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RESEARCH

Patterns of Water Use in California

John Helly*[1, 2], Dan Cayan[1], Tom Corringham[1], Jennifer Stricklin[3], Todd Hillaire[3]

ABSTRACT

Recent patterns of water use and supply in California are presented based on a new data set compiled from the California Department of Water Resources water balance data for 2002 through 2016. The water use and supply include surface water and groundwater, although groundwater reporting has been incomplete. These data are used to support the Water Plan released every 3 to 5 years and are the most comprehensive and finest spatial- and temporal-scale data set for California water resources. First, using the Bay–Delta watershed as a case example, we show that recent fluctuations in water use are highly correlated with variations in precipitation. Developed water supplies and use show these fluctuations, but they are modified by reservoir inflows and releases, groundwater supplies, and Delta outflows. Second, although the annually precipitated water supply in the Bay–Delta varies by about 30%, the developed water supply damps this considerably. The water management system maintained nearly constant agricultural water use even in periods of intense drought, with year-to-year variation of about 7%. Variability in urban water use is higher (~20%), largely from conservation during periods of drought. Finally, this information can help improve water resource management because it connects regional-scale data to meaningful policy decision-making at county and sub-county levels. At a time when water policy and management are being re-evaluated across the American West in the light of changing climate, decision-making informed by science and data is urgently needed. The statewide water balance data provide the means to establish a consistent, quantitative framework for water resource analysis throughout the state.

KEY WORDS

California, water, hydrology, Bay–Delta, precipitation, regional, data, agriculture, urban, managed wetlands, California Water Plan

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* Corresponding author: *hellyj@ucsd.edu*

1 Climate, Atmospheric Science and Physical Oceanography, Scripps Institution of Oceanography, University of California–San Diego La Jolla, CA 92098 USA

2 San Diego Supercomputer Center, University of California–San Diego La Jolla, CA 92098 USA

3 California Natural Resources Agency, Department of Water Resources Sacramento, CA 95814 USA

INTRODUCTION

Local decision-making about water is limited by the availability of consistent, integrated data about water supply and use at meaningful scales of measurement. Global and regional estimates of changes in precipitation must be coupled to operational management of water resources at the watershed-level to be relevant to the policies that govern them. At a time when water rights and policy are being re-evaluated across the American West in the light of changing climate, decision-making informed by science and data is urgently needed (Grantham and Viers 2014). The California statewide water balance data provide a consistent, quantitative framework for water resource analysis throughout the state. The California Department of Water Resources (CDWR) recently published statewide water balance data in a comprehensive form not previously available. This data set covers the water years 2002–2016 at the finest level of spatial granularity available within the CDWR.

For water balance analysis, the state of California data are spatially organized in a four-level hierarchy such that the highest-level of aggregation is the entire state and the smallest watershed-based partition is a Detailed Analysis Unit (DAU), which is further subdivided by county to create DAU–County partitions: called DAUCOs (Figure 1). Other spatial aggregations include planning areas (PAs) and hydrologic regions (HRs) using the DAUCO-level data since 1998 as the basis of water balance reporting. To summarize, the four levels are: (1) state, (2) PA, (3) HR, and (4) DAUCO.

When aggregating DAUCO-level data into state-, PA-, or HR-level statistics, adjustments must be made to ensure accuracy across spatial boundaries. The CDWR publishes data at each level of aggregation to provide appropriately corrected data for a given spatial scale. In this work, we use data at the HR and DAUCO-levels and will indicate what level is used in each analysis.

The data are standardized, geo-referenced, and quality-controlled using new methods defined by the Open Water Information Architecture (OWIA; Helly 2017, 2019), that ensure semantic, spatial, and temporal consistency across the entire data set, making it interoperable: for example, suitable for integration with other data to bridge climate-scale process models (1 to 10 km) at the regional and global scale to the sub-county and watershed-level data at the municipal level (1 m–1 km). The DAUs approximate watershed boundaries defined by the United States Geological Survey (USGS; USGS 2013) as HUC-8; however, the polygonal boundaries of the watersheds are not the same and diverge especially in the Central Valley of California. Work is now underway at the CDWR to migrate from the DAU partitioning to the USGS partitioning, to further standardize to the national framework.

Water balance reporting is founded on a framework of observations—accounting begun in the early 1900s and formalized by legislation that formed the CDWR in 1947. The modern form of this accounting is used to support recent versions of the historical California Water Plan initiated in 1957 and published every 5 years since 1993 (California Water Atlas 1979; CDWR 1957; 2020 email between K. Guivetchi, CDWR, and JH, unreferenced, see "Notes"). The data are now published separately to release data annually in compliance with the 2016 Open and Transparent Water Data Act of the California State Legislature (AB 1755).

From the CDWR Water Plan Update 2018 (CDWR 2019c), the following is a description of the data presented in this work.

> *... [the water balance data] is the only statewide analysis that exists. The California Water Plan (Water Plan) water balance data is used by many in and out of the water community. Data and information requests come from other DWR programs, State and federal agencies, cities and counties, local water agencies and purveyors, research institutes, universities, non-governmental organizations, private sector companies, lawyers, elected officials, news media, documentaries, book writers, students, interested public, other states, and even other*

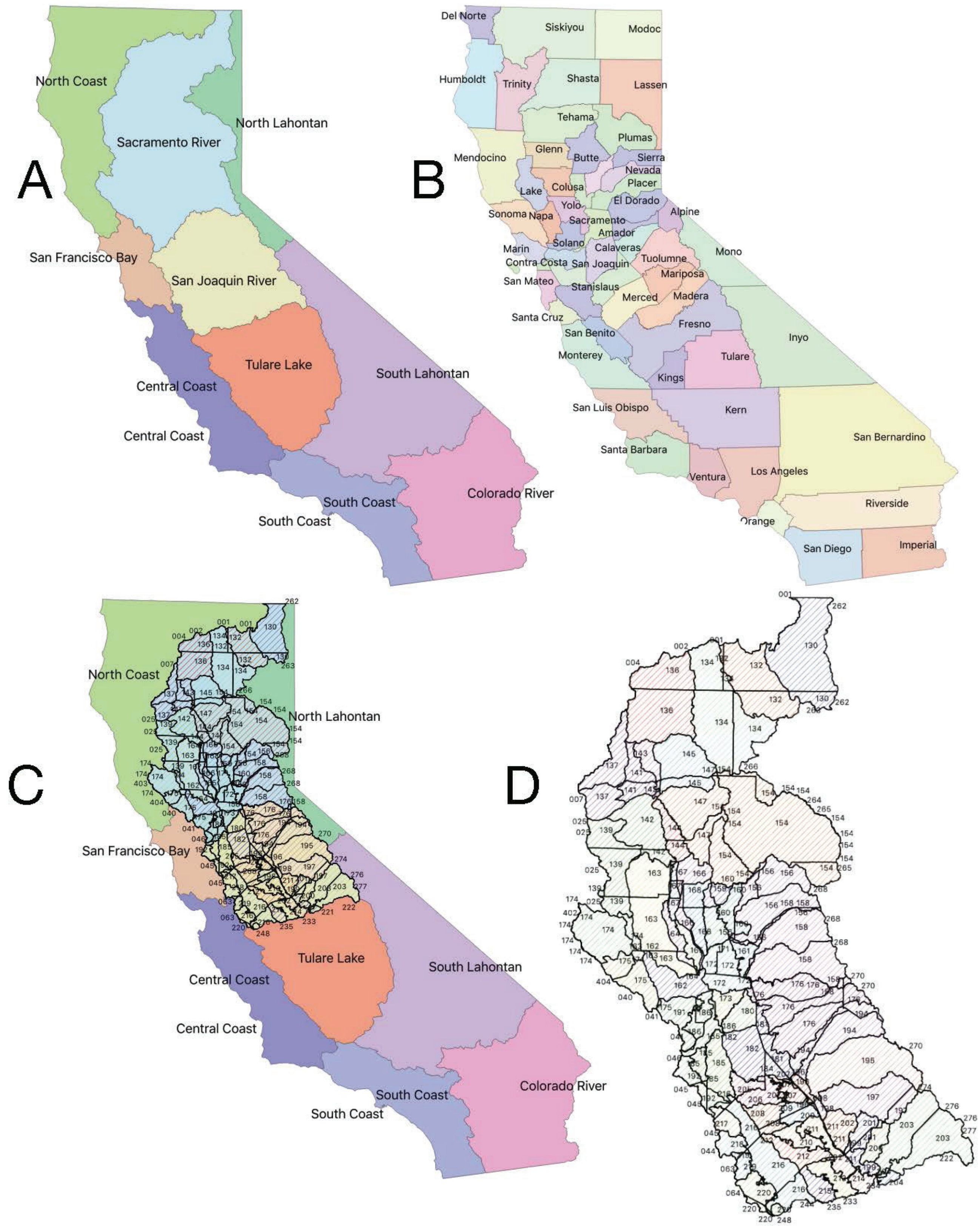

Figure 1 (**A**) California's Hydrologic Regions (HRs) as defined by the California Department of Water Resources. (**B**) Counties. (**C**) Bay–Delta watershed formed from Sacramento River and San Joaquin River HRs partitioned into counties and labeled with Detailed Analysis Unit (DAU) codes. (**D**) DAUs within the Bay–Delta watershed. Note that there may be multiple DAUs within a county or multiple counties with parts of one or more DAUs.

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countries because California is recognized as a leader in integrated water resources management.

While the water balance data have been widely used in summaries within the Water Plan report, this paper presents a more comprehensive analysis based on the complete DAUCO-scale data set.

The data sets are assembled at CDWR's regional offices where the data are collected from many sources, entered, and translated into Water Plan reports by a team of 50 to 100 staff in five offices: four regional offices across the state, as well as the Sacramento headquarters. The methods used in this study were recently introduced into the workflow of how the Water Plan is processed to provide new methods of quality control and automation beyond what was practical in the previous, spreadsheet-based management of data (see "Water Quantity Parameters and Uncertainties" section). Data is still entered via spreadsheets, so the skills necessary for data entry have not needed to change, but both quality control and report processing have been converted to interoperable ASCII data, which is processed using an open-source, procedural language (Helly 2017, 2019).

