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RESEARCH ARTICLE

Freshwater flow to the San Francisco Bay-Delta estuary over nine decades (Part 1): Trend evaluation

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Abstract

The San Francisco Bay-Delta estuary and its upstream watershed have been highly modified since exploration and settlement by Europeans in the mid-18th century. Although these hydrologic alterations supported the growth of California's economy to the eighth largest in the world, they have been accompanied by significant declines in native aquatic species and subsequent efforts to reverse these declines through flow management. To inform ongoing deliberations on management of freshwater flows to the estuary, we examined a recent nine-decade hydrologic record to evaluate seasonal and annual trends in reported Delta outflow. Statistically significant trends were observed 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). Trend significance in early-to-mid autumn (September and October) is ambiguous due to uncertainty associated with in-Delta agricultural water use. In spite of increasing water use over the period examined, we found no statistically significant annual trend in Delta outflow, a result likely due to large inter-annual variability. Linkages between outflow trends and changes in upstream flows and coincident developments such as reservoir construction and operation, out-of-basin imports and exports, and expansion of irrigated agriculture are discussed. To eliminate inter-annual variability as a factor, change attribution is explored using modelled flows and fixed climatology in a companion paper.

KEYWORDS

Central Valley, Delta outflow, Mann–Kendall, trend analysis, unimpaired flows

1 | INTRODUCTION

Estuarine ecosystems worldwide are subject to a variety of stressors, including pollutants, invasive species, habitat loss, and hydrologic alteration (Kennish, 2002). International restoration efforts are ongoing in response to these stressors, with the recognition that impacts to many ecosystems are a consequence of multiple interacting factors that are often poorly understood (e.g., Elliott, Burdon, Hemingway, & Apitz, 2007; Kennish, 1999; Thom et al., 2005; Williams & Orr, 2002). The desired restoration target or baseline is an important consideration in structuring flow regulations and other restoration actions. Because of the general absence of direct observed data from pre-development periods, restoration targets are typically guided by earliest available records, even when it is recognized that these observations reflect some degree of alteration. In other words, the restoration baselines are themselves not entirely representative of natural conditions, a concept termed *shifting baselines* in the ecological literature (e.g., Duarte, Conley, Carstensen, & Sánchez-Camacho, 2009; Villnäs & Norkko, 2011; Wagener et al., 2010).

The San Francisco Bay-Delta estuary on the Pacific coast of California (Figure 1) has been the focus of large-scale restoration and management efforts over the past four decades to address multiple stressors (Hanak, 2011). This estuary and its associated watershed are of great practical importance because of its role in the water supply and economic development of California (Luoma, Dahm, Healey, & Moore, 2015). With freshwater withdrawals believed to constitute a significant fraction of natural flows to the system, hydrologic alteration has been the stressor of primary focus. The study presented herein

FIGURE 1 Bay-Delta watershed showing the major rivers that flow through the California Central Valley, most of which are regulated through reservoirs. The approximate location of 10 major reservoirs in the Sacramento and San Joaquin basins of the Central Valley are identified

was motivated by the need to inform ongoing deliberations on management of freshwater flows to the estuary, given the pervasive issues and concerns regarding restoration targets and shifting baselines as introduced in the previous paragraph.

Anthropogenic modifications to the estuary and its watershed occurred rapidly upon European settlement of the region in the mid-18th century (Hundley, 2001) and include development of surface water storage equivalent to a year's average runoff (Graf, 1999), landscape conversion for agriculture and urban uses, and construction of large water projects to export water from the system. Although the estuary and its watershed have been dramatically altered over the past century, flow trends are often difficult to discern because of the large seasonal and inter-annual variability in watershed precipitation. Some of the underlying drivers of precipitation, such as sea surface temperatures, vary on decadal timescales (Cayan, Dettinger, Diaz, & Graham, 1998) and thus mask flow trends due to watershed changes over shorter time horizons. Detecting and attributing natural and human-induced changes to the hydrologic regime is needed to support restoration activities in general and flow and salinity management in particular. Specifically, there is interest in understanding historical changes to Delta outflow, the nontidal freshwater flow from the Delta to San Francisco Bay, which is a strong driver of estuarine salinity and habitat conditions (Feyrer, Newman, Nobriga, & Sommer, 2010; Feyrer, Nobriga, & Sommer, 2007; Jassby et al., 1995; Kimmerer, Gross, & MacWilliams, 2009; Moyle, Lund, Bennett, & Fleenor, 2010). Delta outflow, which is directly regulated to protect fish and wildlife beneficial uses and indirectly regulated through salinity standards to protect urban and agricultural beneficial uses (California State Water Resources Control Board, 2006), is managed through control of upstream reservoir releases and out-of-basin water exports from the Delta.

Here, we characterize how Delta outflow has changed as a result of anthropogenic and natural drivers using observed flow and precipitation data across the watershed over a period spanning more than nine decades. This hydrologic period reflects extensive change throughout the watershed, particularly the construction of the State Water Project (SWP) and the Central Valley Project (CVP) with their network of dams, pump stations, and aqueducts for water storage and transport to other parts of the state, construction of other nonproject dams, expansion of irrigated agriculture, and growth in population (Figure 2). It is important to recognize that this hydrologic period does not extend sufficiently far back in time to measure change from pristine or natural baseline conditions. Alterations to the landscape had already occurred by the mid-to-late 19th century (Fox, Hutton, Howes, Draper, & Sears, 2015) and substantial irrigated areas in the watershed existed by the 1920s. This work generally relies on directly observed quantities, or simple calculations thereof, and thus foregoes examination of important water budget terms (e.g., evapotranspiration and groundwater flows) that require modelling approaches. However, building on the flow trend evaluation presented here, a companion paper (Hutton et al., 2017) adopts a modelling framework to attribute the causes of Delta outflow and salinity change in the estuary, recognizing the inter-relationship between outflow and salinity. The companion paper also builds on prior work that explored salinity trends in the San Francisco Bay-Delta estuary (Hutton, Rath, Chen, Ungs, & Roy, 2015). The analyses presented in this paper, as well as the companion paper, employ time steps of 1 month to 1 year and therefore do not consider extreme events such as floods.

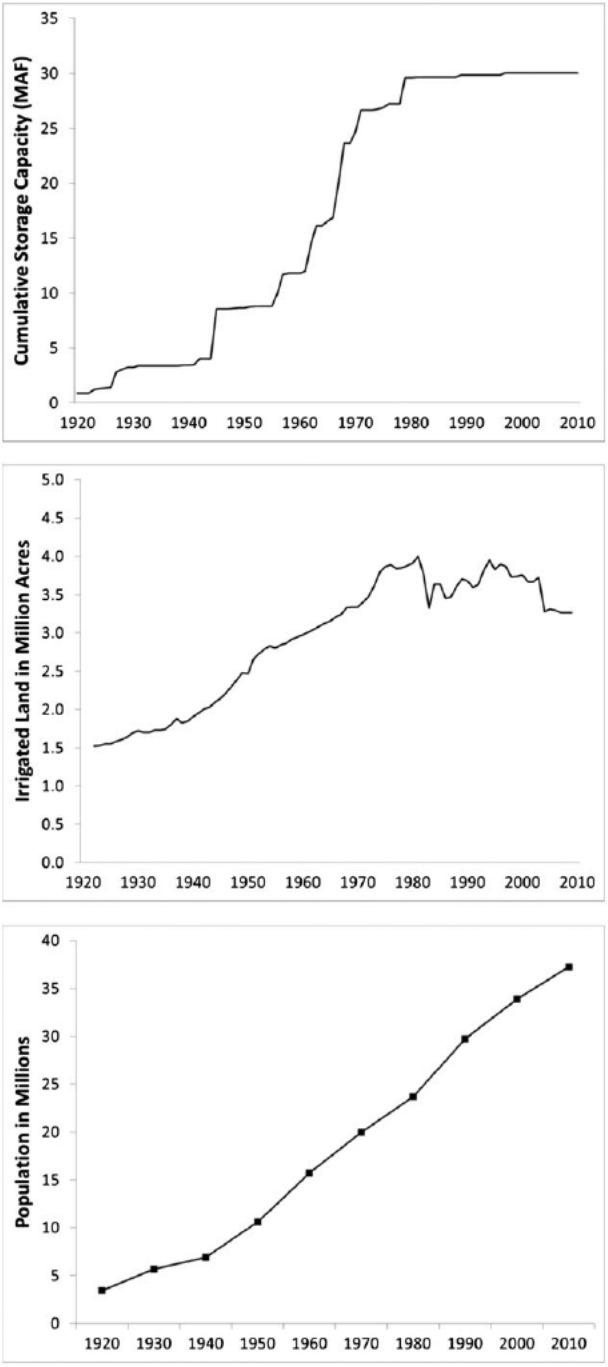

FIGURE 2 Growth in water development in the Bay-Delta watershed and commensurate California population growth over the nine-decade period spanning 1920 through 2010. (top panel) Change in cumulative reservoir storage in the Sacramento and San Joaquin River basins, (middle panel) change in irrigated area in the Bay-Delta watershed, and (bottom panel) population growth in the state of California. Sources: Storage and irrigated area compiled for California Central Valley Groundwater-Surface Water Simulation model (Brush et al., 2013); population data from California Department of Finance

