a net depletion (1.2 maf) in the wet year, with groundwater depletion (1.9 maf) exceeding reservoir storage gains (0.2 maf). The runoff coefficient for water year 2006 was 0.34 in the SJR watershed (Table 3).

Critically Dry Year (2008)

In a critically dry water year, total water input (19.4 maf excluding the input through groundwater depletion) was much smaller than the 12-year annual

Table 5 Annual average water budget of the San Joaquin River watershed (in maf) for water years 1998–2009

Inputs	Subtotal (maf)	Total (maf)	Outputs	Subtotal (maf)	Total (maf)	Change in storage	Total (maf)
Precipitation		**21.1**	Flow to Delta		**3.9**	Groundwater	**−1.8**
			San Joaquin River	3.0			
Imports from Delta		**5.3**	Eastside tributaries	0.9		Surface	**−0.1**
CVP	2.4		Valley Floor ET		**6.9**	Reservoirs	
SWP	2.8		Agriculture	5.2			
Other imports	0.1	**0.1**	Urban	0.4			
Subsurface inflow	0.1	**0.1**	Natural land	1.3			
			Water Surface E		**0.7**		
			Reservoir E	0.5			
			Stream E	0.1			
			Montane ET[a]		**11.6**		
			Exports		**5.6**		
			South Bay Aqueduct	0.2			
			Mokelumne Aqueduct	0.2			
			Hetch Hetchy Aqueduct	0.3			
			Pacheco Tunnel	0.1			
			Friant–Kern Canal	1.0			
			Fresno Slough	0.1			
			California Aqueduct (SWP)	2.7			
			California Aqueduct (CVP)	0.9			
Total inputs		**26.6**	**Total outputs**		**28.7**	**Total change**	**−1.9**

a. ET from the mountain ranges was estimated by closing the water budget (see "Methods").

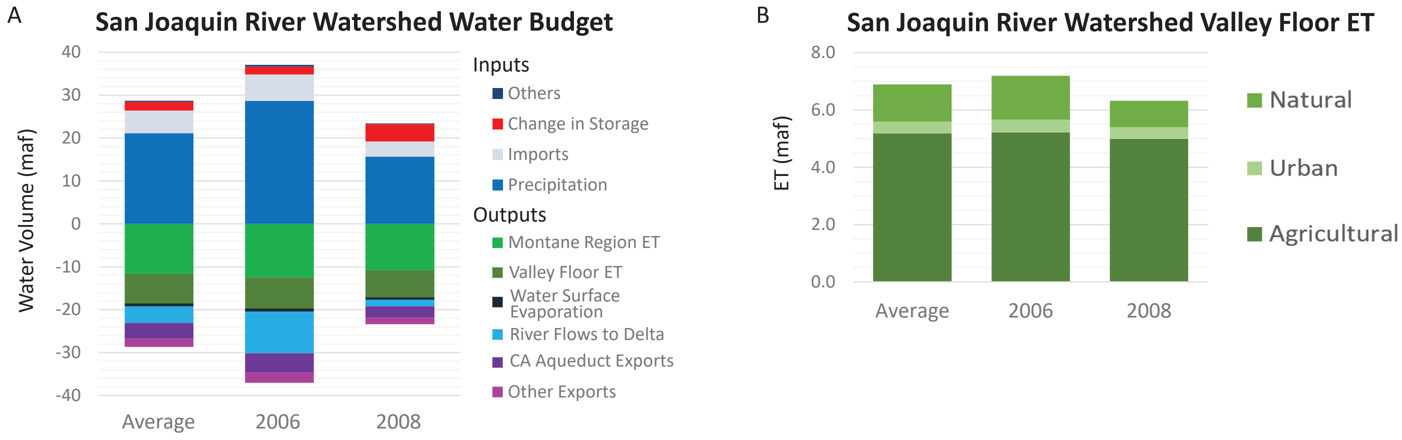

Figure 4 Annual water budgets for the San Joaquin River watershed (**A**), and ET estimates in different land use/land cover areas in the valley floor region (**B**). Figure explanations are the same as Figure 3.

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average (27.1 maf) because of lower precipitation (15.7 maf) and reduced imports from the Delta (3.5 maf; Figure 4A). ET estimates from the montane region (46%; 10.8 maf) and valley floor region (27%; 6.3 maf) of the SJR watershed accounted for the largest water outputs in the critically dry year. Water exports from the system (18%; 4.2 maf) were important output components, and exceeded river outflows (7%; 1.5 maf). Groundwater overdraft (3.0 maf) and reservoir storage decreases (1.0 maf) contributed to the large water storage loss (4.0 maf) in the critically dry year. The runoff coefficient was 0.10 (Table 3).

Valley Floor ET

ET in the valley floor region of the SJR watershed ranged from 6.3 maf (2008) to 7.9 maf (1998) annually. ET from agricultural lands was the largest water output component (5.2 maf), accounting for 75% of the valley floor ET, followed by natural lands (1.3 maf; 19%), and urban areas (0.4 maf; 6%; Figure 4B). Agricultural land in this region produced a high net depletion because the annual ET exceeded precipitation in the agricultural land by 3.4 maf (the precipitation was derived from C2VSim input data). Although ET estimates from agricultural lands (~5.2 maf) and urban areas (~0.4 maf) in the valley floor region were relatively stable across different water years, those from natural lands varied from 0.9 maf in the critically dry year (2008) to 1.5 maf in the wet year (2006; Figure 4B).

DISCUSSION

Effective water resources management requires information on water availability, storage, and flows. A water budget integrates and summarizes this information so it can be used to inform water management actions, including allocating water for the environment (Carrillo–Guerrero et al. 2013; Escriva–Bou et al. 2016; Hanak et al. 2017). The water budgets presented here compare how different regions of the Delta watershed (e.g., Sacramento River versus San Joaquin River and montane versus valley regions) differ from each other, as well as how they are interconnected (Figure 5). This information is vital for managing a watershed at this scale, which requires recognizing both the unique management needs and opportunities of different sub-regions, and the inter-connected nature of all these unique sub-regions.

The water budgets presented here are meant to inform high-level planning and understanding at the watershed scale, rather than capture all information needed for detailed water operations. Many management decisions benefit from—or even require—water budgets at fine time-scales, such as irrigation or daily reservoir operations. However, such a level of detail would not fulfill this paper's goal of providing a comprehensive yet easily understandable reference of the major sources and losses of water within the Delta watershed in recent years. The annual water budgets presented here provide important baseline data (including examples of wet and dry extremes) that give the context needed for better understanding the relative effects of stressors such as climate change or shifting land use. In addition, many data sets have greater levels of certainty at annual rather than sub-annual scales (as discussed below), and therefore the data presented here are less uncertain than a monthly or weekly water budget.

Examining other water budgets helps to illustrate this paper's potential benefits. Water budgets that quantify the water balance at the geographic scale of the Delta watershed (154,000 km^2) are rare, although water budgets for the Murray–Darling Basin (MDB) of Australia (Guerschman et al. 2008; Kirby et al. 2008) have been prepared that span 1990 through 2006. At 1,000,000 km^2, the MDB is comparable in geographic scale to this study's effort to develop comprehensive water budgets for the Delta and its two major contributing watersheds: the SR and SJR watersheds. Like the Delta watershed, most of the precipitation falling in the MDB evaporated or transpired within the watershed. However, outflow was a much smaller component of the water budget compared to the Delta, with only 1.2% of the precipitation within the MDB discharged to the Southern Ocean (Guerschman et al. 2008). The high level of water consumption within the MDB illustrates why the Australian government needed a water budget to "inform establishment of a new sustainable diversion limit for surface and groundwater" (Kirby et al. 2008). This demonstrates the importance of quantifying water availability, in the form of a water budget, to manage water resources sustainably. As does this

