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RESEARCH

Estimating Freshwater Inflow to San Francisco Estuary During the First Six Decades After the California Gold Rush: WYs 1851–1911 Reconstruction Based on Legacy Hydrologic Data

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ABSTRACT

Freshwater inflow is vital for the ecological health of estuaries. Understanding historical flow volume and timing is therefore essential for sustainable management and restoration of these environments. Using legacy hydrologic data—including riverine water-level measurements, watershed runoff estimates, and wetland reclamation records—we extended a monthly time-series of freshwater inflow to San Francisco Estuary by 6 decades, back to California's Gold Rush era. This period marks the onset of significant anthropogenic modifications to the waterscape. Our analysis of the extended series, normalized to unimpaired runoff, reveals an increasing trend in systemwide water use that was preceded by a decline in the latter half of the 19th century. We hypothesize this decline resulted from reduced evapotranspiration as a result of vegetation removal and reduced overbank flows from levee construction. These findings align with earlier research that shows similarities between natural and contemporary long-term annual average inflow, comparing pre-development conditions to those of the early 20th century and today. Monthly flow trends, however, displayed more nuanced, season-specific effects of human modifications. Despite unusually wet hydrology during the reconstruction period, our findings comprise an important contribution to ongoing dialogue on ecosystem-restoration targets.

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KEY WORDS

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INTRODUCTION

Understanding the historical baseline of freshwater inflow to San Francisco Estuary—including volume and timing—is essential for sustainable management, conservation, and restoration planning. Because directly observed data are rarely available to characterize a study area's pre-development flow conditions, management and restoration targets are generally guided by earliest available records, even when it is recognized that these observations reflect some degree of alteration. In other words, the restoration baselines may themselves not entirely

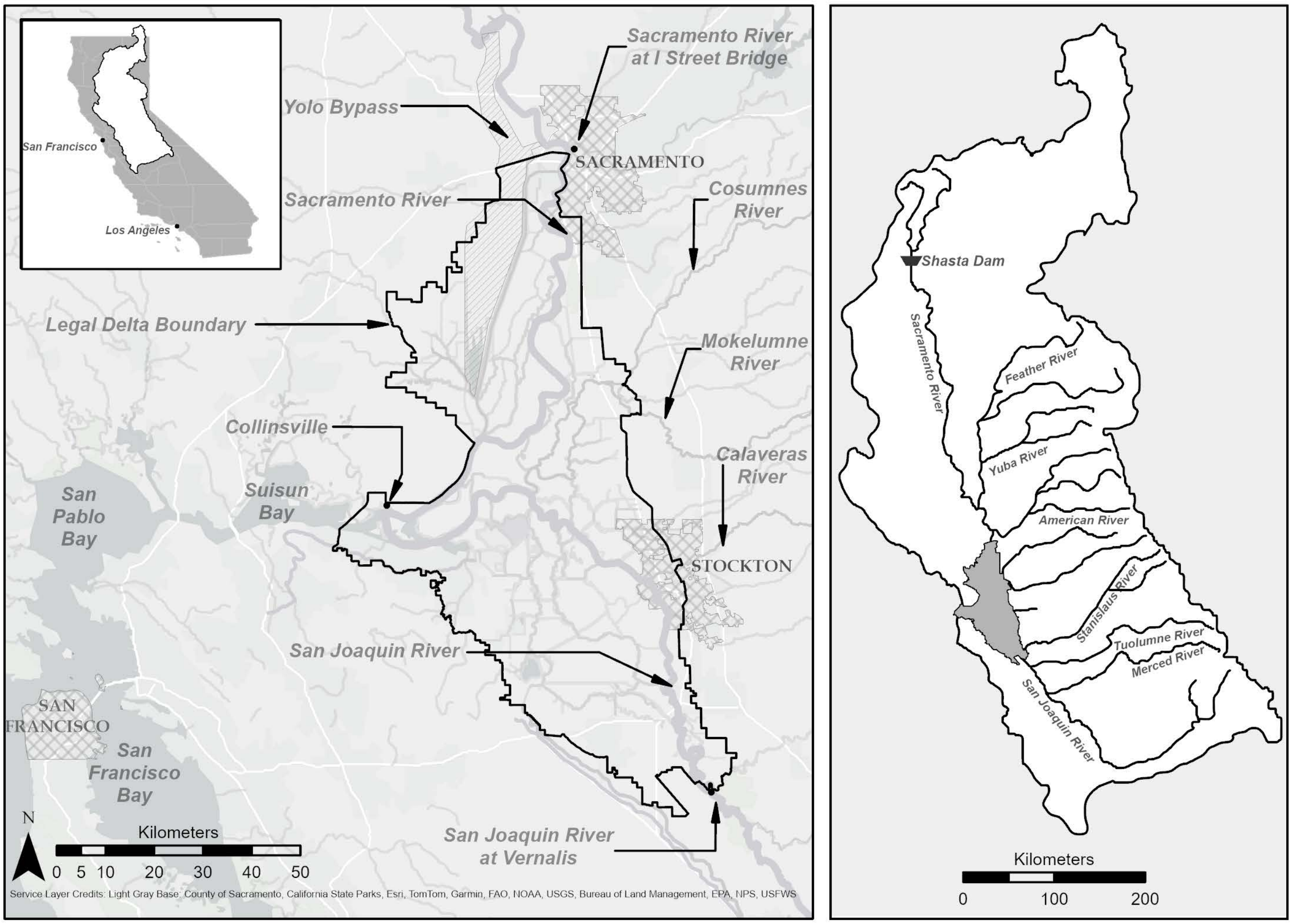

Figure 1 The study area, spanning a large part of the state of California, includes San Francisco Estuary and its upstream watershed. The estuary consists of the Sacramento–San Joaquin Delta and downstream open water bodies that are collectively referred to as San Francisco Bay. The Sierra Nevada mountain range and Central Valley comprise the upstream watershed. The maps identify the major rivers that flow through the Central Valley, as well as the City of Sacramento where measurements of riverine water levels were recorded beginning in the mid-19th century.

represent natural conditions, a concept termed *shifting baselines* in the ecological literature (Duarte et al. 2009; Wagener et al. 2010; Villnäs and Norkko 2011). Expanding the time-frame of historical flows beyond the directly observed record can benefit restoration planning.

The historical volume and timing of freshwater inflow to San Francisco Estuary—consisting of the Sacramento–San Joaquin Delta (Delta) and open water bodies downstream of the Delta—has been widely studied (Fox et al. 1990; Knowles 2002; Enright and Culberson 2009; Cloern and Jassby 2012; Hutton et al. 2017a). Prior research has for the most part focused on net flow exiting the Delta to downstream bays of the estuary—a quantity commonly known as Delta outflow (Figure 1). Delta outflow represents approximately 90% of the freshwater inflow to the bays in the estuary (Fox et al. 1990). Direct measurement of Delta outflow is confounded by relatively large tidal flows and wide channels near the confluence of the Sacramento and San Joaquin rivers (Monismith 2016). While advancements in direct measurements will likely continue, the current regulatory framework relies on Delta outflow estimates that are based on the water-balance computation: Delta Outflow = Delta Inflow – Delta Net Channel Depletions (NCDs) – Delta Exports. Systematic measurement of Delta inflows began in the 1920s; the resulting outflow estimates are the basis for contemporary water-resources management, regulations, and research (SWRCB 2000). Recent work has extended the Delta outflow time-series back to water year (WY) 1912 (Hutton and Roy 2019). The California water year begins on October 1 of the preceding calendar year. Several researchers have used legacy information to reconstruct Delta outflow time-series even further back to California's Gold Rush era (circa 1850) (Moftakhari et al. 2013, 2015; MacVean et al. 2018) and have developed estimates of Delta outflow that may have existed under the study area's natural conditions, hereafter pre-development conditions (Fox et al. 2015; CDWR 2016; Hutton, Meko et al. 2021).

Hutton et al. 2017a observed no statistically significant trend in long-term annual average Delta outflow since the 1920s, despite the increasing in-basin agricultural and urban water use and out-of-basin transfers and relatively stationary in-basin water supply that occurred during the period. This counter-intuitive finding may be explained in part by the large inter-annual hydrologic variability that masks underlying trends. Assuming modeling scenarios with similar watershed runoff but different levels of land-use and water-resources development, others have also reported counter-intuitive findings with respect to annual average Delta outflow over this period: (1) Fox et al. (2015) and subsequent "natural" flow-modeling studies by the California Department of Water Resources (CDWR 2016) concluded that pre-development and contemporary outflows are similar, and (2) Gross et al. (2018) concluded that Delta outflow was higher under 1920-level conditions than under pre-development conditions. Assuming that the above findings are valid, we hypothesize that an increasing trend in systemwide in-basin water diversions and exports during the 20th century was preceded by a decreasing trend in basin water use during the latter half of the 19th century because of the removal of high-water-using natural vegetation and reduction in overbank flows as a result of levee construction, and consequent reduction in evapotranspiration. However, only limited information has heretofore been available to validate this hypothesis.

In this paper, our research objectives are to extend the available time-series of Delta outflow on a monthly time-step back to the Gold Rush era of the 1850s based on legacy hydrologic data, normalize this time-series to runoff data that excludes the effects of dams and diversions (termed unimpaired runoff), study long-term annual and seasonal trends associated with the normalized time-series, and evaluate the validity of our hypothesis that a systemwide decrease in evapotranspiration occurred in the latter half of the 19th century. We utilize available datasets based on legacy hydrologic information to estimate Delta inflows between WYs 1851–1911, including Sacramento River water-level data measured at Sacramento (Figure 1) and unimpaired runoff. By further utilizing information on historical Delta reclamation and evapotranspiration of natural vegetation to estimate in-Delta water use during this period, we compute Delta outflow as the difference between inflow and water use. By adding 60 years to the existing Delta outflow time-series record, this work provides additional and unique information for restoration planning and flow regulation. In particular, the extended period covers an extremely wet hydrologic period (Lai et al. 2024) and—when linked with the following years of existing data—characterizes a period of dramatic change from extremely wet to extremely dry conditions (Hutton, Meko et al. 2021).