2 | BACKGROUND

2.1 | Geographic setting

The watershed of the San Francisco Bay-Delta estuary, including the portion of California's Central Valley that is drained by the Sacramento and San Joaquin Rivers and the Delta formed by these rivers (Figure 1). is a vital part of California's water supply and its hydrology has been the focus of measurement and study for more than a century (California Department of Public Works, 1923; 1931; Hall, 1886). The watershed, with its Mediterranean climate, receives most of its precipitation over a 5-month period spanning November through March. Much of this precipitation occurs as snowfall in the Sierra Nevada mountain range on the eastern slope of the Central Valley. Runoff from this mountain range flows through the Central Valley to the Sacramento–San Joaquin River Delta (Delta), where it exits to the Pacific Ocean through San Francisco Bay. Stream flows and watershed precipitation are subject to large natural variability on which are overlaid multiple anthropogenic changes that have occurred through time, such as levee construction and channelization, storage reservoir construction, basin imports and exports of water, and land-use change (including irrigated agriculture). In the contemporary system, virtually all major stream flows are regulated through dams and are impacted 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 CVP and SWP support agricultural irrigation over more than three million acres and municipal supply for more than 20 million people (Delta Plan, 2013), providing a vital foundation for California's large and diverse economy, the eighth largest in the world (Luoma et al., 2015).

2.2 | Literature review

Long-term changes in hydrologic variables are of general interest in water resources management. Flow evaluations have been performed to understand climatic and anthropogenic drivers in North America (e.g., Bawden, Linton, Burn, & Prowse, 2014; Fox, Mongan, & Miller, 1990), Europe (e.g., Déry, Hernández-Henríquez, Owens, Parkes, & Petticrew, 2012; Hannaford, 2015; Hannaford, Buys, Stahl, & Tallaksen, 2013; Karlsson, Sonnenborg, Jensen, & Refsgaard, 2014; Lorenzo-

Lacruz, Vicente-Serrano, López-Moreno, Morán-Tejeda, & Zabalza, 2012), and Asia (e.g., Abghari, Tabari, & Talaee, 2013; Chen & Grasby, 2009; Chen et al., 2014; He, Miao, & Shi, 2013; Jiang, Su, & Hartmann, 2007; Sharif, Archer, Fowler, & Forsythe, 2013). The Mann–Kendall (MK) test (Kendall, 1938; Mann, 1945), a common non-parametric statistical procedure to test the presence of monotonic trends, has been used extensively in hydrology trend studies (including the studies cited above) and is the primary tool employed in this analysis.

Historical flow trends in the San Francisco Bay-Delta estuary and watershed have been explored by several researchers. Fox et al. (1990) found that annual Delta outflows over the period spanning water years (WYs) 1922–1986 did not show a decline despite the increase in Delta exports during the latter half of their study period. The California WY runs from October 1 of the preceding calendar year through September 30 of the current calendar year. They attributed this finding to a variety of factors, including increasing rainfall in the upper watershed, changes in land use, water imports from other basins, and redistribution of groundwater. They observed changes on a seasonal basis with downward trends in April and May and upward trends from July to November.

Knowles (2002) evaluated the effect of management and natural changes on variability in Delta outflows using a modelling approach and observed data from WYs 1967–1987. Although he identified a reservoir effect that altered flows on a seasonal pattern (increased flows in July through October and decreased flows in January through June) as well as a Delta withdrawal effect that decreased flows at roughly the same level over all months, he concluded that natural inter-annual hydrologic variability greatly exceeds the range of management effects on salinity in the estuary.

Enright and Culberson (2009) explored changes in Delta outflow over the period WYs 1930–2006. They found, in a manner similar to Knowles (2002), that the effect of natural variability was much greater than that of water project operations. They also found a seasonal pattern in flows similar to Fox et al. (1990), with downward trends in February through June and upward trends in July through September. Enright and Culberson (2009) explored flow patterns using nonmonotonic techniques and related these to large-scale oceanic oscillations in temperature (Pacific Decadal Oscillation). Although a simple correlation between flow and Pacific Decadal Oscillation was not found, they observed some correspondence between these two variables on a decadal scale.

Dettinger and Cayan (2003) explored changes in unimpaired flows over the period WYs 1906–1992 from the eight major Sierra Nevada rivers. The sum of these unimpaired flows, termed the *Eight River Index*, is a calculated quantity obtained by synthetically removing the effects of reservoir storage and diversions from observed stream flows. This flow index does not represent observed conditions but is widely used to classify seasonal and annual water supply conditions. As discussed in the following Section 3, we use a subset of the Eight River Index (i.e., the Four River Index) to characterize climatic conditions in the Sacramento Basin. Dettinger and Cayan (2003) noted changes in the hydrograph characteristics of each river and its individual contributions to Delta outflow. Although they found that about two thirds of the flow variability was shared among the different river basins, the remaining variability contributed differently to flows in different seasons. Because their work did not use actual flows for analysis, time trends were not reported.

Cloern and Jassby (2012) evaluated trends in Delta inflows, outflows, and exports over WYs 1956–2010. Over this truncated study period, they found significant increases in Delta inflow in July and August (indicative of reservoir releases) and significant decreases in Delta outflow from September through December. In the remaining months, no significant trends in Delta outflows were detected. Lack of significant outflow trends in winter and spring months was attributed to the large underlying flows; lack of significant outflow trends in July and August was attributed to exports being compensated by reservoir releases.

In this work, we use the most recent data available (through WY 2015) and expand the geographic scope of previously published analyses summarized above by incorporating Delta outflow as well as all major contributing flows from upstream locations. Our research objective is to understand the change in Delta outflow and to explain the causes of change based on observed hydrologic quantities (primarily flows and precipitation). Of necessity, these observation-based explanations are qualitative because of the complex interaction of multiple drivers of change over time. This approach has the benefit of relying upon direct measurements rather than modelled quantities (with embedded assumptions on the underlying processes) and provides an independent explanation of the causes of flow change. Model-based approaches are also beneficial, particularly given their flexibility to control key drivers such as development or climate, and in a companion paper, we examine changes in Delta outflow using alternative modelled flow scenarios (Hutton et al., 2017).

3 | METHODS

A simplified schematic representation of the major San Francisco Bay-Delta watershed flows is shown in Figure 3 to provide conceptual clarity to the flow trend evaluation methodology. As stated previously, the goal of this paper is to characterize how Delta outflow has changed over time. To more fully understand these changes, we also consider the primary hydrologic components that constitute Delta outflow. These components include major inflows to the Delta from the Sacramento Basin (Sacramento Basin inflow) as well as smaller inflows from the San Joaquin Basin and east side tributaries (other Delta inflow). Within the Delta, the net flow from precipitation and local agricultural water use is referred to as “Delta net channel depletions” and diversions by the CVP, SWP, and a local urban water district (Contra Costa Water District) are collectively referred to as “Delta Exports”. Inflow to the Sacramento Basin is aggregated into three groups: “Four River inflow” representing inflow from the Feather, Yuba, American, and Sacramento Rivers; “Minor Rim inflow” representing inflow from other smaller tributaries; and “Trinity imports” representing imports to the Sacramento Basin from the Trinity River. The net of remaining Sacramento Basin diversions, return flows, and runoff is referred to as “Sacramento Basin net channel depletions.” Volumes representing positive contributions to river flow are positive, whereas volumes representing withdrawals (exports and channel depletions) have negative sign (i.e., “increasing exports” refers to values that are becoming more negative). To maintain focus on drivers of Delta outflow change, flow trends of individual rivers were not examined. In the remainder of this section, we describe the data used for the flow

FIGURE 3 Schematic representation of Bay-Delta watershed flows. The Sacramento Basin is the primary source of freshwater to the estuary. Inflows to the Delta from this basin are the result of rim inflows in the Sacramento River watershed, out-of-basin imports from the Trinity River, and net channel depletions from the basin. The San Joaquin Basin and other east side tributaries are a secondary source of freshwater and are not differentiated further in this study. Water use within the Delta includes net channel depletions (gross depletions by local agriculture minus precipitation) and out-of-basin exports. The remaining Delta outflow is transported through San Francisco Bay into the Pacific Ocean

trends evaluation, the statistical methodology deployed to evaluate trends in time, and the time intervals examined for trends. Codes used for statistical analysis are provided as part of the Supporting Information.