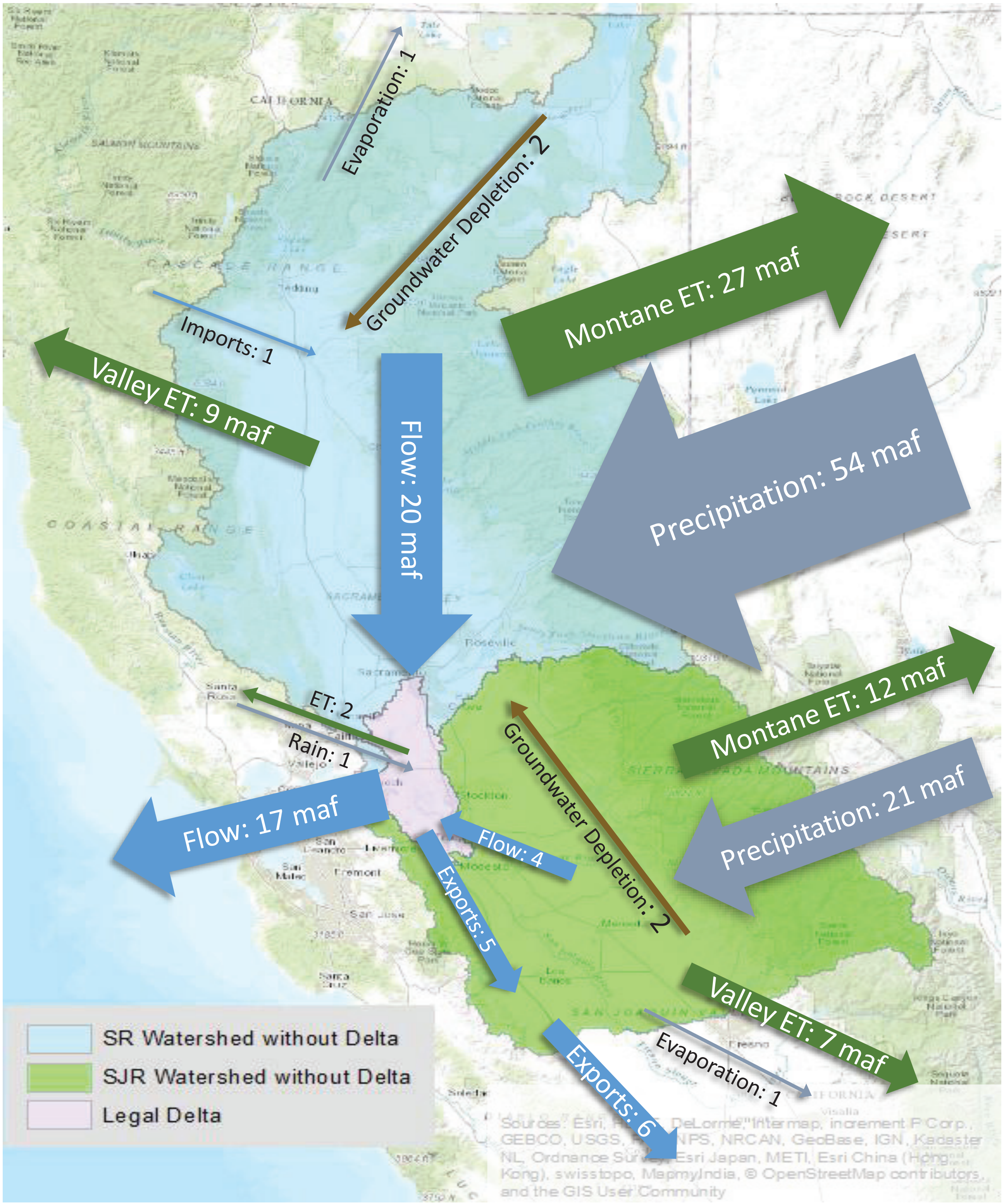

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Figure 5 Major movements of water in and out of each watershed (Delta, Sacramento River, and San Joaquin River) averaged from 1998–2009. All values are rounded to the nearest maf, and only values of at least 1 maf are shown. Arrows denote direction in or out of each watershed, rather than exact flow directions. Details are given in Tables 2, 4, and 5.

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paper, the water budgeting exercise for MDB helped identify uncertainty in the components and generated suggestions for future improvements to reduce the uncertainties (Kirby et al. 2008).

Insights From the Water Budgets of the Three Regions

Water budgets for the Delta and the SR and SJR watersheds provided some unique insights about large-scale inter-annnual variablility and stability of managed flows and uses. This increased understanding of the hydrological dynamics of the system is fundamental to effective water resources management.

Inter-Annual Variability

For the water budgets constructed for all three of our study areas, water input and output components demonstrated considerable inter-annual variability (Figures 2-4). We primarily observed larger inter-annual variabilities in natural systems compared to managed systems (Figures 2-4, A4, and A5). Within the 12 water years we considered, the year with the highest precipitation received more than 2.5 times the precipitation volume of the lowest precipitation year in both the SR and SJR watersheds. ET from natural lands varied a good deal, depending on the water-year type in all watersheds (Figures 2B, 3B, 4B, A4, and A5), with annual ET from natural landscapes varying 3-fold and 2-fold in the Delta and in its contributing watersheds, respectively. River flows varied even more greatly: there were 6.9-, 3.9-, and 8.6-fold differences between the maximum and minimum annual flows in Delta outflow, SR flow to the Delta, and SJR flow to the Delta, respectively.

This variability is attributable to California's highly dynamic and variable climate, especially its precipitation patterns, which is typical of a Mediterranean climate region (Dettinger et al. 2011). Data from more recent years show that during 2014–2017 the Delta experienced high and low annual inflow values slightly outside the range of what was measured during the 1998–2009 study period (Figure A3). This is an important reminder that water budgets using historical data should not be expected to always capture the full range of conditions that could occur. Such water budgets, however, are still valuable tools for understanding the big-picture relationships between different regions and different water budget components. For example, if our analysis had extended from 1998 to 2017, the mean annual Delta inflows and outflows would only have been 4% (~1 maf) smaller, which is dwarfed by these values' inter-annual variability.

Although the analyses presented earlier provide examples of the range in values possible between some wet and dry years, it is important to bear in mind water balance responses to climate can still vary, even within years of similar precipitation. For example, two consecutive wet or above-normal years (2005 and 2006) showed different responses in surface reservoir storage, flows, and import–export, even though water consumption patterns were similar. During the first wet year (2005), the surface reservoir storage increased much more than in the second wet year (2006) in the SR and SJR basins (Tables A4 and A5). This likely resulted from reservoir refilling in the first wet year, thereby precluding the ability to further store additional water in the second year. This difference in reservoir status in the 2 years explains the larger inflow to and outflow from (>100% higher outflow) the Delta in 2006 compared to 2005. In the SJR watershed, the export in 2006 slightly decreased from 2005. This can be explained by reduced water demand in the recipient region. In wet years, the water management system in the Delta watershed stores water when storage space is available, while allowing water to continue flowing to the sea when storage is full.

In the consecutive dry or critically dry years of 2007 and 2008, surface storage decreased much more in the first dry year, possibly because of the high reservoir storage at the beginning of 2007 (Tables A4 and A5). Through-Delta CVP and SWP water transfers to the SJR watershed and further south decreased more in 2008. Though the inflow to the Delta decreased from 13.2 maf in 2007 to 11.5 maf in 2008, the outflow from the Delta was slightly higher in 2008 (Table A2). During the dry years, surface water components related to human water uses, such as import–export and surface reservoir storage, can be affected more than other components by the previous year's condition.

Stability

Compared to natural systems, managed flows and uses in the Delta watershed demonstrated a remarkable degree of stability (Figures 2–4 and A4). Total volumes of water exported from the facilities in the Delta (CVP and SWP) were relatively stable during the 12 data years, fluctuating by 1.8-fold between the largest and smallest export years compared to much larger relative fluctuations in streamflow (Figure 2A). Data over longer time-periods show a decrease in exports during the 2013–2016 drought years, which is slightly greater than the decrease experienced during the dry year 2008 (Figure A3). Because of the time-period restrictions of our data set, our full analysis does not cover this extended drought period, which should be kept in mind when the numbers presented here are used.

