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RESEARCH

Climate and Land-Use Controls on Surface Water Diversions in the Central Valley, California

Jordan P. Goodrich*[1], Daniel R. Cayan[1], David W. Pierce[1]

ABSTRACT

California's Central Valley (CV) is one of the most productive agricultural regions in the world, enabled by the conjunctive use of surface water and groundwater. We investigated variations in the CV's managed surface water diversions relative to climate variability. Using a historical record (1979–2010) of diversions from 531 sites, we found diversions are largest in the wetter Sacramento basin to the north, but most variable in the drier Tulare basin to the south. A rotated empirical orthogonal function (REOF) analysis finds 72% of the variance of diversions is captured by the first three REOFs. The leading REOF (35% of variance) exhibited strong positive loadings in the Tulare basin, and the corresponding principal component time-series (RPC1) was strongly correlated ($\rho > 0.9$) with contemporaneous hydrologic variability. This pattern indicates larger than average diversions in the south, with neutral or slightly less than average diversions to the north during wet years, with the opposite true for dry years. The second and third REOFs (20% and 17% of variance, respectively), were strongest in the Sacramento basin and San Francisco Bay–Delta. RPC2 and RPC3 were associated with variations in agricultural- and municipal-bound diversions, respectively. RPC2 and RPC3 were also moderately correlated with 7-year cumulative precipitation based on lagged correlation analysis, indicating that diversions in the north and central portions of the CV respond to longer-term hydrologic variations. The results illustrate a dichotomy of regimes wherein diversions in the more arid Tulare are governed by year-to-year hydrologic variability, while those in wetter northern basins reflect land-use patterns and low-frequency hydrologic variations.

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* Corresponding author: jordanpgoodrich@gmail.com

1 Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093 USA

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INTRODUCTION

California's Central Valley (CV), including the San Francisco Bay and Sacramento–San Joaquin Delta, is one of the world's most productive agricultural regions, enabled by a complex engineered network of dams, reservoirs, and aqueducts, as well as numerous groundwater wells that provide irrigation supply. A majority of California's $50 billion-per-year agricultural production is generated from CV crops (CDFA 2018), and the region constitutes one-sixth of the nation's irrigated land (Faunt et al. 2009). Additionally, urban growth in the CV has nearly doubled the population since 1980, with continued increases projected by Census data (CDOF c2019). Also, approximately one-fifth of the nation's groundwater demand is in the CV (Faunt et al. 2009).

In recent decades, groundwater withdrawals have increased throughout the CV (Scanlon et al. 2012). These increases, together with the characteristic year-to-year volatility of precipitation in the region (Dettinger et al. 2011), have exposed the vulnerability of water resources in the CV, with dramatic declines in groundwater levels since the 1960s (Faunt et al. 2009). These pressures have led to new guidelines and legislation that govern how surface water (SWRCB 2014) and groundwater (State of California 2015) are managed in the region. There is a clear need to better understand conjunctive surface and groundwater budgets, and effectively manage climate effects on the region's water resources. Surface water rights allocations exceed water supply by a factor of five in California (Little Hoover Commission 2010; Grantham and Viers 2014), while groundwater pumping has been largely unmonitored statewide and generally not monitored at all in the CV. This lack of comprehensive data on the CV hydrologic system has led to persistent uncertainties in how groundwater storage fluctuates over time, and in response to droughts or extreme precipitation years, and therefore in how to manage regional water resources (Faunt et al. 2009; Faunt et al. 2015; Xiao et al. 2017).

To help reduce uncertainties in surface and groundwater budgets for the CV, our focus here is on one part of the system: managed surface water diversions, or points where surface water is unnaturally directed or transported to a different location. Although surface diversions do not represent the entirety of the CV water budget, they are nonetheless a key part. For example, we find that surface water diversions can vary more than precipitation, based on the data analyzed here. Surface water rights are generally determined based on beneficial merit (SWRCB 2014) and, especially in cases of drought, may be curtailed in response to declining supplies (Famiglietti et al. 2011). Adding to the complex landscape of water rights, diversions respond regionally to climate variability as well as land-use changes, but the extent to which these effects operate in causing regional patterns or trends has been unclear. Studies of climate effects on surface hydrology in California have tended to focus on natural or naturalized streamflow and/or runoff (e.g., Stewart et al. 2005; Maurer et al. 2007; Hidalgo et al. 2009), with some important exceptions. For example, VanRheenen et al. (2004) used a model to represent reservoir releases in the CV under climate-change scenarios, in part to assess the potential effect of changing surface water availability on hydropower generation and fish-flow targets. Ficklin et al. (2009) explored potential changes in aggregate surface water use in CV basins with varying emissions scenarios. However, a comprehensive empirical analysis of observed surface water diversions to assess drivers of variability is still lacking. Such an analysis is especially important in light of the growing proportion of high-risk perennial crops with no fallow season that are being planted in the CV (Wilson et al. 2016) and the increasing likelihood of more variable precipitation (Pierce et al. 2013; Berg and Hall 2015; Swain et al. 2018).

Here, we analyze a multi-decade record of managed surface water diversions, largely compiled by the California Department of Water Resources (CDWR) for input to the California Central Valley Groundwater–Surface Water Simulation Model (C2VSim; Brush et al. 2013) but also tailored to the U.S. Geological Survey (USGS) Central Valley Hydrologic Model (CVHM; Faunt et al. 2009). In particular, we are interested in understanding fluctuations and changes in CV diversions over the historical period 1979–2010 in response to varying hydroclimate and land-use patterns. This period provides a good record of diversions, of observed hydroclimatic measures, and of the influence of land-cover and land-use type (and therefore water demand).

The results of this work should help to improve understanding of CV regional diversions, providing a better framework for generating up-to-date hydrologic assessments and supporting decision-making. A key issue in our ability to track how droughts and floods affect current and future groundwater pumping is the multi-year delay in surface-water diversion data reporting, which this work may partially alleviate, by quantifying relationships with regularly updated climate and hydrologic measures.

DATA AND METHODS

Central Valley Surface Water Diversions

The CV covers approximately 52,000 km^2, spanning three major river basins from the Sacramento to the north, the San Joaquin and Tulare basins to the south, as well as the Sacramento–San Joaquin Delta east of the Bay Area (Figure 1). The valley is delineated by the Coast Ranges to the west and the Sierra Nevada to the east. Surface sediments in the CV derive from erosion of igneous and metamorphic rock mixed with marine sediment, and deposits that generally increase in thickness from east to west (Faunt et al. 2009).