Each regional office is responsible for a different part of the state, resulting in similarities and

Table 1 Data sources and date ranges

Precipitation	1.	Source: PRISM data and methodology
	2.	PRISM filename: *cai_ppt_us_us_30s_189501.bil*
	3.	Daily [monthly] total precipitation (rain+melted snow)
	4.	Local path and filename: */ascii/master-BayDelta.xyz*
	5.	Range: 1895–2018
	6.	Type, Version: an81/r1308, M2
Surface reservoir levels	1.	Source: CDWR Sacramento Office
	2.	Local path and filename: *Reservoirs/ResStor_2000-2015_2016-02-02Level1.csv*
	3.	Range: 2000–2015. Missing data for 2002–2005.
	4.	From the CDWR description: Carryover storage for reservoirs defined as the amount of water in surface reservoirs at the beginning or at the end of the water year and represents one of the potential sources of water in a drought year. Information from California Division of Safety of Dams shows that there were 1381 dams with jurisdictional size in operation during water year 1999. Jurisdictional size reservoirs are defined as those with a height greater than 25 feet, or a capacity greater than 50 acre-feet. Some of the jurisdictional size reservoirs are detention reservoirs. For 1999 we were able to find storage data for 243 reservoirs, out of 1368, which have a total storage capability of 39,941 thousand acre-feet (TAF). This represents 96% of the total of all 1358 reservoirs. For example, carryover storage at the beginning of water year 1999 was 31,190.3 TAF and decreased to 27,062.6 TAF at the end of the year, for a loss of 4,127.7 TAF for the year.
Total Delta outflow	1.	Source: CDWR Bay–Delta Office
	2.	Local path and filename: *Unimpaired-Flows/Unimpaired-Flow-Master.csv*
	3.	Parameter name and units: TOTAL (TAF)
	4.	Delta Outflow Dayflow Metadata
	5.	Dayflow data - CNRA Open Data website
	6.	Range: 1922–2015
Crops	1.	Source: CDWR Sacramento Office
	2.	Local path and filename: *Crops/1998_2010_AgData_ByDauCounty_WMacroRevised_Jan15_16.csv*
	3.	Range: 1998–2010
Water balance	1.	Source: CDWR Sacramento Office
	2.	*https://data.ca.gov/dataset/water-plan-water-balance-data*
	3.	Range: 2002–2016

differences in content and methods of data acquisition across theses offices. Internal workflow diagrams document the process, although there is no comprehensive description of how this work is done. As technology changes, procedures are updated to incorporate better sources and method of data acquisition. For example, until recently, agricultural water use data were developed by the regional offices using county-level field surveys by team members to provide ground-truth estimates of crop production to support a single crop model, CALSIM ETAW, run by the CDWR. This model estimates evapotranspiration as a proxy for crop production and water consumed by agriculture on a crop-by-crop basis. Over the past 2 to 3 years, new methods using remote-sensing data have been developed to replace field-based ground-truthing.

Data in other categories—such as urban, managed wetlands, and environmental—are estimated by other methods managed within each regional office.

As an example of the significance and utility of these water balance data, we examine the Sacramento River and the San Joaquin River HRs, which comprise the Bay–Delta watershed. This enables a comparison with the state's other HRs. The Bay–Delta is a major element of the water supply for central and southern California, and is the state's largest water resource feature, providing approximately 41% of statewide water supply (see "Patterns in the Volume of Water Supply and Use;" USGAO 2018).

A recent analysis of water resource data in California highlighted their quality and variety but noted limitations in supporting decision-making (Ariyama et al. 2019). The authors concluded that, even in the Bay–Delta watershed where there is relatively low uncertainty in surface water supply and use data at fine temporal and spatial scales, there is high uncertainty in groundwater supply and evapotranspiration estimates. The importance of working at sufficiently high spatial resolution was also emphasized (Abatzoglou et al. 2009).

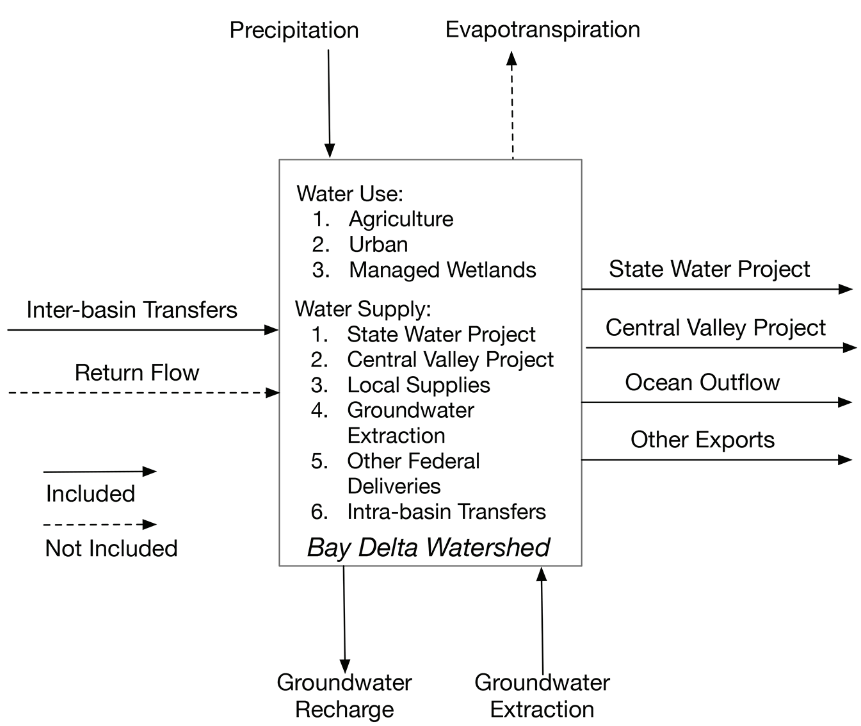

Figure 2 Schematic of water balance for Bay–Delta watershed. Detailed descriptions of the parameters, inputs and outputs can be found in CDWR (1957) and CDWR (2019c)

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More recently, statistical down-scaling techniques—which translate global climate model (GCMs) simulations to the California region with higher spatial resolution and improved representation of climate extremes—have been developed and applied (Pierce et al. 2014; Bedsworth et al. 2018). Correspondingly, to inform decision-making and constrain it to the realities of natural variability, an obvious challenge is to further improve our ability to understand the spatial and temporal dynamics of water use and supply at scales of measurement meaningful to policy decision-making.

This study includes only (1) agricultural, (2) urban and (3) managed wetlands: water uses that focus on human consumptive use, including those that extract water from the developed supply as crops or landscape irrigation. The CDWR considers another broad category of water to be environmental flows. This category can be thought of as a constraint on the water balance since it includes legislatively mandated flows (e.g., Required Delta Outflow) to sustain biological populations and ecosystems, maintain appropriate salinity levels, and avoid drying up rivers by consumptive uses. We have excluded environmental flows from this study to focus on the urban, agricultural, and managed wetland categories of use.

Here, we consider the newly available water balance data along with water data from other sources (Table 1) to address three questions:

1. How does recent water use in the Bay–Delta watershed, and in the broader statewide HR, compare with the precipitation received in recent years and across a longer historical record?

2. What are the dominant components of Bay–Delta watershed water supply and use, and how do they vary in time?

3. How might this information be used to improve water management?

MATERIALS AND METHODS

The quality control and data publication methods for the data used here were developed as part of a USEPA-funded project begun in 2014. A collaboration of the CDWR, the Western States Water Council (WSWC) and the University of California, San Diego (UCSD) enabled state of California water resources data to be electronically reported within a WSWC-developed system for national water resource data collection and analysis entitled WaDE (Water Exchange Data Network; *https://www.westernstateswater.org/wade/*. That approach has been generalized as the Open Water Information Architecture (OWIA; Helly 2017). The software developed for the research presented here employed: (1) R (R Core Team 2019), (2) GMT (Wessel 2013), (3) QGIS (QGIS Development Team 2020) and (4) Bash (Free Software Foundation 2007) based on OWIA standards and conventions.

The change point detection results used the At Most One Changepoint (AMOC) method with the default settings of the “cpt.meanvar” function (Killick and Eckley 2011), which selects AMOC. Water years are used throughout this work; a water year differs from a calendar year by 3 months, so that, for example, October 1, 2020, is the beginning of water year 2021, which ends on September 30, 2021.

Water Use and Water Supply Data

Annual water balance data for the water years 2002 through 2016 were organized using parameterization and a standardized vocabulary. The parameters are quantitative and categorical variables used in analyses, and the vocabulary is the naming used to categorize and aggregate them. Such standardization enables quality control procedures to be automated using the current CDWR workflow methods and resources and enables new computing methods to be integrated into analysis of the data. Geospatial metadata from CDWR were merged with the water balance data to provide geographic position(s) for the data (i.e., georeferencing) and categories for spatial aggregation using the World Geodetic System 1984 (WGS84; Snyder 1987). The resultant georeferenced data set was processed using CDWR standard operating procedures (SOPs; Helly 2019). The data were then further integrated with other data listed in Table 1 for the analyses reported here. Water volumes in the water balance data are reported by CDWR in units of thousand acre-feet (TAF) where an acre-foot is the volume of water required to cover an acre to a depth of 1 foot, which is equal to $1.23 \times 10^3\,m^3$ or 3.25×10^5 gallons.

