State of the Estuary Report
2019 Update

Combined Technical Appendices

October 2019

Contents

State of the San Francisco Estuary 2019

Technical Appendix

Freshwater Inflow Indicators and Index

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April 2019

I. Background

The San Francisco Bay Estuary, which extends upstream from the Golden Gate south to the South Bay and east through San Pablo Bay, Suisun Bay and the Delta to the limit of tidal influence in the Sacramento, Mokelumne and San Joaquin rivers, is the interface between California's largest rivers and the Pacific Ocean. It is important spawning, nursery and rearing habitat for a host of fishes and invertebrates, a migration corridor for anadromous fishes like salmon, steelhead and sturgeon, and breeding and nesting habitat for waterfowl and shorebirds.

Estuaries are defined by the amounts, timing and patterns of freshwater inflow. In the San Francisco Bay estuary, freshwater inflows control the quality and quantity of estuarine habitat drive key ecological processes and significantly affect the abundance and survival of estuarine biota, from tiny planktonic plants and animals to shrimp and fish (Jassby et al. 1995; Kimmerer 2002, 2004; Kimmerer et al. 2008; Feyrer et al. 2008, 2010; Moyle and Bennett, 2008; Moyle et al., 2010; SWRCB 2010; and see Flood Events indicators [SOTER 2019] and the Open Water Habitat indicators [SOTER 2015 report]). The mixing of inflowing fresh water and saltwater from the ocean creates low salinity, or "brackish" water habitat for estuary-dependent species. Seasonal and inter-annual changes in inflow amounts trigger biological responses like reproduction and migration, and high flows transport nutrients, sediments and organisms to and through the Bay, promote mixing and circulation within the estuary and flushing contaminants.

Most of the fresh water that flows into the San Francisco Bay Estuary comes from the Sacramento and San Joaquin river basins, which provide >90% of total inflow in most years and have large impacts on salinity regimes in the estuary (Kimmerer 2002, 2004). Smaller streams around the estuary, like the Napa and Guadalupe rivers, Alameda, San Francisquito, Coyote, Sonoma creeks, and many smaller tributaries, contribute the balance and can have large environmental effects on a local level. All of these rivers have large seasonal and year-to-year variations in flow, reflecting California's seasonal rainfall and snowmelt patterns, and unpredictable times of floods and droughts.

Freshwater inflows to the Delta and the Bay from the Sacramento-San Joaquin watershed are affected by a number of factors, including:

- Precipitation and runoff – flow amounts can vary from year to year by as much as an order of magnitude between wet and dry years;
- Dams – which capture and store runoff from the mountains for release into rivers at different times of the year and in different years, and can change variability of seasonal and inter-annual flows (nine of the ten largest Sacramento-San Joaquin watershed tributaries to the estuary are dammed and managed for flood control and water supply);
- In-river diversions – which remove water from rivers for local agricultural or urban use or export to other regions in California, reducing the amount of water that flows to the estuary;
- Return flows and discharges – which add (or return) water to river flows (return flow and discharge amounts are usually smaller than the amounts of water diverted);
- In-Delta diversions – which remove water from the upper reach of the estuary for local agriculture and urban use and for export to other regions in California, reducing the amount of water that flows from the Delta into the Bay;

- Climate change – warmer temperatures and shifts in precipitation from snow to rain have altered the amounts, timing and duration of seasonal flows in the estuary's tributary rivers.

The State of the Estuary Report uses ten indicators to measure and evaluate the amounts, timing and patterns of freshwater inflow from the Sacramento-San Joaquin watershed to the Delta and the Bay. These indicators are designed specifically to look at various aspects of freshwater inflow conditions in the estuary, not the aquatic habitat conditions or ecological processes that result from or are affected by inflow. The ten indicators are also aggregated into a Freshwater Inflow Index, which combines the results of all the indicators into a single metric.

Five indicators measure aspects of the amounts of freshwater flow into the Delta and the Bay:
- Annual Delta Inflow;
- Spring Delta Inflow;
- San Joaquin River Inflow;
- Annual Bay Inflow; and
- Spring Bay Inflow.

One indicator measures the amount of water diverted directly from the Delta:
- Delta Diversions.

Four indicators measure the variability of freshwater flows into the Bay:
- Inter-annual Variation in Inflow;
- Seasonal Variation in Inflow;
- Peak Flow; and
- Dry Year Frequency.

In order to account for the watershed's large year-to-year variations in hydrology, all of the indicators are measures of the alterations in freshwater inflow conditions, rather than measures of absolute amounts of inflow. Except for the Delta Diversions indicator, all of the indicators are calculated as comparisons of actual freshwater flow conditions to the freshwater flow conditions that would have occurred if there were no dams or water diversions, referred to as "unimpaired" conditions. By incorporating unimpaired inflow as a component of the indicator calculation, the indicators are "normalized" to account for natural year-to-year variations in precipitation and runoff. The Delta Diversions indicator compares Delta inflows to Delta outflows.

II. Data Sources and Definitions

A. Data Sources

Because most of the fresh water that flows into the San Francisco Bay Estuary comes from the Sacramento, Mokelumne and San Joaquin river basins (collectively the Sacramento-San Joaquin watershed), which provide >90% of total inflow in most years,[1] all of the Freshwater Inflow indicators were calculated using flow data from the Sacramento-San Joaquin watershed only.

The indicators were calculated for each year[2] using data from the California Department of Water Resources (CDWR) DAYFLOW model (for "actual flows), CDWR's Central Valley Streams Unimpaired Flows, and the California Data Exchange Center's (CDEC) Full Natural Flows (FNF) datasets (for "unimpaired flows"). DAYFLOW is a computer model developed in 1978 as an accounting tool for calculating daily historical Delta inflow, outflow and other internal Delta flows.[3] DAYFLOW output is used extensively in studies by State and federal agencies, universities, and consultants. DAYFLOW output is available for the period 1930-2018.[4] Annual and monthly unimpaired flow data for total Delta inflow, Delta outflow and San Joaquin River inflow are from the CDWR California Central Valley Unimpaired Flow dataset (1921-2003).[5] For 2004-2018, annual and seasonal unimpaired flows were calculated by regressions developed from the Central Valley unimpaired flow data (using the 1930-2003 period) and the corresponding unimpaired runoff estimates from the CDEC Full Natural Flows dataset[6] for the ten largest rivers in the watershed (for Delta inflows and outflows) and the four major San Joaquin Basin rivers for San Joaquin River inflows.[7] Figure 1 shows regressions of CDWR's unimpaired flows on Full Natural Flows for annual and spring (Feb-June) Delta inflow, annual and spring Delta outflow, and San Joaquin River inflow.

[1] The Sacramento River provides 69-95% (median=85%) and the San Joaquin River provides 4-25% (median=11%) of total freshwater inflow to the San Francisco Bay (Kimmerer, 2002).
[2] Flow indicators were calculated for each water year. The water year is from October 1-September 30.
[3] More information about DAYFLOW is available at www.water.ca.gov/dayflow.
[4] For actual flows, various indicators used DAYFLOW parameters for QTOT (for total Delta inflow), QOUT (net Delta outflow), and QSJR (San Joaquin River inflow).
[5] California Central Valley Unimpaired Flow dataset and report is available at: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spprtinfo/dwr_2007a.pdf
[6] Full Natural Flows datasets are available at: http://cdec.water.ca.gov/cgi-progs/previous/FNF
[7] The ten rivers are the Sacramento, Feather, Yuba, American, Cosumnes, Mokelumne, Stanislaus, Tuolumne, Merced and San Joaquin Rivers. For the San Joaquin basin, the four rivers are the Stanislaus, Tuolumne, Merced and San Joaquin Rivers.

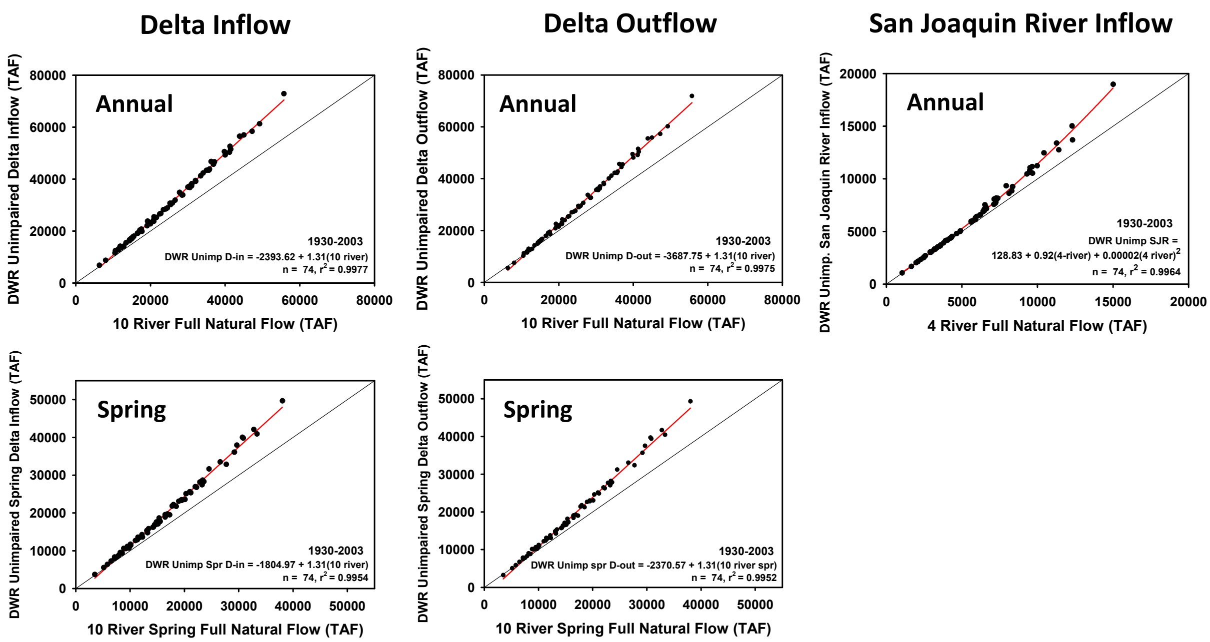

Figure 1. Regressions of CDWR unimpaired flows on Full Natural Flows for annual and spring (Feb-June) Delta inflow, annual and spring Delta outflow, and annual San Joaquin River inflow, 1930-2003.
Data sources: California Department of Water Resources, Central Valley Streams Unimpaired Flows, and California Data Exchange Center, Full Natural Flows.

B. Tidal Effects on Flows in the Delta

Flows in Delta channels and the Bay are influenced by tidal action as well as freshwater inflows from upstream and in-Delta diversions. The estuary experiences two tides every day, two high tides and two low tides, and magnitude of the high and low tides varies over a 28-day spring-neap cycle. Under conditions of low to moderate inflows, tidal flows in Delta channels can be an order of magnitude greater than the freshwater inflow and the direction of flow in the channels typically reverses twice daily with the tides. However, all daily flow data used to calculate the indicators (i.e., Dayflow data) have been filtered to remove tidal effects.

C. Definitions

Unimpaired Inflow: Unimpaired inflow is the freshwater inflow that, under the same hydrological conditions but without the effects of dams and diversions in the Sacramento-San Joaquin watershed and Delta, would have flowed into the Delta or Bay (see Figure 2). Unimpaired inflow is not the same as “natural” or “historical” inflow that would have occurred in the watershed prior to human development and land use changes; it is instead an estimate of what flows over the *existing landscape* would have been if there were no dams or diversions.

Pre-dam Inflow: The period prior to the completion of major dams in the watershed, from 1930-1943, is referred to as the "pre-dam" period. During this period, actual flows were somewhat similar to unimpaired flows, particularly in very wet years and during periods of high flows.

Post-water Development Inflow: Most of the major dams and water diversion facilities (such as the state and federal Delta pumping facilities) were completed and operational by 1970. Water export rates at the Delta pumping facilities increased rapidly during the 1970s, reaching "full operation" with export rates leveling off by 1980.

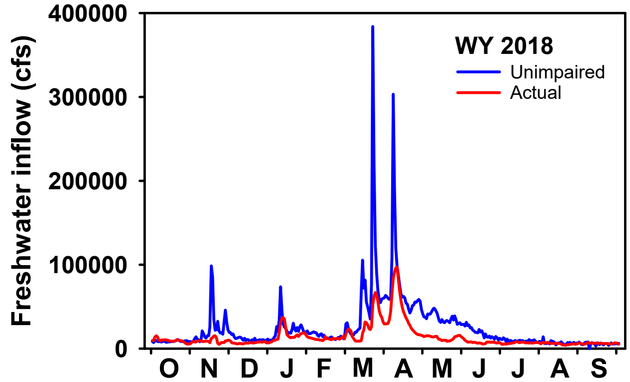

Figure 2. Unimpaired and actual freshwater inflows to the San Francisco Estuary in Water Year 2018.
Data sources: California Department of Water Resources, Dayflow, and California Data Exchange Center (CDEC), Full Natural Flows.

Delta Inflow vs. Bay Inflow: Delta inflow is the amount of water that flows into the Delta from the Sacramento-San Joaquin watershed. Bay Inflow (or Delta outflow) is the amount of water that flows from the Delta into the Suisun Bay region of San Francisco Bay. Bay inflow amounts are less than Delta inflow amounts because in-Delta diversions by local water users and the state and federal water export facilities remove a portion of Delta inflow before it reaches the Bay.

Water Year Type: Runoff from the Sacramento-San Joaquin watershed can vary dramatically from year to year, a function of California's temperate climate and unpredictable occurrences of droughts and floods. To categorize these large year-to-year variations in flow, annual unimpaired inflows were classified for each year as one of five water year types: very wet, wet, median, dry and very dry. Year types were established based on frequency of occurrence during the period of 1930-2009, with each year type comprising 20% of all years. Figure 3 shows annual unimpaired Delta outflows to the Bay with year type classification shown by the different colors of the bars.

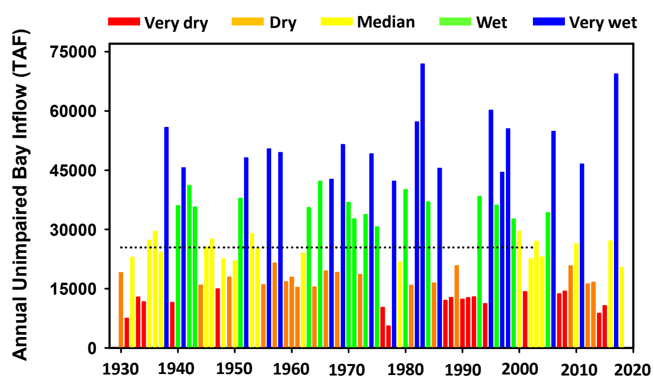

Figure 3. Annual unimpaired freshwater inflow to the Bay (TAF) for 1930-2018. Bars are colored to show frequency-based water year type (see text). Dotted line shows median unimpaired Bay inflow for the 1930-2003 period. Data source: California Department of Water Resources, Central Valley Streams Unimpaired Flows and CDEC Full Natural Flows datasets.

