Title

A Comparison of Outflow and Salt Intrusion in the Pre-Development and Contemporary San Francisco Estuary

Journal

San Francisco Estuary and Watershed Science, 16(3)

Authors

Gross, Edward S.
Hutton, Paul H.
Draper, Andrew J.

Publication Date

2018

DOI
10.15447/sfews.2018v16iss3art6

OCTOBER 2018

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

RESEARCH

A Comparison of Outflow and Salt Intrusion in the Pre-Development and Contemporary San Francisco Estuary

Edward S. Gross,*[1] Paul H. Hutton,[2] Andrew J. Draper[3]

Volume 16, Issue 3 | Article 6
https://doi.org/10.15447/sfews.2018v16iss3art6

* Corresponding author: *ed@rmanet.com*

1 Resource Management Associates
Walnut Creek, CA 94596 USA
and
Center for Watershed Sciences
University of California, Davis
Davis, CA 95616 USA

2 Tetra Tech
Lafayette, CA 94549 USA

3 Stantec
Sacramento, CA 95816 USA

ABSTRACT

The San Francisco Estuary and its upstream watershed have been highly altered by human development following the California Gold Rush in the mid-19th century. In this paper, we explore the inter- and intra-annual variability of freshwater flow to this estuary and the resulting salt intrusion under scenarios that represent pre-development and contemporary conditions. To place this comparison in context with the advent of systematic and accurate flow and salinity measurements in the estuary, we consider an additional "pre-project" scenario that represents early 20th-century water management (circa 1920), after major flood control and reclamation but before the introduction of large water storage, diversion, and export operations. We use an observed climate record that spans 82 years to compare freshwater flow associated with the scenarios' landscape and water use characteristics. Using published relationships between flow and salt intrusion length developed from three-dimensional hydrodynamic modeling, we evaluate the effect of these flow alterations as well as estuarine geometry modifications and historically observed sea level rise on salt intrusion. We conclude that the pre-development estuary exhibited a more seasonally variable salinity regime, resulting from a more variable inflow regime from the upstream watershed.

KEY WORDS

Sacramento–San Joaquin Delta, hydrology, natural flow, hydrodynamic modeling, salt intrusion, X2, pre-development Delta, ecology

INTRODUCTION

Estuaries throughout the world are exposed to a variety of stressors, including hydrologic alteration, invasive species, pollutants, eutrophication, and habitat loss (Kennish 2002). International restoration efforts are responding to these stressors, with the recognition that ecosystem effects are a consequence of multiple interacting factors that are often poorly understood (Kennish 1999; Williams and Orr 2002; Thom et al. 2005; Elliott et al. 2007). Defining a restoration target or baseline is implicit in identifying ecosystem effects, and is important in structuring flow regulations and other restoration actions.

Because observed data from pre-development periods are normally unavailable or limited in scope, restoration targets are typically guided by the earliest available records, even when these observations are recognized to reflect some degree of anthropogenic alteration. Therefore, restoration baselines do not truly represent pre-development conditions, a concept termed shifting baselines in the ecological literature (e.g., Duarte et al. 2009; Wagener et al. 2010; Villnäs and Norkko 2011).

Flow regime, a key characteristic of any restoration baseline, is essential to the ecological integrity of riverine and estuarine ecosystems, and alteration of a natural regime has cascading ecological effects (Poff et al. 1997). Although pre-development conditions may not be a practical baseline for establishing restoration targets, understanding the general properties associated with such a flow regime can provide a basis for defining reasonable restoration expectations and informing effective regulations and actions. Annual magnitude is an important property of a flow regime; however, characteristics such as return frequency, seasonal timing, duration, and rate of change are also significant properties (Poff et al. 1997).

Flow has been described as the "master variable" that affects several characteristics of riverine and estuarine ecosystems, including geomorphology and water quality (Poff and Zimmerman 2010). Salinity, a key estuarine water-quality characteristic affected by flow, influences estuarine ecology through a number of direct pathways, such as quantity and quality of habitat (Kimmerer et al. 2013), and indirect pathways, such as retention of estuarine organisms by estuarine circulation patterns (Kimmerer et al. 2014). Native species have evolved specific life history strategies in response to natural flow and salinity patterns (Bunn and Arthington 2002); hydrologic alterations can disrupt these life history strategies and favor invasive species. Although divergence from natural flow patterns is associated with declining native fish populations (Poff and Zimmerman 2010), specific biological responses to such alterations are often difficult to discern because of other confounding anthropogenic changes such as landscape modification (Bunn and Arthington 2002).

The ecological concerns discussed thus far apply to the San Francisco Estuary (estuary) on the Pacific Coast of California, USA. (Figure 1). This estuary and its associated watershed are of great importance to California's water supply and economic development (Luoma et al. 2015). Home to 14 species of imperilled migratory or resident fishes (Cloern et al. 2011), the estuary has been the focus of large-scale restoration and management efforts over the past 4 decades (Hanak et al. 2011). Hydrologic alterations to the estuary and its watershed occurred rapidly during and after the California Gold Rush of the 1850s,

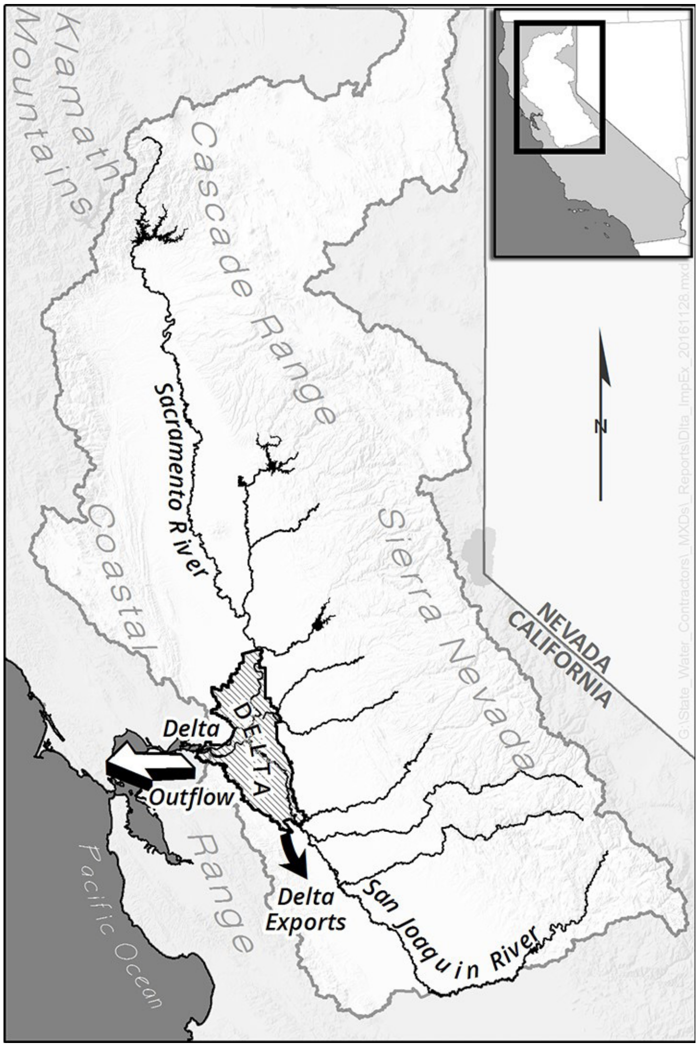

Figure 1 The Sacramento–San Joaquin Delta and its tributaries and watershed. The Delta is the entry point for over 90% of the freshwater inflow to the San Francisco Estuary. Its upstream watershed includes a portion of the Sierra Nevada, Cascade, Klamath, and Coastal mountain ranges.

landscape conversion of wetlands and riparian forests for agriculture and urban uses (Kimmerer et al. 2005), channel modifications, reservoir construction, and operation of large water projects to export water to central and southern California. Other anthropogenic stressors include introduction of invasive species (Kimmerer 2004), toxicity from contaminants (Kuivila and Foe 1995), wastewater discharges (Luoma et al. 2015), and changes in temperature, sea level, and precipitation patterns from climate change (Cloern et al. 2011).

Although multiple stressors influence individual species and the estuary's overall ecosystem, flow and associated salt intrusion are known to be critical variables. The observed abundance of several pelagic organisms in the estuary is negatively correlated with X2, a salt intrusion length defined as the distance in kilometers from the Golden Gate inlet to the location of tidally averaged, 2-psu near-bed salinity (Jassby et al. 1995; Kimmerer et al. 2009; Kimmerer et al. 2013). Not only is a low (seaward) X2 believed to be favorable for pelagic organisms, a more variable salinity regime is believed to favor native species over non-native species (Lund et al. 2007).

In this paper, we compare freshwater flows and salt intrusion in the estuary for scenarios that represent pre-development and contemporary conditions. To provide additional context, we also consider a "pre-project" scenario that represents water management in the system circa 1920—preceding construction of major reservoirs in the watershed. Characteristics of the system in the early 1920s can be quantified with greater certainty (relative to pre-development conditions) given the advent of systematic and accurate salinity and flow measurements. The primary driver of flow and salinity differences among the scenarios is altered watershed hydrology, storage regulation, and water diversions; however, the scenarios also capture salt intrusion response to alterations in estuarine bathymetry and mean sea level.

BACKGROUND

Geographic Setting

The geographic focus of this paper is the central and northern portion of the estuary and the watershed draining to the Sacramento–San Joaquin Delta (Figure 1). Key geographic features of the estuary include Central Bay, San Pablo Bay, Carquinez Strait, Suisun Bay, the Delta, and associated tidal sloughs and marshes (Figure 2). The Delta is the entry point for over 90% of the freshwater inflow to the estuary (Cheng et al. 1993). Its upstream watershed includes a portion of the Sierra Nevada, Cascade, Klamath, and Coastal mountain ranges (Figure 1) and is drained primarily by the Sacramento and San Joaquin rivers.

Under pre-development conditions, the channels of the Sacramento, San Joaquin, and other Central Valley rivers had insufficient capacity to carry winter and spring flows generated by wet-season precipitation and snowmelt. These rivers overflowed their banks in most years, discharging into adjacent low-lying basins, including approximately 4,000 km^2 (nearly 40%) of the Sacramento Valley (Grunsky 1929). As river stage fell, water would partially drain back to the river through well-defined channels and sloughs (Hall 1880; Rose et al. 1895; Grunsky 1929). However, the basins typically remained inundated through late summer. Thus, under pre-development conditions, this extensive natural storage in the Central Valley floodplain attenuated flood flows and provided water to native vegetation.

The seasonal flooding pattern of the pre-development watershed supported vast inland marshes located in natural flood basins along major rivers (Alexander et al. 1874; Hall 1887; Garone 2011; Fox et al. 2015), while lush riparian forests existed on natural river levees (Katibah 1984), and vast swaths of grasslands interwoven with vernal pools and savannas with immense valley oaks extended from the floodplains to the oak- and pine-covered foothills (Burcham 1957; Dutzi 1978; Holland 1978). At lower elevations, permanent wetlands were supported by a shallow groundwater table fed by seasonal overflows from the rivers. Deep-rooted hardwood habitat and chaparral were found at higher elevations. In the transition zone, seasonal wetlands and seasonal grasslands fluctuated from periods of high water availability in winter and spring, to periods of water shortage and senescence in the summer and early fall when overbank flooding ceased and groundwater elevation dropped below the root zone.

