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Salinity trends, variability, and control in the northern reach of the San Francisco Estuary

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Keywords:
Delta, Suisun Marsh, outflow, salinity, trend, variability

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Salinity trends, variability, and control in the northern reach of the San Francisco Estuary

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ABSTRACT

The California State Water Project and federal Central Valley Water Project decoupled long-term trends in annual mean outflow and salinity from long-term trends in precipitation. The water projects also dampen seasonal and annual outflow and salinity variability. Despite this, both seasonal and annual timescale outflow and salinity are generally more variable in the water project era concordant with watershed precipitation. We re-constructed monthly time series of precipitation, outflow, and salinity for the northern reach. These include salinity at Port Chicago (since 1947), Beldons Landing (since 1929), and Collinsville (since 1921), Sacramento-San Joaquin Delta outflow (since 1929), and a San Francisco Estuary watershed precipitation index (since 1921). We decomposed data into seasonal, decadal, and trend components to clarify the superposition of variability drivers. With the longest time series over 1,000 months, these are the longest data records in the estuary, save for Golden Gate tide. We used the precipitation index to compare trends and variability in climate forcing to outflow and salinity trends before and after construction of the state and federal water projects and the Suisun Marsh Salinity Control Gate. We test the widely held conceptual model that water project reservoir and delta export operations reduce seasonal and annual outflow variability. We found that the water projects influence the trend of the annual and some monthly means in outflow and salinity, but exert far less influence on variability. We suggest that climate is the primary variability driver at timescales between one-month and ~20 years. We underscore the understanding that identifying trends and mechanisms requires data sets that are longer than the timescale of the lowest frequency forcing mechanism.

KEYWORDS

Sacramento-San Joaquin Delta, outflow, salinity, trend, variability.

INTRODUCTION

State and federal water projects in California modify the magnitude and seasonal timing of San Francisco Estuary watershed river inflows and outflow from the Sacramento-San Joaquin Delta. Water project exports from the Sacramento-San Joaquin Delta reduce river outflow through the estuary more than 20% on average since 1968, primarily for southern state agricultural and municipal water demands. From the inception of the water projects, investigators have warned that these activities change the physical and chemical estuarine environment in ways that are detrimental to estuary-dependent species (Mall 1969; Hedgepeth 1979; Moyle and others 2004). Outflow reduction and modification of seasonal outflow timing affects biota by changing their transport fate, modifying salinity habitat, and shifting the availability of geomorphic habitat types, especially those associated with or adjacent to salinity habitat (e.g. Kimmerer 2003; Simenstadt 2001).

State and federal water agencies responded to concerns about water project impacts with large-scale and long-term mitigation efforts including the Suisun Marsh Plan of Protection (1977), the CALFED Ecosystem Restoration Program (CALFED 2000), and the Bay-Delta Conservation Plan (BDCP 2009). In the case of Suisun Marsh, over $130 million has been spent on salinity control facilities and local assistance to private landowners. During planning for the State Water Project (SWP) in the 1960s, investigators suggested that waterfowl habitat in the Suisun Marsh could be degraded when lower outflow increased channel water salinity leading to higher soil water salinity and reduction in waterfowl food plant abundance (George 1965; Mall 1969; Rollins 1973).

The northern reach of the San Francisco Estuary (Figure 1) has long been a focus of ecosystem management and attempts to control salinity (Means 1928; California Water Plan 1957; George 1965; Mall 1969; Rollins 1973; Jackson and others 1977). The estuarine salinity gradient is generally steepest and many organisms have abundance maximums in Suisun Bay (Jassby and others 1995). The seasonal magnitude of outflow is positively correlated with abundance of aquatic species across trophic levels (Jassby and others 1995; Kimmerer 2004). Mechanisms for the relationship remain somewhat uncertain and are different from one species and life-stage to the next (Kimmerer 2002). Despite the lack of demonstrated direct or indirect mechanistic linkages, considerable water resources and management effort (via regulatory water quality standards) are dedicated to affecting seasonal outflow conditions to protect salinity habitat (SWRCB 1995). In parallel,

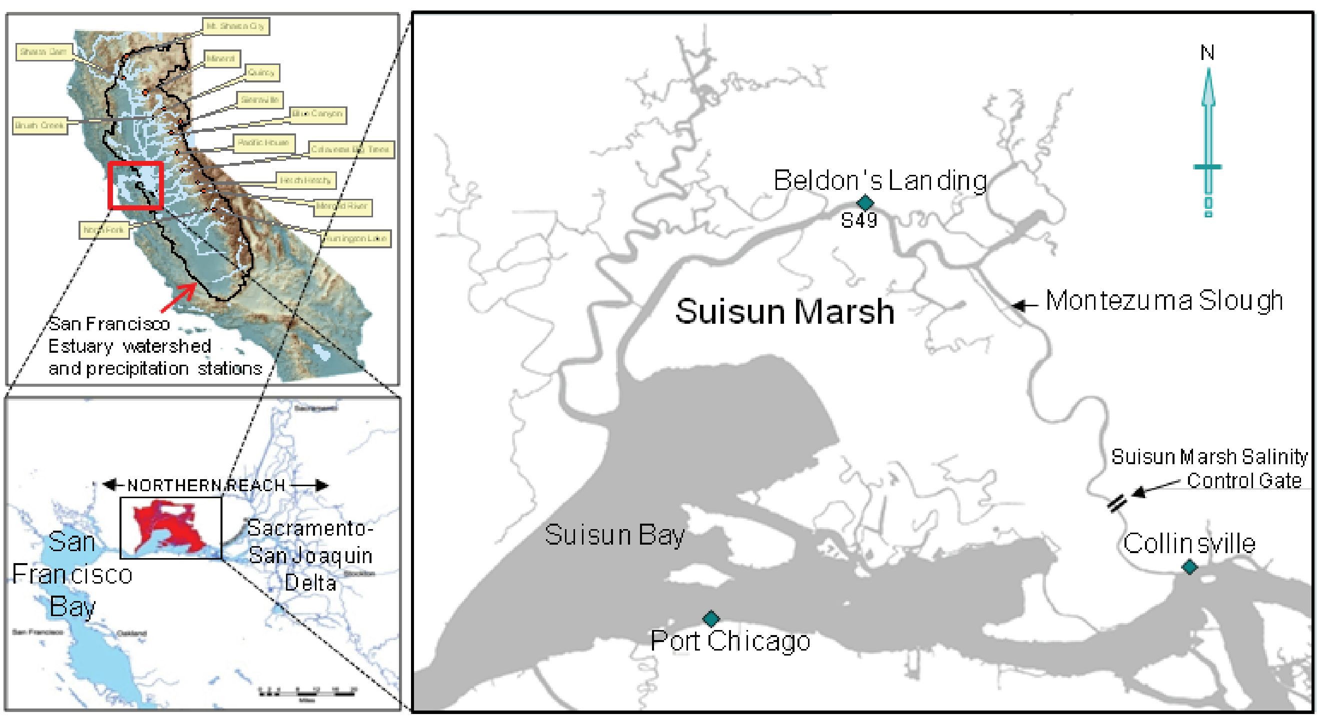

Figure 1 Location of Suisun Marsh, the northern reach of the San Francisco Estuary and historical salinity stations Port Chicago, Beldons Landing, and Collinsville. California map shows location of thirteen foothill precipitation stations within the San Francisco Estuary watershed.

there are ongoing science programs that would identify the process linkages between outflow, and native species abundance, presumably to improve the effectiveness of future water quality standards (e.g. Healy and others 2008).

The purpose of this paper is to describe long-term trends and variability in San Francisco Estuary watershed precipitation, and northern reach outflow and salinity. It is complementary to the work of Knowles (2002) who considered the same problem using a combination of data and modeling to discern the contribution of climate and water project operations on monthly and interannual salinity variability. This analysis also updates of the work of Fox and others (1990) who showed that despite increasing water depletions, outflow had not declined. They cite increasing precipitation, land use induced runoff increase, increased surface flow resulting from groundwater overdraft, and water imports from other drainages.

This work relies on up to 86 years of precipitation, outflow, and salinity data. The length of the data sets allows us to examine trend and variability differences between pre- and post-water project periods (defined later as before and after 1968). These time series offer a unique opportunity to investigate long-term trends because they are long enough to span decadal timescale climate processes. We posit several physical processes that affect long-term salinity trends and variability and compare them to the magnitude of water project induced change.

DATA FOR ANALYSIS OF PRE-PROJECT AND POST- PROJECT TRENDS

A primary aim of this analysis is to detect precipitation, outflow, and salinity trends and modes of variability to discern outflow and salinity response to State and federal water project operation (Figure 2). Monthly average specific conductance (SC), delta outflow, and San Francisco Estuary watershed precipitation were divided into "pre" and "post" water project periods. The federal Central Valley Project began delta water exports in 1950, the State Water Project in 1969 (Figure 2, panel B). Up to 1967, there were no facilities south of the delta to store winter and spring Sierra Nevada runoff through the delta. The water projects began year-round pumping operations in 1968 when San Luis Reservoir was completed. The advent of south-of-delta storage allowed four-season water project export from the delta. For the purposes of this analysis, we define the "pre" water project period as years prior to San Luis Reservoir operation (1929-1967). Accordingly, we define the "post" water project period as 1968 to the present. Since the three salinity stations are also influenced by the Suisun Marsh salinity control gate (SMSCG), the pre- and post-SMSCG periods around 1988 are also delineated.

Precipitation Data

The California Department of Water Resources (DWR) maintains records of monthly average tributary precipitation for the San Joaquin and Sacramento River watersheds as an index of runoff potential to the State and federal water project reservoirs (California Water Supply Outlook). The Sacramento River tributary average includes eight northern Sierra Nevada foothill and northern coast range stations while the San Joaquin river tributary average includes five central and southern Sierra Nevada stations (Figure 1). We aggregated the two indexes into one monthly 13-station average index to represent the 140,000 square kilometer estuary watershed region, an area comprising about 40% of the State (Conomos 1979). We also produced an annual average watershed precipitation time series by summing October through September (water year) monthly averages (Figure 2, panel A). The precipitation records cover the period from October 1920 to September 2006.

For our purpose, the 13-station average represents an index of climate forcing for the San Francisco Estuary watershed. To the extent that trends in 13-station precipitation variability and mean are correlated with delta outflow, the index is a proxy for outflow trends we would expect without water project influence or changes in watershed runoff dynamics. We acknowledge that the index is influenced by antecedent soil moisture, north-to-south Sierra Nevada elevation differences (Dettinger and others 1998), the temporal trend toward earlier Sierra Nevada runoff with time (Roos 1987), and differences

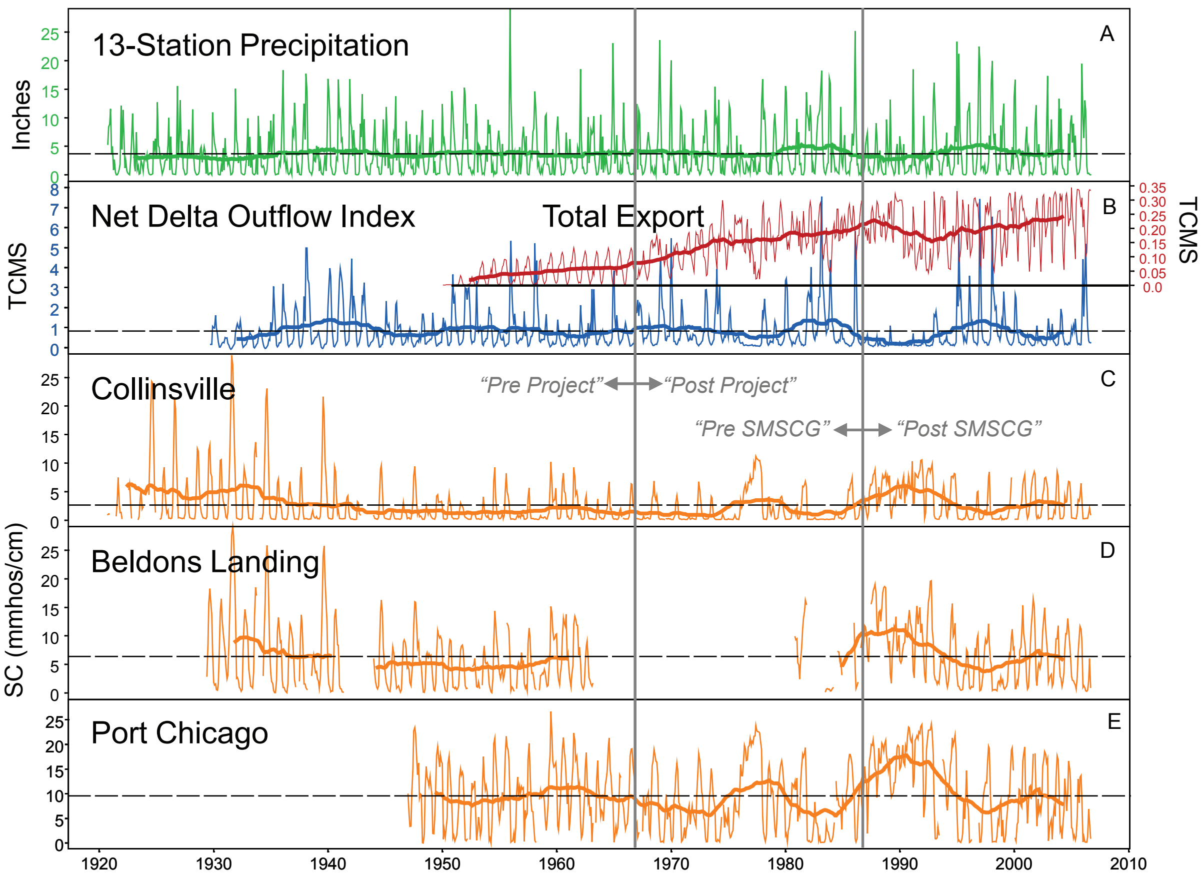

Figure 2 (A): Monthly average of 13 Sierra Nevada foothill precipitation stations on tributaries of the San Francisco Estuary watershed (1920-2006). (B): Monthly Delta outflow index. Right axis is monthly average total water project export. (C,D,E): Monthly average specific conductivity for Collinsville, Beldons Landing, and Port Chicago. Prior to 1966, SC is estimated from approximately four high tide TDS grab samples per week. Heavy solid line is 5-year running average. Dotted line is period of record mean.

in the variability modes between Sacramento and San Joaquin River inflows (Dettinger and Cayan 2003). For our purpose, aggregating tributary watershed precipitation enfolds changing tributary processes to maintain the focus on delta outflow and the coupled salinity response.

