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RESEARCH

Characterizing Early 20th Century Outflow and Salinity Intrusion in the San Francisco Estuary

Paul H. Hutton[1,2] and Sujoy B. Roy*[1]

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* Corresponding author: *sujoy.roy@tetratech.com*

1 Tetra Tech, Inc.
Lafayette, CA 94549 USA

2 Executive Director
California Water and Environmental Modeling Forum
Vacaville, CA 95696-5051 USA

ABSTRACT

We evaluated two historically important data sets to characterize the San Francisco Estuary's salinity regime before the State of California began systematic data collection in the early 1920s. One set documents barge travel along the Sacramento and San Joaquin rivers to obtain water of adequate quality for local industry; a second set documents Delta inflow used to compute antecedent outflow. The barge travel distance reported over 2 decades (1908–1929) was well explained by flow–salinity modeling, indicating internal consistency in these measurements. However, absolute salinity intrusion estimated through the barge travel data is systematically lower than suggested by contemporaneous water-quality measurements available since 1921. Through integration of these data sets, our work showed substantial similarities between 1908–1921 and the subsequent period before construction of Shasta Dam (1922–1944). Our analysis reveals an apparent shift in the estuary's salinity regime, with lesser salinity intrusion occurring in pre-1919 summer and fall months as a result of higher summer Delta outflow; this shift may be related to lower storage and irrigation diversions as well as a preponderance of wet years with higher summer runoff in the pre–1919 period. We found seasonal patterns of wet year salinity intrusion to be comparable over the full study period (1908–1944), indicating that the relative effect of upstream water management is minimal when flows are high, consistent with findings reported in later periods. The barge and flow data provide qualitative insights on early 20th century conditions, when limited data are available. Post–1920 hydrology and salinity data are preferable for quantitative analyses because of better documentation associated with collection and analysis, and sustained reporting over several decades. This work provides a foundation for future efforts to characterize the hydrologic and hydrodynamic changes that occurred in the system between the 1850s (i.e., natural or pre-development conditions) and the 1920s.

KEY WORDS

Sacramento–San Joaquin Delta, hydrology reconstruction, estuarine salinity, C&H barge data, X2

INTRODUCTION

The settlement and economic development of California after the Gold Rush era of the 1850s was closely associated with large-scale hydrologic modification, especially in the San Francisco Estuary (estuary) and its upstream watershed. Changes over the following decades included conversion of land use from natural vegetation to agriculture, removal of riparian vegetation, levee construction as well as stream channelization and dredging to aid navigation and flood control, mining of hillsides with water jets (termed hydraulic mining), extensive water diversions from streams to support growing demands for irrigated agriculture and urban uses, and early development of in-stream storage facilities (CDPW 1931; Kelley 1989; Hundley 2001; Lund et al. 2010). These changes—which dramatically affected the hydrology, geomorphology, water quality, and ecosystem of the estuary and its watershed—were followed, beginning in the 1940s, by further hydrologic alterations associated with the federal Central Valley Project (CVP) and California's State Water Project (SWP).

Today, there is great scientific and regulatory interest in restoring the historical functions of the estuary, and, toward that end, in reconstructing the system's hydrologic changes, starting from the earliest major anthropogenic modifications. Much of the early information is anecdotal or incomplete, with scientific observations on flows and water quality beginning in the late 19th and early 20th centuries. Systematic measurements of flows across the region and salinity in the estuary began in the 1920s, and are the basis of most quantitative studies today. The California Department of Water Resources (CDWR) Joint Hydrology Study (CDWR 1957)—the seminal compilation of early hydrologic data for the region—employs water year (WY) 1922 as its starting point. California's water year runs from October 1 through September 30. Routine salinity sampling along the estuarine gradient was initiated during this time by the California Department of Public Works (CDPW), the predecessor to CDWR (CDPW 1931). An evaluation of salinity trends and the flow–salinity relationship in the estuary that spanned WYs 1922–2012, based on a digitization of the early grab-sample salinity data from 1922–1971 and integration with modern continuous data from 1967–2012, has been presented in Hutton et al. (2015).

Early 20th century anthropogenic changes in the watershed were coincident with a period of declining runoff, typical of wet and dry cycles in California's Mediterranean climate. Thus, flow and salinity trends during much of the "pre-project" period (i.e., before initial operation of the CVP Shasta Dam in 1944), were a consequence of decreasing precipitation in the watershed as well as the various hydrologic modifications enumerated in the opening paragraph.

This work examines the characteristics of outflow from the Sacramento–San Joaquin Delta (Delta) and flow–salinity behavior during the decade and a half preceding WY 1922 (1908–1921); this period is characterized by flow and salinity data that are limited in spatial and temporal coverage relative to the more systematic data collection beginning in the 1920s. We used two historic data sources to extend the early part of the flow-salinity record back to 1908. The first data source records salinity intrusion as characterized by an industrial user of Delta water, and the second data source records Delta inflow, through which Delta outflow was estimated.

The first data source provides a characterization of the estuary's salinity regime through proxy measurement. The California and Hawaiian Sugar Refining Corporation (C&H), whose sugar refinery is located at Crockett (Figure 1), obtained its freshwater supply from barges that traveled upstream on the Sacramento and San Joaquin rivers, with greater distance of travel in months with lower freshwater flows. A record of the barge travel over calendar years 1908–1929, showing both the distance traveled and the quality of water obtained, is documented in CDPW (1931) (Figure 1). The sugar refining process required a water quality to not exceed 5 parts of chlorine per 100,000 parts of water (i.e., 50 mg L^{-1} chloride), and the salinity was recorded when water was obtained (CDPW 1931). These records serve as a surrogate for the approximately 50 mg L^{-1} chloride isohaline during this period. Importantly, the C&H barge travel data overlap with early records of salinity data at fixed locations across the estuarine gradient, which were collected beginning in WY 1922 and reported by the CDPW in annual Bulletin 23 documents (CDPW 1924–1955; digitized data in Hutton et al. 2015).

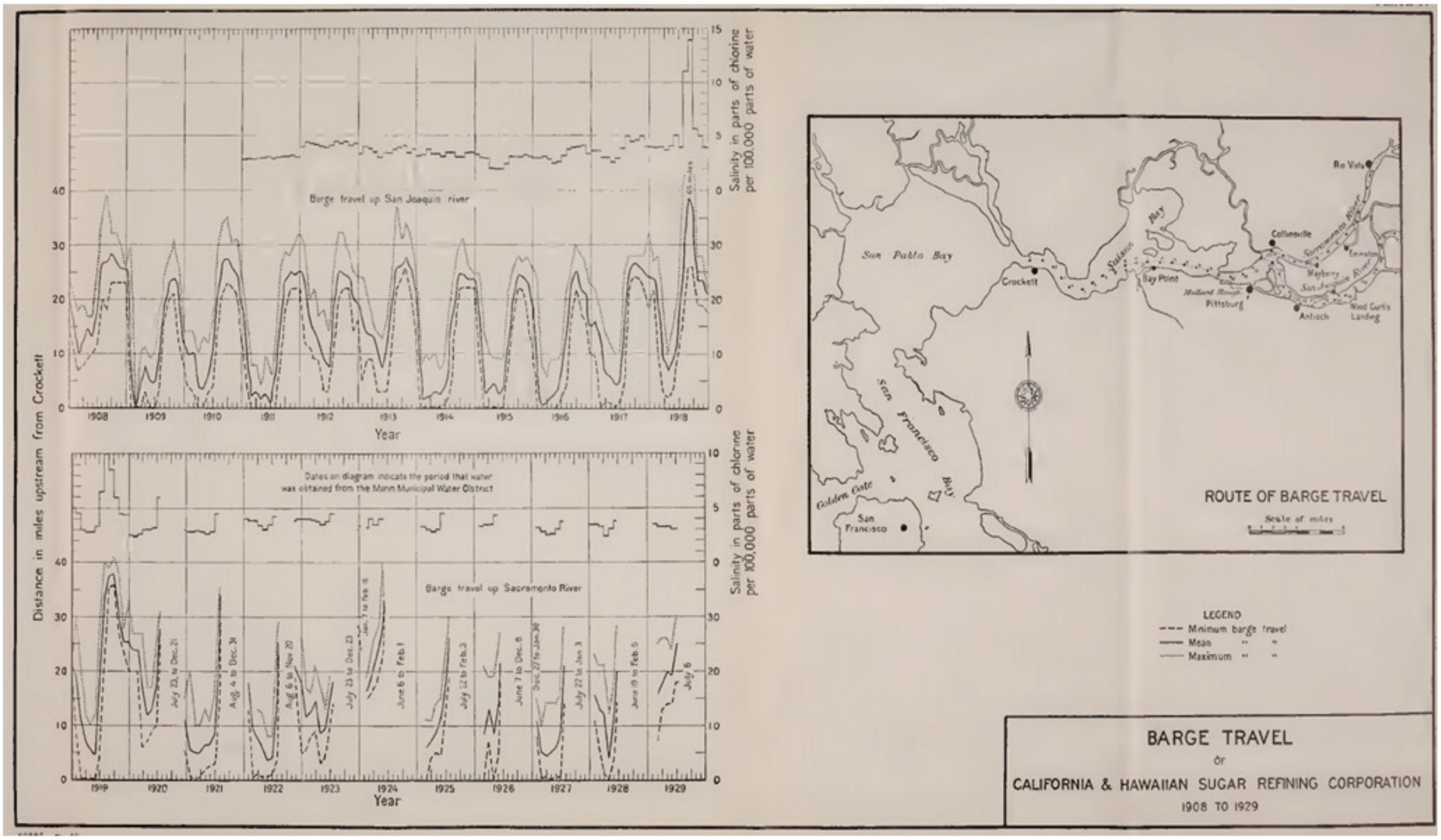

Figure 1 Barge travel data recorded by the California and Hawaiian Sugar Refining Corporation (C&H) over the period that spanned 1908–1929 are shown as a reproduction of Plate IV from CDPW (1931). The raw data time-series shown in this plate represent the approximate 50 mg L^{-1} chloride isohaline as measured upstream from Crockett, California (in miles). Concurrent chloride measurements are also provided on the time-series charts (in parts of chlorine per 100,000 parts of water). The time-series plots also indicate that barge travel was along the San Joaquin River in the early part of the record, and along Sacramento River after 1924. The map shown in this plate identifies the route of barge travel and identifies key features of the San Francisco Estuary.