BACKGROUND

Study Area

The study area, spanning a large part of the state of California, includes the San Francisco Estuary and its upstream watershed (Figure 1). The estuary consists of the Delta and downstream open water bodies that are collectively referred to as San Francisco Bay. The northern portion of the Sierra Nevada mountain range and Central Valley comprise the upstream watershed. Freshwater flow from the study area is a vital part of California's water supply and its hydrology has been the focus of measurement and study for

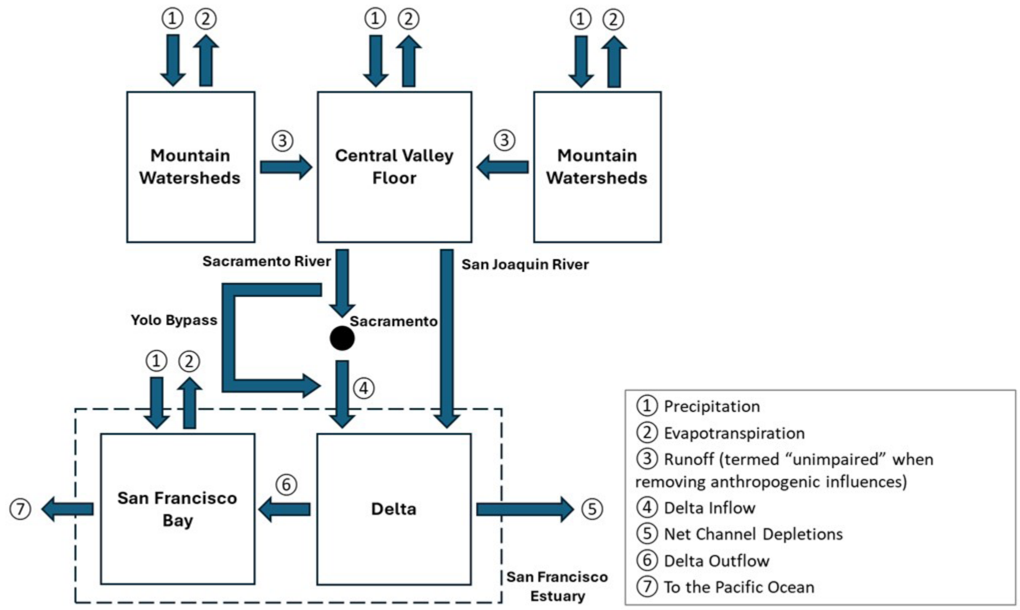

Figure 2 Water flow in the study area, from the mountain watersheds to the Pacific Ocean, is shown schematically in this figure. Flow terms used extensively in this work are identified in the schematic.

more than a century (Hall 1886; CDPW 1923, 1931). Water flow in the study area, from the mountain watersheds to the Pacific Ocean, is shown schematically in Figure 2.

The study area, with its Mediterranean climate, receives most of its precipitation over a 5-month period that spans November through March. Much of this precipitation occurs as snowfall in the Sierra Nevada mountain range. Runoff from the mountain range flows through the Central Valley to the Delta, where it exits to the Pacific Ocean through San Francisco Bay (Figure 1). Streamflow and watershed precipitation are subject to large natural variability, on which are overlaid multiple anthropogenic changes that have occurred through time (see Figure 3). The study area's pre-development waterscape—including riparian forests, tule marsh floodplains, and rainfed grasslands—is described elsewhere (Kharl 1979; Bay Institute 1998; Whipple et al. 2012; Fox et al. 2015; Hutton, Meko et al. 2021).

The settlement and economic development of California's Central Valley after the Gold Rush era (circa 1850) resulted in large-scale hydrologic modification in the San Francisco Estuary and its upstream watershed. Early hydrologic alterations included stream channelization, levee construction, and land use conversion to support agricultural (Figures 3A, 3B) and mining. Hydraulic mining, which used high-pressure water sprays on hillsides to displace sediment and reveal gold-bearing layers, led to extensive erosion and sedimentation of waterways until it was banned in the 1880s. Figure 3D shows the effects of sediment deposition on minimum annual water levels in the Sacramento River at Sacramento. Other changes after this period included the construction of smaller reservoirs and irrigation networks. Significant growth in systemwide reservoir storage capacity began in the early 20th century, and by 1929, storage capacity reached 5 billion cubic meters (billion m^3) (CDPW 1931). See Figure 3C. Although flood-basin reclamation was carried out over several years, complete closure from floods occurred over a relatively brief period between 1913 and 1920. Widening and deepening of the lower Sacramento River was carried out during this period, as part of the Sacramento Flood Control Project, modifying tidal flows and salinity intrusion in the estuary.

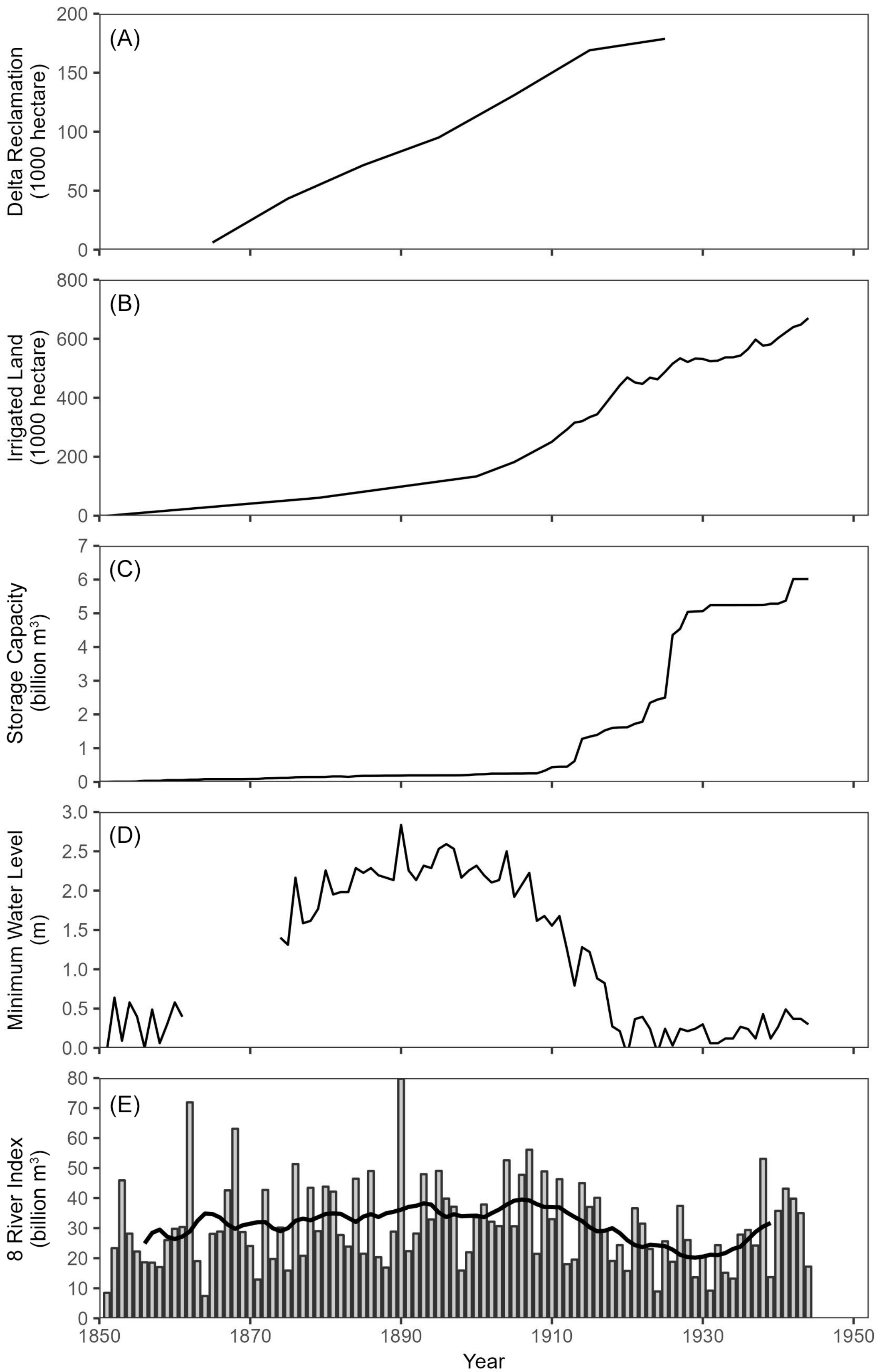

Figure 3 Significant alterations to the study area waterscape followed the California Gold Rush of the 1850s. Panels **A** through **D** show the timeline of early alterations over the period spanning 1850–1944. Land-use conversion to agricultural is shown in Panels **A** and **B**; cumulative reservoir storage capacity is shown in Panel **C**, and the effect of sediment deposition (from hydraulic mining) on minimum annual water levels in the Sacramento River at Sacramento is shown in Panel **D**. Panel **E** shows annual unimpaired runoff to the study area over the same period. Waterscape alterations grew substantially after construction of Shasta Dam in 1945.

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In the contemporary system, virtually all major stream flows are regulated through dams, and are affected by withdrawals for agricultural and municipal uses. Similarly, the Delta supports diversions for local agricultural and urban uses as well as out-of-basin uses. Delta exports by the federal Central Valley Project (CVP) and the State Water Project (SWP) support agricultural irrigation over more than 3 million acres, and municipal supply for more than 20 million people (Delta Stewardship Council 2013), providing a vital foundation for California's large and diverse economy—the eighth largest in the world (Luoma et al. 2015).