3.1 | Data

The observed data used for this analysis, drawn from California state and federal data sources, include raw data as well as secondary sources where raw data has been compiled and cleaned for related studies. The period of record spans nine decades between WYs 1922 through 2015. Data used for this analysis are provided electronically as part of Supporting Information.

The California Department of Water Resources (CDWR) maintains a digital, publicly accessible database through its California Data Exchange Center (http://cdec.water.ca.gov); this database was our source of raw data on hydrologic variables, including many of the key flows. A network of Bay-Delta watershed stream gauges maintained by the U.S. Geological Survey was an additional source of useful information (http://waterdata.usgs.gov/ca/nwis/nwis) for this analysis. All Delta flow components were obtained from CDWR's DAYFLOW programme (http://www.water.ca.gov/dayflow/). Because of the complexity of direct observation of freshwater outflows, particularly during low-flow conditions (Monismith, 2016), the Delta outflow reported in DAYFLOW is not based on tidal flow measurements; rather, it is estimated from a budget of inflows and diversions from the Delta. We also draw upon some flow data used as historical boundary conditions for the California Central Valley Groundwater-Surface Water Simulation Model (Brush, Dogrul, & Kadir, 2013; Dogrul, Kadir, Brush, & Chung, 2016). The California Central Valley Groundwater-Surface Water Simulation Model boundary inflow data come primarily from data collected and published by the U.S. Geological Survey. Although in-Delta agricultural water use is an important fraction of total water use in the Delta (Figure 4) particularly in dry years, Delta net channel depletions are not routinely measured and are therefore highly uncertain. We used an alternate estimate of Delta net channel depletions developed by CDWR (CDWR, 1995) and developed a second Delta outflow time series to explore how uncertainty associated with this ungauged flow component impacted our trend analysis. Statistical findings of significance on Delta outflow trends were reported when the same result was obtained for both the DAYFLOW time series and the alternate time series; trend significance was considered ambiguous if significance was found only for one of the two outflow time series.

Table 1 presents a summary of the data used in this work, including the data sources, and partitions these data into three categories: "Delta flow components," "Sacramento Basin inflow components," and "Climate components." Delta Flow is comprised of the following elements as previously described: Sacramento Basin inflow, other

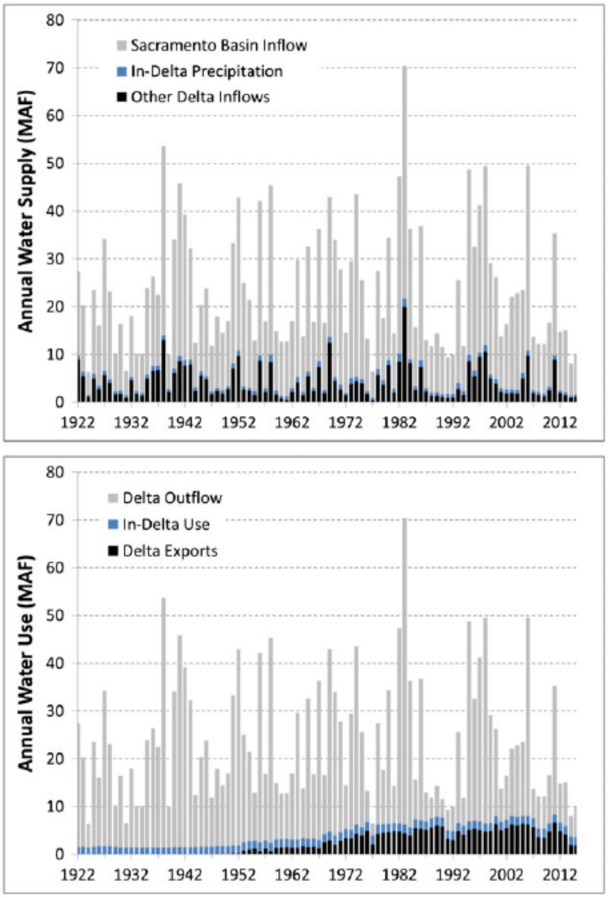

FIGURE 4 Time series of Delta annual water supply (top panel) and water use (bottom panel). The water supply and use components are as shown schematically in Figure 3. Delta outflow is the difference between total water supply and the sum of in-Delta use and Delta exports

TABLE 1 Data categories and associated sources used for the flow trend evaluation. All data are monthly averages over the period WYs 1922–2015

Variable	Data source	Comments
Delta flow components		
Delta outflow	DAYFLOW	
Sacramento Basin inflow	DAYFLOW	Sum of Freeport and Yolo Bypass flows
Other Delta inflow	DAYFLOW	Sum of San Joaquin River and other smaller tributary flows
Delta net channel depletions	DAYFLOW	Difference of gross channel depletions and in-Delta precipitation
Delta exports	DAYFLOW	Sum of CVP, SWP, and Contra Costa Water District diversions
Sacramento Basin inflow components		
Four River inflow	USGS/CDEC	Sum of Feather, American, Yuba, and Sacramento river flows
Minor Rim inflows[1]	USGS/CDEC	Sum of 16 smaller stream flows as compiled for C2VSim historical simulation
Trinity imports	USGS	Out-of-basin imports into the Sacramento River watershed
Sacramento Basin net channel depletions	Calculated	Four River inflow + Minor Rim inflows + Trinity imports − Sacramento Basin inflow
Climate components		
Four River Index	CDEC	Sum of unimpaired flows of the Feather, American, Yuba, and Sacramento rivers
Eight River Index	CDEC	Sum of the Four River Index and the unimpaired flows of the Stanislaus, Tuolumne, Merced, and San Joaquin rivers
Sacramento Basin precipitation (valley floor)	PRISM[2]	Valley floor average precipitation volume from gridded values; runoff inputs from the upper elevation portion of the watershed are represented through the Four River Index above.

Note. C2VSim California Central Valley Groundwater-Surface Water Simulation Model; CDEC California Data Exchange Center; CVP Central Valley Project; SWP State Water Project; USGS U.S. Geological Survey; WY, water year.

[1] Minor Rim inflow data were available for water years 1922 2009. Data were extended for 6 years to 2015 using monthly correlations between Minor Rim inflows and Four River inflows.

[2] Obtained from the PRISM website, see http://www.prism.oregonstate.edu/documents/PRISM datasets.pdf for documentation. Interpolated data as downloaded were from the AN81 calculation method at 800-m spatial resolution. For this work, these values were averaged over the valley floor area.

Delta inflow, Delta net channel depletions, and Delta exports. Sacramento Basin inflow is comprised of four elements: Four River inflow, Minor Rim inflows, Trinity imports, and Sacramento Basin net channel depletions. Finally, Climate is comprised of the Four River and Eight River indices as well as Sacramento Basin precipitation (volume of precipitation falling on the valley floor). The Eight River Index, as previously defined, represents the unimpaired inflow to the valley floor from the eight major Sierra Nevada rivers. The Four River Index, a subset of the Eight River Index, represents the unimpaired inflow from the four largest rivers in the Sacramento Basin—the Sacramento, Feather, Yuba, and American rivers. The Eight and Four River indices are distinct from the inflow components, as they represent theoretical quantities that remove (i.e., unimpair) anthropogenic influences such as reservoir impoundments and land use modifications and thus do not reflect actual runoff conditions. These three flow components are characteristic of the climatic conditions associated with the nine-decade period of record.

3.2 | Statistical analysis

A pair of tests used extensively to detect hydrologic trends was applied in this work: Sen's non-parametric estimate of slope and the MK test. The Sen slope is the median of all slopes between all possible unique pairs of individual data points in the time period being analysed. If there are n time points, then there are a total of $n(n - 1)/2$ possible pairs of time points one could use to calculate a slope, and Sen's slope is the median of these values (Sen, 1968). The method is robust and fairly insensitive to the presence of a small fraction of outliers, nondetect, or extreme data values. Thus, trend estimates based on Sen slope are not biased by the occurrence of drought in the early part and latter part of the flow record. The MK test (Kendall, 1938; Mann, 1945) is a common non-parametric statistical procedure to determine significance of trend. The rank-based, non-parametric MK test is useful for this purpose because stream flow data are likely to exhibit non-Gaussian residuals, contrary to what is assumed in many classical regression models.