Data from the first decade of monitoring were also synthesized in CDPW (1931). The second data source, also included in CDPW (1931), consists of pre-WY 1922 monthly inflow volumes to the Delta, beginning in October 1911 (i.e., WY 1912). Using an estimate of in-Delta channel depletions, we developed an estimate of monthly Delta outflow that could be related to the salinity proxy in the C&H record.

Our research objective is to develop relationships from the early flow and C&H barge travel data, spanning 1908–1929, and to explore whether flow–salinity behavior differs from our current understanding of the pre-project period, based on more systematic data collection from WY 1922–1944. The C&H data, along with the pre-WY 1922 Delta inflow data, are arguably the earliest direct record of monthly Delta flow and salinity intrusion, distinct from paleolimnological methods using sediment cores and tree rings, which represent temporal resolutions no smaller than annual or decadal (e.g., Malamud–Roam and Ingram 2004; Watson 2004; Stahle et al. 2011). Although the time-frame and data are limited, this evaluation is important because it adds to our overall understanding of the pre-project transition in Delta outflow and salinity conditions as the region's water resources were rapidly being developed and waterways were being transformed. Insight into this transition is useful in the broader context of restoration, with the goal of improving our understanding of pre-development conditions in the Delta. An alternative approach for exploring pre-

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project salinity is to use flow data for different levels of development with modeled estimates of salinity (as reported by Gross et al. 2018). This work differs from Gross et al. (2018) in utilizing the best available observations of salinity intrusion as well as flow observations to evaluate changes in the early part of the 20th century.

BACKGROUND

Geographic Setting and Early 20th Century Alterations

Our study's geographic focus is the central and northern reaches of the estuary and the watershed draining to the Delta (Figures 1 and 2). The Delta is the entry point of over 90% of the freshwater inflow to the estuary (Cheng et al. 1993), and is drained primarily by the Sacramento and San Joaquin rivers.

After the significant landscape alterations of the latter half of the 19th century—including removal of riparian vegetation, construction of man-made levees, "reclamation" of wetlands, hydraulic mining, and channelization—the turn of the 20th century was a period of steady change in the hydrography of the estuary and its watershed. Most of the major irrigation systems along the San Joaquin River tributaries had been initiated by 1890; however, irrigation development along the main stem of the San Joaquin River was carried out primarily after 1915. In about 1916, the inception and growth of the rice industry, stimulated by World War I demand and construction of the Panama Canal, brought about a rapid increase in water use in the Sacramento Valley. Significant growth in system-wide storage capacity began after about 1905. Before this date, storage capacity grew slowly at a rate of 3.6 thousand acre-feet (taf) per year (from 2 taf in 1850 to 200 taf in 1905). Between 1905 and 1929, storage capacity increased to 4,100 taf at a rate of about 200 taf per year (CDPW 1931). Although flood basin reclamation was carried out progressively over several years, complete closure from floods occurred over a relatively brief period between 1913 and 1920. Widening and deepening of the lower Sacramento River was carried out progressively from 1913 through the 1930s as part of the Sacramento Flood Control Project, modifying tidal flows and salinity intrusion. During this construction period, several islands in the western Delta region permanently flooded, further altering system hydrodynamics. The period spanned by the C&H data thus represents a system transformed from its natural condition—although less modified than it would come to be in future decades—with the construction of storage reservoirs on virtually all major tributaries of the Sacramento and San Joaquin River basins, and with the development of out-of-basin exports from the Delta to locations in the south of the state (Lund et al. 2010). Pre-project outflow and salinity conditions associated with the system's 1920 level of development, based on a flow–salinity model, are characterized in Gross et al. (2018). Pre-project developments in the watershed continued into the 1930s and early 1940s, culminating with the initial operation of Shasta Dam on the main stem of the Sacramento River in 1944. Shasta Dam remains the largest reservoir in the Delta watershed (capacity of 4.5 million acre-feet) and its operation led to a significant change in seasonal flow patterns. Although outside the period of this study, extensive development in the Delta watershed continued after 1944, with major dams on tributary rivers built into the late 1960s. Contemporary flow and salinity conditions in the Delta are influenced by these changes as well as by evolving salinity regulations that have been applied since the 1970s (see Hutton et al. 2015 for discussion).

Characterization of Climatic Conditions

The estuary's upstream watershed is characterized by large natural variations in annual precipitation and runoff, with peak annual runoff more than two times the average annual runoff. Annual streamflow volume in eight major rivers in the watershed (Sacramento, Feather, Yuba, American, San Joaquin, Stanislaus, Tuolumne, and Merced) (Figure 2), correcting for the effects of reservoirs and diversions and termed "unimpaired" runoff, is reported as the Eight River Index for measuring and comparing climatic conditions among years. Over WYs 1906–2017, the peak annual runoff from the Sacramento and San Joaquin River basins was 52.7 million acre-feet (maf); over this same period, mean annual runoff was 23.7 maf, and drought year runoff was often less than 10 maf (CDEC 2018). These unimpaired runoff estimates, along with an

Figure 2 Map of the Sacramento–San Joaquin Delta and watershed identifying the eight major rivers that flow through the California Central Valley and enter the San Francisco Estuary as Delta outflow. The approximate location of the Central Valley Project's Shasta Dam, part of the largest reservoir in the watershed, is also shown.

accounting of antecedent runoff conditions, are the basis for classifying water years into five categories: wet, above normal, below normal, dry, and critical. For this work, we employed an older water year classification based on the Sacramento River Index (CSWRCB 1978) in lieu of the more contemporary 40–30–30 classification (CSWRCB 2006), recognizing that (1) the latter was developed to account for the role of upstream storage on Delta operations, and (2) significant upstream storage was unavailable in the early 20th century.

Delta Salinity Intrusion

Salinity intrusion into the Delta varies as a function of freshwater inflow and tidal mixing, ranging from near ocean salinity at the mouth of the San Francisco Bay at Golden Gate, to near freshwater salinity in the Delta channels, with an intermediate zone of salinity moving landward and seaward seasonally as a function of freshwater outflow. Extensive salinity intrusion in the Delta beginning in 1918, caused by a combination of low runoff years and upstream land use and hydrologic change, motivated a series of water quality studies in the Delta that led to a better understanding of the relationship between sources of water flows and salinity patterns in the Delta (CDPW 1931). Since this time, salinity has been monitored regularly at fixed locations across the estuarine gradient, first through grab samples (until the early 1970s), and subsequently through continuous conductivity sensors. A recent data synthesis effort has compiled the historical flow and salinity data, and performed an evaluation of the flow–salinity relationship over WYs 1922–2012 (Hutton et al. 2015). Trends in seasonal Delta inflow and outflow over this period of record have affected salinity intrusion (Hutton et al. 2017). However, no significant change in the relationship between Delta outflow and the position of the low salinity zone was found over WYs 1922–2012 (i.e., a fixed set of parameters in an empirically fitted relationship were adequate to represent low salinity zone behavior over the entire 9-decade period) in spite of measured sea level rise, and extensive landscape and bathymetric change in the Delta and upstream watershed (Hutton et al. 2015; Gross et al. 2018).

The low salinity zone in the estuary, specifically the location or position of two parts per thousand (ppt) bottom salinity isohaline—hereafter referred to as X2 and measured as the distance in kilometers from the Golden Gate—has been correlated with the abundance of several estuarine species (Jassby et al. 1995) and is considered ecologically important. The position of the X2 isohaline during the months of February through June is currently used as the basis of flow management in the estuary (CSWRCB 2006). Estuarine flows are managed through upstream reservoir releases and exports of water from the Delta. A recent Biological Opinion on the endangered Delta Smelt (USFWS 2008) regulates X2 position in fall months (September through November) after wet and above-normal water years. A large published literature relates X2 to various ecological metrics

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(e.g., Feyrer et al. 2007; Mac Nally et al. 2010; Cloern et al. 2017), and regulation of X2 or some similar measure of the low salinity zone is likely to evolve over time. Although the concept of X2 position did not exist as a formal regulatory metric before the early 1990s, it can nonetheless be computed from historical data and used to compare salinity conditions over different time-periods during which infrastructure, regulation, and water use changed significantly. Over a long period of record (i.e. several decades), salinity behavior is affected by climatic variability and changes in water management. To minimize the confounding effect of both factors simultaneously, analyses are often performed with variable hydrology but with a fixed level of development (e.g., Gross et al. 2018).

METHODS

We selected the methods we use here to compare the C&H barge travel data with independent, overlapping data sources and allow for a systematic evaluation and characterization of early 20th century outflow and salinity intrusion in the estuary, with primary emphasis on the pre-WY 1922 period and secondary emphasis on the period before initial operation of Shasta Reservoir (i.e., WYs 1922–1944). Although contemporaneous flow and salinity data are not available for the entire pre-WY 1922 period, we used intervals of considerable overlap to integrate the C&H data with other more commonly used flow and salinity data sets. The key data sources, time-frames, and analysis procedures are described in Hutton and Roy (2019) and summarized below.