Land-use changes in the foothill and mountain watersheds that surround the Central Valley have

https://doi.org/10.15447/sfews.2018v16iss3art6

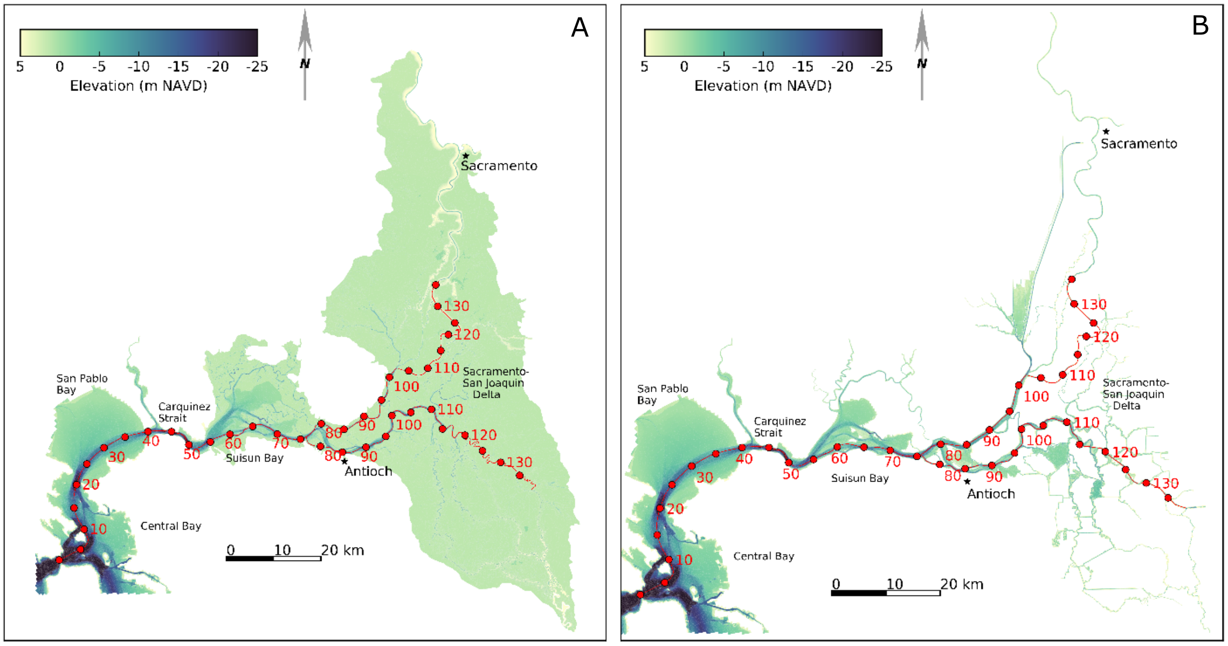

Figure 2 Bathymetry and transects of distance from the Golden Gate for the northern portion of the (A) pre-development and (B) contemporary San Francisco Estuary model (Andrews et al. 2017). Key geographic features of the San Francisco Estuary include Central Bay, San Pablo Bay, Carquinez Strait, Suisun Bay, the Delta, and associated tidal sloughs and marshes.

been relatively minor. In contrast, the valley floor has been extensively developed for irrigated agriculture, and contains large urban areas. Under pre-development conditions, water use by natural vegetation (Howes et al. 2015), in combination with the annual cycle of overbank flooding, reduced the amount of water that reached the Delta. As natural levees were raised, and wetlands and riparian forests were drained and cleared, water use by agriculture replaced water use by native vegetation in the Central Valley. Fox et al. (2015) estimated that annual water use from the natural landscape was similar to that of the contemporary system, such that Delta outflow—computed as Delta inflow minus consumptive uses in the Delta and water exports—was minimally changed.

Before the mid-19th century, the estuary included extensive tidal marsh with a total area of approximately 2,200 km^2, which was nearly twice the area of the bays (Atwater et al. 1979). Substantial anthropogenic modifications of the estuary and watershed began during the 1850s in response to the California Gold Rush (Whipple et al. 2012). These changes include diking of over 90% of the estuary's tidal marshes (Atwater et al. 1979), and dredging and straightening of channels, primarily in the Delta. The network of channels in the contemporary Delta is formed by an extensive constructed levee system, cuts to straighten channels, dredging to deepen select channels for navigation, and installation of rock barriers and operable gates to control flows and salinity in portions of the Delta. This highly modified system is the hub of California's water-supply infrastructure, including the Central Valley Project (CVP) operated by the U.S. Bureau of Reclamation (USBR) and the State Water Project (SWP), operated by the California Department of Water Resources (CDWR). The primary export facilities of these water projects are located in the south Delta, as identified in Figure 1.

The bathymetry of the portion of the estuary seaward of the Delta is typical of a drowned river valley estuary, with broad shoals and deep relict channels (Walters and Gartner 1985; Figure 2), and is influenced by tectonic activity (Atwater et al. 1979). The estuary has mixed diurnal and semidiurnal tides, and both salinity and stratification vary seasonally with freshwater inflow, typically resulting in partially mixed conditions (Walters and Gartner 1985).

Regulatory Setting

Ongoing public debate over Delta flows and salinity has accompanied watershed development since the early 20th century. Although early levee construction initially *increased* stream flows by reducing evaporative losses in former floodplains and other wetlands, by 1870, irrigation diversions in the San Joaquin Valley had noticeably reduced Delta inflow from the San Joaquin River. Diversions for rice irrigation in the Sacramento Valley increased in the early 20th century and, in combination with drought conditions, led the California Water Commission to warn that stream diversion would make Delta water too saline for irrigation (CDPW 1931; Jackson and Paterson 1977). In 1920, the City of Antioch sued upstream irrigators to protect the city's intake from salt intrusion. In response to this lawsuit, the state of California implemented a monitoring program and published the first authoritative review of Delta salinity and its control in 1931 (CDPW 1931), recommending that a salinity standard be maintained in the Delta at Antioch.

Although an early planning document (CDPW 1931) envisaged control of Delta salinity by means of storage regulation on the Sacramento River, the first formal regulations were not established until 1965, when the USBR and CDWR agreed on water quality standards at multiple compliance locations in the Delta. Since 1967, the California State Water Resources Control Board (SWRCB) has regulated water quality through adoption of water right decisions and water quality control plans. Current Delta water quality standards, which were developed to balance competing beneficial uses—including agriculture, municipal and industrial, and fish and wildlife—include specific requirements for year-round Delta outflow and spring (February through June) X2 position (SWRCB 1995). In 1999, the SWRCB assigned responsibilities for meeting these standards to USBR and CDWR; this responsibility is met through CVP–SWP export reductions, and storage withdrawals from upstream project reservoirs. In 2008 and 2009, the U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS) issued biological opinions for the long-term operations of the CVP and SWP, in accordance with the 1973 Endangered Species Act (USFWS 2008; NMFS 2009). The 2008 USFWS biological opinion contains additional restrictions on X2 position (USFWS 2008).

Models of Pre-Development, Pre-Project, and Contemporary Delta Hydrology and Salt Intrusion

Several water-resource simulation models of the Delta and its upstream watershed are publicly available, including C2VSim (CDWR 2013) and CalSIM II (Draper et al. 2004). C2VSim is an integrated hydrologic model that simulates both the surface water and groundwater of the Central Valley floor (CDWR 2013). Our work employs applications of this model to predict daily Delta outflow under (1) pre-development conditions by routing flows through the stream network and simulating bank overflow and floodplain storage (CDWR 2016a), and (2) pre-project conditions by routing flows through the same stream network modified by levees and reclaimed flood basins (MWH 2016; Hutton et al. 2017b). The pre-project scenario, which represents water management in the system circa 1920, assumes approximately 5% and 30% of the contemporary scenario's system-wide reservoir storage and irrigated area, respectively. C2VSim does not dynamically simulate surface-water storage operations and, therefore, is not used to simulate contemporary water operations in the Central Valley. CalSIM II is a reservoir systems operation model that is used primarily to evaluate coordinated CVP–SWP operations under a variety of planning scenarios. Our work employs a recent version of the model to represent CVP–SWP reservoir storage, Delta exports, and Delta outflow under contemporary conditions (CDWR 2015). As discussed in the following section, all model applications used for this work assume constant scenario-specific land use over a common historical climate sequence.

Pre-development salinity conditions in the estuary were investigated and compared to contemporary salinity conditions by Andrews et al. (2017) using a three-dimensional (3-D) hydrodynamic model. This work was the first to estimate how human-induced bathymetry changes in the estuary (i.e. large-scale loss of wetlands, levee construction, dredging, and other modifications) influenced salinity. Their pre-development model was based on planform developed by Whipple et al. (2012) and bathymetry from multiple sources as described in Andrews et al. (2017). Based on observed water levels at San Francisco (NOAA 2015), mean sea level was specified as 0.31 m lower than contemporary conditions to represent historically observed sea level rise. Their model was calibrated against historical observations of tidal range, inundation frequency, and inundation depth.

Andrews et al. (2017) found the dramatic changes in estuary planform and bathymetry and the difference in mean sea level between the pre-development and contemporary scenarios to have a limited influence on salt intrusion. The pre-development estuary was found to have salt intrusion that responded faster to changes in Delta outflow and was lower for the same Delta outflow. Because of the changes in seasonal distribution of Delta outflow, salt intrusion was found to be less variable for the contemporary scenario than for the pre-development scenario. Changes to seasonal timing of freshwater flows influenced salt intrusion more than changes in estuarine planform and bathymetry. As described below, we employed the work of Andrews et al. (2017) to characterize the relationship between Delta outflow and salt intrusion for the pre-development and contemporary scenarios. We assume that the pre-project relationship between Delta outflow and salt intrusion is identical to the contemporary relationship developed by Andrews et al. (2017). Although significant geometric alterations have been widely recognized to have occurred in the system since the 1920s, analysis of historical data (Hutton 2014; Hutton et al. 2015) indicates little change over the past 9 decades in the accuracy of the predicted flow–salinity relationship.

METHODS

We adopted publicly available simulation output from the C2VSim and CalSIM II models, as described in the previous section, to define and compare Delta outflow under pre-development, pre-project, and contemporary scenarios. Our comparison assumed a common historical climate sequence from water year 1922 to 2003, an 82-year period inclusive of widely varying hydrologic conditions. The CDWR selected water year 1922, which began October 1, 1921 as the starting point for its model simulations because it is the first year of available robust streamflow data. Using these Delta outflow predictions, we generated salt intrusion time-series representative for all three scenarios based on the work of Andrews et al. (2017).

Level-of-Development Methodology

Water resource conditions evolve over time in response to a variety of natural and anthropogenic drivers, including (but not necessarily limited to): climate, land and water use, construction and operation of water management facilities, and environmental regulations. Time evolution of water resource conditions can be evaluated through a transient analysis, whereby all drivers are allowed to vary according to a historical or other pre-defined pattern. Alternatively, time evolution can be evaluated through a static or steady-state analysis, whereby one or more evolving conditions are held constant. In a static analysis known as “level of development” (Draper et al. 2004), one or more scenarios are defined by holding land use and watershed characteristics constant, then water management facilities are operated according to fixed criteria, and scenarios are compared assuming a common hydrologic sequence. The common hydrologic sequence may represent climatic variability associated with the distant past, contemporary conditions, or potential climate-change scenarios. In this work, we compare three levels of development (pre-development, pre-project, and contemporary), assuming a recent historical 82-year climatic sequence. Thus, the Delta outflow and salt intrusion time-series used to represent the three scenarios are not estimates of flows and salt intrusion that actually occurred under Paleolithic, early 20th-century, or contemporary conditions. Rather, each time-series represents a simulated response of the estuary and its upstream watersheds to a common precipitation and runoff pattern, assuming three distinct and static levels of development.