The highly developed and complex water management infrastructure in the CV reflects the uneven distribution of water resources, populations, and agricultural sectors. For example, 75% of California's precipitation is received north of Sacramento, although 75% of water demand is south of there (Hanak et al. 2011). Furthermore, most of the area in the CV is arid to semi-arid (Bertoldi 1989), but the CV also is prone to flooding (Dettinger et al. 2011), leaving both agricultural centers and municipal areas dependent on extensive water-transport and flood-control infrastructure (e.g., canals, aqueducts, and levees) that distributes water from surface reservoirs and helps manage excess flows (Hanak et al. 2011). In addition to spatially disparate resource distribution, delayed snowmelt runoff from the Sierra Nevada, which has historically provided over 70% of the regional average runoff (Li et al. 2017), governs the timing of water supply to much of the CV.

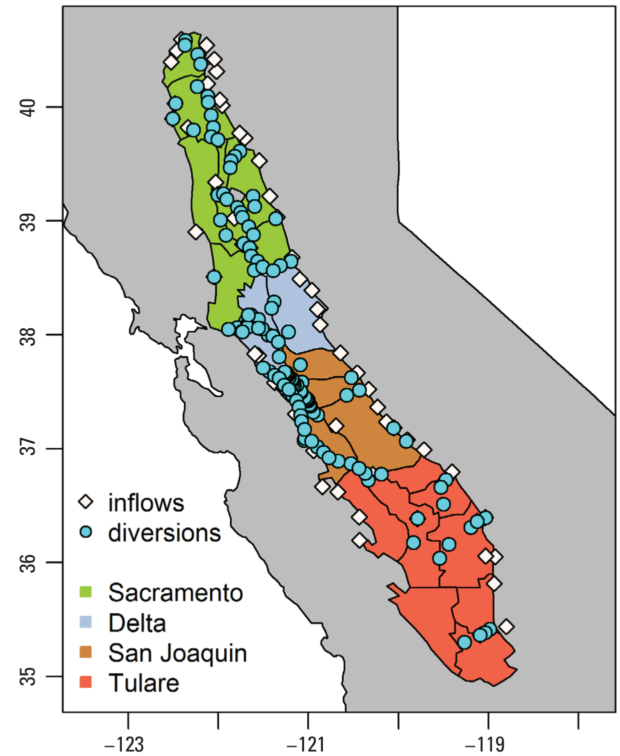

Figure 1 Central Valley sub-region boundaries designated by the California Central Valley Groundwater–Surface Water Simulation Model (C2VSim) and Central Valley Hydrologic Model (CVHM), and the major river basins identified using different colors. Locations of stream inflows and surface water diversion records used in this analysis are indicated with diamonds and circles, respectively.

Most water diversions in the CV are used for agriculture, often exceeding 90% of all regional use, although growing urban populations are increasing municipal surface water use, which is roughly 20% of state-wide use (Brandt et al. 2014). Any entity intending to gain the rights to an allotment of surface water and establish a diversion within California must satisfy the water rights permitting requirements with the State Water Resources Control Board, which generally includes provisions that cover supply availability, reasonable use, and adherence to environmental guidelines (SWRCB 2014; Grantham and Viers 2014). Monthly or annual allotments are issued, but actual water use typically is well below the maximum allowable individual diversion volumes (Littleworth and Garner 2007; Grantham and Viers 2014).

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Historical Surface Water Diversion Data

For this analysis, we used historical surface-water diversions data compiled by CDWR (Brush 2013) and USGS (Faunt et al. 2009). This data set was initially intended for CDWR's C2VSim, along with additional data from the US Bureau of Reclamation (Reclamation) as input into the USGS's counterpart, CVHM (Faunt et al. 2009). The data originate from over 100 local, state, and federal agencies, but most are available from a handful of sources including the USGS, California Data Exchange Center (CDEC), National Water Information System, Reclamation, and US Army Corps of Engineers. California operates under a dual water-rights system that recognizes both riparian and appropriative rights. A discussion of the water-rights system and history in California is provided in Grantham and Viers (2014). Metadata for the surface water diversions used in this study included categories that identify the fate of water being delivered as agriculture, municipal and industrial, refuges, spreading, or seepage (Brush et al. 2013). Adequate data were not available to conduct a comprehensive analysis of water-rights reliability in the context of our analysis. However, in many years, shortages cause water-delivery shortfalls by local, state, and federal water purveyors. These shortfalls result in greater utilization of other supplies, such as groundwater or water transfers, fallowing of cropland, or increased water conservation.

The data set for our analysis began with 531 individual monthly diversion records covering 1979–2010. The 2010 end date of these records reflects the rather long lag time for reporting and also the time required for quality assessment by water agencies. Before analyses, we discarded diversion sites where >95% of the values were zero, removing 41 sites. Additionally, we removed records from 47 more sites because they showed little to no interannual variation. Many of these records registered a diversion of the maximum water allocation every year, which may be spurious or at best would offer little information about how the diversions vary with climate.

The records for 443 remaining sites contained, on average, 90% of annual diverted water volume totaled over the original data set, and so represent all diversions. "Sites" is a slight misnomer because many entries in the data set report water diverted from the same locations but delivered to different areas. We summed these so each diversion location was represented only once in the analysis. Finally, we aggregated records from the resulting 113 diversion locations to a much smaller number of sub-regions of the CV, as is done for both C2VSim and CVHM, to simplify the interpretation of results. Thus, in this study, we compiled diversions into 21 pre-determined sub-regions based on delivery locations, where all but two in the Tulare basin contained at least one diversion record, illustrated by the geographic units in Figure 1.

Hydroclimate and Land-Use Data Sets

To understand the hydroclimatic (including surface hydrology, precipitation, and temperature) drivers of variability in surface-water diversions, we used a set of open-access meteorological data sources over 1973–2010, covering 6 years prior through the end of the diversion data set. Gridded monthly precipitation and temperature data were obtained from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) data source (Daly et al. 2008; PRISM Climate Group 2018) at 4-km spatial resolution. When calculating area-averaged precipitation for sub-regions of the CV, we included adjacent portions of the Coast Ranges to the west or the Sierra Nevada to the east, to represent water likely to affect the CV regional budget.

Monthly reservoir storage data were compiled from the CDEC website for 173 reservoirs throughout California (Dettinger and Anderson 2015). CDEC is an open-access CDWR data archive (*http://www.cdec.water.ca.gov/*). Stream inflow data, also at monthly resolution, were compiled by CDWR and USGS together with the diversions outlined above (Brush 2013; Faunt et al. 2009). These inflow data include all the flows from gaged streams and largely represent reservoir releases at the boundaries of the CV (Figure 1). Un-gaged watershed flows make up less than 10% of that accounted for in the inflow data, and these generally seep into the ground as they leave the mountain front. The reported magnitude of Delta inflows is relatively small, in part because of stream losses (most of the streams are losing in long stretches, particularly south of the Delta), and upstream diversions, where a large amount is diverted to the California Aqueduct for transport south, in addition to the diversions used in the CV for municipal, industrial, and agricultural irrigation.