III. Indicator Evaluation

The San Francisco Estuary Partnership's Comprehensive Conservation and Management Plan (CCMP) calls for "increase[ing] freshwater availability to the estuary", "restor[ing] healthy estuarine habitat" and "promot[ing] restoration and enhancement of stream and wetland functions to enhance resiliency and reduce pollution in the Estuary" (SFEP 2007). These goals are non-quantitative; therefore, we used information from the scientific literature, current regulatory standards and objectives, and historical and/or unimpaired conditions to identify and define levels of freshwater flows that promote restoration and enhance ecological function and resiliency.

There is a growing body of scientific literature on environmental flow requirements for riverine and estuarine ecosystems, including Arthington et al. (2006), Poff et al. (2010) and Richter et al. (2011). In particular, Richter et al. (2011) proposed conservative and precautionary "presumptive standards" for river flows to maintain ecological integrity, identifying 80% of unimpaired flow as needed to maintain ecological integrity and 90% of unimpaired to protect rivers with at-risk species.[8] In addition, California's State Water Resources Control Board (SWRCB) recently determined that, in order to protect public trust resources in the Sacramento-San Joaquin Delta and San Francisco Estuary, 75% of unimpaired flow from the Sacramento-San Joaquin watershed should flow out of the Delta and into the Bay during the winter and spring seasons and that winter and spring lower San Joaquin River flows should be 60% of unimpaired San Joaquin River flow (SWRCB 2010).[9] The SWRCB has also established regulatory standards for minimum flow and maximum diversion levels for the Delta and Bay (SWRCB 2006). Information on historical conditions, prior to major water development in the watershed, was derived from DAYFLOW data from the pre-dam period.

For each indicator, a primary reference condition, the quantitative value against which the measured value of the indicator was compared, was established. For most of the indicators, this reference condition was developed based on recommendations of either Richter et al. (2011) or SWRCB (2010). The SWRCB 2006 regulatory standards (SWRCB 2006), pre-dam flow conditions and various metrics from unimpaired flow data (e.g., variability) were also used to inform development of reference conditions for some indicators. Measured indicator values that were higher than the primary reference condition were interpreted to mean that aspect of freshwater inflow condition, as measured by the indicator, met the CCMP goals and corresponded to "good" ecological conditions in that year. For the most recent 29 year period (since 1990, when the CCMP was being developed and established), CCMP goals were considered to be "fully met" is indicators met or exceeded the primary reference conditions in at least 67% of years; "partially met" if the indicators met or exceeded this level in 33-66% of years; and "not met" if indicators met or exceeded this level in less than 33% of years.

In addition to the primary reference condition, information on the range and trends of indicator results, results from the scientific literature and other watersheds, and known relationships

[8] The standards proposed by Richter et al. (2011) were for daily flows.
[9] The SWRCB recommendation was for the winter-spring period (January-June) and it was expressed as the 14-day running average of estimated unimpaired runoff, rather than as an annual or seasonal total. On an annual basis, the majority of runoff in the watershed and unimpaired flows occur in the winter and spring.

between freshwater inflow conditions and physical and ecological conditions in estuaries was used to develop several intermediate reference conditions. The intermediate reference conditions were used to create a five-point scale that categorized and assigned a quantitative "score" to the indicator's measured value, ranging from zero (0), which was considered to correspond to "very poor" conditions with highly altered flow conditions, to four (4), which was considered to correspond to "excellent" conditions with minimally altered flow conditions. The primary reference condition was assigned a point value of three (3), corresponding to flow conditions that had been altered but which were sufficient to maintain ecological integrity and thus meet the CCMP goals. The size of the increments between the different levels was, where possible, based on observed levels of variation in the measured indicator values (e.g., standard deviations) in order to ensure that the different levels represented meaningful differences in the measured indicator values. For each year, these scores of the ten indicators were averaged to calculate the Freshwater Inflow Index. Specific information on the primary and intermediate reference conditions for each indicator is provided in the following sections describing each of the indicators.

The results for each indicator and the Index are shown graphically, with all graphs showing the results for each year and each decade (e.g., 1950-1959). All graphs show the measured indicator (or Index) values and the indicator score using a consistent orientation on the Y axis, with values corresponding to good conditions shown above values corresponding to poorer conditions on the Y axis regardless of the unit of measure or numeric scale. To evaluate trends and differences over time and between other variables (e.g., water year types), indicator and Index results were analyzed using t-tests, analysis of variance and simple linear regression.

IV. Freshwater Inflow Indicators

A. Annual Delta Inflow

1. Rationale

The Delta receives freshwater inflow from more than a dozen rivers and streams, including the Sacramento, Mokelumne, Cosumnes, Calaveras and San Joaquin Rivers, as well as a number of smaller tributaries from the west side of the Sacramento Valley (including Putah and Cache Creeks). Collectively, these rivers drain more than 40% of the California landscape, from the Cascade Mountains in the north to the southern Sierra Nevada. From year to year, the amounts of flow from these rivers into the Delta can vary more than ten-fold, reflecting California's temperate climate and unpredictable cycle of droughts and floods. By the mid-1900s, nearly all of these rivers were dammed for water storage, flood control and/or hydropower, altering the amounts and timing of freshwater flows into the Delta. Runoff from rainstorms and the melting mountain snowpack that formerly flowed into the Delta in the winter, spring and early summer is now captured behind massive dams, and diverted from rivers and reservoirs for local and distant use. Flow from some rivers, such as the upper San Joaquin and the Calaveras, no longer even reaches the Delta in many years. In contrast, in some years (and in some seasons), water captured and stored in reservoirs in previous years is released and flows in to the Delta in excess of what would have flowed into the Delta under unimpaired conditions.

2. Methods and Calculations

The Annual Delta Inflow indicator measures the total amount of fresh water that flowed into the Delta each year from all of its tributary rivers, compared to the amount that would have flowed into the Delta from these rivers under "unimpaired" flow conditions, without the effects of dams or water diversions, for that year. Capture and storage of watershed runoff for release in subsequent years and diversion of water from the Delta's tributary rivers reduces annual Delta inflow; release of water captured and stored in watershed reservoirs in previous years and imports of water from the Trinity River watershed increase annual Delta inflow.

The indicator was calculated for each year (1930-2018) as the percentage of annual unimpaired Delta inflow that flowed into the Delta using the following equation:

Annual Delta Inflow indicator (% of unimpaired)
= (actual annual Delta inflow/unimp. annual Delta inflow) x 100

3. Reference Conditions

The primary reference condition for the Annual Delta Inflow indicator was established as 80%, the level identified by Richter et al. (2011) as needed to maintain the ecological integrity of most rivers. Annual inflows that were greater than 80% of unimpaired inflows were considered to reflect "good" conditions and meet the CCMP goals; annual inflows that were less than 50% of unimpaired inflows were considered to correspond to "very poor" conditions. The other reference condition levels were established based on Richter et al. (2011; 90% of unimpaired to protect rivers with at-risk species for "excellent" and minimally altered flows) and use of equal increments between the primary and lowest reference condition levels. Table 1 below shows the quantitative reference conditions that were used to evaluate the results of the Delta Inflow indicator.

Table 1. Quantitative reference conditions and associated interpretations for results of the Annual Delta Inflow indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Annual Delta Inflow		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>90% of unimpaired	"Excellent," minimal alteration	4
>80% of unimpaired	***"Good," meets CCMP goals***	***3***
>65% of unimpaired	"Fair"	2
>50% of unimpaired	"Poor"	1
≤50% of unimpaired	"Very Poor," extreme alteration	0

4. Results

Results of the Annual Delta Inflow indicator are show in Figure 4.

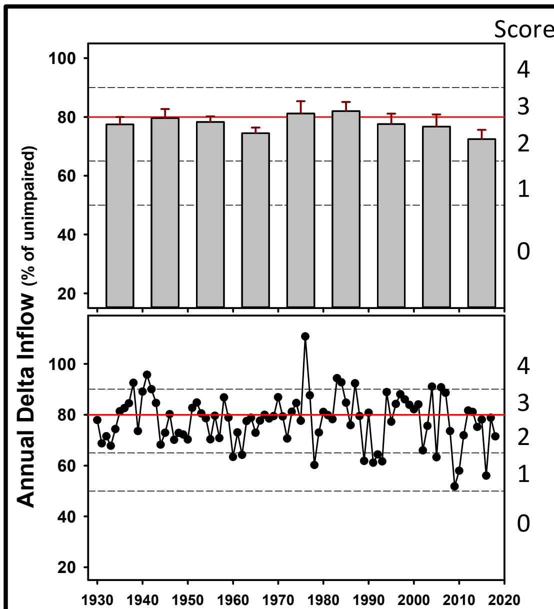

Figure 4. Results for the Annual Delta Inflow indicator, expressed as the percentage of unimpaired flow that actually flowed into the Delta for 1930 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

The total amount of fresh water flowing into the Delta each year has been reduced in almost all years.
On an annual basis, the percentage of the freshwater runoff from the Sacramento-San Joaquin watershed that flows into the Delta has been reduced, averaging 78% of unimpaired Delta inflow for the period of 1930-2018. The greatest reduction in annual Delta inflow occurred in 2009, the third year of the recent three-year drought, when only 52% of unimpaired inflow reached the Delta. In 1976, a very dry year, annual Delta inflow was greater than it would have been under unimpaired conditions, 111% of unimpaired inflow, reflecting large releases of water stored in earlier years from Sacramento basin reservoirs. For the most recent 10-year period (2009-2018), an average of 70% of unimpaired inflow actually flowed into the Delta, similar to the amount for 2018, 71%; this level of freshwater inflow to the Delta corresponds to "fair" condition.

The proportional reductions in annual Delta inflow to the estuary differ by water year type.
In general, the annual Delta inflow is higher in very wet years than in drier years. The greatest alterations to Delta inflow occur in dry years, when an average of 27% of unimpaired flow is diverted before reaching the Delta, significantly more than the 18% of unimpaired Delta inflow diverted in very wet years (ANOVA, $p<0.05$).

Annual freshwater flow into the Delta, as a percentage of unimpaired flow, has not changed over time.
The percentage of unimpaired flow that actually flowed into the Delta has not significantly changed over the past eight decades (regression, $p=0.4$). Since 1980, an average of 6.5 (±4.3 SD) million acre feet of water was diverted from the Sacramento-San Joaquin watershed before it reached the Delta.

Based on annual Delta inflows, CCMP goals to increase fresh water availability to the estuary have been partially met.
Since 1990, annual freshwater inflows to the Delta were "good," meeting or exceeding conditions considered to satisfy CCMP goals, in 45% of years (13 of 29 years). However, Delta

inflow conditions were “poor” in 7 years (24% of years) and the three lowest annual Delta inflows on record, in which inflows were reduced by nearly half, have all occurred during the most recent decade. During the last decade, flows have been below the threshold for ecological integrity recommended by Richter et al (2011) for 80% of years, averaging just 70% of unimpaired. In addition, this indicator does not reflect within-year, or seasonal, alterations, which can be substantial (e.g., see Spring Delta Inflow).

B. Spring Delta Inflow

1. Rationale

Historically, two thirds of total annual freshwater inflow to the Delta occurred during the spring, as snow in the northern and central California mountain ranges melted and filled the Delta’s tributary rivers. Prolonged high flows during this period are still the dominant feature of Estuary’s hydrograph, the annual picture of the timing and amounts of flow (see Figure 2). However, since the early 1900s, growing numbers of large storage and flood control dams on most of the Delta’s tributary rivers captured much of the snowmelt runoff for use later in the year, reducing Delta inflows during the spring (and increasing inflows during the summer and fall). Additionally, regulatory protections for flow, water quality and fisheries standards (SWRCB 2006) that reduce the percentage of Delta inflow that can be diverted by the state and federal export facilities have influenced management of seasonal reservoir releases.

2. Methods and Calculations

The Spring Delta Inflow indicator measures the total amount of fresh water that flowed into the Delta from all of its tributary rivers during the spring (February-June) of each year, compared to the amount that would have flowed into the Delta from these rivers under unimpaired flow conditions during that period, without the effects of dams or water diversions. Capture and storage of springtime watershed runoff for release later in the year or in subsequent years and diversion of water from the Delta’s tributary rivers reduces spring Delta inflow; springtime release of water captured and stored in watershed reservoirs earlier in the year or in previous years and imports of water from the Trinity River watershed increase annual Delta inflow.

The indicator was calculated for each year (1930-2018) as the percentage of spring unimpaired Delta inflow that flowed into the Delta using the following equation:

Spring Delta Inflow (% of unimpaired)
= (actual Feb-June Delta inflow/unimpaired Feb-June Delta inflow) x 100

3. Reference Conditions

The primary reference condition for the Spring Delta Inflow indicator was established as 80%, the level identified by Richter et al. (2011) as needed to maintain the ecological integrity of most rivers. Spring inflows that were greater than 80% of unimpaired inflows were considered to reflect “good” conditions and meet the CCMP goals; annual inflows that were less than 50% of unimpaired inflows were considered to correspond to “very poor” conditions. The other reference condition levels were established based on Richter et al. (2011; 90% of unimpaired to protect rivers with at-risk species for "excellent" and minimally altered flows) and use of equal increments between the primary and lowest reference condition levels. Table 2 below shows the quantitative reference conditions that were used to evaluate the results of the Spring Delta Inflow indicator.

Table 2. Quantitative reference conditions and associated interpretations for results of the Spring Delta Inflow indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Spring Delta Inflow		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>90% of unimpaired	"Excellent," minimal alteration	4
>80% of unimpaired	***"Good," meets CCMP goals***	***3***
>65% of unimpaired	"Fair"	2
>50% of unimpaired	"Poor"	1
<u><</u>50% of unimpaired	"Very Poor," extreme alteration	0

4. Results

Results of the Spring Delta Inflow indicator are show in Figure 5.