Delta Outflow

The simulated Delta outflow time-series for the pre-development scenario (CDWR 2016a) and pre-project scenario (Hutton et al. 2017a) were available at a daily time-step, whereas the Delta outflow time-series for the contemporary scenario (CDWR 2015) was only available at a monthly time-step. Because a daily Delta outflow time-series is necessary to predict salt intrusion length, following the approach of Hutton et al. (2015), we disaggregated the contemporary Delta outflow time-series from a monthly to daily time-step, based on historically observed flow patterns as discussed in the following paragraph.

CDWR (2016b) has developed an estimate of historical daily Delta outflow beginning October 1, 1929 (water year 1930). We obtained daily outflow estimates before October 1929 from work described in Hutton et al. (2015) and appended them to the larger time-series. Following three key steps, we adjusted the 82-year historical daily time-series to represent a flow pattern that would have occurred under contemporary water-management conditions. First, we adjusted the historical time-series to remove the effects of upstream storage regulation, trans-watershed imports and exports, Delta exports, and historical consumptive use from developed lands in the Delta and upstream watershed. This adjusted or "un-impaired" Delta outflow time-series was then "re-impaired" to account for in-basin consumptive use and CVP–SWP operations (i.e., storage and import–export operations) as assumed in the contemporary scenario (CDWR 2015). As part of this re-impairment, reservoir and import–export operations were generally assumed uniform within each month, except during flood-control operations when releases were set equal to daily inflows. The resulting re-impaired daily Delta outflow time-series does not account for all aspects of contemporary hydrology (e.g., groundwater pumping to meet irrigation demands), but we assume it to be a credible representation. Finally, we adjusted the re-impaired daily outflow time-series as necessary to meet contemporary Delta outflow standards while preserving the simulated monthly volumes associated with CDWR (2015).

Salt Intrusion Length

Given the daily Delta outflow time-series discussed in the previous paragraph, we applied an empirical relationship between Delta outflow and salt intrusion to generate a daily X2 time-series that spanned water years 1922 to 2003. Monismith et al. (2002) proposed a fitting equation to relate previous X2 and current flow to current X2

$$X2(t) = \omega_1 X2(t-1) + \omega_2 Q(t)^{\gamma} \tag{1}$$

where ω_1, ω_2 and γ are empirical parameters and $Q(t)$ is outflow. Hutton et al. (2015) built upon this approach by assuming a steady form of Equation 1 and a definition of antecedent outflow (Q_{ant}) from Denton (1993).

$$\frac{dQ_{ant}(t)}{dt} = \frac{(Q(t) - Q_{ant}(t))Q_{ant(t)}}{\beta_G} \tag{2}$$

where β_G is an additional fitting parameter ($\mathrm{m^3\,s^{-1}}$ per day). The antecedent outflow can be thought of as the equivalent steady flow that accounts for the time history of the outflow on salinity. We then calculated X2 by substituting the antecedent flow from Equation 2 for the flow in the steady form of Equation 1 to yield

$$X2(t) = \beta Q_{ant}(t)^{\gamma} \tag{3}$$

where $\beta = \omega_2 / (1 - \omega_1)$. Andrews et al. (2017) discusses the advantages of this approach over previously published flow–X2 relationships—including accommodating negative daily Delta outflow and providing a time-scale of adjustment that varies with X2 (as suggested by Monismith (2017). Equation 3 with a single set of parameters was found to predict X2—as estimated from observed salinity along the Sacramento River transect—with a standard error of 3.2 km in Hutton et al. (2015) over the calibration period that spanned water years 2000–2009.

Hutton (2014) found little change in model accuracy over the 9 decades spanning 1922 to 2012. However, he found higher model variance in the early part of the record, with decadal average standard errors that ranged between 4.0 km for 1950–1979 and 5.2 km for 1930–1939. Although not formally examined, this apparent temporal trend is likely an artifact of increasing data quality and decreasing peak seawater intrusion events.

In Andrews et al. (2017), the free parameters in Equation 2 and Equation 3 (β, γ, and β_G) were fit to X2 values predicted by the hydrodynamic model in 2006 through 2008 along the transects shown in Figure 2 for the contemporary and pre-development scenarios; this fitting yielded the parameters shown in Table 1. The standard error characterizing the ability of the regression equation to represent X2 estimated by UnTRIM was 1.7 km for the contemporary scenario and 2.3 km for the

https://doi.org/10.15447/sfews.2018v16iss3art6

pre-development scenario; the regression equation predicted X2 accurately across the full range of Delta outflow under both scenarios (Andrews et al. 2017). For our work, the 82-year time-series of contemporary-scenario and pre-development-scenario daily Delta outflows were first substituted into Equation 2 to generate daily antecedent flow time-series. Then, using the parameters in Table 1 for each scenario, we used Equation 3 to generate daily salt intrusion length (i.e., X2) time-series. We transformed the pre-project scenario outflow time-series into a daily X2 time-series assuming parameters calibrated for the contemporary scenario. We then monthly averaged the daily salt intrusion length.

Table 1 Isohaline regression fit parameter values. The contemporary scenario parameters are also used for the pre-project scenario.

Parameter	Scenario	
	Contemporary	Pre-development
β	281	277
γ	–0.230	–0.237
β_G	5739	4458

RESULTS

Delta Outflow

Figure 3 shows a modified box and whisker plot of monthly and annual Delta outflow volume quantiles and means associated with the three scenarios. Interannual variability in Delta outflow is determined largely by variation in annual precipitation over the mountain and foothill watersheds of the Central Valley (which is common to all scenarios) but is also strongly influenced by changes in end-of-year storage, which varies by scenario. Under pre-development conditions, winter and spring flows spilled over the banks of the Sacramento and San Joaquin rivers, filling low-lying basins adjacent to these rivers and attenuating peak flows. Under pre-project conditions, man-made levees largely isolated these rivers from their floodplains and other wetlands (thereby decreasing evapotranspiration) and conveyed their flows more directly to the Delta, resulting in higher peak flows consistent with the findings of Fox et al. (2015) and Howes et al. (2015). Under contemporary conditions, both river levees and flood-control projects are present, and the major reservoirs diminish seasonal flow variability as did the natural floodplain. Reservoirs have a greater capacity than natural floodplains to control flows in dry years when overbank flow would be minimal, through both storage operations during the winter and spring and release operations during the summer and fall.

Mean annual precipitation over the Delta and upstream drainage area was 90.3 billion m^3 over the 82-year period of record (water years 1922–2003), with a standard deviation of 25.2 billion m^3. Mean annual Delta outflow for the pre-development scenario is 24.5 billion m^3 over the same period of record, with a standard deviation of 13.7 billion m^3. The pre-development scenario Delta outflows lie slightly above the range of 14 to 23 billion m^3 reported by Fox et al. (2015) for water years 1922 through 2009. The pre-project scenario mean annual Delta outflow is 30.2 billion m^3, with a standard deviation of 17.1 billion m^3. Mean annual net Delta outflow for the contemporary scenario is 19.4 billion m^3, with a standard deviation of 13.4 billion m^3, which corresponds to a coefficient of variation of 0.69, relative to 0.56 for the pre-project scenario and 0.564 for the pre-development scenario. For the contemporary scenario, interannual outflow variability is partially attenuated by annual carry-over storage in the state's larger reservoirs, especially in drier years. The difference in mean annual outflow volume between the pre-development scenario and contemporary scenario is of similar magnitude to contemporary CVP and SWP exports from the south Delta, which together average approximately 6.1 billion m^3.

Annual hydrologic conditions for the Sacramento River have been classified into one of five water year classes based upon an index computed as a weighted average of current year April-through-July runoff, current year October-through-March runoff, and the previous water year index (CDWR 2016c). Figure 4 presents monthly Delta outflow averages and ranges by water year class. Although the California water years run from October through September, we assigned the months of October and November to the previous water year to illustrate the effects of current regulatory requirements on contemporary outflows,

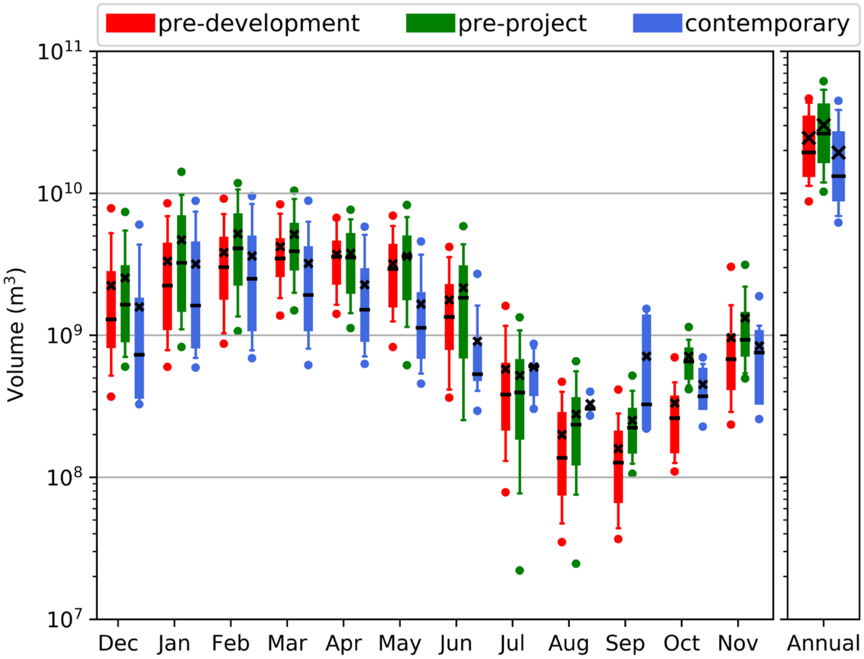

Figure 3 Modified box and whisker plot of Delta outflow volume for the pre-development, pre-project, and contemporary scenarios, given a historically observed climate sequence spanning water years 1922 through 2003. Boxes represent the interquartile range (25th to 75th percentile) for each month and scenario. The black lines represent the median value (50th percentile), the whiskers represent the 10th and 90th percentiles, the circles represent the 5th and 95th percentiles, and the "x" symbols represent the mean values.

consistent with Hutton et al. (2015). To improve habitat for endangered Delta Smelt, the 2008 USFWS biological opinion (USFWS 2008) regulates X2 in fall months (September through November) after "Above Normal" and "Wet" water year classes.

The top panels of Figure 4 shows that average seasonal outflow patterns are remarkably similar between the pre-development and pre-project scenarios. One exception to the scenarios' general similarity is that fall and winter flows tend to be higher under pre-project conditions. This finding is consistent with an early 20th-century analysis of upstream reclamation development effects on flow to the Delta (CDPW 1931) in which the authors remark:

> "...it is of interest to note that the flow into the delta during the late fall and early winter months, starting occasionally as early as September, appears to have been increased due to the effect of return water from irrigation combined with water releases from power reservoirs in excess of the simultaneous irrigation diversions."

Another exception to the scenarios' general similarity is that the range of pre-project critical year flows drops substantially lower than the corresponding pre-development flows in spring and summer months, presumably because of upstream irrigation demands. This second finding is consistent with a conclusion drawn by Malamud–Roam et al. (2006) that the drought of the 1920s and 1930s (a period well-represented by the pre-project scenario) was the most saline period in the Bay–Delta over the last 2,500 years.

The bottom panels of Figure 4 show a dramatic difference in average seasonal outflow patterns between the pre-development and contemporary scenarios; the difference is greatest in "Critical" years and least in "Wet" years. The comparison shows larger seasonal variability in pre-development outflows, with higher winter and spring flows, and lower summer and fall flows. This dramatic difference in seasonal outflow patterns can be largely attributed to upstream reservoir operations, exports, and Delta outflow standards.