Spatial Units and Aggregation

DAUCOs are the finest spatial partition of watersheds the CDWR defines. As a result of resource management decisions since 1919, and because DAUs sometimes cross county lines (which leads to a jurisdictional need to sub-divide a DAU), DAU identification codes are concatenated with CDWR county codes to produce unique identifier labels referred to as DAUCOs. The CDWR county codes differ from federal information processing (FIPS) county codes, so the two are not interchangeable (i.e., not interoperable). Efforts are underway to rationalize the DAUCO-based spatial partitioning to the USGS hydrologic unit code (HUC) system, but the DAUCO partitioning should be retained to reconcile historical data and support transitions across the two partitioning schemes.

Consequently, the state is now partitioned into 486 DAUCO spatial units, aggregated into ten HRs (HRs; Figure 1), excluding the Channel Islands and some smaller islands. A complete description is found in CDWR (2019c). The Channel Islands were not included in this study because they are not contiguous with the rest of the state's sub-aerial land and freshwater resources and are separate from the state's primary major water infrastructure. At each level above the DAUCO scale, the boundary conditions at each higher-level partition are adjusted (e.g., HR, state) to avoid double-counting when DAUCO-level flows cross one or more higher-level partition boundaries or involve identified transfers across management boundaries.

Figure 2 illustrates the elements of the water balance of the Bay–Delta watershed and is provided as a reference for later figures and tables. It is a box diagram of the water balance that shows inputs and outputs within an arbitrary spatial unit that might be a DAUCO, HR, or—as in our case—the Bay–Delta watershed. The outputs include ocean outflow and major diversions to the engineered infrastructure (i.e., conveyance, storage, and distribution) represented by the State Water Project (SWP) and the federal Central Valley Project (CVP). "Other Exports" includes flows from the San Joaquin River (SJR) HR to San Francisco Bay (SFB) HR, Hetch-Hetchy Mokelumne Aqueduct and the Sacramento River (SR) HR to North Lahontan (NL) HR and Pit River. "Return Flow" from outside the watershed is excluded to isolate the effects of variability in precipitation on water supply within the watershed. "Inter-Basin Transfers" are included to account for reservoir storage outside of the Bay–Delta watershed that supply water within the watershed. "Intra-Basin Transfers" within the Bay–Delta watershed are included in the data but not detailed in this study.

Data Sources

The data sources used in this study appear in Table 1. These include: (1) Water Balance data from the CDWR for the water years 2002–2016, (2) precipitation data from the PRISM Climate Group (*https://prism.oregonstate.edu/historical/*) at Oregon State University, (3) total Bay–Delta outflow data from the CDWR Division of Environmental Services DAYFLOW program, and (4) reservoir levels from the State of California Data Exchange Center (CDEC; *https://cdec.water.ca.gov/*) system.

The California Water Plan (CDWR 2019b) defines water use to include water for urban and agricultural sectors, managed wetlands, and environmental flows. Environmental flows include (1) Minimum Delta Outflow, a legally required Bay–Delta outflow; (2) Instream Flow Requirements; and (3) Wild and Scenic River flows. This study excludes "Environmental Flows" and includes only "Agricultural," "Urban," and "Managed Wetlands" water uses to focus on human consumptive use: by definition, this type of use extracts water from the developed water supply for crops, landscape irrigation, and residential consumption.

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The PRISM precipitation data set used here uses the term "precipitation" to describe water from the atmosphere as rain and melted snow (Table 1). Melted snow refers to any snow accumulating on a rain-gauge that eventually melts into the gauge. In the context of California water resources, some fraction of precipitation is diverted for "consumptive use," referred to as "developed supply," and the rest flows to the ocean, percolates into the ground, or evaporates back into the atmosphere. Some of the diverted precipitation is stored to prevent flooding, for later use seasonally or in drought, or to maintain ecosystems. Water is stored in a variety of ways (e.g., rivers and lakes, reservoirs, aquifers) and for different durations (e.g., annually, interannually, decadally, centurally, millennially) before it is released, diverted, or extracted to be used as part of the developed supply, flood management, environmental flows, or in combination. Precipitation therefore results in: (1) surface-water runoff within a water year, (2) multi-year surface water stored in reservoirs and (3) groundwater stored in aquifers or not recoverable, (4) flow to the ocean, (5) evaporation to the atmosphere. Since we have excluded minimum Delta outflow from this analysis because it is part of environmental flows within the water balance data, we include data for total Delta outflow to the ocean as a more complete estimate of precipitation flowing to the ocean from a mass balance perspective.

Water Quantity Parameters and Uncertainties

The CDWR uses the water quantity parameters applied water use and net water use. They are not the same. In the water balance data set, they are defined as in Equations 1 and 2.

$$\text{Net Water Use} = \text{ETAW} + \text{Irrecoverable Distribution Loss} + \text{Outflow(ocean, salt sink)} \tag{1}$$

Outflows to the ocean and salt-contaminated land (i.e., salt sink) are considered irrecoverable where they occur. The ETAW term (evapotranspiration of applied water) is an estimate of water use from crop and vegetation production generated by the CALSIMETAW crop model the CDWR operates. In contrast, applied water use (Equation 2) includes reuse.

$$\text{Applied Water Use} = \text{Net Water Use} + \text{Reuse} \tag{2}$$

From this, we obtain another expression for net water use in Equation 3.

$$\text{Net Water Use} = \text{Applied Water Use} - \text{Reuse} \tag{3}$$

These two formulas for net water use, parameterized as NW2 and NW1, respectively, in the data set, are used in the quality control procedures as cross-checks to verify the data, and their computed values are included in a report distributed with the published versions of the data. Unless otherwise noted, we use "water use" as a synonym for Net Water Use according to Equation 1.

Uncertainty and Propagation of Uncertainty

Each of the 485 DAUCOs used in this work has about 15 parameters, besides ETAW, within each net water use estimate (Equation 1) for each category of water use and supply (e.g., agriculture, urban, managed wetlands) and to account for distribution losses and outflows. Each parameter is estimated without sampling: that is, it is a point estimate by experts each water year.

Outflows and losses across spatial boundaries are corrected, so, for example, return flows between DAUCOs within an HR are not counted as flows out of the HR. Similar adjustments are done for PAs. The formulas for the parameters and the spatial adjustments were originally developed and implemented in spreadsheets and translated into the procedural R language (R Core Team 2019) as part of the automation efforts referred to previously. They are documented, along with their associated controlled vocabulary, in the SOP for the water balance processing (Helly 2019).

The parameters are estimated in a variety of ways across regional offices without explicit estimates of uncertainty. Here, we invoke the methodology of Taylor and Kuyatt (1994) based on the use of uncertainty estimates, which may be either statistical or non-statistical, and avoid using the terms accuracy and precision. Uncertainty estimates may be based on non-statistical methods, such as those used for water balance estimates, and may include: (1) previous measurement data, (2) experience with, or general knowledge of, the behavior and property of relevant materials and instruments, (3) manufacturer specifications, (4) data provided in calibration and other reports, and (5) uncertainties assigned to reference data taken from handbooks. To cope with the recognized uncertainties across these tens of thousands of individual parameter estimates (i.e., 485 DAUCOs × 15 parameters × 3 sectors), the water balance team prescribes a standard uncertainty of 100 acre-feet (i.e., ±50 acre-feet). For example, an estimate of 0.1 TAF represents the range of values (0.15, 0.05]—an interval open on the left defined by a rounding rule.

This reported uncertainty is recognized to be a goal, and the best the water balance team can do; the uncertainty of any given estimate may be substantially higher. Given the CDWR's current resources and methodology, there are no methods to accurately determine uncertainty more robustly, although some of the references used to develop some of the parameter estimates use statistical methods that might be useful. Notably, a side-effect of this standard, as optimistic as it is, is that any community within the state with use and supply in the range (0.05, 0.00) TAF is misrepresented as having zero supply or use, while those in the range (0.1, 0.05) TAF may have their use and supply over-estimated by almost 100%. These side-effects may result in disproportionate economic and infrastructure effects within disadvantaged groups across the state as water management policies change.

Uncertainty is propagated into aggregated data at each higher spatial level (i.e., PA, HR, state) where DAUCO-level quantities are summed into HR-level quantities. For example, the San Joaquin River (SJR) and Sacramento River (SAC) HRs have 71 and 85 DAUCOs, respectively.

Given the prescribed uncertainty at each DAUCO and the rule of additive uncertainties for addition (NIST 2012), the parameter estimates for SJR and SAC are ± 7.1 and ± 8.5 TAF, respectively. These uncertainties, when added, represent approximately ± 2% uncertainty in the water balance data for the lowest values of parameters (i.e., urban, managed wetlands at ~1,000 TAF) before any statistics are calculated. Again, this is most likely an underestimate of the uncertainty in the data, considering the limitations in data and statistics within the current methodology.

However, another approach to uncertainty is available from the linear regression residuals (see "Skill and Uncertainty of Regression Modeling"). This approach estimates water supply components produced by a linear model formed with PRISM-derived precipitation. We use precipitation to predict values of water supply based on the water balance data as described more fully below (see "Estimating Water Balance Components Using Observed Precipitation"). This produces a range of uncertainty, via the annual residuals from the regression, over the 15 years of data from −11% to 7% of the observed values in each year, with a residual standard error of 925 TAF. The fit of this regression is not especially good—albeit statistically significant (i.e., multiple R-squared: 0.31, $p = 0.03$), because of a couple of adjacent drought years as outliers—but it provides another method of examining the uncertainty in the water balance data from precipitation. The overall residual error above results in an estimate of ±5% of the developed supply mean.

Estimating Water Balance Components Using Observed Precipitation

We implemented a simple method for extending the 2002 through 2016 time-series to include 2017 through 2019, based on linear correlations between water supply and within-year precipitation. We do this both to fill gaps in water balance reporting, which lag 3 to 5 years behind present day for administrative reasons, and to provide the beginnings of methods to project future water conditions in concert with weather and climate models that run over seasonal time-scales or for decades into the future.

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All water, surface and groundwater, is ultimately from precipitation unless derived from the Earth's lithosphere (Schmandt et al. 2014), but the surface water supply is seasonally variable, while groundwater varies on a much longer time-scale, unless it is extracted by pumping, in which case a new source of short-term variability is introduced into long-term groundwater patterns. Ultimately, water supply is tied to precipitation, which is the independent variable used for prediction here.