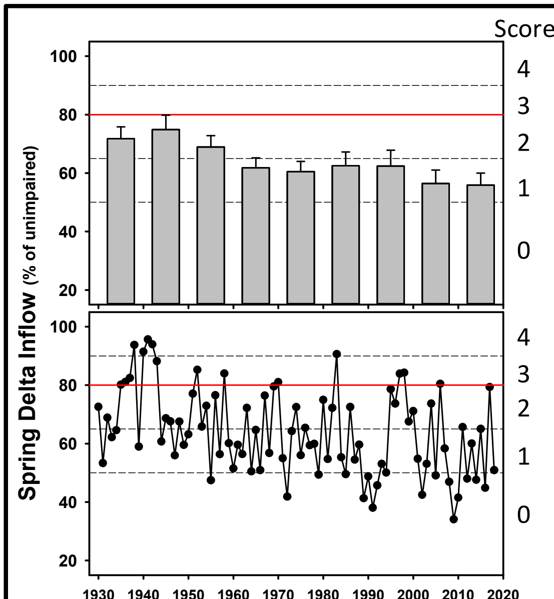

Figure 5. Results for the Spring Delta Inflow indicator, expressed as the percentage of spring (Feb-June) unimpaired flow that actually flowed into the Delta for 1930 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

The amount of fresh water flowing into the Delta during the spring has been reduced.
The percentage of the springtime runoff from Sacramento-San Joaquin watershed that flows into the Delta has been significantly reduced. The greatest alteration in spring Delta inflow occurred in 2009, the third year of the recent three-year drought, when only 34% of unimpaired spring inflow reached the Delta. For the most recent 10-year period (2009-2018), on average only 54% of springtime unimpaired Delta inflow actually flowed into the Delta during the spring. During this period, spring Delta inflows were never "good," greater than 80% of unimpaired, and "very poor," less than 50% of unimpaired, in five years. In 2018, only 51% of unimpaired spring inflow reached the Delta, corresponding to "poor" conditions.

The proportional reductions in spring inflow to the Delta differ by water year type.
The greatest alterations to freshwater inflows occur in dry years when springtime inflows are reduced by nearly half, 47%, on average compared to the average 20% reduction in very wet years (for the 1930-2018 period). Since 1970, the percentages of springtime unimpaired flow that reached the Delta during the spring

averaged 53% in very dry years, 47% in dry years, 53% in median years, 63% in wet years and 76% in very wet years.

Spring flow into the Delta, as a percentage of unimpaired flow, has declined over time.
The percentage of unimpaired flow that actually flowed into the Delta during the spring has declined significantly over the past several decades (regression, $p<0.001$). Significant declines have occurred in all water year types except very wet years (regression, $p=0.07$) and very dry years (regression, $p=0.14$). Before construction of most of the major dams on the Delta's watershed (1930-1943, the pre-dam period), an average of 78% of springtime unimpaired flow actually reached the Delta. By the 1980s, the percentage had decreased significantly to just 63% (1980-1989 average; t-test, $p<0.05$). The average for the most recent 10-year period (2009-2018), 54%, is lower than spring Delta inflows during the 1980s but, because of large year-to-year variations, not significantly different (t-test, $p=0.18$).

Based on spring inflows, CCMP goals to increase fresh water availability to the estuary have not been met.
Since 1990, springtime freshwater inflows to the Delta were "good," meeting or exceeding conditions considered to satisfy CCMP goals, in only 10% of years (3 of 29 years). Spring Delta inflow conditions were "very poor" in 11 years (38% of years). Current spring inflows to the Delta are well below the 80% level recommended by Richter et al. (2011), averaging just 54% of unimpaired during the last decade, which included the lowest spring inflow on record, 34% of unimpaired spring inflow in 2009.

C. San Joaquin River Inflow

1. Rationale

The Delta's vast watershed extends more than 500 miles north to south, from the headwaters of the Sacramento River to the southern end of the San Joaquin basin. Historically, the southern portion of the watershed, San Joaquin River basin, provided just under a quarter (21%) of the total freshwater inflow to the Delta on average.[10] However, since the early 1900s, flows on most San Joaquin basin rivers have been stored behind increasingly large dams and diverted to supply water for San Joaquin Valley agriculture. Even before Friant Dam on the upper San Joaquin River near Fresno began operation in 1949, local water diversions dried up long stretches of the basin's mainstem river in some years. Since the 1950s, additional water has been imported into the San Joaquin Valley from the Delta and, in some areas, agricultural drainage water discharged into the river has added to flow levels, although the quality of drainage water can be very poor and even toxic.

[10] The historical contribution of the San Joaquin basin to total Delta inflow was calculated as: (unimpaired inflow SJR/unimpaired Delta inflow) x 100. In some years, hydrological conditions (i.e., whether it's a wet or dry year) can differ between the basins. The San Joaquin River's contribution was higher in years when it was wetter in the southern basin than in the north and lower when the San Joaquin was drier than the Sacramento basin.

2. Methods and Calculations

The San Joaquin River Inflow indicator measures the amount of water that flowed into the Delta from the San Joaquin River compared to the amount of water that would have flowed into the Delta from this river under unimpaired conditions, without the effects of dams, water diversions or water imports.[11] Capture, storage and diversion of San Joaquin watershed runoff by dams and on-river diversions reduces San Joaquin River inflow to the Delta; discharge of return water derived from water imported to the San Joaquin basin from the Sacramento River basin via the Delta increases San Joaquin River inflows.

The indicator was calculated for each year (1930-2018) as the percentage of annual unimpaired freshwater inflow from the San Joaquin Basin using the following equation:

San Joaquin River Inflow (% of unimpaired)
= (actual San Joaquin River inflow/unimpaired San Joaquin River inflow) x 100

3. Reference Conditions

The primary reference condition for the San Joaquin River Inflow indicator was established as 80%, the conservative level identified by Richter et al. (2011) as needed to maintain the ecological integrity of most rivers. Annual inflows that were greater than 80% of unimpaired inflows were considered to reflect “good” conditions and meet the CCMP goals; annual inflows that were less than 50% of unimpaired inflows were considered to correspond to “very poor” conditions. The other reference condition levels were established based on Richter et al. (2011; 90% of unimpaired to protect rivers with at-risk species for “excellent” and minimally altered flows) and use of equal increments between the primary and lowest reference condition levels. This primary reference condition is higher than the flow level identified by the SWRCB in 2010 for seasonal San Joaquin River inflows to the Delta, 60% of unimpaired, and for Delta outflow, 75% of unimpaired, as needed to protect public trust resources (SWRCB 2010). (In 2018, the SWRCB adopted an update to the Bay-Delta Plan for the lower San Joaquin River that requires even lower flows, 40% of unimpaired flow, with a range of 30% to 50%; SWRCB 2018).[12] However, the rationale used by the SWRCB for the 60% unimpaired flow levels was based only on minimum requirements to protect migrating salmonids, rather than the broader based objective of protecting ecological integrity used by Richter et al. (2011). Therefore, and for consistency with the other inflow indicators, the work of Richter et al. (2011) was used as the basis for the primary reference condition for this indicator. Table 3 below shows the quantitative reference conditions that were used to evaluate the results of the San Joaquin River Inflow indicator.

[11] San Joaquin River inflow is measured at Vernalis.
[12] The SWRCB flow requirements are for the spring period, February-June.

Table 3. Quantitative reference conditions and associated interpretations for results of the San Joaquin Inflow indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

San Joaquin River Inflow		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>90% change in SJR inflow	"Excellent," minimal alteration	4
>80% change in SJR inflow	***"Good," meets CCMP goals***	***3***
>65% change in SJR inflow	"Fair"	2
>50% change in SJR inflow	"Poor"	1
<u><</u>50% change in SJR inflow	"Very Poor," extreme alteration	0

4. Results

Results of the San Joaquin River Inflow indicator are shown in Figure 6.

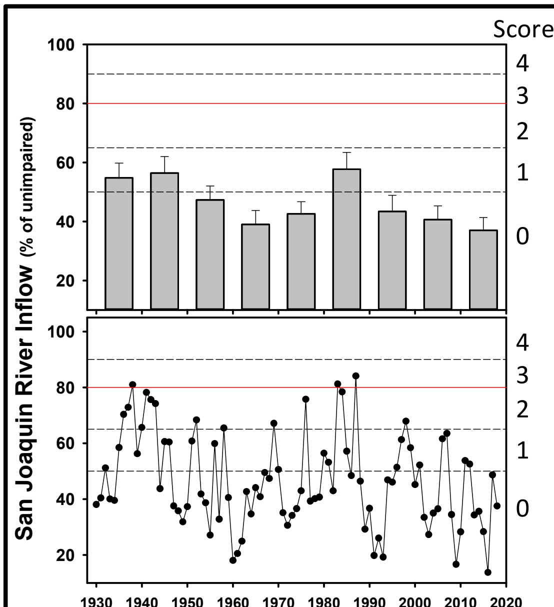

Figure 6. Results for the San Joaquin River Inflow indicator, expressed as the percentage of unimpaired flow from the San Joaquin basin that actually flowed into the Delta for 1930 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

The amount of fresh water flowing into the Delta from the San Joaquin River has been reduced.

The percentage of the annual runoff from San Joaquin River watershed that flows into the Delta has been substantially reduced, averaging just 47% of unimpaired inflow for the 1930-2018 period. The greatest reduction in San Joaquin River inflow occurred in 2016, a year with median runoff that followed the record-breaking 2012-2015 drought, when only 14% of unimpaired inflow reached the Delta. Inflows were lower than 20% of unimpaired in several other years: 18% in 1960 (a dry year following a dry year), 19% in 1993 (a very wet year following a multi-year drought), and 16% in 2009 (a dry year that followed two very dry years). For the most recent 10-year period (2009-2018), on average only 35% of unimpaired San Joaquin River inflow actually flowed into the Delta. During this period San Joaquin River inflows were "very poor," less than 50% of unimpaired, in eight of the ten years; in the other two years inflow were "poor," each with inflows less than 55% of unimpaired. San Joaquin River inflows were at least 60% of unimpaired, the level identified by the SWRCB (2010) as necessary to protect public trust resources, in no years during the last decade, and only nine years in the last 50 years (18% of years). In 2018, only 38% of unimpaired San Joaquin River flow reached the Delta, corresponding to "very poor" conditions.

The proportional reductions in San Joaquin River inflow to the Delta differ by water year type.

The greatest alterations to San Joaquin River inflows occur in dry years when annual inflows are reduced by nearly two thirds, averaging just 36% of unimpaired, significantly lower than inflows in very wet and wet years (ANOVA for the 1930-2018 period, $p<0.05$). Since 1930, the percentages of San Joaquin River inflow that reached the Delta averaged 45% in very dry years, 36% in dry years, 43% in median years, 52% in wet years and 59% in very wet years.

San Joaquin River flow into the Delta, as a percentage of unimpaired flow, has declined over time.

The percentage of unimpaired flow that actually flowed into the Delta from the San Joaquin River has declined significantly since the 1930s (regression, $p<0.05$). Inflows before most of the major dams were completed (the pre-dam period, 1930-1943) were significantly higher, 60% of unimpaired, than those measured since 1970, which have averaged 44% (t-test, $p<0.01$).

The contribution of the San Joaquin River to total Delta inflow has been reduced.

Compared to unimpaired flow conditions, the fractional contribution of the San Joaquin River to total Delta inflow has been reduced by an average of 41% (1930-2018).[13] For the most recent ten-year period, 2009-2018, San Joaquin River's contributions to total Delta inflow were reduced by an average of 51%; in 2018, the San Joaquin River's contribution to total Delta inflow was just 12%, 47% lower than it would have been under unimpaired conditions.

San Joaquin River diversions constitute the majority of Sacramento-San Joaquin watershed runoff that is diverted before reaching the Delta.

Since 1980, an average of 3.3 (±2.1 SD) million acre feet of freshwater inflow was diverted from the San Joaquin River each year before it reached the Delta. Even though runoff from the San Joaquin River Basin is less than a quarter to the total runoff from the Sacramento-San Joaquin watershed, diversions from the San Joaquin River constitute 51% of the reduction in Delta inflow and 30% of the total reduction in freshwater inflow to the Bay.

Based on San Joaquin River inflows to the Delta, CCMP goals to increase fresh water availability to the estuary have not been met.

Since 1990, freshwater inflows to the Delta from the San Joaquin River have not been "good," meeting or exceeding conditions considered to satisfy CCMP goals, in any year (0 of 29 years). Current San Joaquin River inflows to the Delta, which have averaged 40% since 1990, are much lower than the 80% level recommended by Richter et al. (2011) to maintain ecological integrity and, with the exception of few years (1997, 1998, 2006, and 2007), well below the 60% of unimpaired level identified by the SWRCB as necessary to protect public trust resources and estuarine health (SWRCB 2010). Since 1990, San Joaquin River inflows have been "very poor"

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[13] Change in the proportional contribution of the San Joaquin River to total Delta inflow as calculated as:

$$\text{SJR Inflow indicator} = \frac{\{[(\text{SJR-in as \%D-in})-(\text{unimp. SJR-in as \%unimp. D-in})]\}}{(\text{unimp. SJR-in as\%unimp. D-in})} \times 100$$

where SJR-in as %D-in is the percent contribution of total annual actual SJR inflow to total annual actual Delta inflow, and Unimp. SJR as %unimp. D-in is the percent contribution of total annual unimpaired SJR inflow to total annual unimpaired Delta inflow. The San Joaquin River's proportional contribution to Delta inflow is highly correlated to San Joaquin River inflow expressed as percent of unimpaired ($p<0.001$, Pearson product moment correlation coefficient=0.953).

in 20 of 29 years (69% of years), below 40% of unimpaired in 16 years (55%) and below 30% in 8 years (28%).

D. Annual Bay Inflow

1. Rationale

Fresh water that flows out of the Delta, the upstream region of the estuary, provides >90% of the total freshwater inflow to the San Francisco Bay. As it enters the Bay, inflowing fresh water mixes with salt water from the Pacific Ocean and lower Bay, creating brackish water[14] habitat that is a key characteristic of estuaries, and the amounts, timing and seasonal and inter-annual variability of inflows function as physical and ecological drivers that stimulate productivity, reproduction and movement (Jassby et al. 1995; Kimmerer 2002; 2004 Feyrer et al. 2008; Moyle et al., 2010). In the Bay's Sacramento-San Joaquin watershed, annual runoff varies substantially for year-to-year, but during the past century, freshwater inflows into the Delta and the Bay downstream have been greatly altered by upstream dams and water diversions. Nine of the ten largest rivers in the Sacramento-San Joaquin watershed have large storage dams, where runoff is captured, stored and diverted. Additional water diversions are located along the rivers downstream of the dams and, in the Delta where the rivers flow into the estuary, local, state and federal water diversions extract more water for local and distant urban and agricultural use. The resultant changes in the amount of freshwater flow that actually reaches the Bay have affected the estuarine ecosystem and the plants and animals that depend on it.