We analysed the annual flow time series (WY total) and each monthly subseries (e.g., the January subseries is all the January observations) with the MK test at the 5% significance level. For the analysis of annual flow trends, we summed monthly flows by WY before computing the trend using the standard MK test. This approach allowed for a consistent methodology across monthly and annual data sets. The “two-sided” MK test was used in this analysis and examines if data show a trend that is either increasing or decreasing over time. Absent prior knowledge of the direction of the change anticipated (either an increase or a decrease), the two-sided test is appropriate.

For a limited number of flow terms, the seasonal trend decomposition test based on loess (STL) (Cleveland, Cleveland, McRae, & Terpenning, 1990) was applied. The STL is a filtering procedure for decomposing a time series into trend, seasonal, and remainder components. This approach has been used previously in hydrologic studies (Enright & Culberson, 2009; Gudmundsson, Tallaksen, Stahl, & Fleig, 2011; Shamsudduha, Chandler, Taylor, & Ahmed, 2009) to identify the presence of an underlying change that is detectable once the seasonal component is removed. This method is considered a diagnostic test for our present purpose in that, while the resulting "trend" is representative of an underlying change, the resulting "trend" is not necessarily statistically significant as determined through the MK test described above. The STL approach has some advantages over the MK test. The MK test is limited to detecting monotonic trends, yet changes in flow often exhibit a more complicated pattern. Indeed, flow variables often exhibit natural variability on long timescales, described as low frequency variability or long-term memory (Gudmundsson et al., 2011; Koutsoyiannis, 2003), which are expressed as a nonmonotonic behaviour; that is, over a long period of record flow may increase as well as decrease. The decomposition of a time series is helpful for identifying the presence of this nonmonotonic behaviour and understanding whether the application of a monotonic test such as MK test is fully appropriate. However, STL is not a hypothesis test and is meant to describe and characterize seasonal and long-term trend components rather than provide statistically significant trend results.

3.3 | Time periods examined

Trend analyses were performed over the entire period of record (WYs 1922–2015) and over two sub-intervals: WYs 1922–1967 and 1968–2015. These intervals were defined to coincide with Enright and Culberson's (2009) "pre" and "post" water project periods, corresponding to the completion of the CVP and the SWP by the late 1960s. These intervals segregate the record into two periods of near-equal duration: the earlier period representing a time of rapid watershed change and the later period representing a time of more limited change. As illustrated in Figure 2, the earlier period (WYs 1922–1967) should not be considered "natural" or "predevelopment" because significant hydrologic alteration took place over this period to support agricultural development and population growth. Furthermore, the later period (WYs 1968–2015) should not be considered to be uniform in terms of watershed conditions, as land and water use continued to change, albeit at a slower pace than in the preceding period. This more recent period is also characterized by regulated water operations to meet outflow and salinity standards in the estuary. These outflow and salinity regulations have also undergone change over this period (CSWRCB, 1978; CSWRCB, 2000; CSWRCB, 2006).

4 | RESULTS

The annual water supply to the Delta over WYs 1922–2015 shows large year-to-year variation, ranging from 6 MAF in a critically dry year such as 1924 to more than 50 MAF in wet years such as 1938 and 1983 (Figure 4). Over the study period, there is an increase in Delta exports prior to 1980, with smaller inter-annual variations thereafter. This is consistent with the construction and full implementation of the water projects noted above. Water use within the Delta is relatively uniform in magnitude over the entire period but larger as a percentage during years with low water supply.

Trends were examined on a monthly and annual basis for the hydrologic components shown in Table 1; results were reported as a significant or non-significant outcome and as a magnitude of the Sen slope. In the narrative summary of results that follows, we use the term *nominal trend* to refer to the Sen slope for cases when the MK results do not confirm significance.

4.1 | Seasonal trends

When the flow components in Table 1 are examined on a monthly basis, significant trends are found in different months for virtually all terms, reflecting human-induced changes to the seasonal hydrology through reservoir storage and stream withdrawals. Significant outflow trends were found in 6 of the 12 months over the nine-decade record. Trends for these 6 months, and the underlying data, are depicted as time series in Figure 5 (adjacent months are grouped). As described previously in Section 3, Delta outflow trends are reported as statistically significant only when both time series (with different Delta net channel depletion assumptions) indicate significance. Although Figure 6 indicates nominally increasing and decreasing trends over the nine-decade record in September and October, respectively, these fall month trends are considered ambiguous as only one of the two Delta outflow time series indicates significance. Significant Delta outflow decreases observed in April and May over WYs 1922–2015 likely correspond to increases in upstream storage in reservoirs, as suggested by the significant decreases in Sacramento Basin inflow shown in Figure 6. Significant Delta outflow increases in July and August over WYs 1922–2015 are likely related to increased reservoir releases to meet export needs and salinity control objectives in the estuary, as suggested by the significant increases in Sacramento Basin inflow shown in Figure 6. Significant Delta outflow decreases observed in February and November over the nine-decade record are not well explained by upstream reservoir storage operations and may relate to increases in Delta exports.

Figure 6 shows monthly trends in all major Delta flow components in addition to Delta outflow. Delta net channel depletion trends are not reported given the inherent uncertainty in these ungauged flow estimates. Over the full period of record, the monthly changes in Delta outflow shown in Figure 5 generally track changes in Sacramento Basin inflow, with other Delta inflow playing a smaller role. Delta exports mute the positive influence of reservoir releases on Delta outflow trends in July and August; similarly, Delta exports amplify the negative influence of reservoir storage on Delta outflow trends in April and May. Sacramento Basin inflow trends are characterized by significant increases in July through November during WYs 1922–1967 (with no significant changes in the remaining months). Nearly all monthly Sacramento Basin inflow trends are downward during WYs 1968–2015, with significant decreases in October and November (thus reversing the trends of the earlier sub-interval).

Examination of the Sacramento Basin inflow components (Figure 7) also helps explain some, but not all, of the seasonal trends that are present in the Delta outflow and Sacramento Basin inflow time series. Over the full period of record as well as the two sub-intervals, trends in Four River inflow and Sacramento Basin net channel depletions are the main drivers of monthly trends, with the Minor Rim inflows and Trinity imports playing a smaller role. Four River inflows increase during June through November, largely corresponding to periods with reservoir releases. Trends in the Four River Reservoir effect, defined as the Four River inflow minus Four River Index are also

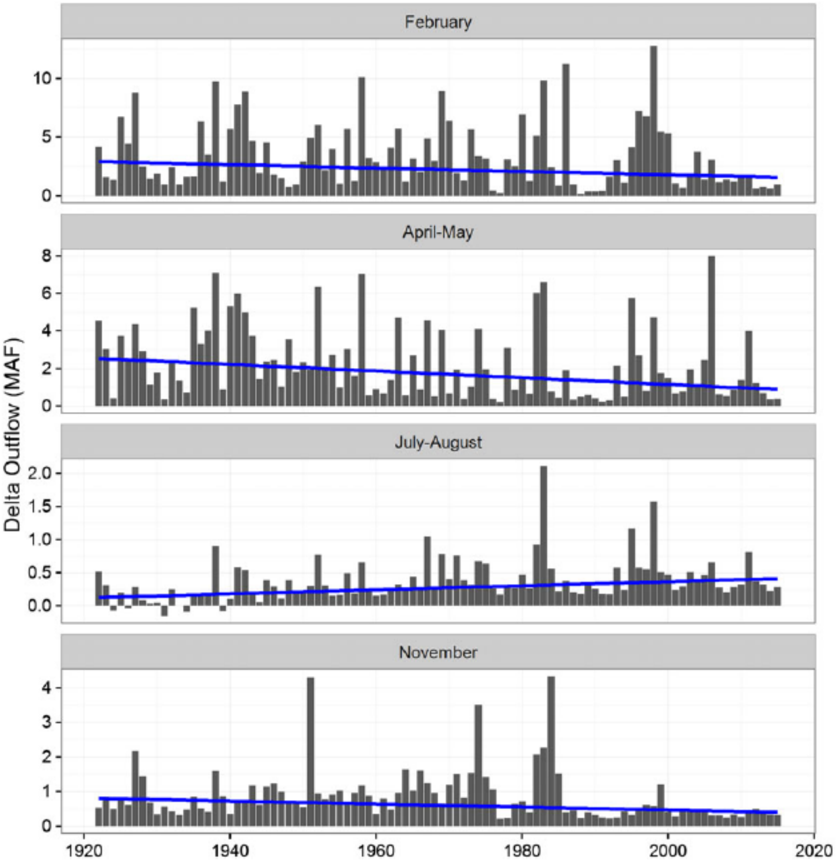

FIGURE 5 Time series trends in Delta outflow for months with statistically significant change over WYs 1922–2015. Sen's slope estimate is shown as a blue line. Months not shown fail to exhibit statistically significant change at the $p < .05$ level