Sacramento-San Joaquin River Delta Outflow

Outflow from the Sacramento-San Joaquin Delta is the key physical process of the northern reach of the San Francisco Estuary. On subtidal time scales, outflow is the primary governor of ocean salt transport to the delta (Cheng 1990). While about 80% of outflow is contributed by the Sacramento River watershed, the San Joaquin River watershed accounts for much of the variability in late spring and summer delta salinity (Dettinger and Cayan 2003). We developed monthly and annual outflow estimates from the delta outflow index data set maintained by DWR (DWR Dayflow, 2003). Figure 2 (panel B) shows the monthly average delta outflow index for the period 1929 to 2006.

Suisun Bay and Suisun Marsh Salinity

We assembled long-term salinity time series for three northern reach stations (Figure 2, panels C,D,E). Monthly salinity as specific conductance (SC) was estimated for Port Chicago (Suisun Bay), Collinsville (Sacramento-San Joaquin River confluence), and Beldons Landing (Suisun Marsh) (Figure 1). Data were gathered and digitized from multiple paper records in DWR hydrologic data bulletins (DWR Bulletin 27, and Bulletin 23, and Bulletin 130 series). Between 1920 and 1971, salinity data was collected as surface zone grab samples by local observers 1.5 hours after high-high tide (nominal high slack) every four days. The monitoring programs were initiated in response to early century drought concerns (Jackson and others 1977). Samples were bottled, time tagged, and mailed to an analysis laboratory where chloride and total dissolved solids (TDS) concentrations were measured. The observers recorded time deviation when samples were not collected at high-high tide. Depending on the station, 25% to 45% of the data was not collected at the prescribed time, though the majority of the deviations were recorded at 1.5 hours after low-high tide. We did not attempt to correct data to 1.5 hour after high-high tide salinity. We averaged grab samples within each month (seven to eight samples per month) to obtain an estimate of monthly average TDS at each station. Monthly average values were set to "missing" if less than four grab samples are available within a given month.

Continuous electrical conductivity (SC) recorders were installed in 1966 at Port Chicago and Collinsville affording approximately five years of overlapped grab sample TDS and continuously recorded SC. Data are available though the Bay/Delta and Tributaries Cooperative Data Management System (DWR/BDAT 2007). We averaged all data within each month to generate monthly average time-series. Monthly average values were set to "missing" if more than one-third of the 15-minute or hourly data is missing.

We converted the TDS data to an estimate of monthly average SC for the historical period with seasonal linear relationships between the overlapping continuous SC and grab sample TDS data. Scatter plots of the overlapping period (1966-70 for Collinsville, 1966-71 for Port Chicago) showed that simple linear models provide unbiased estimators of monthly average SC from TDS and explain 93% to 98% of the variance (Figure 3). Linear models were developed for the nominal wet (October through March) and dry (April through September) periods of the year. There is good agreement between the predicted monthly average SC based on the seasonal linear models versus the measured values. No overlapping SC and TDS data are available for Beldons Landing so the seasonal linear models developed for Collinsville were used to estimate Beldons Landing SC from the historical TDS data.

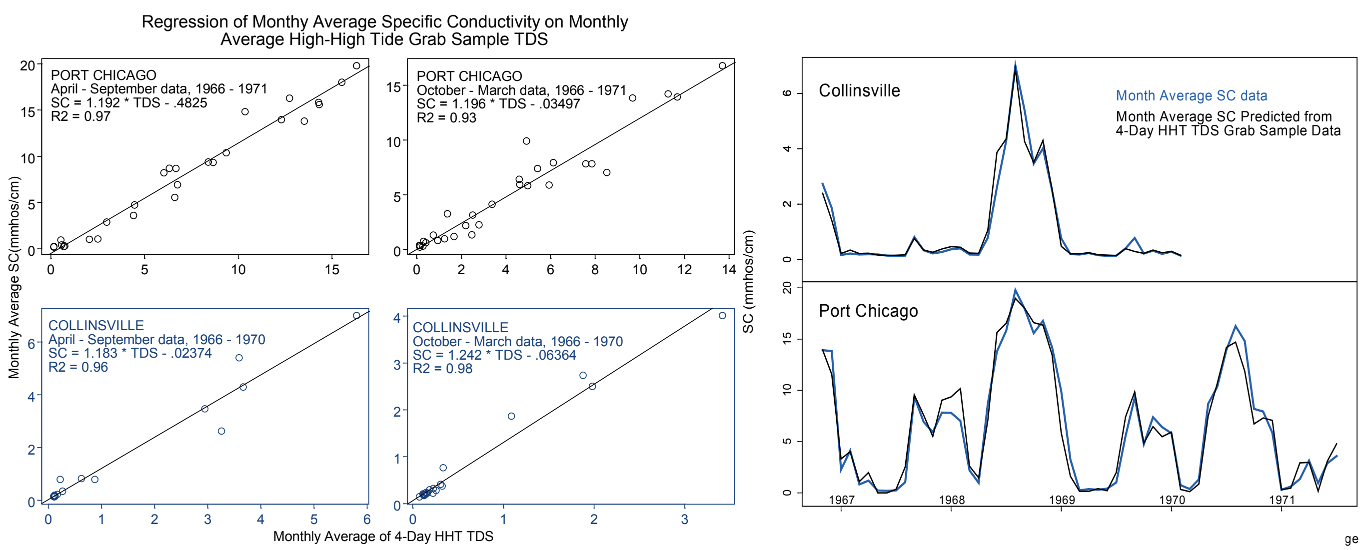

Figure 3 Regression of monthly average specific conductivity on monthly average high-high tide grab sample TDS. Continuous (15-minute) specific conductivity measurements and one per four day HHT TDS grab samples were taken simultaneously between 1966 and 1971. Separate regressions were calculated for approximately wet (Oct-Mar) and dry (Apr-Sep) periods. Right panels show actual monthly average SC for Port Chicago and Collinsville (blue line) versus monthly average SC predicted from regression models of monthly average SC on historical monthly average of 4-day HHT TDS (black).

DATA ANALYSIS METHODS

We used two nonparametric procedures to detect long-term trends and periodic processes. Kendall's tau is a measure of correlation or the strength of the relationship between a variable and, in this case, time (Hirsh 1984). "Seasonal loess time-series decomposition," was also used to differentiate seasonal climate and possible long-term climate teleconnections from long-term trends (Cleveland 1993). This method decomposes the monthly precipitation, outflow, and salinity time-series into frequency components of variation and trend by a sequence of local regression smoothings (Cleveland 2000). The "seasonal" component consists of 12 separate loess fits, one for each month. This feature allows analysis of among-month trends. The procedure does not allow for missing data. Since each of the three salinity data time-series contains missing data, we collapsed the time series and kept track of the missing data periods. We applied the seasonal loess procedure to the collapsed data, acquired a set of smooth decompositions, and then the decompositions were broken apart where data is missing.

RESULTS

In this section, we present and discuss trends in the mean and variability of San Francisco Estuary watershed precipitation, delta outflow, and northern reach salinity at decadal, annual, and seasonal timescales. Table 1 presents all of the summary statistics.

Historical Precipitation, Outflow, and Salinity Time-Series

Figure 2 shows the compiled monthly average time-series for the 13-station precipitation index (1920-2006; panel A), delta outflow (1929-2006; panel B), total export (1951-2006; panel B, expanded right axis), Collinsville (1920-2006; panel C), Beldons Landing (1929-2006; panel D), and Port Chicago (1947-2006; panel E). Each plot also includes the five-year running average the help visualize trends. With over 1,000 months in the time-series, Collinsville salinity is one of the longest records of any parameter in the San Francisco Estuary.

Figure 4 displays summary annual average means and standard deviations for 13-station precipitation, delta outflow, and salinity at the three Suisun Bay and Suisun Marsh stations. The first column covers the full period of record for each data set, while columns two, three, and four divide the data between pre-project, post-project, and post-SMSCG periods, respectively. Despite marginally higher post-project precipitation (47 inches/yr) compared to the pre-project average (43 inches/yr), delta outflow is lower in the post-project period (0.79 TCMS post-project vs. 0.84 TCMS pre-project). Mean salinity is consistent with outflow during pre- and post-project periods. The standard deviation of precipitation increases from 12 inches per year in the pre-project period to 17 inches per year in the post-project period. Similarly, Granger 1979 reported increasing northern California precipitation variability between 1961-1977. Delta outflow and each of the three salinity stations exhibit the same pattern of increased variability in the post-project period. Annual outflow is reduced after 1988 with concomitant increases in Suisun Bay salinity. Table 2 depicts pre- and post-project coefficient of variation as an index of variability on the annual and monthly time-scales. Post-project variability is greater than pre-project variability. In addition, salinity variability decreases from east to west.

Long-term Trend Decomposition: Possible Climate Teleconnections to Watershed Precipitation and Outflow

We applied the seasonal loess trend decomposition procedure to the monthly average data sets. Figure 5 shows each monthly time series decomposed into "seasonal," "decadal," and "trend" fits. Superposition of these signals along with the residual (not shown) returns the original time series (Figure 2). The right column shows the "seasonal" component that we tuned knowing there would be a 12-month frequency mode. The seasonal fit of the precipitation and outflow data well shows the annual pattern of the Mediterranean climate. The seasonal fits also indicate the tendency of wet and dry years to cluster together in nominally decadal pulses, especially in precipitation and outflow. Decadal pulses are somewhat less evident in the salinity data suggesting that additional

Table 1 Summary statistics–period of record for 13-station precipitation, delta outflow, and Collinsville, Beldons Landing, and Port Chicago specific conductivity