Finally, we used daily Sierra Nevada snow water equivalent (SWE) data from a 90-m-resolution gridded reanalysis product that incorporated meteorological observations, remote sensing data, and snow model estimates (Margulis et al. 2015, 2016). These data were aggregated into monthly averages for five sub-regions of the Sierras designated by the Sierra Nevada Conservancy (*http://www.catalog.data.gov*) for analysis. The SWE data set begins in 1985, so comparisons between SWE and diversions are limited to the overlap period 1985–2010. Land-use data were derived from the largest percentage of crop per 1 mile^2 based on the land-use grids for the CVHM (Faunt et al., 2009). These land-use grids are based largely on the CDWR's county land-use surveys (CDWR 2000)

Analytical Approach

To elucidate interannual relationships between fluctuations in precipitation and diversions, we calculated correlation coefficients between total water year diversions and cumulative precipitation during the present and several antecedent years. To account for the potential influence of sustained wet or dry periods, besides the current total water year values, cumulative precipitation over the previous 2 through 10 water years also was included in these correlation analyses.

For a more efficient and physically-interpretable representation of the spatio-temporal variability in surface water diversions, we performed rotated empirical orthogonal function (REOF) analysis on the spatially-weighted, standardized diversion residuals aggregated by CV sub-region. We calculated the standardized residuals for each sub-region by subtracting the long-term (1979–2010) mean from seasonal (April–September) total diversions, and dividing by the long-term standard deviation. Empirical orthogonal function (EOF) analysis (Preisendorfer and Mobley 1988) decomposes a data set into orthogonal patterns of spatial and temporal variation such that the leading EOF mode (or loadings) maximizes the proportion of the total variance explained. Given that the orthogonality constraint employed in EOF analysis can create patterns that are not physically meaningful, and are difficult to interpret (Richman 1986), we rotated the EOFs using a standard varimax approach (Kaiser et al. 1958). Spatially, this form of REOF emphasizes regions of the domain within which variability is most coherent. Thus, varimax rotation generally isolates regions that vary more or less as distinct units and that vary differently from everywhere else. REOF analysis preserves the orthogonality of the temporal weights (rotated principal components; RPC), meaning that the time-series associated with each REOF is uncorrelated with that from any of the others, so there is no (temporal) redundancy in the description of overall variability. For this REOF analysis, we included the total diversion data for April through September of each water year because this is the period of the year when most of the water volume is diverted (Figure 2).

To determine the number of REOF modes that contain meaningful information, we constructed the eigenvalue spectrum following Wilks (2006). Assuming that modes containing uncorrelated noise should result in eigenvalues that decay exponentially with increasing principal component number, we retained the first three modes, as these fell above such a noise threshold (Figure A1).

RESULTS

Temporal Variability of Surface Water Diversions

Long-term (1979–2010) mean annual diversion volumes were highly variable from site to site, ranging from 0.01 to 86.6 thousand acre-feet (TAF; Figure 3). There is a generally even spatial distribution of diversion locations covered in this data set, with the exception of the Delta Mendota

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Table 1 Average water year magnitudes and coefficient of variation for precipitation, stream inflows, and surface water diversions in the major river basins of the Central Valley, CA, including the Sacramento–San Joaquin Delta and the Central Valley as a whole over the period 1979–2010

	Precipitation		Inflows		Diversions	
	WY sum (cm)	WY CoV (%)	WY sum (TAF)	WY CoV (%)	WY sum (TAF)	WY CoV (%)
Sacramento	61.9	32	825.9	64	196.6	12
Delta	41.6	34	40.6	78	57.0	1
San Joaquin	41.6	34	154.1	72	72.6	11
Tulare	26.2	35	225.3	25	84.1	45
Central Valley	43.6	33	1212.9	54	410.0	13

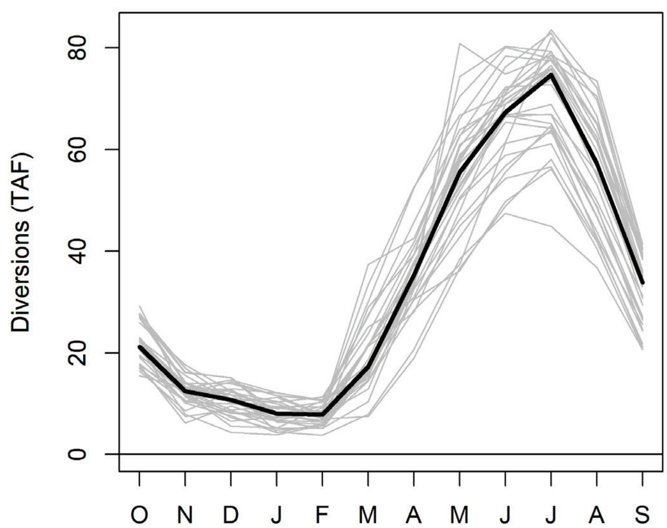

Figure 2 Seasonality of total monthly streamflow diversions (in thousand-acre-feet; TAF) for the Central Valley from 1979–2010. Each year is plotted as a *grey line* to illustrate the interannual variability; the long-term median is shown by the *black line*.

and San Luis Canals, along which there are more smaller-volume diversions (Figure 3). As a general rule, the standard deviation (ranging from 0.002 to 17.3 TAF) scales with diversion magnitude. However, locations within the Tulare basin to the south tend to have the largest coefficients of variation (CoV; standard deviation/mean), from 0.30% to 260% (Figure 3).

Total surface water diversions for the Central Valley have a consistent seasonality, with the smallest volumes diverted in February and the largest in July (Figure 2). Diversions over April to September average 80% of total diverted water volume, and so drive much of the inter-annual variability in water year totals. We investigated the associations of climate variability and changing societal water-use patterns with regional aggregated diversions over major river basins within the CV and the Bay/Delta. Hydroclimate variability in the CV and Delta region was represented by temperature, accumulated precipitation, and total inflows. Notably, groundwater supplies are not employed in this analysis because they have not been comprehensively monitored over this historical period.