2. Methods and Calculations

The Annual Bay Inflow[15] indicator measures the amount of fresh water from the Sacramento-San Joaquin watershed that flows into San Francisco Bay from the Delta each year compared to the amount that would have flowed into the Bay under unimpaired conditions. Capture and storage of watershed runoff for release in subsequent years and diversion of water from the estuary's tributary rivers and the Delta reduces annual Bay inflow; release of water captured and stored in watershed reservoirs in previous years and imports of water from the Trinity River watershed increase annual Bay inflow.

The indicator was calculated for each year (1930-2018) using data for total annual actual freshwater inflow and estimated total annual unimpaired inflow as:

Annual Bay Inflow (% of unimpaired)
= (actual annual Bay inflow/unimpaired annual Bay inflow) x 100

3. Reference Conditions

The primary reference condition for the Annual Bay Inflow indicator was established as 75%, a level based on the SWRCB's recommendation for freshwater inflows (or Delta outflows) needed to support public trust resources in the estuary. This level also corresponds to an average annual

[14] Brackish water is defined as water that has more salinity than fresh water, but not as much as seawater.
[15] Bay inflow is measured and frequently expressed as Delta outflow, or net Delta outflow.

in-Delta flow depletion of 2.4 million acre-feet (approximately 10% of unimpaired Delta inflow) a level that is more than twice the amount of unimpaired in-Delta depletion.[16] Annual inflows that were greater than 75% of unimpaired inflows were considered to reflect "good" conditions and meet the CCMP goals; annual inflows that were less than 50% of unimpaired inflows were considered to correspond to "very poor" conditions. The other reference condition levels were based on equal increments between these two levels. Table 4 below shows the quantitative reference conditions that were used to evaluate the results of the Annual Bay Inflow indicator.

Table 4. Quantitative reference conditions and associated interpretations for results of the Annual Bay Inflow indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Annual Bay Inflow		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>87.5% of unimpaired	"Excellent," minimal alteration	4
>75% of unimpaired	***"Good," meets CCMP goals***	***3***
>62.5% of unimpaired	"Fair"	2
>50% of unimpaired	"Poor"	1
≤50% of unimpaired	"Very Poor," extreme alteration	0

4. Results

Results of the Annual Bay Inflow indicator are shown in Figure 7.

The amount of fresh water flowing into the San Francisco Bay from the Delta each year has been reduced.

On an annual basis, the percentage of the freshwater runoff from estuary's largest watershed that flows into the Bay has been substantially reduced. For the most recent 10-year period (2009-2018), on average only 50% of unimpaired inflow actually flowed into the Bay, with inflows less than 50% in six of those years. In 2009, a dry year that followed two consecutive very dry years, annual Bay inflow was only 32% of unimpaired, the third lowest percentage of freshwater inflow in the 85-year data record. In 2018, a median year, only 48% of unimpaired inflow reached the Bay.

The proportional alteration in annual freshwater inflow to the Bay differs by water year type.

The greatest alterations to freshwater inflows (expressed as a percentage of estimated unimpaired inflow) occur in drier years. Since the 1970s, the percentages of unimpaired flow that

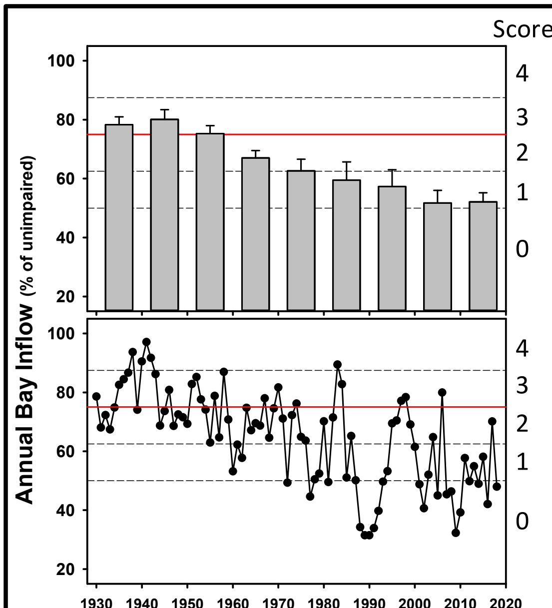

Figure 7. Results for the Annual Bay Inflow indicator, expressed as the percentage of unimpaired flow that actually flowed into the Bay from the Delta for 1930 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

[16] Unimpaired in-Delta depletion was calculated as (unimpaired Delta inflow – unimpaired Delta outflow).

reached the estuary averaged 46% in very dry, 45% in dry years, 50% in median years, 68% in wet years and 71% in very wet years.

Freshwater flow into the Bay, as a percentage of unimpaired flow, has declined over time. The percentage of unimpaired flow that actually flows into the Bay has declined significantly over the past several decades (regression, $p<0.001$). Significant declines in the percentage of unimpaired inflow reaching the Bay have occurred in all water years types (regression, all tests, $p<0.05$). Before construction of most of the major dams on the estuary's tributary rivers (1930-1943, the pre-dam period), an average of 82% of estimated unimpaired flow actually reached the estuary. By the 1980s, the percentage had decreased significantly to just 60% (1980-1989 average; Mann-Whitney, $p<0.01$). The average for the most recent 10-year period, 50%, is somewhat lower but, due to the large inter-annual variability associated with hydrology, not significantly different than flows during the 1980s. Since 1980, an average of 11.1 ($\pm$4.5 SD) million acre feet of freshwater inflow was diverted from either the Sacramento-San Joaquin watershed or Delta before it reached the Bay. Of this amount, reductions in Delta inflow constitute 49% percent of the reduction in Bay inflow and in-Delta diversions 52% percent.

Based on annual inflows, CCMP goals to increase fresh water availability to the estuary have not been met.
Since 1990, freshwater inflows to the Bay were "good," meeting or exceeding conditions considered to satisfy CCMP goals, in just 10% of years (3 of 29 years). Current freshwater inflows to the estuary are well below the 75% level identified by the SWRCB as necessary to protect public trust resources and estuarine health. Current inflows are also somewhat lower than those measured in the 1990s, the period during which the CCMP was developed and established. In 15 of the past 29 years (52% of years), Bay inflows were "very poor," cut by more than 50%.

E. Spring Bay Inflow

1. Rationale

Freshwater inflows to the Bay during the spring provide important spawning and rearing habitat for many estuarine fishes and invertebrates (Jassby et al. 1995; Kimmerer 2002; 2004; see also Estuarine Open Water Habitat indicator in SOTER 2015). For a number of species, population abundance and/or survival are strongly correlated with the amounts of inflow the estuary receives during the spring and the location of low salinity, brackish water habitat, where fresh water from the rivers meets saltwater from the Pacific Ocean. Abundance and/or survival are higher when spring inflows are high and low salinity habitat is located downstream in the estuary compared to years in which it is located further upstream (Jassby et al. 1995; Kimmerer 2002, 2004; Kimmerer et al. 2008).

2. Methods and Calculations

The Spring Inflow indicator measures the amount of fresh water from the Sacramento-San Joaquin watershed that flows into San Francisco Estuary during the spring, February-June, compared to the amount that would have flowed into the estuary during that season under unimpaired conditions. Capture and storage of spring runoff for release later in the year or in subsequent years, and springtime diversion of water from the estuary's tributary rivers and the Delta reduces spring Bay inflows; springtime release of water captured and stored in watershed reservoirs in previous years and imports of water from the Trinity River watershed increase spring Bay inflow.

The indicator was calculated for each year (1930-2018) using data for February-June actual freshwater inflow and estimated spring unimpaired inflow as:

> Spring Inflow (% of unimpaired)
> = (actual Feb-June inflow/unimpaired Feb-June inflow) x 100

3. Reference Conditions

The primary reference condition for the Spring Bay Inflow indicator was established as 75%, a level based on the SWRCB's recommendation for freshwater inflows needed to support public trust resources in the estuary. Spring inflows that were greater than 75% of unimpaired inflows were considered to reflect "good" conditions and meet the CCMP goals; annual inflows that were less than 50% of unimpaired inflows were considered to correspond to "very poor" conditions. The other reference condition levels were based on equal increments between these two levels. Table 5 below shows the quantitative reference conditions that were used to evaluate the results of the Spring Inflow indicator.

Table 5. Quantitative reference conditions and associated interpretations for results of the Spring Bay Inflow indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Spring Bay Inflow		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>87.5% of unimpaired	"Excellent," minimal alteration	4
>75% of unimpaired	***"Good," meets CCMP goals***	***3***
>62.5% of unimpaired	"Fair"	2
>50% of unimpaired	"Poor"	1
≤50% of unimpaired	"Very Poor," extreme alteration	0

4. Results

Results of the Spring Bay Inflow indicator are shown in Figure 8.

The amount of fresh water flowing in the Bay during the spring has been reduced.
The percentage of the springtime runoff from estuary's largest watershed that flows into the Bay has been significantly reduced. For the most recent 10-year period (2009-2018), on average only 44% of unimpaired inflow actually flowed into the estuary. In 2009, spring inflow was only 27% of unimpaired, the seventh lowest percentage of freshwater inflow in the 89-year data record. In 14 of the past 20 years (70% of years), the percentage of unimpaired flow that flowed into the Bay during the spring was less than 50%. In 2018, only 42% of unimpaired inflow reached the estuary.

The proportional alteration in spring inflow to the estuary differs by water year type.
The greatest alterations to springtime freshwater inflows occur in drier and median years. Since the 1970s, the percentages of unimpaired flow that reached the estuary averaged 34% in very dry, 33% in dry years and 43% in median years, all significantly lower than spring inflows in wet years (57%) and very wet years (73%) (ANOVA, p<0.05).

Spring flow into the Bay, as a percentage of unimpaired flow, has declined over time.
The percentage of unimpaired flow that actually flowed into the estuary during the spring has declined significantly over the past several decades (regression, p<0.001). Significant declines in the percentage of unimpaired inflow reaching the estuary have occurred in all water years types (regression, all tests, p<0.05). Before construction of most of the major dams on the estuary's tributary rivers (1930-1943, the pre-dam period), an average of 79% of springtime unimpaired flow actually reached the Bay. By the 1980s, the percentage had decreased significantly to just 49% (1980-1989 average; t-test, p<0.001). The average for the most recent 10-year period, 44%, is somewhat lower but, due to the large inter-annual variability associated with hydrology, not significantly different than flows during the 1980s.

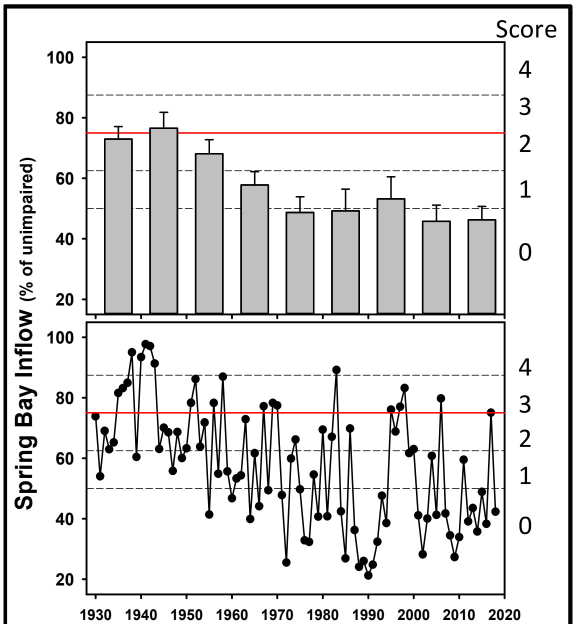

Figure 8. Results for the Spring Bay Inflow indicator, expressed as the percentage of spring (Feb-June) unimpaired flow that actually flowed into the Delta for 1930 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Based on spring inflows, CCMP goals to increase fresh water availability to the estuary have not been met.
Since 1990, springtime freshwater inflows to the Bay were "good," meeting or exceeding conditions considered to satisfy CCMP goals, in just 17% of years (5 of 29 years). Current spring inflows to the Bay are well below the 75% level identified by the SWRCB as necessary to protect public trust resources and estuarine health. In 19 of the past 29 years (66%), spring inflows to the Bay have been "very poor", cut by more than 50%. Recent inflows are also lower than those measured in the 1990s, which averaged 53%.

F. Delta Diversions

1. Rationale

The Delta, now a complex network of interconnected river channels, sloughs, canals and islands, has been a site for water diversion for more than a century (CDWR 1995). The first Delta diverters were farmers irrigating the rich island soils and small local communities like Antioch.

Today, there are more than 2,200 of these agricultural and local urban water diversions scattered throughout the Delta's 1152-square mile area. Beginning in the 1950s, the Delta also became the main "switching station" for much of California's managed water supply. Two giant pumping facilities located in the southern Delta—the Central Valley Project (CVP) operated by the U.S. Bureau of Reclamation and the State Water Project (SWP) operated by the California Department of Water Resources—divert and export large amounts of water into man-made canals for delivery to the San Francisco Bay area, San Joaquin Valley and Southern California. Removal of water from Delta channels at a pipe or diversion canal can alter flow patterns and kill fish and other small animals trapped in the diverted water, particularly if the diversion rate is high relative to flow in the channel (Kimmerer 2008).

2. Methods and Calculations

The Delta Diversions indicator measures the amount of water that is diverted from the Delta diversions as the percentage of total Delta inflow for each year (1930-2018). Diversion of water from Delta channels reduces the amount of fresh water that flows into the Bay and can alter flow velocity and direction in Delta channels.

The indicator was calculated for each year using data for actual annual Delta inflow and actual annual Delta outflow (or Bay inflow) as:

Delta Diversions indicator
= [(actual Delta inflow – actual Delta outflow)/actual Delta inflow] x 100.

3. Reference Conditions

The primary reference condition for the Delta Diversions indicator was established as 13%. This level corresponds to the amount of in-Delta diversions that would result in Bay inflows that met or exceeded the primary reference condition for the Annual Bay Inflow indicator, 75% of unimpaired, when the primary reference condition for the Annual Delta Inflow indicator, 80% of unimpaired, was met or exceeded. This level is also more than double the average unimpaired in-Delta depletion rate (4%),[16] the average pre-dam in-Delta diversion rates (5% for the 1930-1943 period) and average pre-export pumping facilities period (6% for 1930-1958 period). In-Delta diversions that were less than 13% of actual annual Delta inflow were considered to reflect "good" conditions and meet the CCMP goals; annual diversions that were three times greater than this level, 39%, and more than six times greater than pre-export pumping facility in-Delta depletion rates and which would approach current regulatory standards limiting state and federal pumping facility exports to protect fish and wildlife (SWRCB 2006) in most years were considered to correspond to "very poor" conditions. The intermediate reference condition ("fair") was based on equal increments between these two levels and the upper ("excellent") reference condition was based on the average pre-export pumping facilities level. Table 6 below shows the quantitative reference conditions that were used to evaluate the results of the Delta Diversions indicator.