Delta Outflow

Freshwater inflow to San Francisco Estuary, commonly referred to as Delta outflow, has great ecological and economic significance (Delta Stewardship Council 2013; Lund 2016). Control of the estuary's freshwater flow is a key aspect of Delta water management and affects many regions of California that depend on imported sources of water. The US Geological Survey operates a flow monitoring network near the confluence of the Sacramento and San Joaquin rivers that allows direct measurement of Delta outflow (Oltmann 1998; Burau et al. 2016); however, direct measurement is compromised by relatively large tidal flows and wide channels near the confluence (Monismith 2016). The current regulatory framework, rather than relying on direct measurement, employs a water balance estimate of Delta outflow that is calculated as the sum of river inflows along the Delta's periphery minus water exports and in-Delta channel depletions. Channel depletions, which represent the sum of diversions (including seepage) from Delta channels onto adjacent lands minus in-Delta return flows, is an ungauged quantity that is based on crop evapotranspiration estimates and appears to be subject to seasonal bias (Hutton, Rath et al. 2021). Channel depletions are generally a relatively small part of the annual average Delta water balance, accounting for approximately 6% of the total output over WYs 1998–2009 (Ariyama et al. 2019). However, the influence of channel depletions on the Delta water balance is greater in dry months and magnified during drought years; even in typical years, summer–fall channel-depletion estimates for summer and fall months are significant in magnitude (typically 30% to 80%) compared to Delta outflow (Hutton, Rath et al. 2021).

Delta outflow estimates, based on water-balance calculations as described above, are available from CDWR on a daily time-step beginning in WY 1930 (*https://water.ca.gov/Programs/Integrated-Science-and-Engineering/Compliance-Monitoring-And-Assessment/Dayflow-Data*). Earlier estimates are available on a monthly time-step for the period that spans WYs 1922–1929 (CDWR 1957) and WYs 1912–1921 (Hutton and Roy 2019). MacVean et al. (2018) reconstructed a Delta outflow time-series that spanned 1850 to 1920 by synthesizing reconstructed time-series of precipitation, basin inflows, land use, and levee construction in a semi-distributed hydrologic model, and reported results on an annual basis. Moftakhari et al. (2013, 2015) utilized distinct methods, as discussed in the following paragraph, to estimate Delta outflow on a sub-monthly basis. We summarize an analysis of their results and methods in Appendix A, and discuss our rationale for not directly adopting their outflow estimates in our work.

Employing sequential harmonic analyses of tidal properties, Moftakhari et al. (2013) related San Francisco tide data and Delta outflow data over the period WYs 1930–1990, then used the resulting correlation—along with digitized tide records reported by Talke and Jay (2013)—to estimate 7-day Delta outflow for periods back to 1858. The authors demonstrated non-linear relationships between tidal properties (e.g., M2 tidal constituent) and outflow; furthermore, they found that no single tidal property provided robust hindcasts through the full range of observed outflows. Thus, they used separate relationships to represent low outflow conditions ($< 1{,}000\ m^3s^{-1}$ or 35,000 cfs) and high outflow conditions. The authors reported better predictive ability associated with high-outflow conditions than low-outflow conditions. Specifically, they reported RMS errors of approximately $1{,}000\ m^3s^{-1}$ for low outflows (i.e., larger than the flows) and ≤ 500 m^3s^{-1} for high outflow conditions. Moftakhari et al. (2015) digitized archival records of Sacramento River water levels at Sacramento (Figure 1) and calibrated these water-level data to Delta outflow over the period WYs 1930–1946 to estimate daily Delta outflow for earlier periods back to 1849. For periods when water-level data were unavailable, the researchers augmented their time-series with estimates from Moftakhari et al. (2013). They used their flow reconstruction to develop a long-term sediment load time-series to San Francisco Bay. The authors reported a methodology to adjust the water level data to account for (1) bed aggradation from upstream hydraulic mining activities, and (2) other system changes such as increased levee heights, wetland reclamation, and the development of managed floodplains.

Pre-development or "natural" Delta outflow was characterized by CDWR (2016) utilizing two models to simulate watershed hydrology and assuming a repeat of a 93-year contemporary climate sequence that spanned WYs 1922–2014. They used the Soil Water Assessment Tool (SWAT) (Arnold et al. 2012) to model precipitation-runoff characteristics of the upper-elevation Central Valley watersheds and the (California) Central Valley Simulation Model, or C2VSim (Brush et al. 2013), an integrated hydrologic model, to simulate groundwater and surface-water hydrology on the pre-development Central Valley floor. Land use was based on prior characterizations of natural vegetation (Fox et al. 2015). Potential evapotranspiration from natural vegetation was estimated using reference evapotranspiration and vegetation coefficients (Orang et al. 2013; Howes et al. 2015).

Historical Delta outflow trends, both annual and seasonal, have been explored by several researchers (Fox et al. 1990; Knowles 2002; Enright and Culberson 2009; Cloern and Jassby 2012; Hutton et al. 2017a); these analyses have been confined to instrumented periods no earlier than the 1920s. Hutton et al. (2017a) observed no statistically significant trend in long-term annual average Delta outflow since the 1920s, despite increasing in-basin agricultural and urban water use and out-of-basin transfers and relatively stationary in-basin water supply during the period. The researchers suggested that this finding may be explained in part by large inter-annual hydrologic variability that masks underlying changes. In contrast to trends in annual flows, Hutton et al. (2017a) reported statistically significant temporal trends in seasonal outflows, with decreasing trends observed in 4 months (February, April, May, and November) and increasing trends observed in 2 months (July and August). Hutton et al. (2017b) reported results from a modeling analysis that ascribed post-1920 outflow trends to different anthropogenic and natural causes. Gross et al. (2018), assuming a fixed level of development scenarios (corresponding to levels of land use and water-resource development that reflected different points in time), compared long-term annual average and seasonal Delta outflow associated with pre-development, 1920-level, and contemporary conditions. The authors found annual average Delta outflow under 1920-level and contemporary conditions to be 23% higher and 21% lower than pre-development Delta outflow, respectively.

Trends explicitly accounting for year-to-year variability in annual and seasonal Delta outflow—partly driven by climatic variability—have also been evaluated by normalizing outflow with unimpaired runoff, a measure of system-water availability. The quotient of Delta outflow and unimpaired runoff is hereafter referred to as "normalized outflow." Temporal trends in normalized outflow reveal the net effect of water storage, diversion, and project water export operations on Delta outflow (Reis et al. 2019). Hutton et al. (2017a) reported a statistically significant downward trend for normalized annual outflow over WYs 1922–2015. By classifying the data into wet and dry subsets, the researchers found that the declining trend associated with dry years stopped or even reversed in the 1980s, reflecting regulations to manage flows and salinity in the estuary (SWRCB 2000). Reis et al. (2019) and Gartrell et al. (2022) evaluated normalized outflow trends for the February-to-June period, a period of special interest for fishery management. Assuming a single linear fit, Reis et al. (2019) observed a statistically significant, downward, normalized outflow trend over WYs 1930–2018. Assuming a more complex piece-wise fit, Gartrell et al. (2022) evaluated WYs 1930–2020 and reported a long-term decline followed by a flattening from the mid-1990s onward—again reflecting regulations to manage flows and salinity in the estuary.

METHODS

Data

Five categories of data were used in this work: Sacramento River water-level data, Delta inflow data, Delta net channel depletion (NCD) data, Delta outflow data, and Central Valley unimpaired runoff data. Water-level data are summarized in Table 1; other data and their sources are summarized in Table 2.

Sacramento River water-level data were used for model calibration and flow reconstructions. Various gauging sites have historically been located along the river at Sacramento, California (see Figure 1) in the vicinity of the I Street bridge. Moftakhari et al. (2015) digitized, evaluated, and adjusted legacy data to account for hydraulic mining deposition. Adjusted water-level data were provided to us by H. Moftakhari (2024 email communication to SBR, unreferenced, see "Notes"). We utilized a subset of the raw and adjusted water-level data to align more closely with available Central Valley runoff estimates (beginning in WY 1851) and installation of Shasta Dam on the Sacramento River (WY 1945). The water data include two significant gaps: a gap spanning 228 months between September 1862 through August 1881, and a smaller gap spanning 31 months between May 1888 through November 1890. The earliest data (before September 1862) includes several missing values; these data gaps were filled through linear interpolation. Visual evaluation of the time-series suggests that data before 1857 were smoothed, and are likely subject to significant uncertainty. Furthermore, we observed that data from the first 3 months of this subset (October 1850–December 1850) duplicated the data reported for the October 1849–December 1849 period, and were not utilized in this work.

Delta inflow comprises several riverine inflows from the Sacramento and San Joaquin rivers, Yolo Bypass, and smaller eastside rivers (including the Cosumnes, Mokelumne, and Calaveras rivers). Delta inflow data spanning WYs 1930–1944 were obtained from CDWR's Dayflow program (CDWR 1986); inflow data that spanned WY 1912–1929 were obtained from previous work reported by the authors (Hutton and Roy 2019; Hutton et al. 2015).

Delta net channel depletions (NCD), a quantity that is estimated rather than directly measured in the Delta, is defined as the difference between Delta gross channel depletions and Delta precipitation. We obtained net channel depletion data spanning WYs 1930–2022 from CDWR's Dayflow program (CDWR 1986), and the same data spanning WYs 1912–1929 from previous work reported by the authors (Hutton and Roy 2019; Hutton et al. 2015). We used legacy precipitation measurements at Stockton and Sacramento (Hall 1886; CDEC; Masters–Bevan 2000) to reconstruct a Delta precipitation time-series before WY 1912.

Delta outflow may be estimated as the difference between Delta inflow and NCD. We obtained Delta outflow data from CDWR's Dayflow program (CDWR 1986) for WYs 1930–2022 and from previous work reported by the authors (Hutton and Roy 2019; Hutton et al. 2015) for WYs 1912–1929. We assembled additional outflow-related data to support this work, including reconstructions reported in the literature (Moftakhari et al. 2013, 2015) and legacy flow measurements (WYs 1879–1885) at the confluence of the Sacramento and San Joaquin rivers at Collinsville (Hall 1886) (see Figure 1). Regarding the latter data, MacVean et al. (2018) notes that "… the Sacramento River flow at Collinsville is fully tidal, and it is not clear how the oscillating component of the flow at this section was removed to leave only the net freshwater flow; the uncertainties in these flow estimates are likely significant."