The seasonal cycle of temperature, derived from the PRISM data set, is similar among basins in the CV, having amplitudes of approximately 19 °C from winter to summer. The overall mean temperature in the Tulare basin is roughly a degree warmer than the central and northern basins (Figure 4). Historically, annual temperature for the CV, as a whole, has ranged from 15.7° to 17.9 °C, with a long-term mean of 16.7 °C and standard deviation of 0.5 °C. Throughout the domain, including the region's upstream watersheds, more than 80% of the precipitation occurs from November through April. Within the CV and the Delta, annual long-term mean precipitation has a strong north–south gradient toward lower precipitation totals in the south (26.2 cm in the Tulare) than in the north (61.9 cm in the Sacramento) (Table 1; Figure 4). Variability from year to year is high, wherein valley-wide, water year precipitation ranges from 24 to 76 cm,

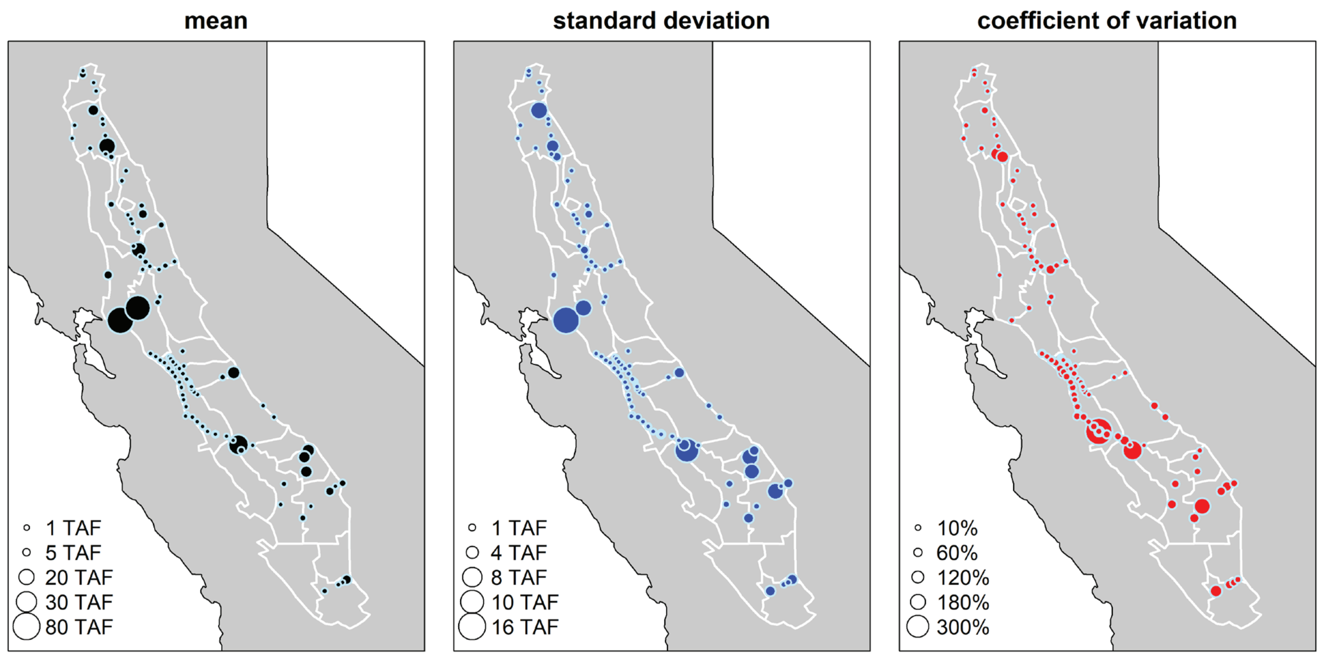

Figure 3 Long-term (1979–2010) mean annual diversions for locations in the Central Valley compiled in this analysis as well as the standard deviation of annual magnitudes, and the coefficient of variation (CoV) (standard deviation divided by the mean)

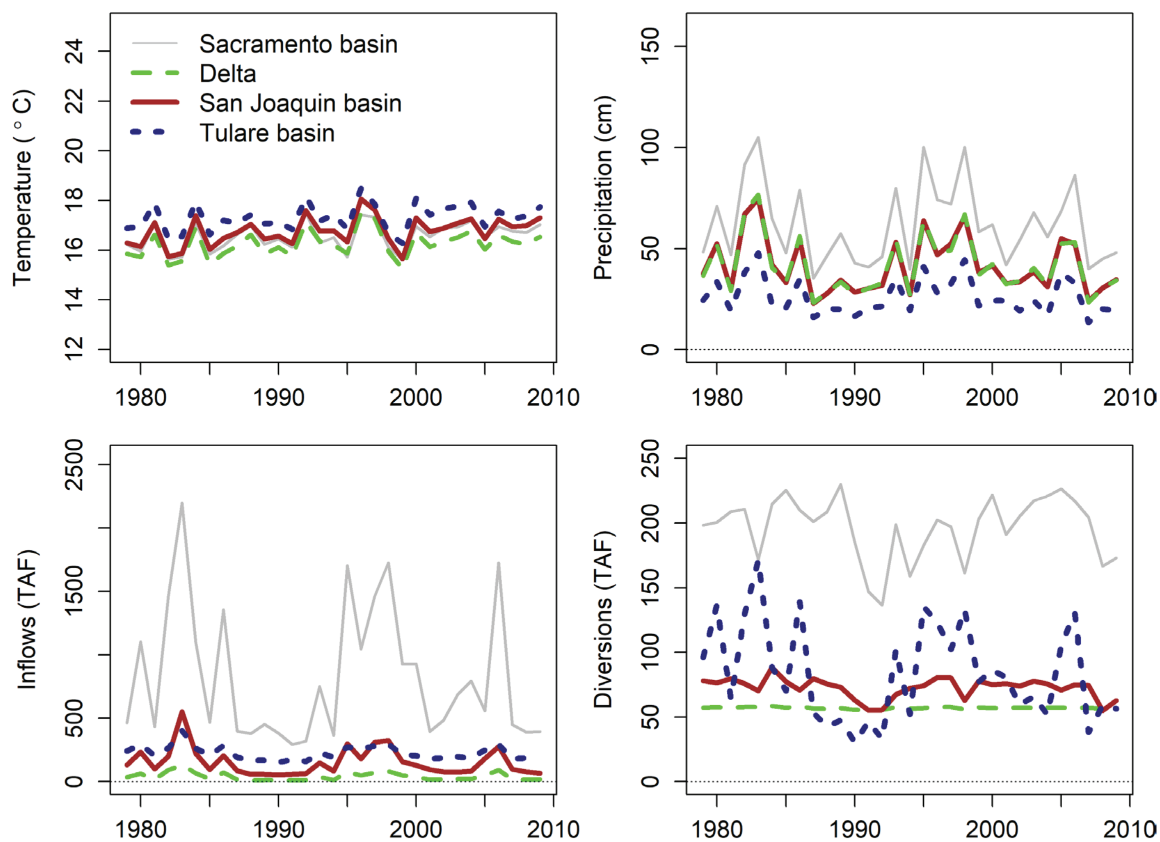

Figure 4 Area-averaged water-year time-series for major Central Valley river basins and the Sacramento–San Joaquin Delta from 1979–2010 of (**A**) temperature, (**B**) precipitation, (**C**) stream inflows, and (**D**) surface water diversions

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with a long-term mean of 43 cm. All CV basins and their contributing watersheds have a large annual CoV (32% to 35% for the CV and Delta regions) that sets California's precipitation and water regimes apart from the rest of the US (Dettinger et al. 2011).