Table 6. Quantitative reference conditions and associated interpretations for results of the Delta Diversions indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Delta Diversions		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
<6% of Delta inflow	"Excellent," minimal alteration	4
<13% of Delta inflow	***"Good," meets CCMP goals***	***3***
<26% of Delta inflow	"Fair"	2
<39% of Delta inflow	"Poor"	1
≥39% of Delta inflow	"Very Poor," extreme alteration	0

4. Results

Results of the Delta Diversions indicator are shown in Figure 9.

A large percentage of the fresh water that flows into the Delta is diverted.
The amount of fresh water diverted from the Delta, expressed as a percentage of annual Delta inflow, exceeded 39% of Delta inflow in 16 of the last 40 years (40% of years). The highest proportional diversion rates occurred during droughts in the 1970s, 1980-1990s, and 2000s, exceeding 50% of inflow diverted in several years and a record 65% of inflow diverted in 1990. During the past ten years, Delta diversion rates have averaged 33% and, in 2018, 37% of total Delta inflow was diverted and did not flow into the Bay.

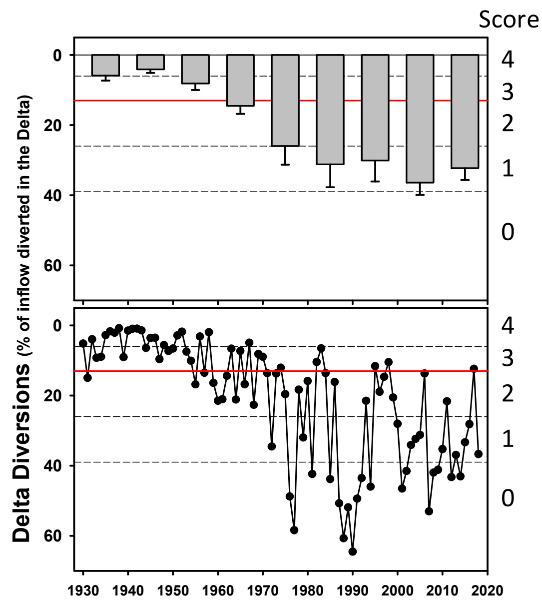

Figure 9. Results for the Delta Diversions indicator, expressed as the percentage of Delta inflow that is diverted in the Delta for 1930 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

The percentage of Delta inflow that is diverted in the Delta differs with water year type.
Since 1970, when both the state and federal export facilities were operational, the percentage of Delta inflow diverted from the Delta has been consistently higher in drier years compared to wetter years (ANOVA, $p<0.05$ for all comparisons except wet v very wet year types). The highest proportional diversions occur in very dry years, averaging 49%. Diversion rates are progressively lower with wetter years, averaging 42%, 34%, 18% and 13% for dry, median, wet and very wet years respectively.

The percentage of Delta inflow diverted from the Delta has increased over time.
The percentage of inflow diverted from the Delta has increased significantly during the past eight decades (regression, $p<0.001$) and since the 1970s, when both state and federal export facilities became operational (Mann Whitney, 1930-1969 v 1970-2014, $p<0.001$). Significant increases in Delta diversion rates occurred in all water year types (regression, all tests, $p<0.001$). Before

construction of most of the major dams on the Delta's tributary rivers (1930-1943, the pre-dam period), an average of 5% of Delta inflow was diverted in the Delta. Not until the federal and then the state export facilities became operational in the 1950s and 1960s did Delta diversion rates begin to increase substantially.

Based on Delta diversion rates, CCMP goals to increase fresh water availability to the estuary have not been met.

Since 1990, Delta diversion rates were "good," meeting or exceeding conditions considered to satisfy CCMP goals, in just 10% of years (3 of 29 years). Current Delta diversion rates, combined with upstream diversions that reduce Delta inflow, reduce freshwater inflows to the Bay to well below the 75% of unimpaired level identified by the SWRCB as necessary to protect public trust resources and estuarine health. Since the 1990s, Delta diversion rates have been higher than 39%, corresponding to "very poor" conditions in increased, reducing freshwater availability to the estuary rather than increasing it; in 11 of the past 29 years (38% of years).

G. Inter-annual Variation in Inflow

1. Rationale

Runoff from the Sacramento-San Joaquin watershed, which provides >90% of the total freshwater inflow to the San Francisco Estuary, varies dramatically from year to year, a function of California's temperate climate and unpredictable occurrence of droughts and floods. Just as the amount of freshwater inflow into an estuary is a physical and ecological driver that defines the quality and quantity of estuarine habitat (Jassby et al. 1995; Kimmerer 2002, 2004), the inter-annual variability of freshwater inflows, a key feature of estuaries, drives spatial and temporal variability in the ecosystem and creates the dynamic habitat conditions upon which native fish and invertebrate species depend (Moyle et al. 2010).

2. Methods and Calculations

The Inter-annual Variation in Inflow indicator measures the ratio, expressed as a percentage, of the inter-annual variation in actual annual inflow to Bay (or Delta outflow) and that of unimpaired annual Bay inflow for the same period. For the two annual inflow measures, variation was measured as the standard deviation (expressed in units of thousands of acre-feet, TAF) for prior ten-year period that ended in the measured year.[17] Reductions in inflows from upstream and in-Delta diversions, particularly in median and wetter years, reduce the differences between annual inflow amounts in very wet years and dry years, making successive years more similar to each other in annual inflow amounts.

[17] Inter-annual variation in inflow was not measured using the coefficient of variation (i.e., SD/mean) because, for comparisons of actual to unimpaired inflows, both the mean (of monthly inflow levels) and the variation around the mean (SD of monthly inflows) change.

The indicator was calculated for each year (1939-2018) using actual annual Bay inflow (or Delta outflow) and unimpaired annual Bay inflow as:

Inter-annual Variation in Inflow (% of unimpaired)
= [(SD actual Bay inflow for year$_{(0\text{ to }-9)}$)/(SD unimpaired Bay inflow for year$_{(0\text{ to }-9)}$)] x 100.

3. Reference Conditions

The primary reference condition for the Inter-annual Variation in Inflow indicator was established by calculating the difference in inter-annual variation of unimpaired annual Bay inflows and calculated unimpaired inflows that had been reduced by 25%, the level of inflow reduction used for the primary reference condition for the Annual Bay Inflow indicator, for the same period. Based on this calculation, the reference condition was set at 75%. Levels that were greater than this were considered to reflect "good" conditions and meet the CCMP goals; levels that were less than 50%, more than double the reduction in inter-annual variability compared the primary reference condition, were considered to correspond to "very poor" conditions. The other reference condition levels were established based on equal increments of values based from these two levels. Table 7 below shows the quantitative reference conditions that were used to evaluate the results of the Inter-annual Variation in Inflow indicator.

Table 7. Quantitative reference conditions and associated interpretations for results of the Inter-annual Variation in Inflow indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Inter-annual Variation in Inflow		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
> 87.5%	"Excellent," minimal alteration	4
> 75%	***"Good," meets CCMP goals***	***3***
> 62.5%	"Fair"	2
> 50%	"Poor"	1
≤ 50%	"Very Poor," extreme alteration	0

4. Results

Results of the Inter-annual Variation in Inflow indicator are show in Figures 10 and 11.

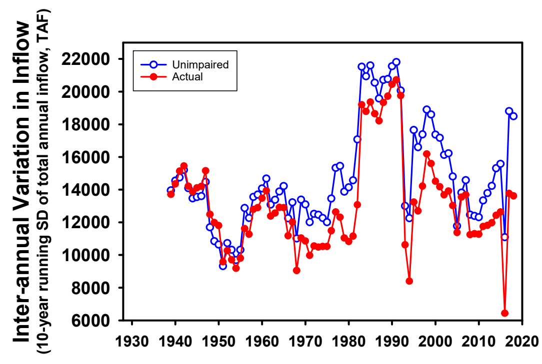

Figure 10. Inter-annual variation in actual and unimpaired freshwater inflows to the Bay for 1939-2018. Each point is the standard deviation for running 10-year periods ending in that year.

Inter-annual variability in inflows to the San Francisco Bay has varied substantially over time. The magnitude of inter-annual variability of unimpaired and actual freshwater inflows to the San Francisco Bay is itself highly variable, reflecting unpredictable periodic differences in total annual flows that can vary by an order of magnitude (i.e., high inter-annual variation and large standard deviation) as well as periodic sequences of years with relatively similar annual flows (i.e., low inter-annual variation and low small standard deviation) (Figure 10). Beginning in the early 1980s, the unimpaired annual inflows became substantially more variable (1980-2004 average variability: 18,038 TAF) than annual unimpaired inflows during the earlier 40 years (1939-1979 average variability: 12,908 TAF). For the most recent decade, inter-annual variability levels have declined to level to levels comparable to the earlier period (2009-2018 average variability: 14,533 TAF), with large spikes in variability reflecting first a sequence of consistently dry years (i.e., low variability) and then a very wet year in 2017, which increased variability. Inter-annual variation in actual annual flows showed a similar pattern (1939-1980 average: 12,082 TAF; 1980-2004 average: 15,579 TAF; and 2009-2018 average: 11,696 TAF).

Inter-annual variability in inflows to the San Francisco Bay has been reduced. Inter-annual variability has decreased significantly during the past eight decades (regression, p<0.001). For the 1939-1967 period (the first 25 years of record), prior to completion of most of the large dams in the watershed, the inter-annual variability of Bay inflows was essentially the same as for unimpaired inflows during the period, averaging 99% of unimpaired inter-annual variability. In contrast, the inter-annual variability of Bay inflows for the most recent 25 years, 1994-2018, is significantly lower than that of unimpaired inflows, averaging just 83% (t-test, p<0.001). The greatest reductions in inter-annual variation in Bay inflows occurred in the mid-1990s and the last several years (2015-2018), following prolonged droughts when actual Bay inflows were reduced to record low levels (see Annual Bay Inflow indicator). In 2018, inter-annual variation in the most recent 10 years of Bay inflows was 74% of unimpaired inter-annual variation for that period.

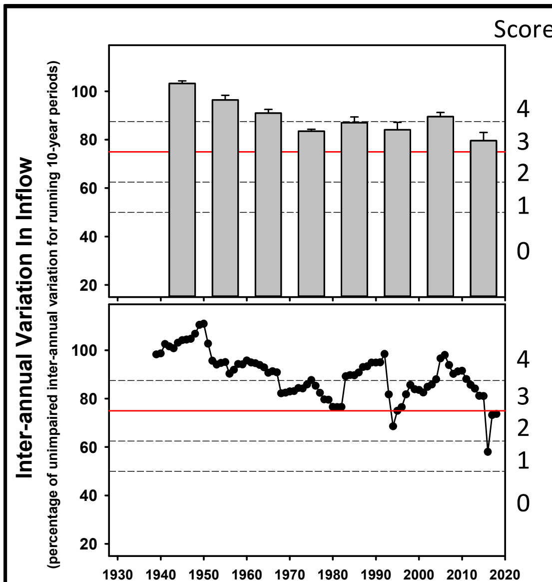

Figure 11. Results for the Inter-annual Variation in Inflow indicator, expressed as the percentage of unimpaired inter-annual variation of Bay inflows (calculated as the ratio of 10-year SD for actual inflow to the 10-year running SD for unimpaired inflows) for 1939 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Based on recent inter-annual variation of inflows to the estuary, CCMP goals to increase freshwater availability to the estuary and restore healthy estuarine habitat and function have been fully met.

Since 1990, inter-annual variation in freshwater inflows to the Bay was "good," meeting or exceeding conditions considered to satisfy CCMP goals in all but five years, 83% of years (24 of 29 years). However, the recent period also saw the greatest reductions in inter-annual variability measured during the past 89 years and, since the mid-2000s, inter-annual variation in Bay inflows has been declining. Inter-annual inflow conditions in the three most recent years were the lowest (2016), 3rd lowest (2017) and 4th lowest (2018) for the 89-year hydrological record.

H. Seasonal Variation in Inflow

1. Rationale

Freshwater inflow to the San Francisco Bay varies dramatically within the year, reflecting both California's Mediterranean climate with its wet and dry seasons as well as the high elevations in estuary's Sacramento-San Joaquin watershed in which large proportions of precipitation fall as snow that melts and runs off to the rivers later in the spring and early summer (see Figure 2). These seasonal variations in inflow create different kinds of habitat, for example, seasonal high inflows create large areas of low salinity open water habitat in the estuary (Kimmerer 2002, 2004; Moyle et al. 2010). They drive important ecological processes such as flooding, which transports sediment, nutrients and organisms downstream and promotes mixing and circulation of estuary waters. And they trigger and facilitate key life history stages of both plants and animals, including reproduction, dispersal and migration.

2. Methods and Calculations

The Seasonal Variation in Inflow indicator measures the ratio, expressed as a percentage, of the seasonal (or intra-annual) variation in actual monthly average inflow to the San Francisco Bay and that of unimpaired monthly inflow for the same year. For the two monthly inflow measures, variation was measured as the standard deviation (expressed in units of cubic feet per second, cfs).[18] The standard deviation of monthly inflows is large in years with large seasonal changes in inflow, such as from a strong springtime snowmelt pulse, and low in years when springtime flows are low compared to summer and fall flows.

The indicator was calculated for each year (1930-2018) using average monthly unimpaired and actual Bay inflow (or Delta outflow) as:

Seasonal Variation in Inflow (% of unimpaired)
= [(SD of actual average monthly Bay inflow)/(SD in unimpaired monthly Bay inflow)] x 100.

3. Reference Conditions

The primary reference condition for the Seasonal Variation in Inflow indicator was established by calculating the difference in seasonal variation of unimpaired monthly Bay inflows and calculated unimpaired monthly inflows that had been reduced by 25%, the level of inflow reduction used for the primary reference condition for the Annual and Spring Bay Inflow indicators, for the same period. Based on this calculation, the reference condition was set at 75%. Levels that were greater than this were considered to reflect "good" conditions and meet the CCMP goals; levels that were less than 50%, more than double the reduction in seasonal variability compared the primary reference condition, were considered to correspond to "very poor" conditions. The other reference condition levels were established based on equal increments of values based from these two levels. Table 8 below shows the quantitative

[18] Seasonal inflow variation was not measured using the coefficient of variation (i.e., SD/mean) because for comparisons of actual to unimpaired inflows both the mean (of monthly inflow levels) and the variation around the mean (SD of monthly inflows) change.

reference conditions that were used to evaluate the results of the Seasonal Variation in Inflow indicator.