Table 1 Sacramento water level data

Period	No. of months	Comments
Oct 1850 – Dec 1850	3	Data not used. (Data appear to be duplicates of Oct–Dec 1849.)
Jan 1851 – Aug 1862	140	Several missing values were filled through linear interpolation; data before 1857 appear to be smoothed.
Sep 1862 – Aug 1881	228	No data
Sep 1881 – Apr 1888	80	Complete data set
May 1888 – Nov 1890	31	No data
Dec 1890 – Sep 1944	646	Complete data set

Table 2 Monthly average hydrology data

Inflow	Period	No. of months	Sources
Delta Inflow	Oct 1911 – Sep 1944	396	Hutton and Roy 2019 Hutton et al. 2015 Dayflow 1986
Delta Outflow	Oct 1911 – Sep 2022	396	Hutton and Roy 2019 Hutton et al. 2015 Dayflow 1986
Gross Delta Channel Depletions	Oct 1911 – Sep 1944	96	Hutton and Roy 2019 Hutton et al. 2015 Dayflow 1986
Precipitation at Stockton, CA	Jan 1853 – Jan 1857 Sep 1867 – Aug 1884 Dec 1904 – Sep 1944	719	Hall 1886 CDEC 2023
Precipitation at Sacramento, CA	Oct 1850 – Sep 1944	1128	Masters–Bevan 2000
Net Delta Channel Depletions	Oct 1911 – Sep 1944	96	Hutton & Roy 2019 Hutton et al. 2015 Dayflow 1986
Sacramento River at Collinsville, CA	Nov 1878 – Sep 1885	83	Hall 1886; McGlashan and Henshaw 1912
SDE Reconstruction (Water Level Based Outflow Estimate)	Oct 1850 – Aug 1862 Sep 1881 – Apr 1888 Dec 1890 – Sep 1944	864	Moftakhari et al. 2015
TDE Reconstruction (Tide Based Outflow Estimate)	Jan 1859 – Sep 1944	1029	Moftakhari et al. 2013
Central Valley Unimpaired Runoff (8 River Index)	Oct 1850 – Sep 2022	2064	Lai et al., submitted CDEC 2023

Central Valley unimpaired runoff data—specifically 8 River Index data (representing the sum of flows from the Sacramento at Red Bluff, Feather, Yuba, American, Stanislaus, Tuolumne, Merced, and San Joaquin rivers)—were used to (1) reconstruct Delta inflow for periods when Sacramento River water-level data were unavailable, (2) reconstruct Delta inflow for periods when the Sacramento River was likely at flood elevations near Sacramento, and (3) compute a Delta outflow metric "normalized" to the eight River Index. 8 River Index data were obtained from CDWR estimates (CDEC 2023; CDWR 2016) beginning in the early 20th century—WY 1906 for the Sacramento basin and WY 1902 for the San Joaquin basin. We used unimpaired runoff estimates developed by Lai et al. (2024) for ungauged periods back to WY 1851.

Model Framework and Conceptualization

The model framework developed and used in this work to reconstruct a monthly Delta outflow time-series before WY 1912 is shown schematically in Figure 4. For periods when Sacramento River water-level data are available, these data are first adjusted to account for sediment deposition associated with upstream hydraulic mining activities. We generally used adjusted water-level data developed by Moftakhari et al. (2015); exceptions are discussed later under Results. For months when the adjusted water level is <5 m, these values are used to estimate Delta inflow. For periods when either water-level data are unavailable, or during high flow events when adjusted water level is ≥5 m, unimpaired runoff data (i.e., 8 River Index) are used to estimate Delta inflow. As suggested by Moftakhari et al. (2015), Sacramento water-level-based flow estimates are suspect during high flow periods when levee breaks may have occurred, and/or when bypass flows were likely significant. Finally, given reconstructed NCD estimates, Delta outflow is computed as the difference between Delta inflow and NCD.

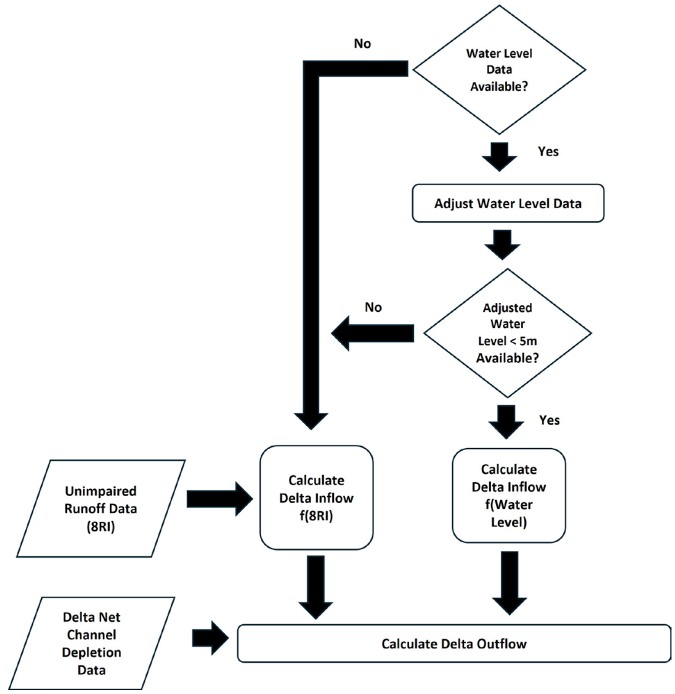

Figure 4 This schematic presents the model framework developed and used in this work to reconstruct a monthly Delta outflow time-series before WY 1912 based on legacy hydrologic data.

Our model framework reflects a key assumption that, under most hydrologic conditions, water level at Sacramento is an effective measure of flow that enters the Delta from the Sacramento River, and this flow is a robust proxy of total inflow to the Delta. This assumption is supported by the fact that the Sacramento River typically provides about 70% of the total inflow to the Delta, and that other key inflows are reasonably correlated with Sacramento River inflow. For example, inflows from the San Joaquin River and the Cosumnes–Mokelumne Rivers represent 28% ($R^2 = 0.73$) and 7% ($R^2 = 0.83$) of Sacramento River inflow, respectively. However, under high runoff conditions when excess flows spill into the Yolo Bypass from the Sacramento River, Sacramento water level no longer provides a robust measure of Delta inflow. As part of the contemporary flood-control system, flood flows are regulated through a system of weirs along the Sacramento River. Before 1917, spills under high flow conditions were unregulated. Hall (1886) noted that:

When the water surface comes to the 18-ft (5.5-m) mark on the Sacramento gauge, which corresponds to about 41,000 cubic feet in volume of flow ... the stream is losing an appreciable part of its volume through breaks (crevasses) ... This water flows down the valley over the low lands ... whence it again joins the river between Sacramento and Collinsville ... Thus at high-water stages large volumes of Sacramento river water escape around the Sacramento channel-station, and joined by other waters enter the river below, forming with the flow past Sacramento its total output into the bay.

Our model framework accounts for this high runoff phenomenon by estimating Delta inflow as a function of unimpaired runoff (rather than water level) when Sacramento water level exceeds 5 m.

We note that our model conceptualization deviates from that of Moftakhari et al. (2015). While our model framework includes a separate step to calculate Delta outflow as the difference between Delta inflow and NCD, their flow reconstruction directly predicts Delta outflow from Sacramento water-level data. Their conceptualization implicitly assumes that in-Delta water use (i.e., NCD) was stationary during the latter half of the 19th century and the early 20th century. However, in-Delta water consumption was likely greater before land reclamation (Fox et al. 2015; CDPW 1931), with CDPW (1931) observing that reclamation "... has eliminated a large area of aquatic vegetation ... which consume three to four times as much water as the crops which are now grown on these reclaimed lands. As a result, it appears probable that the consumption of water within the delta has been decreased by reclamation development ... ."

RESULTS

We developed time-series spanning WYs 1851–1911 for NCD, Delta inflow, and outflow following the model framework discussed earlier. In addition to presenting the resulting monthly values, we describe the assumptions associated with estimating NCD as well as calibration and validation of supporting Delta inflow models. Finally, we present results from an analysis of normalized Delta outflow trends over the full period of record spanning WYs 1851–2022. Differences between our work and Moftakhari et al. (2013, 2015) in model framework, conceptualization and results are discussed in Appendix A.

Delta Net Channel Depletion (NCD) Reconstruction

We reconstructed a monthly time-series of Delta NCD spanning WYs 1851–1911 by developing supporting time-series of Delta gross channel depletions (GCD) and precipitation, and computing the difference to arrive at monthly NCD values. Figure 5 provides annual time-series plots of reconstructed volumes, and extends the period through WY 1944 by including previously available estimates spanning WYs 1912–1944. Figure 5A illustrates the decreasing annual trend in GCD associated with Delta reclamation. Counter to the annual trend, monthly volumes in November, January, and February changed little or increased over the reconstruction period. Figure 5B presents the resulting annual Delta precipitation time-series; this time-series highlights several years of high Delta precipitation during the reconstruction period—notably WYs 1862 and 1890—years also characterized by high Central Valley unimpaired runoff (Figure 3E). The resulting NCD time-series, provided in Figure 5C, shows a decreasing trend in peak depletions over the period, aligning with the decreasing trend in GCD associated with Delta reclamation. Assumptions used in the NCD reconstruction are provided in Table 3.

Delta Inflow Reconstruction

As shown schematically in Figure 4, Delta inflow was estimated using two distinct approaches, depending on availability and magnitude of Sacramento water-level data. Below we present results of model calibration and validation for periods when inflow was measured, and present resulting estimates for the WYs 1851–1911 pre-instrumented period.

