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RESEARCH ARTICLE

Freshwater flow to the San Francisco Bay-Delta estuary over nine decades (Part 2): Change attribution

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Abstract

This paper explains observed trends in freshwater flow to the San Francisco Bay-Delta estuary as reported in a companion paper (Hutton, Rath, & Roy, 2017). We employ a historical hydrologic record spanning nine decades and define a set of idealized flow scenarios to identify drivers of change in delta outflow and consequent salinity regime. Flow changes are measured against a baseline scenario representing 1920-level land use and water management conditions. Additional scenarios are defined to represent the system absent state and federal water project reservoir and export operations, absent key non-project reservoir operations, and absent historically-observed sea level rise. These scenarios, in conjunction with the principle of superposition, are used to ascribe outflow and salinity trends to different anthropogenic and natural causes. We find that project and non-project water management are attributed similar responsibility for decreasing outflow trends in April and May and consequent increasing spring salinity trends. In contrast, we find that increasing July and August outflow trends (and lagged decreasing salinity trends) are attributed to flow contributions from project water management; these contributions more than fully attenuate impacts associated with non-project water management.

KEYWORDS

Delta outflow, Mann–Kendall, reservoir operations, trend attribution

1 | INTRODUCTION

The San Francisco Bay-Delta estuary (or "Delta") on the Pacific coast of California, United States and its contributing watershed have been subjected to extensive hydrologic alterations following European settlement in the mid-18th century (Hundley, 2001). These changes have included conversion of natural lands to irrigated agriculture, disposal of hydraulic mining debris into streams, channelization of streams, widespread loss of riparian and tidal wetland habitat, withdrawals of streamflows for irrigation and urban uses, and construction of reservoirs to store winter and spring flows for release in the summer and fall months and other low flow periods. Some of the earliest changes have adversely affected downstream communities in the watershed for well over a century; examples include increased flooding risk due to hydraulic mining waste disposal (Kelley, 1998) and salinity intrusion in the Delta affecting agricultural and urban users as a consequence of irrigation withdrawals further upstream (Department of Public Works, 1931).

By the mid-20th century, evolving societal values led to a growing awareness and concern for the adverse ecosystem effects that resulted from anthropogenic disturbances. In addition to the early hydrologic alterations described above, other evolving disturbances include out-of-basin exports, entry of invasive species and discharges and runoff of pollutants from a highly urbanized estuary margin. Restoration and environmental management efforts have been implemented in the region over the last four decades to address many of these stressors; however, hydrologic alteration (in general) and flow management (in particular) have been the stressor of primary focus. Freshwater flow (i.e., Delta outflow), which is essential for repelling salinity intrusion into the Delta and is critical to the ecosystem health of the estuary, is regulated to support both human uses and aquatic life (CSWRCB, 2006). Precipitation from the upstream watershed is partially regulated through reservoirs on the major rivers (Figure 1). Delta outflow, a quantity ignoring the effects of subdaily tidal flows, is estimated as the sum of watershed inflows minus exports and other in-Delta uses. Exports from the Delta are primarily transferred to other river basins in the southern part of the state and do not reenter the estuary. Therefore, freshwater flow to the estuary is subject to a significant degree of human control through exports and reservoir releases by the federal Central Valley Project (CVP) and the California State Water Project (SWP), especially during the drier summer–fall months and during drought conditions.

Because of the importance of freshwater flow in the overall water management and regulatory structure in the San Francisco Bay-Delta estuary, this work and a companion paper (Hutton et al., 2017) are focused on understanding how and why Delta outflow has changed over a nine-decade period during which streamflow data have been systematically collected in the contributing watershed. This analysis acknowledges that the starting point of the record (October 1921) is not representative of pristine or "natural" conditions, and that numerous landscape changes had already occurred by this date. The watershed continued to undergo significant hydrologic alteration following this date, the most important being the construction of major reservoirs (Figure 1) and export facilities and the further conversion of undisturbed lands to irrigated agriculture (Figure 2). In a companion paper (Hutton et al., 2017), we examine trends in the observed Delta outflow time series and the contributing flows from the watershed. In spite of increasing water use over the period

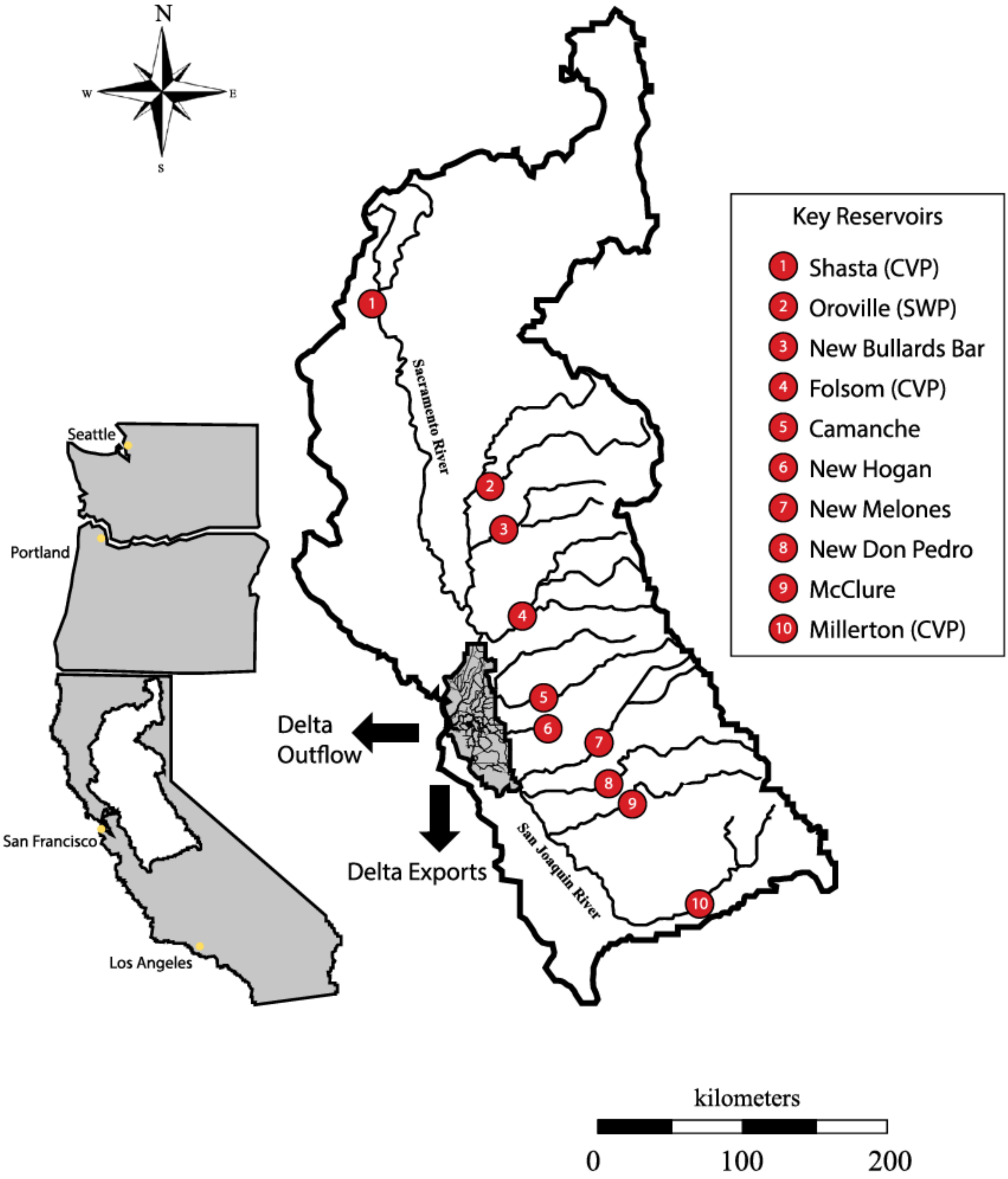

FIGURE 1 San Francisco Bay-Delta estuary and watershed showing the major rivers that flow through the California Central Valley, most of which are regulated through reservoirs. The 10 major reservoirs in the Sacramento and San Joaquin River basins are identified