	Period	n	Median	Mean	Stnd Dev	CV	Lag-1 correl.	Lag-1 p	Kendall slope	Kendall p
Annual Average	13-STATION PRECIPITATION (inches)									
All data	1921-2006	86	42.4	44.9	14.4	0.32	-0.03	0.68	0.09	0.18
Pre-Water Project	1921-1967	47	42	42.8	11.8	0.27	-0.07	0.45	0.12	0.34
Post-Water Project	1968-2006	39	45.7	47.5	16.8	0.35	0.008	0.94	0.14	0.61
Pre-SMSCG	1921-1987	67	42.5	44.3	14.1	0.32	-0.1	0.22	0.12	0.19
Post-SMSCG	1988-2006	19	45.7	47.3	15.4	0.32	0.09	0.65	0.76	0.16
Monthy Average										
All data	10/21-9/06	1041	2.08	3.74	4.46	1.19	0.39	0		
Pre-Water Project	10/21-9/67	552	2.12	3.57	4.14	1.16	0.38	0		
Post-Water Project	10/67-9/06	480	2.08	3.92	4.77	1.22	0.4	0		
Pre-SMSCG	10/21-9/87	793	2.14	3.70	4.29	1.16	0.4	0		
Post-SMSCG	9/88-9-06	239	1.93	3.86	4.95	1.28	0.37	0		
Annual Delta Outflow	OUTFLOW (CMS)									
All data	1929-2006	86	709	820	530	0.64	0.15	0.06	-1.9	0.45
Pre-Water Project	1929-1967	47	691	837	476	0.57	0.03	0.79	1.8	0.76
Post-Water Project	1968-2006	39	710	795	575	0.72	0.28	0.02	-3.1	0.75
Pre-SMSCG	1929-1987	67	757	853	518	0.61	0	0.95	-6.2	0.98
Post-SMSCG	1988-2006	19	586	700	543	0.68	0.43	0.03	30	0.03
Monthly Delta Outflow										
All data	1929-2006	1041	383	821	1052	1.3	0.59	0		
Pre-Water Project	1929-1967	573	478	906	1076	1.18	0.54	0		
Post-Water Project	1968-2006	468	334	800	1124	1.41	0.65	0		
Pre-SMSCG	1929-1987	814	458	899	1106	1.22	0.58	0		
Post-SMSCG	1988-2006	227	270	706	1076	1.52	0.6	0		
Annual Average	COLLINSVILLE SPECIFIC CONDUCTIVITY (SC umhos/cm)									
All data	1920-2006	86	2057	2570	1988	0.77	0.33	0	-5.8	0.39
Pre-Water Project	1920-1967	47	1999	2537	1960	0.77	0.31	0.005	-72	0
Post-Water Project	1968-2006	39	2116	2605	2041	0.78	0.38	0.001	40	0.082
Pre-SMSCG	1920-1987	67	1951	2335	1954	0.84	0.28	0.002	-32	0.001
Post-SMSCG	1988-2006	19	2573	3326	1953	0.75	0.47	0.02	-200	0.042
Monthly Average										
All data	7/20-9/06	1041	884	2701	3820	1.41	0.64	0		
Pre-Water Project	7/20-9/67	552	809	2847	4493	1.59	0.6	0		
Post-Water Project	10/67-9/06	480	954	2577	2955	1.15	0.68	0		
Pre-SMSCG	7/21-9/87	793	659	2521	4016	1.59	0.63	0		
Post-SMSCG	10/88-9/06	239	2191	3342	3105	0.93	0.64	0		
Annual Average	BELDONS LANDING SPECIFIC CONDUCTIVITY (SC umhos/cm)									
All data	1929-2006	86	5898	6471	2663	0.41	0.4	0	-8.5	0.59
Pre-Water Project	1929-1967	47	5816	5983	2063	0.34	0.28	0.07	-76	0.073
Post-Water Project	1968-2006	39	6546	7097	3224	0.45	0.49	0.011	-290	0.007
Pre-SMSCG	1929-1987	67	5876	6244	2239	0.36	0.28	0.07	-36	0.51
Post-SMSCG	1988-2006	19	5994	6816	3242	0.46	0.48	0.01	-300	0.03
Monthly Average										
All data	6/29-9/06	1041	5033	6227	5347	0.86	0.62	0		
Pre-Water Project	6/29-9/67	552	4240	5878	5577	0.95	0.61	0		
Post-Water Project	10/67-9/06	480	6422	6817	5009	0.73	0.64	0		
Pre-SMSCG	6/29-9/87	793	4276	5830	5480	0.94	0.61	0		
Post-SMSCG	10/88-9/06	239	6797	7085	5039	0.71	0.64	0		
Annual Average	PORT CHICAGO SPECIFIC CONDUCTIVITY (SC umhos/cm)									
All data	1947-2006	86	9537	9595	4150	0.43	0.24	0.01	-8	0.82
Pre-Water Project	1947-1967	47	9955	9500	2396	0.25	0.03	0.84	-44	0.65
Post-Water Project	1968-2006	39	8741	9648	4888	0.51	0.32	0.008	35	0.6
Pre-SMSCG	1947-1987	67	9565	8989	3673	0.41	0.09	0.39	-58	0.25
Post-SMSCG	1988-2006	19	8931	10975	4912	0.51	0.41	0.05	-640	0.006
Monthly Average										
All data	1/47-9/06	1041	9135	9635	6718	0.7	0.64	0		
Pre-Water Project	1/47-9/67	552	9613	9584	6227	0.65	0.56	0		
Post-Water Project	10/67-9/06	480	9182	9786	6925	0.71	0.68	0		
Pre-SMSCG	1/47-9/87	793	8278	8931	6382	0.71	0.62	0		
Post-SMSCG	10/88-9/06	239	11404	11272	7056	0.63	0.66	0		

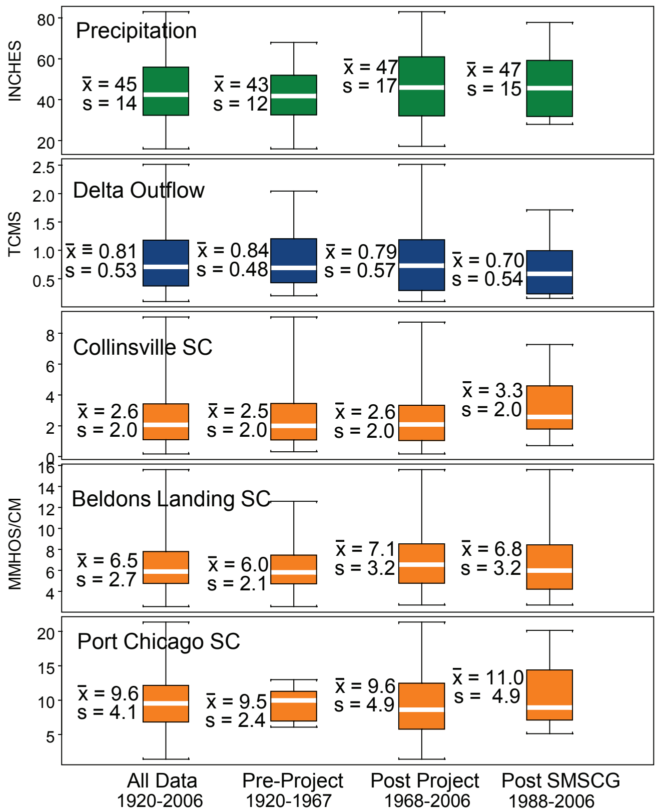

Figure 4 Box and whisker plot of annual average statistics for 13-station precipitation, outflow and SC data. Data is binned as 1) all data, 2) pre-project (prior to 1968), 3) post project (after 1968), and post SMSCG (after 1988) periods. Box is inner quartiles, line is median. The mean and standard deviation are posted aside each box.

factors influence long-term salinity trends. The seasonal loess procedure allows fitting low-frequency processes, in this case possibly associated with decadal scale climate oscillations (Figure 5, middle column). With seasonal and decadal oscillations removed, a robust estimate of the period of record trend is available (Figure 5, right column).

Long-term Trend Decomposition: Climate Teleconnections to Watershed Precipitation and Outflow

The decomposition is useful because we can remove the seasonal signal to reveal lower frequency processes. While the seasonal fits explain most of the variability, the decadal scale fits (Figure 5, middle column) appear to add additional explanatory power. Decadal time-scale north Pacific temperature and pressure anomalies have been observed and correlated with North American climate for some time (e.g. Cayan and Peterson 1989; Schonher and Nicholson 1989; Mantua and others 1997). Zhang and others (1997) developed an index of the sea-surface temperature (SST) anomaly dubbed the Pacific Decadal Oscillation (PDO) and demonstrated reversals in the prevailing polarity of the oscillation, positive and negative, in 1925, 1947, and 1977. Another polarity shift may have occurred in 1998 (Rodionov 2004) though, since 2002, it has turned more positive again. The PDO is correlated with interdecadal fluctuations in north Pacific sea-level pressure and thus integrates interdecadal time-scale, ocean-atmosphere covariability. The monthly PDO from 1921 to 2006 is shown in Figure 7, panel A.

We found no correlation between the monthly PDO and precipitation/outflow indexes. However, the PDO index is correlated with the precipitation and outflow indexes when all are filtered to the decadal scale. We considered loess filter windows between 12 and 300 months to determine the timescale of maximum PDO:precipitation and PDO:outflow correlation (Figure 6). Considering all years (both positive and negative PDO polarity), peak correlation occurs with a loess filter window of about 100-120 months. Figure 7 shows the 120-month fit to monthly average PDO (panel D), precipitation (panel E), and outflow (panel F). In the case of precipitation, the 120-month filter reveals an approximately decadal oscillation. Within an overall period-of-record precipitation mean of 3.7 inches per month, there is a decadal oscillation of about 1 inch. The correlation coefficient is only about 0.1 at 120 months, likely because PDO appears to be positively correlated with precipitation and outflow during positive PDO phase and negatively correlated with precipitation and outflow during negative PDO phase (similar to Gershunov and others 1998). We then separately considered positive and negative PDO polarity years. For positive polarity years, the correlation coefficient peaks at around 180 months at ~0.6 (p=0, Figure 6). With a mean positive PDO year precipitation of 3.8 inches (Figure 8,

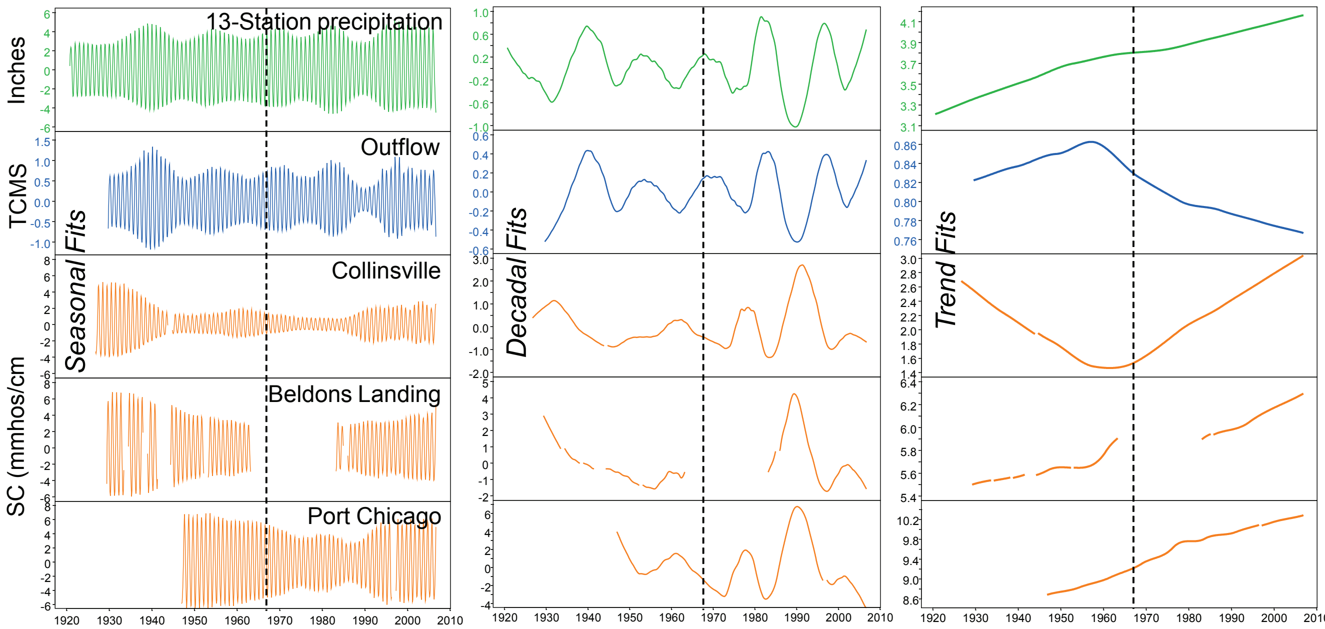

Figure 5 Seasonal loess trend decomposition on monthly average 13-station precipitation, outflow, and salinity data. Right column is the "seasonal" fit based on a 12-month frequency mode. Middle column is the 120 month "decadal" fit of the seasonal fit residuals. Right column is the "trend" fit to the decadal fit residuals. Dotted vertical lines delineate "pre" and "post" project periods.

panel B), the range of the 180 month decadal fit is greater than 2 inches (Figure 8, panel E). Figure 8 also shows the 180-month loess fits to the positive PDO year data (panel D) and corresponding monthly precipitation (panel E) and outflow data (panel F). By contrast, "negative" PDO years produced strong negative correlation peaking between 180 and 240 months (Pearson = ~-0.4 to -0.6, p=0) (Figure 6). The mean negative PDO year precipitation is 3.7 inches and the range of the decadal fit is greater than 2 inches. The 180-month fits are shown in Figure 9.

Table 3 shows a rough estimate of the variance in the original data explained by the decomposition components. Summed R2 is greater than 100 because components are correlated. Therefore, the method is rather conservative (that is, seasonal loess applies iterative component fits to higher frequency component fit residuals), and the estimates of explained variability are inflated somewhat. Bearing this in mind, only the trend components fail to add significant explanatory power by this metric (except for Collinsville salinity). The seasonal component explains 35% to nearly half of the variability of all parameters. Decadal scale vari-

Table 2 Coefficient of variation (standard deviation divided by mean) for annual and monthly average precipitation, outflow, and SC. Data is binned into pre- (prior to 1968) and post- (after 1968) project periods.