A similar stable water use trend was evident in the valley floor regions of the Delta watershed (Figures 2B, 3B, and 4B), because overall consumption from agricultural and urban land varied little in proportion to the variations in precipitation and streamflow. Urban consumptive use (based on C2VSim ET estimates) remained around 0.6 maf and 0.4 maf in the SR and SJR regions, respectively, during the 12-year period. There was no clear upward trend of urban water consumption during this period (Figure A2), despite increasing urban areas and populations in the region (population increased from 4.33 million in 2000 to 5.08 million in 2010 in the SR and SJR hydrologic regions; CDWR 2014a). The annual maximum to minimum ratio during the 12-year period was 1.3 for both regions. This indicates that the pattern of urban water consumption might have changed over time, potentially as a result of water conservation measures mandated after major droughts. This period of steady urban water consumption falls within a longer trend of increasing urban water consumption correlated with urban expansion (according to C2VSim output for 1922–2009; Figure A2), and thus our analysis might be different if the water budget were calculated over a longer time-period. More detailed descriptions in the model's documentation (Brush et al. 2013) of the methods used to calculate urban consumptive water use would allow for a more robust analysis.

Average ET estimated in the agricultural lands in the valley floor regions (C2VSim) were 1.0, 6.0, and 5.2 maf in the Delta, SR watershed, and SJR watershed, respectively (Figures 2B, 3B, and 4B). The annual maximum to minimum ratio of agricultural water consumption was less than 1.1 for all three regions during the 12-year period. This pattern of relatively stable water consumption by agriculture regardless of varying precipitation reflects, in part, storage depletion in dry years and changes in crop composition that have occurred in the Central Valley. Though the total cropland area decreased slightly in the state, the perennial cropland area increased, and the annual cropland area decreased from 1992 to 2009 (Wilson et al. 2016). Permanent tree and vine crops require constant irrigation regardless of the water-year type. Indeed, the inter-annual agricultural ET variation in the Delta watershed obtained from C2VSim has become more stable since the mid-1990s (Figure A2). C2VSim uses crop area time-series data as an input to calculate ET. However, it does not produce outputs of ET per crop (or at least not publicly released in CDWR 2014). Analysis of annual ET from each crop over time would provide additional insight into how agricultural activities affect the water budget, and providing this more detailed information would likely require only slight modifications to C2VSim or similar models.

Runoff Coefficients and Comparisons to Smaller California Watersheds

The watershed-level runoff coefficient, or the fraction of annual precipitation that leaves the catchment as runoff (Q/P), highlighted the high water consumption areas (such as the SJR basin and the valley floor) and water-generating areas (such as the SR basin and the upper watersheds). The runoff coefficienct provides information on the scope of in-basin water consumption and can inform water policies, including the development of environmental flows. For the entire Delta watershed, including the SR and SJR watersheds, 23% (range: 11%–39%) of precipitation was discharged as Delta outflow, and the remaining 77% was used (via ET) within the basin or exported to other regions. Subdividing the discharge and precipitation by basin showed that Q/P ratios for the SR watershed were much higher (average: 0.36; range: 0.23–0.51) than for the SJR watershed (average: 0.18; range: 0.07–0.34). Lower Q/P ratios in the SJR than in the SR watershed clearly showed that a larger proportion of water from the SJR watershed is consumed within it or exported to other watersheds before it reaches the Delta.

Several water budgets have been constructed for small watersheds in the Sierra Nevada Mountains of California. The Q/P ratios from these upland watersheds were higher than those for the SR and SJR watersheds. The Upper Kings River basin (within Tulare Lake basin, adjacent to the southern end of the SJR watershed) produced 57% of precipitation (984 mm y^{-1}) as streamflow, on average (Goulden et al. 2012). Smaller mountain watersheds (1.4–2.2 km^2) in the American River and Merced River watersheds (within the SR and SJR watersheds, respectively), had highly variable Q/P ratios that ranged from 25% to 61%, depending on the annual precipitation (Saksa et al. 2017). Water data measured for these watersheds reflected the natural hydrologic processes occurring in the Sierra Nevada. The higher Q/P ratios observed in these upper watersheds, when compared to the whole SR and SJR watersheds, demonstrate the importance of upland watersheds for providing water to the Central Valley, which has a much greater magnitude of human-dominated water consumption.

Delta Water Data Limitations

We derived the water data used to construct the Delta water budget from many disparate sources that different agencies and research groups measured (e.g., gauges) or estimated (e.g., models). Each data set has unique sources of uncertainty. For most water budget components, however, this uncertainty is relatively small.

Flows to the Delta, and exports from it, are measured directly using a variety of techniques (CDWR c2017c); thus, they represent the most accurate parameters in the water budget. Precipitation input directly to the Delta is estimated using seven rain gauges located throughout the Delta and spatially interpolating to the entire area, therefore potentially missing fine-scale spatial variations in precipitation.

Consumptive water use, often used interchangeably with ET, from the Delta is estimated using the DICU model (Mahadevan 1995). The DICU model is essentially a bookkeeping system that tracks water that enters, leaves, or is stored in the system on a monthly time-step. Factors such as precipitation, seepage, ET, irrigation, soil moisture storage, leach water, runoff, crop type, and acreage are used to estimate consumptive use (Mahadevan 1995). The DICU model estimates Delta ET using fixed, long-term, monthly average ET values for different land use types based on surveys conducted in the late 1970s and early 1980s, which are adjusted monthly using average pan evaporation data measured at a single location in the Delta. The limitations of using DICU-derived ET include using pan evaporation from a single location to represent spatial variations in the Delta and using a monthly time-step. For more effective water management decisions and policy-making, a more accurate estimation is needed of consumptive use of water in the Delta—particularly ET—along with other hydrologic estimates. For example, the Delta Evapotranspiration of Applied Water (DETAW) model was developed to better estimate consumptive use with a daily time-step in the Delta (Kadir 2006). However, we did not use it here to estimate Delta consumptive water use because of the uncertainties related to water seepage from the channels to the islands and groundwater uptake. In addition, a recent comparative study of consumptive water use measurements for agricultural land in the Delta aims to reduce the information gaps and uncertainties associated with estimating Delta ET (Medellín–Azuara et al. 2018). Because that study only covers 2015–2016, does not include the entire legal Delta, and the agricultural area has changed over time, we cannot directly compare it to the Delta agricultural ET estimates we use here. However, it shows that a suite of models all estimated Delta agricultural ET to be approximately 1.4 maf in each of those years, with 527,603 acres of agricultural land in 2015 and 521,612 acres in 2016. This is equivalent to annual ET values of 84 mm in 2015, and 81 mm in 2016 (Medellín–Azuara et al. 2018). The average annual ET from agricultural land (339,474 acres) estimated by C2VSim for 1998–2009 is roughly 1.0 maf or 88 mm. To understand where this difference comes from—although the two estimates of ET in mm yr^{-1} agree within 10%—the land use maps need to be compared in more detail. Medellín–Azuara et al. (2018) also found that mean departure of individual models from the ensemble mean was approximately

6.5% for annual ET, while discrepancies between models was larger at shorter time-scales, which has important implications for uncertainty in consumptive use estimates.

We used the Net Delta Outflow Index (NDOI), a parameter in Dayflow (CDWR c2015), as the river outflow estimate for the Delta. The NDOI is estimated as a water balance between tributary inflows (inputs), and channel depletion (DICU) and water exports (outputs), and does not consider the tidal fluctuations of water in the Delta. Thus, NDOI ignores the effects of tidal fluxes. Net Delta Outflow (NDO), a generic term for the computed sum of tidally filtered flows at four flow stations (Dutch Slough, Jersey Point, Rio Vista, and Threemile Slough) at the western edge of the Delta, is also estimated. NDOI and NDO often provide very different flow estimates, although these differences are less important on an annual scale (CDWR c2017b). CDWR prefers the NDOI over the NDO based on its greater clarity and general utility for regulatory purposes (Sandhu et al. 2016). We used the NDOI here because the NDO calculation requires data from ultrasonic velocity meters at the four monitoring stations, and these data are not available for some parts of our study period. Estimation of Delta outflow could be improved through direct metering of channel diversions and return flows, more detailed estimates of consumptive use, and accurate flow measurements using more advanced technologies (Fleenor et al. 2016).