shown. Trends are larger over WYs 1922–1967, reflecting a period of expanding reservoir storage and indeed suggest that decreasing trends over WYs 1968–2015 may be related to more stable operations as well as some non-significant decreases in precipitation runoff, as shown through the annual Four River Index trends discussed below (Figure 8). Net channel depletion volumes in the Sacramento Basin, tied to irrigation water use, show a significant increase (values more negative) in May through November over the full WYs 1922–2015 period. The irrigation-related trends are larger over WYs 1922–1967 because of the more rapid expansion of agricultural area during this period (Figure 2). There are fewer significant trends in depletions over WYs 1968–2015, especially during the irrigation season, corresponding to more stable irrigated acreage in the Sacramento Valley.

Our work also investigated seasonal flow changes as a consequence of 20th century climate change (not shown). Previous work, using temperature and precipitation data over the past decades, have shown positive trends in temperature and reduced snow water equivalent in the Sierra watersheds, as well as more precipitation occurring as rain instead of snow (e.g., Barnett et al., 2008; Knowles, Dettinger, & Cayan, 2006; Mote, 2006). Using the Four River Index as a proxy for basin inflow in the absence of reservoirs, we found that cumulative arrival of runoff, or the fraction of total annual that has arrived by a certain month, appears to occur earlier in the wet season over time. Using the centre of timing of the Four River Index flow as a metric, that is, identifying the day at which 50% of the WY's flow has passed (following Hidalgo et al., 2009), we found that this occurred roughly 10 days earlier at the end of the record versus the beginning of the record. However, when the actual Four River inflow is used (reflecting the presence of reservoirs), no trend in the cumulative arrival of runoff during a WY was observed over the study period. In other words, the effect of historical climate change on basin runoff has been muted by the presence of reservoirs. Future climate change effects on runoff may be more extensive and visible in the observed data.

4.2 | Annual trends

In contrast to the results for specific months above, on an annual basis, the MK test did not detect a statistically significant trend in Delta outflow. The Sen slope was nominally positive for WYs 1922–1967 and nominally negative for WYs 1968–2015 and for the full nine-decade period (Figure 8). Of the remaining Delta flow components, exports show a significant positive trend for all three periods, whereas Sacramento Basin and other inflows do not show significant changes. The Delta inflow components show minimal changes over the full period of record, although the two sub-intervals are contrasted by a nominal increasing trend over the earlier period and a nominal decreasing trend over the later period. These changes in Delta inflow are in turn related to inflows to the Sacramento Basin. Over the full period, there is minimal change in the Sacramento Basin inflow components; however, over the two sub-intervals, there are nominal increases over WYs 1922–1967 and nominal decreases over WYs 1968–2015 (with both trends being significant for the Four River inflow). The climate components behave in a manner similar to the inflow components, although none of the changes are statistically significant: changes over the full period are minimal, and nominal increases and decreases are observed over the earlier and later periods, respectively. Sacramento Basin net channel depletions, which represent net water use within the basin, show a decrease in volume (positive sign of trend) over

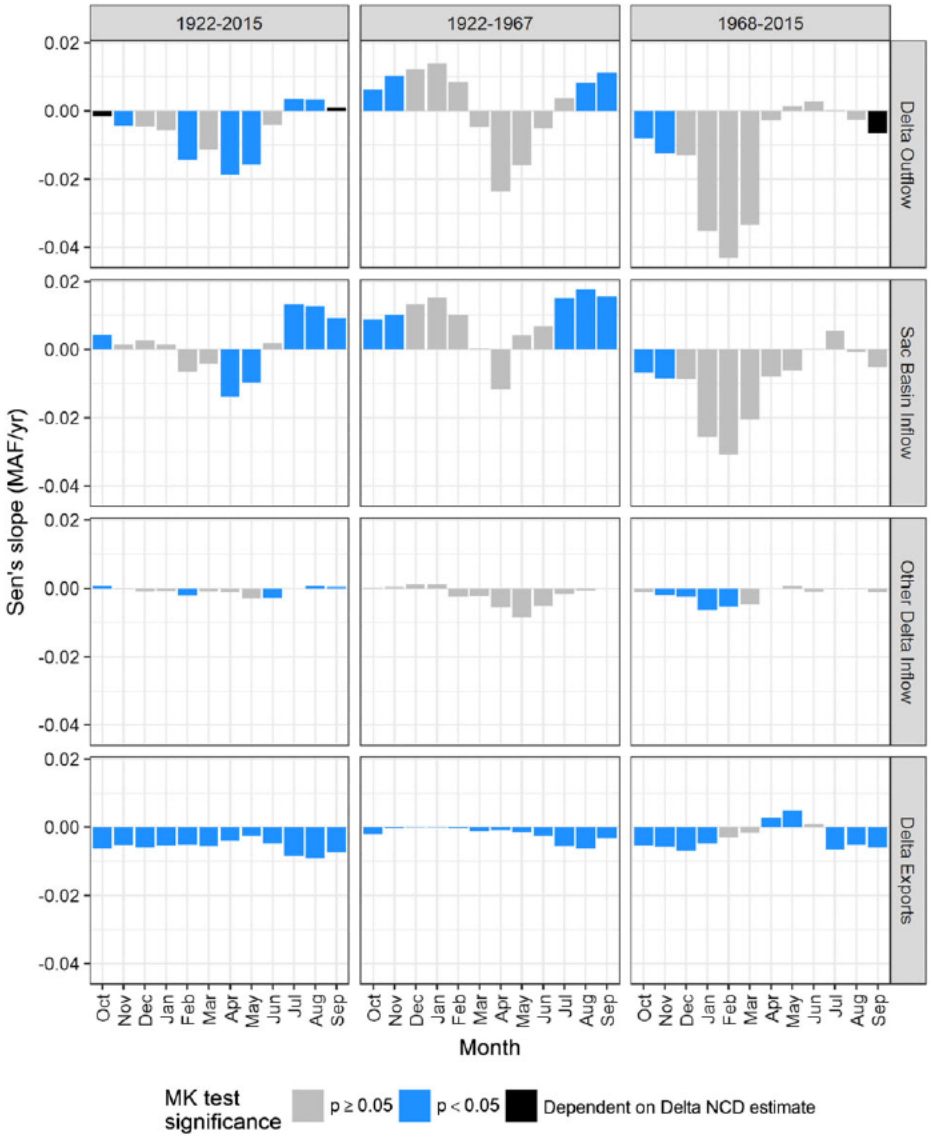

FIGURE 6 Mann–Kendall (MK) monthly trends and Sen slopes for Delta flow components. The Sen slope estimates in units of MAF/year are shown on the *y*-axis. A statistical significance at $p < .05$ level is shown by blue bars; grey bars indicate statistical significance at $p \geq .05$. Months where the result of the significance test (for Delta outflow) depends on the choice of net channel depletions estimate are shown in black. Results are shown for three time periods: the entire period of record (WYs 1922–2015); the earlier subperiod when many reservoirs were constructed (WYs 1922–1967); and the most recent subperiod following completion of water export infrastructure (WY 1968–2015). Increasing volumes of Delta exports are shown as negative trends

WYs 1968–2015 and an increase in volume over WYs 1922–1967 and the nine-decade record, the latter being statistically significant. Trinity imports, which began in 1964, are a small contributor to the overall water budget but are characterized by statistically significant trends over the nine-decade record (increasing) and over WYs 1968–2015 (decreasing).