The greatest surface inflows originate in the Sacramento basin, with water year totals ranging from 294 to 2200 TAF, with the other basins ranging from 72 to 360 TAF (Figure 4). Valley-wide (including the Delta) inflows had a long-term mean of 1,246 TAF, but contained a large range of interannual variation, from 531 to 3,284 TAF per water year. Surface-water diversions were most variable in the Tulare basin, ranging from 29 to 171 TAF per water year with a CoV of 46%, in contrast to the other major basins, which had CoVs less than 30% (Table 1; Figure 4). However, as with inflows, the Sacramento basin had the largest mean volume of diverted water in the CV, with water year totals ranging from 133 to 226 TAF (Figure 4). Valley-wide, the diversions range from 281 to 480 TAF per water year, with a long-term mean of 410 TAF. Thus, annual surface water diversions have amounted to about 33% of inflows regionally, although this proportion varies by major basin, amounting to 23% in the Sacramento, 44% in the Delta, 67% in the San Joaquin, and 37% in the Tulare.

The Tulare was the only basin whose diversions were strongly correlated with current water year precipitation ($\rho = 0.92$), and were decreasingly correlated as precipitation from antecedent years was included (Figure 5). In contrast, diversions in the Delta region had largest correlations with current and previous year's precipitation, and the San Joaquin basin had relatively high correlations with current and previous year's precipitation and maximum correlation with the cumulative precipitation over the last 6 years. The Sacramento basin was the only region whose correlation increased as precipitation of previous water years was successively incorporated into the cumulative value, peaking at 7 years of cumulative precipitation (Figure 5). Finally, surface water diversions in the Tulare basin stand out in having higher CoV (46%) than

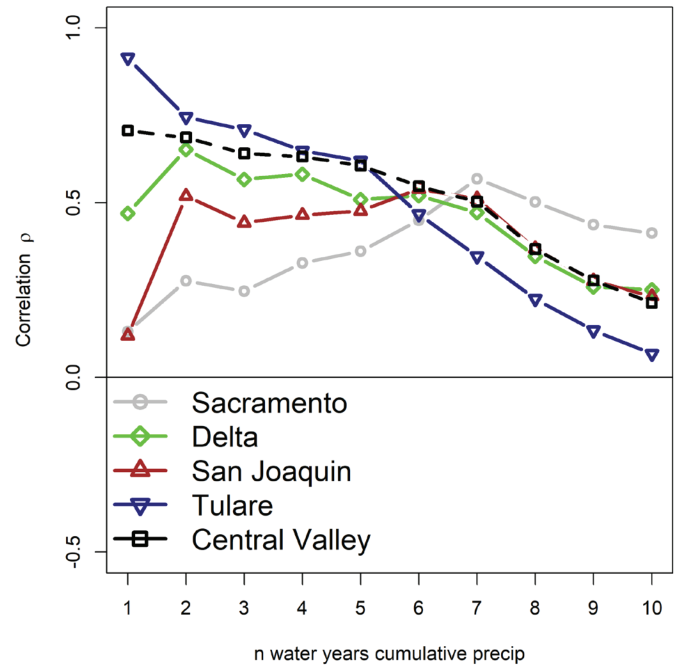

Figure 5 Correlations between total water year diversions grouped by major Central Valley river basin as well as the Delta region and CV as a whole, and cumulative precipitation for the associated regions over the previous 1 to 10 water years (i.e., 1 = current total water year precipitation)

inflows (25%) (Table 1). In contrast, surface water diversions in the Sacramento basin, Delta, and San Joaquin basin have CoV of only 11% to 26%, with CoV of inflows from 64% to 78% (Table 1). Some individual diversion sites in the Tulare basin exhibit CoV over 150% (Figure 3).

Regional Hydroclimate and Land-Use Associations with Diversions

We employed a two-term linear regression model to investigate the dependence of total CV diversions upon current water year precipitation and 7-year cumulative precipitation (in accordance with results from Figure 5). Both terms were significant ($p < 0.001$) and R^2 was 0.67, indicating that overall CV diversions are strongly related to current and prior years' precipitation.

In analyzing the space–time variability of April–September surface water diversions, the first three REOFs capture 72% of the total variance over the CV/Delta system (Figure 6). The leading mode of variability (REOF1), accounting for 35% of total variance of surface diversions, represents variability in the southern part of the CV. REOF1 is most strongly weighted in the Tulare and southern San Joaquin basins, with near-zero loadings in the northern CV (Figure 6), indicating that a major share of diversion variability in the south is uncorrelated with that in the north. Principal component weights (RPC1) for REOF1 are strongly ($\rho > 0.9$), positively, and relatively uniformly correlated with precipitation during the current water year throughout most of the central to northern California region (Figure 7). Not surprisingly, RPC1 is also strongly positively correlated with associated hydroclimate measures, including Sierra Nevada SWE, surface