Fully understanding the management implications of the Delta's river outflow values may require greater context than that provided by total numbers alone. For example, Mount et al. (2018) showed that, averaging from 1998–2009, 27% of Delta outflow to San Francisco Bay comprised flows necessary to maintain in-Delta salinity low enough for human use; 16% was solely for ecosystem purposes; and 57% was uncaptured water (calculated from associated data available from Gartrell et al. 2018). When using the full record from Mount et al. (2018) that spans 1981–2016, these averages change by less than seven percentage points. Although the water budgets we present earlier valuable high-level context, details such as those presented by Mount et al. (2018) and by monthly water budgets are necessary for detailed planning purposes. For example, our water budgets show the amount of potential water that could be gained from reducing ET, but availability of the saved water for downstream users or through-Delta export (if that was the goal) depends on the year, or the time of the year, because there are uncapturable outflows even during critically dry years (SWRCB 2015; Mount et al. 2018).

SR and SJR Water Data Limitations

Precipitation

We estimated watershed-wide precipitation in the water portfolios using PRISM (NACSE c2018) and gauged data. PRISM estimates precipitation by interpolating the precipitation gauge network data using topographic information and inverse distance weighting. Uncertainties in estimating precipitation depend on the density of rain gauges and topological and atmospheric complexities that affect model interpolation. Differences between PRISM estimates and actual precipitation are likely higher in the high-elevation sites that have complex topography (where most of California's precipitation falls; see Table A8) because the few gauging stations in such areas cannot always capture spatial variations in precipitation (Jeton et al. 2006; Henn et al. 2018). Anderson et al. (2012) assumed the uncertainty of annual precipitation to be 10% and monthly precipitation to be 15% for PRISM-based estimates in the Central Valley region. (These assumptions were based on studies conducted in Nevada, and the degree of uncertainty in the Delta watershed could be different.) It is possible that the uncertainty might have been reduced by CDWR's additional use of gauged data, although documentation of their methods does not provide enough information to determine this, or to allow further analysis. Remote-sensing technology, along with a more advanced sensor network with more densely-spaced precipitation gauges, would help reduce the uncertainty in estimating precipitation and hydrology (Daly et al. 2017; Zhang et al. 2017).

Storage

Storage can be separated into surface storage (reservoirs) and groundwater storage (aquifers). In the Delta watershed, reservoir storage is estimated daily based on reservoir basin topography, hydrologic measurements (inflows, outflows, and diversions) and

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modeling, and lake surface evaporation (CDWR c2017d). Information on the accuracy of reservoir storage change was not available. However, given the accuracies of basic hydrologic and geomorphic parameters, reservoir storage change can be estimated with relatively high confidence (e.g., McPherson et al. 2011).

Estimating groundwater storage and its temporal change at the watershed-level remains highly uncertain. We used annual groundwater change data provided by the water portfolios because this is the only groundwater data set available at the spatial scale of our study that includes the montane regions. The water portfolios estimate groundwater storage change as the difference between water extracted from and water recharged into the groundwater basins in managed landscapes in a region (CDWR 2014a). However, this estimation only addresses human-directed water movements and does not consider natural recharge processes or stream–groundwater exchanges.

Previous studies have focused mostly on groundwater storage in the Central Valley floor, under the assumption that montane groundwater storage is negligible (Famiglietti et al. 2011; Anderson et al. 2015). However, a recent study (Xiao et al. 2017) estimated groundwater change for the entire Central Valley basin and the montane regions (SR, SJR, and Tulare basins) using the water balance method for 2002 to 2016. However, their estimates of change in montane groundwater varied from 120 maf of net recharge to 100 maf of net depletion, depending on the specific model used, indicating high uncertainty in these values. We believe that ours is the only current study that systematically estimates groundwater storage change for the entire watershed, including the Central Valley and non-valley regions. Xiao et al. (2017) found that the upland regions contributed a significant portion of overall groundwater storage. The temporal dynamics were also different from the valley floor region.

Because of the difficulties of estimating groundwater storage changes, levels of uncertainty are most readily assessed by comparing estimates that use different methods. Xiao et al. (2017) demonstrated how different methods and time-periods can provide greatly varying estimates of groundwater change for the Central Valley. For water years 2003–2010, they estimated 0.5 maf yr^{-1} of recharge based on a water balance approach, and 3.7 maf yr^{-1} of depletion using GRACE data. (The Gravity Recovery and Climate Experiment [GRACE] was a joint mission of NASA and the German Aerospace Center.) Xiao et al. (2017) suggested that the GRACE-based data did not show recovery of groundwater storage during the non-drought years that was evident in the water balance approach. This might be a result of errors associated with the spatial resolution or measurement footprint and the time truncation of the GRACE data (Wahr et al. 2006; Kuss et al. 2012; Landerer and Swenson 2012; Xiao et al. 2017). Even different methods using the same data set can provide disparate results. For example, another study using GRACE data estimated a depletion of 2.5 maf yr^{-1} from October 2003 to March 2010 in the Central Valley (Famiglietti et al. 2011)—32% less than what Xiao et al. (2017) estimated over nearly the same time-period.

As mentioned earlier, different methods used to assess groundwater change in the Central Valley and its watershed can result in greatly varying estimates (Table 1; Lund 2016). Substantial variations also depend on the specific geographic area and time periods covered (Table 1). To reduce the uncertainties associated with this parameter, more comprehensive and systematic approaches to estimate groundwater storage are clearly needed. The GRACE satellite mission provides a promising new data set for measuring groundwater storage changes, but its spatial resolution is too coarse for studies at scales smaller than the entire Central Valley (including the Tulare basin, which has a much higher groundwater depletion rate than the SR and SJR watersheds) and still has an uncertainty of approximately 20% (Anderson et al. 2012). California passed the Sustainable Groundwater Management Act (SGMA) in 2014 to improve groundwater management. SGMA requires groundwater-dependent regions, especially in the region classified as critically overdrafted, to halt overdraft and bring basins into balanced levels of pumping and recharge (CDWR c2018b); this will require groundwater levels to be monitored, and surface water and groundwater models to be developed. Implementation of SGMA should improve the accounting and preservation of groundwater resources in the Central Valley and California. However, most montane regions are not considered critically overdrafted under SGMA, and separate efforts to account for groundwater storage in the montane regions must be implemented to improve water budget accuracy. Advancements in ET estimation through a combination of different approaches in the montane region discussed below can also help improve estimates of changes in groundwater storage in the montane regions.

Valley Floor ET

We used C2VSim model output to determine consumptive use in the valley floor of the Delta watershed. Although this model provides the best available estimates of these types of water use in this region, modeled values cannot provide the same level of certainty as would be possible if more complete measurements of actual consumptive use were available for inclusion in this water budget.

Montane Region ET

The montane regions (upland regions above the valley floor) potentially represent the largest output component in both the SR and SJR watersheds, but are also highly uncertain.

Previous studies have estimated ET rates in smaller montane sub-watersheds within the SR and SJR watersheds (e.g., Jeton et al. 1996; Dettinger et al. 2004; Koczot et al. 2005; Goulden et al. 2012). However, direct extrapolations of ET rates from these smaller areas to the entire montane region of SR and SJR watersheds are not practical because montane ET rates are affected by changes in environmental conditions (soil moisture content, temperature, solar radiation, etc.) and in vegetation composition along the elevation gradient (Armstrong and Stidd 1967; Goulden et al. 2012; Goulden and Bales 2014). Approaches to spatially extrapolate the field-estimated ET rates to the larger areas are available through remotely sensed environmental data. Goulden et al. (2012) estimated ET in the Upper Kings River basin (3,998 km^2, 1,544 mi^2) using spatial interpolation with an empirical relationship between remotely sensed vegetation index and ET rates measured with flux towers. Given that the Upper Kings River basin covers a relatively large watershed area and elevation range (285–4,313 m), a similar method possibly could be used to estimate montane region ET in the larger SR and SJR watersheds.