Skill and Uncertainty of Regression Modeling

Regression modeling is used to fit a parametric equation using empirical data to predict a dependent variable by interpolation or extrapolation. The variability of the data is used to estimate uncertainty in the parameters and confidence intervals for annual predictions.

Interpolation and extrapolation are both predictions, but extrapolation extends predictions beyond the domain of the data used to generate the parameters. Therefore, extrapolation assumes that the future will be like the past. Different assumptions can be used to construct alternative scenarios (i.e., that the future will be different from past); this is commonly done to investigate climate-change scenarios and other problems to estimate uncertainty and the sensitivity of predictions to assumptions.

Various methods for generating predictions are available, and the quality, or skill, of the results of each must be checked by comparison to observations. Since we are using a regression approach with water use data, we can update the predictions and evaluate the method's skill annually.

Here, we limit ourselves to simple linear regression because we are not focusing primarily on the model's predictive skill. Rather, one objective is to demonstrate that it is possible to use precipitation data to extrapolate recent years of water use and supply from precipitation data that is more current than the most recent water balance data. We have experimented with other approaches (see "Patterns in Water Variability") that seem to have better predictive skill (see "Results").

Data Publication and Supplementary Materials

All data used in this study is published by the CDWR as the Water Plan Water Balance Data (*https://data.cnra.ca.gov/organization/dwr/portal/data?q=water+balance&sort=score+desc%2C+metadata_modified+desc#search-data*) with additional access provided by the California Coastal Atlas Water Balance Library (*https://californiacoastalatlas.net/california-department-of-water-resources-water-balance-library*). Along with these data is also a copy of the Standard Operating Procedures (SOPs; *https://data.cnra.ca.gov/dataset/water-plan-water-balance-data/resource/529ead9b-2a3b-48b7-ba8b-a875d243f183*).

RESULTS

Results are organized into two sub-sections: "Patterns of Water Use and Supply" is an analysis of temporal patterns of water use and supply, including groundwater, across the state, in both magnitude and variability. This analysis includes agriculture, managed wetland, and urban sectors, with a focus on the Bay–Delta watershed, in the context of precipitation, reservoir storage, and ocean outflow. "Characterization of Applications" is an evaluation of patterns of water use and supply in the light of which applications and sub-components are most water-intensive in California.

Patterns of Water Use and Supply

California's water supply depends highly on precipitation, including contributions from snowpack and snowmelt over mountainous locations dominated by Sierra Nevada catchments, since annual precipitation is the primary source of surface water and groundwater, and varies widely across space and time as a result of climate and weather (CDWR 2019a). The water balance data, on which the Water Plan is based, describe consumptive uses: those uses that extract water from the developed supply as crops or landscape irrigation, which are primarily agricultural and urban.

Figures 3 and 4 show the historical precipitation record in the Bay–Delta watershed since 1895. These figures show the magnitude of water each parameter measures, their variability and range, and the length of each time-series. The historical perspective is important when evaluating the relative effects of climate, weather, and human behavior. Although the water balance data set is short, it connects water management practices with annual time-series of precipitation and other key hydrologic measures that provide statewide coverage over a much longer time-period.

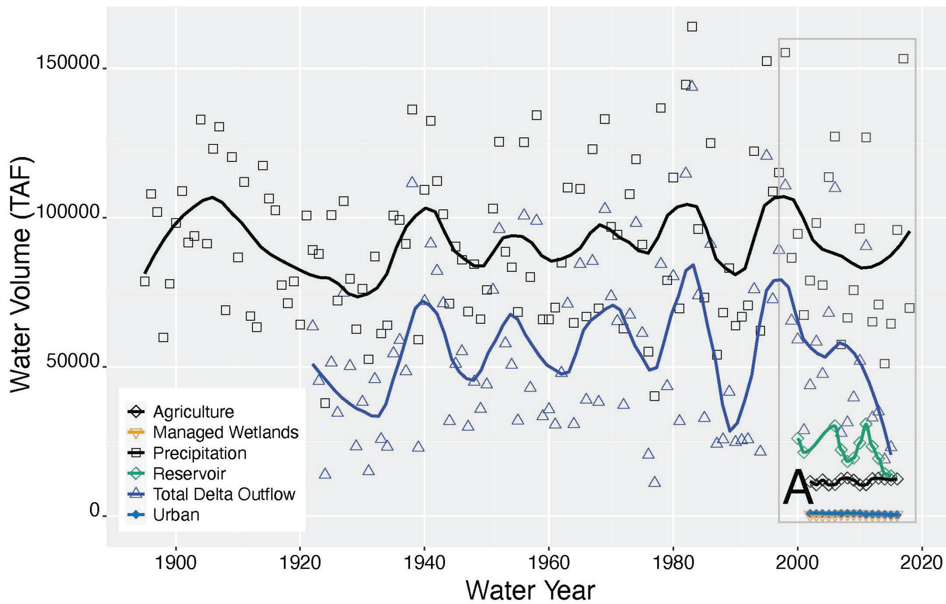

Figure 3 Historical context for contemporary water use and supply in the Bay–Delta watershed in contrast to long-term records of precipitation and total Bay–Delta outflow plotted from 1895–2019 and 2002–2016, respectively. **(A)** For scale comparison here with details in Figure 4. This is the new CDWR water balance data that are the primary subject of this study along with reservoir data integrated with CDWR data and long-term precipitation and outflow data. Smoothing is provided by the R loess algorithm with a span parameter of 0.2

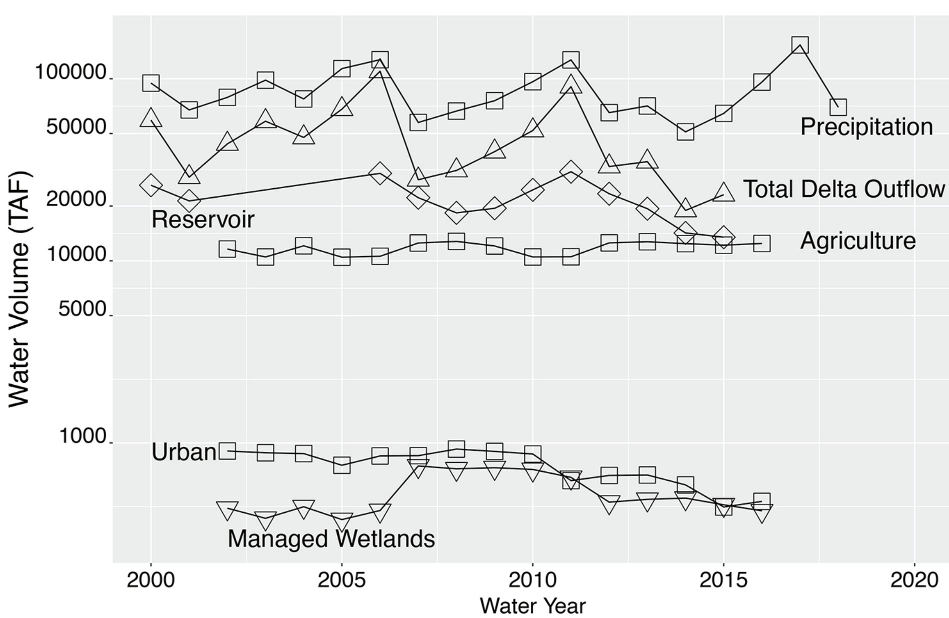

Figure 4 Inset **A** from Figure 3. Comparison of recent patterns of water use and precipitation. Supply is characterized here by precipitation and reservoir storage.

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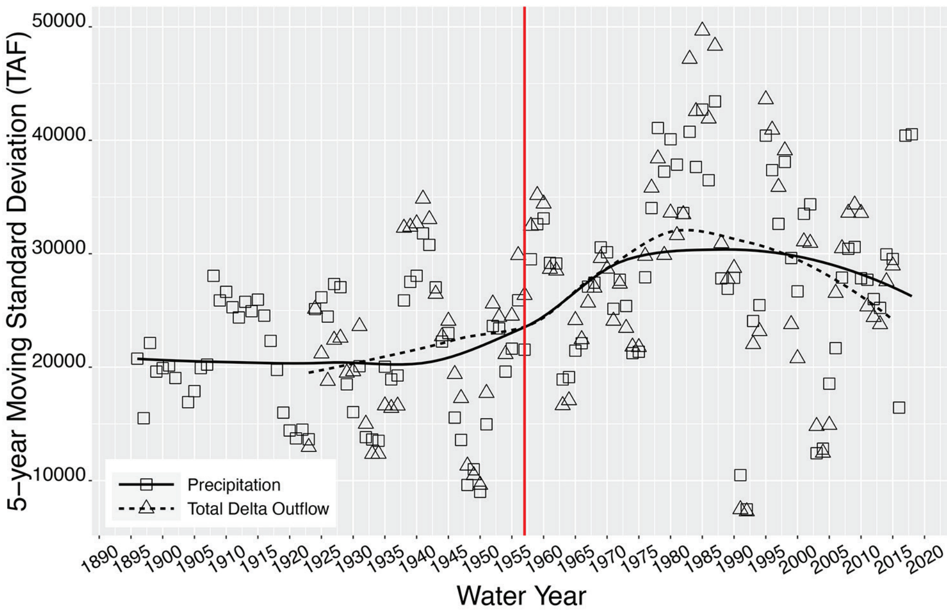

Figure 5 Long-term moving standard deviation of volumes (TAF) in precipitation and water use categories. *Vertical red-line* at 1957 indicates a statistically significant change point ($p < 0.001$) in precipitation mean and variance.

Figure 5 shows annual precipitation, total Bay–Delta outflow, and water balance data using a moving 5-year standard deviation as a measure of annual variability. This longer-term record of precipitation and Bay–Delta outflow show the same patterns around an increase in mean amplitude, with increasing variability from increasing extremes. The results indicate that both the levels and the variability changed over the 125-year history around 1957 ($p < 0.001$; Killick and Eckley 2011), reflecting a transition from moderate variability during the period before 1957 to strong alternating spells of wet and dry years after. We discuss these features in the water balance data below.