Annual Data CV	Pre-Project (prior to 1968)	Post-Project (1968-2006)
Precipitation	0.27	0.37
Outflow	0.57	0.75
Collinsville	0.77	0.82
Beldons Landing	0.34	0.45
Port Chicago	0.25	0.51

Monthly Data CV	Pre-Project (prior to 1968)	Post-Project (1968-2006)
Precipitation	1.16	1.22
Outflow	1.18	1.42
Collinsville	1.17	1.59
Beldons Landing	0.95	0.75
Port Chicago	0.65	0.71

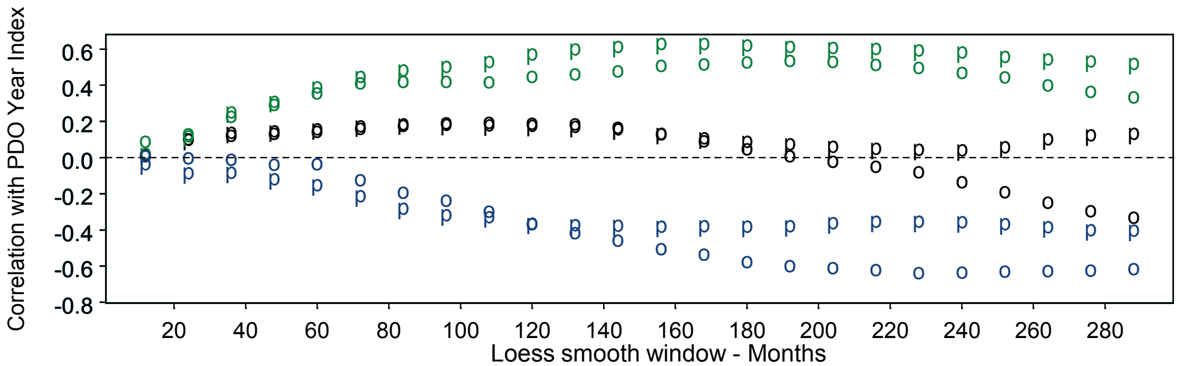

Figure 6 Correlation of monthly PDO with monthly 13-station precipitation and delta outflow. Y-axis is Pearson correlation, x-axis is loess smooth window in months. "p" indicates 13-station precipitation:PDO correlation, "o" indicates outflow:PDO correlation. Black symbols represent correlations with PDO for all months in the record. Green symbols represent correlations only in positive PDO phase months. Blue symbols are correlations in negative PDO months. Maximum correlation in positive PDO months is 160-200 months. Maximum correlation in negative PDO months is 160-240 months.

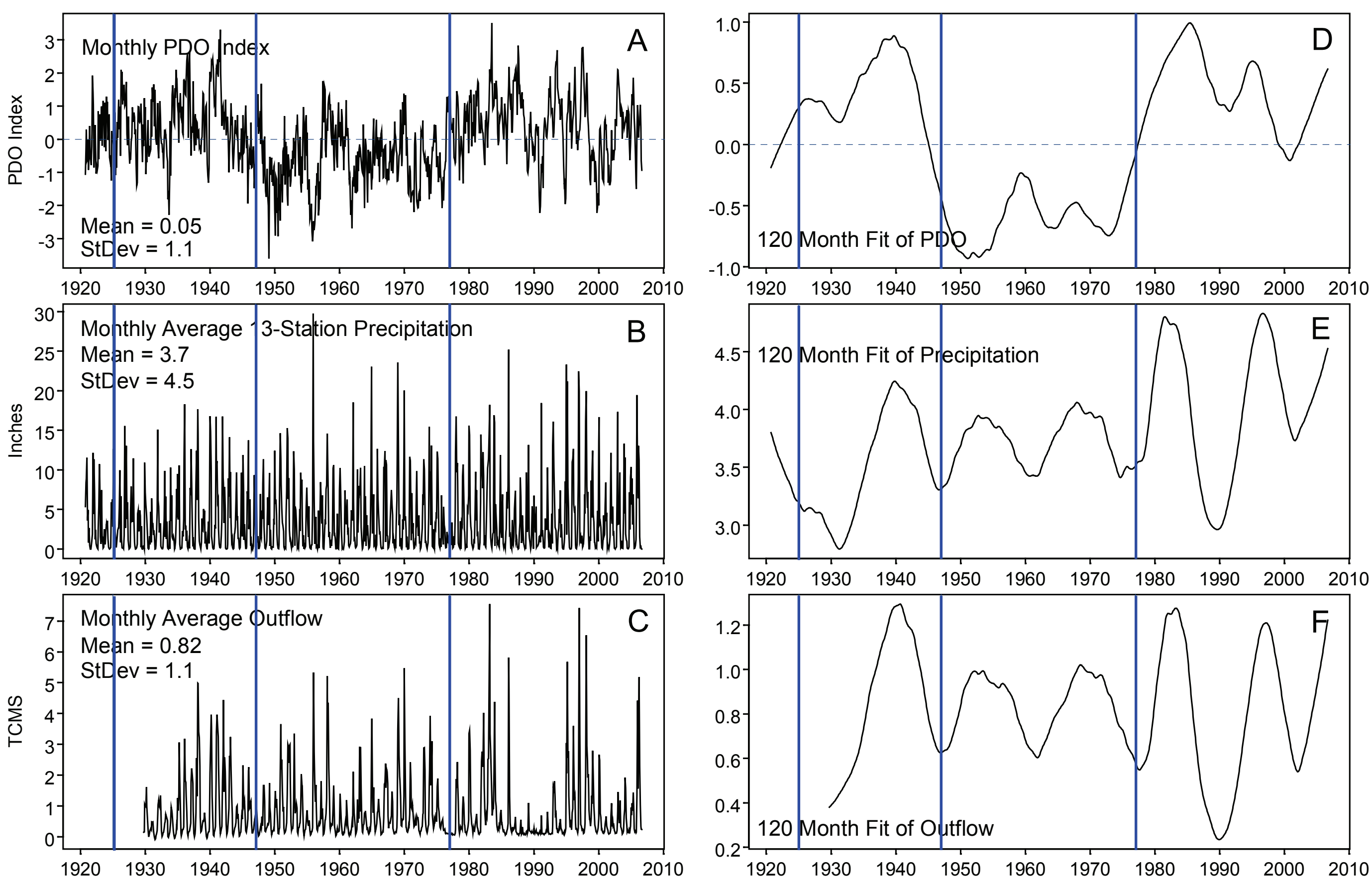

Figure 7 Left column (A, B, C) shows PDO, 13-station precipitation and outflow time-series. Right hand column (D, E, F) shows 120-month loess fits to the data to highlight possible correlation between "decadal" scale variability in PDO and precipitation and outflow. Blue verticals indicate PDO polarity shift.

ability accounts for about 2% of monthly precipitation variability, 10% of monthly outflow and 11% to 15% of salinity data variability.

Long-term (Greater than Decadal) Trends

With loess estimates of the seasonal and decadal oscillations removed, an estimate of the long-term trend emerges. Figure 5 (right column) shows the multi-decade trend fit for each data set. Precipitation exhibits increasing trend from approximately 3.2 to 4.1 inches per month over the period of record. Outflow is concordant up to about 1960, and then decreases from approximately 0.85 TCMS in 1960 to 0.72 TCMS in 2006. As for the salinity station trends, only Collinsville inversely mirrors outflow for the entire record. In contrast, pre-project Beldons Landing and Port Chicago salinity rather unexpectedly trends upward despite rising outflow. In these cases, the rising pre-project salinity trend suggests that other factors, perhaps including changing delta bathymetry, may also play a strong role in salinity transport (see "Discussion").

We also investigated long-term trends using Kendall's nonparametric test of independence. Figure 10 shows the slope of the long-term annual average trend (y-axis) for each of the five data sets. Trends for all data (1920-2006), pre-project (1920-1967), and post-project (1968-2006) periods are represented. P-values are also shown above each bar. Overall, Kendall's tau and seasonal loess methods predict broadly simi-

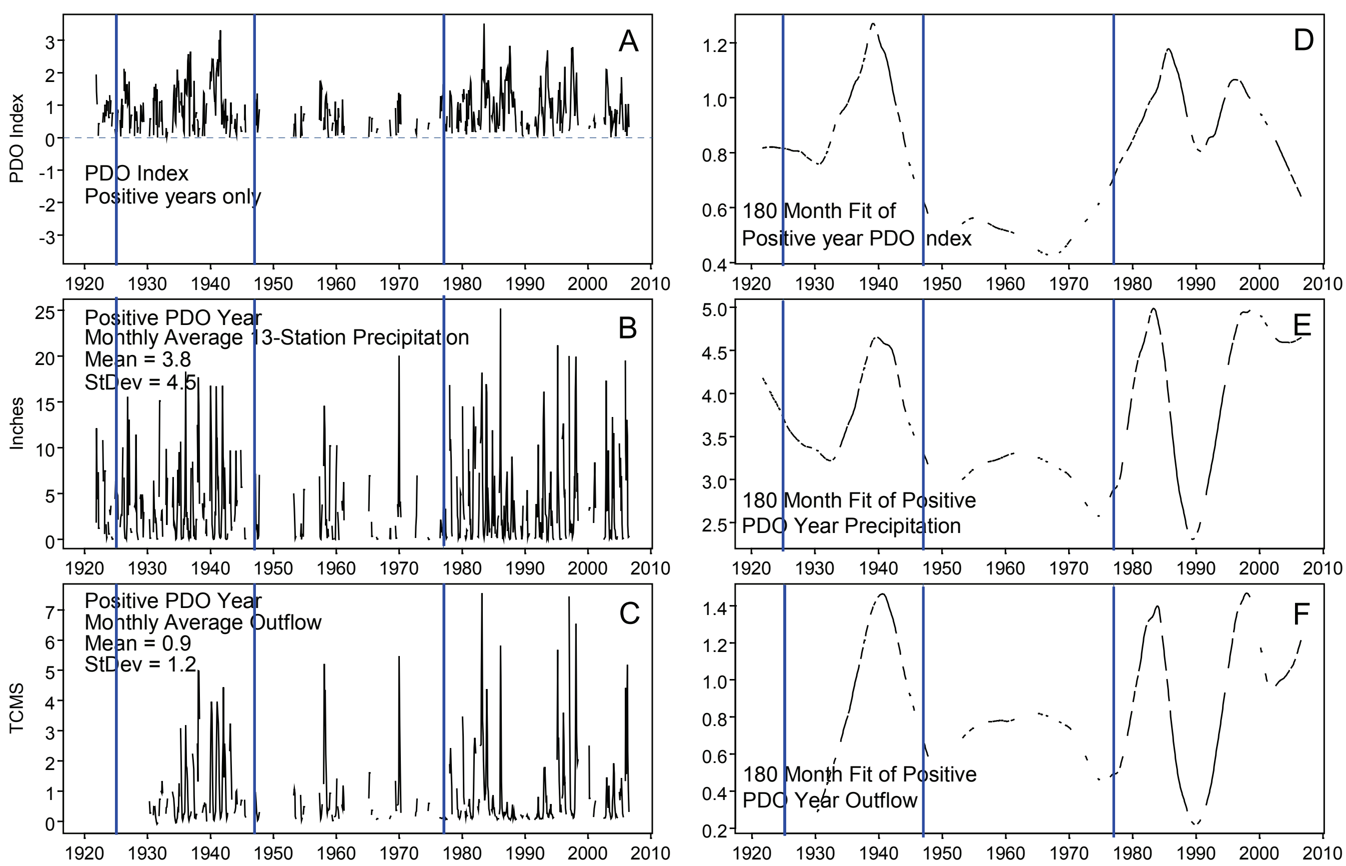

Figure 8 Left column (A, B, C) shows positive polarity PDO years only with corresponding 13-station precipitation and outflow time-series. Right hand column (D, E, F) shows 180 month loess fits to the data to highlight possible correlation between "decadal" scale variability in positive PDO years and same timescale precipitation and outflow. Blue verticals indicate PDO polarity shift.