Stage-Discharge Model Calibration

Stage–discharge rating curves between Delta inflow and water level for WYs 1930–1944 were calibrated with least squares piece-wise linear fits, which were applied to evenly spaced, bin-averaged, daily flows and water levels (Figure 6A) to support the reconstruction of a Delta inflow time-series for the period spanning WYs 1851–1911. The calibration period was selected because, before construction of Shasta Reservoir in 1945, upstream water management did not significantly alter Delta inflow. Moftakhari et al. (2015) utilized the same calibration period in their work, citing the same rationale. Clearly, the stage–discharge relationships are not uniform over the range of water level, with different slopes at high flow (daily water level > 6.2 m), moderate flow, and low flow (daily water level < 1.4 m), thus providing a rationale for employing a piece-wise fit. The change in slope at high flow reflects flood flow spills into Yolo Bypass. We found that the low-flow variance could be explained by season. Specifically, we found that for water levels < 1.4 m, corresponding flows were lower from April through October and higher during the remaining months. We hypothesize that this observation is related to tidal influence at Sacramento during low-flow periods. Based on these observations, we split the low-flow calibration data into three

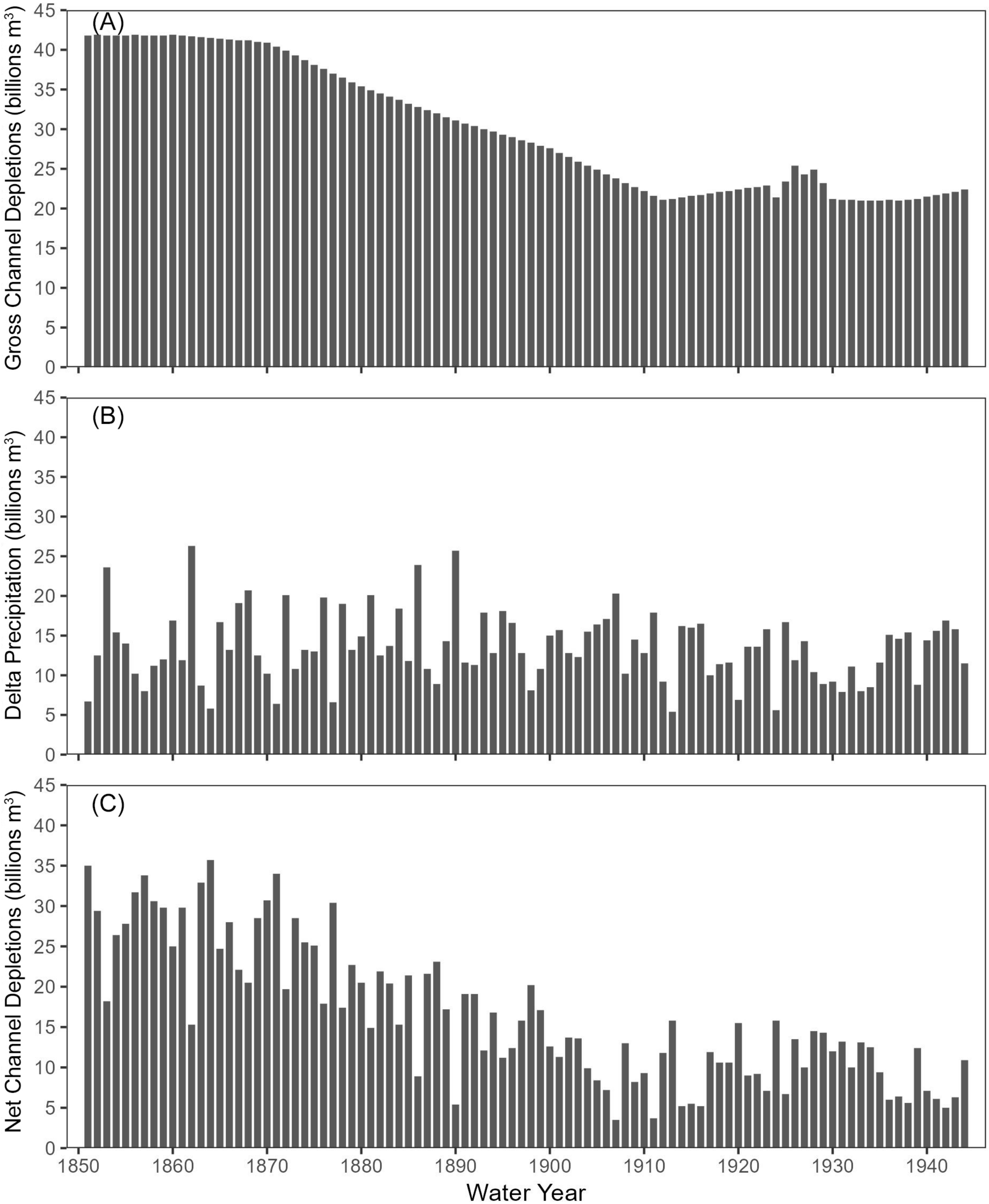

Figure 5 Annual time-series of Delta gross channel depletions, precipitation, and net channel depletions are presented in Panels **A** through **C**, respectively, for the period spanning WYs 1851–1944. The time-series include reconstructed values (through WY 1911) and previously available estimates. Gross channel depletions are assumed to reflect pre-development evapotranspiration conditions as described in Fox et al. (2015) through WY 1860. Net channel depletions are computed as the difference between gross channel depletions and precipitation.

Table 3 Assumptions used in Delta net channel depletion reconstruction WYs 1851–1911

Hydrologic component	Period	Comments	Source
Delta gross channel depletions	Oct 1850– Sep 1860	Reflect pre-development evapotranspiration conditions	Fox et al. 2015
	Oct 1860–Sep 1911	Change in proportion to the area of annual Delta reclamation — see Figure 3A	CDPW 1931
Delta precipitation	Oct 1850– Nov 1904	Monthly volumes estimated from records at Sacramento and transformed into equivalent Stockton precipitation volumes[a,b,c,d]	Masters–Bevan 2000; Hall 1886
	Dec 1904–Sep 1911	Monthly volumes estimated from records at Stockton Fire Station 4[d]	CDEC 2023

a. Transformation based on least squares regression of monthly Sacramento and Stockton records spanning Dec 1904–Sep 1944: Slope = 0.816; R^2 = 0.94; standard error = 1.3 billion m^3.
b. Transformed precipitation volumes compared with Stockton records (Jan 1853–Sep 1884) through least squares analysis: slope = 1.04; R^2 = 0.88; standard error = 2.1 billion m^3.
c. Transformation resulted in five extreme outlier months (Mar 1853, Dec 1867, Dec 1871, Dec 1873, Apr 1880); these estimates were replaced with Stockton records.
d. Monthly precipitation intensity (cm mo^{-1}) was multiplied by Delta watershed area (299,000 hectares) and appropriate conversion factors to arrive at monthly values in units of billion m^3, following methodology utilized by CDWR in the Dayflow model (CDWR 1986).

seasonal subsets (April–August, September–October, and November–March), and the remaining calibration data into moderate- and high- flow subsets. Table 4 provides model constants. Although model constants are provided for a high-flow condition (water level >6.2 m), following Figure 4, we did not use this model for inflow reconstruction.

Table 4 Delta inflow as a piece-wise linear function of Sacramento water level Q (m^3s^{-1}) = $\Phi_1 * WL$ (m) + Φ_2

Water level range (m)	Season	Φ_1	Φ_2
<1.4	Apr–Aug	190	–4.6
	Sep–Oct	107	116
	Nov–Mar	270	67.6
1.4 – 6.2	Oct–Sep	377	–118
>6.2 (not used)	Oct–Sep	2200	–11500

Unimpaired Runoff-Discharge Model Calibration

A second Delta inflow model, employing the 8 River Index as the independent variable, was used for periods when Sacramento water-level data are unavailable, or when adjusted water level values are ≥5 m. We observed as part of our data analysis that the relationship between Delta inflow and unimpaired runoff has changed over time (particularly under lower runoff conditions) and were concerned that the calibration period used for the first model (i.e., WYs 1930–1944) would not be characteristic of 19th-century conditions. Therefore, we utilized water-level-based Delta inflow predictions for WYs 1882–1911 (discussed later) to calibrate the second model with a least squares fit with a form $Q = \alpha * (8\,\text{River Index})^{\beta}$, where α and β are fitting constants. The regression equation was applied to evenly spaced, bin-averaged, monthly inflows (in units of cubic meters per second, m^3s^{-1}) and monthly runoff (in units of billion m^3), producing a best fit with α = 239 and β = 1.27. We truncated the bin-averaged calibration dataset to exclude high-flow conditions, as water-level-based flow estimates are suspect during high-flow periods when levee breaks may have occurred and/or when bypass flows were likely significant. The resulting model fit is overlaid with observed data for WYs 1912–1921 and a curve that represents binned data for WYs 1922–2022 in Figure 6B. We observe that model results, even when extrapolated under high-flow conditions, align reasonably well with observed relationships beyond WY 1911.

Goodness of Fit Assessment

Observed and predicted monthly Delta inflow values are compared as a time-series for the calibration period (WYs 1930–1944) and the WYs 1912–1929 validation period in Figure 7A. Corresponding time-series of monthly water level (not adjusted) and 8 River Index values are provided in Figure 7C. Values of average observed Delta inflow, RMS error, and Nash–