The absence of a statistically significant trend in annual Delta outflow over WYs 1922–2015 is counterintuitive given the significant growth in exports over this period (Figure 8). This finding may be explained in part by the large inter-annual hydrologic variability that masks underlying changes, as well as the changing sign of the slope in the climate and inflow terms over the two sub-intervals noted above. The Delta outflow STL analysis is supportive of these observations of variability and nonmonotonicity. Figure 9 shows a decomposition of the Delta outflow time series using the STL approach. The decomposition reveals a small "trend" component term that is nonmonotonic, with an increasing trend through the mid-1960s followed by a gradual decline, and a relatively large "remainder" component that cannot be explained by the seasonal signal or the trend. A similar nonmonotonic pattern is observed for the Sacramento Basin inflow to the Delta as well (results not shown). These observations provide some insight into why the MK trend line for annual Delta outflow, although nominally negative, does not report a statistically significant downward trend. We note that, although our selection of a 5% significance level is in line with standard scientific practice (Craparo, 2007), an additional test at the 10% level was conducted and revealed a significant downward trend in the nine-decade annual Delta outflow time series at this weaker level.

Trends explicitly accounting for year-to-year variability in Delta outflow, partly driven by climatic variability, were also evaluated by

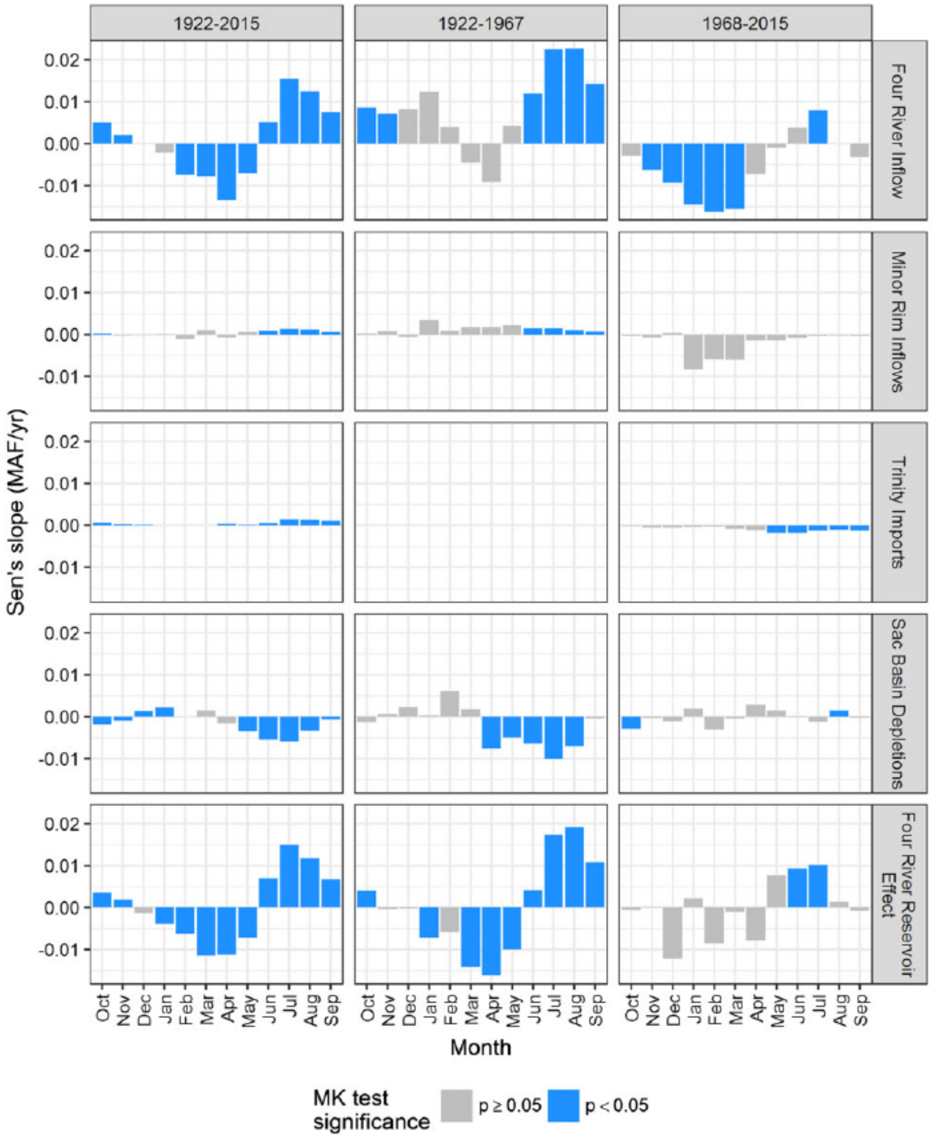

FIGURE 7 Mann–Kendall (MK) monthly trends and Sen slopes for Sacramento Basin inflow components and the Four River reservoir effect. The Sen slope estimates in units of MAF/year are shown on the *y*-axis. A statistical significance at $p < .05$ level is shown by blue bars; grey bars indicate statistical significance at $p \geq .05$. Results are shown for three time periods: the entire period of record (WYs 1922–2015); the earlier subperiod when many reservoirs were constructed (WYs 1922–1967); and the most recent subperiod following completion of water export infrastructure (WY 1968–2015). Increasing volumes of Sac Basin depletions are shown as negative trends

normalizing flow terms with the annual Eight River Index, a measure of water availability in the system. The MK test detected a statistically significant downward trend for normalized Delta outflow over WYs 1922–2015. Figure 10 shows Delta outflow (upper panel), exports (middle panel), and Sacramento Basin net channel depletions normalized by the Eight River Index and divided into two subsets: wetter years with the index above 20 MAF and drier years with the index at or below 20 MAF. Lines are drawn through these points using a locally weighted scatterplot smoothing function and are provided in Figure 10 to aid interpretation of the normalized data points. With this aid, it can be seen that normalized Delta outflow is smaller in drier years and is characterized by a decreasing trend for both subsets. The declining trend in drier years appears to have stopped or even reversed in the 1980s. This can be explained in part by normalized export trends, which are typically larger and therefore more consequential in drier years. Between the 1950s and the 1980s, normalized exports increased for both data subsets. However, following this period and reflecting regulations for managing flows and salinity in the San Francisco Bay-Delta estuary (California State Water Resources Control Board, 1978, 2006), normalized exports have decreased in drier years, whereas they have continued to increase in wetter years. The declining Delta outflow trend in drier years can also be explained by normalized Sacramento Basin net channel depletions, which display a modest increase over the early period followed by a flat trend over recent decades reflecting a similar trend in irrigated land use (Figure 2).

5 | DISCUSSION

This paper examined a robust hydrologic record spanning nine decades to evaluate annual and seasonal trends in freshwater flow to the San Francisco Bay-Delta estuary. This freshwater flow, that is, Delta

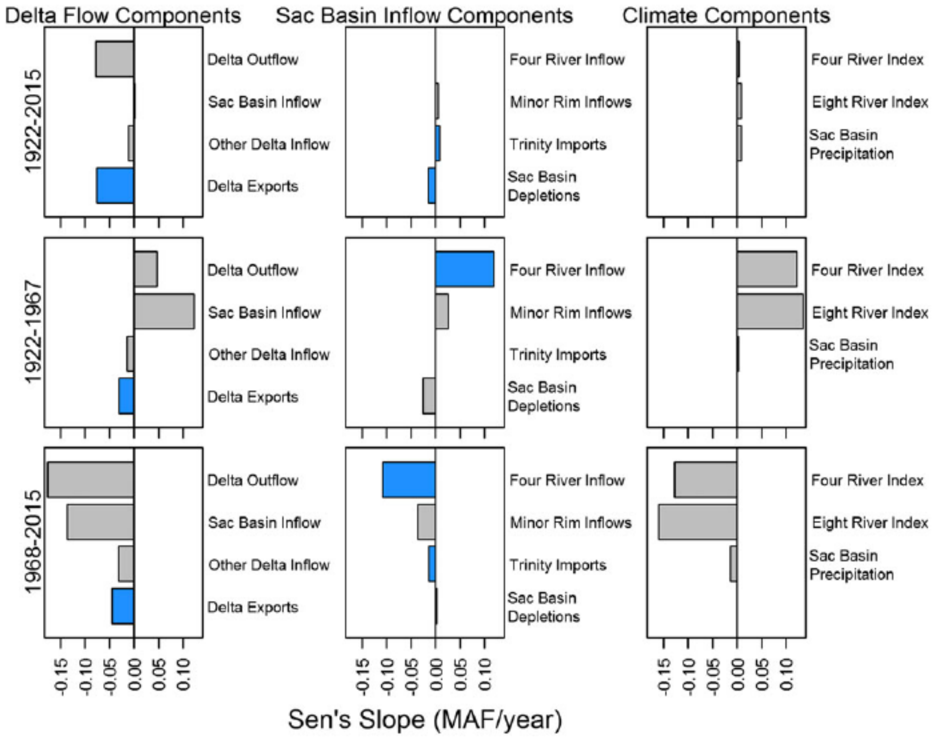

FIGURE 8 Summary of annual Mann–Kendall trend and Sen slope results for the flow components identified in Figure 3 and Table 1. The Sen slope estimates in units of MAF/year are shown on the *x*-axis. A statistical significance at $p < .05$ level is shown by blue bars; grey bars indicate statistical significance at $p \geq .05$. Results are shown for three time periods: the entire period of record (WYs 1922–2015); the earlier subperiod when many reservoirs were constructed (WYs 1922–1967); and the most recent subperiod following completion of water export infrastructure (WY 1968–2015). Increasing volumes of Delta exports and Sac Basin depletions are shown as negative trends