Data

Table 1 summarizes sources of hydrologic and water quality data used in our analysis. Key data include C&H barge travel data, hydrology data (including unimpaired runoff, Delta precipitation, and Delta inflow, outflow and gross channel depletions), and grab-sample salinity measurements at various locations in the estuary. We conducted all analyses using monthly averages to accommodate prevailing data frequency. Figure 3 presents a timeline that shows the availability of key data sets we used; a brief narrative description of these data follow.

C&H Barge Travel Data

A graphical display of these data, presented in CDPW (1931) for the period that spans January 1908 through December 1929, are reproduced in Figure 1. A monthly average tabulation of a subset of the chart's data is provided in Means (1928). Other than

Table 1 Summary of data sources used in this work

Category	Description	Source	Comments
C&H barge travel data	Average barge travel distance (upstream of Crockett) and chloride concentration: January 1908 – December 1929 Average barge travel distance (upstream of Crockett): January 1908 – July 1920	Bulletin 27, Plate IV (CDPW 1931) Salt Water Problem, Table 1 (Means 1928)	Digitized daily interpolation of travel data 1908–1918 provided by CCWD (2011, unreferenced, see "Notes")
Unimpaired runoff	Eight River Index, annual and monthly unimpaired runoff: WYs 1908–1944	CDEC (2018)	—
Delta precipitation	Monthly intensity: WYs 1908–1944	CDEC (2018)	Measured at Stockton Fire Station 4
Delta Inflow, outflow, and gross channel depletions	Monthly volumes: WYs 1922–1929 Monthly volumes: WYs 1930–1944	CDWR (2011) DAYFLOW (1986)	
Delta Inflow	Monthly volumes: WYs 1912–1929	Bulletin 27, Table 38 (CDPW 1931)	Presented as Sacramento and San Joaquin River inflow
Delta salinity concentrations	Monthly average cleaned & filled EC data at various locations: WYs 1922–1944	Hutton et al. (2015)	EC data based on original grab-sample chloride data reported in Bulletin 23 (CDPW 1924–1955)
X2 position	Monthly average X2 estimates: WYs 1922–1944	Hutton et al. (2015)	X2 estimates based on original grab sample chloride data reported in Bulletin 23 (CDPW 1924–1955)

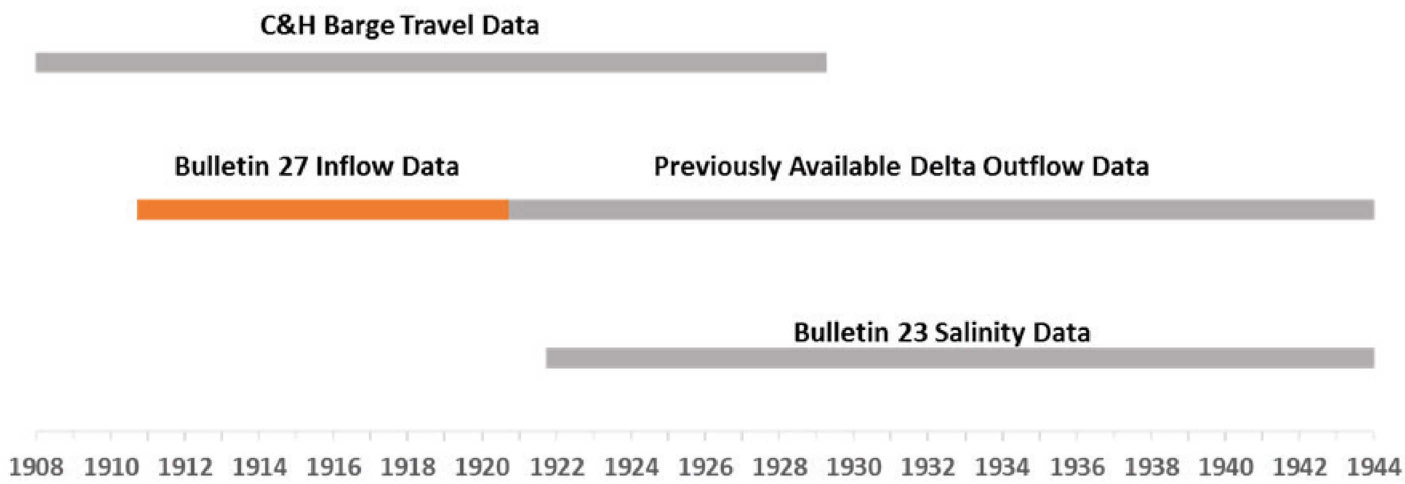

Figure 3 Timeline showing the availability of key data sets used in this work

a brief narrative description of the water collection process in CDPW (1931), no other primary data on the collection methodology is readily available.

Hydrology Data

We obtained monthly unimpaired runoff (as measured by the Eight River Index) and Delta precipitation, used to evaluate climatic conditions over the pre-project period that spans 1908–1944, from the California Data Exchange Center (CDEC 2018). We obtained monthly Delta inflow volumes over the period that spans WYs 1912–1921 from CDPW (1931). We obtained post-WY 1921 hydrology data, including Delta inflow, outflow, and gross channel depletions, from CDWR's DAYFLOW database (CDWR 1986) and their Bay–Delta office (CDWR 2011, unreferenced, see "Notes").

Salinity Data

The State of California's Bulletin 23 (CDPW 1924–1955) is a well documented series of reports on a multi-decade effort to characterize salinity behavior across the Bay and Delta. Data were collected several times each month at numerous locations; sampling date and time were recorded, and sampling was adjusted for tide levels to measure the highest daily salinity at each location. Despite these efforts, data inconsistencies are revealed when evaluated along the salinity gradient during a single day. Hutton et al. (2015) corrected these inconsistencies, and filled gaps. Monthly average salinity at fixed locations and calculated X2 values for WYs 1922–1944 are based on work reported in Hutton et al. (2015).

Interpretation of C&H Barge Travel Data

The C&H barge travel data, shown in Figure 1, include time-series of minimum, mean, and maximum travel distances in miles upstream of Crockett. The figure also includes a time-series of average chloride concentration in parts per 100,000, consistent with units reported for grab-sample data collected by the State of California (CDPW 1924–1955). The figure indicates that travel was along the San Joaquin River in the early part of the record, and along the Sacramento River in the latter part of the record. Furthermore, the figure shows that the 50 mg L^{-1} chloride threshold was exceeded in the late summer and fall of 1918 and 1919 and, starting in 1920, barge travel was halted during the summer and fall months, and water was obtained elsewhere. An earlier interpretation of a subset of the mean travel data is reported in CCWD (2010).

We digitized mean barge travel distances from Figure 1, and a monthly tabulation is available in Means (1928) for a subset of the period January 1908 through July 1920. The Contra Costa Water District (CCWD) provided interpolation of the mean travel data on a daily time-step for the period January 1908

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through December 1918 (CCWD 2011, unreferenced, see "Notes"). We estimated travel distances for the remaining period (i.e., January 1919 through December 1929) through visual inspection of the figure. We re-computed distances, recorded as miles upstream of Crockett, as kilometers upstream of Golden Gate by adding 27.5 miles and converting from miles to kilometers. We refer to these travel distances, in units of kilometers, as $X_{C\&H}$ to indicate the barge travel distance; this nominally corresponds to the 50 mg L^{-1} chloride isohaline position, although often the water collected was of lower salinity—and occasionally of higher salinity—as indicated by the concurrent chloride measurements Figure 1 reports.

Because no information is available on the analytical method or sample-collection method used in the C&H effort, direct comparisons with contemporaneous grab-sample salinity data from WYs 1922–1929, as reported in CDPW (1931), is challenging. For this analysis, we consider $X_{C\&H}$ to be an independent isohaline measured over 2 decades with an internally consistent methodology. In the absence of a primary source on the C&H water-collection effort, we made the following additional assumptions in quantitatively interpreting the C&H data:

- We assumed the end-of-month (EOM) value was the actual monthly average, because temporal resolution of the raw C&H data is not reported. This interpretation is well aligned with the average monthly tabulation provided by Means (1928) and, as described in the results, provides a strong correlation with available flow data. Results presented in this analysis assume the average monthly C&H barge travel distance is represented by (1) the Means (1928) tabulation for the period January 1908 through December 1918, and (2) our EOM interpolation of Figure 1 for the remaining period, i.e., through December 1929 used as average monthly values. Two individual points in Means (1928) appeared to be incorrectly transcribed, and were corrected using the CCWD EOM tabulation (Hutton and Roy 2019).
- We assumed C&H data collection was systematic relative to the tidal cycle; however, no explicit information is available to relate distance records with the tidal cycle. According to CDPW (1931), "It has been the usual practice to make two trips each day, going up on the flood tide and returning on the ebb tide." As noted elsewhere (CCWD 2010), "... depending on the source of information, the C&H barges are said to have traveled with the tide, indicating they either took water at high tide (moving up river on the flood and down on the ebb) or at low tide (traveling against the tide, but moving a shorter distance). Thus, the C&H records either represent the daily maximum or daily minimum distance traveled. ... The difference between daily average distance and daily minimum or maximum is approximately 2 to 3 miles."
- Periods associated with barge travel up the San Joaquin and Sacramento river transects are uncertain. The upper time-series panel in Figure 1 includes a centered notation that barge travel was up the San Joaquin River; the lower panel of the same figure includes an offset notation that barge travel was up the Sacramento River. Given the offset notation and the premise that the critically dry year of 1924 may have motivated a change in procedure, we assumed barge travel switched from the San Joaquin River to the Sacramento River beginning in 1925. Before 1920, barge travel was conducted year-round. Between 1920 and 1923, barge travel was halted in late July or early August. In 1924, because of the particularly dry conditions, barge travel was halted in early June.