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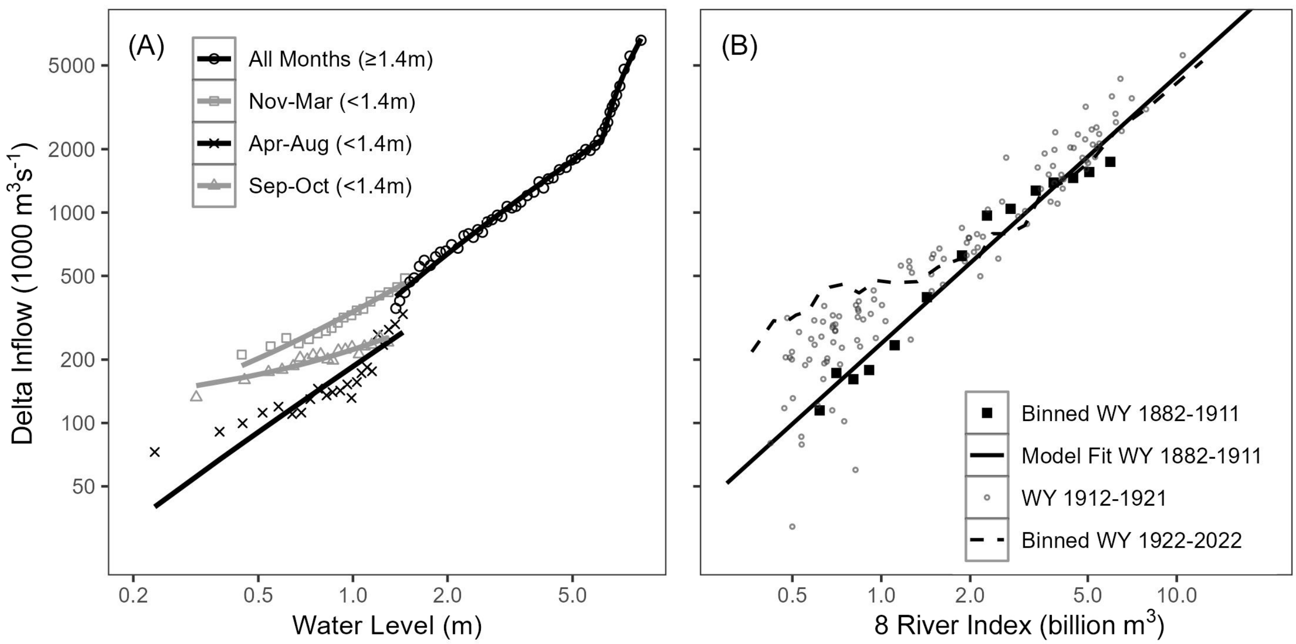

Figure 6 Delta inflow models were calibrated using two distinct approaches and were utilized for flow reconstruction depending on availability and magnitude of Sacramento water-level data. Panel (**A**) presents stage-discharge rating curves that were used when water-level data were available and adjusted values were < 5 m. Panel (**B**) presents an alternate model, employing unimpaired runoff (i.e., 8 River Index) as the independent variable, for periods when water-level data were unavailable or when adjusted values were ≥ 5 m. Data presented in these panels were bin-averaged unless otherwise noted.

Sutcliffe efficiency coefficient (NSE) for the calibration period are 916 m^3s^{-1}, 324 m^3s^{-1}, and 0.90, respectively. Values of average observed Delta inflow, RMS error, and NSE for the validation period are 888 m^3s^{-1}, 248 m^3s^{-1}, and 0.93, respectively. Although Moftakhari et al. (2015) computed Sacramento water-level adjustments before WY 1930, we did not use these adjusted values in estimating Delta inflow for the validation period, because they appear to over-compensate for hydraulic mining deposition effects, and result in systematic flow under-prediction bias. Although calibration residuals do not show ideal random scatter (rather they show a downward time trend), validation period residuals appear well behaved, except for the first 2 years of the period (WYs 1912–1913) when estimates were consistently higher than observed values.

Model Application: WYs 1851–1911

We generally used monthly averaged, adjusted Sacramento water-level data (Moftakhari et al. 2015) in conjunction with the water-level-based model discussed above to reconstruct a monthly Delta inflow time-series for periods within WYs 1851–1911 when water-level data were available (see Table 1), and when the adjusted values were < 5 m. As discussed in the appendix, we re-computed water-level adjustments for the period spanning January 1851–August 1862 before computing Delta inflow estimates, lowering the scaling factor applied by Moftakhari et al. (2015) from 1.3 to 1.1. For the remaining periods within WYs 1851–1911, we used monthly 8 River Index values to estimate Delta inflow using the unimpaired runoff-based model discussed above.

Delta Outflow Reconstruction

A monthly time-series of Delta outflow spanning WYs 1851–1911 was developed by computing the difference between Delta inflow and NCD reconstructions. Figure 7B compares observed and predicted monthly time-series for the inflow calibration period (WYs 1930–1944) and the inflow validation period (WYs 1912–1929). Since the NCD values used to compute Delta outflow for the calibration and validation periods are "given," residual values are identical to those computed for

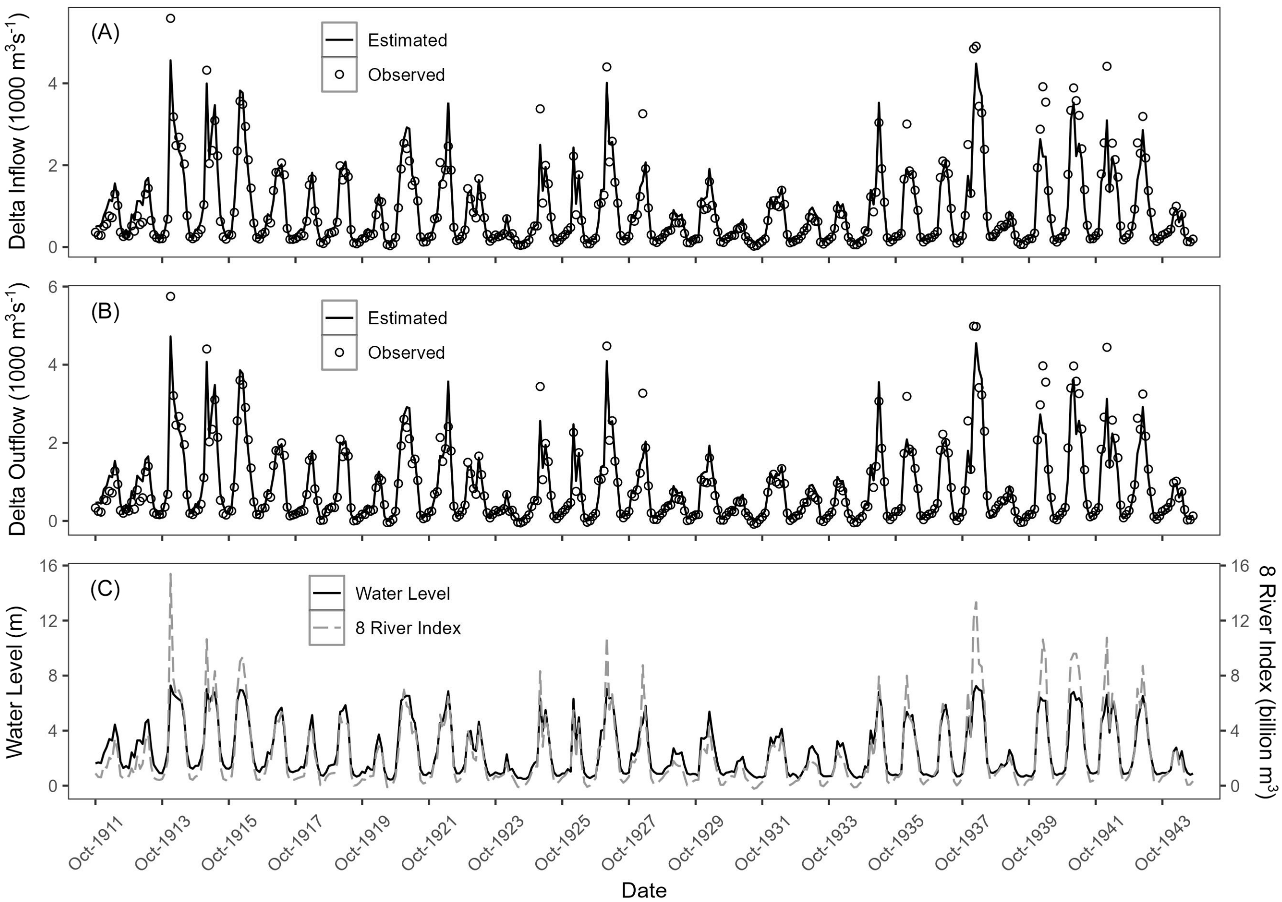

Figure 7 Estimated and observed Delta inflow and outflow monthly time-series are compared in Panels (**A**) and (**B**), respectively, for the calibration (WYs 1930–1944) and validation (WYs 1912–1929) periods. Corresponding time-series of monthly water-level (not adjusted) and unimpaired runoff (8 River Index) are presented in Panel (**C**).

Delta inflow. Thus, further analysis of goodness of fit and residuals was not conducted for WYs 1912–1944.

Figure 8 presents the reconstructed monthly Delta outflow time-series. Figure 8A covers the earlier sub-period (WYs 1851–1881) when Sacramento water-level data are limited, and Delta inflow estimates are most frequently computed as a function of 8 River Index. Figure 8B covers the later sub-period (WYs 1882–1911) when Sacramento water-level data are generally available, and Delta inflow estimates are most frequently computed as a function of water level. Monthly flow measurements at Collinsville (Hall 1886) overlay the reconstructed time-series in Figures 8A and 8B; Figure 8C focuses on the period when these measurements were taken. This figure demonstrates reasonable coherence between the reconstructed values and the measured flows at Collinsville (NSE = 0.82), although the reconstructed values are consistently higher during low-flow summer and fall months. Delta outflow estimates over WYs 1851–1911, when computed from water-level-based Delta inflow estimates, were also compared with 8 River Index values as a measure of prediction robustness in the absence of measured values. The correlation coefficient is 0.83 for the earlier sub-period (WYs 1851–1881) and 0.89 for the later sub-period (WYs 1882–1911).