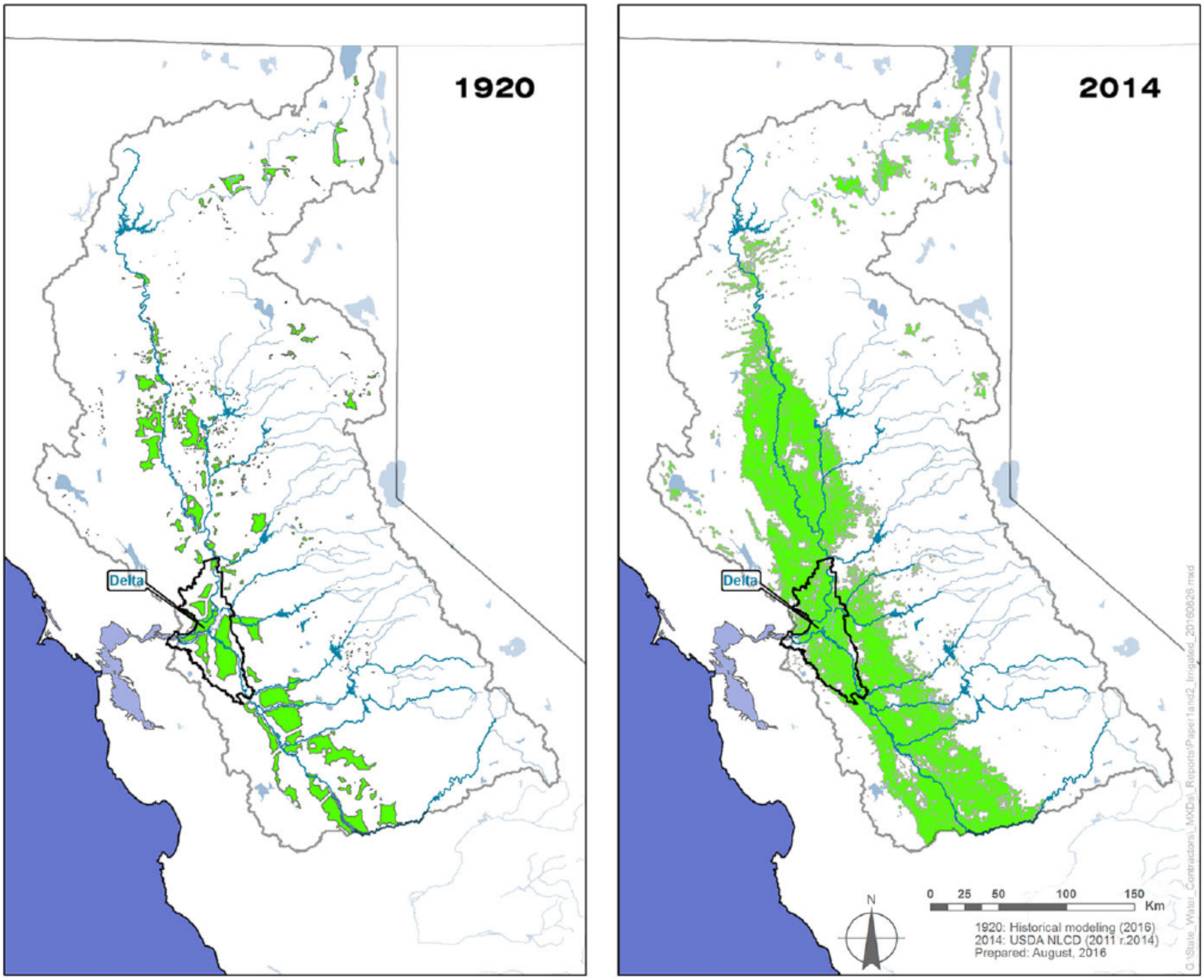

FIGURE 2 These maps compare the extent of irrigated area in the San Francisco Bay-Delta watershed under 1920-level and current-level (2014) conditions. Land use data associated with 1920-level conditions are from MWH (2016). Current-level land use data (representing the "cultivated area" classification) are from the National Land Cover Dataset (http://www.Mrlc.Gov/)

examined, we found no statistically significant annual trend, a result likely due to large year-to-year climatic variability. Statistically significant trends were observed in seasonal outflows however, 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. Although the observed data make suggestions about causes of these changes, the data do not permit direct attribution of driving processes, particularly when multiple interacting processes are possible and where nonmonotonic changes are occurring over an extended period of record. Thus, although the changes reported in Hutton et al. (2017) were linked with several coincident factors such as reservoir operations, increases in exports and irrigation diversions, and changes in climatic patterns, individual effects were not rigorously parsed.

Here, we explain why Delta outflow has changed over time and quantitatively attribute the changes to specific causes in a manner not possible solely by examining the observed record. We accomplish this objective by constructing alternative time series of daily Delta outflow corresponding to scenarios with different levels of development (land use and reservoirs) but forced by the same climatic record over a nine-decade period. The idealized flow scenarios are constructed using two approaches: (a) the baseline scenario is developed using the results from an integrated hydrologic model (MWH, 2016) where land use was fixed at a 1920 level (left panel of Figure 2) and (b) additional scenarios are developed by adjusting the historical Delta outflow for daily export operations and volumes released or stored by the 10 major reservoirs shown in Figure 1. Changes from baseline conditions are quantified and attributed to specific causes, such as reservoirs or diversions. We also examine the effect of changes in Delta outflow on the salinity in the estuary using a newly developed salinity model that accounts for freshwater flow and coastal water level (Rath, Hutton, Chen, & Roy, 2017), allowing attribution of the effect of historical sea level rise in the region beyond changes in freshwater flow.

2 | BACKGROUND

Temporal and spatial disparities between water availability and water use make its management vital for sustaining California's large agricultural economy and its growing population. Freshwater flow to the San Francisco Bay-Delta estuary directly influences the salinity gradient in these waters, which affects agricultural and urban water users in the Delta and the aquatic life in the estuary. Flows and salinity in the estuary are highly dynamic, varying from tidal to seasonal scales, albeit somewhat controlled through the management of reservoir releases and exports. The system is managed to balance the beneficial uses of the urban, agricultural, and environmental sectors, in large part through flow and salinity standards. A brief overview of the region's salinity regime and regulatory environment is presented below; this overview is followed by a brief survey of previous research on hydrologic change attribution.

2.1 | Salinity regime

Mixing of freshwater and saltwater in estuaries with seasonally varying flow patterns such as the San Francisco Bay-Delta estuary follows a basic conceptual model: freshwater flows repel salinity downstream (seaward) across a mixing zone (with longitudinal and vertical gradients) and saltwater intrudes upstream (landward) during periods of low freshwater flow. The resulting salinity regime varies with tides on hourly to daily time scales and varies with freshwater flows on daily to seasonal time scales. A convenient metric of the estuary's salinity regime is the longitudinal position of the near-bottom two parts per thousand salinity isohaline. This metric, referred to as X2, is measured as a distance from the mouth of the estuary near San Francisco (see Figure 1). X2 is translated to a surface salinity assuming a fixed vertical stratification and obtained by interpolation from fixed surface salinity stations (Jassby et al., 1995). Figure 3 offers a stylized representation of the estuary's salinity gradient and X2 position under high- and low-flow scenarios.