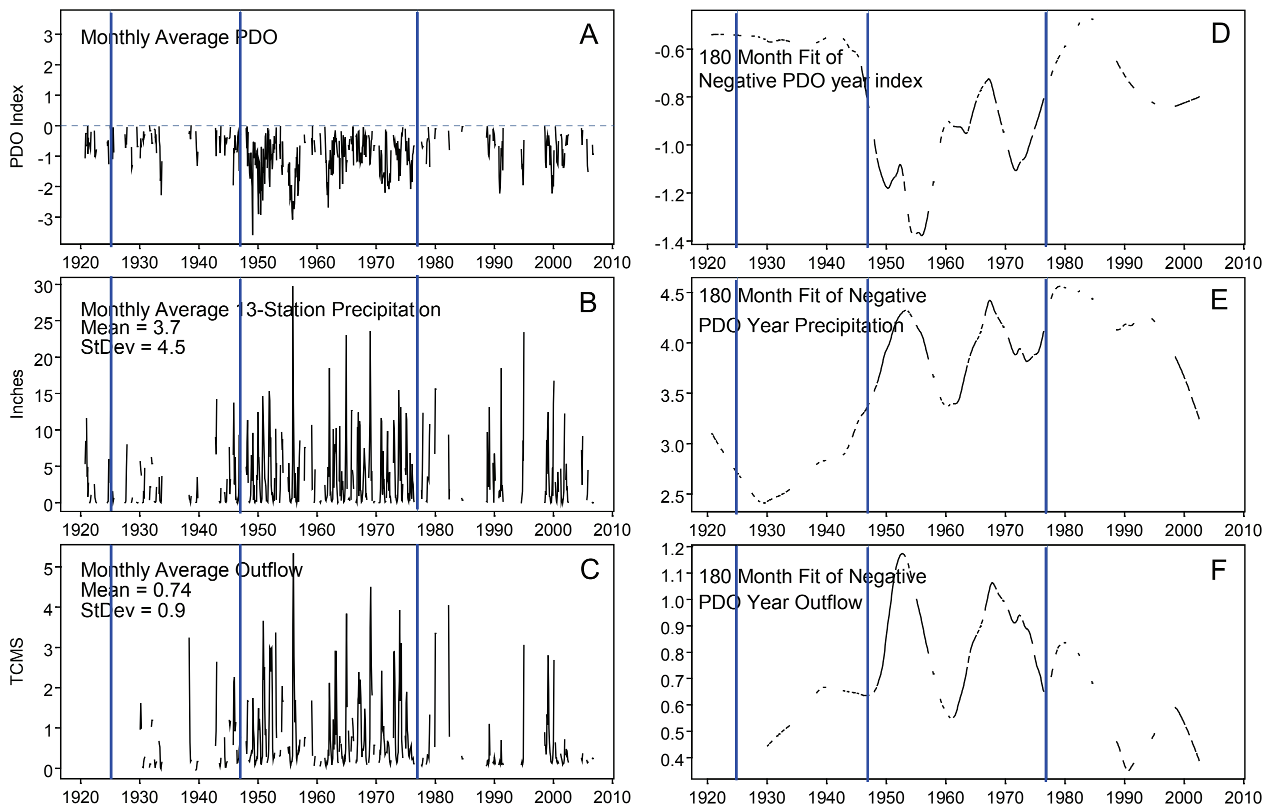

Figure 9 Left column (A, B, C) shows negative polarity PDO years only with corresponding 13-station precipitation and outflow time-series. Right hand column (D, E, F) shows 180 month loess fits to the data to highlight possible correlation between "decadal" scale variability in negative PDO years with same timescale precipitation and outflow. Blue verticals indicate PDO polarity shift.

lar trends. Pre-project outflow and salinity trends are consistent with the suggestion of increased precipitation between 1920-1967 (not significant). Fox and others (1990) similarly found no trend in delta outflow between 1921 and 1986. The pre-project Collinsville salinity trend is significant at approximately -0.07 specific conductivity units per year. In contrast to the suggestion of pre-project salinity trend increase at Beldons Landing and Port Chicago with seasonal loess decomposition, Kendall's tau suggests some (not significant) pre-project salinity trend decrease. Considering the post-project period, there is a non-significant suggestion of precipitation increase in the post-project period as Granger 1979 reported, while, as expected, delta outflow is trending down approximately 5 cms/yr (not significant). Collinsville and Port Chicago specific conductivity are coherent with the outflow trend (p=0.07 and 0.15, respectively). By contrast, Beldons Landing shows significant salinity decrease. Missing data in the early post-project period likely affect the comparability of this estimate to Collinsville and Port Chicago. The sequencing of a six-year drought starting in 1988 followed by several above normal water years further confounds the trend estimate. In addition, note that the SMSCG commenced operation in 1988 reducing Beldons Landing salinity by tidally pumping Sacramento River water into Montezuma Slough (Figure 1) each ebb tide. The seasonal loess trend decomposition untangles some of these confounding influences. The decadal fit (Figure 5) captures the influence of the late 1980s drought and the SMSCG effect beginning about 1989. With the decadal fit removed, the trend fit suggests some salinity increase after 1980.

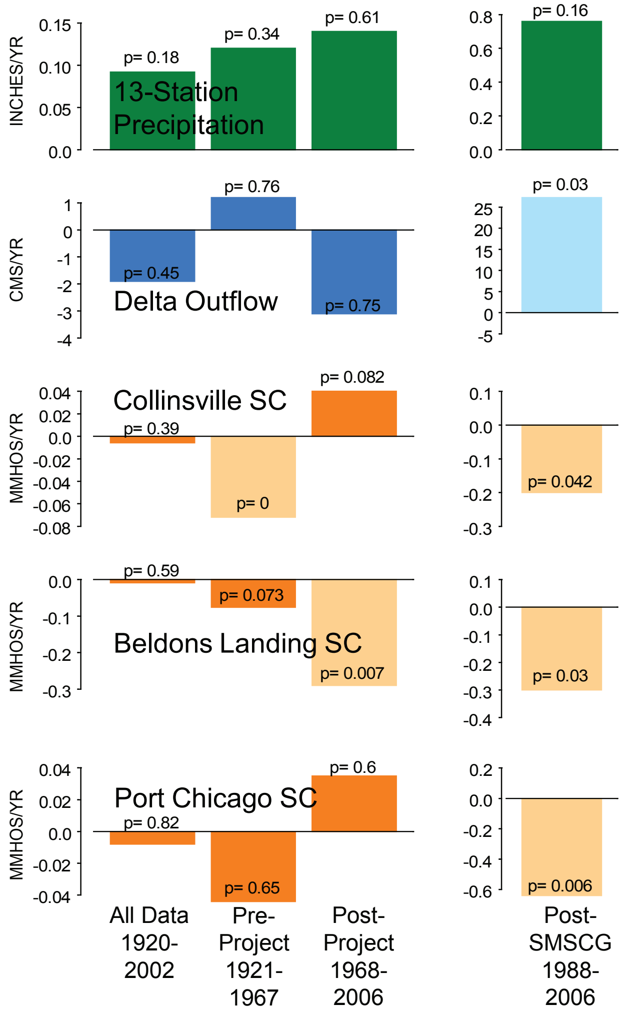

Figure 10 Slope of trend in annual data by Kendall's test. Annual data binned as all data, pre-project, post-project, and post SMSCG. Note SC is plotted on different y-axis scales. All post-SMSCG data is plotted on a different y-axis scale. Pastel bars are significant.

Among-month Trends

A considerable advantage of the seasonal loess procedure is that among-month trend fits are byproducts of the cycle subseries fits. Figure 11 (panels A-E) show among-month loess fits for 13-station precipitation, outflow, and Collinsville, Beldons Landing, and Port Chicago salinity records, respectively. We also applied Kendall's tau to each month series to obtain significance and confidence interval estimates. Trend fits to the log data are shown in blue if not significant, or green if significant ($p<0.05$). There is no significant trend in any month for the precipitation data (Figure 11, panel A). Delta outflow exhibits significant negative trends in April and May, and significant positive trends in July and August consistent with export and reservoir operations beginning in the 1950's (Figure 11, panel B). Also evident are trend inflections upturning between January and June, and down turning August through December. Notwithstanding reservoir effects, the January-February upturn may also reflect snow pack runoff trends noticed first by Roos (1987). The March-April-May upturn likely reflects more recent increased delta outflow requirements in the spring after the 1994 Delta Accord (SWRCB 1995). Down turning outflow trends between August and September likely reflect increased fall pumping after the 1994 Delta Accord.

Salinity trends by month are broadly consistent among stations. Collinsville salinity trends significantly downward in August and September (Figure 11, panel C). However, whether trending up or down over the period of record, Collinsville also shows upward salinity trend inflections in the late 1960's in every month. Beldons Landing salinity trends significantly upward in April, May, and

Table 3 Estimate of the percentage of variability in original data explained by seasonal loess decomposition: Regression of original monthly data on component. Values are R-squared. Note that component R-squares sum to greater than 100.

Component	13-Sta. Precip	Outflow	Collinsville SC	Beldons Lg SC	Pt. Chicago SC
Seasonal	46.0 (p<0.001)	35.0 (p<0.001)	35.0 (p<0.001)	46.0 (p<0.001)	35.0 (p<0.001)
Decadal	2.0 (p<0.01)	10.0 (p<0.001)	14.0 (p<0.001)	15.0 (p<0.001)	11.0 (p<0.001)
Trend	0.2 (p=0.14)	0.2 (p=0.17)	4.6 (p<0.001)	0.04 (p=0.65)	0.6 (p=0.06)
Residual	65.0 (p<0.001)	69.0 (p<0.001)	76.0 (p<0.001)	66.0 (p<0.001)	59.0 (p<0.001)

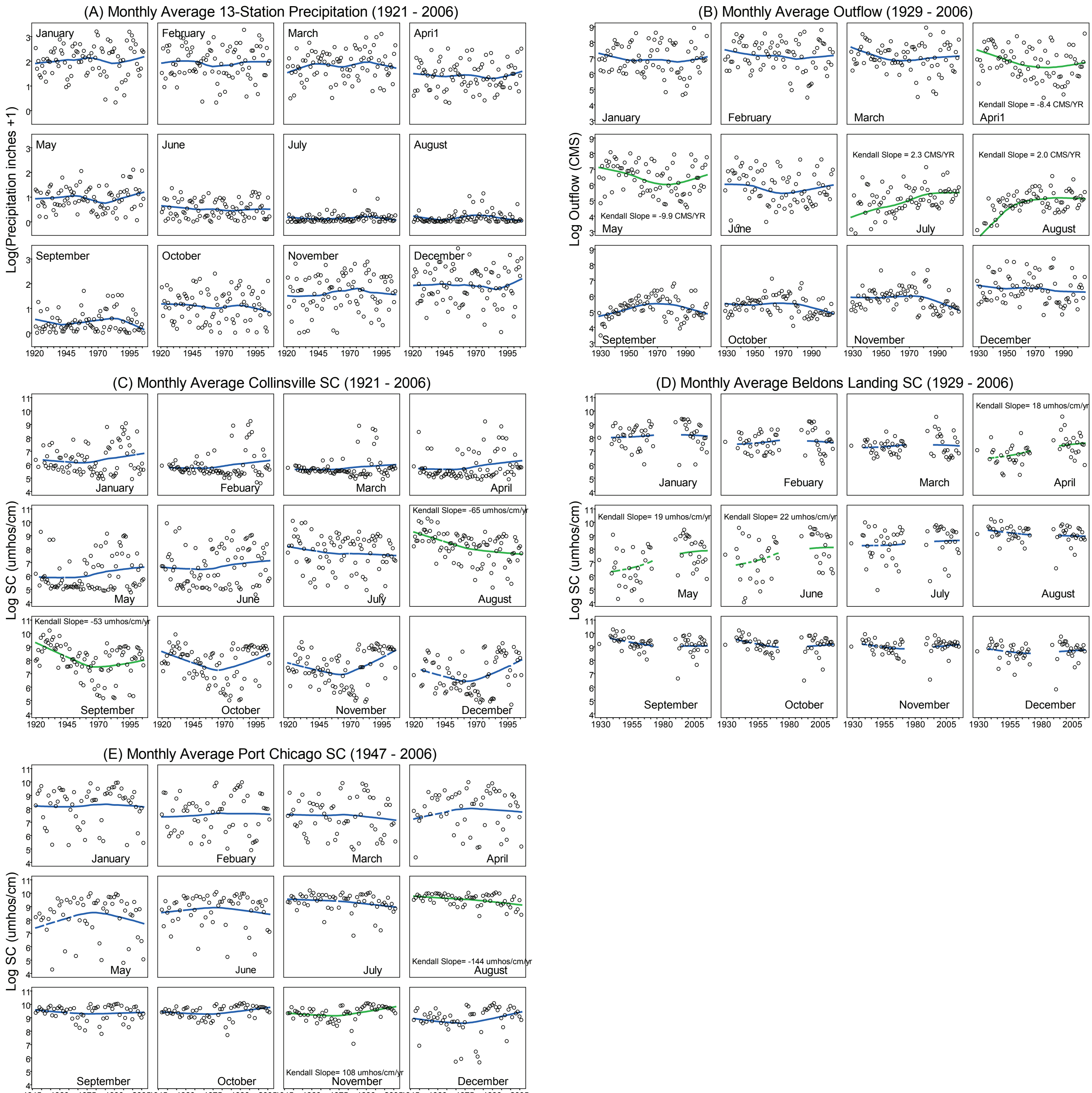

Figure 11 Local regression fits to the log of monthly average data by month. The local regression window spans 60% of the data; the local fitting degree = 1. Local regression fit shown in green if Kendall trend slope is significant at the 95% level.

June, consistent with outflow (Figure 11, panel D). Port Chicago trends downward in spring and summer, significantly downward in August. Salinity trends higher in the fall, significantly in November (Figure 11, panel E). In contrast to Collinsville, but consistent with outflow, Beldons Landing and Port Chicago show slight negative inflections in the post-project period for all months between January and August. All stations have positive post-project inflections between September and December consistent with negative outflow trend.

The slope of the among-month trends as determined from Kendall's Test are shown in Figure 12. Each diamond represents the period of record trend slope for the month. Verticals depict 95% confidence intervals—solid verticals indicate significant trends. For precipitation and outflow, only 4 of 12 months trend in the same direction—due primarily to water project reservoir and export operations. Using data from 1929 to 1986, Fox and others (1990) found significant downward trends in annual outflow in April and May and significant upward trends between July and November. Extending the annual outflow data set now from 1921 to 2006, April and May continues to show significant downward trend while upward trends are now limited to July and August only owing perhaps to greater fall project pumping since the 1994 Delta Accord.