The Delta outflow reconstruction, as summarized in Figure 8, provides a basis for evaluating long-

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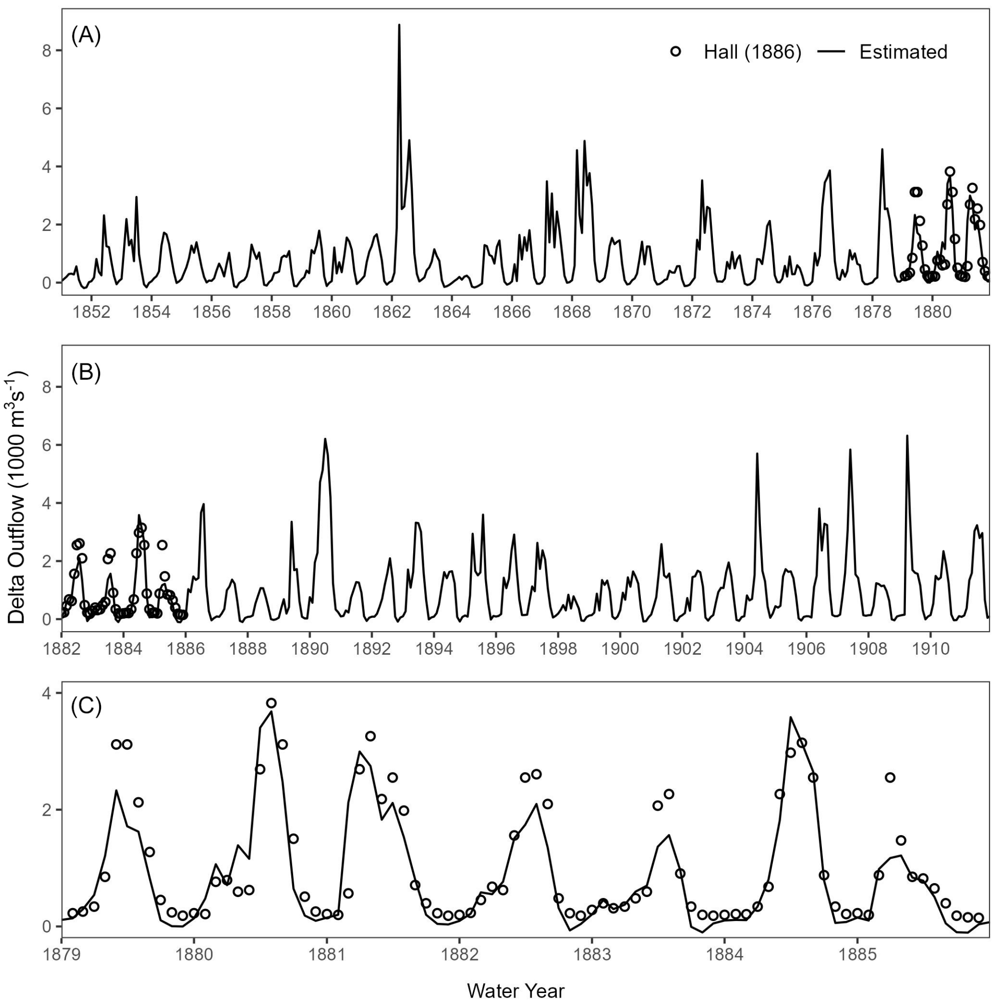

Figure 8 Panels (**A**) and (**B**) present the reconstructed monthly Delta outflow time-series spanning WYs 1851–1911. Panel (**A**) covers the earlier sub-period when Sacramento water-level data are limited, and Delta inflow estimates are most frequently computed as a function of 8 River Index. Panel (**B**) covers the later sub-period when Sacramento water level-data are generally available, and Delta inflow estimates are most frequently computed as a function of water level. Monthly flow measurements at Collinsville (Hall 1886) overlay the reconstructed time-series in Panels (**A**) and (**B**); Panel (**C**) focuses on the period when these measurements were taken.

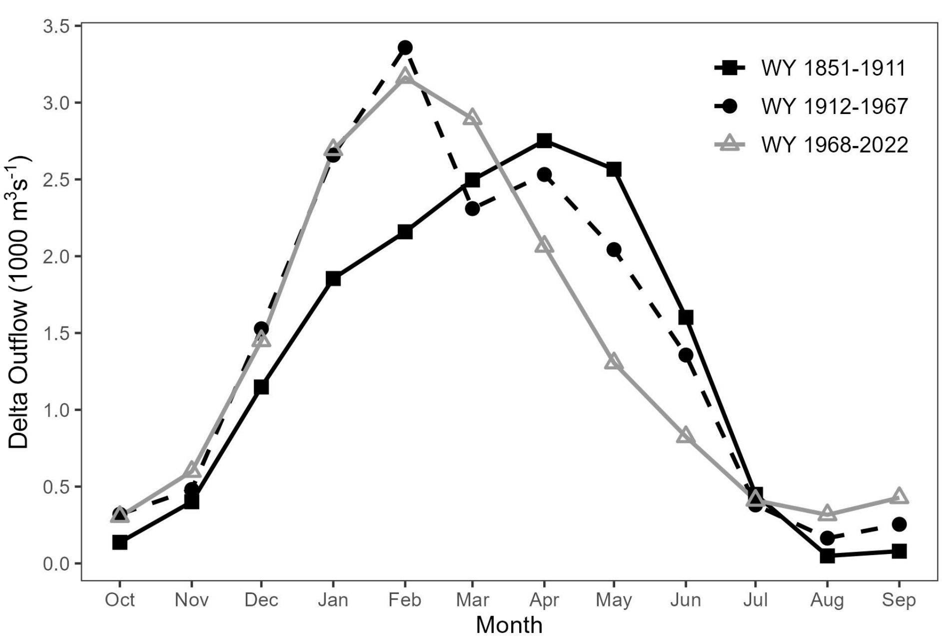

Figure 9 Reconstructed monthly Delta outflow (WYs 1851–1911), computed as wet year averages, are compared with the same data computed over two subsequent time-periods. Several trends are noteworthy; collectively, they resulted in shifting peak flow from spring (April) to winter (February). Declining spring flows and increasing summer–fall flows align with trends reported elsewhere.

Table 5 Seasonal trend summary associated with reconstructed wet year delta outflow hydrograph (as depicted in Figure 9)

Season	Trend	Comments	Source
Spring (Apr–Jun)	Decrease	Trend likely in large part because of upstream irrigation diversions and upstream reservoir operation. Even in the absence of reservoirs, this decline would have been observed due to earlier snowmelt runoff resulting from climate change impacts	Hutton et al.-2017b Lai et al. submitted
Summer–Fall (Aug–Nov)	Increase	Trend likely because of decreasing Delta NCD and upstream reservoir operation.	Hutton et al. 2017b
Winter (Dec–Mar)	Increase	Trend may be a result of earlier snowmelt runoff and levee construction that kept flood flows in the river and prevented spills into upstream floodplains.	Lai et al. submitted

term changes in the annual hydrograph. Figure 9 compares reconstructed monthly Delta outflow over WYs 1851–1911, computed as wet year averages, with the same data computed over two subsequent sub-periods: WYs 1912–1967 and WYs 1968–2022. Water year 1968 was selected as the break between the latter sub-periods, because it represents the year when the SWP became operational; this date coincidentally provides a nearly equal sample size between the latter sub-periods. Wet year annual average outflow was similar between these sub-periods: 41.1 billion m^3 for the reconstruction period spanning WYs 1851–1911, 45.3 billion m^3 for WYs 1912–1967, and 42.9 billion m^3 for WYs 1968–2022. Several trends are noteworthy and consistent with those reported by Moftakhari et al. (2013); collectively, they resulted in shifting peak flow from spring (April) to winter (February). The seasonal trends observed in Figure 9 and summarized in Table 5—notably declining spring flows and increasing summer flows between the second sub-period (WYs 1912–1967) and third sub-period (1968–2022)—align with those reported elsewhere (Hutton et al. 2017a; Gross et al. 2018).

Normalized Inflow and Outflow Trends

We analyzed trends associated with normalized inflow and outflow time-series that included both reconstructed and contemporary flows spanning WYs 1851–2022. Normalized values are computed as Delta flow volumes divided by 8 River Index volumes. Figure 10 presents results for annual and seasonal time-series, with separate charts for the annual time-series and seasonal time-series for December–March, April–June, and July–November: Figures 10A through 10D present normalized inflow trends, while Figures 10E through 10H present normalized outflow trends. Following the approach of Hutton et al. (2017a), the time-series are segregated into low-runoff years defined by an annual index <24.7 billion m^3 (20 million acre-ft) and high-runoff years defined by an annual index ≥ 24.7 billion m^3. Curves are drawn through these points using a locally weighted scatterplot smoothing function to aid interpretation of the normalized data points. A sensitivity of the normalized flow trends to the selected threshold suggested that conclusions are not highly sensitive to modest changes in the assumed threshold.

Figure 10E, which shows the normalized, annual Delta outflow time-series, is nearly identical to that presented in Hutton et al. (2017a) but extends the time-series back to WY 1851. They observed (1) normalized values are smaller in low-runoff years than in high-runoff years, (2) decreasing trends in both subsets, and (3) the declining trends in low-runoff years stopped or even reversed in the 1980s as a result of flow and salinity regulations in the estuary that limited out-of-basin exports. The extended time-series demonstrates that, although normalized outflow has declined since the 1920s, conditions are similar to those that existed in the mid-1800s. This finding supports our hypothesis that a systemwide reduction in evapotranspiration occurred in the latter half of the 19th century and early 20th century. As Figure 10A shows, the normalized, annual Delta inflow time-series shows similar trends over the period of record.