outflow, is a metric of considerable importance for the region's water quality and ecosystem. Understanding how it has changed over time will inform ongoing deliberations on management of the estuary and its watershed. Natural inter-annual variability is a dominant feature of the system's hydrology; therefore, trend evaluation was performed using statistical methods to parse out true significant changes in Delta outflow and its related component flows on annual and monthly timescales. Relying primarily on the MK test, trend evaluation was performed over the entire hydrologic period of record as well as over two sub-intervals. The period studied, bounded by severe drought conditions in the 1920s and 1930s and the recent drought of WYs 2012–2015 (Cheng et al., 2016), represents a time when the population of California increased from roughly five million to nearly 39 million.

The trend evaluation revealed statistically significant changes to Delta outflow in 6 of 12 months, with decreases observed in 4 months (February, April, May, and November) and increases observed in 2 months (July and August). These findings are consistent with other research (Enright & Culberson, 2009; Fox et al., 1990) and mirror estuarine salinity trends reported elsewhere (Hutton et al., 2015) in terms of X2 position as derived from observed surface salinity data. X2, defined as the position of the two parts per thousand near-bottom isohaline as measured from Golden Gate Bridge, increases with decreasing flows and is used for outflow management in the San Francisco Bay-Delta estuary (California State Water Resources Control Board, 2006; Jassby et al., 1995). Consistent with the Delta outflow trends reported in this paper, Hutton et al. (2015) reported statistically significant decreasing X2 trends in August and September, statistically significant increasing trends in April and May, and no statistically significant change on an annual average basis. Trends in X2 position over the two sub-intervals (WYs 1922–1967 and WYs 1968–2012), as reported by Hutton et al. (2015), are also consistent with the Delta outflow sub-interval trends reported in our work. The correspondence between trends in Delta outflow and estuarine salinity is especially important because these were derived from entirely independent data sets.

On an annual time scale, a somewhat complex picture emerges from our analysis of Delta outflow changes since the early 1920s. Annual water supply available to the system, as measured by unimpaired runoff from the Sierra Nevada mountain range (i.e., Eight River Index) and precipitation in the valley floor of the Sacramento Basin, is characterized by nominally increasing trends in the early part of the record (WYs 1922–1967) and nominally decreasing trends in the latter part of the record (WYs 1968–2015), with no statistically significant changes over the full nine decades. When this lack of climatic trend is contemplated in conjunction with anthropogenic changes such as greater water use within the watershed and the advent of facilities to export water from the estuary, it is reasonable to expect a statistically significant decreasing annual trend in Delta outflow over the nine-decade period. However, a statistically significant trend was not revealed by the MK test for the annual Delta outflow record. Fox et al. (1990) studied a subset of this time series (through WY 1986) and reported similar results. They attributed their finding to a variety of factors, including changes in land use, imports from other basins, and redistribution of groundwater. An STL provided a counterpoint to the MK test results by identifying a slight nonmonotonic Delta outflow pattern consistent with the climatic time series, which may

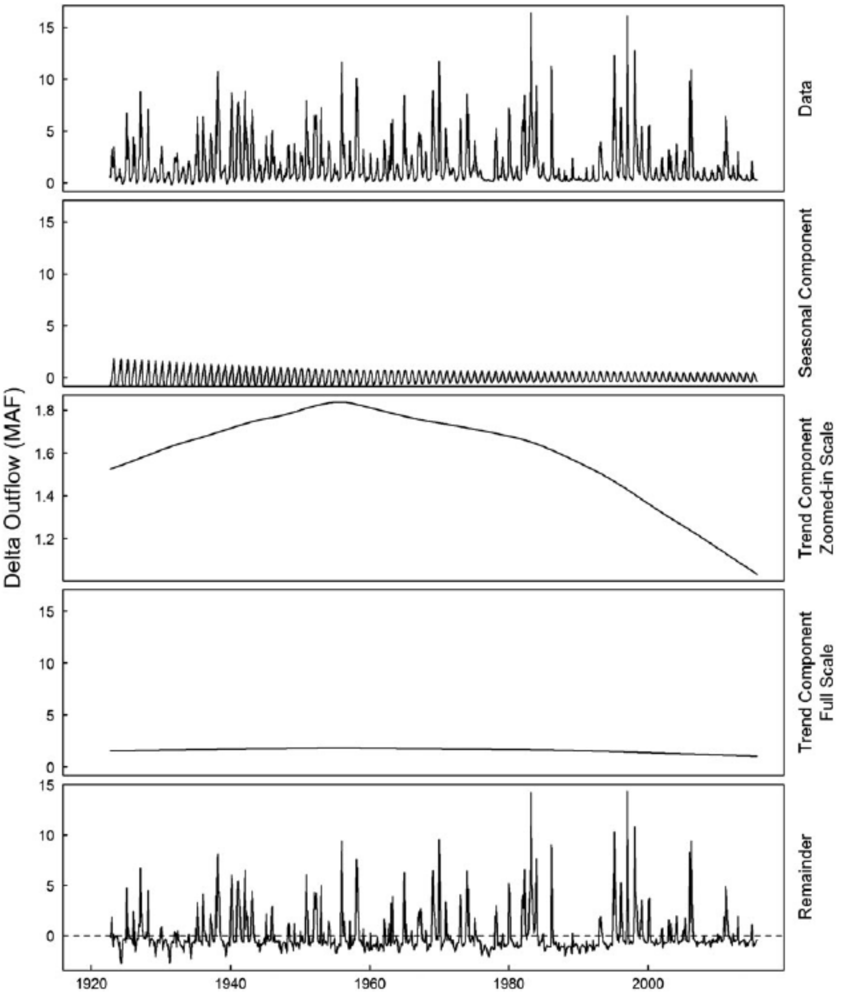

FIGURE 9 Seasonal trend decomposition test based on loess results for Delta outflow in units of MAF. The top panel shows the time series of outflow, and the remaining panels show a decomposition of the flow into a seasonal component, a "trend" component, and a remainder term. The trend component, which is distinct from the Mann–Kendall trend test result, shows a slight increase in Delta outflow between WYs 1922 and 1960 and a slight decrease thereafter. The trend component is shown in two panels (with different y-axis scales) to emphasize both its change and its relative magnitude

partially explain the absence of a significant trend over the entire period of record and support the investigation of trends over two sub-intervals. A statistically significant downward trend was revealed when the annual Delta outflow time series was normalized to remove inter-annual variability; this trend appears to have been curbed (and possibly reversed) over the last few decades in drier years due to more restrictive water management in the estuary and stabilization of irrigated land use in the Sacramento Basin, though this conclusion is based on results that are not necessarily statistically significant. Finally, it is worth noting that data record length has a bearing on the statistical detection of trend (Wilby, 2006). The nine-decade annual Delta outflow record associated with the full period, while substantial, may nonetheless be inadequate to detect trends given high inter-annual variability.

The observed changes in Delta outflow are broadly associated with changes in other flow terms, most notably inflows to the Sacramento Basin, inflows to the Delta from the Sacramento Basin, and exports from the Delta. Attributing flow trends to drivers of change can be accomplished in qualitative terms, given an understanding of the underlying characteristics of the drivers. For example, it is well understood that reservoirs impound water during the high flow winter and spring months and release water during the low flow summer and fall months. As another example, it is well understood that the majority of agricultural water use is concentrated during the typical growing season of April through September. However, the hydrology of the estuary and watershed is sufficiently complex that we were unable to rely solely on trend evaluation of component flow terms to attribute Delta outflow changes to key drivers. We examine the question of change attribution in a companion manuscript through the creation of idealized flow scenarios (Hutton et al., 2017).