Previous work has examined long-term changes in X2 position using salinity data collected across the estuary from water years 1922–2012 (Hutton, Rath, Chen, Ungs, & Roy, 2015). The California water year (WY) spans the period October 1 through September 30. The construction of upstream reservoirs and increased in-basin and out-of-basin water use has affected the isohaline position over time. When the data were evaluated over two subintervals, WYs 1922–1967 and WYs 1968–2012, similar to those examined for flow trends in Hutton et al. (2017), it was observed that X2 position exhibits less intra-annual variability in the later period compared to the earlier period, largely as a consequence of actions in recent decades to manage salinity in the estuary. The X2 data were also examined by WY type; California classifies each WY into five categories (wet, above normal, below normal, dry, and critically dry). Over WYs 1968–2012, X2 position was typically further upstream (i.e., higher) in wet months (February through May) of dry and critically dry years and further downstream (i.e., lower) in the dry months of August and September. This reduction in dry year variability is a result of reservoirs being operated to store water in wet periods and to release water during dry periods, thus damping the variation in Delta salinity. At the other hydrologic extreme (i.e., wet years), flows were sufficiently high that reservoir operations have less impact on the Delta salinity gradient, resulting in general similarity between the two subintervals. The monthly trend evaluation for the entire period of record showed statistically significant increases in X2 position from November through June (reflecting lower freshwater flows) and statistically significant decreases in August and September (reflecting higher freshwater flows). Note that the X2 trend analyses in Hutton et al. (2015) were performed with a slightly different version of the Mann–Kendall (MK) trend test than employed here (described further in the Methods section).

Several empirical flow–salinity relationships have been reported in the literature and are available to predict X2 position as a function of the time history of Delta outflow. Most of these models are algebraic formulations driven by a Delta outflow term accounting for a time lag (Denton, 1993; Hutton et al., 2015; Jassby et al., 1995;

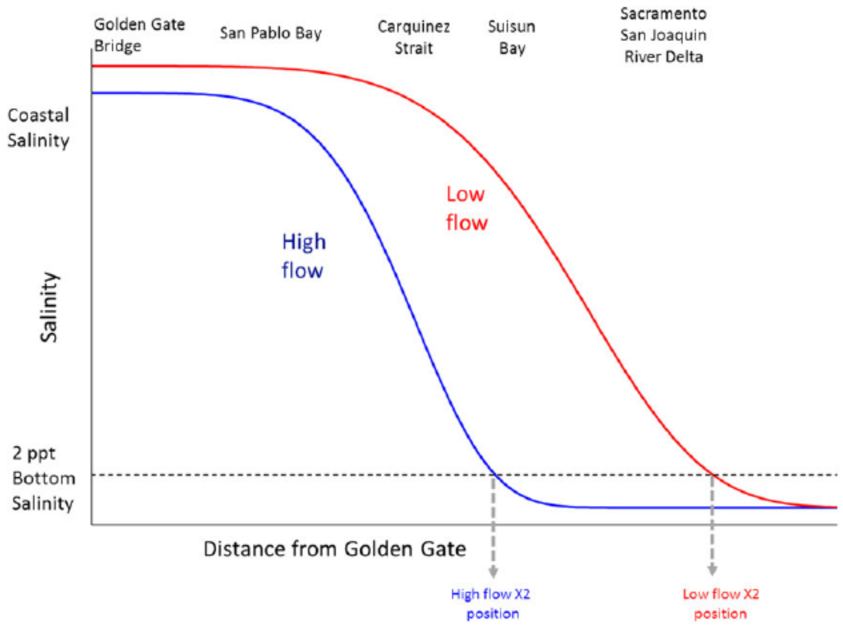

FIGURE 3 Schematic illustrating the salinity gradient and the relationship of X2 with flow in the San Francisco Bay-Delta estuary. X2 is defined as the location where the salinity at the estuary bottom is two parts per thousand. Under low freshwater flow conditions, the salinity gradient moves further inland, and X2 is at a greater distance from Golden Gate. Under high freshwater flow conditions, the salinity gradient is pushed toward the ocean, and X2 is closer to Golden Gate

MacWilliams et al., 2015; Monismith, Kimmerer, Burau, & Stacey, 2002). A recent modeling advancement utilizes a hybrid approach and integrates an artificial neural network with an available empirical model (Hutton et al., 2015). This model utilizes Delta outflow as well as coastal water level terms (mean sea level and daily tidal range) as inputs to predict X2 position and salinity along the estuarine gradient (Rath et al., 2017). This hybrid model was adopted for the work presented in this paper because (a) it demonstrated superior performance in predicting X2 relative to the other available empirical models and (b) it allowed consideration of historical rise in mean sea level as a potential contributor to salinity trends over time.

2.2 | Regulatory environment

The California State Water Resources Control Board (CSWRCB) sets water quality objectives to protect beneficial uses of water in the estuary. Freshwater flow (i.e., Delta outflow) is currently managed such that the low salinity zone falls within a certain geographic range in the estuary. Specifically, the position of X2 is regulated during the months of February through June (CSWRCB, 2006). Statistical relationships between pelagic species abundance and X2 position in the estuary (Jassby et al., 1995) are the scientific foundation of this Delta outflow objective, which has controlled water management during spring months over the past two decades. More recently, a biological opinion on Delta smelt from the U.S. Fish and Wildlife Service (USFWS, 2008) regulates X2 position in fall months (September through November) following wet and above normal WYs. Other flow and salinity objectives are in place to protect human and ecosystem needs. In sum, these objectives are met through coordinated operation of upstream reservoir releases and exports of water from the Delta. Given continued advances in understanding of physical and biological processes in the estuary (e.g., Feyrer, Nobriga, & Sommer, 2007; Feyrer, Newman, Nobriga, & Sommer, 2010; Kimmerer, Gross, & MacWilliams, 2009; Moyle, Lund, Bennett, & Fleenor, 2010; MacWilliams et al., 2015; Bever, MacWilliams, Herbold, Brown, & Feyrer, 2016; Nobriga & Rosenfield, 2016), the regulatory environment is subject to periodic review by the California State Water Resources Control Board and reconsultation under the Endangered Species Act.

2.3 | Previous work on flow attribution

The general concept of using models to attribute changes in flows has broad application in hydrology, especially when there are multiple drivers of change. The most common applications currently relate to the detection and attribution of climate change. For example, Hidalgo et al. (2009) and Pierce et al. (2008) evaluated the role of climate change on streamflows in river basins in the United States, including California. They used modeled flows from a rainfall-runoff model, forced by climate models, to show that the detected change in timing of naturalized streamflow with reservoir effects removed—earlier center of timing of the hydrograph due to earlier snowmelt—could be attributed to warmer temperatures. In other applications, Doyle and Barros (2011) utilized a modeling framework in a river basin in Paraguay to understand increasing flow trends over a four-decade period. Their modeling framework, which allowed independent examination of land use change and precipitation change, suggested that increasing flow was related to decreasing evapotranspiration (from loss of forest land) and increased precipitation. Adam, Haddeland, Su, and Lettenmaier (2007) examined flow trends in large rivers discharging into the Arctic Ocean utilizing a flow and reservoir routing model; they used this model to parse the effect of reservoir contributions, thus allowing examination of climate change drivers. Performing trend analyses on the observed and simulated flows, they found that reservoirs had a significant effect on seasonal trends but not on annual trends. Cuo, Zhang, Gao, Hao, and Cairang (2013) used observed streamflow data in the upper Yellow River Basin in China, along with a runoff model, to examine flow changes resulting from land use modification and climate change over a four-decade period. In each of the investigations cited above, the occurrence of natural variability and multiple human-induced changes limited the researchers' abilities to attribute change directly from observations and motivated the use of models to provide additional insight into underlying processes.

Flow as well as salinity change attribution in the San Francisco Bay-Delta estuary was previously explored by Knowles (2002). The effects of reservoir and export operations on Delta outflows were evaluated over two decades (WYs 1967–1987) by creation of alternative flow scenarios. Three scenarios were developed: historical flow with management effects removed (baseline), baseline plus reservoir effects, and baseline plus Delta export effects. These scenario flows were then used as input to an estuarine salinity model to compare the change in X2 position. He found that reservoir retention and release reduced salinity and exports raised salinity, although the effect varied by season. Between January and June, the combined effect raised salinity (i.e., moved X2 upstream), whereas in the dry season, the combined effect lowered salinity (i.e., moved X2 downstream). Our work builds upon and extends that of Knowles (2002) in two main aspects. First, our work considers a longer time period (WYs 1922–2009), which represents a wider range of watershed alterations and hydrologic conditions. Second, our work evaluates additional drivers of change, including reservoirs, exports, stream diversions in the Central Valley, and historical sea level rise.