This recent experience of a more variable climate may simply reflect California's high interannual—and longer time-scale—fluctuations of precipitation (Dettinger 2011). Proxy records derived from tree rings exhibit considerable multi-decadal variability (Meko et al. 2014; Griffin and Anchukaiti 2014). Additionally, anthropogenic climate change has begun to affect this recent period, and global climate models suggest changes toward higher interannual variation (Berg and Hall 2015).

Figure 4 shows that the timing and amount of annual precipitation are temporally out of phase with annual agricultural and urban uses of developed supply; that is, increased precipitation correlates with decreased water use. Some of this correlation reflects reduced developed water demand from increased local precipitation. It also underscores the importance of water infrastructure and management to supply water when precipitation is diminished. The dynamics of the supply–demand cycles for water have implications for every component of the water system, as evidenced by the 2014 Sustainable Groundwater Management Act (SGMA; *https://water.ca.gov/Programs/Groundwater-Management/SGMA-Groundwater-Management*) of 2014, the effects of urban water conservation (Figure 13), and the types and amounts of crops planted in the various agricultural regions of the state (see "Water Use by Agricultural Crop Type").

California's water resources are provided by an engineered infrastructure, constructed starting roughly in the 1800s, to move water from where it falls from the atmosphere to where it is used (California Water Atlas 1979). Most of this water conveyance occurs within the state, but some

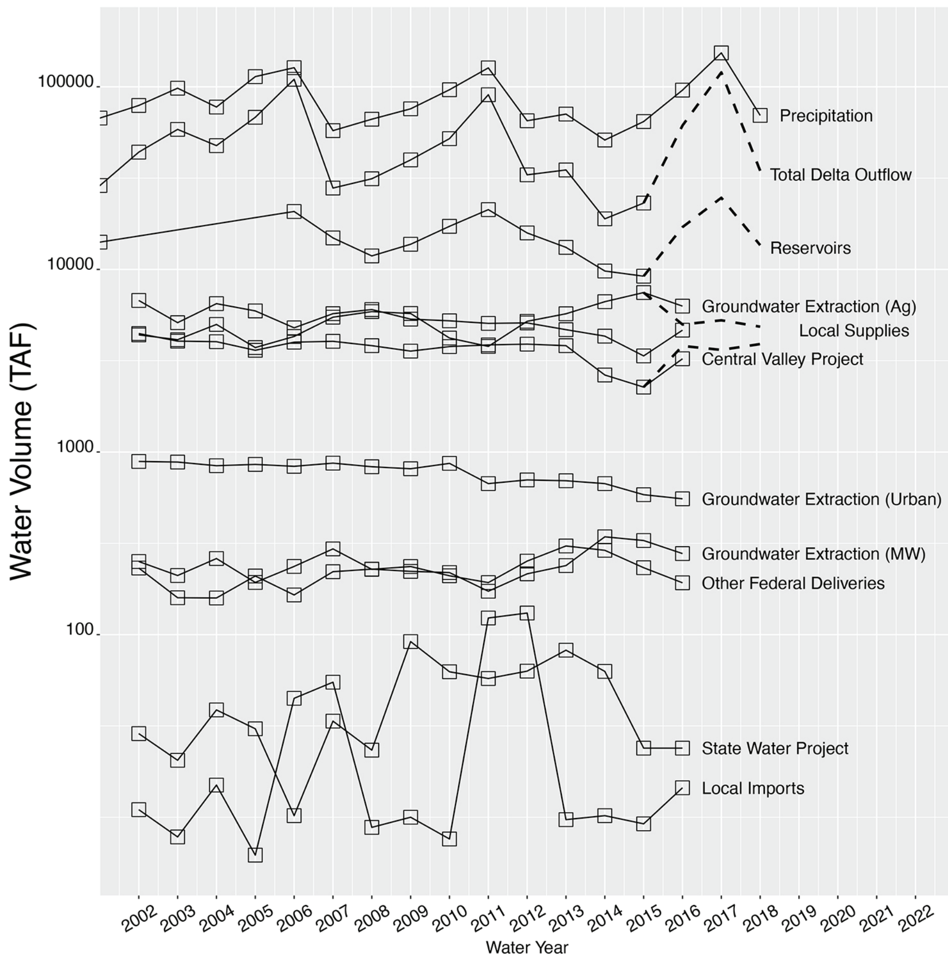

Figure 6 Comparison of precipitation and developed supply. Predicted values for Total Delta Outflow, Reservoirs, Groundwater Extraction (Ag), and Central Valley Project, shown as *dashed lines.* Confidence intervals have been omitted to aid legibility.

imported supply comes from the Colorado River and other sources in Oregon, and a tiny amount comes from ocean desalination. Using precipitation data external to the water balance data allows the effects of changes in climate and weather on the overall supply to be evaluated, and the relationships between precipitation and the developed supply to be investigated. It also provides a cross-check on the validity of the water balance data itself.

As described above and detailed in Figure 6, water supply has at least two sources: the supply from precipitation and the developed water supply. Precipitation includes everything that falls from the atmosphere as precipitation within a water year as well as multi-year water stored in reservoirs and groundwater aquifers. The developed supply includes water from precipitation that is (1) diverted and transferred within the state, (2) imported from outside the state, (3) extracted from groundwater, and (4) released from prior-year storage in reservoirs. The central purpose of the developed supply is to stabilize the water supply from temporal variability (driven by seasonal and inter-annual variability in precipitation) and from spatial variability (where water is used vs. where it falls from the atmosphere).

Since the developed supply is engineered and managed, it varies in phase with water use as seen in Figure 7 while it is out of phase with precipitation. If more water is needed—for

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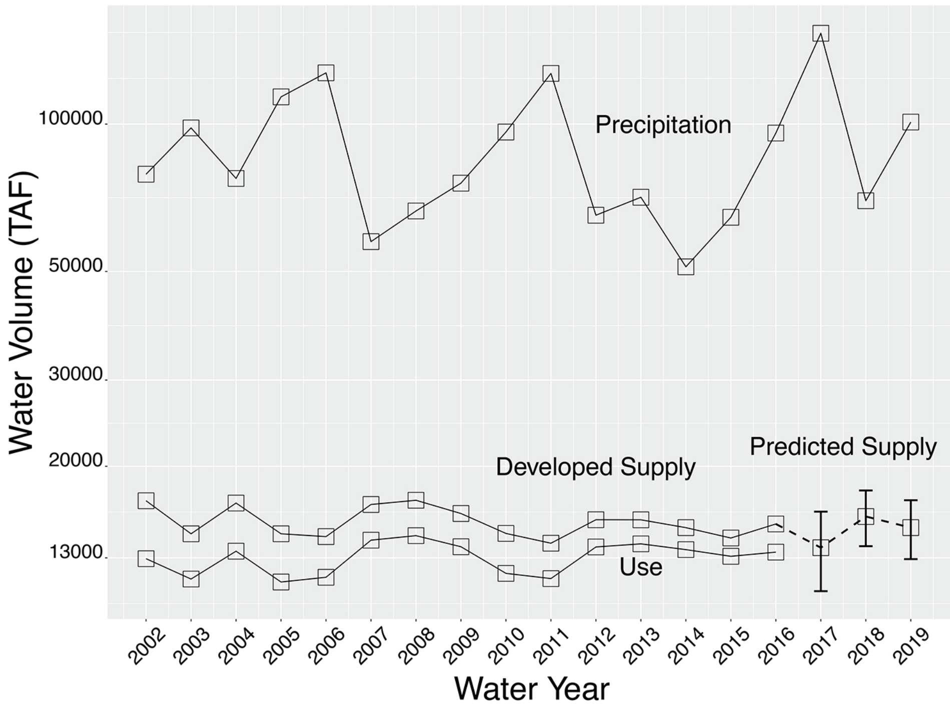

Figure 7 Annual volumes of precipitation, water use and developed supply are shown here. Predicted Supply, with 95% confidence limits for years 20172018, is estimated from a simple linear regression model (see "Estimating Water Balance Components Using Observed Precipitation"). Note that developed supply and use vary in-phase with each other but out-of-phase with precipitation.

example, during droughts—it is locally pumped from groundwater aquifers, released from reservoirs, or imported via aqueducts and pipelines. The difference between the annual usage and developed supply has decreased since 2011 as a result of reductions in the developed supply.

Available technology and a mostly inelastic demand for water has led to unsustainable groundwater pumping, causing multiple problems, including depleted aquifers and land-subsidence. This motivated the California legislature (i.e., SMGA 2014) to end further groundwater overdraft by 2040. Although there is a tendency to think that California's water resource strategy is predominantly to supplement supplies with groundwater in drought, federally subsidized, relatively low-cost surface water supplies were developed in California to augment local groundwater supply, since more groundwater pumping costs more energy and requires deeper wells (California Water Atlas 1979; Reisner 1993). Nonetheless, in agricultural use, when the less expensive surface water supply is diminished (for example, in drought), groundwater pumping is increased to compensate (Figure 6). Urban water use shows reductions apparently from conservation (see "Characterization of Applications").