Delta Outflow Estimates

Monthly estimates of Delta outflow are available beginning October 1921 (Hutton et al. 2015). In this work, we extended the monthly time-series back to October 1911, assuming the following water balance and approach shown in Equation 1:

$$\textit{Delta Outflow} = \textit{Delta Inflow} + \textit{Delta Precipitation} - \textit{Delta Gross Channel Depletion} \quad (1)$$

Monthly Delta inflow volume is reported for the Sacramento and San Joaquin rivers in Table 38 of CDPW (1931). According to documentation associated with the table, Sacramento River inflow represents the sum of flow from the Sacramento River at Freeport and the Yolo Bypass; San Joaquin River inflow represents the sum of Delta inflows from the Cosumnes, Mokelumne, and Calaveras rivers, as well as flow in the San Joaquin River at Vernalis. We estimated Delta precipitation from monthly precipitation records (in inches per month) measured at Stockton Fire Station 4 (CDEC 2018). We estimated monthly flow volumes assuming a total Delta area of 738,000 acres. Pre-WY 1922 gross channel depletion was estimated assuming (1) the temporal trend in annual gross channel depletion was consistent with the subsequent period that spanned WYs 1922–1944 (i.e., an annual increase of approximately 11.4 taf), and (2) monthly distribution of gross channel depletion (i.e., percent of annual depletion) was identical to that estimated for WY 1922.

Using the above approach, we produced monthly estimates of Delta outflow to extend the time-series back to October 1911. As a validation step, we also produced monthly estimates for the period October 1921 through September 1929, and compared them to estimates provided by CDWR's Bay–Delta Office (CDWR 2011, unreferenced, see "Notes"). The Delta outflow estimates compared favorably with the CDWR estimates (Hutton and Roy 2019), providing a level of confidence in the reported inflow volumes and the approach we used.

Isohaline Distance Estimates

Conceptually, any number of isohalines can be used to measure salinity intrusion in the estuary. Furthermore, the locations of these isohalines can be directly measured (as in the case of the C&H barge travel data) or estimated through interpolation of salinity data collected at fixed locations. Alternatively, the isohaline positions may be predicted through mathematical flow–salinity relationships. We consider two specific isohalines. Given our objective to analyze the C&H barge travel data, emphasis is on the 50 mg L^{-1} chloride isohaline. However, we also consider the 2 ppt bottom salinity isohaline (X2), given its importance in contemporary Delta water management (Jassby et al. 1995; CSWRCB 2006). To complement the C&H isohaline distance records (i.e., $X_{C\&H}$), we also estimated 50 mg L^{-1} chloride isohaline distances through interpolation of available salinity records, and we refer to them as X_{50} to distinguish them from the C&H barge data.

As described below, we also use flow–salinity relationships to estimate isohaline distances. Hereafter, we distinguish isohaline distances predicted from these flow–salinity relationships from measured or interpolated distances through consistent nomenclature:

- $X_{C\&H}$* refers to the predicted 50 mg L^{-1} isohaline distance based on C&H data
- X_{50}* refers to the predicted 50 mg L^{-1} isohaline distance based on available salinity data
- X2* refers to the predicted 2 ppt bottom salinity isohaline distance based on available salinity data

Isohalines from Grab Sample Salinity Data

We used cleaned and filled salinity data, reported by Hutton et al. (2015) and based on Bulletin 23 grab samples (CDPW 1924–1955), to estimate X_{50} isohalines for the period October 1921 through September 1929, and compared these X_{50} estimates with $X_{C\&H}$ where concurrent measurements were available. To estimate X_{50}, we used the log salinity-linear distance interpolation approach employed by Hutton et al. (2015) to estimate X2. However, we found interpolation of an isohaline distance in the range of relatively low salinity values such as X_{50} difficult, given that (1) the seawater signal can be confounded by land-derived salts, and (2) the salinity gradient is very flat. We used relationships between interpolated X2 and X_{50} values to guide interpretation of salinity data and interpolation of X_{50}.

Isohalines from Flow–Salinity Relationships

We used the flow–distance modeling approach described by Hutton et al (2015), summarized in Appendix A, to predict isohaline distances $X_{C\&H}$*, X2*, and X_{50}* as a function of antecedent outflow. We used the reconstructed monthly Delta outflow time-series to estimate a monthly average antecedent outflow time-series following Denton's (1993) approach shown in Equation A2. We assumed a nominal value for β of 475 cfs-years in the calculation of antecedent outflow, consistent with Hutton et al (2015). We generated a predicted monthly X2* time-series using Equation A4,

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assuming the reconstructed monthly average antecedent outflow time-series and parameter values ϕ_1 and ϕ_2 from Hutton et al (2015). Similarly, we correlated the $X_{C\&H}$ and antecedent outflow time-series through recalibration of Equation A4. Finally, based on the characteristic salinity gradient in the estuary (Monismith et al. 2002), the entire gradient can be expressed as a function of X2*, and we generated a predicted monthly X_{50}* time-series using Equation A7.

RESULTS

We used the data sources and methods described above to evaluate the C&H barge travel and reconstructed Delta outflow data sets. We first correlated the $X_{C\&H}$ estimates with antecedent outflow derived from reconstructed Delta outflow data; we compared this relationship with that predicted by Hutton et al. (2015). We then directly compared the $X_{C\&H}$ estimates with X_{50} estimates from Bulletin 23 grab-sample data. Next, we extended the X2 time-series back to January 1908, using antecedent outflow predicted from correlation with $X_{C\&H}$ estimates. Finally, we evaluated the relationship between watershed unimpaired runoff and Delta conditions to account for the influence of climatic variability on observed trends during the pre-project period.

Flow–Distance Relationship Calibrated with C&H Data: $X_{C\&H^*}$

We plotted $X_{C\&H}$ values against monthly antecedent outflow estimates for the period January 1912–December 1918 and statistically fit them to the empirical form proposed by Hutton et al (2015) (Equation A4), resulting in regression constants $\phi_1 = 600$ and $\phi_2 = -0.218$ with $R^2 = 0.957$ and a 3.1 km standard error of estimate (see Figure 4). Although the reconstructed outflow time-series begins October 1911, initial conditions were unavailable to compute antecedent outflow for that month. By January 1912, flows were sufficiently high that the uncertainty of the October conditions little affected the antecedent outflow estimate.

The ϕ_2 estimate for $X_{C\&H}$* is similar to that obtained in other studies. For example, when calibrated to X2 estimates derived from surface salinity measurements, Hutton et al. (2015) reported $\phi_2 = -0.203$ along the San Joaquin River transect. As another example, Andrews et al. (2017) reported $\phi_2 = -0.230$ average of the Sacramento and San Joaquin river transects when calibrated to X2 bottom salinity estimates derived from a hydrodynamic model of the contemporary system.

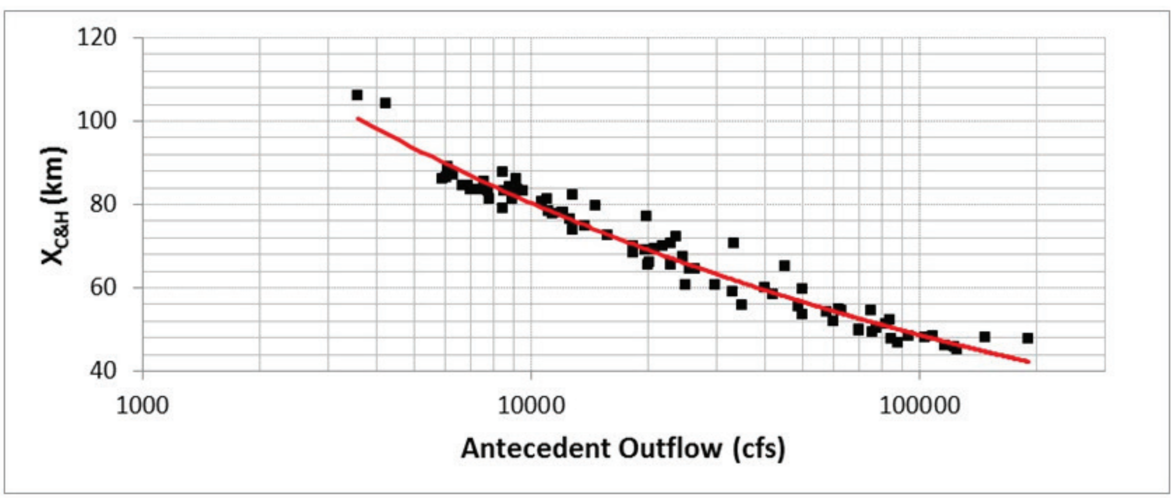

Figure 4 The California and Hawaiian Sugar Refining Corporation (C&H) barge travel data ($X_{C\&H}$), as generally tabulated in Means (1928), are shown as a function of antecedent outflow for the period that spanned January 1912 through December 1918. Equation A4 was fit to the data, resulting in regression constants $\phi_1 = 600$ and $\phi_2 = -0.218$ with a 3.1 km standard error of estimate.