Table 8. Quantitative reference conditions and associated interpretations for results of the Seasonal Variation in Inflow indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Seasonal Variation in Inflow		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
> 87.5%	"Excellent," minimal alteration	4
> 75%	***"Good," meets CCMP goals***	***3***
> 62.5%	"Fair"	2
> 50%	"Poor"	1
≤ 50%	"Very Poor," extreme alteration	0

4. Results

Results of the Seasonal Variation in Inflow indicator are show in Figures 12 and 13.

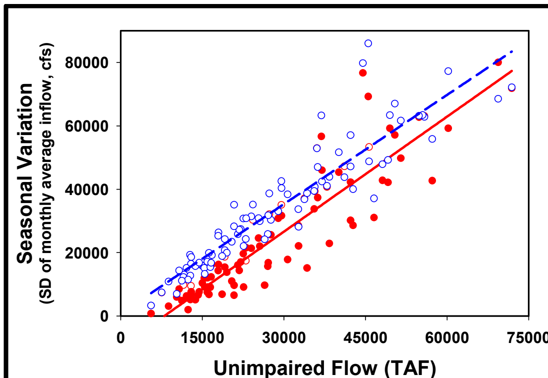

Figure 12. Seasonal variation in Bay inflows (SD of average monthly inflows, cfs, Y axis) is directly related to hydrology, as expressed by unimpaired inflow to the Bay (TAF, X axis). Seasonal variation in unimpaired inflows is shown in open blue circles. Seasonal variation in actual inflows is shown in open red circles (pre-dam period, (1930-1943) and solid red circles (1944-2018).

Seasonal variability in inflows to the San Francisco Estuary is directly related to hydrology.
The magnitude of seasonal variation in unimpaired and actual freshwater inflows to the San Francisco Estuary varies directly with hydrology, as measured by unimpaired inflows: variability is high in very wet years and low in dry years (regression, both tests, $p<0.001$) (Figure 12).

Seasonal variability in inflows to the San Francisco Estuary has been reduced.
Seasonal variability of freshwater inflows to the Bay has declined significantly (regression, $p<0.001$) (Figure 13). The decline began in the mid-1940s, when the first of large storage dams in the estuary's watershed were completed and, since then and until the 2010s, each decade has seen progressive reductions in seasonal variation in Bay inflows. In the pre-dam period (1930-1943), actual seasonal variation in Bay inflows were 90% of seasonal variation of unimpaired inflows; by the 1980s the actual seasonal variation in inflows was significantly lower, averaging 66% of unimpaired seasonal variation (Mann Whitney Rank Sum test, $p<0.05$). Seasonal variation continued to decline, averaging 62% in the 1990s and then just 53% in the 2000s. For the most recent 10 years (2009-2018), seasonal variation was 56%. The greatest reductions in seasonal variation were in 1977 (23%), 1990 (17%) and 2009 (23%), all dry years that followed dry or very dry years. In 2018, a median year that followed a very wet year, seasonal variation in Bay inflow was 47%, less than half of what it would have been in unimpaired conditions.

Changes in seasonal variation in freshwater inflows to the Bay differ by water year type.

Seasonal variation in Bay inflows have significantly declined in all water year types except very wet years (regression, all tests except very wet, p<0.01). The greatest reductions in seasonal variation have occurred dry and very dry years, although large reductions in seasonal variation have occurred in some recent wet years (e.g., seasonal variation was reduced by 61% in 2005, a wet year). Since 1970, compared to unimpaired conditions, seasonal variation in Bay inflows have averaged 41% in very dry years, 37% in dry years, 55% in median years, 77% in wet years and 89% in very wet years.

Based on recent seasonal variations of inflows to the estuary, CCMP goals to increase freshwater availability to the estuary and restore healthy estuarine habitat and function have not been met.

Since 1990, seasonal variability of freshwater inflows to the Bay were "good," meeting or exceeding conditions considered to satisfy CCMP goals, in just 31% of years (9 of 29 years). In 14 of the past 29 years (48% of years), seasonal variability of Bay inflows has been "very poor."

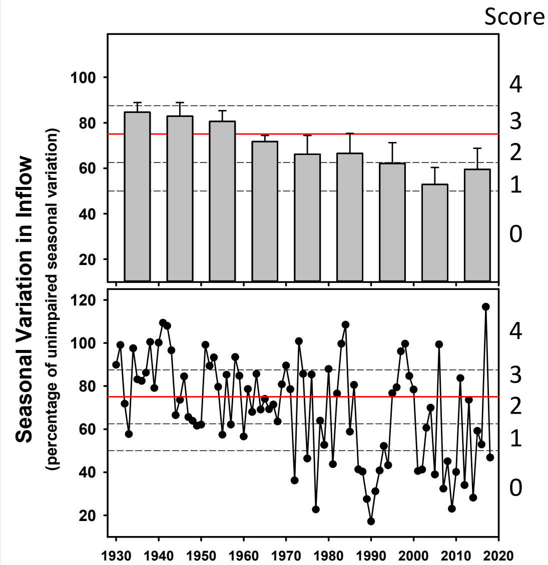

Figure 13. Results for the Seasonal Variation in Inflow indicator, expressed as the percentage of unimpaired seasonal variation of Bay inflows (calculated as the ratio of the SD for actual monthly inflows to the SD for unimpaired monthly inflows) for 1930 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

I. Peak Flow

1. Rationale

High, or "peak", freshwater inflows to the San Francisco Bay occur following winter rainstorms and during the spring snowmelt. High inflows transport sediment and nutrients to the estuary, increase mixing of estuarine waters, and create low salinity habitat in Suisun and San Pablo Bays (the upstream reaches of the estuary), conditions favorable for many estuary-dependent fish and invertebrate species. In rivers and estuaries, peak flows and the flood events they typically produce are also a form of "natural disturbance" (Kimmerer 2002, 2004; Moyle et al., 2010).

2. Methods and Calculations

The Peak Flow indicator measures the frequency, as number of days per year, of peak flows into the San Francisco Bay, compared to the number of days that would be expected based on unimpaired runoff from the estuary's watershed. Peak flow was defined as the 5-day running average of actual freshwater Bay inflow>50,000 cfs. Selection of this threshold value was based on two rationales: 1) flows of this magnitude shift the location of low salinity habitat[19]

[19] The location of low salinity habitat in the San Francisco Estuary is often expressed in terms of X2, the distance in km from the Golden Gate to the 2 ppt isohaline.

downstream to 50-60 km (depending on antecedent conditions), providing favorable conditions for many estuarine invertebrate and fish species; and 2) examination of DAYFLOW data suggested that flows above this threshold corresponded to winter rainfall events, as well as some periods during the more prolonged spring snowmelt. Therefore this indicator evaluated the estuary's responses to a key aspect of seasonal flow variation in its watershed.

The indicator is calculated for each year (1930-2018) using the 5-day running average of actual Bay inflow (or Delta outflow) as:

> Peak flow (days)
> = (# days actual Bay inflow>50,000 cfs) – (# days predicted Bay inflow >50,000 cfs)

Daily unimpaired flow data are available for only a few recent years. Therefore, to predict the number of days of peak flow per year under unimpaired conditions, a polynomial regression was developed based on actual flows from the 1930-1943 pre-dam period, before major storage dams were constructed on the watershed's large rivers (Figure 14). Water Year 1983, the year with the highest annual unimpaired inflow on record and during which flows were minimally affected by water management operations, was also included in this regression analysis to provide a high inflow value and anchor the regression. The regression equation is shown in Figure 14. For years in which the polynomial regression predicted a number of days of peak that was less than zero and in which the actual number of days of peak flows was zero, the indicator value (the difference between actual and predicted) was set to zero.[20]

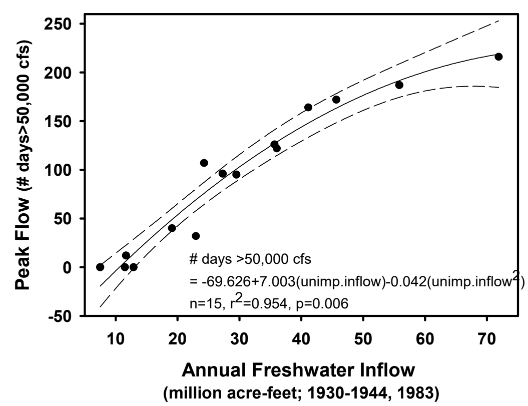

Figure 14. Actual (symbols) and predicted (regression with confidence limits) number of days with peak flow per year in relation to total annual Bay inflow for 1930-1944 and 1983. This relationship was used to establish the reference conditions for the Peak Inflows indicator.

3. Reference Conditions

Reference conditions were established based on the 95% confidence interval for the polynomial regression developed from pre-dam and 1983 data (see Figure 14 above). Over most of the range of annual freshwater inflows, the maximum value for the 95% confidence interval for predicted days of peak flows was 15 days; the primary reference condition was set at twice this value, or -30 days (i.e., 30 fewer days of peak flow compared to the number predicted based on pre-dam inflows). Differences between actual and predicted number of days of peak flow that were less than this (i.e., less negative) were considered to reflect "good" conditions and meet the CCMP goals; reductions in days of peak flows that were more than double this level (or four times greater than the 95% confidence interval) were considered to correspond to "very poor" conditions. The other reference condition levels were established based on equal increments of values based from these two levels, with the upper reference conditions ("excellent") set at -15

[20] This occurred in only four years: 1931, 1976, 1977 and 2014.

days. Table 9 below shows the quantitative reference conditions that were used to evaluate the results of the Peak Flow indicator.

Table 9. Quantitative reference conditions and associated interpretations for results of the Peak Flow indicator. The primary reference condition, which corresponds to “good” conditions, is in bold italics.

Peak Flow		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
> -15 days	“Excellent,” minimal alteration	4
> -30 days	***“Good,” meets CCMP goals***	***3***
> -45 days	“Fair”	2
> -60 days	“Poor”	1
≤ -60 days	“Very Poor,” extreme alteration	0

4. Results

Results of the Peak Flow indicator are shown in Figure 15.

The frequency of peak flows into the San Francisco Bay varies with water year type. Actual peak flow frequency (as number of days per year) is highest in very wet years, when there are of 141 days of peak flow per year on average for the 89-year data record, lowest in very dry years (<2 days/year). Dry years have an average of 12 days/years, median years an average of 45 days/year and wet years an average of 85 days.

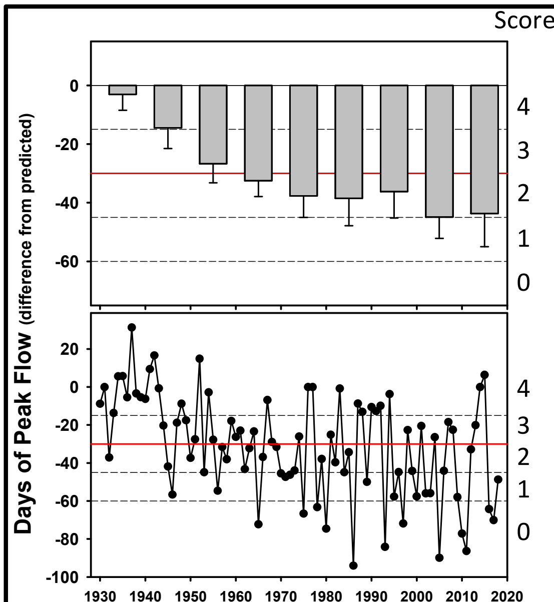

Figure 15. Results for the Peak Flows indicator, expressed as the number of days of peak flow different from predicted for 1930 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Peak flow frequency has declined over time. Peak flow frequency, expressed as the difference between actual peak flow frequency and predicted peak flow frequency under estimated unimpaired flow conditions, is highly variable but has declined significantly over the 89-year period of record (regression, $p<0.001$). The decline began after 1943, immediately following completion of many of the large dams on the estuary’s largest tributaries. Peak flow frequency has significantly declined in all water year types except very dry years (regression, $p<0.05$ all tests, regression for very dry years, $p=0.46$). On average, there are 36 fewer days of peak flows per year since the mid-1940s than during the 1930-1943 period. In the most recent ten-year period (2009-2018), peak flow frequency was reduced by an average of 45 days per year. In 2018, a median year in which 56 days of peak flows were predicted based on total annual Bay inflow, there were just 7 days in which the 5-day average Bay inflow exceeded 50,000 cfs.

Decreases in peak flow frequency differ with water year type.
Since 1944, the largest decreases in peak flow frequency have occurred in wet years, which have 56 fewer days of peak than predicted, a 44% decrease. In very wet years there are an average of 44 fewer days of peak flow in very wet years (25% decrease), 44 fewer days in median years (56% decrease), and 31 fewer days in dry years (76% decrease). Peak flows have been eliminated in most very dry years, cut by 91% to just one day per year, compared to the predicted average of 11 days per year.

Based on recent peak flow frequency, CCMP goals to increase freshwater availability to the estuary and restore healthy estuarine habitat and function have been partially met.
Since 1990, peak flow conditions in the Bay were "good," meeting or exceeding conditions considered to satisfy CCMP goals, in 41% of years (12 of 29 years). However, peak flows were completely eliminated in 7 of 29 years (i.e., 0 days of peak flow in 24% of years) in which they would have occurred based on predictions from estimates of unimpaired conditions from pre-dam inflows.

J. Dry Year Frequency

1. Rationale

California's Mediterranean climate is characterized by unpredictable cycles of droughts and floods. Runoff from the Sacramento-San Joaquin watershed, which provides >90% of the total freshwater inflow to the San Francisco Estuary, can vary dramatically from year to year, and freshwater inflow to the San Francisco Estuary is a key physical and ecological driver that defines the quality and quantity of estuarine habitat (Jassby et al. 1995; Kimmerer 2002, 2004). Water storage and diversions in the estuary's watershed reduce the amounts of fresh water that reach the estuary and can result in inflow conditions comparable to dry hydrological conditions in years when actual hydrological conditions in the watershed are not dry. In dry years, total annual freshwater inflow, seasonal variations in inflow and the quantity and quality of low-salinity estuarine habitat are all reduced, resulting in stressful conditions for native resident and migratory species that rely on the estuary. Multi-year sequences of dry years or droughts, whether the result of hydrological drought or "man-made" drought from water diversion, exacerbate these stressful conditions and often correspond to population declines and shifts and/or decreases in species' distributions.