Salt Intrusion Length

We estimated daily salt intrusion length (X2) for the pre-development, pre-project, and contemporary scenarios using the previously described daily Delta outflow estimates in combination with Equation 2, Equation 3, and the parameters in Table 1. Though our scenario-based level-of-development approach

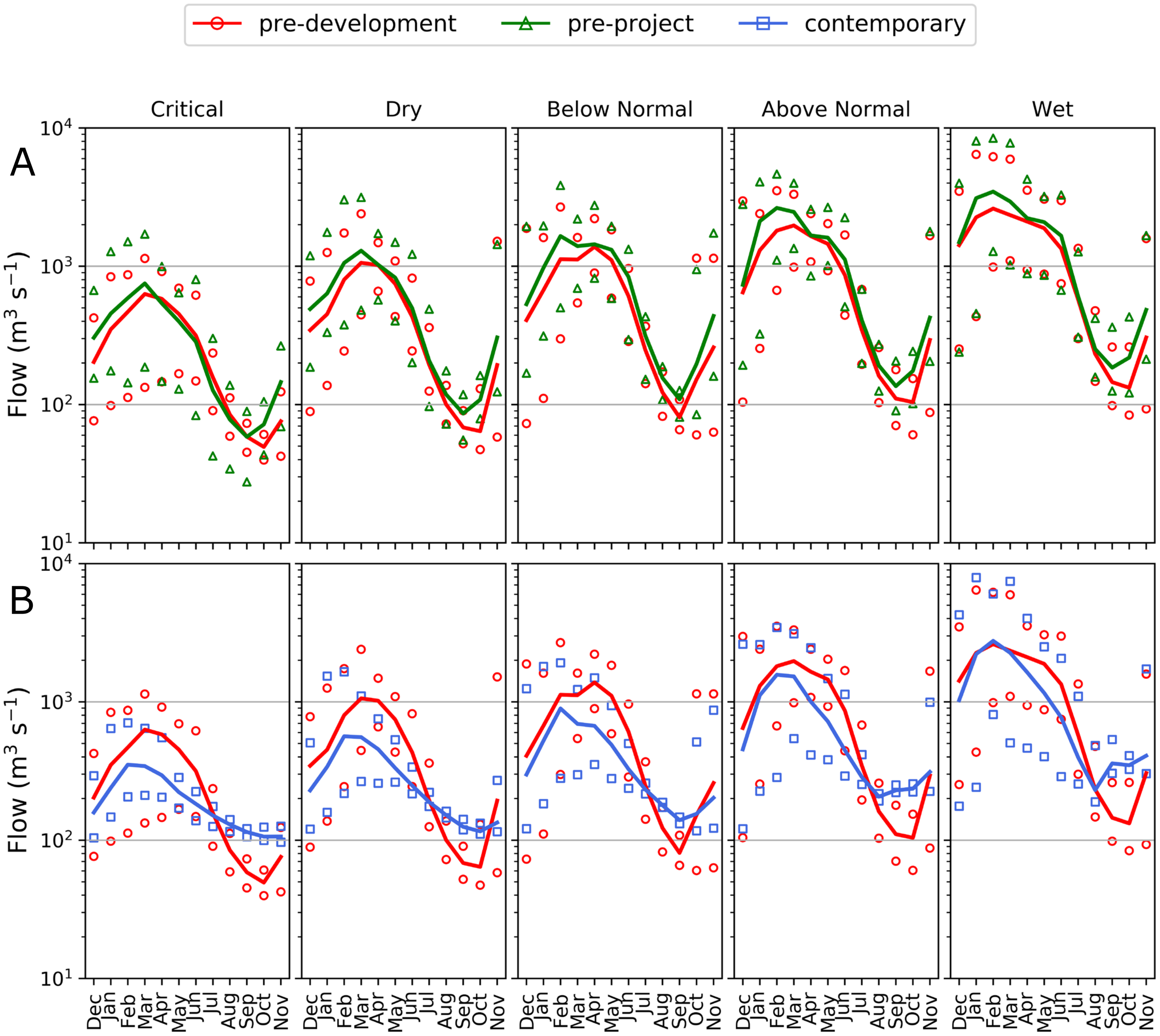

Figure 4 Comparison of pre-development scenario with the (A) pre-project scenario and (B) contemporary scenario monthly Delta outflows subdivided by water year class, with lines indicating the median monthly Delta outflow and symbols indicating the largest and smallest monthly flow for years within the given water year class on the Sacramento River. The flow and X2 in October and November is generally more closely associated with the previous water year (their own calendar year) than the current water year; thus, these months are classified with the previous water year, and the X-axis spans the months of December through November.

is not intended to reproduce a historical time-series, the approach should produce flow and salinity time-series that are similar to historical observations for a limited period that most closely approximates the fixed level-of-development time-frame. Figure 5 compares salt intrusion estimates from historical salinity observations (CDPW 1924–1942), as described by Hutton et al. (2015), with pre-project scenario X2 values over the 20-year period that spans water years 1922 through 1941. In general, the scenario values are similar to the observed values in both wet and dry years. The standard error in comparing the scenario-based and historical X2 is 5.5 km; this error is higher than the 3.2-km and 3.6-km standard errors reported by Hutton et al. (2015) for comparisons between predicted and observed X2 time-series (water years 2000 through 2009) along the Sacramento and San Joaquin river transects, respectively. We expected higher error in the scenario-based estimates for several reasons, including (1) imperfect correspondence between scenario-based outflow and historical outflow, (2) scenario-based X2 values are computed from isohaline regression fits (see Table 1) that are based

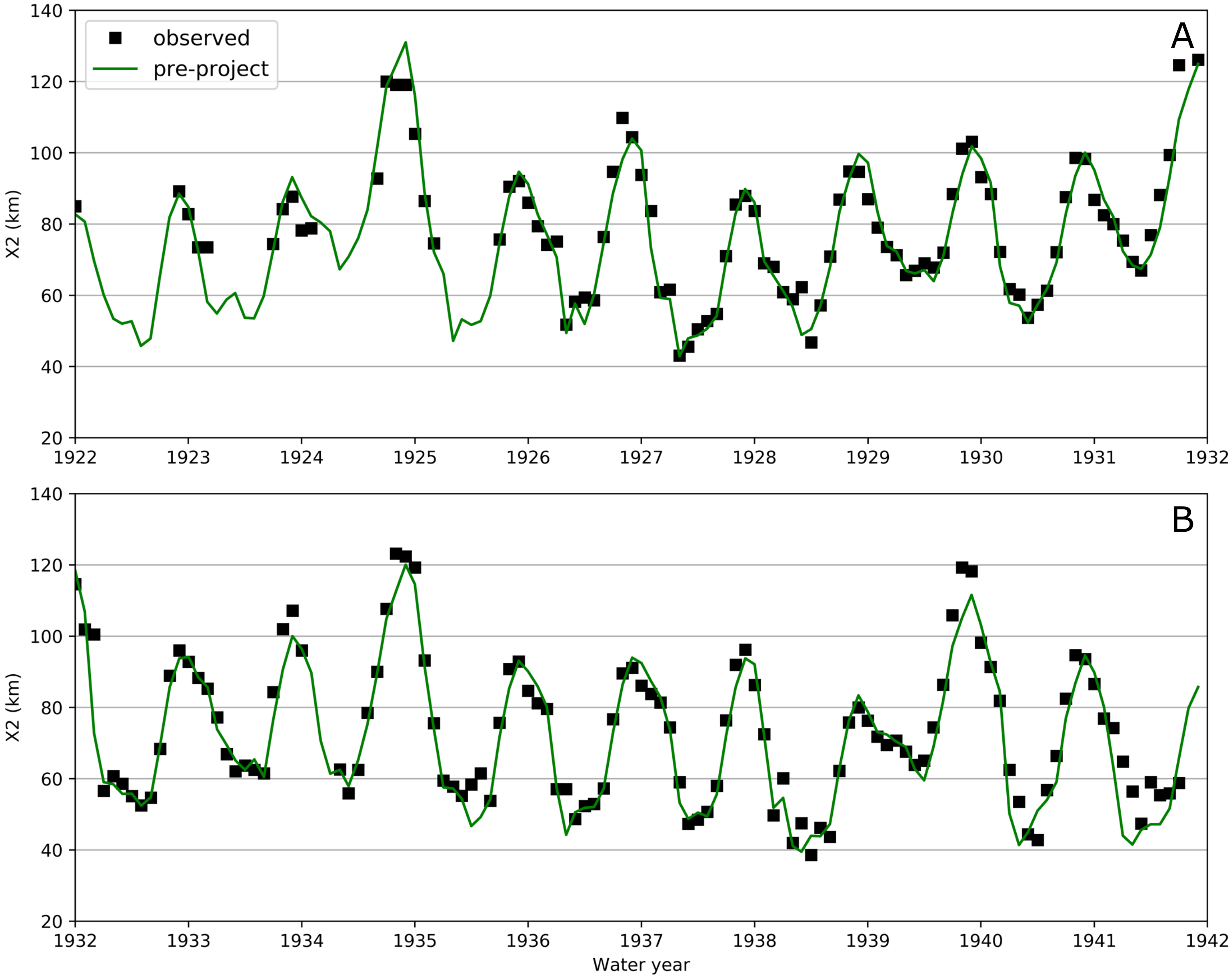

Figure 5 Historically observed X2 and scenario-based pre-project X2 during a 20-year period approximately characterized by a pre-project level of development (circa 1920). Historically observed X2 values are based on work reported in Hutton et al. (2015).

https://doi.org/10.15447/sfews.2018v16iss3art6

on model data rather than observed data, (3) there is greater uncertainty associated with the early salinity measurements and resulting X2 estimates, and (4) the earlier salinity record is associated with greater seawater intrusion.

The modified box and whisker plot in Figure 6 indicates that monthly averaged salt intrusion length is less seasonally variable for the contemporary scenario than for the pre-development scenario. Delta outflow is typically higher for the contemporary scenario than for the pre-development scenario in summer and fall months, leading to lower summer and fall X2. In contrast, Delta outflow is typically lower for the contemporary scenario than for the pre-development scenario in winter and spring months, leading to higher winter and spring X2. The pre-project scenario X2 follows seasonal trends similar to the pre-development scenario, but with slightly higher salt intrusion in the spring and lower salt intrusion in fall. However, the pre-project scenario is characterized by significantly higher X2 in the spring and summer of drier years, as quantified by the 75, 90, and 99 percentile values. Interannual X2 variability is notably higher in spring months (March and April) and lower in summer months (July and August) under the contemporary scenario than for the pre-development scenario, although interannual X2 variability is notably higher in summer months under the pre-project scenario than for the pre-development scenario. The difference in interannual X2 variability during the summer reflects the change from an unregulated irrigation paradigm (associated with the pre-project scenario) to a highly flow-regulated paradigm (associated with the contemporary scenario).

Monthly averaged X2 classified by Sacramento River water year class is shown in Figure 7. As provided in the bottom panels, X2 is consistently higher in winter and spring, and lower in late summer and fall in the contemporary scenario than for the pre-development scenario for all water year classes, further illustrating the contemporary scenario's characteristic of lower seasonal variability. These differences are more pronounced in "Critical" and "Dry" years, and less pronounced in "Wet" years. As provided in the top panel, differences between the pre-project and pre-development scenario are typically small, with key exceptions being (1) higher pre-project salt intrusion during spring and summer in "Critical" years and (2) lower pre-project salt intrusion during fall in all water years.