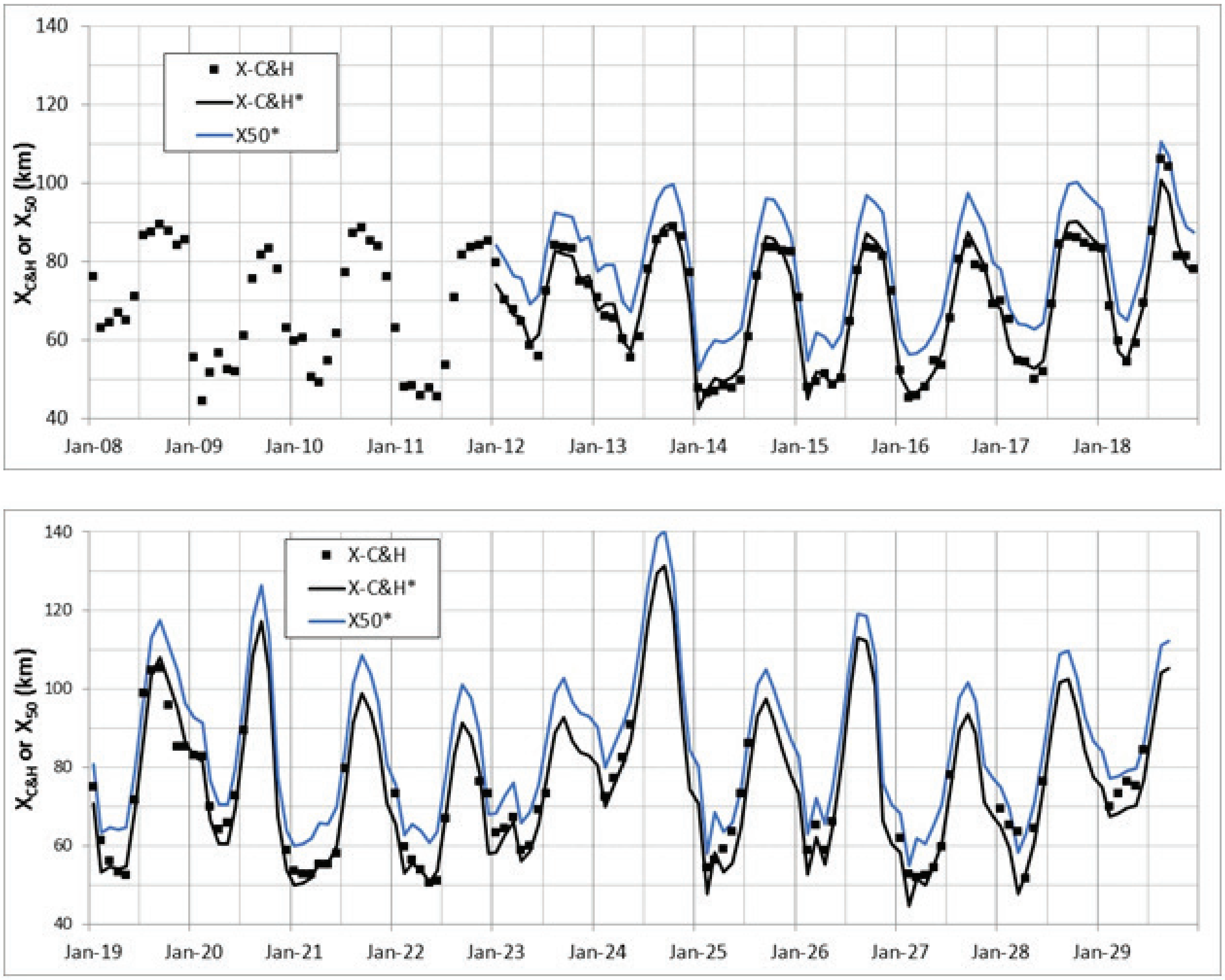

Figure 5 Time-series comparison of monthly average 50 mg L^{-1} chloride isohaline (km from Golden Gate) as measured by the California and Hawaiian Sugar Refining Corporation (C&H) barge travel data ($X_{C\&H}$ shown as symbols) and as predicted by both the re-calibrated Equation A4 shown in Figure 4 ($X_{C\&H*}$) and by Equation A7 (X_{50*}) over the period January 1908 through September 1929

Flow–Distance Relationship Predicted by Hutton et al. (2015): X_{50}*

We used Equation A7 to independently estimate X_{50}* for the period January 1912 through September 1929 as a function of antecedent outflow. This approach implicitly assumes that salinity values reported in Bulletin 23 are the basis of the X_{50}* isohaline. We computed monthly average X_{50}* values assuming (1) monthly average antecedent outflows, (2) model constants for the Sacramento and San Joaquin river transects as reported by Hutton et al. (2015), and (3) a salinity of 50 mg L^{-1} chloride assumed equivalent to 0.35 milliSiemens per centimeter (mS cm^{-1}) specific conductance (Denton 2015).

Figure 5 compares the reported monthly average $X_{C\&H}$ values (digitized from Figure 1) with two model estimates: $X_{C\&H}$* (from calibration of Equation A4 as described above in "Flow–Distance Relationship Calibrated with C&H Data: $X_{C\&H}$*" and X_{50}* (from the Hutton et al. (2015) calibration of Equation A7). The $X_{C\&H}$* time-series (shown as a black line) is generally well aligned with observed $X_{C\&H}$ values, both in absolute value and seasonal variability. Deviations between post-1924 observed and predicted values are from, in part, the former being measured along the Sacramento River transect and the latter being based on an equation calibrated with San Joaquin River transect data. The X_{50}* time-series derived from Equation A7 (shown as a blue line) is systematically

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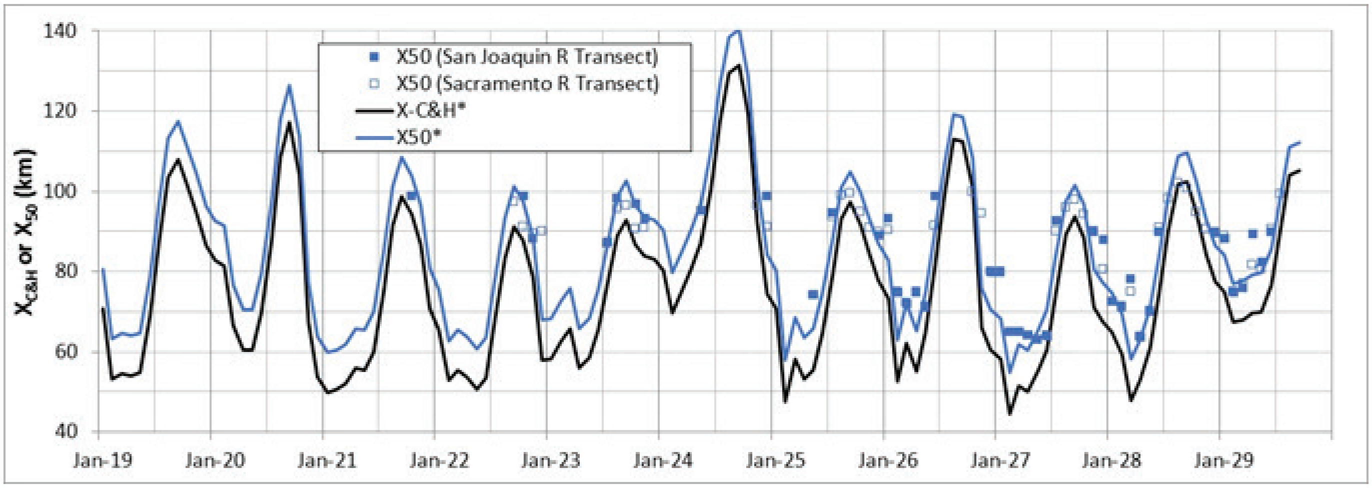

Figure 6 Monthly averages of X_{50}, estimated from the cleaned and filled daily salinity data reported in Hutton et al. (2015) along the San Joaquin and Sacramento river transects (closed and open squares), are compared with predictions of $X_{C\&H*}$ from the re-calibrated Equation A4 (see Figure 4) and X_{50*} from Equation A7

higher than the $X_{C\&H}$ and $X_{C\&H}^*$ time-series by approximately 10 km. This difference, which could indicate a step change in the system's flow–salinity relationship or a systematic bias in the C&H records, is explored below.

Isohalines Estimated from Bulletin 23 Salinity Data: X_{50}

Figure 6 compares interpolated Bulletin 23 X_{50} estimates for both San Joaquin and Sacramento river transects with the $X_{C\&H}^*$ and X_{50}^* time-series presented in Figure 5. Figure 6 spans the latter half of the C&H data record (1919–1929 rather than 1908–1929), more closely aligning with Bulletin 23 X_{50} data availability beginning in WY 1922. The $X_{C\&H}^*$ time-series is systematically lower than the Bulletin 23 X_{50} estimates by approximately 10 km, whereas the X_{50}^* time-series matches the Bulletin 23 X_{50} estimates reasonably well. Comparing interpolated Bulletin 23 X_{50} estimates with reported (rather than predicted) $X_{C\&H}$ distance shows a similar bias. Table 2, which presents the two data sets for months of concurrent measurement, reveals a bias of approximately 10 km, with individual differences ranging between 4 and 18 km.

These comparisons suggest that the difference between $X_{C\&H}$ and X_{50} estimates represent a systematic bias and not a step change in the flow–salinity relationship between the periods measured by the barge travel and Bulletin 23 data. The Bulletin 23 data—part of a major, multi-year scientific analysis of Delta salinity at a nominally fixed frequency across more than a dozen locations—are considered to be a credible salinity record that correlated strongly with Delta outflow over a period of more than 4 decades (Hutton et al. 2015). The above comparison, with a systematic difference between the X_{50} values derived from the Bulletin 23 data and the $X_{C\&H}$ values derived from the barge travel data, indicates that the C&H data are consistent and useful for year-to-year relative comparisons of salinity intrusion over 1908–1929. The C&H barge travel distance values are considered to be operational estimates that are assumed to be internally consistent over the 2-decade period of record. In terms of quantifying absolute salinity, the Bulletin 23 data provide greater confidence because of the program's greater volume of data, as well as its contemporaneous documentation (CDPW 1924–1955) and scientific focus.