Remote sensing provides another option for large-scale estimates of ET. For example, a global 500-m-resolution ET data set calculated from Moderate Resolution Imaging Spectroradiometer satellite data (MODIS) is available for the years 2001 onward (Running et al. 2017). Although extremely useful for many applications, this data set has a 24% mean error when compared to flux tower measurements (which themselves have a 10–30% uncertainty range), which could lead to large total errors over our study area (Mu et al. 2011). The sparsity of flux towers also makes it difficult to ascertain the true levels of uncertainty for this type of data set. Unfortunately, annual-scale data are currently unavailable for this data product because of input data issues, and therefore we could not compare values for this paper (Running et al. 2017). We could not use data that used shorter time-scales to compare to our other estimates of ET because they contained too many gaps from cloud cover.

Future studies employing remote-sensing data, land surface models, groundwater monitoring, and field ET measurements—along with calibration for local environmental conditions and vegetation changes (Guerschman et al. 2008; Famiglietti et al. 2011; Anderson et al. 2012; H. Wang et al. 2014; S. Wang et al. 2014; Wan et al. 2015; Lv et al. 2017; Xiao et al. 2017)—would improve ET estimation in large-scale montane regions. Practices such as mechanical thinning, controlled burns, and managing (rather than suppressing) wildfire are gaining increased attention as practices that can effectively reduce ET, resulting in increasing streamflow and/or groundwater recharge (Boisramé et al. 2017; Saksa et al. 2017). Comprehensive measurements of ET in the Sierra Nevada watersheds would better inform the extent of such forest management practices (Conklin et al. 2015; Downing 2015).

To develop a better water budget in the future, it is important to improve the measurement of components that are large in scale and uncertain. Precipitation and montane ET are the components that have relatively large uncertainty and scale (Table 6). Also, information on groundwater in the montane region is currently very limited, making it

Table 6 Comparison of scale and uncertainty of major water budget components. Orange, green and blue indicate large, medium, and small size of the components and uncertainty.

Major water budget components	1998–2009 annual average from Tables 1, 3, and 4 (maf)			Relative scale to the other components	Uncertainty description
	Delta	SR	SJR		
Precipitation	0.8	54.0	21.1	Large	🟩 10%–15% uncertainty on PRISM in Central Valley (Anderson et al. 2012), higher uncertainty in montane regions (Henn et al. 2018).
Stream flows	inflow 23.4, outflow 17.1	outflow 19.5	outflow 3.9	Large	🟦 Measured by gauges and likely with low uncertainty in annual scale.
Imports and exports	5.4	import 0.8, export 0.2	import 5.4, export 5.6	Medium	🟦 Measured by gauges and likely with low uncertainty.
Montane ET	N/A	26.7	11.6	Large	🟧 One of the most uncertain components as it is the residual in the water budget.
Valley floor agricultural ET	1.0	6.0	5.2	Medium	🟦 Relatively reliable as C2VSim and Medellín–Azuara et al. (2018) shows decent agreement for Delta (<10% error when assessed in annual ET in depth).
Valley floor natural land and urban ET	0.5	3.1	1.7	Small	Insufficient Information
Groundwater in montane region	N/A	-0.2	0.0	Small	🟦 Possibly small as the water portfolios and Xiao et al. (2017) show a relatively small difference (Table 1), but very limited information is available.
Groundwater in the valley floor	0	−1.6	−1.8	Small	🟧 Large uncertainty exists as water portfolios show >5 times more depletion than C2VSim.

difficult to assess this component's importance to water budgeting in the Delta watershed (Table 6).

CONCLUSIONS

High-quality water data for California is available from many sources, but uncertainties surrounding some water budget components (e.g., ET and groundwater storage, and other data sources if they are at fine time-scales) may still affect their usefulness for informing water management decisions in the Delta and California. In this study, we constructed water budgets for the legal Delta and the Sacramento River and San Joaquin River watersheds using water data available from disparate sources. This approach of comparing multiple data sources for each component—when possible—and assessing the respective uncertainties is beneficial because it identifies future areas where data collection and analysis should be improved.

The degree of certainty associated with the majority of the water budget data for the Delta watershed is high; this is because the data are either directly measured or are estimated using models that have high certainties (Table 6). California maintains a comprehensive water monitoring network, and detailed water measurement data for reservoir storage and streamflows are available (CDWR c2018c). However, groundwater storage change and ET (especially in the montane regions) are not systematically measured or regularly reported, and precipitation measurements are sparse at high elevations, leading to greater uncertainty. Improvement in data collection, research, and synthesis for these uncertain water budget components is necessary to build a more detailed and accurate water budget.

The budgets we present here reveal higher variability of annual ET from naturally vegetated areas compared to urban and agricultural ET (Figures 2B, 3B, 4B, and A4). The proportion of total available water that is exported from or used in the Delta also varies greatly between wet and dry years (Figures A6, A7). The relative stability of urban and agricultural consumptive use compared to the high variability of precipitation and streamflow (Figures A4, A5) demonstrates the importance of year-to-year water storage to California's water system. Models show storage depletions in both the SR and SJR basins even in wet years (Figures 2A, 3A, and 4A), suggesting that sustainable water use will require either fewer withdrawals from storage or increases in water stored. Active groundwater recharge, conjunctive use, and wetland restoration are some of the management actions that can reverse groundwater depletion (Hunsaker et al. 2015; Scanlon et al. 2016).

In this paper we focus on long-term average and inter-annual variability in water supply and consumption that can inform long-term planning and policy-making, but variations within years are also important for effective day-to-day water resource management. This is especially true in California, where precipitation is concentrated in the winter months. Unfortunately, comparisons between different data sources show that estimates for many water budget components (especially Delta outflow, precipitation, and ET) are more uncertain at monthly than at annual time-scales. Therefore, verifying and improving the accuracy of water budgets at finer time-scales (e.g., monthly rather than annual) is an important next step for informing decision-makers about water management options and their consequences.

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REFERENCES

Anderson RG, Lo M–H, Famiglietti JS. 2012. Assessing surface water consumption using remotely-sensed groundwater, evapotranspiration, and precipitation. Geophys Res Lett. [Internet]. [accessed 2017 Nov 3]; 39(16). *https://doi.org/10.1029/2012GL052400*

Anderson RG, Lo M–H, Swenson S, Famiglietti JS, Tang Q, Skaggs TH, Lin Y–H, Wu R–J. 2015. Using satellite-based estimates of evapotranspiration and groundwater changes to determine anthropogenic water fluxes in land surface models. Geosci Model Dev [Internet]. [accessed 2019 Mar 29]; 8(10):3021–3031. Available from: *https://www.geosci-model-dev.net/8/3021/2015/* *https://doi.org/10.5194/gmd-8-3021-2015*

Armstrong CF, Stidd CK. 1967. A moisture-balance profile on the Sierra Nevada. J Hydrol [Internet]. [accessed 2018 Feb 27]; 5:258–268. Available from: *https://www.sciencedirect.com/science/article/pii/S0022169467801057* *https://doi.org/10.1016/S0022-1694(67)80105-7*

Batchelor C, Hoogeveen J, Faures J, Peiser L. 2016. Water accounting and auditing—a sourcebook. FAO Water Reports 43 [Internet]. [accessed 2017 Oct 26]. Available from: *http://www.fao.org/land-water/water/water-management/water-accounting/en/*

Boisramé G, Thompson S, Collins B, Stephens S. 2017. Managed wildfire effects on forest resilience and water in the Sierra Nevada. Ecosystems 20(4). *https://doi.org/10.1007/s10021-016-0048-1*