The substantial differences in pre-development, pre-project, and contemporary scenario Delta outflows result in smaller proportional differences

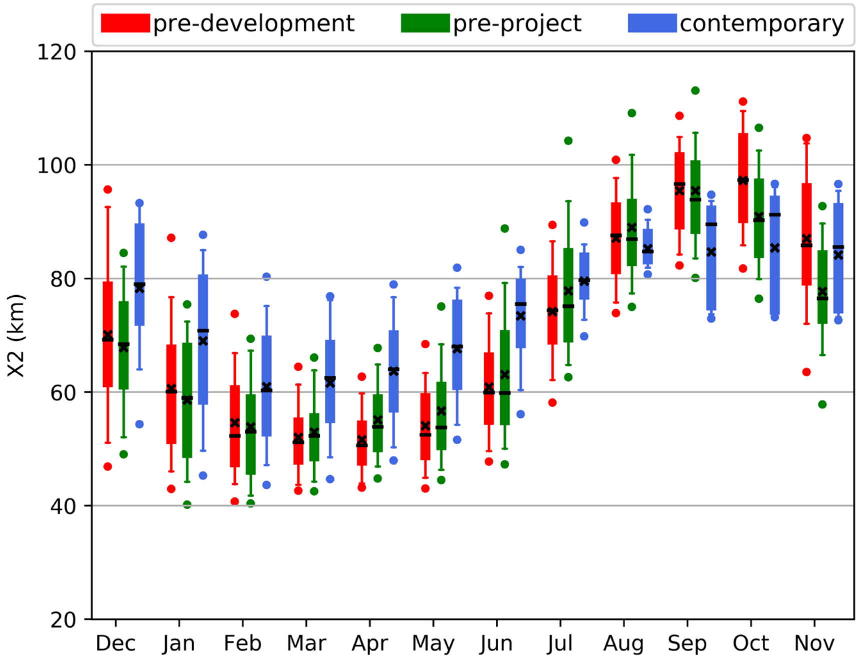

Figure 6 Modified box and whisker plot of salt intrusion length (X2) for the pre-development, pre-project, and contemporary scenarios given a historically observed climate sequence spanning water years 1922 through 2003. Boxes represent the interquartile range (25th to 75th percentile) for each month and scenario. The black lines represent the median value (50th percentile), the whiskers represent the 10th and 90th percentiles, the circles represent the 5th and 95th percentiles, and the "x" symbols represent the mean values.

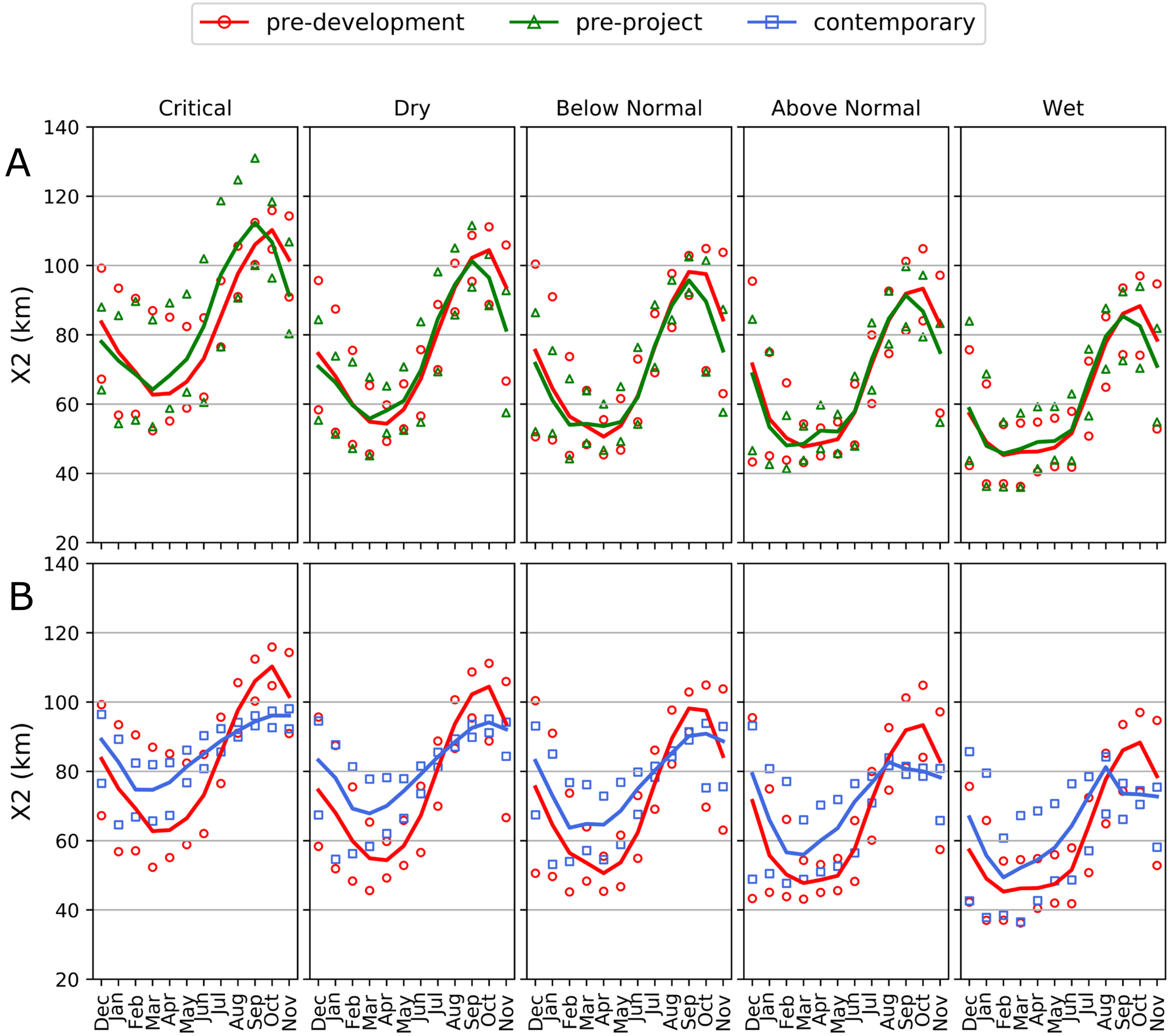

Figure 7 Comparison of (A) pre-development and pre-project scenario and (B) pre-development and contemporary scenario isohaline length (X2) subdivided by water year class, with lines indicating the median monthly X2 and symbols indicating the largest and smallest X2 for years within the given water year class on the Sacramento River. The X2 in October and November is generally more closely associated with the previous water year (their own calendar year) than the current water year; thus, these months are classified with the previous water year, and the X-axis spans the months of December through November.

in X2. To illustrate, steady outflows of 100 and 1,000 $\mathrm{m^3\,s^{-1}}$ correspond to X2 of 97.3 km and 57.3 km (respectively) for the contemporary scenario, and X2 of 93.1 km and 53.9 km (respectively) for the pre-development scenario. This weak dependence of predicted salt intrusion on Delta outflow follows from the parameter gamma in Equation 3, which was similar for the contemporary scenario (–0.230) and pre-development scenario (–0.237). For a given change in flow, a smaller-magnitude (less negative) coefficient corresponds to a weaker salinity response. Monismith et al. (2002) suggest that the observed weak response of salt intrusion to flow is partially from increases in estuarine circulation with increased flow muting the overall adjustment of salt intrusion. The limited X2 response is visible in Figure 7, which shows that X2 ranges from 37 km to 98 km in the contemporary estuary and 36 km to 116 km in the pre-development estuary.

Figure 8 compares the monthly (top panel) and annual (bottom panel) X2 exceedance probability for the three scenarios. The exceedance probability of annual average X2 was highest for the contemporary scenario, indicating more annual averaged salt intrusion under contemporary conditions. Annual X2 was only slightly lower for the pre-project scenario across a range of moderate X2 than for the pre-development scenario. The exceedance probability of monthly X2 up to 80 km was highest for the contemporary scenario, indicating that the contemporary scenario generally had higher salt intrusion for moderate salt intrusion lengths.

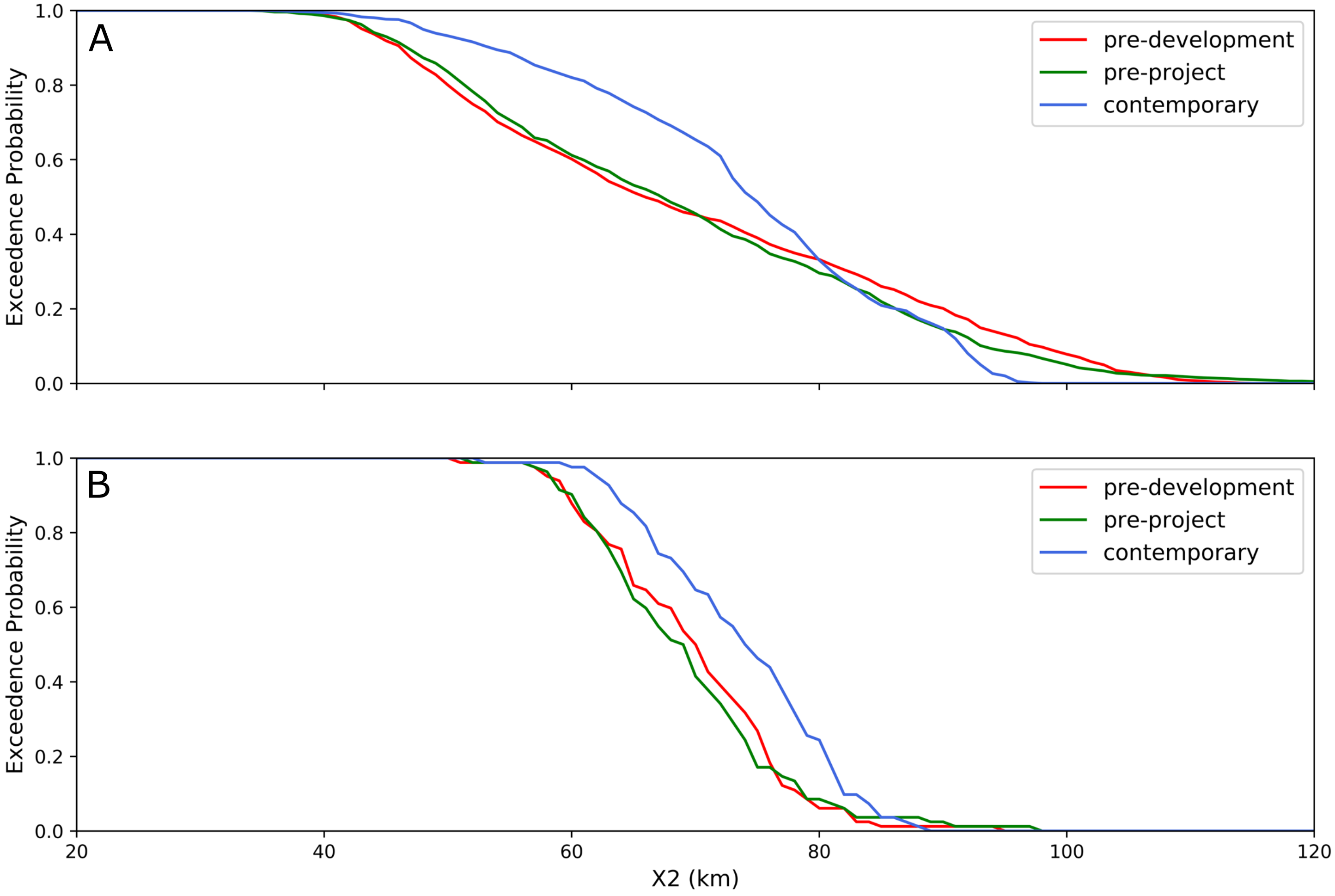

Figure 8 Exceedence probability for (A) monthly and (B) annual pre-development, pre-project, and contemporary-scenario isohaline length (X2).

However, X2 higher than 80 km was most common in the pre-development scenario and least common in the contemporary scenario.