2. Methods and Calculations

The Dry Year Frequency indicator measures the difference between the frequency of very dry years based on estimated unimpaired freshwater inflows to the estuary (and actual hydrological conditions in the Sacramento-San Joaquin watershed) and the frequency of very dry years experienced by the estuary based on actual annual freshwater Bay inflow amounts. Very dry (VD) years were defined as the driest 20% of years in the 80-year unimpaired Delta outflows dataset (1930-2009), with total annual unimpaired inflows to the estuary of less than 15,000 thousand acre-feet (TAF) (see Table 10).

Table 10. Frequency-based classification of water years based on estimated unimpaired annual San Francisco Bay inflow (Delta outflow) from 1930-2009.

Water Year Type	Unimpaired inflow to the San Francisco Bay (total annual, TAF)	Years (1930-2009)
Very dry (driest 20% of years)	≤15,000 TAF	1931, 1933, 1934, 1939, 1947, 1976, 1977, 1987, 1988, 1990, 1991, 1992, 1994, 2001, 2007, 2008
Dry	>15,000-21,500 TAF	1930, 1944, 1949, 1955, 1957, 1959, 1960, 1961, 1964, 1966, 1968, 1972, 1981, 1985, 1989, 2009
Median	>21,500-29,500 TAF	1932, 1935, 1936, 1937, 1945, 1946, 1948, 1950, 1953, 1954, 1962, 1979, 2000, 2002, 2003, 2004
Wet	>29,500-42,000 TAF	1940, 1942, 1943, 1951, 1963, 1965, 1970, 1971, 1973, 1975, 1980, 1984, 1993, 1996, 1999, 2005
Very Wet (wettest 20% of years)	>42,000 TAF	1938, 1941, 1952, 1956, 1958, 1967, 1969, 1974, 1978, 1982, 1983, 1986, 1995, 1997, 1998, 2006

For the indicator, actual annual freshwater inflows to the Bay for each year were categorized using this water year type classification scale; for example, a year with actual annual Bay inflow of less than 15,000 TAF was categorized as "very dry" even if the unimpaired inflow for that year was higher and placed that year in a different water year category based on its unimpaired inflow. For each year, the number of very dry years (i.e., inflow<15,000 TAF) that occurred for the prior ten-year period that ended in the measured year was calculated for both unimpaired flows and actual flows.

The indicator was calculated for each year (1939-2018) as the difference between the number of very dry (VD) years that occurred under unimpaired conditions and the number that occurred in actual conditions as:

Dry Year Frequency
= (# VD years, actual Bay inflow <15,000 TAF for year$_{(0\text{ to }-9)}$) – (# VD years, unimpaired Bay inflow <15,000 TAF for year$_{(0\text{ to }-9)}$)

3. Reference Conditions

The reference condition for the Dry Year Frequency indicator was established by calculating the average difference between very dry year frequency in unimpaired Bay inflows and for unimpaired Bay inflows that had been reduced by 15-25% (depending on water year type).[21] The results of this analysis showed that reductions in unimpaired Bay inflows at the level specified increased the frequency of very dry years by 1.5 years. Therefore, the primary reference condition was set at 2 years. Differences in the numbers of very dry years between 10-year sequences of actual and unimpaired flows that were 2 years or less were considered to reflect "good" conditions and meet the CCMP goals; differences in the numbers of very dry years between 10-year sequences of actual and unimpaired flows that were more than double this level were considered to correspond to "very poor" conditions. The other reference condition levels were established based on equal increments of values based from these two levels. Table

[21] For calculation of the reference condition, unimpaired inflows<29,500 TAF (60% of years) were reduced by 25%, unimpaired inflows between 29,500 and 42,000 TAF were reduced 20%, and unimpaired inflows >42,000 TAF were reduced by 15%.

11 below shows the quantitative reference conditions that were used to evaluate the results of the Dry Year Frequency indicator.

Table 11. Quantitative reference conditions and associated interpretations for results of the Dry Year Frequency indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Dry Year Frequency		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
<u><</u>1 additional year of VD conditions	"Excellent," minimal alteration	4
<u><</u>**2** additional years of VD conditions	***"Good," meets CCMP goals***	***3***
<u><</u>3 additional years of VD conditions	"Fair"	2
<u><</u>4 additional years of VD conditions	"Poor"	1
>5 additional years of VD conditions	"Very Poor," extreme alteration	0

4. Results

Results of the Dry Year Frequency indicator are shown in Figures 16 and 17.

***The frequency of very dry inflows to the San Francisco Estuary has varied over time*.**
While the classification of very dry (VD) year inflows is based on the bottom quintile from the 80-year unimpaired dataset, the frequency of very dry hydrological conditions (i.e., hydrological conditions that result in VD unimpaired freshwater inflow to the estuary) has been more variable over that period (Figure 16, upper panel). The number of VD years per 10-year period for unimpaired conditions ranged from zero, during the 1950s and 1960s, to as high as six out of ten years, during the late 1980s and early 1990s. For actual conditions, which were affected by the amounts of water stored and diverted from the estuary's watershed, the frequency of freshwater inflows in amounts comparable to what the estuary would experience in VD years under unimpaired conditions, was higher (Figure 16, bottom panel, and Figure17). The largest increases in VD year frequency occurred in the 1960s, a period during which there were no VD years based on hydrological conditions in the

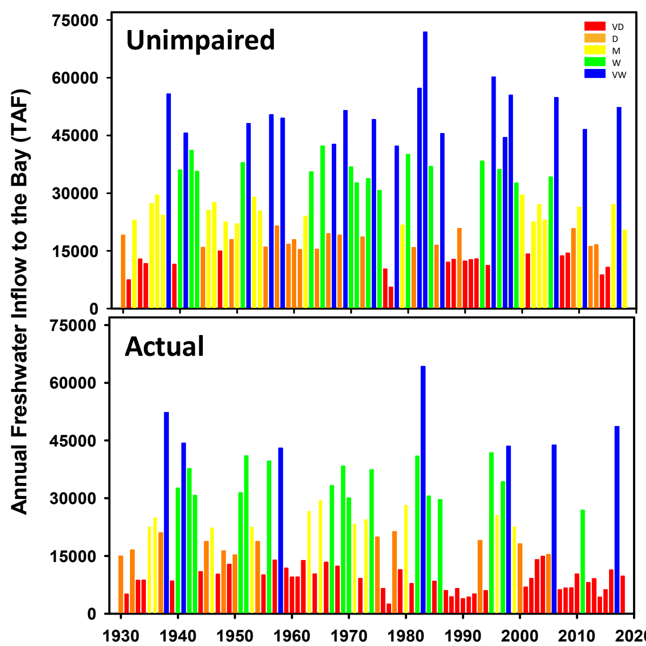

Figure 16. Freshwater inflow to the San Francisco Bay under unimpaired conditions (top panel) and actual conditions (bottom panel) for 1930-2018. Each histogram bar has been colored to the show the water year type, for example, red for critically dry years with inflows<15,000 TAF and blue for wet years with inflows >42,000 TAF. Water year type is based on frequency for unimpaired inflows and actual annual inflow amounts for actual inflows. See text for more details.

estuary's watershed, but during which the estuary received freshwater inflows comparable to VD conditions in an average of six out of 10 years. In the 1980s, an average of 1.8 years were very dry in the watershed but in the estuary an average of 4.4 years were very dry (i.e., there were an average of 2.6 more VD years out of 10 years than there were based on hydrological conditions in the estuary's watershed). Conditions during the most recent decade (2009-2018) were worse, with an average of 7.6 VD years out of 10 years for the estuary, 4.8 more years of very dry conditions than the average 2.8 VD years based on unimpaired conditions in the estuary's watershed. In 2018 (as well as for 2015 and 2017), the Bay had experienced critically low inflows in eight of the past 10 years (80% of years), a level of chronic, man-made drought conditions that had persisted since the late 2000s. Two years earlier, in 2016, the Bay had experienced a decade in which 90% of years were very dry.

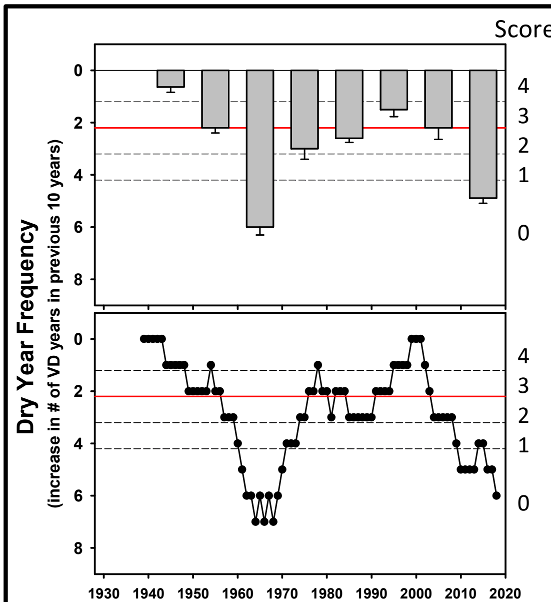

Figure 17. Results for the Dry Year Frequency indicator, expressed as the increase in the number of years of very dry actual inflow conditions (inflows<15,000 TAF) during the immediate past 10-year period, compared to the number of very dry years during that period under unimpaired conditions, for 1939 to 2018 (left Y axis) and indicator score (right Y axis). The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

The frequency of freshwater inflow conditions in the San Francisco Estuary that are comparable to very dry years has increased.

Since 1944, when major dams on the estuary's tributary rivers were completed, the frequency of freshwater inflow conditions that correspond to VD years has increased significantly (Wilcoxon Signed Rank test, $p<0.001$) (Figure 16). On average, the estuary experienced 3 more VD years per 10-year period than it would have based on estimated unimpaired inflows and actual hydrological conditions in its largest watershed. On the basis of actual freshwater inflows, the estuary is experiencing chronic, man-made drought conditions, particularly during the 1960s, 2000s, and 2010s, when conditions in the estuary's watershed were not chronically dry.

Based on recent very dry year frequencies in the estuary, CCMP goals to increase freshwater availability to the estuary and restore healthy estuarine habitat and function have been partially met.

Since 1990, dry year frequency conditions in the Bay were "good," meeting or exceeding conditions considered to satisfy CCMP goals, in 45% of years (13 of 29 years). However, all of these years occurred during the 1990s and early 2000s and reflected a sequence of several consecutive extremely dry years followed by several consecutive extremely very wet years. Since the early 2000s, when hydrological conditions were more moderate, the frequency of man-made drought conditions has increased. The CCMP goal has not been met in any of the past 15 years and, in the past decade, the Bay has experienced very dry inflow conditions in more than 80% of years.

V. Freshwater Inflow Index

The Freshwater Inflow Index combines the results of the ten indicators into a single number to measure the aggregate degree of alteration to the freshwater inflows to the San Francisco Bay Estuary.

A. Index Calculation

For each year, the Freshwater Inflow Index was calculated by averaging the quantitative scores of the ten indicators. Each indicator is weighted equally. For any single year, an index score that was between 2.5 and 3.5 was interpreted to represent "good" conditions in which, collectively (or an average), the different aspects of freshwater inflow conditions met the CCMP goals.

B. Results

Results of the Freshwater Inflow Index are shown in Figures 18, 19 and 20.

Freshwater inflows to the San Francisco Estuary are highly altered.
All of the ten indicators, which measured different aspects of freshwater inflow conditions, showed alteration in flows compared to estimated unimpaired conditions. Measured collectively using the Freshwater Inflow Index, the degree of flow alteration corresponds to "poor" conditions in most years (53% of years) since the 1970s. Since 1990, 61% of years have been "poor" or "very poor." The four lowest Freshwater Inflow Index values have all occurred in the last decade (2009, 2010, 2016 and 2018), with the record low Index of 0.4 in 2016, a median year that followed a multi-year drought. In 2018, a median year that followed a very wet year, the Index was 0.7, tying 2009 for the third lowest Index during the 80-year data record.

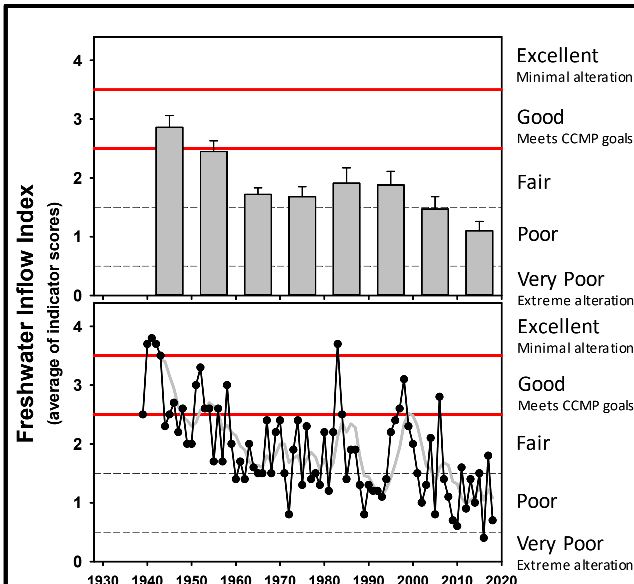

Figure 18. Results for the Freshwater Inflow Index for 1939 to 2018, expressed as the average score of the 10 component indicators. The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year, with the 5-year running average shown as the grey line. The horizontal red lines and dashed lines show the reference conditions and Index evaluation.

Freshwater inflow conditions in the estuary have declined over time.
Freshwater inflow conditions to the estuary have been increasingly altered over time; the Index has declined significantly (regression, $p<0.001$). The decrease in the Index is driven by declines in nine of the ten indicators of freshwater inflow conditions (i.e., all indicators except Annual Delta Inflow). Most of the decline occurred during the 1950s and 1960s, the period after and during which major dams on the majority of the estuary's largest tributary rivers were

completed. The Index fell from an average of 2.9 in the 1940s (1939-1949 average), to 2.4 in the 1950s, and 1.7 in the 1960s. The Index was relatively stable during the 1970s, averaging 1.7, somewhat higher during the 1980s and 1990s, averaging 1.9, before declining again to an average of 1.5 in the 2000s and an average of 1.1 for the most recent nine years. The Index has declined significantly in all water year types (regression, $p<0.01$ for all year types except very wet; very wet years, $p=0.04$) (Figure 19). The lowest Index value, 0.4, occurred in 2016, a median year that immediately followed the 2012-2015 drought. The second lowest Index, 0.6, was in 2010, another median year following drought. With the exception of 2005, most of the other years with Index values below 1.0 were dry (1972, 1989, 2009 and 2012). Water Year 2005, a wet year following a median year, stands out however with an Index of 0.8, indicating that, in recent years, high levels of alteration to freshwater inflows can occur even in wet years. The 2018 Index value, 0.7, in a median year that followed a very year, was also an indication that high levels of flow alteration are now occurring during multi-year sequences of moderate to wet hydrological conditions, was also the same as in 2009 and the third lowest Index in the 80-year period for which it was measured.