Extension of X2 Record Using Antecedent Outflow Estimates: X2*

We computed X2* monthly averages (using Equation A4) as a function of antecedent outflow

Table 2 50 mg L^{-1} chloride isohaline, reported as the distance from Golden Gate in kilometers and based on C&H barge travel data ($X_{C\&H}$) compared to Bulletin 23 salinity data (X_{50}). The isohaline distance estimates based on C&H barge travel data are systematically lower than the Bulletin 23 estimates by about 10 km.

Date	River transect	Measured 50 mg L^{-1} isohaline distance (km from Golden Gate)		
		$X_{C\&H}$	X_{50}	Difference
Nov 1922	San Joaquin	76.4	88.2	−11.8
Jul 1923	San Joaquin	73.2	87.5	−14.2
May 1924	San Joaquin	90.9	95.2	−4.3
May 1925	Sacramento	63.6	74.3	−10.7
Jul 1925	Sacramento	86.1	93.7	−7.6
Feb 1926	Sacramento	58.7	75.0	−16.3
Mar 1926	Sacramento	65.2	72.1	−7.0
Apr 1926	Sacramento	58.7	75.0	−16.3
May 1926	Sacramento	66.0	71.3	−5.3
Jan 1927	Sacramento	61.9	80.0	−18.1
Feb 1927	Sacramento	52.8	65.0	−12.2
Mar 1927	Sacramento	51.8	65.0	−13.2
Apr 1927	Sacramento	52.3	64.2	−11.9
May 1927	Sacramento	54.4	63.0	−8.6
Jun 1927	Sacramento	59.5	64.0	−4.5
Jul 1927	Sacramento	78.0	90.0	−12.0
Jan 1928	Sacramento	69.3	72.6	−3.3
Feb 1928	Sacramento	65.2	71.3	−6.2
Mar 1928	Sacramento	63.6	75.0	−11.4
Apr 1928	Sacramento	51.5	63.7	−12.2
May 1928	Sacramento	64.4	70.2	−5.8
Jun 1928	Sacramento	76.4	91.0	−14.6
Feb 1929	Sacramento	70.0	75.0	−5.0
Mar 1929	Sacramento	73.2	77.0	−3.8
Apr 1929	Sacramento	76.4	81.7	−5.2
May 1929	Sacramento	75.3	80.6	−5.3
Jun 1929	Sacramento	84.5	90.6	−6.1

for the pre-project period that spanned 1908–1944, assuming model constants reported by Hutton et al. (2015). Figures 7 and 8 present a subset of the resulting values, which extends the X2* time-series nearly 14 years relative to the time-series reported in Hutton et al. (2015), for the San Joaquin and Sacramento river transects, respectively. In general, we computed antecedent outflow as a function of Delta outflow following Equation A2 and as described earlier in "Isohalines from Flow-Salinity Relationships." However, to account for the incomplete Delta outflow record, we back-calculated antecedent outflow before January 1912 from Equation A4, given C&H data (i.e., $X_{C\&H}$) and recalibrated model constants presented earlier in "Flow–Distance Relationship Calibrated with C&H Data: $X_{C\&H}$*." The pre-WY 1922 X2* estimates are thus based partly on an outflow reconstruction from Delta inflow (January 1912 through October 1921) and partly on an antecedent outflow reconstruction based on $X_{C\&H}$ values (January 1908 through December 1911). X2 monthly averages—as estimated through interpolation of Bulletin 23 salinity data (CDPW 1924–1955) and as reported by Hutton et al. (2015)—overlay the X2* time-series in Figures 7 and 8, and demonstrate the overall consistency between the model (Equation A4) and the Bulletin 23 observations in the overlapping WYs 1922–1929 period.

Relationship Between Unimpaired Watershed Runoff and Delta Conditions

A visual inspection of Figures 5, 7, and 8 suggests an apparent shift in the estuary's salinity regime in 1918. Between 1908 and 1918, our estimates of September X2* (nominally the month with peak salinity intrusion) average about 83 km on the San Joaquin and Sacramento river transects. For the remainder of the pre-project period, our estimates of September X2* rarely drop below 90 km. Detection of trends in Delta hydrologic and water quality data is generally confounded by large inter-annual climatic variability (Hutton et al. 2017). To account for this variability in evaluating the apparent X2* increase in 1918, we explored correspondence between pre-project unimpaired watershed runoff and Delta outflow. We hypothesize that, if the relationship between unimpaired runoff and Delta outflow is similar over the pre- and post-1919 periods, apparent hydrologic and water quality trends are likely the result of climatic variability rather than anthropogenic drivers such as land-use changes or water-management practices.

The top panel of Figure 9 plots average Delta outflow for the June–September summer irrigation season as a function of April–July unimpaired runoff (a

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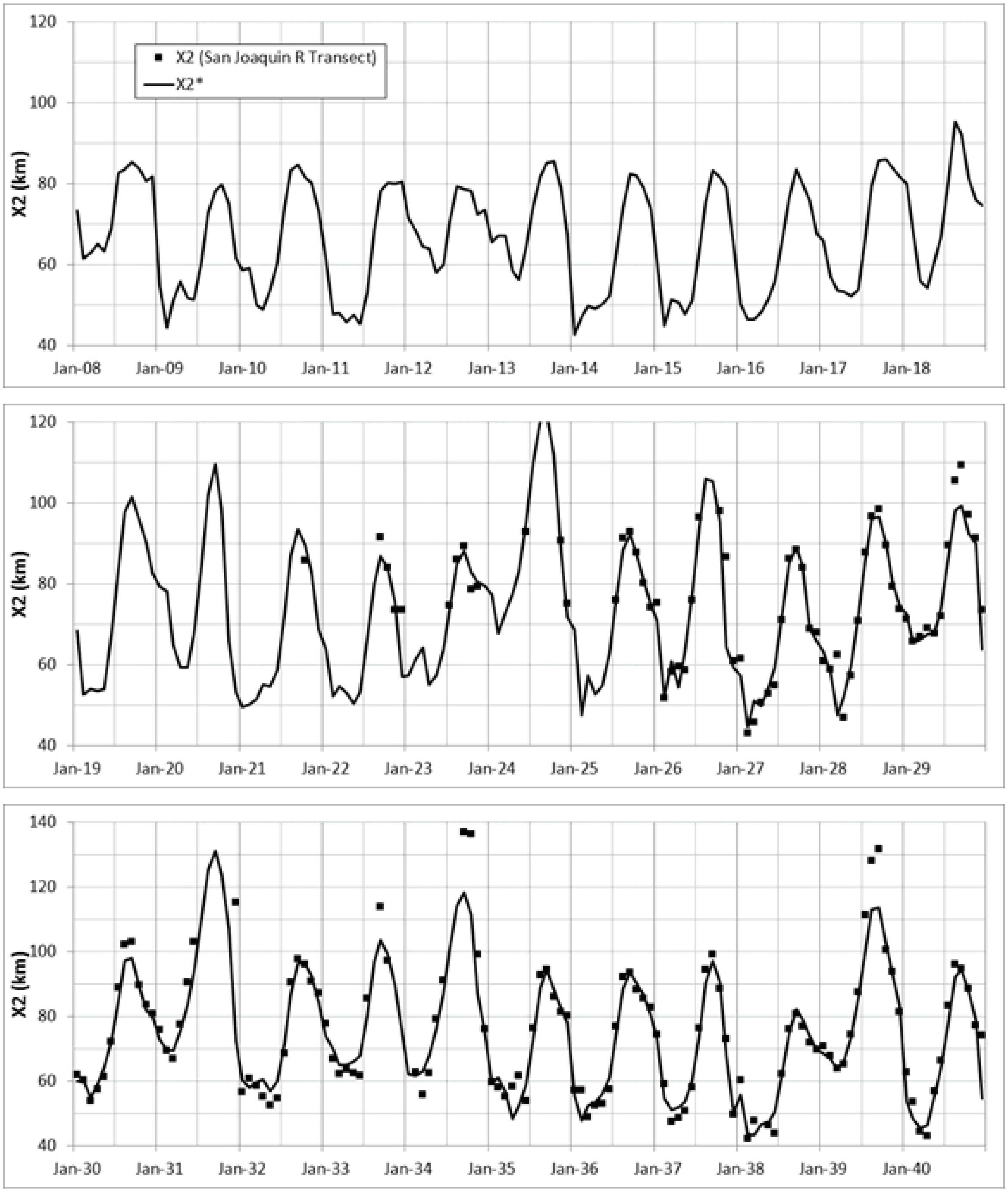

Figure 7 Time-series comparison of monthly average X2 as measured from Golden Gate along the San Joaquin River transect and as predicted by Equation A4 (X2*) for a subset of the pre-Project period that spanned January 1908 through December 1940.