Patterns in the Volume of Water Supply and Use

The relationship between developed water supply and water use in the water balance data is shown in Figure 8 for the ten hydrologic regions of California from 2002 through 2016. The Figure emphasizes that water use and developed water supply are highly correlated by design. Figure 8 shows that four geographic regimes account for much of the state's water use. Ranked from highest to lowest water usage, these are: (1) Tulare Lake, (2) the Bay–Delta Watershed (San Joaquin River and Sacramento River), (3) the South Coast and Colorado River, and (4) the Central Coast, North Coast, North Lahontan, San Francisco Bay, and South Lahontan. The Bay–

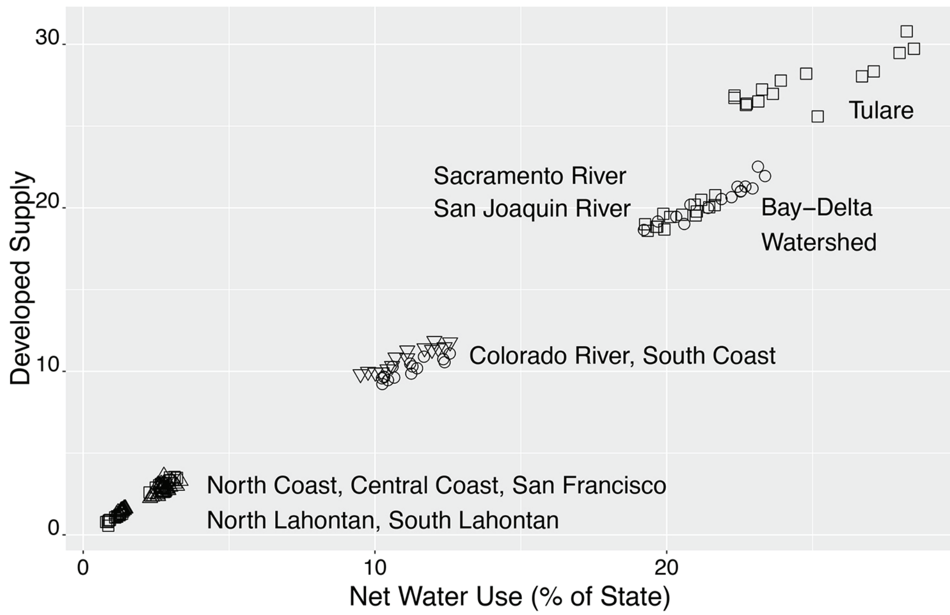

Figure 8 Statewide summary of net water use and developed supply (2002–2016) across all hydrologic regions within California including agriculture, urban and managed wetland with no environmental flows. The Bay–Delta watershed is comprised of the Sacramento and San Joaquin rivers. Each symbol represents one year.

Delta watershed ranks below only Tulare Lake, in the south Central Valley of California, in both supply and use. Table 2 shows that the Bay–Delta watershed accounts for more than 42% of the human water use in the state.

Figure 4 is an enlargement of Figure 3A, showing coherence in the patterns in water use despite orders-of-magnitude difference in the amounts of water across the categories. First, the patterns of Total Delta Outflow and reservoir storage volumes are coherent with precipitation but, second, inversely coherent (i.e., out of phase) with water use for agriculture, urban, and managed wetlands. That the variability in agricultural water use is small is noteworthy (10%, Table 3, Figure 9), demonstrating how the agricultural water supply has been manipulated to compensate for fluctuations in precipitation. Also, urban water use has decreased overall since about 2013.

Agricultural water supply is managed to minimize variability since agricultural use is essentially constant and does not show responses to intense drought. By comparison, urban water use—and possibly managed wetlands—show the effects of conservation in response to intense drought

Table 2 Summary of the consumption of water by hydrologic region from 2002-2016. The Bay-Delta watershed is comprised of the San Joaquin River and Sacramento River hydrologic regions (Figures 1A, 8). Water use includes agricultural, urban and managed wetlands and does not include environmental flows.

	Water use (%)	
Hydrologic region	**Mean**	**SD**
Central Coast	2.8	0.4
Colorado River	11.2	0.8
North Coast	2.7	0.2
North Lahontan	1.1	0.2
Sacramento River	21.8	1.3
San Francisco Bay	2.8	0.2
San Joaquin River	20.5	0.9
South Coast	11.0	1.2
South Lahontan	1.3	0.1
Tulare Lake	24.9	2.3

(Figure 4). As shown below, the apparent large increase in agricultural water use in Tulare Lake since 2010 (Figure 10) is possibly from changes in crop coefficients used in modeling ETAW. ETAW is also known to increase during drought as a result of reduced precipitation. Nonetheless, there

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Table 3 Coefficients of variation by category of water supply and use

Category	Coefficient of variation
Agriculture	0.1
Urban	0.2
Precipitation	0.3
Reservoir	0.3
Outflow	0.3

appears to be a linear increase in underlying changes in Tulare Lake water use as a result of episodic drought or distortions from changes in crop-modeling methods. The Tulare Lake region, located in the southern San Joaquin Valley, is the largest agricultural region in California, with about 3 million of the region's 10.9 million acres under irrigation.

Patterns in Water Variability

Figure 6 shows the breakdown of the developed water supply sources, precipitation, reservoir storage, and ocean outflow within the Bay–Delta watershed. The data show that the greatest volumes of developed water supply are from three sources: (1) groundwater extraction for agriculture, (2) local supplies and (3) the Central Valley Project. Each of these is of comparable magnitude. As a result of storage operations, fluctuations in these supplies are out of phase for precipitation and ocean outflow. Within the 15-year data set, the interannual fluctuations of precipitation and water use are dominated by three statewide droughts (2002–2004, 2007–2009 and 2012–2015, punctuated by the 2005, 2010 and 2017 wet years. The dry spells had reservoir drawdown, decreased local supplies, and diminished Central Valley Project deliveries. Similar patterns are present in the other, lesser, supplies, although urban groundwater extraction shows a continuous downward trend even as agricultural groundwater extraction increases. Notably, local imports (water transfers by local agencies within the state) jump dramatically during the drought.

Figure 7 shows precipitation, water use, and developed water supply within the Bay–Delta. Developed water supply and use are temporally in phase but converging in value over the period from 2002 through 1016. The variability is comparable (CV ~7% each) but the difference

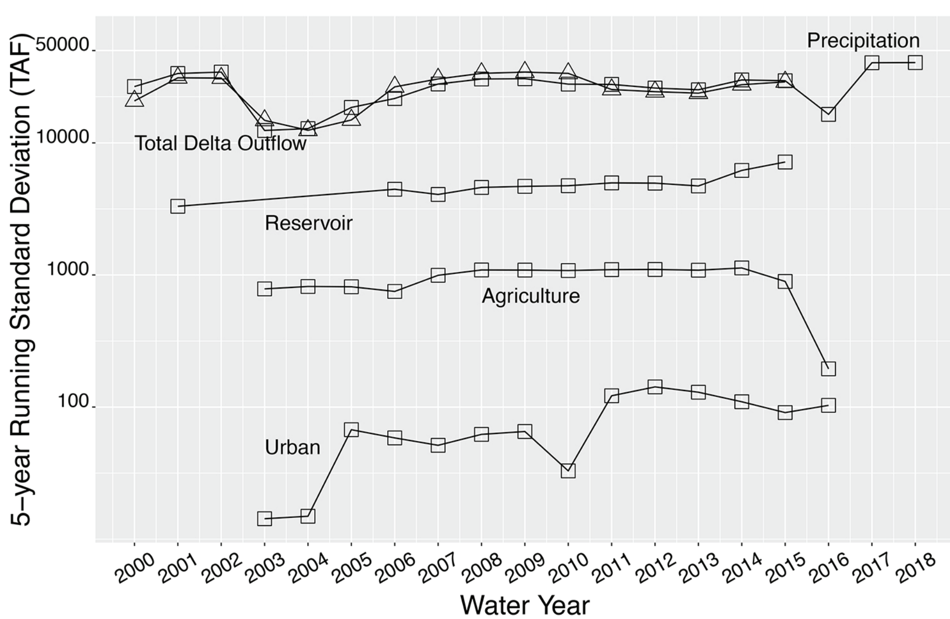

Figure 9 Comparison of recent patterns of water use and precipitation depicted as running 5-year standard deviations. Supply is characterized here by precipitation and reservoir storage. Note that the running standard deviation is computed with < 5 years of data until the first 5-year window is reached.