Climate change has been widely identified as a potential future stressor for California's water resources (CDWR, 2015). Statistically significant changes in observed climatic and hydrologic metrics have been identified, including weather, snow-water equivalent, and the ratio of snow to total precipitation (Barnett et al., 2008; Knowles et al., 2006; Mote, 2006). However, changes in runoff have been considered less often, particularly in regulated rivers. Our work found that, although changes in unimpaired runoff are detectable in the form of earlier arrival of flows, changes in actual observed flows are masked by reservoir operations. This general finding regarding timing changes of unimpaired flows is consistent with a related study of the San Francisco Bay-Delta watershed, which found increases in winter runoff under warmer temperatures and decreases in spring runoff (RMC, 2015). The absence of significant flow change downstream of reservoirs was linked to the relatively modest climate-related change that has occurred in the past century. Note that 21st century climate change was not part of this study and will be considered in future work. Future climate change, with larger projected deviations from

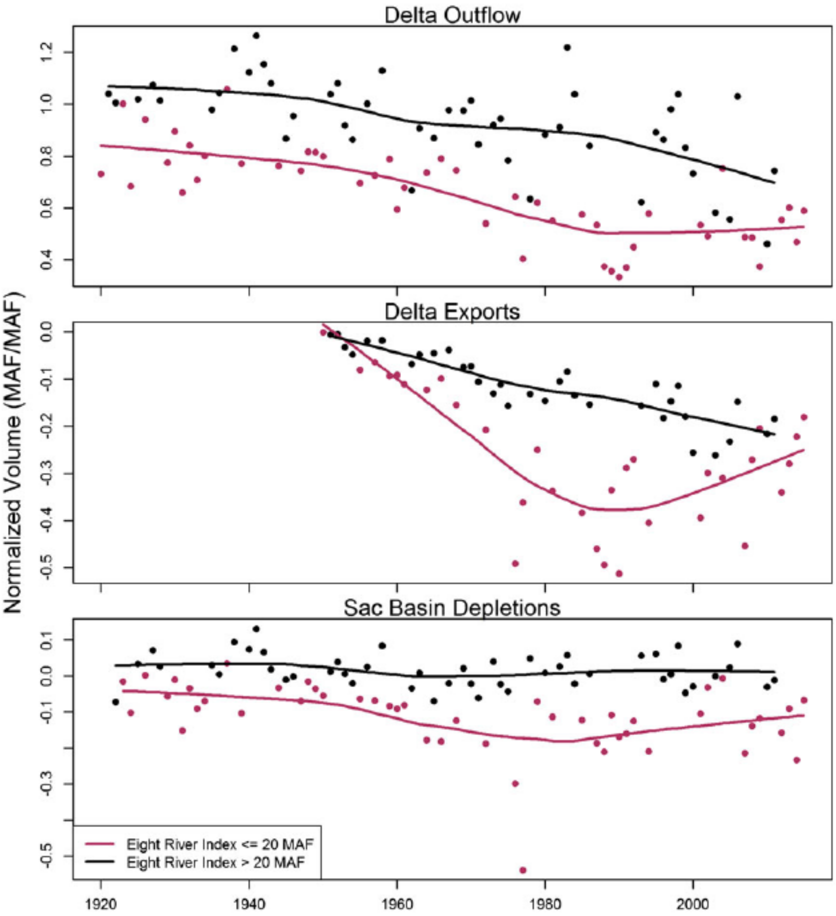

FIGURE 10 Annual time series of Delta outflow (upper panel), exports (middle panel), and Sacramento Basin net channel depletions (lower panel) normalized to the Eight River Index. The trend lines through the points are locally weighted scatterplot smoothing fits as described in the text. In drier years, the downward trend in normalized Delta outflow appears to have been curbed (and possibly reversed) over the last few decades due to more restrictive water management (i.e., lower normalized Delta exports) in the estuary and a leveling of water use in the upstream watershed (i.e., flat trend in Sacramento Basin net channel depletions). Increasing volumes of Delta exports and Sac Basin depletions are shown as negative trends

the historical hydrograph, may have greater consequences and require changes to operations to attempt to support the functions performed by the present-day system (CDWR, 2015).

Flows analysed in this work may also be compared to millennium-scale paleoclimatic flow reconstructions on the basis of tree ring data. Although specific conclusions differ on the basis of the particular tree ring time series examined, the range of observed 20th century flows in the Sacramento River basin generally spans a range similar to reconstructed flows over the past five centuries (Diaz & Wahl, 2015; Meko & Woodhouse, 2005) as well as the past millennium (Woodhouse, Meko, MacDonald, Stahle, & Cook, 2010; Griffin & Anchukaitis, 2014). A notable exception is the major drought occurring towards the end of the flow series (i.e., WYs 2012–2015). Diaz and Wahl (2015) noted the significance of the recent drought but estimated that similar droughts have occurred over the past 440 years. Griffin and Anchukaitis (2014), however, argue that this drought was among the most severe in the last 1,200 years. It is noteworthy that paleoclimatic analyses published to date have not considered WY 2015, which was also an extremely dry year.

The Delta outflow trend evaluation reported in this paper provides much-needed context for ongoing ecosystem management efforts in the San Francisco Bay-Delta estuary, particularly efforts that seek to relate freshwater flow and estuarine salinity to various ecological metrics, such as characterizing fishery habitat volume in the estuary's low salinity zone, or hypothesizing relationships between flow, salinity, and species abundance (Bever, MacWilliams, Herbold, Brown, & Feyrer, 2016; Feyrer et al., 2007; Jassby et al., 1995; Latour, 2016; Nobriga & Rosenfield, 2016). A key challenge associated with interpreting results from these and other ecosystem-oriented data analyses is the absence of biological data for the estuary prior to the 1960s. Thus, biological inferences are based on a truncated subset of the flow (and salinity) record which, as this work clearly shows, are not representative of the trends associated with the full period of observed data. Importantly, even the full hydrologic record is not indicative of pristine or natural conditions, because land use development prior to the 1920s had already led to well-documented alterations in flows and salinity (Department of Public Works, 1931).

Waterbodies throughout the world are impacted by hydrologic alterations as well as other ecosystem stressors. Presumably, in the majority of these waterbodies, meaningful hydrologic alterations predate the collection of data for defining an undisturbed baseline and corresponding restoration targets. In the United States, restoration efforts are guided by the Clean Water Act of 1972 to "restore and maintain the chemical, physical and biological integrity of the Nation's waters". This paper clearly highlights the challenge associated with defining a restoration baseline as implied by the Clean Water Act, even under circumstances where data exist over several decades. In the case of the San Francisco Bay-Delta estuary, defining restoration targets based on a truncated subset of the flow (and salinity) record—representative of the period when biological data were collected—is a classic form of the shifting baselines problem highlighted in Section 1 of this paper and described in the literature. Mathematical modelling offers a potentially useful approach to transparently address the problem of shifting baselines when defining restoration baselines and targets. Conceptually, such baseline modelling would evaluate fixed land and water use conditions overlaying an assumed set of climatic conditions. MWH (2016) reports the development of several fixed hydrologic baselines (in 20-year increments) for the San Francisco Bay-Delta watershed spanning more than a century. Similarly, Fox et al. (2015), and Andrews, Gross, and Hutton (n.d.) report hydrologic and hydrodynamic modelling efforts to characterize the estuary and watershed under predevelopment or natural conditions. Given the extent of alteration in the San Francisco Bay-Delta system and other waterbodies around the world, full restoration to natural conditions would rarely (if ever) be a realistic goal. However, we believe that explicit acknowledgment of alternative hydrologic baselines can aid in identifying indirect measures of ecosystem conditions—through paleolimnological conditions in soil cores (e.g., Goman & Wells, 2000; Ingram, Ingle, & Conrad, 1996; May, 1999) or through mechanism-oriented ecosystem modelling of components using these alternative flows (e.g., Drexler, de Fontaine, & Deverel, 2009; Nobriga & Feyrer, 2007)—that may be considered part of a more robust restoration framework.

Acronyms and key terms

CVP	Central Valley Project
DAYFLOW	programme used to summarize inflows, water exports, and outflow from the Delta
MK	Mann–Kendall (non-parametric trend test)
Net channel depletions	Term used to characterize water losses or gains in the Delta channels because of island exchanges, precipitation, and evaporation
SWP	State Water Project
WY	Water Year
X2	Position of the two parts per thousand isohaline in San Francisco Estuary

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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