While the three salinity stations are broadly similar, there are notable differences between station salinity trends and trend detection methods. First, Kendall's test suggests a remarkable lack of salinity trend in response to outflow reduction between November and April (Figure 12)—broadly similar to the loess results (Figure 11). The seasonal loess and Kendall trends diverge at Collinsville where, after the late 1960s, loess captures a strong suggestion of positive salinity trend (Figure 11, panel C). We might expect Collinsville salinity to be somewhat more sensitive to delta outflow (while Port Chicago is more ocean influenced). We also note that the Suisun Marsh Salinity Control Gate (SMSCG) began operation in 1988 and tends to increase Collinsville

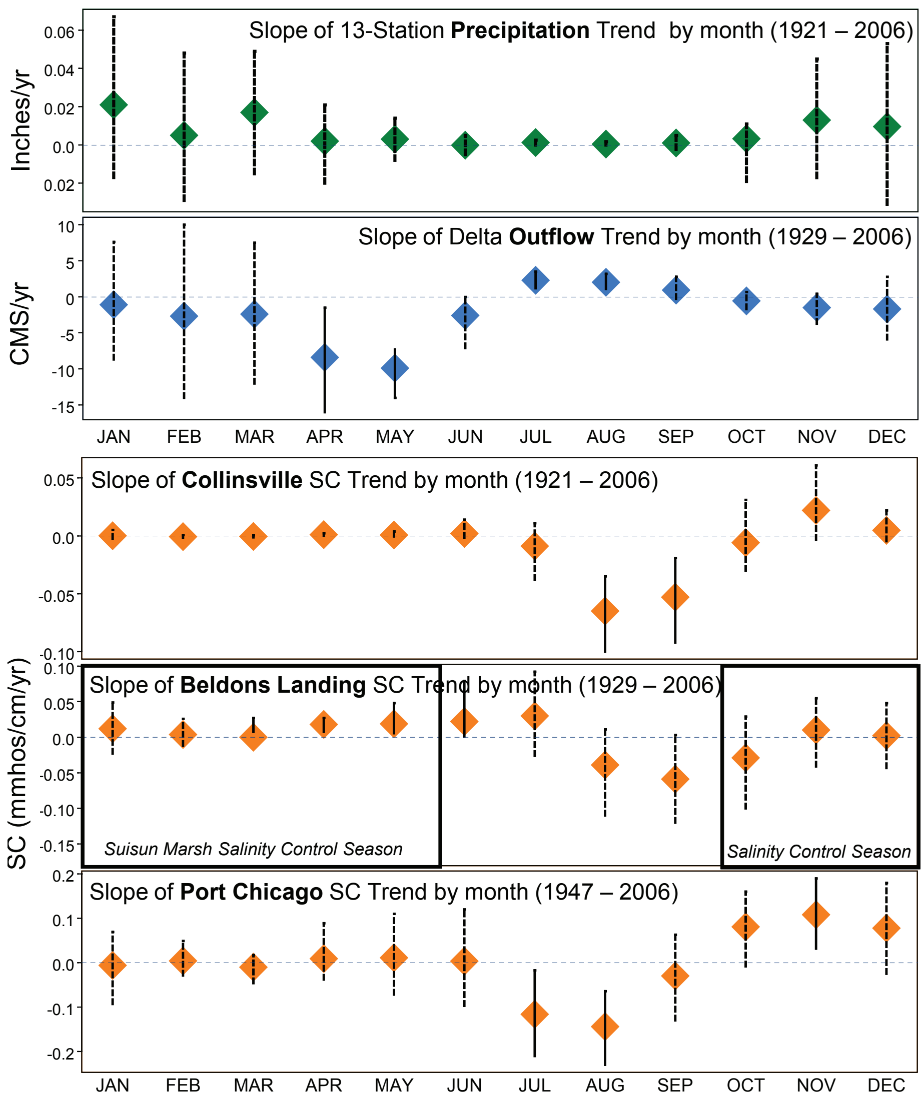

Figure 12 Slope of trends by month using Kendall's test. Confidence limits are 95%. The SMSCG control season is delineated by boxes in the Beldons Landing panel.

salinity between October and May (more below). Despite that, Kendall's test shows Collinsville continuing to resist trending even in May, June, and July despite significant delta outflow reduction in May and June, and significant increase in July. Seasonal loess seems to capture these more subtle nuances of trend. Notably, Beldons Landing broadly tracks the other salinity stations though it alone exhibits significant upward trend in April, May, and June, consistent with the negative trend of outflow in those months.

Long-term Trend of Annual Time-scale Variability

The variability of system drivers—including precipitation and river inflow—are a key physical control on the system. The watershed's Mediterranean climate is characterized by an approximately six-month, wet-dry season cycle. In addition, variability in the general pattern can manifest as clusters of dry (drought) or wet years. A key emerging assumption for ecosystem restoration is that native species evolved to persist under sometimes extreme seasonal, annual and decadal-scale variability of outflow and salinity during the Holocene. On the annual scale, water project reservoir and export operations tend to reduce intra-annual variability by storing winter-spring runoff for summer-fall release and export (Knowles 2000). While watershed land use changes also intervene in multiple ways (Fox 1990), the water projects impose a general homogenizing affect on northern reach salinity by reducing flood peaks and releasing reservoir storage in the dry season. The nascent conceptual model suggests that seasonal variability reduction by water project operations could enhance non-native species opportunities to the detriment of natives that evolved under more variable conditions (e.g., Lund and others 2007).

Table 2 shows a rough test of the water project homogenization conceptual model where annual and monthly data coefficient of variation (CV) is shown for the pre- and post-project periods. Contrary to the conceptual model, there is more variability in the post-project period. Consistent with precipitation CV, post-project CVs are consistently higher than those for the pre-project period. The only exception is Beldons Landing monthly data where CV is lower post-project, likely due at least in part to SMSCG operations by DWR since 1988.

Long-term Trend of Seasonal Scale Variability

We considered trends in seasonal variability by analyzing the residuals of seasonal loess fits by month. We subtracted the local regression fits from the log data and fit simple linear regressions to the absolute value of the residuals (Figure 13, panels A-E). Positive regression line slopes suggest increasing variability—negative slopes suggest declining variability. Green lines indicate significant slope ($p<0.05$), blue is not significant. Only January shows significant positive trend in precipitation variability, though nine of the twelve months at least suggest increasing variability since 1920 (Figure 13, panel A). Outflow variability trends are consistent with precipitation except in April, July, and August. In April neither the precipitation slope (positive) nor the outflow slope (negative) is significant ($p<0.2$ in each case). Outflow variability is trending significantly downward in July and August when precipitation is inconsequential (Figure 13, panel B). This could be due to earlier snow pack melts and increasing reliability of water project reservoir releases to the delta. As for seasonal salinity variability, Collinsville (Figure 13, panel C) exhibits increasing salinity variability in eleven of twelve months—seven months are statistically significant. At Port Chicago (Figure 13, panel E) all twelve months suggest that variability is increasing; March, August, and September are significant. Beldons Landing is somewhat the exception as it exhibits variability increase in six of twelve months, two of those significant (Figure 13, panel D). Notably, salinity variability at Beldons Landing in May is declining ($p=0.15$) in direct opposition to increased outflow variability ($p=0.1$) in May. Keeping in mind that Beldons Landing is missing data between 1964 and 1981, the Suisun Marsh Salinity Control Gate may be compressing variability when it has operated since 1988. The general trend toward increasing salinity variability is only nominally consistent with outflow. Salinity variability in June, July, and August does not well track significant downward trends in outflow variability for the same months. This suggests that other mechanisms are at play including land use

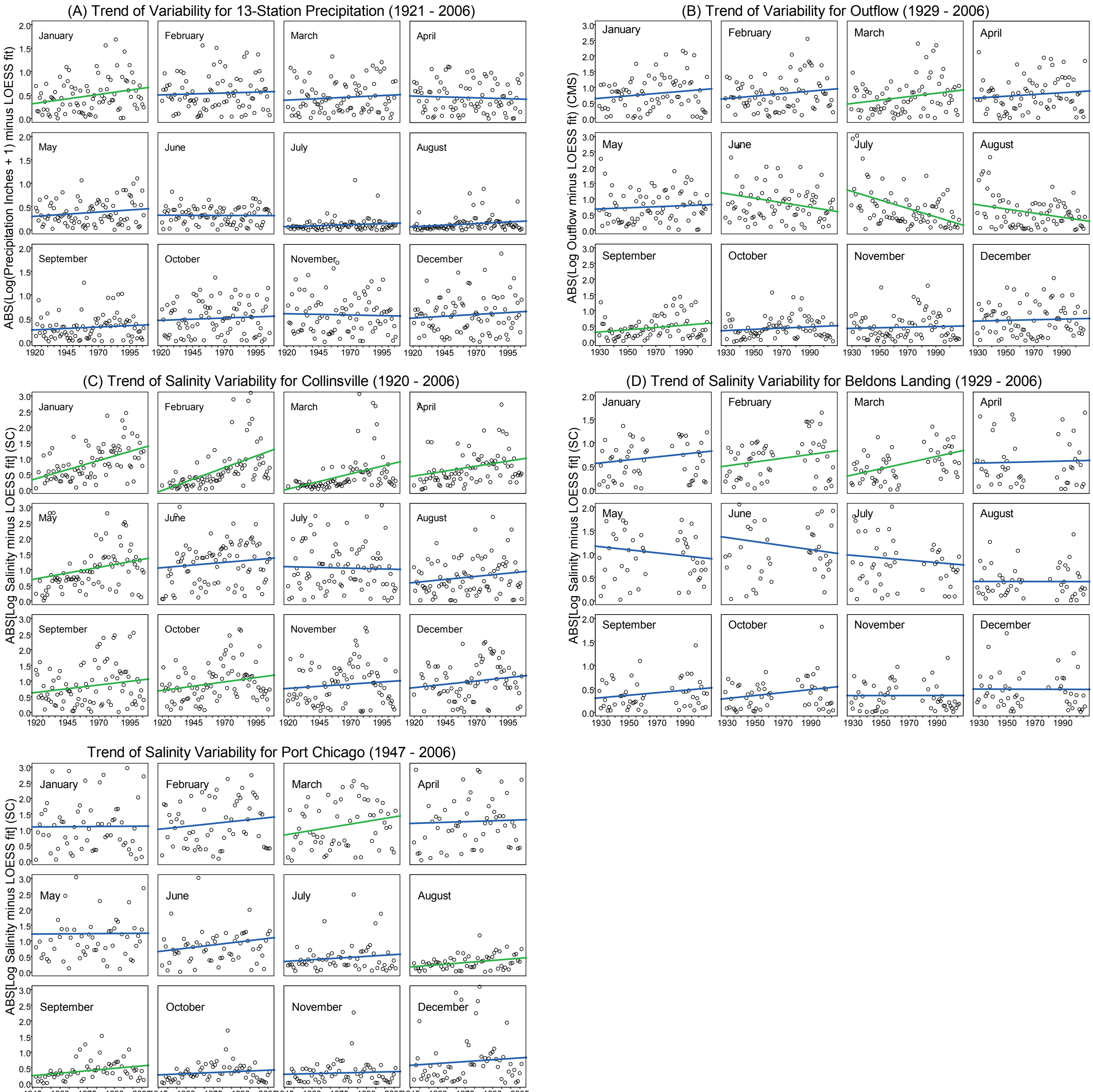

Figure 13 Trend of variability based on local regression fits to the average of 13 Bay-Delta watershed precipitation stations by month. Circles are absolute value of data residuals minus loess fit. Lines are regression fits. Green regression fits indicate significant slopes ($p<0.05$) suggesting trend in variability. Blue is not significant.