Brush CF, Dogrul EC, Kadir TN. 2013. Development and calibration of the California Central Valley Groundwater–Surface Water Simulation Model (C2VSim), Version 3.02-CG. [Internet]. [accessed 2016 May 16]. [Sacramento (CA)]: California Department of Water Resources. Technical Memorandum. Available from: *http://baydeltaoffice.water.ca.gov/modeling/hydrology/C2VSim/download/C2VSim_Model_Report_Final.pdf*

CDWR: California Department of Water Resources. 2014a. California water plan update 2013. [Internet]. [accessed 2017 Jul 5]. [Sacramento (CA)]: CDWR. Available from: *https://water.ca.gov/Programs/California-Water-Plan/Water-Plan-Updates*

CDWR: California Department of Water Resources c2014b. C2VSim: California Central Valley groundwater–surface water simulation model. [Internet]. [accessed 2016 Sep 28]. [Sacramento (CA)]: CDWR. Available from: *https://water.ca.gov/Library/Modeling-and-Analysis/Central-Valley-models-and-tools/C2VSim*

CDWR: California Department of Water Resources. c2015. Dayflow. [Internet]. [accessed 2015 Jul 17]. [Sacramento (CA)]: CDWR. Available from: *https://www.water.ca.gov/Programs/Environmental-Services/Compliance-Monitoring-And-Assessment/Dayflow-Data*

CDWR: California Department of Water Resources c2017a. Chronological reconstructed Sacramento and San Joaquin Valley water year hydrologic classification indices. [Internet]. [accessed 2018 Nov 29]. Available from: *http://cdec.water.ca.gov/cgi-progs/iodir/WSIHIST*

CDWR: California Department of Water Resources c2017b. Net Delta outflow vs net Delta outflow index. [Internet]. [accessed 2018 Nov 24]. Available from: *https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Environmental-Services/Compliance-Monitoring--Assessment/Dayflow/Files/Publications/Dayflow-Net-Delta-Outflow-vs-Net-Delta-Outflow-Index.pdf*

CDWR: California Department of Water Resources c2017c. Dayflow: an estimate of daily average Delta outflow. [Internet]. [accessed 2019 Apr 1]. Available from: *https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Environmental-Services/Compliance-Monitoring--Assessment/Dayflow/Files/Publications/Current-Dayflow-Documentation.pdf*

CDWR: California Department of Water Resources c2017d. Active daily reservoir data. [Internet]. [accessed 2017 Oct 1]. Available from: *http://cdec.water.ca.gov/misc/daily_res.html*

CDWR: California Department of Water Resources c2018a. Water portfolios. [Internet]. [accessed 2018 Feb 1]. Available from: *https://water.ca.gov/Programs/California-Water-Plan/Water-Portfolios*

CDWR: California Department of Water Resources c2018b. SGMA groundwater management. [Internet]. [accessed 2018 Nov 29]. Available from: *https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management*

CDWR: California Department of Water Resources c2018c. California data exchange center. [Internet]. [accessed 2018 Nov 29]. Available from: *http://cdec.water.ca.gov/cdecstation2/*

Carrillo–Guerrero Y, Glenn EP, Hinojosa–Huerta O. 2013. Water budget for agricultural and aquatic ecosystems in the delta of the Colorado River, Mexico: implications for obtaining water for the environment. Ecol Eng [Internet]. [accessed 2019 Apr 1]; 59:41–51. Available from: *https://www.sciencedirect.com/science/article/abs/pii/S0925857413001651?via%3Dihub* *https://doi.org/10.1016/J.ECOLENG.2013.04.047*

Conklin M, Bales R, Saksa P, Martin S, Ray R. 2015. SNAMP final report. Appendix E: water final report [Internet]. [accessed 2016 Aug 11]. Available from: *http://snamp.ucanr.edu/documents/675/index.html*

Daly C, Slater ME, Roberti JA, Laseter SH, Swift LW. 2017. High-resolution precipitation mapping in a mountainous watershed: ground truth for evaluating uncertainty in a national precipitation dataset. Int J Climatol [Internet]. [accessed 2019 Apr 2]; 37:124–137. *https://doi.org/10.1002/joc.4986*

Dettinger M. 2016. Historical and future relations between large storms and droughts in California. San Franc Estuary Watershed Sci [Internet]. [accessed 2018 Feb 15]; 14(2):1–21. *https://doi.org/10.15447/sfews.2016v14iss2art1*

Dettinger M, Udall B, Georgakakos A. 2015. Western water and climate change. Ecol Appl [Internet]. [accessed 2018 Feb 15]; 25(8):2069–2093. *https://doi.org/10.1890/15-0938.1*

Dettinger MD, Cayan DR, Meyer MK, Jeton AE. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900–2099. Clim Change [Internet]. [accessed 2018 Feb 15]; 62(1–3):283–317. Available from: *http://link.springer.com/10.1023/B:CLIM.0000013683.13346.4f* *https://doi.org/10.1023/B:CLIM.0000013683.13346.4f*

Dettinger MD, Ralph FM, Das T, Neiman PJ, Cayan DR. 2011. Atmospheric rivers, floods and the water resources of California. Water [Internet]. [accessed 2018 Feb 15]; 3(4):445–478. Available from: *http://www.mdpi.com/2073-4441/3/2/445* *https://doi.org/10.3390/w3020445*

Downing J. 2015. Forest thinning may increase water yield from the Sierra Nevada. Calif Agric [Internet]. [accessed 2018 Feb 15]; 69(1):10–11. Available from: *http://calag.ucanr.edu/Archive/?article=ca.v069n01p10* *https://doi.org/10.3733/ca.v069n01p10*

Escriva-Bou A, McCann H, Hanak E, Lund J, Gray B. 2016. Accounting for California's water. Calif J Polit Policy [Internet]. [accessed 2018 Feb 15]; 8(3):1–26. Available from: *https://www.ppic.org/content/pubs/report/R_716EHR.pdf* *https://doi.org/10.5070/P2cjpp8331935*

Famiglietti JS, Lo M, Ho SL, Bethune J, Anderson KJ, Syed TH, Swenson SC, de Linage CR, Rodell M. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophys Res Lett. 38(3). *https://doi.org/10.1029/2010GL046442*

Faunt CC, editor. 2009. Groundwater availability of the Central Valley Aquifer, California. [Sacramento (CA)]: U.S. Geological Survey. Professional Paper 1766 [Internet]. [accessed 2015 Jun 12]. Available from: *https://pubs.usgs.gov/pp/1766/*

Faunt CC, Sneed M, Traum J, Brandt JT. 2016. Water availability and land subsidence in the Central Valley, California, USA. Hydrogeol J. 24(3):675–684. *https://doi.org/10.1007/s10040-015-1339-x*

Fleenor W, Goodwin P, Monsen N, Ruhl C. 2016. An independent peer review report for the Delta Science Program on the CDWR report "On estimating net Delta outflow (NDO): approaches to estimating NDO in the Sacramento–San Joaquin Delta." [Sacramento (CA)]: Delta Stewardship Council, Delta Science Program [Internet]. [accessed 2019 Jan 8]. Available from: *http://deltacouncil.ca.gov/docs/independent-peer-review-report-delta-science-program-dwr-report-estimating-net-delta-outflow*

Gartrell G, Mount J, Hanak E, Gray B. 2018. PPIC Delta water accounting. [Internet]. [accessed 2018 Sep 1]. [San Francisco (CA)]: Public Policy Institute of California. Available from: *https://www.ppic.org/data-set/ppic-delta-water-accounting/*

Goulden ML, Anderson RG, Bales RC, Kelly AE, Meadows M, Winston GC. 2012. Evapotranspiration along an elevation gradient in California's Sierra Nevada. J Geophys Res Biogeosciences 117(G3). *https://doi.org/10.1029/2012JG002027*