3 | METHODS

The attribution of outflow and salinity change in the San Francisco Bay-Delta estuary, as presented in this paper, relies on the development of several idealized flow scenarios and the computation of associated Delta outflow and estuarine salinity (represented as X2 position). The flow scenarios were combined, through the principle of superposition, to parse individual drivers of change, such as diversions or sea level rise. As described below, the methodology was supported by compilation of historical flow and reservoir storage data, the definition and development of model scenarios, and a statistical approach to quantify the significance of observed changes.

3.1 | Data

Time series representing observed daily Delta outflow and exports spanning WYs 1930–2009 were obtained from the California

Department of Water Resources (CDWR) DAYFLOW program (http://www.water.ca.gov/dayflow/). As detailed elsewhere (Hutton, 2014), a daily outflow time series spanning WYs 1922–1929 was estimated from monthly outflow volumes (CDWR, 1957) and daily inflow volumes (CDPW, 1931). Because of the complexity of direct observation of freshwater flows, particularly during low flow conditions, 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 (Monismith, 2016). The period of record used for the analysis spanned WYs 1922 through 2009, corresponding to the availability of modeled scenario information as described below. Note that this is marginally different from the WYs 1922–2015 time frame examined in Hutton et al. (2017), based on available *observed* data.

The observed daily storage volume time series of 10 major reservoirs in the Sacramento and San Joaquin River basins were obtained from the California Data Exchange Center (http://cdec.water.ca.gov) and the United States Geological Survey National Water Information System (http://waterdata.usgs.gov/nwis). Four of the 10 reservoirs are integral to the federal CVP and the California SWP; these are collectively referred to as “project” reservoirs and have storage capacities ranging between 1.0 and 4.6 MAF. The remaining six reservoirs are herein referred to collectively as “non-project” reservoirs; these represent the largest non-project, downstream reservoirs along the western slope of the Sierra Nevada mountain range with storage capacities ranging between 0.3 and 2.4 MAF. The locations of the 10 major reservoirs are identified in Figure 1.

A time series of X2 position was computed for each flow scenario (see below) using a newly developed hybrid empirical-Bayesian artificial neural network model (Rath et al., 2017). Rath et al. (2017) improved upon a published empirical model of freshwater flow and salinity in the San Francisco Bay-Delta estuary (Hutton et al., 2015) by incorporating a Bayesian artificial neural network model and consideration of coastal water level and tidal inputs. Time series representing coastal water level and daily tidal range (the difference between the daily maximum and minimum water level) were obtained from the National Oceanic and Atmospheric Administration (NOAA, 2015).

3.2 | Idealized flow scenarios

Five flow scenarios were developed in support of the change attribution analysis presented in this paper (Table 1). Scenarios 1A and 1B represent the historical daily outflow time series. Although Scenario 1A represents the historical sea level record at Golden Gate, Scenario 1B assumes a de-trended sea level record (using linear regression) that is representative of 1920-level conditions. Although coastal water level is subject to annual and decadal variation, a long-term rising trend of 1.9 mm/year has been documented in the estuary (Ryan & Noble, 2007), corresponding to a change of 18.3 cm between 1920 and 2012. This de-trended sea level record was also used for Scenarios 2, 3, and 4. In Scenario 2, the historical outflow record was adjusted (or “unimpaired”) by removing the reservoir and export operations associated with the CVP and SWP. In Scenario 3, a modeling approach was used to generate a synthetic Delta outflow time series corresponding to a 1920 level of land and water use, as described further below. Scenario 4 builds on Scenario 2 by removing operations of all 10 major reservoirs shown in Figure 1.

The above flow scenarios, in conjunction with the principle of superposition (i.e., the individual drivers of flow change are additive and outflow and sea level together determine salinity), are used to ascribe outflow and salinity trends to specific drivers. Thus, by assuming 1920-level conditions (i.e., Scenario 3) as the baseline, the difference between Scenarios 1A and 3 corresponds to the total change. Similarly, the difference between Scenarios 1A and 1B corresponds to the change associated with sea level rise. The difference between Scenarios 1B and 2 isolates the effects of CVP-SWP project reservoir and export operations. The difference between Scenarios 2 and 4 is associated with effects of non-project reservoir storage, and the difference between Scenarios 4 and 3 is associated with effects of non-project diversions. All five change attribution categories (summarized in Table 2) are relevant for measuring salinity alterations, and four of the five categories are relevant for measuring flow alterations (sea level rise affects salinity only).

3.3 | Hydrologic modeling for 1920 level of development

The hydrology of the San Francisco Bay-Delta watershed is highly complex and is influenced by the interaction of surface water and groundwater, natural rainfall-runoff processes, reservoir operations from multiple agencies, and diversions of surface water and groundwater to meet various agricultural and urban demands. In a prior study of the watershed (MWH, 2016), several “level of development” scenarios using the California Central Valley Groundwater-Surface Water Simulation Model (Brush, Dogrul, & Kadir, 2013) were created to simulate a suite of hydrologic conditions that existed in the 20th and early 21st century. California Central Valley Groundwater-Surface Water Simulation Model

TABLE 1 Summary description of hydrology and sea level assumptions associated with the five idealized flow scenarios defined for the change attribution analysis

Scenario ID	Scenario description	
	Hydrology	Sea level
1A	Historical	Historical
1B	Same as Scenario 1A	Historical de-trended to represent 1920-level conditions
2	Scenario 1A + unimpairment of CVP-SWP storage and export operations	Same as Scenario 1B
3	1920-level land use and water management conditions[a]	Same as Scenario 1B
4	Scenario 2 + unimpairment of key non-project storage operations	Same as Scenario 1B

[a] Hydrology is based on an integrated hydrologic model of the Central Valley; simulated data were bias corrected using observed data.

TABLE 2 The idealized flow scenarios identified in Table 1, in conjunction with the principle of superposition, are used to ascribe outflow and salinity trends to different anthropogenic and natural causes (identified below as flow and salinity change attribution categories). By retaining a fixed climatic record, the analysis approach removes precipitation as a factor underlying outflow and salinity trends

Change attribution category	Calculation approach		Relevance
Total	Scenario 1A	Scenario 3	Outflow/salinity
Sea level	Scenario 1A	Scenario 1B	Salinity
CVP-SWP projects	Scenario 1B	Scenario 2	Outflow/salinity
Non-project storage	Scenario 2	Scenario 4	Outflow/salinity
Non-project diversion	Scenario 4	Scenario 3	Outflow/salinity

Note. CVP Central Valley Project; SWP State Water Project State Water Project.

has been used previously in a variety of hypothetical outflow scenarios (Dale et al., 2013; Dogrul, Brush, & Kadir, 2016; Miller et al., 2009). Under a fixed level of development, water facilities, land use, water supply contracts, and regulatory requirements are held constant over the period of simulation. A historical climate sequence spanning WYs 1922–2009 was used to represent the possible range of water supply conditions for each model scenario on a monthly time step, and each scenario produced a time series of Delta outflow that could be compared to evaluate changes over time. As described in the following paragraph, we adapted the modeled 1920-level Delta outflow time series to represent baseline conditions (i.e., Scenario 3) for our work.

We compared the early part of the modeled 1920-level Delta outflow time series with data collected in the 1920s to validate its use as a baseline for our work. This comparison revealed some inconsistencies, with differences varying by season. Because small differences in flow (particularly in dry months) can have a disproportionate effect on salinity calculations (Rath et al., 2017), we applied seasonally-based bias corrections to the entire outflow time series. We further adapted the bias-corrected time series by disaggregating it to a daily time step for compatibility with our salinity (X2) calculations. The modeled 1920-level Delta outflow time series, after bias correction and disaggregation to a daily time step, was used as our hydrologic baseline (i.e., Scenario 3).