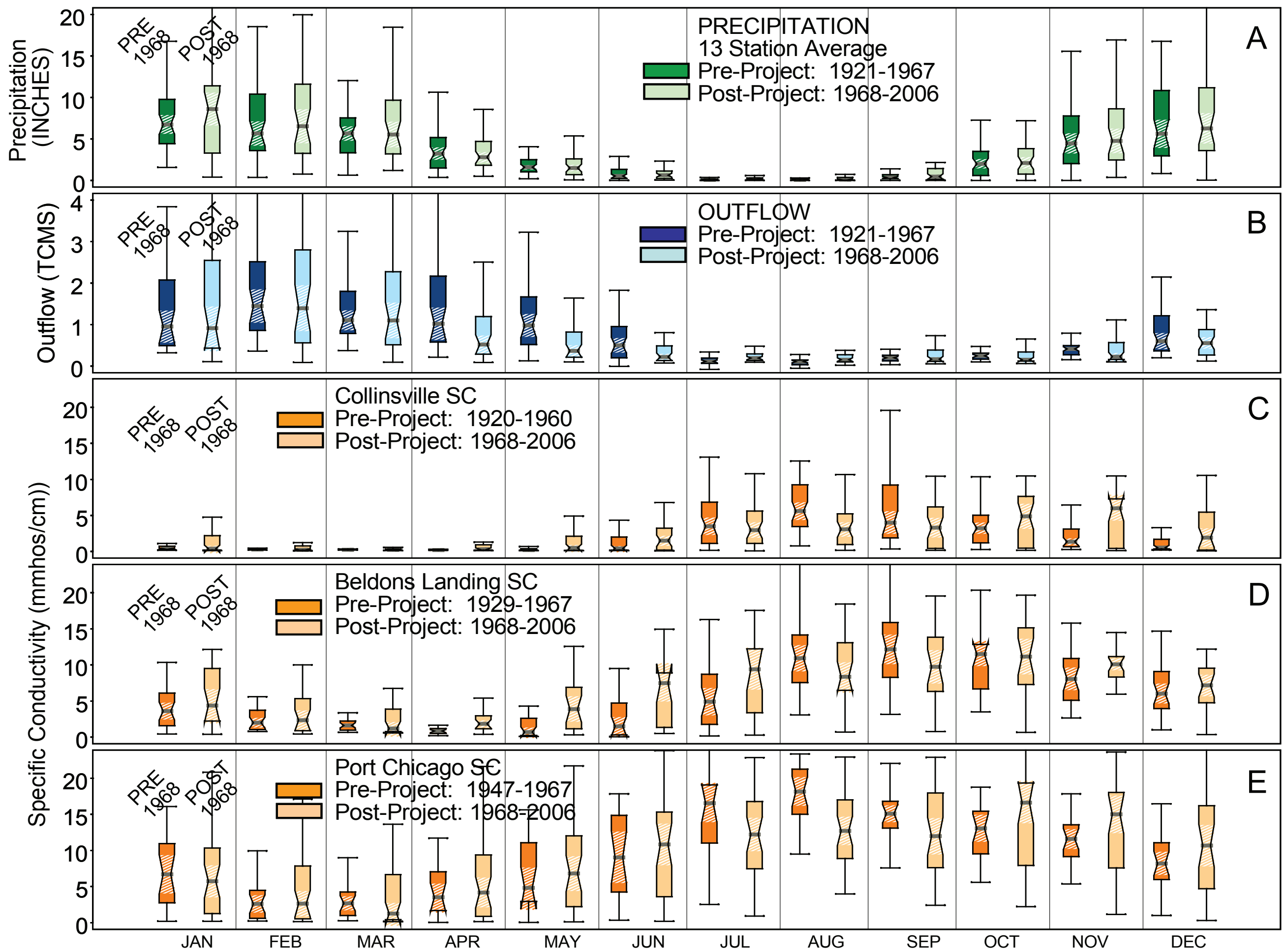

Figure 14 Distribution of pre- and post-project precipitation, outflow, and salinity by month. Box-plot indicates median, 95% confidence interval, inner quartile, and range of data for each month. Pre-project and post-project distributions are shown side-by-side for each month.

and bathymetry changes that could influence tributary and baroclinic flows. Also noteworthy is the apparent reduction in fall outflow and salinity variability in the last decade as the water projects have operated more closely to maximum export-inflow ratios.

Figure 14 compares the pre-project and post-project distributions for precipitation, outflow, and salinity, by month. The five panels show box plots indicating the median, inner quartile, and range of the data for each period and month. If we accept the conceptual model that the water projects reduce month-to-season-scale variability, we would expect Figure 14 to reflect it. In general, the opposite is true. Panel A shows that, excepting April, all wet months (November through May) have wider inner quartile variability and most have greater range in the post-project period. While reservoir and export operations influence outflow medians generally in opposition to precipitation medians, outflow variability matches the precipitation variability pattern in most months (panel B). Salinity is roundly more variable in the post-project period. Port Chicago is more variable in all months, Beldons Landing in ten of twelve months, Collinsville in eight of twelve months. Notably, differences in pre- and post-project salinity variability are often not consistent with

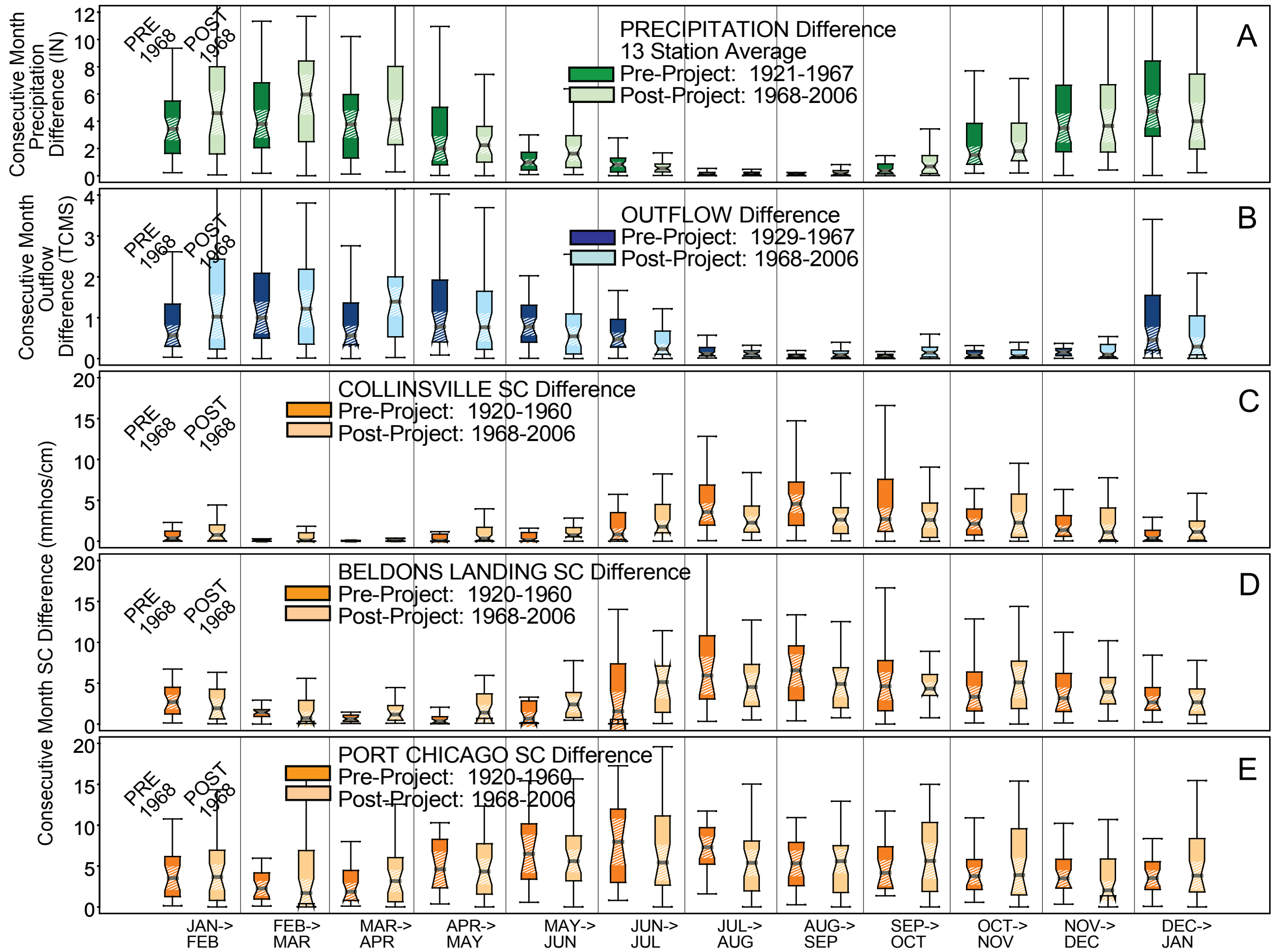

Figure 15 Distribution of consecutive month differences. Box-plot indicates median change, 95% confidence interval, inner quartile, and range of month-to-month difference for each two-month sequence shown on x-axis. Pre-project and post-project difference distributions are shown side-by-side for each month.

outflow variability changes. In general, this occurs in spring and summer months. In April, May, and June, median outflow is lower in the post-project period resulting in higher median salinity that is less often bounded at the low end (by zero) allowing more variability as an artifact of higher salinity despite lower outflow variability. Summer months may be less variable due to earlier snow pack melting and water project efforts to meet delta salinity standards. In general, the water projects influence means, not variability, except when higher means unbound variability.

Another perspective on seasonal scale variability is to examine the pre- and post-project periods for consecutive month-to-month differences in the five data sets. Figure 15 depicts the consecutive month change in precipitation, outflow, and salinity for the periods of record. Again, if water project operations reduce seasonal outflow variability by storing run-off peaks for late spring-summer release that may otherwise have been dryer, then we would expect consecutive month outflow changes to be smaller in the post-project period compared to the pre-project period. The box plots depict the median consecutive month change, 95% confidence interval, inner data quartiles, and range. Figure 15, panel B shows consecutive month change in outflow that, contrary to the conceptual model, shows a tendency for more consecutive month difference in the post-project period. Consecutive month outflow differences are completely consistent with the same metric for watershed precipitation (Figure 15, panel A). This suggests that climate is a more powerful mechanism controlling seasonal variability than water project operations. This does not negate the conceptual model that water project operations dampen seasonal variability as demonstrated by Knowles (2006). However, it does suggest that seasonal outflow and salinity variability is primarily climate driven. Salinity differences are largely coherent with outflow (Figure 15, panels C, D and E). Port Chicago shows the greatest tendency to deviate from outflow coherence possibly because it is more influenced by bay and ocean conditions.

DISCUSSION

Several themes are cultivated in this work including aspects of trend detection, the relative effect of climate (as watershed precipitation), and influence of water projects on salinity trends and variability at different time scales. We have also considered the effect of northern reach geometry, including the operation of the Suisun Marsh Salinity Control Gate. While other investigators have used models to elucidate trend and variability, we rely on over 80 years of monthly average data and attempt to untangle the superposition of forcing influences. We summarize each of these themes in the following discussion.

Data and Models

This study examines over 1,000 months of data to elucidate the relative influences of climate and water project operations on long-term trends and variability of outflow salinity in the northern reach of the San Francisco Estuary. Our study is complementary to that of Knowles (2002) who used a hybrid of data and modeling to discriminate the individual and combined effect of exports and reservoirs on seasonal and annual outflow. Similar to Fox 1990, we relied only on data allowing examination of the prevailing conventional wisdom about the trajectory of northern reach salinity and associated variability on monthly, annual, and decadal time scales. As shown by others (for example Peterson and others 1995), both data and modeling reveal that natural climate variability often overwhelms water project influence on seasonal and interannual scale salinity.

The advantage of models is that mechanisms included in the formulation can be teased apart for their relative contribution to change. In Knowles' 2002 paper, export and reservoir effects are well scrutinized. A potential limitation of models is that not all mechanisms underlying variability may be represented. In contrast, long-term salinity data implicitly contains all driving mechanisms—though untangling one from another and the interactions between is challenging. For example, during the 86 years of monthly data examined in this study, the hydrologic linkage between watershed precipitation and inflow to the delta has profoundly changed with increasing forest management, valley agriculture, and urban hardscape. Moreover, changes have been incremental, inducing unknown non-stationary influence. That our salinity data and Knowles' modeling agree does not necessarily mean that the same suite and weighting of mechanisms will be identified.

We decomposed data into seasonal, decadal, and trend components. On first glance, Figure 2 shows that the long-term salinity trend is essentially indiscernible within the much larger seasonal, annual, and even decadal scale variability in the record. At the annual timescale, Knowles estimated that reservoir and export operations increase mean annual salinity in the northern reach by 10% to 15% (Knowles 2002, Figure 8). While we could not produce a comparable estimate, the loess trend decomposition explains some of the subtle points. First, both nonparametric trend detection methods (loess and Kendall's tau) clearly show that outflow and Collinsville salinity trends are consistent with the precipitation trend in the pre-project period (1921-1967). Precipitation increased about one-tenth of an inch per year with concomitant increase in outflow of about one CMS/year up to 1967 (Figures 5 and 10). After 1968, the outflow trend turns negative (approximately -3 CMS/yr) in opposition to the continuing upward trend in precipitation (nearly 0.15 in per year) (Figures 5 and 10). In the post-project period both Port Chicago and Collinsville have slightly higher annual mean salinity while Beldons Landing is up more than 10% (Figure 4). During the post-SMSCG period (after 1988), all three salinity stations increase in the range that Knowles predicts. Outflow is about 15% less since 1988 than the pre-project period (Figure 4).

Importance of Long Time Series for Trend Detection

We found that trend detection is challenging for several reasons. For example, there is disagreement between the trend detection methods for salinity at Beldons Landing and Port Chicago in the pre-project period. The decadal component of the loess salinity decomposition appears to absorb much of the downward trend at each of the stations. The remaining long-term trend component is positive (Figure 5). In contrast, the Kendall's tau method suggests that pre-project salinity is decreasing. All else equal, with the early century passing of hydraulic mining sediments Suisun Bay likely experienced a long-term positive salinity intrusion trend as its bathymetry eroded and baroclinic circulation increased. Overall, Suisun Bay has eroded approximately 1 m since 1920 (Cappiella and others 1999). When Suisun Bay was shallower during the early part of the century, tidal range, current speed, tidal excursion, and salinity dispersion were likely reduced east of Carquinez Strait (Enright and Miller 2004). The disagreement between trend detection methods suggests that the Kendall method is influenced by sub-trend scale power. This indicates an advantage of the seasonal loess method that it can discern robust long-term trends from shorter timescale influences.