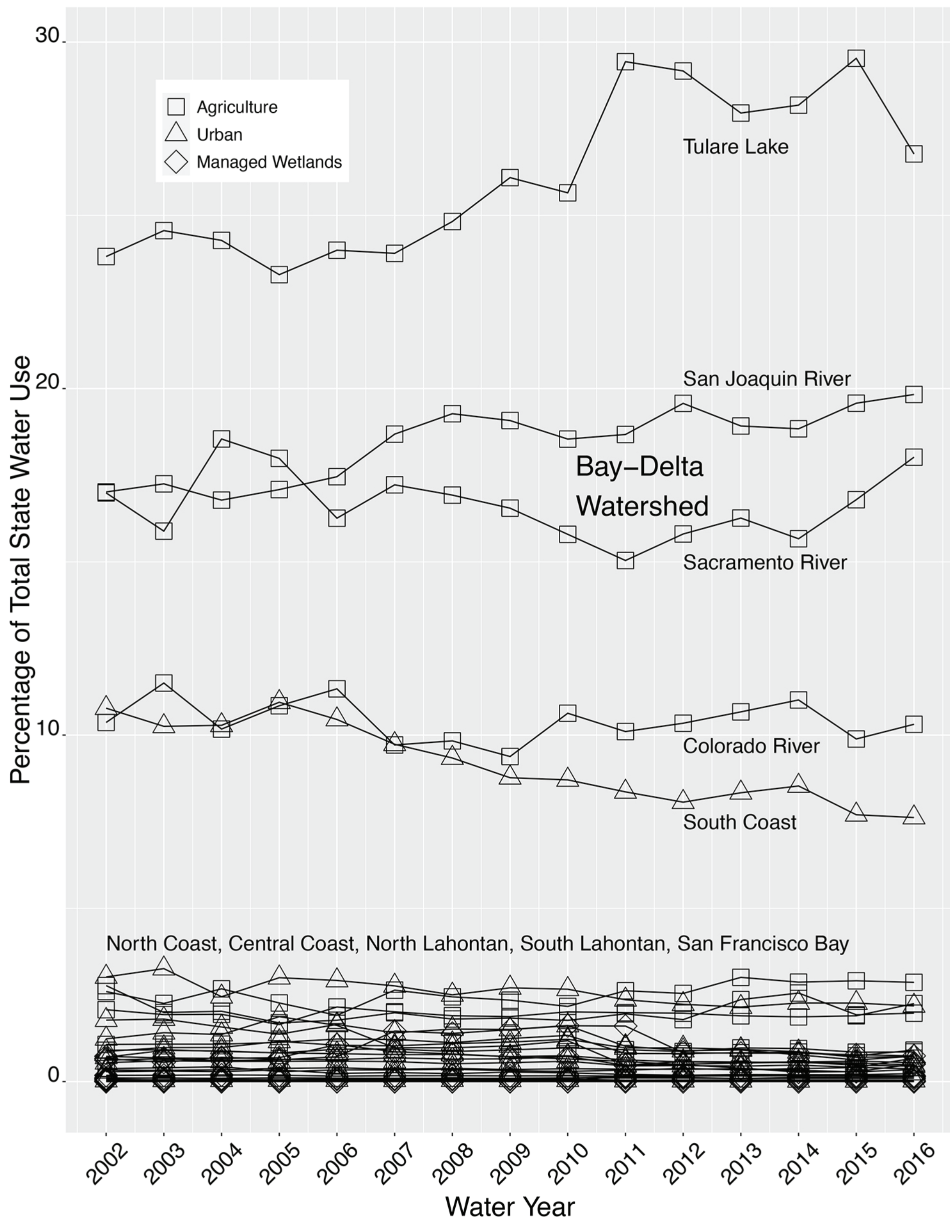

Figure 10 Water use by management sector (Agriculture, Urban, Managed Wetlands) over time and hydrologic region. Environmental flows are excluded as described in text.

between them shows a pronounced narrowing in the annual total volumes. The marginal difference between developed water supply and use ranges from a maximum of 23% in 2002 to a minimum of 8% in 2015 in a linear decrease over the period of the data. This is a 15% decrease in 14 years. This statistic is a measure of vulnerability and risk in that it represents the percentage by which the developed water supply exceeds use. The regression model estimates for 2017 through 2018 are displayed using dashed lines in Figure 6. The predicted values are based on statistical models that account for more than 75% of the variance in the data (see "Estimating Water Balance Components Using Observed Precipitation"). We tested other models that account for ~86% of the variance in this watershed as well, which apply in the Central Valley of California (Goodrich et al. 2020) and continue to evaluate them for future use.

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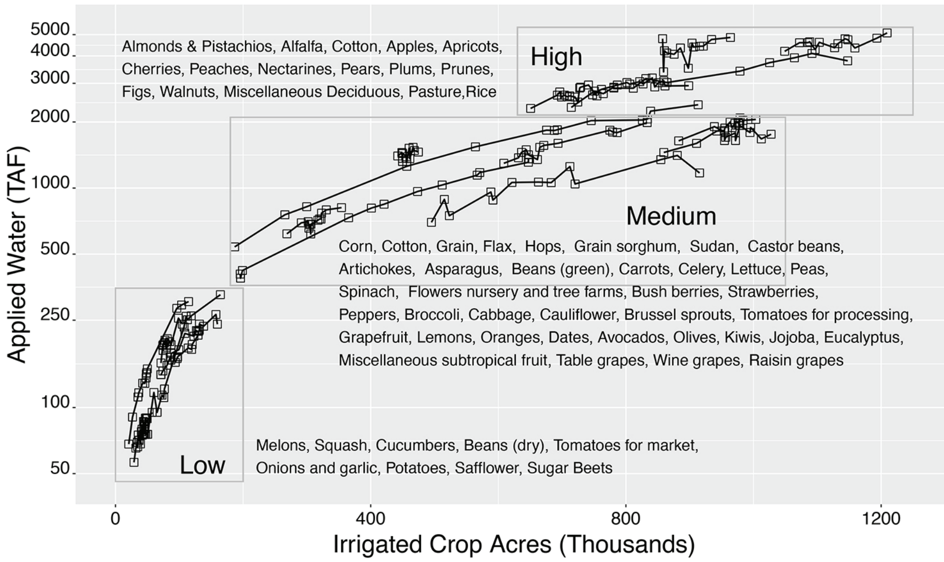

Figure 11 CDWR agricultural applied water by crop type in the Bay–Delta watershed from 1998–2010. *Rectangles* classify crops into water use categories: high, medium, low. Each *data point* corresponds to one year of crop production and the *lines connecting them* indicate the neighborhood of their amounts over the time-series. Individual crops are grouped with labels described in Table 4 and it is the groups that are represented by the points in the plots.

Characterization of Applications

Table 2 summarizes the percentages of water use reported for each of California's ten HRs for 2002 through 2016. The Bay–Delta watershed, comprising the San Joaquin River and Sacramento River HRs (Figure 1A), uses more than 42% (2002 through 2016) of the developed water in California. Figure 8 shows the annual developed water supply and use for the same period for the entire state; Figure 6 details the sources of developed water supply and precipitation for the Bay–Delta.

From Figure 8, agricultural regions dominate water use in California, with three HRs consuming more than 65% of the statewide total. The three are the Tulare Lake, San Joaquin, and Sacramento River HRs, the latter two comprising the Bay–Delta watershed. The Bay–Delta watershed (Figure 1) uses more than 42% (2002 through 2016) of the developed water supply in California. The two other substantial water users are the Colorado River HR, also heavily agricultural, and the strongly urban South Coast HR. Each consumes about 11% of the statewide total. The five remaining HRs have water use nearly an order of magnitude lower. Interannual variability in the five major water use regions was quite moderate, with standard deviations ranging from 4% to 8% of their respective 15-year averages; this compares to the standard deviation of annual precipitation of approximately 30% of its long-term average.

Water Use by Agricultural Crop Type

Delving further into the agricultural water use drivers, Figure 11 classifies twenty crop types in the Bay–Delta watershed into subjective categories of high, medium and low applied water use. Applied water includes re-use of water (see "Water Quantity Parameters and Uncertainties") which, in general, will be larger than net water used elsewhere. It is used uniquely here since this is the way the data are reported, and it is used only to rank-order the crops. This analysis parses water use of crop types tracked by CDWR by number of irrigated crop acres and the total number of acres cultivated within a water year. While subjective, these categories seem reasonable based on inspection (see Figure 11). The organization of the Figure provides a sense of the variability of each group of crops, both in water use and irrigated acreage. Table 4 tabulates the crop groupings by acronym used in the data

Table 4 Crop labels

Acronym	Description
Al Pist	Almonds and pistachios
Alfalfa	Alfalfa and alfalfa mixtures
Corn	Corn (field and sweet)
Cotton	Cotton
Cucurb	Melons, squash, cucumbers
DryBean	Beans (dry)
Fr Tom	Tomatoes for market
Grain	Wheat, barley, oats, miscellaneous grain and hay, mixed grain, hay
Miscellaneous fields	sunflowers, hybrid sorghum/sudan, millet,sugar cane
On Gar	Onions and garlic
Oth Dec	Apples, apricots, cherries, peaches, nectarines, pears, plums, prunes, figs, walnuts, miscellaneous deciduous
Oth Fld	Flax, hops, grain sorghum, sudan, castor beans
Oth Trk	Artichokes, asparagus, beans (green), carrots, celery, lettuce, peas, spinach, flowers nursery and tree farms, bush berries, strawberries, peppers, broccoli, cabbage, cauliflower, brussel sprouts
Pasture	Clover, mixed pasture, native pastures, induced high water table native pasture, miscellaneous grasses, turf farms, bermuda grass, rye grass, klein grass
Potato	Potatoes
Pro Tom	Tomatoes for processing
Rice	Rice and wild rice
Safflwr	Safflower
SgrBeet	Sugar beets
Subtrop	Grapefruit, lemons, oranges, dates, avocados, olives, kiwis, jojoba, eucalyptus, miscellaneous subtropical fruit
Vine	Table grapes, wine grapes, raisin grapes

set. For example, the high category comprises almonds and pistachios (Al Pist), alfalfa, other deciduous (Oth Dec), rice, grapes (Vine) for all years, and other truck (Oth Trk), corn, and cotton crops.

Comparison of Agricultural and Urban Water Use

Figure 12 shows the distributions of agricultural and urban water use across the state by HR in rank order by greatest water use. These data show that agriculture dominates water use across the state, as previously described in Figure 10; the high urban water consumption of the South Coast HR; and the dominance of statewide total water use in the Tulare, Sacramento, San Joaquin, and Colorado HRs. Mentioned earlier, the abrupt increase in water use in Tulare in 2011 is possibly from a change in the crop coefficients in the CALSIM ETAW model used to estimate evapotranspiration. There is on-going discussion about what the appropriate coefficients should be.

Figure 13 breaks down 2002 through 2016 urban applied water use by sub-category across the state, and shows that residential water use dominates urban water use.