3.4 | Statistical approach

The statistical approach employed for trend detection was identical to that in Hutton et al. (2017), and included Sen's nonparametric 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 analyzed (Sen, 1968). The MK test (Kendall, 1938; Mann, 1945) is a common nonparametric statistical procedure to determine significance of trend. The rank-based, nonparametric 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. The "two-sided" MK test, which was used in our work, tests the null hypothesis of a monotonic increasing or decreasing trend. Absent prior knowledge of the direction of the change anticipated (either increasing or decreasing), the two-sided test is appropriate. The "one-sided" MK test can also be applied when the study focus is on a single direction of change. In prior work on San Francisco Bay-Delta salinity trends (Hutton et al., 2015), the one-sided MK test was employed twice (first to test for an increasing trend and second to test for a decreasing trend). Conclusions regarding trend significance can be somewhat different depending on the method used.

4 | RESULTS

Results from the change attribution analysis are summarized in this section for both Delta outflow and salinity (i.e., X2 position). Trends for each of the attribution categories identified in Table 2 (i.e., total, sea level, projects, non-project storage, and non-project diversion) are presented in the form of time series and bar charts. The results presented here are limited to the annual time series and months with statistically significant trends in Delta outflow and X2 position.

4.1 | Flow change attribution

Figure 4 shows Delta outflow and change times series over the analysis period spanning WYs 1922–2009. The top panels show historical (i.e., Scenario 1A) Delta outflow for months that were shown to have statistically significant trends in Hutton et al. (2017), with adjacent months combined, and as an annual average. The bottom panels show outflow change for each of the attribution categories (excepting sea level) identified in Table 2. The principle of superposition dictates that the change associated with the three project and non-project categories sum to the total change. As discussed previously, change is measured relative to a 1920-level baseline (i.e., Scenario 3). February and November outflow changes are primarily attributed to project effects, although non-project effects (the combination of non-project storage and diversions) account for some of the February Delta outflow change after about 1980. Total February and November outflow changes over the period of analysis are less than 2 and 0.5 MAF, respectively. In the months of April–May, the outflow change is negative for all categories after about 1950. The sum of non-project storage and diversions effect is visually similar but somewhat smaller than the project effect. Total April–May outflow change over the period of analysis is less than 3 MAF, with the negative trend flattening by about 1980. Outflow change in the months of July–August is distinctly different from the other periods analyzed. One notable difference is that the trajectory of total outflow change is positive over the period of record. Another notable difference is that the total outflow change switches from negative to positive in the 1950s. Positive outflow change is attributed primarily to project effects and to a lesser degree non-project storage. These effects more than fully attenuate impacts

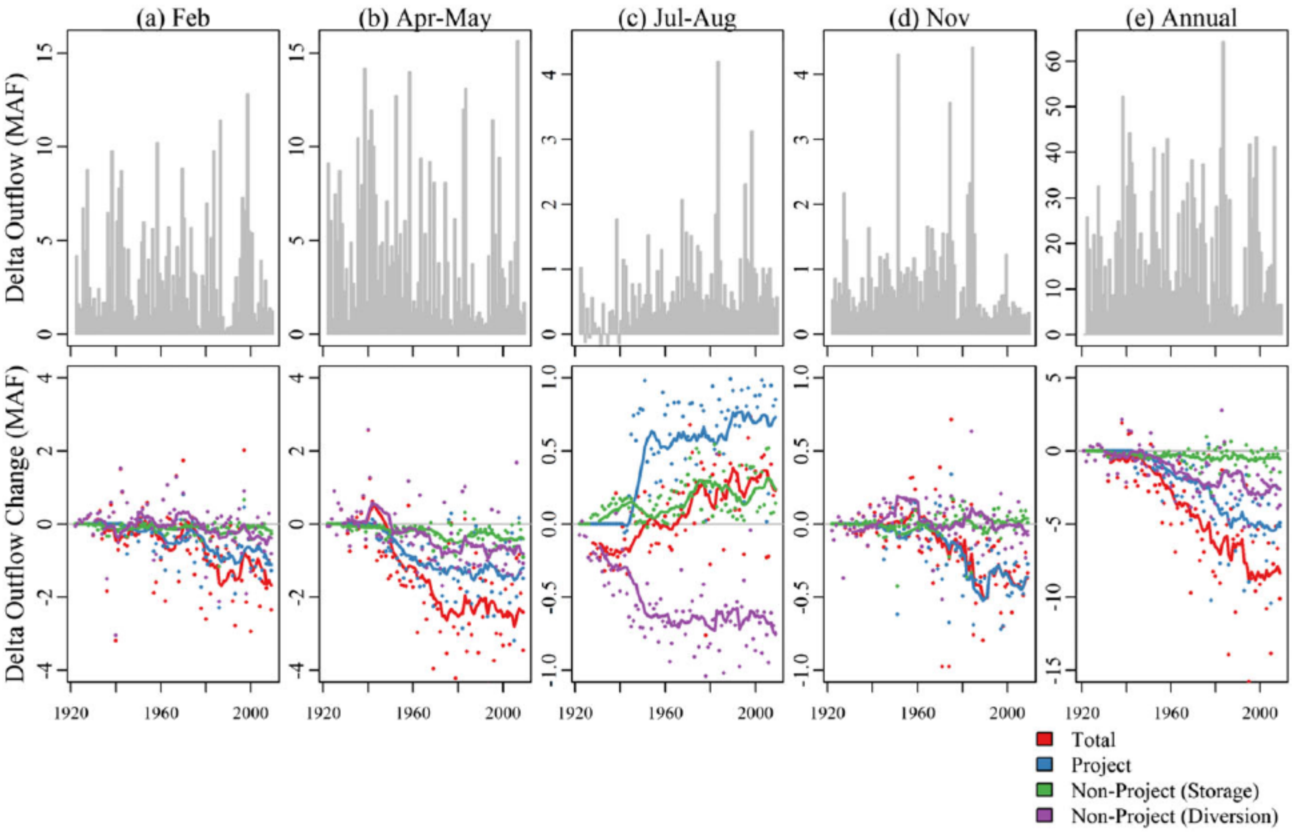

FIGURE 4 Historical Delta outflow and change time series over water years 1922–2009 for (a) February, (b) April–May, (c) July–August, (d) November, and (e) annual flow. The top panel represents historical flows (Scenario 1A). The bottom panel represents change attribution categories identified in Table 2, as shown in individual data (points) and 10-year moving averages (lines). The time periods are limited to months with statistically significant trends in historical Delta outflow (shown in Hutton et al., 2017)

associated with non-project diversions. On an annual basis, the outflow change is negative for all categories with the project and non-project diversions being the primary and secondary drivers of change, respectively. Both categories show a similar trajectory through about 1980; thereafter, the project change continues to trend negative, whereas the non-project diversions change flattens. Total annual outflow change over the period of analysis is approximately 8 MAF. Key drivers of outflow change are summarized in Table 3.

The visual patterns in Figure 4 are confirmed through statistical trend evaluation of flow changes. Figure 5 shows the magnitudes of the Sen slope (the median slope) for each change attribution category. We generally expect the component slopes to approximately sum to the total; however, there need not be an exact match because the slopes are computed as medians across all pairs of points within each time series. Similar to the interpretation drawn from Figure 4, February and November outflow changes are primarily attributed to project effects. Outflow change is the greatest in April–May, and change attribution is similar for project and the sum of non-project effects. Positive outflow change is confirmed in July–August in spite of non-project diversion effects due primarily to positive project effects.

4.2 | Salinity change attribution

Figure 6 shows Delta salinity (expressed as X2 position) and change times series over the analysis period spanning WYs 1922–2009. The top panels show historical (i.e., Scenario 1A) X2 position for months that

TABLE 3 This table summarizes the Delta outflow change attribution analysis depicted in Figure 4. Total flow change is measured relative to the 1920-level baseline (i.e., Scenario 3). The analysis is limited to months with statistically significant trends in Delta outflow (shown in Hutton et al., 2017)

Period	Direction of total change	Primary driver(s) of change	Secondary driver(s) of change
Annual	Decreasing	Project	Non-project diversion
February	Decreasing	Project	n/a
April May	Decreasing	Project	Non-project storage; non-project diversion
July August	Increasing	Project; non-project Diversion[a]	Non-project storage
November	Decreasing	Project	n/a

[a] The effects of Project operations and non-project diversion are divergent, with Project operations contributing to increasing Delta outflow and non-project diversions contributing to decreasing Delta outflow. The Project effect more than fully attenuates the non-project effect, resulting in a net trend of increasing Delta outflow.