Another example of the importance of separating out decadal-scale influences from long-term trend can be seen by comparing salinity means and trends (Figures 4 and 10). Figure 4 shows that mean salinity at Collinsville and Port Chicago is higher in the post-SMSCG period. At the same time, Figure 10 shows that post-SMSCG salinity is trending significantly lower. The peculiar sequence of hydrology since 1988 accounts for the declining salinity trend as the early years of the period (1988-1992 and 1994) were considered "below normal" or "critically dry" years. Since 1994, nine of twelve years have been classified as "wet" or "above normal" water years (DWR 2007). Despite the declining trend, the 1988 to 2006 salinity mean is higher than any other subset examined in this paper. The 18-year "trend" as determined by the Kendall method is well captured by seasonal loess (Figure 5, "decadal fits"). Once the decadal trend is removed, a rather monotonic upward trend fit emerges at all three salinity stations (Figure 5, "Trend Fits").

This is an important distinction since the forcing mechanisms behind the decadal fit may be entirely different from the trend fit. On the one hand, we suggested above that decadal scale ocean/atmosphere climate teleconnections explain about 10% of the total outflow and salinity variability. On the other hand, slowly changing watershed runoff characteristics, northern reach bathymetry deepening, and expanding water project operations together explain long-term (greater than decadal) trends. This underlines the importance of using data sets longer than the scale of the lowest frequency forcing mechanism. In this case, decadal timescale variability is approximately 20-25 years. There is a risk of misidentifying the forcing mechanisms when trend identification is attempted using shorter data sets. The seasonal loess method effectively sequesters the decadal variability in the decadal fit. It thereby better accounts for drought and ocean/climate teleconnection-scale variability and provides a more robust estimate of the long-term (multi-decadal) trend.

Drivers of Long-term Trends and Variability

All else equal, we would expect outflow and salinity to be well correlated with San Francisco Estuary watershed precipitation trends and variability. Two primary findings of this work are: (a) the water projects have decoupled long-term trends in annual mean outflow and salinity from long-term trends in climate forcing, and (b) climate has primary control over monthly to decadal scale outflow and salinity variability. The conceptual model of variability reduction by water project operation turns out to be only a secondary driver of variability.

a. Water projects have decoupled the long-term delta outflow trend from the long-term precipitation

trend. Outflow trend downward in opposition to the precipitation trend in the post-project period (Figure 5, "Decadal Fits"). While there have been significant changes in the watershed affecting soil permeability and water retention in the post-project period, on the annual time-scale, water project export is the primary driver of outflow reduction. Despite precipitation trending upward, Port Chicago and Collinsville respond to outflow reduction with annual salinity increases of about 1% and 4%, respectively, and positive trends each around 0.04 mmhos/cm per year (Figure 5, "Decadal Fits"). Beldons Landing curiously shows an 18% increase in the annual mean, but significant negative salinity trends in the post-project period. The apparent mean increase owes partly to the large section of missing data in the early post-project period (Figure 5), while the sequence of drought to wet years from 1988 to 2006 along with SMSCG operations accounts for the downward salinity trend.

The water projects also modify annual averages of outflow and salinity and generate year-to-year serial correlation. The summary statistics in Appendix 1 show that lag-1 annual outflow is not correlated in the pre-project period, however it becomes significantly correlated (0.28, $p<0.05$) in the post-project period. The monthly lag-1 correlation is always significant but the correlation is somewhat higher post-project (0.54 pre-project; 0.65 post-project). The annual 13-station precipitation index is not lag-1 correlated in either period.

We also suspect that the northern reach salinity regime was significantly influenced by bathymetry changes in the Suisun Bay due to land use and changing sediment supply. Erosion of Suisun Bay since about 1920 (Cappiella 1999), along with about 10 cm of sea-level rise, likely eased dispersive transport of ocean salt up estuary. All else equal, we would expect the trend toward increased depth in Suisun Bay to generate an upward salinity trend over time. It could be that the long term, positive salinity trend at Beldons Landing and Port Chicago in opposition to increasing watershed rainfall reflects unrelated serial processes: First, after 1920, the gradual erosion of Suisun Bay with concomitant increases in baroclinicity and shear flow dispersion generated greater salinity intrusion than increasing precipitation and outflow could repel. Second, just as Suisun Bay had passed most of the mining sediments, the water projects began reducing outflow thus keeping Suisun Bay salinity on a steady long-term positive trend (Figure 5, "Trend Fits").

b. **Revising the conceptual model about water project effect on salinity variability.** Water project operations reduce seasonal salinity variability by storing winter runoff and releasing it for dry season demands. Over-year storage further reduces annual variability by storing more during wet years and releasing it in dry years. A prevailing ecosystem conceptual model holds that flow and salinity variability represents a key physical-chemical process underpinning ecosystem resilience (for example, Lund 2007). A corollary is that native species coevolved with variable seasonal-to-decadal salinity and may therefore lose competitive advantage by temporal homogenization of the flow/salinity regime. A conceivable irony is that these trends, while indicative of the previous 86 years of development, may imitate the buffering capacity of the historical landscape with its vast wet season floodplain storage and slow surface and groundwater drainage into the dry season. In any case, Table 1 indeed shows that annual outflow is serially correlated in the post-project period while precipitation is not. Moreover, Figure 12 shows spring outflow decreasing while summer outflow is increasing. Knowles' findings support the conceptual model. He estimates that annual salinity variability along the northern reach is reduced by water project operations about 10% (Knowles 2002, Figure 8). However, despite the soundness of the conceptual model, and the magnitude of the effect estimated by Knowles, the data do not verify variability reduction. Our results suggest that annual average salinity variability (Figure 4, Table 1, and Table 2) and by-month salinity variability (Figure 13, Table 1, and Table 2) is generally greater than the pre-project period. This is not because the prevailing conceptual model is incorrect. On the contrary, more post-project variability strongly suggests that there are other powerful mechanisms at play including climate and land use changes that overpower the homogenizing influence of project operations. There is however, emerging evidence to suggest that water project operations are making incursions into salinity variability in the fall since the late 1990's when export/inflow ratio limits have been approached more consistently.

The Influence of Climate

Large-scale Pacific Ocean and atmosphere interactions profoundly influence the climate of the San Francisco Estuary watershed. In general, the gradient between Pacific Ocean pressure systems determines storm system tracks through the seasons. At the inter-annual timescale, the El Niño-Southern Oscillation (ENSO) influences the pressure system gradient with opposite polarity effects on the Pacific Northwest and Southern California. The San Francisco Estuary is positioned near the fulcrum of the latitude polarity and ENSO influence is sensitive to the longitudinal position of the Aleutian low. ENSO status influences estuary salinity in rather complex ways, including north to south snowpack variability, leading to variability of intra-annual runoff patterns (Schonher and Nicholson 1989; Dettinger and Cayan 1995; Knowles 2000). We enfolded the complexity of these climate forcings by lumping runoff from the vast San Francisco Estuary watershed in to one precipitation index—the average of 13 monthly average Sierra foothill precipitation gauges (Figure 1). The 13-station precipitation index is well correlated with monthly average delta outflow (0.67, p=0), even though the linkage between them is influenced by reservoir operations, antecedent soil moisture, and whether precipitation falls as rain or snow. The 13-station precipitation index is thus an effective proxy for the outflow trends we would expect without water project influence or changes in watershed runoff dynamics. With it, we were able to investigate the relative influence of seasonal and annual water project effects on delta outflow compared to watershed scale climate forcing. In addition, with 86 years (1,032 months) in the record, we investigated the influence of decadal-scale Pacific Ocean and atmosphere variability on San Francisco Estuary precipitation and outflow.

Decomposing precipitation data into various timescale components revealed a considerable periodic oscillation at the decadal timescale. We investigated these low-frequency oscillations and possible teleconnections between Pacific Ocean/atmosphere variability. We found: (1) strong correlation between PDO and precipitation/outflow indexes when all are filtered to the decadal scale; (2) about 10% of monthly precipitation and outflow variability is explained by decadal scale oscillations in the PDO index; and (3) decadal scale variability in the monthly outflow and salinity data explains 10% to 15% of their total variability. Collinsville (western delta) salinity is somewhat better explained by decadal scale variability than Port Chicago (Suisun Bay). This suggests that climate teleconnection to northern reach salinity may also have differential effect depending on proximity to coastal ocean salinity influence. By virtue of their positions in the northern reach, delta salinity is more influenced by watershed precipitation, while Suisun Bay salinity is marginally more influenced by other coastal ocean processes like the California current and upwelling.

Other Salinity Trend and Variability Drivers

This paper focuses on first and second moment trends in outflow and salinity due to the influence of climate and water project operations. Over the 86-year period of the data, several other physical processes have influenced salinity trends and variability that are beyond the scope of this paper. When we examine any long time-series for the estuary, we must be mindful that the trends and variance result from a complex superposition of process influences and feedbacks. Some of the other salinity mixing mechanisms and timescales of influence include:

- ENSO scale fluctuations of the California current and associated upwelling modify San Francisco Bay/ocean water exchange and influence San Francisco Bay salinity available for tidal dispersive transport upstream (Walters and Gartner 1985; Peterson and others 1989).

- Salt dispersion by the northern reach channel network greatly increased during period of rapid delta reclamation. This tidal timescale process efficiently mixes salinity upstream as the characteristic length between channel bifurcations is reduced. Linear channel "cuts" and meander cutoffs in Suisun Bay and the delta along with ship channel dredging and ongoing channel island erosion is increasing the ratio between tidal excursion and channel reach length. As the ratio increases, salinity is mixed by bifurcation flow asymmetries (Burau and others 2008).
- Tidal energy dissipation in the northern reach has diminished over time as the land-water interface was sharpened and simplified by levees. The pre-settlement physiography of the northern reach exhibited more complex land-water interfaces and biogeomorphic processes that absorbed tidal energy. Complex landscape allometry attenuates tidal range, tidal currents, and shear dispersion of salinity gradients (Simenstad and others 2000). Modification of the northern reach geometry may be the single most important long-term driver of salinity regime change since European settlement.
- Sea-level rise is occurring at almost 2 mm per year accumulating perhaps 10 cm since 1921. This is a slow but significant impact on northern reach salinity regime by marginally increasing wave speeds, tidal velocity, baroclinicity, shear dispersion, and tidal flow asymmetries (tidal trapping). Each process tends to increase upstream salinity mixing.
- Permanent island flooding since 1921, including Mildred Island, Little Mandeville Island, and Sherman Lake, increase salinity mixing by tidal trapping. Other islands, including Liberty Island, may reduce ocean salt transport to the delta by absorbing tidal energy. The importance of this physical salinity driver may increase in the future.
- Drastic changes in watershed land use especially in the first half of the century modified soil permeability and runoff characteristics. The well-known alterations include levees, bypasses, soil compaction, forest modification, groundwater overdraft, imports from other watersheds, conversion of emergent marshes, and surface hardening (Fox and others 1990).

CONCLUSION

We re-constructed monthly time series of San Francisco Estuary watershed precipitation (since 1921), delta outflow (since 1929), and northern reach salinity at Port Chicago (since 1947), Beldons Landing (since 1929), and Collinsville (since 1921). We decomposed the data into seasonal, decadal, and trend components to clarify the superposition of variability drivers. With the longest time series over 1,000 months, these are the longest data records in the estuary save for Golden Gate tide. We used the precipitation index to compare trends and variability in climate forcing to outflow and salinity trends before and after construction of the water projects and the Suisun Marsh Salinity Control Gate. Our primary conclusions extend and clarify the work of other investigators:

- The state and federal water projects decoupled long-term trends in annual mean outflow and salinity from long-term trends in precipitation.
- The water projects dampen seasonal and annual outflow and salinity variability.
- Despite this, both seasonal and annual timescale outflow and salinity are generally more variable in the water project era concordant with watershed precipitation.
- Annual average precipitation is not serially correlated. Annual average outflow is likewise not serially correlated until water project influence intensifies in the late 1960s.
- We suggest a revision of the widely held conceptual model that the water projects have reduced flow and salinity variability in the northern reach. While water project operations act to reduce flow and salinity variability, actual sea-

sonal and annual variability has increased since the late 1960's. Therefore, water projects induce secondary influence on annual and seasonal outflow and salinity variability. Climate is a more powerful long–term variability driver at the seasonal and annual scale.

- About 10% of monthly precipitation and outflow variability is explained by decadal scale oscillations in the PDO index. Further, decadal scale variability in the monthly outflow and salinity data explains 10% to 15% of their total variability.
- We underscored the value of long data records for discerning trend and variability drivers. On the one hand, ocean/atmosphere climate teleconnections explained significant decadal scale (20-year to 25-year) variability. On the other hand, slowly changing watershed runoff characteristics, northern reach bathymetry deepening, and expanding water project operations together explain long-term (greater than decadal) trends. Therefore, identifying trends and mechanisms requires data sets that are longer than the scale of the lowest frequency forcing mechanism.
- The seasonal loess method effectively sequesters the decadal variability in the decadal fit. It thereby better accounts for drought and PDO-scale variability and provides a more robust estimate of the long-term (multi-decadal) trend.

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