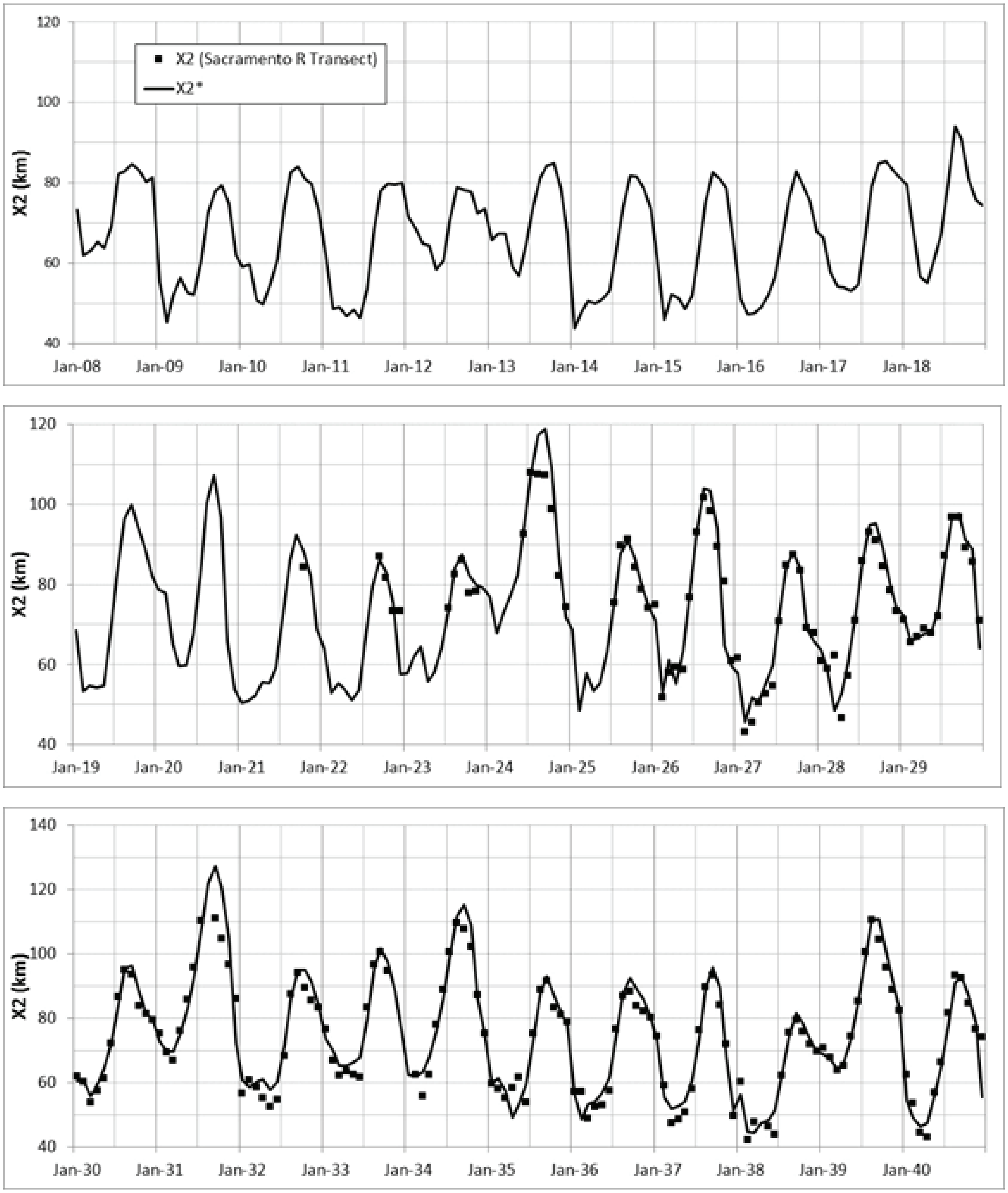

Figure 8 Time-series comparison of monthly average X2 as measured from Golden Gate along the Sacramento River transect and as predicted by Equation A4 (X2*) for a subset of the pre-Project period that spanned January 1908 through December 1940.

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measure of annual climatic conditions) for the periods that span WYs 1912–1918 and 1919–1944; it shows that Delta outflow was systematically higher during the earlier period for the same unimpaired runoff. The bottom panel of Figure 9 plots average December through May (winter-spring) Delta outflow as a function of October–March unimpaired runoff; it shows no difference between the two periods. The dashed lines shown in Figure 9 represent quadratic regression fits to the WYs 1919–1944 data bounded by two standard errors. Systematic differences in Delta outflow observed during the summer irrigation season may suggest that a change in upstream water use occurred in or around 1919 consistent with upstream storage and irrigation records. Figure 10 plots June–September unimpaired runoff as a function of April–July unimpaired runoff; it shows that summer runoff tended to be higher in the early part of the record (pre-WY 1919), as all but one data point lies above the regression line. Thus, differences observed in the top panel of Figure 9 may be partly explained by higher summer runoff in the early part of the hydrologic record.

Building on the relationship between unimpaired runoff and Delta outflow over the pre- and post-1919 periods, we examined the corresponding changes in X2 by water year type as classified by the Sacramento River Index (CSWRCB 1978). We employed this older water-year classification in lieu of the more contemporary 40–30–30 classification (CSWRCB 2006) recognizing that (1) the latter was developed to account for the role of upstream storage on Delta operations, and (2) significant upstream storage was unavailable in the early 20th century. Figure 11 compares predicted monthly average X2* values from 6 wet years of the early period (1908–1918, shown as lines) with observed X2 monthly averages from 2 of the 6 wet years that occurred in the later period (1919–1944, shown as symbols). Wet water years include 1921, 1927, 1938, 1941, 1942, and 1943. However, observed X2 data availability is limited to WYs 1927 and 1938. X2 values in October and November are generally more closely associated with the previous water year; thus, using the convention followed by Hutton et al. (2015) and Gross et al. (2018), the x-axis in Figure 11 spans the months December through November. Based on this comparison, X2 seasonal variability in wet years

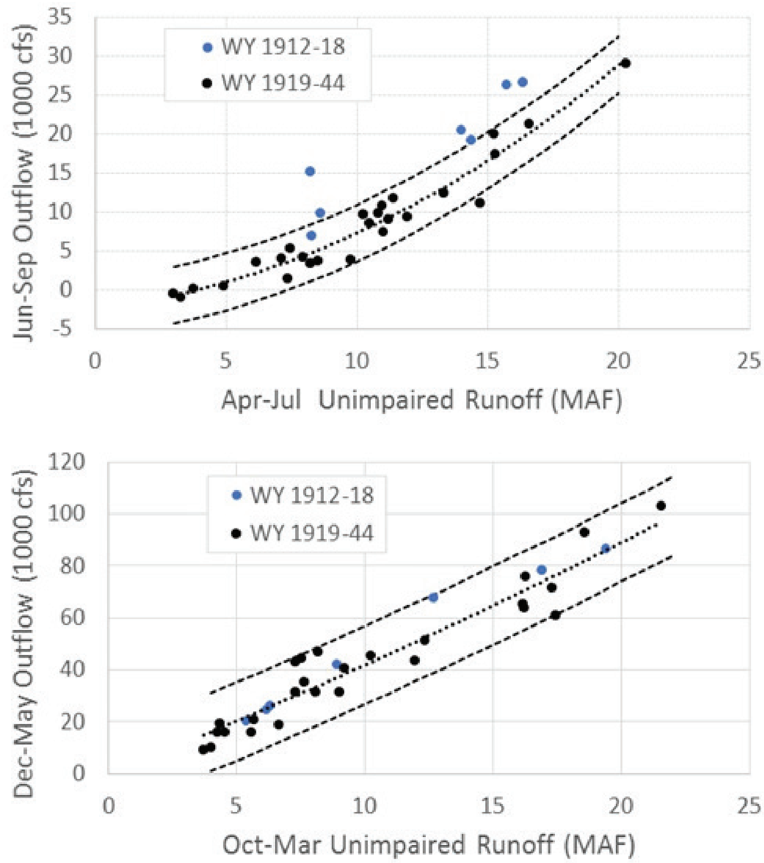

Figure 9 The top panel shows average June–September outflow as a function of April–July unimpaired runoff; the bottom panel shows average December-May outflow as a function of October–March unimpaired runoff. WY 1919–1944 data are fit to a quadratic regression bounded by two standard errors.

appears to be quite similar between the two periods. Hutton and Roy (2019) present similar comparisons for the one above-normal year, two below-normal years, and two dry years that constitute the pre-1919 period. They found the pre-1919 period to be characterized by lower X2* in summer and fall months relative to the post-1919 period, consistent with our analysis of unimpaired runoff and Delta outflow. However, it is difficult to draw firm conclusions about non-wet water year trends during the pre-1919 period, given the dearth of such years in the record.

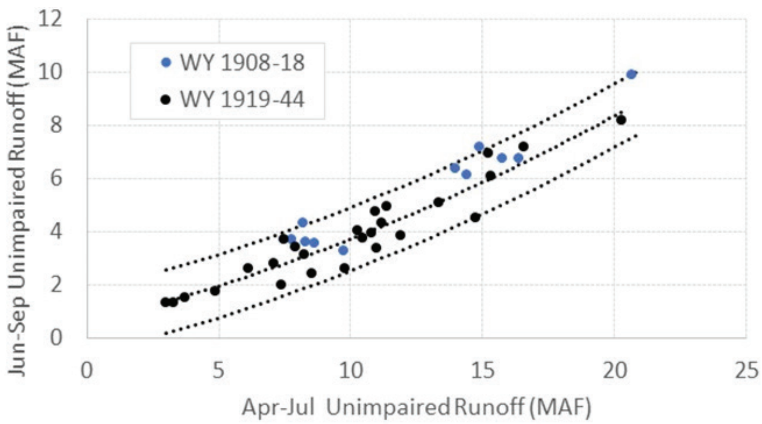

Figure 10 June–September unimpaired runoff is shown as a function of April-July unimpaired runoff. WYs 1919-1944 data are fit to a quadratic regression bounded by two standard errors. Summer unimpaired runoff in the early part of the record (WYs 1908-1918), although generally within the error bounds of the 1919-1944 data, are biased high relative to the latter part of the record. This observation provides a partial explanation for the higher WYs 1912-1918 Delta outflow shown in the top panel of Figure 9.