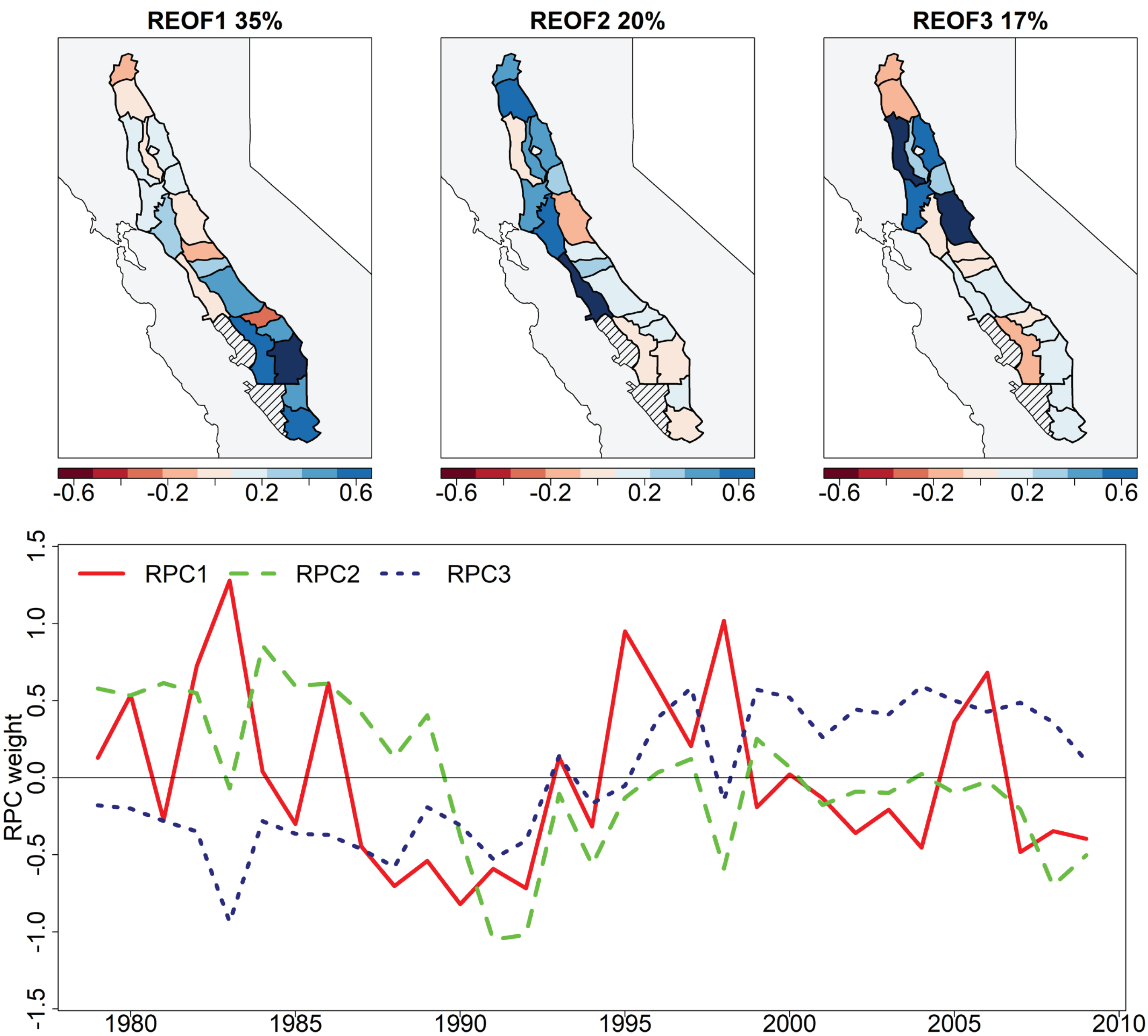

Figure 6 Modes 1–3 of the rotated empirical orthogonal function (REOF) analysis results for the integrated April–September surface water diversions aggregated by Central Valley sub-region. Percentages indicate the proportion of the total variance explained by each mode. The *grey shaded regions* had no diversion records. The associated principle component weights through time are shown in the *bottom panel* for each REOF.

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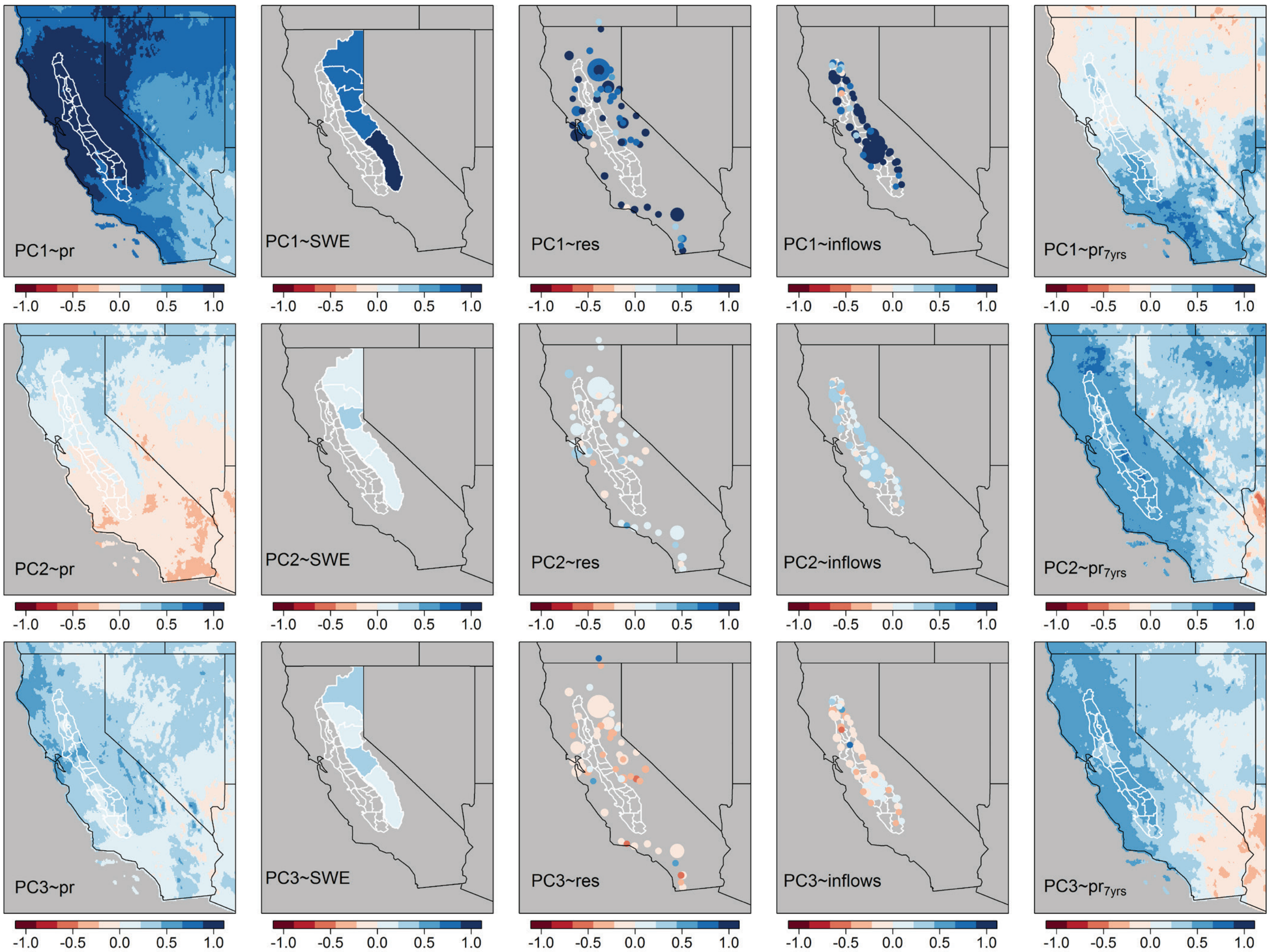

Figure 7 Correlation maps of the principle component weights with water year precipitation (pr), snow water equivalent (SWE), reservoir storage (res), stream inflows (inflows), and cumulative precipitation over the previous 7 water years (pr7yrs). For res and inflows, the *size of dots* corresponds to the mean annual values at each location.

reservoir storage, and stream inflows (Figure 7). Cumulative 7-year precipitation is weakly ($\rho < 0.5$) correlated to RPC1, although still with a positive association strongest in the southern CV.

REOF2, accounting for 20% of the total variance of April–September diversions (Figure 6), most strongly represents diversion variability in the northern Sacramento basin and in the eastern half of the Delta and San Joaquin regions. RCP2 associations with current water-year hydroclimate are modest and vary spatially, being weakly positive in the north and weakly negative in the south (Figure 7). RPC2 has a prominent multi-year component with a moderate positive correlation ($\rho \sim 0.5$–0.6) with cumulative 7-year precipitation across the region (Figure 7). There is some indication that REOF2 is associated with a shift in conditions around 1990 (Figure 6; c.f. discussion of Figure 10).