DISCUSSION

This study compares predicted salt intrusion in the contemporary and pre-development estuary. The primary difference between the two scenarios is the seasonal variability of salt intrusion, which is driven by alterations in Delta outflow. The contemporary estuary is characterized by lower winter–spring flows and higher summer–fall flows as winter runoff is stored in surface reservoirs and later released to meet agricultural, municipal, industrial, and fish and wildlife beneficial uses. In contrast, natural storage regulation under pre-development conditions primarily occurred under high flow conditions as a result of bank overflow. To place this comparison in context with the advent of systematic and accurate flow and salinity measurements in the estuary, this study also compared pre-development conditions with "pre-project" conditions of the early 20th century circa 1920. The primary landscape differences between these scenarios are land-use shifts from natural vegetation to irrigated agriculture, and construction of an extensive levee system in the watershed and estuary.

The time-series presented in this paper do not represent historical flows; rather, each is a time-series of flow through a fixed landscape for a historical climate. The pre-development outflow time-series (CDWR 2016a) builds upon work by Howes et al. (2015) and Fox et al. (2015) by using similar precipitation data sets and assumptions for land and water use on the Central Valley floor. Fox et al. (2015) recommended future research in several areas, including inter- and intra-annual variability in natural Delta outflow and estuarine salinity transport. CDWR (2016a) answered the Fox et al. (2015) recommendation for a refined natural outflow estimate, and, using a slightly longer climate sequence, arrived at a long-term annual average Delta outflow estimate (24.5 billion $m^3\ yr^{-1}$) slightly above the range estimated by Fox et al. (2015). CDWR (2015) reported long-term annual average contemporary Delta outflow and CVP–SWP exports of 19.4 billion $m^3\ yr^{-1}$ and 6.1 billion $m^3\ yr^{-1}$, respectively. Thus, the difference between long-term annual average pre-development and contemporary outflow is similar in magnitude to long-term annual average CVP–SWP exports from the Delta. Flow was generally higher in the pre-project scenario than in the pre-development scenario because of less evapotranspiration in floodplains and estuarine wetlands. However, the range of pre-project flows extends substantially lower than the corresponding pre-development flows in spring and summer months of "Critical" water years, presumably because of upstream irrigation demands.

Our salt intrusion estimates build upon Andrews et al. (2017) by extending the salinity prediction period from 3 years to 82 years to better characterize the range of salt intrusion for pre-development and contemporary conditions. Although winter outflows are similar for the pre-development and contemporary scenarios in "Above Normal" and "Wet" water years (Figure 4), winter salt intrusion is lower in the pre-development estuary across all water year classes (Figure 7), illustrating that the changes in estuarine geometry, bathymetry, and mean sea level significantly influence X2. The relationships between Delta outflow and X2 in Table 1 indicate a higher X2 for the contemporary and pre-project scenarios than for the pre-development scenario for any given flow rate. This finding is consistent with the interpretation that sea level rise and erosion of Suisun Bay have increased dispersive salt transport into the estuary (Enright and Culberson 2009).

Although we have focused primarily on differences between pre-development and contemporary levels of development flow and salt intrusion, differences between the pre-project and contemporary scenarios are noteworthy. Estimated annual average pre-project outflow (30.4 billion $m^3\ yr^{-1}$) is higher than the corresponding contemporary scenario outflow of 19.4 billion $m^3\ yr^{-1}$. This difference is consistent with Enright and Culberson's (2009) observation that, over the historical period spanning 1920–2006, the early part of the period (1920–1967) experienced higher annual average Delta outflow despite lower annual average precipitation. Figure 3 shows that, on a monthly average basis, pre-project scenario outflow exceeds contemporary scenario outflow in all months except July, August, and September; this difference is consistent with Enright and Culberson's

(2009) observation of decreasing historical outflow in all months except July, August, and September. Similarly, Hutton et al. (2017a), in an analysis of historical flow from water year 1922 to 2015, found statistically significant increasing Delta outflow trends only in July and August. Our findings of seasonal change are also consistent with Fox et al. (1990) who report "July through September flows have significantly increased over the period from 1921 to 1986."

Figure 6 indicates that, on average, salt intrusion is higher under the contemporary scenario than for the pre-project scenario except for the months of August, September, and October. Enright and Culberson (2009) compare trends in monthly average Collinsville and Port Chicago salinity pre-1968 to post-1968; they report decreasing trends in July, August, and September, and increasing trends in other months. Hutton et al. (2015) compare monthly average X2 over the 1922–2012 period and report decreasing trends in July, August, and September; no trend in October; and increasing trends in the remaining months—with all but the July and October trends being statistically significant. In general, our broad conclusions are consistent with previously reported findings.

Though a level-of-development approach is not intended to reproduce a historical time-series, the results shown in Figure 5 suggest the pre-project scenario salt intrusion is similar to the observed historical salt intrusion. Directly comparing pre-development scenario flow and salt intrusion to historical conditions before development (before 1850) is not possible because of the limited availability of salinity observations before 1922. However, comparing pre-development annual outflow with work by Moftakhari et al. (2013) is instructive. Using a novel analysis of the tide record in San Francisco, their work generated historical flow estimates that spanned 1858 through 2011, and they report a "~30% decrease in annual average discharge after 1900." The trend estimated by Moftakhari et al. (2013) is influenced by changes in precipitation as well as level of development (i.e. land use and water operations), whereas our estimates of a 21% decrease in annual average discharge in the contemporary scenario relative to the pre-development scenario, and a 36% decrease relative to the pre-project scenario are for the same record of historical climate, and thus isolate the effect of altered level of development.

An interesting data set that provides limited characterization of pre-1920s salinity in the estuary was collected by the California & Hawaiian Sugar Refining Corporation (C&H). C&H, which obtained most of its freshwater supply in the early 20th century by transporting water to its refinery in Crockett, maintained a record that began in 1908 on the distance its barges traveled to obtain freshwater and the quality of water obtained (CDPW 1931; CCWD 2010). The barges were typically filled when salinity was determined to be less than 50 mg l^{-1} chloride, which corresponds to approximately 0.35 $mS\,cm^{-1}$ specific conductance or 0.2 psu. An early report by the state of California (CDPW 1931) concluded from the barge travel data that "... from 1908 to 1920, there have been periods of from 3 to 9 months during each year when all of Suisun Bay up to the lower end of the Delta was impregnated by saline water in varying degrees and that for shorter periods each year, the invasion of salinity has reached points well above the confluence of the Sacramento and San Joaquin rivers." CCWD (2010) concluded from the barge travel data that "Fresh water was present farther downstream and persisted for longer periods of time in the western Delta in the early 1900s than under recent time-periods with similar hydrologic conditions."

Although the barge travel data are of great historical interest, the level of development associated with their period of record aligns neither with our pre-development scenario nor our pre-project scenario. The 1908–1918 subset of data analyzed by CCWD (2010) was substantially different from our pre-project scenario level of development because of rapid increases in upstream reservoir storage, upstream irrigated agriculture (particularly rice), and wetland reclamation before 1920 (CDPW 1931). Furthermore, drawing inferences of broad estuarine salinity distribution (e.g., X2) from the barge travel data is challenging, given (1) the data's low salinity metric (approximately 0.2 psu) that is not easily differentiated from landward conditions, and (2) the lack of information linking measurement frequency to the tidal cycle. Additionally, the 1908–1918 period was notably wet and therefore provides a limited characterization of how the estuarine salinity regime responded to pre-1920-level conditions. Six of the 11 years are classified as "Wet" in the Sacramento River Valley (CDWR 2016c). Of the remaining years, one is classified as "Above Normal," two are classified as "Below Normal," and two are classified as "Dry." Despite the limitations of the C & H barge travel data, the CCWD (2010) drew some conclusions from the data that align with our comparison of pre-project and contemporary scenarios. The CCWD (2010) reports less salt intrusion in the early 20th century than for 1994–2004 historical conditions, consistent with the lower salt intrusion indicated by our pre-project scenario than for our contemporary scenario for all months except August, September, and October (see Figure 6). Also, consistent with the CCWD (2010), Figure 6 indicates the biggest increase in monthly salt intrusion relative to pre-project conditions occurs in winter and spring.

Although annual average salt intrusion to any point in the estuary is more common for the contemporary scenario than the pre-development scenario, the monthly cumulative distribution functions (Figure 8) show that the 2-psu isohaline intruded into the Delta more commonly in the pre-development scenario than in the contemporary scenario. Thus, it can be concluded that although Suisun Bay is fresher under pre-development conditions, brackish water intrudes into the Delta more frequently under those conditions. This conclusion is inconsistent with CCWD (2010) conclusion of lower pre-development salt intrusion in dry years relative to modern conditions. Although Figure 7 suggests substantial salt intrusion in the western Delta during dry and critically dry years under pre-development and pre-project conditions, the CCWD (2010) concludes—based on paleosalinity data at Browns Island reported by Malamud–Roam and Ingram (2004), as well as the C & H data during 1908 to 1918 discussed previously—that the western Delta was predominantly a freshwater system in the 2,500 years before 1920.

Multiple sources of Delta paleosalinity data are available to provide insight to pre-development conditions. Based on a review of these data, including sediment cores collected at Browns Island in 2005, Drexler et al. (2014) concluded that "the western border of the Delta has been a transitional region perched at the ecotone between oligohaline and fresh for more than 6,000 years." The CCWD (2010) discusses a sediment core collected at Browns Island that indicates low abundance of the salt-tolerant *Salicornia virginica* before approximately 1930 and high abundance subsequently (May 1999; Malamud–Roam and Ingram 2004). Malamud–Roam and Ingram (2004) conclude that "during modern times, average precipitation in California has not been anomalously low, yet the salinity in the Bay estuary has been relatively high." Another possible explanation for the shift in vegetation at Browns Island was provided by May (1999) when the data was originally reported:

> "one of the largest changes wrought by the water projects is the loss of high spring flows, and it may be that the absence of these flows, which in previous years could have provided a critical flush of salts from the soils of *Scirpus* and other salt-intolerant plants, was a primary cause of the *Salicornia* increase."

Malamud–Roam et al. (2006) note more generally that "timing of river flows can be critically important to the life histories of the marsh plants."

If lower spring flows are primarily responsible for the observed shift in vegetation at Browns Island reported in Malamud–Roam and Ingram (2004), that does not necessarily imply less salt intrusion during summer and fall under pre-development conditions. However, if the CCWD (2010) and Malamud–Roam and Ingram (2004) correctly interpret the shift in vegetation to arise from increased salt intrusion, that would imply that our pre-development modeling analysis is biased toward higher summer and fall salt intrusion, at least during relatively dry years. If our modeling analysis is indeed biased, one possible explanation for such a bias is that the pre-development scenario (CDWR 2016a) overestimates evapotranspiration from the natural landscape that results from uncertain vegetation coverage and water availability. Another possible explanation for such a modeling bias is that the pre-development scenario underestimates the magnitude of summer base flows because of uncertainties in flood storage and subsequent groundwater accretion to the channels.

Another modeling uncertainty associated with the pre-development scenario is the effect of estuarine

https://doi.org/10.15447/sfews.2018v16iss3art6

geometry and bathymetry alterations on salt intrusion. This uncertainty is substantial because of limited pre-development bathymetric, hydrodynamic, and salinity observations (Andrews et al. 2017). The pre-project response to salt intrusion is less uncertain because of the availability of systematically collected salinity data starting in the early 1920s (Hutton et al. 2015). A single flow–X2 relationship was found to accurately reproduce trends from 1922–2012 in Hutton et al. (2015) despite substantial changes to the geometry of the estuary in that period. This consistency throughout the 91-year historical analysis of Hutton et al. (2015) suggests that the flow–X2 relationship is not strongly sensitive to changes in estuarine geometry. Figure 5 suggests that our pre-project scenario provides a reasonably accurate characterization of 1920-level salinity intrusion. The uncertainty in the pre-development response of salt intrusion to flow likely has a limited influence on our predictions because the changes in seasonal timing of pre-development and contemporary flows are the primary driver of differences in predicted salt intrusion.