DISCUSSION

The Water Plan for California was published by the US Government in 1874, focusing on the potential for irrigation of agricultural lands (Alexander, Mendell, and Davidson 1874). The state of California issued later publications as CDWR bulletins, according to CDWR history (*https://water.ca.gov/Programs/California-Water-Plan*). Since at least the 1957 Water Plan (CDWR 1957), the state of California has published water use and supply data in printed form at

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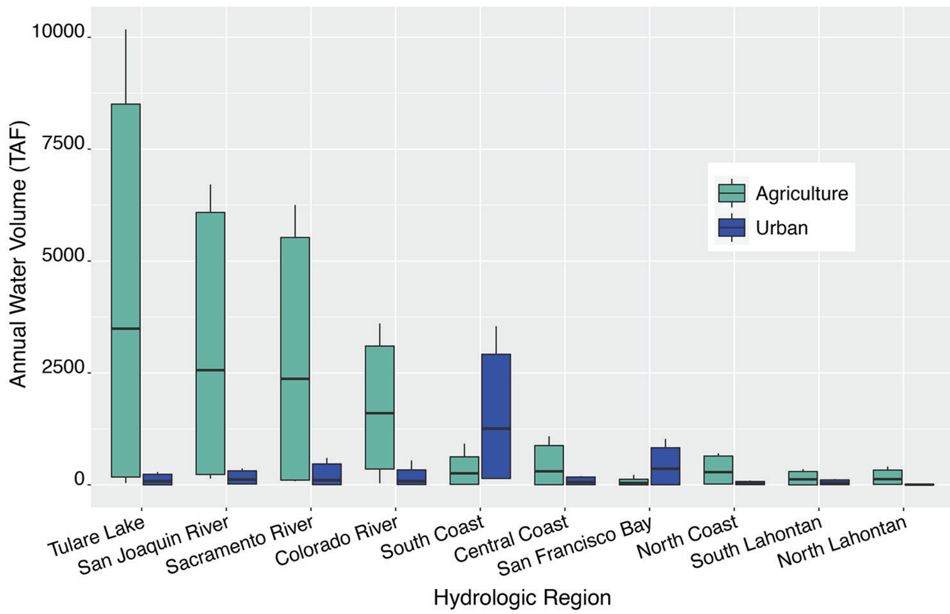

Figure 12 Water use by application type by hydrologic region throughout California (see Figure 1A). Note that the Bay–Delta is comprised of the San Joaquin River and Sacramento River hydrologic regions.

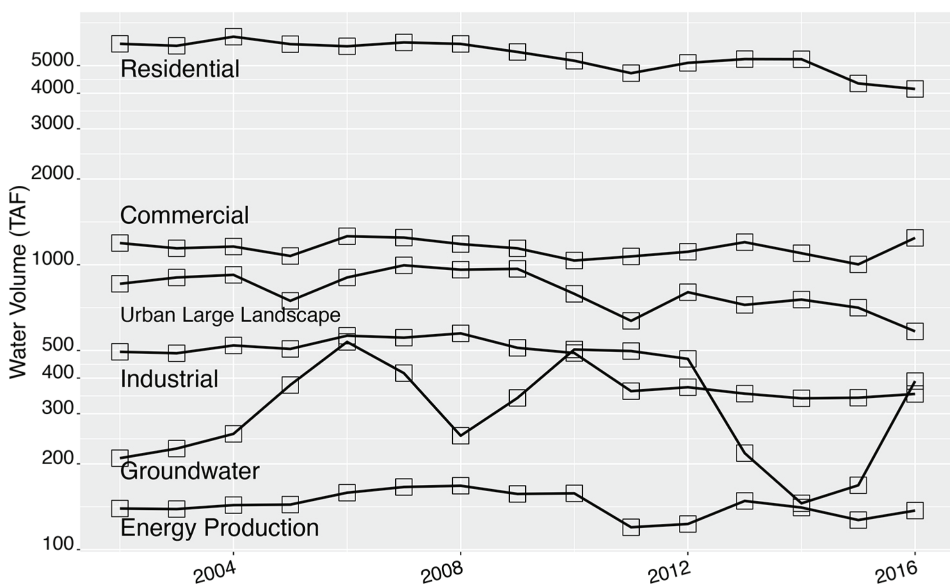

Figure 13 Urban water use throughout California during the period 2002–2016. This is applied water use (Equation 2) which, for urban applications, is approximately the same as net water use (Equation 1).

roughly 5-year intervals. Beginning in 1998, the Water Plan shifted from a focus on water supply development to options for addressing strategic water issues in California. In the most recent few years, the Water Plan has begun to shift toward a more data-centric report, now with published digital data in compliance with AB 1755, the Open and Transparent Water Data Act. This change in emphasis makes water data more available and usable for research and analysis. Also, it offers the opportunity to integrate the water balance data from climate and weather scales of modeling and analysis at finer scales of water resource management statewide. In doing so, it offers the opportunity to further interpret the data into standard federal watershed boundaries, such as USGS hydrologic units (USGS 2013), and into modeling and analysis tools and methods useful to municipal water utilities and groundwater sustainability agencies (GSAs).

Consequently, this work shows how temporal variation of precipitation has affected water use, and how to begin to consider water balance data as a long-term planning resource across different scales of water resource management. For example, we have shown here the integration of water balance data with precipitation data to predict water balance estimates and thus fill the 3- to 5-year gap in the time-series of water balance data to the present day. These predictions can subsequently be evaluated in each successive update of the Water Plan, using updated precipitation data from climate projections and weather forecasts to help focus policy, irrigation, and development planning as the effects of climate change propagate through the hydrology of the state (Bedsworth et al. 2018).

Uncertainty in analyses and predictions underlie empirical data and the methods used to operate on them. The uncertainty analysis is an acknowledgement of this, but not a solution (see "Uncertainty and Propagation of Uncertainty"). A proper assessment of uncertainty should encompass an estimate of the covariance of parameters used in this and other similar types of studies. Barriers to better uncertainty analysis are lack of repeated measures on individual parameters, covariates, and the heterogeneity of spatial and temporal variances in precipitation, water use, and developed water supply across the state and over time. Estimating uncertainty may be useful, and should involve land-use, precipitation, accuracy and precision in the data, and frequency of sampling.

We also show the ongoing dominant agricultural water use at the state level (eight of California's ten HRs). The South Coast and San Francisco Bay are the exceptions, where urban use dominates. Agricultural use in four regions—Tulare Lake, the Sacramento River, the San Joaquin River, and the Colorado River—account for more than 70% of the statewide total developed water use. Recently, analyses of fine-resolution, vertical ground motion has demonstrated how the agricultural water use applied to certain crops has caused subsidence (Levy et al. 2020), as commonly believed for decades.

The Sacramento and San Joaquin River HRs comprise the Bay–Delta watershed, the largest water resource feature in the state, which we have featured as a case study in this paper. By integrating additional crop data, we identify crops that dominate consumption so they can be viewed in statewide historical and modern agriculture contexts (Arax 2019; Lindt 2020). Similarly, we show how urban water use compares to agriculture in toto, and how it varies between HRs across the state. These data help to identify where drought conservation will be most important. Of course, they provide a useful tool to communicate the challenges and choices to be made in how water is used and supplied for many who do not consult the Water Plan. As water resources become more precious, the ability to communicate results effectively increases in usefulness.

State-wide, urban water use over the 15-year data set was about 20% of total non-environmental water use compared to agriculture, which was about 80%. Urban water use is dominated by residential consumption but, even at the highest levels in the South Coast HR, it is a small fraction of statewide agricultural consumption. This means urban water conservation only incrementally affects overall water use in the state. However, urban water conservation will be vitally important where it locally dominates water use and affects groundwater extraction, for example in Santa Barbara, or in areas heavily dependent on imported water, such as San Diego County. Important consequences will likely affect urban and suburban development, and regional as well as municipal planning, in ways that are currently difficult to evaluate until crises begin to emerge, as they have recently with the Upper

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Colorado Basin Plan (USBR 2012) and the Imperial Valley Water District (Olalde 2020).

Using the Bay–Delta watershed as a case study, we estimated major categories of water supply and water use during recent years for which the relevant reporting data are still being gathered. While this is a retrospective prediction, it represents an excellent basis for testing forecast models to provide a longer lead-time for adaptive decision-making. In this study, we used the PRISM data set, a synthesis of observational and modeled precipitation data, to update the estimates of water supply and water use. This approach can be applied to other data sources to address climatological and weather-related questions such as those associated with the CMIP modeling efforts, which the state uses in its ongoing climate assessments (Bedsworth et al. 2018; Pierce et al. 2014).

CONCLUSIONS

Using the newly available CDWR water balance data, we addressed the first two questions we posed: (1) What are recent patterns of water balance in California in comparison with long-term historical records? (2) What are dominant components of water supply and use, and how do they vary in time?

First, the annual coefficient of variation in precipitation within the Bay–Delta watershed is 30%. However, true to its design, the developed water supply has much less interannual variation (4% to 10%). Nonetheless, the annual volume of developed water use reflects the interannual variation in precipitation: developed water use decreases when annual precipitation increases, and vice-versa, perhaps because of more local precipitation for crops via soil-moisture.

Second, agricultural water use (~80%) consumes far greater water than urban use (~20%) statewide: excluding environmental flows as we have done here. This is not a surprise (Reisner 1993). The dominance of agricultural use over urban use is borne out in all but two of the ten HRs of the state, the exceptions being the South Coast and San Francisco Bay HRs. Four HRs comprise most of the State's agricultural water use: Tulare Lake, Sacramento, San Joaquin, and the Colorado HRs together account for more than 75% of the total developed water use in California. Within the 15-year data set, variability in urban water use is less than that of statewide precipitation but much higher than agricultural water use. This is a result of urban water conservation during periods of drought, particularly landscape irrigation. Conservation lowers the mean and extremes of usage, leading to an increased urban-use variability over the period of the data.

The third question—How can this information help to improve water resource management?—does not have a direct answer that can be developed from data analysis alone since it depends strongly on political and economic decisions at all scales. However, these decisions can be informed by what we have presented here. For example, these data illustrate the effects of the variability in precipitation and therefore its effects on the developed water supply. When we compare the agricultural and urban water use data to the developed water supply from 2002 through 2015, we find that the developed water supply dropped 15%: from within 23% to 8% of water use, rising slightly in 2016 to 10%. The margin between developed water supply and use declined steadily from 2002 to 2015, indicating that water use is trending toward the operating limit of the developed water supply.

At scales meaningful to policy and decision-making, these data should help researchers and water planners to analyze scenarios of hydrologic futures for California, and to quantify the consequences for urban and agricultural water use and supply. The water balance and crop data are thus a means to understand the results of California's water-related choices as well as the consequences of policy decisions. At a time when water rights and policy are being re-evaluated across the American West in the light of changing climate, decision-making informed by science and data is urgently needed (Grantham and Viers 2014). The water balance data provides a quantitative framework for water resource analysis throughout the state.

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