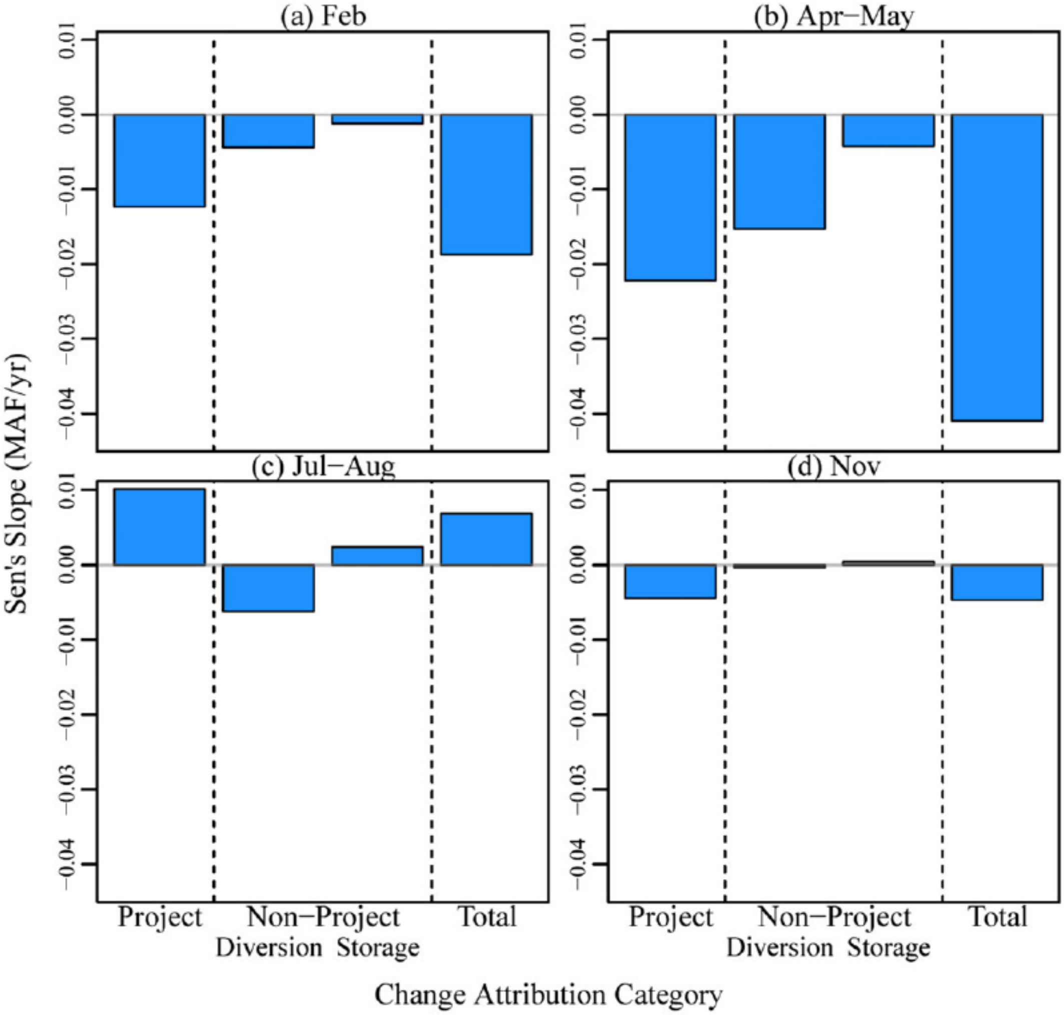

FIGURE 5 Delta outflow change trends (MK trend significance and Sen slope) by attribution category for (a) annual flow, (b) February, (c) April–May, (d) July-–August, and (e) November. This analysis is limited to the four groups of months with statistically significant trends in historical Delta outflow (shown in Hutton et al., 2017). A statistical significance at $p < .05$ level is shown by blue bars; gray bars indicate statistical significance at $p \geq .05$

were shown to have statistically significant trends, with adjacent months combined, as an annual average. In this presentation, X2 was computed on a daily basis, and averaged over different periods, either annually or over one or more months. The bottom panels show salinity change for each of the attribution categories (excepting sea level) identified in Table 2. Sea level change was observed to have a small impact on salinity relative to the other drivers; therefore, it was not shown in Figure 6 for visual clarity. As indicated above, (a) the principle of superposition dictates that the change associated with the individual attribution categories sum to the total change and (b) change is measured relative to a 1920-level baseline (i.e., Scenario 3). X2 position is strongly related to antecedent Delta outflow conditions (Hutton et al., 2015); thus, salinity response tends to lag the flow signal. Because of this time lag, months with significant change often extend beyond the periods with significant changes in flow as shown in Figure 4. This lag effect is illustrated in the present work by the statistically significant outflow changes in July–August manifesting statistically significant salinity changes in August–September, and the November outflow changes manifesting in November–December salinity changes.

Positive X2 change in February (Figure 6a) appears to escalate after the 1960s. This change is attributed largely to project effects and results in an upstream X2 movement of 5–10 km (compared with the 1920 baseline) by the end of the simulation period. In comparison, positive X2 change in April–June (Figure 6b) begins early in the simulation period, with an approximately 10 km increase by the end of the simulation period. These changes are roughly attributed equally to project and non-project diversion effects. August–September X2 change has been significant since the beginning of the simulation period (Figure 6c). Individual driver effects are large relative to total X2 change (an approximate 5 km decrease from the baseline). Furthermore, individual driver effects are strongly divergent. An increase in X2 position of approximately 20 km is attributed to non-project diversions, and an opposite and roughly equal decrease in X2 position is attributed to project effects. The net change in August–September X2 position is thus associated with the remaining non-project storage effect. Positive X2 change in November–December appears to escalate by the 1980s and reaches a level approximately 10 km greater than the baseline toward the end of the simulation period (Figure 6d). This change is roughly attributed equally to project and non-project diversion effects; non-project storage is associated with a small decrease (about 5 km) in November–December X2 position by the end of the simulation period.