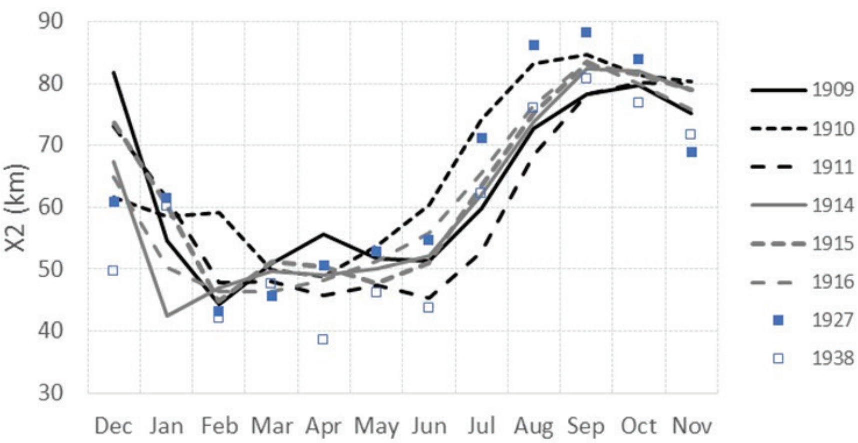

Figure 11 This figure compares predicted monthly X2 values (X2*) from 6 wet years of WYs 1908–1918 (shown as lines) with monthly averaged X2 values interpolated from salinity data from 2 wet years of WYs 1919–1944 (shown as symbols). X2 values in October and November are generally more closely associated with the previous water year; thus, the x-axis spans the months December through November.

DISCUSSION

We evaluated two historically unique and important data sets to characterize the estuary's salinity regime before the State of California began systematic data collection in the early 1920s; one documents barge travel distance along the Sacramento and San Joaquin rivers to obtain water of adequate quality for a regional industrial use by C&H ($X_{C\&H}$) and the other documents monthly inflow volume to the Delta. The latter data set was used to reconstruct a monthly Delta outflow time series, and from these data we derived an antecedent outflow time-series. Using an empirical modeling framework that has been used to relate flow and salinity in the estuary (Hutton et al., 2015), we found a high correlation between $X_{C\&H}$ and reconstructed antecedent outflow, suggesting that the structure of the flow–salinity relationship is consistent over the pre- and post-1922 period. Thus, although there may be differences in salinity intrusion in this period compared to later periods in the record, antecedent outflow can nonetheless similarly predict pre-WY 1922 salinity intrusion. These two independent data sets (barge travel distance and flow) have not been similarly analyzed before.

We found that the C&H data ($X_{C\&H}$) systematically underestimate salinity intrusion by about 10 km when compared with concurrent isohaline estimates (X_{50}) derived from water-quality measurements reported in Bulletin 23 (CDPW 1924–1955). Modeled estimates of $X_{C\&H}$* and X_{50}* show a similar bias. Several interpretations are possible for the difference in absolute values, including different analytical methods for reporting chloride concentrations, the effect of the tidal cycle on the barge's travel distance, timing of chloride measurements relative to tidal cycle, and the frequency of barge travel. Analytical differences in chloride detection may partly explain

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the differences in salinity values; however, this possible explanation is difficult to confirm in the absence of a primary document that describes the C&H field effort. Depending on one's interpretation of the recorded barge travel relative to the tides, the $X_{C\&H}$ data could approximately represent monthly averages of either daily maximum distance or daily minimum distance. However, even if the barge data represented averages of daily minimums, this would account for only 3 to 6 km of difference—significantly less than the 10 km difference we noted.

Our reconstructed pre-project X2* time-series (as well as the measured $X_{C\&H}$ time-series) suggests an apparent shift in the estuary's salinity regime in 1918, with more salinity intruding in summer and fall months after this juncture. Relative to WYs 1919–1944, the period that spans WYs 1908–1918 is associated with higher summer Delta outflow, after accounting for spring runoff conditions. Given the known anthropogenic changes that occurred during the early 20th century, including upstream irrigation development (particularly rice cultivation) and early reservoir construction, increased summer water diversion is a reasonable explanation for the apparent shift in the estuary's salinity regime in 1918. However, upon closer inspection, the explanation appears to be incomplete, because the pre-WY 1919 period is associated with a preponderance of wet years as well as generally higher summer runoff conditions, which explains the lower salinity intrusion. Overall, we found X2 to be comparable between the pre- and post-WY 1919 periods in wet years, indicating that the relative effect of upstream diversions on Delta outflow and salinity is minimal when flows are high. This observation has been shown to be valid over a much longer period of record as well: Hutton et al. (2015) found that wet-year salinity over 1922–1967 (before the CVP and SWP were completed) was similar to that over 1968–2012, despite the large-scale watershed changes. In contrast, in years with lower flows, they found increasing divergence in salinity between pre- and post-1968 periods. The largest differences occurred during critically dry years, highlighting the greater role of anthropogenic influences (diversions and storage) when flows are low.

In broad terms, we found the primary value of the C&H barge travel data to be its strong correlation with our reconstructed antecedent outflow estimates, validating the monthly Delta outflow volumes we derived. Through integration of these data sets, our work showed substantial similarities between WYs 1908–1921 and the subsequent period before Shasta Dam was constructed in 1945. Thus, we conclude that these data are best viewed as an extension of a larger pre-project period—a period of substantial climatic variability as well as a period of dynamic changes in water use in the Delta and its upstream watershed. Specifically, such an extension provides additional data to characterize pre-project wet year salinity intrusion. The 23-year period that spans WYs 1922–1944 was abnormally dry and includes only 5 wet years. And of these 5 years, only 2 (WYs 1927 and 1938) include X2 estimates based on field measurements, because routine salinity monitoring was discontinued during 3 wet years (WYs 1941–1943) coincident with World War II (CDPW 1924–1955). The 14-year period that spanned WYs 1908–1921, in contrast with WYs 1922–1944, was abnormally wet and includes 6 wet years.

Gross et al. (2018) conclude that the level of development associated with the 1908–1918 period does not align with their simulated 1920-level, pre-project representation of the estuary's flow and salinity conditions. Their conclusion is predicated on the qualitative argument that the 1908–1918 period is substantially different from 1920-level conditions as a result of rapid increases in upstream reservoir storage, upstream irrigated agriculture, and wetland reclamation. Gross et al. (2018) present median monthly X2 values by water year type under simulated 1920-level conditions, and graphically report wet year values of 86 km and 83 km in September and October, respectively. Their fall salinity estimates are somewhat higher than the wet year values we predict (median values of 83 km and 81 km in September and October, respectively), consistent with our understanding of dynamic changes during this period.

We reconcile our conclusion that the WYs 1908–1921 period is a reasonable subset of a larger pre-project period that spans WYs 1908–1944 with the conclusion of Gross et al. (2018) by acknowledging that the period is one of dynamic changes, and thus may not easily be represented by a single simulated level of development. We believe that our work

ACRONYMS AND KEY TERMS

Antecedent outflow	Delta outflow that has been re-computed to account for the flow time-history in the estuary
Bulletin 23	Series of annual reports documenting salinity at fixed locations in the San Francisco Bay and Delta beginning in WY 1922
CVP	Central Valley Project
Channel depletions	Term used to characterize water losses or gains in the Delta channels because of island exchanges, precipitation, and evaporation
DAYFLOW	Program used to summarize inflows, water exports, and outflow from the Delta
SWP	State Water Project
WY	Water Year; the California water year spans October 1 through September 30
X2	Position of the 2 parts per thousand bottom isohaline in San Francisco Estuary as estimated through interpolation of surface salinity data collected at fixed locations, reported as distance from Golden Gate in km
X2*	X2 as predicted through flow–salinity relationship
$X_{C\&H}$	Barge travel distance to collect freshwater, nominally of 50 mg L^{-1} chloride concentration, corrected for distance from Golden Gate, and reported in km, as documented by California and Hawaiian Sugar Refining Corporation (C&H)
$X_{C\&H}$*	$X_{C\&H}$ as predicted through flow–salinity relationship
X_{50}	Position of the 50 mg L^{-1} chloride isohaline as estimated through interpolation of Bulletin 23 surface salinity data collected at fixed locations, reported as distance from Golden Gate in km
X_{50}*	X_{50} as predicted through flow–salinity relationship

highlights limitations of the C&H barge travel data (notably a systematic bias in the salinity intrusion estimate) and coincident hydrologic data (relatively uniform wetness of the period) that would discount their use in characterizing a distinct and separate level of development. Our work supports the use of these data in a secondary role in characterizing 20th century pre-project conditions, because post-WY 1921 hydrology and salinity data are better documented and part of a large, multi-decade scientific effort.

Common to other hydrology reconstruction efforts, we faced several challenges in data interpretation that subjected our quantitative results to some uncertainty. Our work provides a foundation for future efforts to characterize the hydrologic and hydrodynamic changes that occurred in the estuary and its upstream watershed between the 1850s (i.e., natural or pre-development conditions) and the 1920s. We recommend future research in several areas of hydrology and estuarine hydrodynamics to build upon our work, including reconstruction of hydrology and change attribution over the 7-decade period that followed 1850, and hydrodynamic modeling of early 20th-century conditions.

ACKNOWLEDGEMENTS

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NOTES

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