The characterization of pre-development Delta outflow and salt intrusion we present provides a baseline to inform flow regulations and restoration actions. Comparison of the pre-development and contemporary scenarios suggests that shifting the contemporary estuary toward a more natural flow and salinity regime would involve allowing higher Delta outflow during spring and lower Delta outflow during summer and fall. On a seasonal basis, the contemporary-scenario Delta outflow is 74% and 131% of the pre-development scenario Delta outflow in January through June and July through November, respectively.

Although our comparison of pre-development, pre-project, and contemporary-scenario Delta outflow and salt intrusion assumes fixed levels of development and a common historical climate sequence, we acknowledge that both land use and climate will continue to change over time (Cloern et al. 2011). The effects of climate change on Central Valley hydrology are already evident in shifts in seasonal runoff patterns toward earlier spring runoff and lower summer stream-flow (Regonda et al. 2005; Kapnick and Hall 2009), and this trend is expected to continue (Knowles and Cayan 2002). Sea level rise caused by climate change will also increase salt intrusion for a given Delta outflow. At a fixed Delta outflow of 260 $m^3 s^{-1}$, additional salt intrusion of 0.9 and 8.1 km has been estimated for mean sea level rise scenarios of 20 and 140 cm, respectively (Gross et al. 2007). Offsetting the effect of these sea level rise scenarios would require an estimated 10 and 68 $m^3 s^{-1}$ additional outflow, respectively (Gross et al. 2007). At a fixed Delta outflow of 260 $m^3 s^{-1}$, the difference between contemporary and pre-development X2 (with an associated difference in mean sea level of 31 cm) is 3.9 km. This difference is larger than the 2.5 km increase estimated by Gross et al. (2007) for a 50-cm sea level rise scenario, suggesting that dredging channels and other bathymetric change associated with the contemporary estuary also contribute to salt intrusion.

Similarly, additional salt intrusion may be incurred by restoration projects or unplanned restoration of Delta islands to tidal inundation due to levee failure (DRMS 2007). Restoration, early runoff, and sea level rise are each likely to contribute to increased salt intrusion in summer and fall, or require increased Delta outflow to maintain salinity-based water quality standards during this period. The summer salt intrusion for the pre-development scenario estimated here suggests that dry conditions and large salt intrusion were common before anthropogenic influence. Paleoclimate research also suggest that both flow and salinity in the estuary have varied widely as a result of variable precipitation (Malamud–Roam and Ingram 2006). The survival of native species through historic droughts in the pre-development landscape suggests that flow regulation alone is not adequate to restore ecological conditions. Restoring a more natural landscape with broader connectivity among different habitat types such as channel, floodplain, and tidal wetland is likely to move the estuarine food web closer to pre-development conditions and to favor some native species (Brown et al. 2016). Successful rehabilitation of the estuary's ecology will also require amelioration of other stressors (Luoma et al. 2015). Furthermore, any set of flow actions may not benefit all native species, because mechanisms underlying "fish–X2" relationships are uncertain and likely to vary by species (Kimmerer 2002). Experience in other settings shows "the impossibility of engineering optimal conditions for all species" (Poff et al. 1997). Though achieving abundant populations of all native species is unlikely in the estuary, a more natural flow and salinity regime is likely to benefit most native species (Moyle et al. 2012).

ACKNOWLEDGMENTS

Funding for this project was provided by Metropolitan Water District of Southern California. The authors wish to thank the California Department of Water Resources for providing model data relating to pre-development and contemporary Delta flow scenarios.

REFERENCES

Alexander BS, Mendell GH, Davidson G. 1874. Report of the Board of Commissioners on the Irrigation of the San Joaquin, Tulare, and Sacramento valleys of the State of California. 43rd Congress, 1st Session. House of Representation, Ex. Doc. No. 290. Washington D.C.: Government Printing Office.

Andrews SW, Gross ES, Hutton PH. 2017. Modeling salt intrusion in the San Francisco Estuary prior to anthropogenic influence. Cont Shelf Res 146:58–91. *http://doi.org/10.1016/j.csr.2017.07.010*

Atwater BF, Conard SG, Dowden JN, Hedel CW, MacDonald RL, Savage W. 1979. History, landforms, and vegetation of the estuary's tidal marshes, in: San Francisco Bay: the urbanized estuary. In: Conomos TJ, editors. San Francisco (CA): Pacific Division, AAAS. p. 347–385.

Brown LR, Kimmerer W, Conrad L, Lesmeister S, Mueller–Solger A. 2016. Food webs of the Delta, Suisun Bay, and Suisun Marsh: an update on current understanding and possibilities for management. San Franc Estuary Watershed Sci 14(3). *http://doi.org/10.15447/sfews.2016v14iss3art4*

Bunn SE, Arthington AH. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ Manage 30(4):492–507. *http://doi.org/10.1007/s00267-002-2737-0*

Burcham LT. 1957. California range land: an historical-ecological study of the range resource of California. [Sacramento (CA)]: California Department of Natural Resources, Division of Forestry. 261 p.

CCWD: Contra Costa Water District. 2010. Historical Fresh Water and Salinity Conditions in the Western Sacramento–San Joaquin Delta and Suisun Bay. [cited 2018 October 26]. Technical memorandum WR10-001. [Concord (CA)]: Available from: *https://www.ccwater.com/DocumentCenter/Home/View/382*

CDPW: California Department of Public Works. 1924–42. Report of the Sacramento–San Joaquin Water Supervisor for the period 1924–1941. Bulletin 23. [cited 2018 October 26]. Available from: *http://www.water.ca.gov/waterdatalibrary/docs/historic/Bulletins/bulletins.cfm*

CDPW: California Department of Public Works. 1931. Variation and Control of Salinity in the Sacramento–San Joaquin Delta and Upper San Francisco Bay. Bulletin 27. [cited 2018 October 26. [Sacramento (CA)]: California Department of Public Works, Division of Water Resources. Available from: *http://www.water.ca.gov/waterdatalibrary/docs/historic/Bulletins/Bulletin_27/Bulletin_27__1931.pdf*

CDWR: California Department of Water Resources. 2013. Development and calibration of the California Central Valley groundwater-surface water simulation model. Version 3.02-CG. [Sacramento (CA)]: Bay–Delta Office, California Department of Water Resources.

CDWR: California Department of Water Resources. 2015. State Water Project delivery capability report. [cited 2018 October 26]. [Sacramento (CA)]: California Department of Water Resources. Available from: *http://baydeltaoffice.water.ca.gov/*

CDWR: California Department of Water Resources. 2016a. Estimates of natural and unimpaired flow for the Central Valley of California: water years 1922–2014. [cited 2016 May 31]. Available from: *http://baydeltaoffice.water.ca.gov/*

CDWR: California Department of Water Resources. 2016b. Dayflow: an estimate of daily average Delta outflow. [cited 2018 October 26]. Available from: *http://www.water.ca.gov/dayflow/*

CDWR: California Department of Water Resources. 2016c. Chronological Reconstructed Sacramento and San Joaquin Valley water year hydrological classification indices. [cited 2016 July 5]. Available from: *http://cdec.water.ca.gov/cgi-progs/iodir/wsihist*

Cheng RT, Casulli V, Gartner JW. 1993. Tidal, residual, intertidal mudflat (TRIM) model and its application to San Francisco Bay, California. Est Coast Shelf Sci 36:235–280. *http://doi.org/10.1006/ecss.1993.1016*

Cloern JE, Knowles N, Brown LR, Cayan D, Dettinger MD, Morgan TL, Schoellhamer DH, Stacey MT, van der Wegen M, Wagner RW, Jassby AD. 2011. Projected evolution of California's San Francisco Bay–Delta river system in a century of climate change. PLoS ONE. 6(9): e24465. *http://doi.org/10.1371/journal.pone.0024465*

Denton RA. 1993. Accounting for antecedent conditions in seawater intrusion modeling—applications for the San Francisco Bay–Delta. Shen HW, Su ST, Wen F, editors. Hydraul Eng 1:448–453.

Draper AJ, Munévar A, Arora SK, Reyes E, Parker NL, Chung FI, Peterson LE. 2004. CalSim: generalized model for reservoir system analysis. J Water Res Pl 130(6):480–489. *http://doi.org/10.1061/(ASCE)0733-9496(2004)130:6(480)*

Drexler JZ, Paces JB, Alpers CN, Windham–Myers L, Neymark, LA, Bullen TD, Taylor HE. 2014. ^{234}U/^{238}U and δ^{87}Sr in peat as tracers of paleosalinity in the Sacramento–San Joaquin Delta of California, USA. Appl Geochem 40:164–179. *http://doi.org/10.1016/j.apgeochem.2013.10.011*

DRMS: Delta Risk Management Strategy. 2007. Hydrodynamics and water quality. Appendix D. In: URS Corporation, Jack R. Benjamin & Associates, Inc. Topical area: water analysis module (WAM). [cited 2018 October 26]. [Sacramento (CA)]: California Department of Water Resources. Available from: *http://www.water.ca.gov/floodsafe/fessro/levees/drms/docs/Water_Analysis_Module_TM.pdf*

Duarte CM, Conley DJ, Carstensen J, Sánchez–Camacho M. 2009. Return to neverland: Shifting baselines affect eutrophication restoration targets. Estuaries Coasts 32:29–36. *http://doi.org/10.1007/s12237-008-9111-2*

Dutzi EJ. 1978. Valley Oaks in the Sacramento Valley: Past and present distribution [thesis]. [Davis (CA)]: University of California, Davis.

Elliott M, Burdon D, Hemingway KL, Apitz SE. 2007. Estuarine, coastal and marine ecosystem restoration: Confusing management and science–a revision of concepts. Estuar Coast Shelf Sci 74:349–366. *http://doi.org/10.1016/j.ecss.2007.05.034*

Enright C, Culberson SD. 2009. Salinity trends, variability, and control in the northern reach of the San Francisco Estuary. San Fran Estuary Watershed Sci 7(2). *http://doi.org/10.1038/sdata.2017.98*

Fox JP, Mongan TR, Miller WJ. 1990. Trends in freshwater inflow to San Francisco Bay from the Sacramento–San Joaquin Delta. J Am Water Res Assoc 26(1):101–116. *http://doi.org/10.1111/j.1752-1688.1990.tb01355.x*

Fox P, Hutton PH, Howes DJ, Draper AJ, Sears L. 2015. Reconstructing the natural hydrology of the San Francisco Bay–Delta watershed. Hydrol Earth Syst Sci 19:4257–4274. *http://doi.org/10.5194/hess-19-4257-2015*

Garone P. 2011. The fall and rise of the wetlands of California's Great Central Valley. Berkeley, CA: University of California Press. 422 p.

Gross ES, MacWilliams ML, Nidzieko N. 2007. Three-dimensional salinity simulations of sea level rise scenarios. Appendix H3. In: URS Corporation, Jack R. Benjamin & Associates, Inc. Topical area: water analysis module (WAM). [Sacramento (CA)]: California Department of Water Resources. [cited 2018 October 26]. Available from: *http://www.water.ca.gov/floodsafe/fessro/levees/drms/docs/Water_Analysis_Module_TM.pdf*

Grunsky CE. 1929. The relief outlets and by-passes of the Sacramento Valley Flood-Control Project. Trans Am Soc Civ Eng 93:791–811.