REOF3, accounting for 17% of the total April–September diversion variance, is weighted most strongly in the southern Sacramento basin and east of the Delta region (Figure 6). The associated RPC3 weights reveal a positive trend, reflecting increasing diversions over the 31-year record. This increase was most pronounced between

1990 and 2000. The RPC3 time-series is weakly but positively correlated with current water year precipitation over the full region. Also, RPC3 is moderately correlated with 7-year cumulative precipitation, quite similar to the magnitude and pattern found in association with RPC2.

Climatic variability only partially explains variability of RCP2 and RCP3. Looking further, variability in RPC2 and RPC3 may be better understood by their association with changing allocations of diversions to municipal and agricultural uses. The RPC2 time-series is strongly related to the regional variation in agriculture-bound surface water diversions over this period in the Sacramento (ρ =0.89) and San Joaquin (ρ =0.73), basins and the Delta region (ρ =0.80) (Figure 8). This is consistent with a general decline in valley-wide agricultural area (Figure 9), which saw particularly sharp reductions in the early 1990s. In particular, the integrated agricultural surface-water diversions from the Sacramento basin, Delta region, and San Joaquin basin correlated strongly with Central

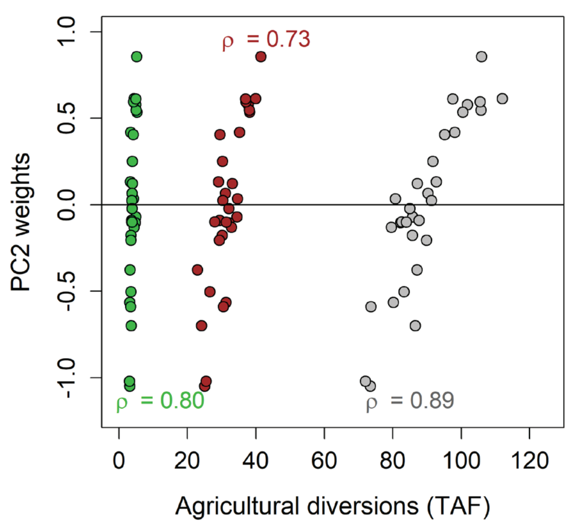

Figure 8 Correlations between agricultural-bound surface water diversions and PC2 weights for the Sacramento basin, Sacramento–San Joaquin Delta, and Tulare basins, and between municipal-bound diversions and PC3 weights in those basins as well as the San Joaquin basin.

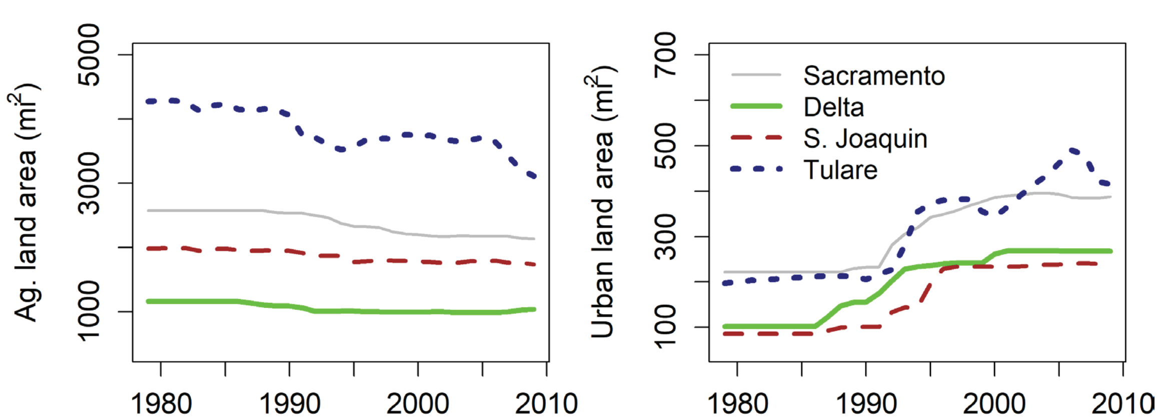

Figure 9 Area-integrated water-year time-series for major Central Valley river basins and the Sacramento–San Joaquin Delta from 1979–2010 of agricultural and urban land area.

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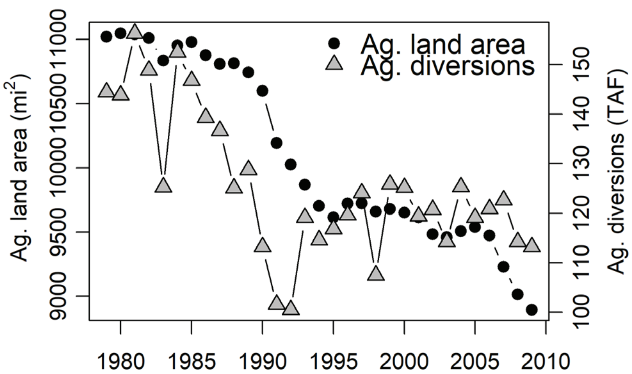

Figure 10 Total Central Valley agricultural land area from 1979–2010 and integrated agricultural diversions from the Sacramento basin, Delta region, and San Joaquin basin over that period

Valley-wide agricultural land area (ρ = 0.70) (Figure 10). As reflected by the weak or neutral REOF2 and REOF3 loadings in the Tulare basin, neither RPC2 nor RPC3 correlates with Tulare municipal diversions (ρ = –0.20) or agriculture diversions (ρ = 0.19), respectively.

DISCUSSION

A primary aim of water management is to reduce the variability of—or improve consistency in—water supply (Hanak et al. 2011). In the Tulare basin, annual diversions are more variable than precipitation and inflows, and strongly driven by contemporaneous fluctuations in hydroclimate. This is a consequence of the large magnitude of irrigation water needed in the arid Tulare basin, resulting in demand being so much higher than supply there (Figure A2; Figure 4).

Not explicitly considered in this analysis are groundwater withdrawals, which are a major component of the water supply that must be considered in understanding effects of fluctuating surface water diversions. Since surface water is cheaper and easier to extract, these surface resources are preferentially used in parts of the CV, and during periods of time that have ample or adequate surface water availability. Groundwater pumping increases during dry periods to satisfy demand. In response to precipitation deficits, surface water diversions become restricted almost immediately in the Tulare basin (Figure 5), which is the CV's most arid region. In the Tulare basin, surface water supplies are used heavily during wet periods and become inadequate during dry periods, which has led to increased pumping and increasing groundwater declines there (Faunt et al. 2009). Although some land use has changed from agricultural to public supply, agricultural water use has not correspondingly declined (Figure A2), likely because this region has been shifting to more water-demanding crops and crops that cannot easily be fallowed (e.g., almonds) (Faunt et al. 2009). Also, surface water availability in the Tulare basin is highly sensitive to interannual variability in precipitation because the limited reservoir storage provides insufficient buffer from precipitation deficits (Dettinger and Anderson 2013). Rainfall in the Tulare basin, even during wet years, is insufficient to satisfy demand, but more water is available to divert from streams and canals during these wetter years, leading to higher diversion totals described here. Furthermore, our analysis suggests the relationship between regional hydrology and diversions in the Tulare is linear. Thus, dry years have the opposite response, with proportionately lower diversions during dry years.