Goulden ML, Bales RC. 2014. Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion. Proc Natl Acad Sci USA [Internet]. [accessed 2019 Apr 1]; 111(39):14071–5. Available from: *http://www.ncbi.nlm.nih.gov/pubmed/25197084* *https://doi.org/10.1073/pnas.1319316111*

Guerschman J, van Dijk A, McVicar T, Van Niel T, Li L, Liu Y, Peña-Arancibia J. 2008. Water balance estimates from satellite observations over the Murray–Darling Basin. [Internet]. [accessed 2018 Feb 22]. CSIRO: Water for a Healthy Country National Research Flagship. 102 p. Available from: *https://publications.csiro.au/rpr/pub?list=BRO&pid=procite:717d9189-69db-4bfe-8886-2e6da0ce1d58* *https://doi.org/10.4225/08/585ac5759d34a*

Hanak E, Lund J, Arnold B, Escriva-Bou A, Gray B, Green S, Harter T, Howitt R, Macewan D, Medellín-Azuara J, et al. 2017. Water stress and a changing San Joaquin Valley. [Internet]. [accessed 2019 Jan 8]. [San Francisco (CA)]: Public Policy Institute of California Available from: *https://www.ppic.org/content/pubs/report/R_0317EHR.pdf*

Hanak E, Lund JR. 2012. Adapting California's water management to climate change. Clim Change 111(1):17–44. *https://doi.org/10.1007/s10584-011-0241-3*

Healy RW, Winter TC, LaBaugh JW, Franke OL. 2007. Water budgets: foundations for effective water-resources and environmental management. [Internet]. [accessed 2018 Feb 15]; 90 p. U.S. Geological Survey Circular 1308 Available from: *https://pubs.er.usgs.gov/publication/cir1308*

Henn B, Newman AJ, Livneh B, Daly C, Lundquist JD. 2018. An assessment of differences in gridded precipitation datasets in complex terrain. J Hydrol [Internet]. [accessed 2019 Apr 1]; 556:1205–1219. Available from: *https://www.sciencedirect.com/science/article/pii/S0022169417301452?via%3Dihub* *https://doi.org/10.1016/J.JHYDROL.2017.03.008*

Huang G. 2016. Estimates of Natural and Unimpaired Flows for the Central Valley of California: water years 1922–2014 (Draft). [Sacramento (CA)]: CDWR, Bay–Delta Office. Available from: *https://water.ca.gov/-/media/DWR-Website/Web-Pages/Library/Modeling-And-Analysis/Files/Modeling-and-Analysis-PDFs/Estimates-of-Natural-and-Unimpaired-Flows-for-the-Central-Valley-of-California-1922-2014.pdf*

Hunsaker C, Swanson S, Viers J. 2015. Effects of meadow erosion and restoration on groundwater storage and baseflow in national forests in the Sierra Nevada, California. [Internet]. [accessed 2017 Nov 9]. [Vallejo (CA)]: USDA Forest Service, Pacific Southwest Region. Available from: *https://meadows.ucdavis.edu/files/FS_Hydrologic_Assessment_Meadow_GW_Final_report_June_2015.pdf*

Ingebritsen SE, Ikehara ME, Galloway DL, Jones DR. 2000. Delta subsidence in California; the sinking heart of the state. [Internet]. [accessed 2019 Jan 31]. [Sacramento (CA)]: U.S. Geological Survey. FS-005-00. Available from: *https://pubs.usgs.gov/fs/2000/fs00500/*

Jeton AE, Dettinger MD, Smith JL. 1996. Potential effects of climate change on streamflow, eastern and western slopes of the Sierra Nevada, California and Nevada. [Internet]. [accessed 2016 Aug 9]. [Sacramento (CA)]: U.S. Geological Survey. Water-Resources Investigations Report 95-4260. Available from: *https://pubs.usgs.gov/wri/1995/4260/report.pdf*

Jeton AE, Watkins SA, Lopes TJ, Huntington J. 2006. Evaluation of precipitation estimates from PRISM for the 1961–1990 and 1971–2000 data sets, Nevada. [Internet]. [accessed 2019 Jan 8]. [Carson City (NV)]: U.S. Geological Survey. Scientific Investigations Report 2005-5291. Available from: *https://pubs.usgs.gov/sir/2005/5291/*

Jiménez Cisneros BE, Oki T, Arnell NW, Benito G, Cogley JG, Döll P, Jiang T, Mwakalila SS. 2014. Freshwater resources. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, et al., editors. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Cambridge (UK)]: Cambridge University Press. [Internet]. [accessed 2018 Feb 15]; p. 229–269. Available from: *https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-PartA_FINAL.pdf*

Kadir T. 2006. Methodology for flow and salinity estimates in the Sacramento–San Joaquin Delta and Suisun Marsh. Chapter 7: estimates for consumptive water demands in the Delta using DETAW. 27th Annual Progress Report [Internet]. [accessed 2019 Jan 8]. [Sacramento (CA)]: CDWR, Bay–Delta Office. Available from: *http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/delta/reports/annrpt/2006/2006Ch7.pdf*

Kirby J, Van Dijk A, Mainuddin M, Peña–Arancibia J, Guerschman J, Liu Y, Marvanek S, McJannet D, Paydar Z, McVicar T, et al. 2008. River water balance accounts across the Murray–Darling Basin, 1990–2006. A report to the Australian government from the CSIRO Murray–Darling Basin Sustainable Yields Project. [Internet]. [accessed 2018 Feb 22]. Australia: CSIRO. Available from: *https://publications.csiro.au/rpr/download?pid=procite:572842b6-15c2-4115-89a2-a59c41aba33f&dsid=DS1*

Koczot KM, Jeton AE, Mcgurk BJ, Dettinger MD. 2005. Precipitation-runoff processes in the Feather River Basin, northeastern California, with prospects for streamflow predictability, water years 1971–97. [Internet]. [accessed 2018 Feb 16]. [Reston (VA)]: U.S. Geological Survey. Scientific Investigations Report 2004-5202. Available from: *https://pubs.usgs.gov/sir/2004/5202/sir2004-5202.pdf*

Kuss A, Brandt WT, Randall J, Floyd B, Bourai A, Newcomer M, Schmidt C, Skiles JW. 2012. Comparison of changes in groundwater storage using GRACE data and a hydrological model in California's Central Valley. In: Proceedings of the American Society for Photogrammetry and Remote Sensing (ASPRS); 2012 Annual Conference; Sacramento, CA. p. 12. Available from: *https://www.researchgate.net/publication/277323993*

Landerer FW, Swenson SC. 2012. Accuracy of scaled GRACE terrestrial water storage estimates. Water Resour Res 48(4). *https://doi.org/10.1029/2011WR011453*

Lund J, Hanak E, Fleenor W, Howitt R, Mount J, Moyle P. 2007. Envisioning futures for the Sacramento–San Joaquin Delta. [San Francisco (CA)]: Public Policy Institute of California. [Internet]. [accessed 2019 Apr 1]; 285 p. Available from: *https://www.ppic.org/publication/envisioning-futures-for-the-sacramento-san-joaquin-delta/*

Lund JR. 2016. California's agricultural and urban water supply reliability and the Sacramento–San Joaquin Delta. San Franc Estuary Watershed Sci [Internet]. [accessed 2018 Feb 15]; 14(3). *https://doi.org/10.15447/sfews.2016v14iss3art6*

Luoma SN, Dahm CN, Healey M, Moore JN. 2015. Challenges facing the Sacramento–San Joaquin Delta: Complex, chaotic, or simply cantankerous? San Franc Estuary Watershed Sci [Internet]. [accessed 2018 Feb 15]; 13(3). *https:// doi.org/10.15447/sfews.2015v13iss3art7*

Lv M, Ma Z, Yuan X, Lv M, Li M, Zheng Z. 2017. Water budget closure based on GRACE measurements and reconstructed evapotranspiration using GLDAS and water use data for two large densely-populated mid-latitude basins. J Hydrol [Internet]. [accessed 2019 Apr 1]; 547:585–599. Available from: *https://www.sciencedirect.com/science/article/pii/S0022169417301063?via%3Dihub*
https://doi.org/10.1016/J.JHYDROL.2017.02.027