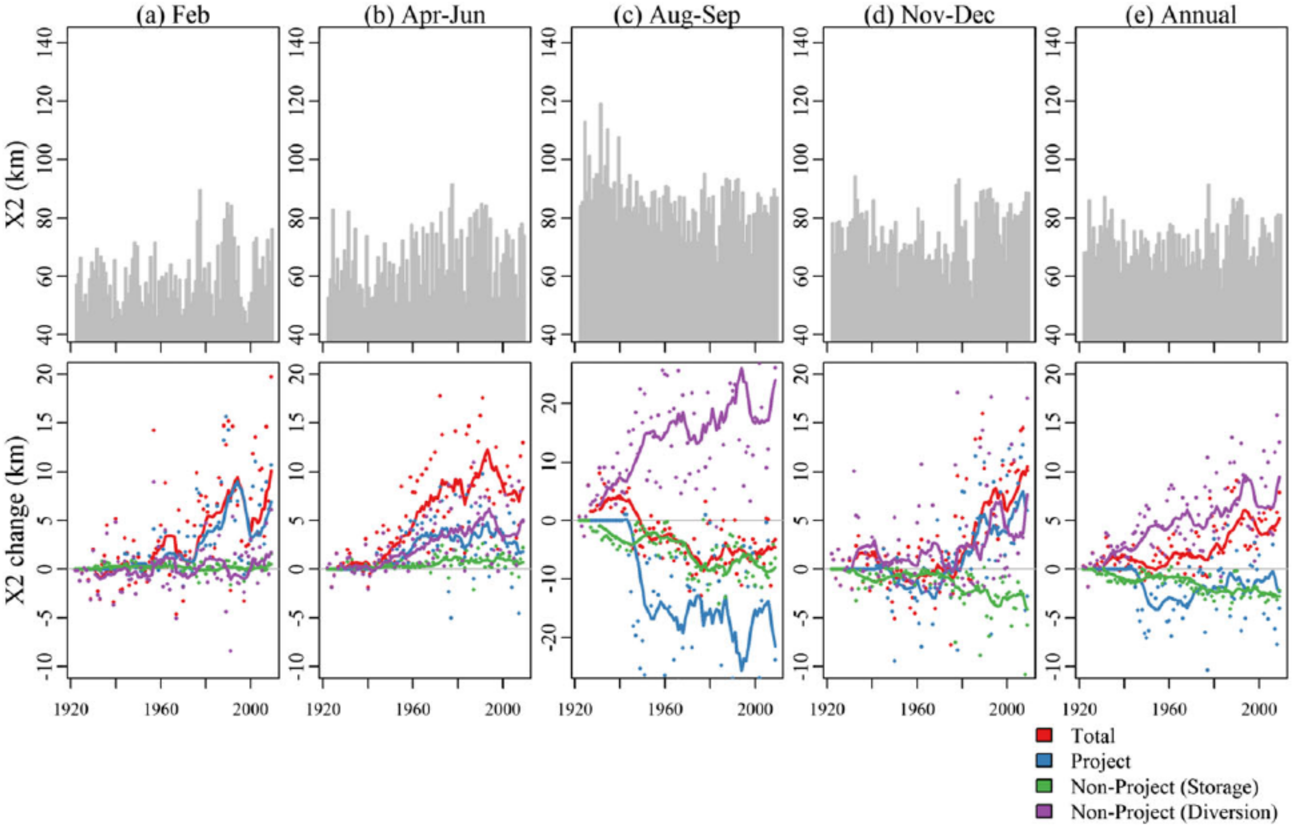

FIGURE 6 Historical salinity, represented as X2 position, and change time series over water years 1922–2009 for (a) February, (b) April–June, (c) August–September, (d) November–December, and (e) annual average X2. The top panel represents historical salinity (Scenario 1A). The bottom panel represents the change attribution categories identified in Table 2, as shown in individual data (points) and 10-year moving averages (lines). The time periods are limited to months with significant X2 trends over the simulation period spanning water years 1922–2009. Because of the lagged salinity response to flow changes, months with significant salinity change often extend beyond the periods with significant flow change (depicted in Figure 4)

The total change in X2 position is positive on an annual basis (Figure 6e), which is consistent with the negative change in total outflow shown in Figure 4 (i.e., X2 position increases as outflow decreases). Project and non-project storage effects both decrease X2 position (i.e., push salinity downstream) on an annual basis, whereas the non-project diversion effect increases X2 position (i.e., push salinity upstream). Although this result may initially seem counterintuitive given that project effects decrease annual outflow (Figure 4e), it is important to highlight the substantial role of the projects during low-flow periods. Project outflow contributions during low-flow periods (Figure 4c) result in large reductions in X2 position in the subsequent months (Figure 6c), as X2 is highly sensitive to Delta outflow changes under low flow conditions (Rath et al., 2017). For example, although a relatively small change in August Delta outflow will have a minimal effect on aggregate annual outflow, the small flow change can have a substantial effect on August–September X2 position, such that the annual X2 position (computed as an arithmetic average over all days in a year) shows a meaningful change. Key drivers of X2 change are summarized in Table 4.

The visual patterns in Figure 6 are confirmed through statistical trend evaluation of salinity changes. Figure 7 shows the magnitude of the Sen's slope for each change attribution category, including sea level rise. Although sea level rise is often a small contributor to total change, its effect is comparable to other drivers in select circumstances. In February and April–June (Figure 7a,b), all X2 attribution

TABLE 4 This table summarizes the Delta salinity change attribution analysis depicted in Figure 6. Total salinity change is measured relative to the 1920-level baseline (i.e., Scenario 3). The analysis is limited to months with statistically significant trends in X2 over the simulation period. Because of the time lag in salinity due to changes in flow, months with significant change often extend beyond the periods with significant changes in flow as identified in Table 3.

Period	Direction of total change	Primary driver(s) of change	Secondary driver(s) of change
Annual	Increasing	Non-project diversion	n/a
February	Increasing	Project	n/a
April June	Increasing	Project; non-project diversion	Non-project storage
August September	Decreasing	Project; non-project Diversion[a]	Non-project storage
November December	Increasing	Project; non-project diversion	n/a

[a] The effects of Project operations and non-project diversion are divergent, with Project operations contributing to decreasing salinity and non-project diversions contributing to increasing salinity. The Project effect more than fully attenuates the non-project effect, resulting in a net trend of decreasing salinity.

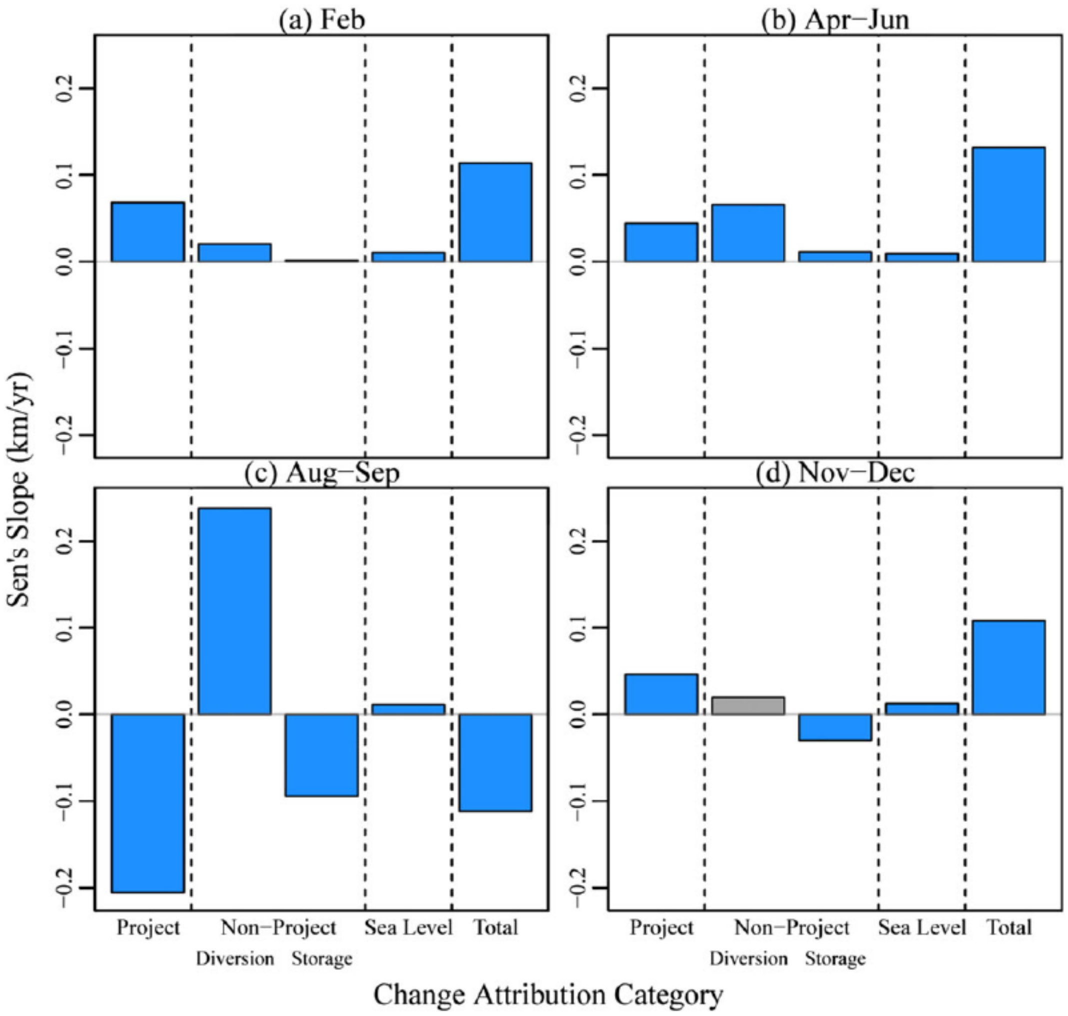

FIGURE 7 X2 change trends (MK trend significance and Sen slope) by attribution category for (a) February, (b) April–June, (c) August–September, and (d) November–December. This analysis is limited to the four groups of months with statistically significant trends in X2 over the simulation period spanning water years 1922–2009. A statistical significance at $p < .05$ level is shown by blue bars; gray bars indicate statistical significance at $p \geq .05$