Figure 10F shows normalized outflow trends averaged over the winter months of December

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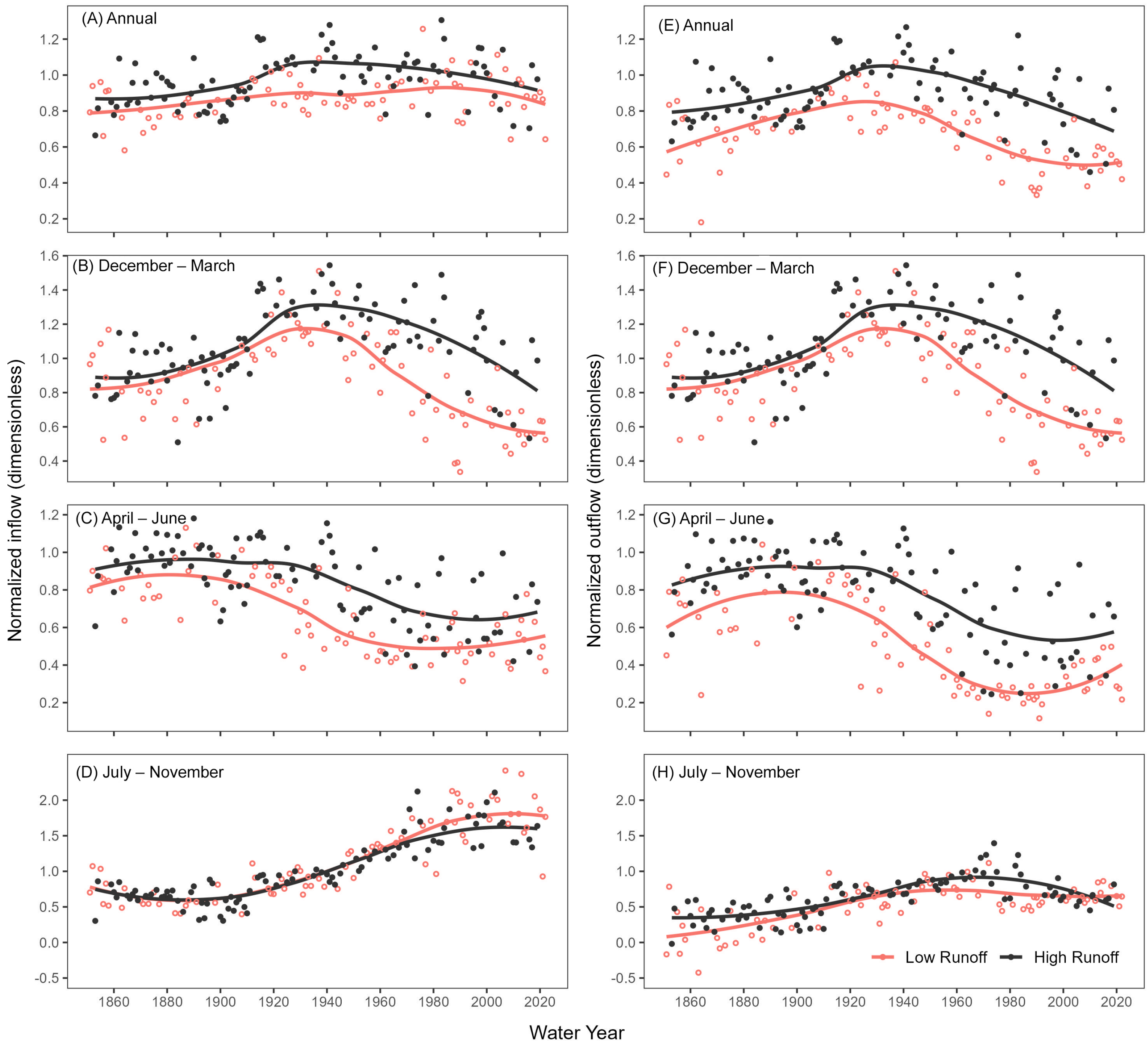

Figure 10 Normalized Delta inflow and outflow time-series, both annual and seasonal, are presented here for the period spanning WYs 1851–2022. Normalized values are computed as Delta flow volumes divided by 8 River Index volumes. The time-series are segregated into low-runoff years defined by an annual index < 24.7 billion m^3 (20 million acre-ft), and high-runoff years defined by an annual index ≥ 24.7 billion m^3. *Curves* are drawn through these points using a locally weighted scatterplot smoothing function to aid interpretation of the normalized data points. The annual outflow time-series (Panel **E**) demonstrates that, although normalized outflow has declined since the 1920s, conditions are similar to those that existed in the mid-1800s. This finding supports our hypothesis that a systemwide reduction in evapotranspiration occurred in the latter half of the 19th century and early 20th century.

through March. The trends presented on this chart are characteristic of those shown in Figure 10E. However, while the low-runoff trend appears to have flattened out, normalized flows for this subset are somewhat lower than those that existed in the mid-1800s. As Figure 10B shows, the normalized Delta inflow time-series shows similar trends over the period of record.

Figure 10G shows normalized outflow trends averaged over the spring months of April through June. The high-runoff subset shows a relatively flat trend before the 1920s, a decline from the 1920s through the 1970s, and a relatively flat trend from the 1980s onward. The low-runoff subset shows a different pattern, with an increasing trend in the 1800s followed by a decline through the 1970s, with an increasing trend from the 1980s onward. For both subsets, normalized flows remain somewhat lower than those that existed in the mid-1800s. As Figure 10C shows, the normalized Delta inflow time-series shows similar trends over the period of record.

Figure 10H shows normalized outflow trends averaged over the summer and fall months of July through November. The high-runoff subset shows a relatively flat trend in the 1800s, an increasing trend through the 1970s, and a decreasing trend from the 1980s onward. The low- runoff subset shows a different pattern, with an increasing trend through the early 20th century followed by a flat trend from the 1920s onward. For both subsets, normalized flows remain higher than those that existed in the mid-1800s. As Figure 10D illustrates, the normalized Delta inflow time-series shows a more dramatic and sustained increasing time trend relative to Figure 10H. The difference between inflow and outflow trends is the result of out-of-basin exports from the Delta associated with the CVP and SWP.

We note that the annual and seasonal trends associated with normalized inflows generally followed those of normalized outflows: see Figures 10A through 10D. Although the focus of our work was on normalized outflow trends, the demonstrated similarity with normalized inflow trends is significant because the inflow trends are independent of assumptions associated with the construction of Delta NCD values.

DISCUSSION

Previous work showed that—although no statistically significant annual trend in freshwater inflow to the open waters of San Francisco Estuary (i.e., Delta outflow) occurred since the 1920s—a decreasing trend could be extracted from the data when normalized to unimpaired runoff (Hutton et al. 2017a). This decreasing trend was attributed to a systemwide increase in water use associated with out-of-basin exports and upstream diversions (Hutton et al. 2017b). By extending the Delta outflow time-series back to the Gold Rush era (circa 1850), the present work shows that the increasing trend in systemwide water use was preceded by a decreasing trend during the latter half of the 19th century. This decreasing water use trend is believed to reflect a systemwide reduction in evapotranspiration that resulted from the removal of high water using natural vegetation and the reduction in overbank flows associated with levee construction. This finding, which suggests similarity between natural and contemporary long-term, annual average freshwater inflow, is consistent with earlier published research that compared pre-development annual flow conditions (circa 1850) with those prevalent in the early 20th century (circa 1920) and those prevalent today (Gross et al. 2018). Findings related to monthly flow trends were more nuanced, and reflect season-specific influences of anthropogenic modifications to the waterscape.

Access to a recently developed runoff reconstruction by Lai et al. (submitted) provides important context for assessing the role of climate in long-term Delta outflow trends. Moftakhari et al. (2013) and Moftakhari et al. (2015) concluded that upstream diversions produced 30% and 35% reductions, respectively, in annual average Delta outflow—the former estimate was based on a pre-1900 baseline while the latter baseline was based on a pre-1946 baseline. The present work draws different conclusions in terms of magnitude and attribution. Our outflow

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reconstruction shows a 20% reduction in annual average Delta outflow when comparing the periods WYs 1882–1911 (30.2 billion m^3) and WYs 1912–2022 (24.4 billion m^3). Importantly, our analysis suggests that part of this reduction can be attributed to climate, and not only upstream diversions, as a nearly identical 20% reduction in annual average 8 River Index occurred between the two periods (36.0 billion m^3 vs. 28.2 billion m^3). Notably, the outflow reconstruction developed by Moftakhari et al. (2015) gives a similar annual average Delta outflow over WYs 1882–1911 (31.3 billion m^3) as our estimate for the same period.

In its statement of purpose and need for updated flow regulations in the San Francisco Estuary, the SWRCB posits that upstream diversions and out-of-basin exports have reduced annual Delta outflow by more than 50% (SWRCB 2017). This quantification conflates unimpaired and historical baseline conditions (i.e., it assumes computed unimpaired outflow would have been realized absent human alterations), assumed a relatively limited period of record (beginning WY 1930), and used general guidelines (Rozengurt et al. 1987; Richter et al. 2011) to conclude that hydrologic alterations have adversely affected the aquatic ecosystem. Our findings run counter to this paradigm, showing that annualized outflow (when normalized to unimpaired runoff) has followed a complex, non-linear trajectory—and currently differs little from pre-development (circa 1850) conditions.

Our work highlights challenges associated with the use of limited observational records (which may reflect significant alteration from pristine conditions) as the basis for identifying trends and setting restoration targets; this problem is referred to as the shifting baseline syndrome in the ecological literature (Pauly 1995). Clearly, baselines reflecting 20th century or even unimpaired conditions—which are typically used within regulatory frameworks for the study area (for example, see SWRCB 2017)—do not reflect pristine or pre-development conditions; such selection of baseline could be viewed as being defined by expediency rather than representing a comprehensive understanding of pre-development conditions. There is no universal definition of an appropriate baseline and, depending on available information, could refer to different points in the system's evolution. Mathematical modeling offers a potentially useful approach to transparently address the problem of shifting baselines when defining restoration baselines and targets. Conceptually, such baseline modeling would evaluate fixed land- and water-use conditions that overlay an assumed set of climatic conditions (Hutton et al. 2017a).

Collecting the data required to compute water balances over large spatial scales is time- and resource-intensive, even for contemporary studies. The task of compiling such information is even more challenging for historical reconstructions, although there is some promise for continued improvement given the well-documented nature of the study area and the vital restoration questions at stake. Future research may continue to refine the understanding of historical hydrology through greater integration of data with more detailed mechanistic models that represent the San Francisco Estuary and its watershed. In particular, more highly resolved time-series of land cover, water diversions, watershed elevations and levee-construction details are needed. Additional data on occurrence of historical floods in the Central Valley (both timing and extent), as noted by MacVean et al. (2018), are needed to improve historical flow reconstructions.

This research contributes to ongoing dialogues about ecosystem-restoration targets, highlighting the challenges of replicating historical inflow patterns. However, these reconstructions offer a valuable framework for setting realistic restoration goals based on a better understanding of natural variability and the multiple human effects on estuarine hydrology. Despite certain limitations—such as high rainfall years that may skew data, and uncertainties in water-level records—this outflow reconstruction provides critical insights and underscores the need for long-term data in managing dynamic, heavily modified ecosystems such as the San Francisco

Estuary. This extended historical dataset and its findings allow for a more informed approach to water-resource management, facilitating targeted conservation measures that balance ecological requirements with contemporary water demands.

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NOTES

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