In the wetter Sacramento basin, managed surface water responds to extended multi-year wet or dry conditions (e.g., the 1987–1992 drought). Short periods of dryness do not strongly affect Sacramento basin surface water diversions—where the surface water demand by volume is similar to that of the Tulare basin (Figure A2) but where precipitation is more than double—so direct rain-fed water supply satisfies a greater percentage of water demand there (Faunt et al. 2009) (Figure 4). This is particularly apparent during spring and early summer of wet years, where large precipitation inputs preclude the need for large water deliveries.

The trend in RPC3 appears to reflect the upward trend in municipal diversions, with strong correlations in the Sacramento basin (ρ = 0.82) and Delta region (ρ = 0.72) (Figure 8). Although a correlation between trends could be a chance occurrence, the RPC3 trend and the increase in surface water diverted for municipal uses are well matched to increases in regional urban land development in the Sacramento basin (Figure 10).

The role of reservoir storage is another contrasting aspect in understanding climate effects on northern San Joaquin and Sacramento basin diversions. The largest Sierra Nevada reservoirs are in the northern range (Dettinger and Anderson, 2013), which provide sufficient storage to buffer the managed surface water diversions to the north from interannual variability in precipitation during many dry years. However, noting that Sacramento basin diversions have a significant correlation to multi-year precipitation, there is clearly a limit to this climate buffer on the order of 5 to 10 years whereupon the larger reservoirs begin to run dry.

Compounding the climate effects on managed diversions, land use controls some of the observed variability, especially in the northern CV (Figure 8). Wilson et al. (2016), in projecting future water use changes from shifting agricultural and municipal demand in California, suggested that agricultural expansion and high urbanization could increase municipal water use by about half as much as agricultural demand out to 2060. Agricultural development may lead to shifts toward greater irrigation efficiency, which has already been observed (Hanak et al. 2012), but potential trends are largely uncertain (Wilson et al. 2017). However, recent increases in perennial crops (e.g., fruit and nut trees and vineyards), particularly in the Tulare basin, make it costly or unacceptable to fallow fields during water-scarce years. Thus, a shift toward higher efficiency may be accompanied by a decrease in elasticity to interannual variation in water resources. Furthermore, shifts in usage that diminish wet season recharge, along with possible increasing dry periods in the future (Pierce et al. 2018), could shorten the response time of diversions to hydrological changes relative to that observed here.

Until recently, groundwater has not been regulated widely in California. Thus, because of the irrigation demand and volatility of surface water supplies, the Tulare basin, in particular, has overdrafted groundwater to meet that demand (e. g., Faunt et al. 2009; Nelson et al. 2016). Overdraft is a key concern, involving groundwater storage losses and subsequent land subsidence (Scanlon et al. 2012; Faunt et al. 2016; Xiao et al. 2017).

The strong dependence of CV surface diversions on interannual fluctuations of precipitation and subsequent water storage and flow in the Tulare and southern San Joaquin basins could provide a predictive tool to help water managers anticipate water demand. These relationships, demonstrated by temporal (Figure 5) and spatial (Figure 7) correlation analyses, should provide a linear model that can predict short-term water use. For example, even a bulk CV-wide multiple linear regression driven solely by current and 7-year cumulative regional precipitation explained 67% of the variance in CV diversions. Existing state and federal hydrologic models used to estimate CV groundwater pumping and storage changes are driven strongly by surface water diversion input data (e.g., Faunt et al. 2009). Since much of the variability in diversions can be captured by precipitation and land use, an initial estimate of diversions could be used to drive these CV groundwater models until official diversion data are made public (often with several years lag). Such preliminary (quasi real-time) versions of regional hydrologic models may provide a valuable tool for water managers, and future work will aim at exploring this method to estimate CV groundwater use.

SUMMARY AND CONCLUSIONS

Within the study period (1979–2010), about one-third of the surface water that flows into the CV is diverted for agricultural, public supply (municipal and industrial), and domestic water uses. Total surface diversions are reasonably steady—aggregated over the CV, the variability of annual CV diversions is 15% of their long-term average. Aggregate CV surface water diversions are strongly correlated with yearly to multi-year precipitation and associated hydroclimatic variables. However, from the wetter northern part of the CV to the drier, southern part of the CV, the amount and variability of diversions and how they respond to regional climate drivers varies considerably. Although inflows are largest and have greatest annual variability in the northern Sacramento basin portion of the CV, diversions have greatest annual variability in the Tulare and southern San Joaquin basins. The variation in the southern CV surface water diversions responds strongly and nearly immediately to regional hydroclimate fluctuations, wherein wet years result in the highest diversions. In the northern CV, the Sacramento basin has higher annual precipitation and the greatest magnitude of annual variability, but diverted water volume is less than average during wet years. Annual surface water diversions in northern CV basins are more strongly governed by longer-term hydrologic variability, and by competing demands from municipal and agricultural land uses. Although water diverted for agricultural uses largely dwarfs urban-bound diversions Central Valley-wide, there has been a trend toward increasing municipal diversions that is consistent with urban population growth.

This analysis should help to inform regional water management, in a future that has continuing changes in land use—with increasing urban demand and likely more variable precipitation and runoff. With estimates that California's population may reach 50 million by 2060 (CDOF 2017), urban encroachment into agricultural land (Mann et al. 2014) will likely also continue. These changes would increase the proportion of public supply water use, which is currently less than 20% of the total (Brandt et al. 2014). However, recent extended droughts have led to some of the first mandated urban water-use restrictions in California, requiring 25% drought reductions state-wide (Brown 2015) and curtailments for even some of the most senior agricultural water users (Wilson et al. 2016). Results here indicate that water diversions in the Sacramento basin do not strongly feel climatic influence until several dry years (Figure 4). Projected increases in precipitation extremes for California (Berg and Hall 2015; Pierce et al. 2018) would directly affect water management in the southern CV, and potentially accentuate the climatic response in northern areas if dry spells lengthen (Pierce et al. 2018). Such extended dry conditions may become more common in the future (Berg and Hall 2015; Pierce et al. 2018), and demand may continue rising with increasing population and crop shifts (USDA 2013; Mehta et al. 2013); thus, the response of northern CV diversions may depend largely on how reservoirs and groundwater are managed.

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