Mahadevan N. 1995. Estimation of Delta Island diversions and return flows. [Internet]. [accessed 2016 Aug 9]. [Sacramento (CA)]: California Department of Water Resources, Division of Planning. C-032893 Available from: *http://www.calwater.ca.gov/Admin_Record/C-032892.pdf*

McPherson KR, Freeman LA, Flint LE. 2011. Analysis of methods to determine storage capacity of, and sedimentation in, Loch Lomond Reservoir, Santa Cruz County, California, 2009. [Internet]. [accessed 2019 Apr 2]. [Reston (VA)]: U.S. Geological Survey. Scientific Investigations Report 2011-5141. Available from: *https://pubs.usgs.gov/sir/2011/5141/pdf/sir20115141.pdf*

Medellín–Azuara J, Tha Paw U K, Jin Y, Lund J. 2018. Delta consumptive water use comparative study. A comparative study for estimating crop evapotranspiration in the Sacramento-San Joaquin Delta [Internet]. [accessed 2018 Apr 24]. [Davis (CA)]: UC Davis, Center for Watershed Sciences. Available from: *https://watershed.ucdavis.edu/delta-et*

Meyers JS, Nordenson TJ. 1962. Evaporation from the 17 western states. [Internet]. [accessed 2016 Aug 9]. [Washington (DC)]: U.S. Geological Survey. Professional Paper 272-D. Available from: *https://pubs.usgs.gov/pp/0272d/report.pdf*

Mount J, Hanak E, Gartrell G, Gray B. 2018. Accounting for water "wasted to the sea." San Franc Estuary Watershed Sci [Internet]. [accessed 2018 Sep 7]; 16(1). *https://doi.org/10.15447/sfews.2018v16iss1/art1*

Mu Q, Zhao M, Running SW. 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens Environ 115(8):1781–1800. *https://doi.org/10.1016/J.RSE.2011.02.019*

NACSE: Northwest Alliance for Computational Science and Engineering c2018. PRISM climate data. [Internet]. [accessed 2018 Nov 29]. Available from: *http://prism.oregonstate.edu/*

Perry C, Steduto P. 2017. Does improved irrigation technology save water? A review of the evidence. [Cairo (Egypt)]; Food and Ag Organization of the UN. ISBN 978-92-5-109774-8 [Internet]. [accessed 2018 Nov 1]. Available from: *http://www.fao.org/3/I7090EN/i7090en.pdf*

Running S, Mu Q, Zhao M. 2017. MOD16A3 v006 MODIS/Terra net evapotranspiration yearly L4 global 500m SIN grid. Dataset. [Internet]. [accessed 2019 Apr 1]. NASA EOSDIS L Process DAAC. Available from: *https://lpdaac.usgs.gov/products/mod16a3v006/*
https://doi.org/10.5067/MODIS/MOD16A3.006

Ryu JH, Contor B, Johnson G, Allen R, Tracy J. 2012. System dynamics to sustainable water resources management in the eastern Snake Plain Aquifer under water supply uncertainty. JAWRA J Am Water Resour Assoc 48(6):1204–1220. *https://doi.org/10.1111/j.1752-1688.2012.00681.x*

Saksa PC, Conklin MH, Battles JJ, Tague CL, Bales RC. 2017. Forest thinning impacts on the water balance of Sierra Nevada mixed-conifer headwater basins. Water Resour Res 53(7):5364–5381. *https://doi.org/10.1002/2016WR019240*

Sandhu N, Suits B, Ateljevich E, Zhong L, Kadir T. 2016. On estimating net Delta outflow (NDO)—approaches to estimating NDO in the Sacramento–San Joaquin Delta. [Internet]. [accessed 2018 Mar 5]. [Sacramento (CA)]: CDWR, Bay–Delta Office. Available from: *https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/ndo_report_march2016.pdf*

Scanlon BR, Reedy RC, Faunt CC, Pool D, Uhlman K. 2016. Enhancing drought resilience with conjunctive use and managed aquifer recharge in California and Arizona. Environ Res Lett [Internet]. [accessed 2018 Feb 15]; 11(3):035013. Available from: *http://stacks.iop.org/1748-9326/11/i=3/a=035013?key=crossref.f5489d73fe4c46e3d922248ee4f32495* *https://doi.org/10.1088/1748-9326/11/3/035013*

SWRCB: California State Water Resources Control Board. 2015. Public workshop on drought activities in the Bay–Delta watershed. [Sacramento (CA)]. [Internet]. [accessed 2018 Nov 24]. Available from: *https://www.waterboards.ca.gov/waterrights/water_issues/programs/drought/docs/workshops/swrcb_staff_pres_session1.pdf*

USGS: U.S. Geological Survey c2017. Water science glossary of terms. [Internet]. [accessed 2017 Apr 19]. USGS Water Science School. Available from: *https://water.usgs.gov/edu/dictionary.html*

Vardon M, Lenzen M, Peevor S, Creaser M. 2007. Water accounting in Australia. Ecol Econ [Internet]. [accessed 2018 Feb 15]; 61(4):650–659. *https://doi.org/10.1016/J.ECOLECON.2006.07.033*

Vörösmarty CJ, Green P, Salisbury J, Lammers RB. 2000. Global water resources: vulnerability from climate change and population growth. Science [Internet]. [accessed 2018 Feb 15]; 289(5477):284–8. Available from: *http://www.ncbi.nlm.nih.gov/pubmed/10894773* *https://doi.org/10.1126/SCIENCE.289.5477.284*

Wahr J, Swenson S, Velicogna I. 2006. Accuracy of GRACE mass estimates. Geophys Res Lett 33(6):L06401. *https://doi.org/10.1029/2005GL025305*

Wan Z, Zhang K, Xue X, Hong Z, Hong Y, Gourley JJ. 2015. Water balance-based actual evapotranspiration reconstruction from ground and satellite observations over the conterminous United States. Water Resour Res 51(8):6485–6499. *https://doi.org/10.1002/2015WR017311*

Wang H, Guan H, Gutiérrez-Jurado HA, Simmons CT. 2014. Examination of water budget using satellite products over Australia. J Hydrol [Internet]. [accessed 2019 Apr 1]; 511:546–554. Available from: *https://www.sciencedirect.com/science/article/pii/S0022169414001127?via%3Dihub* *https://doi.org/10.1016/J.JHYDROL.2014.01.076*

Wang S, Huang J, Li J, Rivera A, McKenney DW, Sheffield J. 2014. Assessment of water budget for sixteen large drainage basins in Canada. J Hydrol [Internet]. [accessed 2019 Apr 1]; 512:1–15. Available from: *https://www.sciencedirect.com/science/article/pii/S0022169414001668?via%3Dihub* *https://doi.org/10.1016/J.JHYDROL.2014.02.058*

Wilson TS, Sleeter BM, Cameron DR. 2016. Future land-use related water demand in California. Environ Res Lett [Internet]. [accessed 2018 Feb 15]; 11(5):054018. Available from: *http://stacks.iop.org/1748-9326/11/i=5/a=054018?key=crossref.ebd2d60977b819b790ff576e69152fbd* *https://doi.org/10.1088/1748-9326/11/5/054018*

Xiao M, Koppa A, Mekonnen Z, Pagán BR, Zhan S, Cao Q, Aierken A, Lee H, Lettenmaier DP. 2017. How much groundwater did California's Central Valley lose during the 2012–2016 drought? Geophys Res Lett 44(10):4872–4879. *https://doi.org/10.1002/2017GL073333*

Zhang Z, Glaser S, Bales R, Conklin M, Rice R, Marks D. 2017. Insights into mountain precipitation and snowpack from a basin-scale wireless-sensor network. Water Resour Res 53(8):6626–6641. *https://doi.org/10.1002/2016WR018825*