categories show positive slopes, with an increase of about 0.1 km/yr in total. Project and non-project diversion effects are the largest single drivers in February and April–June, respectively. In August–September (Figure 7c), X2 attribution categories show divergent effects with a decrease of about 0.1 km/yr in total. Project and non-project diversion effects roughly cancel each other out, thus the net result corresponds to the non-project storage effect. In November–December (Figure 7d), three of the four X2 attribution categories show positive slopes, with an increase of about 0.1 km/yr in total. The sum of the component slopes visually appears to be smaller than the total; this observation may be related to the median value associated with the Sen slope and the fact that there is no clear slope over the first two-thirds of the simulation period for these months (Figure 6e).

5 | DISCUSSION

This paper defined a set of idealized flow scenarios to explain trends in freshwater flow to the San Francisco Bay-Delta estuary (i.e., Delta outflow) as measured over a historical hydrologic record spanning nine decades. The modeling approach retains a fixed climatic record, thereby removing precipitation as a factor underlying outflow and salinity trends and allowing change attribution to anthropogenic drivers. Assuming linear superposition for flows, scenario differences are used to ascribe flow and salinity change to three drivers: project operations, non-project storage, and non-project diversions.

By utilizing a model-based approach and assuming fixed climatology, a clearer picture of annual outflow trends and drivers of change emerges at a level of detail not possible through the observational data record. Our analysis of annual outflow suggests that (a) declines through the mid-to-late 1970s are attributed equally to project operations and non-project diversions, (b) further declines through the 1980s are attributed to project operations, and (c) flow appears to stabilize by the 1990s. These change points are consistent with the peaking of irrigated acreage in the watershed by the mid-1970s (Hutton et al., 2017), increasing Delta exports following expansion of the CVP and construction of the SWP in the late 1960s, and increasingly restrictive Delta outflow standards.

Similarly, our model-based attribution analysis provides a picture of monthly outflow trends and drivers of change at a level of detail not possible through the observational data record. Our analysis suggests that project operations are a primary driver of Delta outflow change in all months when trends are statistically significant. For example, in July and August, flow contributions from project operations counter the negative effect of non-project diversions. Absent these project flows, non-project diversion effects would have been much greater than observed after the 1940s. Indeed, low summer and fall Delta outflow events (and commensurate salinity intrusion) were common just prior to the 1920s through the mid-1940s (CDPW, 1931). Following this period, the largest reservoir in the watershed (Lake Shasta) became operational. Lake Shasta, in tandem with other project reservoirs, now provides a flow contribution greater than the flow reduction due to upstream non-project diversions, resulting in a net increase in summer outflow relative to the 1920-level baseline. Non-project reservoirs also provide additional summer outflow, but are smaller contributors due to their lower storage capacity and their differing purpose. Non-project reservoirs are generally operated to meet water needs within the watershed, whereas project reservoirs are operated in part to meet Delta outflow standards.

Our analysis reveals that the earliest and largest salinity (X2) changes occurred in August and September, an effect of antecedent flow changes in July and August. Non-project diversions result in increasing X2 position during these months from the beginning of the record to the mid-to-late 1970s. Project operations were associated with substantial X2 declines during these months after completion of Lake Shasta (mid 1940s) through the 1950s. Project operations and non-project diversions are equally important contributors to increasing salinity in the spring (April–June) between the 1940s and the 1980s. Non-project storage is a secondary contributor to increasing salinity during this period. Project effects reflect increasing reservoir storage capacity, whereas non-project diversion effects reflect increasing irrigation demand. The cessation of spring X2 increase following the 1980s is attributed to reduction in Delta exports in response to more stringent outflow standards and stabilized irrigation demand. Increase in February X2 is primarily attributed to project operations, reflecting a month when irrigation diversions are minimal. Notable change relative to the baseline began in the 1970s and likely reflects a shift in Delta exports from spring to winter months. Increase in November–December X2, notable from about 1980 to the end of the simulation period, is equally attributed to project operations and non-project diversions. The attribution to project operations may reflect a shift in Delta exports from spring months; the association between non-project diversions and November December X2 increases is not well understood. In sum, the flow and salinity change attribution analysis shows the highly dynamic nature of the estuary throughout the nine-decade period of record examined, with different drivers being dominant in different periods and seasons.

The key limitations of our work relate to (a) definition of a baseline flow scenario (1920-level) and (b) uncertainties associated with our salinity modeling approach. To develop the baseline flow scenario, we used an established integrated hydrologic model of California's Central Valley in conjunction with appropriate data to represent land use and infrastructure present in the 1920s. Although the validity of this hypothetical flow series was evaluated against flows measured in the 1920s, by definition, the flow series cannot be validated for subsequent decades of the climatic record. Salinity (X2) associated with the modeled flow scenarios is based on a modeling framework that has a reported uncertainty range in excess of 3 km (Rath et al., 2017). Thus, small salinity differences between flow scenarios are not of statistical consequence, although the most dramatic differences were greater in magnitude than this uncertainty range.

Waterbody restoration efforts in the United States and throughout the world are challenged by the need to establish restoration targets or baselines for a variety of stressors. With respect to hydrologic alteration, this paper describes the creation of idealized flow scenarios that allow for the analysis and attribution of change from a predefined baseline. Evaluation of individual drivers of change can be used to inform development of restoration goals and to test the achievability of meeting these goals in the contemporary system. Our work assumed a 1920-level baseline to measure change; selection of this baseline was guided primarily by data availability. However, as our collective understanding of pre-1920 hydrologic conditions continue to evolve, earlier baselines may be evaluated within this general framework.

The emerging science of sociohydrology suggests that humans are an integral part of the hydrologic cycle (Sivapalan, Savenije, & Blöschl, 2012). The dynamic role of anthropogenic influence on hydrologic alteration in the San Francisco Bay-Delta estuary and watershed is clearly illustrated in the change attribution analysis presented here. Over time, development has altered annual and seasonal flows to meet a variety of societal objectives. In the early part of the study period, development was dominated by flood control projects and river diversions to support the watershed's growing agricultural economy. This early development resulted in an altered hydrologic regime that, when coupled with a severe drought in the 1920s and 1930s, had a dramatically negative effect on the quantity and quality of water available to downstream users. In response to these changed conditions, the federal government constructed the CVP to manage salinity intrusion and support out-of-basin exports (as well as meet flood control and other project purposes). Hydrologic alterations continued through the 1980s to support growth in the watershed's urban and agricultural sectors, as well as to support growth in water demand in other regions of California through expansion of the CVP and completion of the SWP. As societal values have evolved, Delta outflow has been increasingly managed to preserve the estuary's ecosystem health. As a result, despite continuing population growth since the 1980s, water exports from the Delta have stabilized, contrary to expectations (Nichols, Cloern, Luoma, & Peterson, 1986). Those dependent on water exports from the Delta have adapted through conservation and identification of other water sources. The sophisticated management of today's estuary, although not likely anticipated by water resource managers of the early 20th century, might be a predictable outcome of changing societal values through techniques being advanced in the socio-hydrology literature. Management complexity is likely to grow as the state of the system and societal values continue to change. Outflow and salinity standards may evolve with greater understanding of ecosystem processes and be integrated with other physical and biological metrics. Future management will continue to be challenged by changing sea levels, water temperatures, and runoff patterns; these changing conditions and management responses will result in feedbacks to the human communities that depend upon the estuary and its watershed. The future Delta, like the Delta today, will very much be a product of natural drivers and human decisions.

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