Hall WH. 1880. Report of the State Engineer to the Legislature of California. Session of 1880, part 2. [Sacramento (CA)]: California State Printer. Available from: *https://www.davidrumsey.com/luna/servlet/detail/RUMSEY~8~1~207699~3003430:Topographical-and-Irrigation-Map-of*

Hall WH. 1887. Topographical and irrigation map of the Great Central Valley of California embracing the Sacramento, San Joaquin, Tulare and Kern valleys and the bordering foothills. [cited 2018 October 26]. [Sacramento (CA)]: [California State Engineering Department].

Hanak E, Lund J, Dinar A, Gray B, Howitt R, Mount J, Moyle P, Thompson B. 2011. Managing California's water: From conflict to reconciliation. [cited 2018 October 26]. San Francisco (CA): Public Policy Institute of California. Available from: *http://www.ppic.org/content/pubs/report/R_211EHR.pdf*

Holland RF. 1978. The geographic and edaphic distribution of vernal pools in the Great Central Valley, California. [cited 2018 October 26]. [Fair Oaks (CA)]: California Native Plant Society. Special Publ. No. 4.

Howes D, Fox JP, Hutton PH. 2015. Evapotranspiration from natural vegetation in the Central Valley of California: monthly grass reference-based vegetation coefficients and the dual crop coefficient approach. J Hydrol Eng 20(10). *http://doi.org/10.1061/(ASCE)HE.1943-5584.0001162*

Hutton PH. 2014. Delta salinity gradient (DSG) model, version 1.0 model documentation. [Sacramento (CA)]: Metropolitan Water District. [cited 2017 October 17]. Available from: *http://www.baydeltalive.com/*

Hutton PH, Rath JS, Chen L, Ungs MJ, Roy SB. 2015. Nine decades of salinity observations in the San Francisco Bay and Delta: modeling and trend evaluation. J Water Res Pl Manage 142(3). *http://doi.org/10.1061/(ASCE)WR.1943-5452.0000617*

Hutton PH, Rath JS, Roy SB. 2017a. Freshwater flow to the San Francisco Bay–Delta estuary over nine decades (part 1): trend evaluation. Hydrol Proces *http://doi.org/10.1002/hyp.11201*

Hutton PH, Rath JS, Roy SB. 2017b. Freshwater flow to the San Francisco Bay–Delta estuary over nine decades (part 2): change attribution. Hydrol Proces *http://doi.org/10.1002/hyp.11195*

Jackson WT, Paterson AM. 1977. The Sacramento–San Joaquin Delta: The evolution and implementation of water policy: an historical perspective. Water Resources Center technical completion report W-501. [Davis (CA)]: University of California Water Resources Center.

Jassby AD, Kimmerer WJ, Monismith SG, Armor C, Cloern JE, Powell TM, Schubel JR, Vendlinski TJ. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecol Appl 5:272–289. *http://doi.org/10.2307/1942069*

Kapnick S, Hall A. 2009. Observed changes in the Sierra Nevada snowpack: potential causes and concerns. California Climate Change Center. [cited 2018 October 26]. Available from: *http://www.energy.ca.gov/2009publications/CEC-500-2009-016/CEC-500-2009-016-F.PDF*

Katibah EF. 1984. A brief history of riparian forests in the Central Valley of California. In: Warner RE, Hendrix KM, editors. California riparian forests. Berkeley (CA): University of California Press. p 23–29.

Kennish MJ. 1999. Estuary restoration and maintenance: The National Estuary Program. [Boca Raton (FL)]: CRC Press.

Kennish MJ. 2002. Environmental threats and environmental future of estuaries. Environ Conserv 29:78–107. *http://doi.org/10.1017/S0376892902000061*

Kimmerer WJ. 2002. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages?. Mar Ecol Prog Ser 243:39–55. *http://doi.org/10.3354/meps243039*

Kimmerer WJ. 2004. Open water processes of the San Francisco Estuary: from physical forcing to biological responses. San Fran Estuary Watershed Sci 2(1). *https://doi.org/10.15447/sfews.2004v2iss1art1*

Kimmerer WJ, Murphy DD, Angermeier PL. 2005. A landscape-level model for ecosystem restoration in the San Francisco Estuary and its watershed. San Fran Estuary Watershed Sci 3(1). *http://doi.org/10.15447/sfews.2005v3iss1art4*

Kimmerer WJ, Gross ES, MacWilliams ML. 2009. Is the response of estuarine nekton to freshwater flow in the San Francisco Estuary explained by variation in habitat volume? Estuaries Coasts 32:375–389. *http://doi.org/10.1007/s12237-008-9124-x*

Kimmerer WJ, MacWilliams ML, Gross ES. 2013. Variation of fish habitat and extent of the low salinity zone with freshwater flow in the San Francisco Estuary. San Franc Estuary Watershed Sci 11(4). *https://doi.org/10.15447/sfews.2013v11iss4art1*

Kimmerer WJ, Gross ES, MacWilliams ML. 2014. Tidal migration and retention of estuarine zooplankton investigated using a particle-tracking model. Limnol Oceanogr 59:901–916. *http://doi.org/10.4319/lo.2014.59.3.0901*

Knowles N, Cayan DR. 2002. Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary. Geophys Res Lett 29(18):38-1–38-4. *http://doi.org/10.1029/2001GL014339*

Kuivila KM, Foe CG. 1995. Concentrations, transport and biological effects of dormant spray pesticides in the San Francisco Estuary, California. Environ Toxicol Chem 14:1141–1150. *http://doi.org/10.1002/etc.5620140704*

Lund J, Hanak E, Fleenor WE, Howitt R, Mount J, Moyle P. 2007. Envisioning futures for the Sacramento–San Joaquin Delta. [cited 2018 October 26]. San Francisco (CA): Public Policy Institute of California. Available from: *http://www.ppic.org/main/publication.asp?i=671*

Luoma SN, Dahm CN, Healey M, Moore JN. 2015. Challenges facing the Sacramento–San Joaquin Delta: Complex, chaotic, or simply cantankerous? San Franc Estuary Watershed Sci 13(3). *http://doi.org/10.15447/sfews.2015v13iss3art7*

Malamud–Roam FP, Ingram BL. 2004. Late Holocene $\delta^{13}C$ and pollen records of paleosalinity from tidal marshes in the San Francisco Bay estuary California. Quat Res 62:134–145. *http://doi.org/10.1016/j.yqres.2004.02.011*

Malamud–Roam FP, Ingram BL, Hughes M, Florsheim JL. 2006. Holocene paleoclimate records from a large California estuarine system and its watershed region: linking watershed climate and bay conditions. Quat Sci Rev 25:1570–1598. *http://doi.org/10.1016/j.quascirev.2005.11.012*

May MD. 1999. Vegetation and salinity changes over the last 2000 years at two islands in the northern San Francisco Estuary, California [thesis]. [Berkeley (CA)]: University of California, Berkeley. p. 55.

Moftakhari HR, Jay DA, Talke SA, Kukulka T, Bromirski PD. 2013. A novel approach to flow estimation in tidal rivers. Water Resour Res 49(8):4817–4832. *http://doi.org/10.1002/wrcr.20363*

Monismith SG, Kimmerer WJ, Burau JR, Stacey MT. 2002. Structure and flow-induced variability of the subtidal salinity field in northern San Francisco Bay. J Phys Oceanogr 32:3003–3019. *http://doi.org/10.1175/1520-0485(2002)032<3003:SAFIVO>2.0.CO;2*

Monismith SG. 2017. An integral model of unsteady salinity intrusion in estuaries. J Hydraul Res 55(3):392–408. *http://doi.org/10.1080/00221686.2016.1274682*

Moyle P, Bennett W, Durand J, Fleenor W, Gray B, Hanak E, Lund J, Mount J. 2012. Where the wild things aren't: making the Delta a better place for native species. [cited 2018 October 26]. San Francisco (CA): Public Policy Institute of California. Available from: *http://www.ppic.org/main/publication.asp?i=1025*

MWH: Montgomery Watson Harza. 2016. Evolution of river flows in the Sacramento and San Joaquin valleys: historical level of development study. Prepared for Metropolitan Water District of Southern California. [cited 2017 October 17]. Available from: *http://www.baydeltalive.com/*

NMFS: National Marine Fisheries Service. 2009. Biological opinion and conference opinion of the long-term operations of the Central Valley Project and State Water Project. [cited 2016 June 4]. Long Beach (CA): National Marine Fisheries Service, Southwest Region. Available from: *http://www.swr.noaa.gov/ocap/NMFS_Biological_and_Conference_Opinion_on_the_Long-Term_Operations_of_the_CVP_and_SWP.pdf*

NOAA: National Oceanic and Atmospheric Administration. 2015. Mean sea level trend: 9414290. [cited 2015 December 10]. San Francisco (CA): NOAA. Available from: *http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9414290*

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime—a paradigm for river conservation and restoration. Bioscience 47:769–784. *http://doi.org/10.2307/1313099*

Poff NL, Zimmerman JKH. 2010. Ecological responses to altered flow regimes—A literature review to inform the science and management of environmental flows. Freshw Biol 55:194–205. *http://doi.org/10.1111/j.1365-2427.2009.02272.x*

Regonda SK, Rajagopalan B, Clark M, Pitlick, J. 2005. Seasonal cycle shifts in hydroclimatology over the Western United States. J Climate 18:372–384. *http://doi.org/10.1175/JCLI-3272.1*

Rose AH, Manson M, Grunsky CE. 1895. Report of the Commissioner of Public Works to the Governor of California. Sacramento (CA): State Printing Office.

SWRCB: State Water Resources Control Board. 1995. Water-quality control plan for the San Francisco Bay/Sacramento–San Joaquin Delta Estuary. [cited 2018 October 26]. Sacramento (CA): State Water Resources Control Board. Available from: *https://www.waterboards.ca.gov/rwqcb2/water_issues/programs/basin_plan/docs/basin_plan07.pdf*

Thom RM, Williams G, Borde A, Southard J, Sargeant S, Woodruff D, Laufle JC, Glasoe S. 2005. Adaptively addressing uncertainty in estuarine and near coastal restoration projects. J Coastal Res 40:94–108.

USFWS: U.S. Fish and Wildlife Service. 2008. Formal Endangered Species Act consultation and Biological Opinion on the proposed coordinated operations of the Central Valley Project (CVP) and State Water Project (SWP). Memorandum. [cited 2015 July 31]. Sacramento (CA): U.S. Fish and Wildlife Service. Available from: *http://www.fws.gov/sfbaydelta/documents/SWP-CVP_OPs_BO_12-15_final_OCR.pdf*

Villnäs A, Norkko A. 2011. Benthic diversity gradients and shifting baselines: Implications for assessing environmental status. Ecol Appl 21: 2172–2186. *http://doi.org/10.1890/10-1473.1*

Wagener T, Sivapalan M, Troch PA, McGlynn BL, Harman CJ, Gupta HV, Kumar P, Rao PSC, Basu NB, Wilson JS. 2010. The future of hydrology: An evolving science for a changing world. Water Resour Res 46. *http://doi.org/10.1029/2009WR008906*

Walters RA, Gartner JW. 1985. Subtidal sea level and current variations in the northern reach of San Francisco Bay. Estuar Coast Shelf Sci 21:17–32. *http://doi.org/10.1016/0272-7714(85)90003-4*

Whipple AA, Grossinger RM, Rankin D, Stanford B, Askevold RA. 2012. Sacramento–San Joaquin Delta historical ecology investigation: exploring pattern and process. [cited 2015 December 10]. Richmond (CA): San Francisco Estuary Institute. Available from: *http://www.sfei.org/DeltaHEStudy*

Williams PB, Orr MK. 2002. Physical evolution of restored breached levee salt marshes in the San Francisco Bay estuary. Restor Ecol 10:527–542. *http://doi.org/10.1046/j.1526-100X.2002.02031.x*