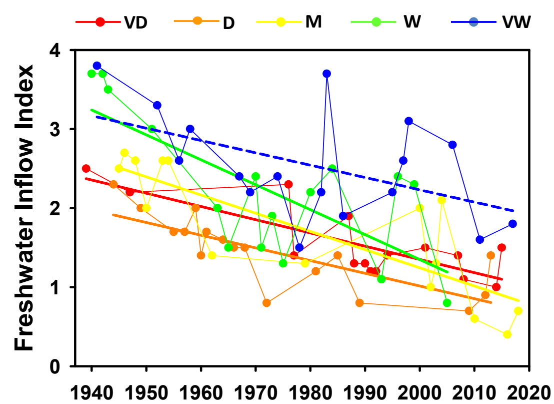

Figure 19. Results for the Freshwater Inflow Index for each water year type, from 1939 to 2018. Each color-coded plot shows the results for individual years (symbols) and the trend over time (connecting lines and regression line). Regressions (heavy solid or dashed lines) are significant for all year types ($p<0.05$).

The Freshwater Inflow Index differs by water year type.

Since 1970, after most of the major dams in the estuaries watershed were completed and the Delta water export facilities became operational, the degree to which freshwater inflow conditions have been altered is significantly greater in dry, median and very dry years, compared to in very wet years and, for dry years, compared to wet years (ANOVA, all tests, $p<0.05$) (Figure 20).

Based on the Freshwater Inflow Index, CCMP goals to increase freshwater availability to the estuary and restore healthy estuarine habitat and function have not been met.

Based on the Freshwater Inflow Index, freshwater inflow conditions in the San Francisco Estuary are rarely “good” (3 of 29 years, or 10% of years since 1990), “fair” in some years (24% of years), and “poor” in most years (62% of years). Degraded inflow conditions reflect severe reductions in the amounts of freshwater inflow in most years, substantial reductions in seasonal variability of inflows, severe reductions in the frequency of peak flows and high frequencies of inflows comparable to very dry conditions, in effect, chronic man-made drought conditions resulting from water management operations in the estuary’s watershed and upstream Delta region.

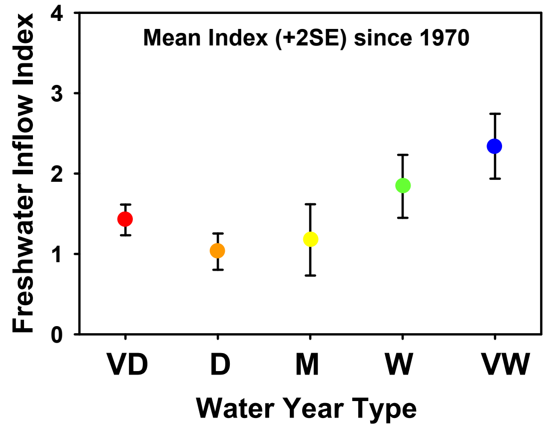

Figure 20. Post-water development (1970-2018) Freshwater Inflow Index for each water year type (mean±2 SE). Dry, Median and Very Dry years had significantly lower Index values than very wet years, and dry years have significantly lower index values that wet years (ANOVA, all tests p<0.05).

C. Summary and Conclusions

Collectively the ten indicators of the Freshwater Inflow Index provide a comprehensive assessment of the status and trends for freshwater inflow conditions to the San Francisco Bay and Sacramento-San Joaquin Delta from it largest watershed. Each of the indicators shows significant alterations to inflows to the estuary, including reductions in the amounts of inflows, reductions in inter-annual and seasonal variability, reduced frequency of peak flows and increased frequency of annual inflows to the estuary that are comparable to the relatively rare very dry hydrological conditions in the watershed. Table 12 summarizes the indicator results relative to the CCMP goals (as they are expressed by the reference conditions).

Table 12. Summary of results for the ten freshwater inflow indicators.

Indicator	**CCMP Goals** Fully met if goal achieved in >67% of years since 1990 Partially met if goal achieved in 33-67% of years Not met if goal achieved in <33% of years	**Trend since 1990**	**Current condition** (average for last 10 years)
Annual Delta Inflow	Partially met; goal achieved in 45% of years	Stable	Fair Inflow reduced by 30%
Spring Delta Inflow	Not met; goal achieved in 10% of years	Mixed but generally deteriorating	Poor Inflow reduced by 46%
San Joaquin River Inflow	Not met; goal achieved in 0% of years	Stable	Very poor Inflow reduced by 65%
Annual Bay Inflow	Not met: goal achieved in 10% of years	Mixed but generally deteriorating	Poor Inflow reduced by 50%
Spring Bay Inflow	Not met; goal achieved in 17% of years	Mixed but generally deteriorating	Very poor Inflow reduced by 56%
Delta Diversions	Not met; goal achieved in 10% of years	Mixed but generally stable	Poor 33% of inflow diverted
Inter-annual Variation in Inflow	Fully met; goal achieved in 83% of years	Stable	Good Reduced by 19%
Seasonal Variation in Inflow	Not met; goal achieved in 31% of years	Highly variable but stable	Poor Reduced by 44%
Peak Flow	Partially met; goal achieved in 41% of years	Highly variable but stable	Fair Reduced by 45 days/year
Dry Year Frequency	Partially met: goal achieved in 45% of years	Significant decline (regression, $p<0.001$)	Very poor Flow reductions triple dry year frequency
Freshwater Inflow Index	**Not met; goal achieved in 10% of years**	**Decline (regression, $p=0.053$)**	**Poor** **Only 1 of 10 indicators show “good” conditions**

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State of the San Francisco Estuary 2019

Technical Appendix

Tidal Marsh Indicator

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Background and Rationale

Tidal marshes—including those found in the San Francisco Bay-Delta Estuary (the "Estuary")—provide a wide array of ecosystem services. They provide habitat and support food webs for wildlife, stabilize shorelines and protect them from storm damage, store floodwaters and maintain water quality, preserve biodiversity, store carbon, and offer opportunities for scientific study, education, recreation, and aesthetic appreciation (Costanza et al. 1997, Peterson et al. 2008, Palaima 2012, Zedler 2012).

Although tidal marshes have a wide array of functions, this study focuses on an indicator that evaluates the Estuary's tidal marshes for their function as habitat for native wildlife. Specifically, the regional extent indicator seeks to help broadly assess the status of tidal marshes in the Estuary for their ability to support the life histories of native tidal marsh wildlife (defined as obligate or transitory plants or animals that occupy tidal marshes). It is worth mentioning, however, that although the focus here is on tidal marshes as habitat for native wildlife, the nature of the indicator means it likely integrates across the other services provided by the Estuary's tidal marshes (the regional extent of tidal marsh is perhaps the most fundamental measurement of tidal marsh habitat). The focus on wildlife support is merited since much, if not most, of the interest and concern about tidal marshes relates to their function as habitat for native fishes, animals, and plants (e.g. BCDC 2008, SFBRWQCB 2010, SFEP 2011, USFWS 2013, SFEI-ASC 2014). Tidal marshes are especially valued for their contribution to the native biological diversity of the San Francisco Estuary. Many of the region's rare and endangered plants and animals rely on tidal wetlands for their survival, and legal mandates to protect these species provide the regulatory framework and funding for a significant portion of tidal marsh restoration activities.

The San Francisco Bay and the Sacramento-San Joaquin Delta are often studied and managed as distinct entities. However, the Bay and Delta function as a unified and complex estuary, which crosses several ecologically significant physical gradients (e.g., in tidal influence, salinity, wave energy, suspended sediment). These physical gradients are manifested in gradients within the Estuary's tidal marsh ecosystems (e.g., in vegetation composition, physical structure, soils types, channel density). When planning for habitat restoration in the Estuary, these gradients are important to consider if we wish to support the full range of ecological functions provided by the estuary's tidal marshes. This analysis seeks to evaluate and inform restoration efforts by considering the Bay and the Delta's tidal marshes side by side in a single document. This said, we do report the status of the tidal marsh habitat indicator separately for the Bay and the Delta (a structure that is reflected throughout this State of the Estuary report). This distinction is driven by a few different considerations, including the following: freshwater and salt marshes are not equivalent (Odum 1988) and the state of the science surrounding each differs greatly within the Estuary; the Bay and Delta have different environmental histories and differences in current environmental stressors; the political realities, regulating authorities, regional goals, and history of restoration are different in the Bay and the Delta; and available data on tidal marsh extent are generally limited to one region or the other. Although the tidal marsh indicator is reported separately for each region, substantial effort was made to integrate the datasets before splitting them, ensuring a "seamless" divide in the analyses of each region.

The tidal marsh regional extent indicator measures the combined area of all tidal marshes in the estuary and is derived from detailed maps of the estuary's wetlands. The importance of tidal marsh extent as an indicator is based on the notion that greatest threat to tidal marsh ecosystems and the species they support is habitat loss (USFWS 2013). Measuring the areal extent of an ecosystem is a simple way to assess its quantitative loss and a critical component of ecosystem conservation (which, in turn, is a complement to species-level conservation; Noss et al. 1995). The regional extent of tidal marsh matters because many of the ecological and hydrological benefits the habitat provides increase along with marsh extent. Put simply, as the total area of tidal marsh in the Estuary increases, so does the abundance and diversity of the plants and animals that utilize marshes. Increasing the regional extent of marsh across the whole Estuary—from the South Bay to the North Delta—will ensure that marsh habitat exists along the full length of important ecological gradients (such as tidal influence, salinity, and vegetation) and provide a range of options for the species that utilize tidal marshes. It is also important to track the regional extent of tidal marsh given the threats posed to tidal marshes by climate change, sea-level rise, and changing sediment supply in the Estuary (e.g., Stralberg et al. 2011).

The tidal marsh regional extent indicator builds on previous work. This indicator relies heavily on the work done for the *Baylands Ecosystem Habitat Goals Project* ("Goals Project"; Goals Project 1999), which assessed changes in the regional extent of bayland habitats, including tidal marsh, between ca. 1800 and ca. 1997. The regional extent of tidal marsh in the Bay was updated for both *The State of San Francisco Bay 2011* (SFEP 2011) and the *Baylands Ecosystem Habitat Goals Science Update* (Goals Project 2015). This indicator also builds on studies analyzing the regional extent of marsh in the Delta over time (Atwater et al. 1979, The Bay Institute 1998, Whipple et al. 2012, SFEI-ASC 2014). Finally, it directly builds on previous releases of State of the Estuary report, particularly the 2011 and 2015 editions (SFEP 2011, 2015).

The analysis of tidal marsh presented in this report differs from the 2015 State of the Estuary report in a few key ways. For this interim 2019 report, only the regional extent indicator has been updated. The Tidal Marsh Patch Size indicator, which evaluated the configuration of tidal marshes in the Estuary, has not been updated for 2019 but is planned to be included in the next full State of the Estuary report. Additionally, the methods and data sources for assessing the regional extent indicator have slightly changed for this interim report and for future reports. Specifically, in 2015, the area of new tidal wetland restoration was retrieved from the Wetland Tracker database. A few months after the release of the 2015 report the current Project Tracker database and data entry forms were released. The old Wetland Tracker and Joint Venture databases were migrated to the new Project Tracker database, allowing us to use this new database to identify recent tidal wetland restoration projects. Delta projects were also added to the Project Tracker database, eliminating the need to use other sources to identify projects in the Delta, as was the case in 2015.

Benchmarks

We utilize separate benchmarks to evaluate the regional extent of tidal marsh in the Bay and in the Delta. **For the Bay, we use a benchmark of 100,000 acres, a long-term tidal marsh acreage goal put forth by the 1999 *Baylands Ecosystem Habitat Goals Report***. This goal was the culmination of science-based public process that sought to evaluate the habitat needs of representative species and to identify changes needed to improve the Bay's ecological functioning and biodiversity. It is approximately half of the tidal marsh area that existed in the Bay at the beginning of the 19th century.

Since no similar quantitative goal exists for tidal marsh regional extent in the Delta, we instead provide three different reference values for context:

(1) *180,000 acres* or approximately half of the tidal marsh area that existed in the Delta at the beginning of the 19th century. Because it equals approximately one half of the historical habitat acreage, this value is comparable to the benchmark used to assess the regional extent of tidal marsh in the Bay. The value was calculated by dividing the total area of tidal freshwater emergent wetland identified by

Whipple et al. (2012) as occurring in the Delta ca. 1800 (364,810 acres) by two and then rounding to the nearest 10,000 acres.

(2) *78,000 acres* or the current area of tidal marsh plus the approximate area of diked lands in the Delta that are at intertidal elevations. This is the current area that would fall between high and low tide in the absence of levees and other water control structures and therefore exists at the right elevation for tidal marsh formation in the Delta. It was calculated by adding the area of diked lands at intertidal elevations in the Delta (70,000 acres) as reported by Siegel (2014) to the ca. 2002 area of tidal marsh reported in this analyses (7,638 acres, see below) and rounding to the nearest 1,000 acres. This value is meant to contextualize the upper bounds of tidal marsh regional extent based on existing elevations alone and does not take into consideration the acreage of land that will be available for tidal marsh restoration given other priority land uses in the region (such as agriculture). As with the other reference values, this value is not presented as a goal or benchmark. This benchmark should be updated in the future using updated and refined data on land surface elevations and tidal datums.

3) 17,000 acres or the current area of tidal marsh plus the maximum amount of tidal marsh habitat that would be restored under the State's current plan for habitat restoration in the Delta (*California Eco Restore*). *California Eco Restore* currently calls for 9,000 acres of tidal and subtidal habitat restoration (California Natural Resources Agency 2015). The 17,000 acre reference value was determined by adding these 9,000 acres to the existing (ca. 2002) area of tidal marsh habitat in the Delta (7,638 acres; see below) and rounding to the nearest 1,000 acres. This calculation assumes that *all* 9,000 acres of proposed tidal and subtidal habitat restoration become tidal marsh (which is not in fact likely). It therefore represents the *maximum* regional extent of tidal marsh habitat that would exist in the Delta after successful implementation of the current iteration of *California Eco Restore*.

Data Sources

GIS data depicting the extent of tidal marshes in the Estuary over time were obtained from multiple regional wetland mapping efforts. These sources described in detail in the 2015 version of this technical appendix (Safran 2015).

Data on recent tidal marsh restoration projects were obtained from the EcoAtlas Habitat Project Tracker and from contributions by expert partners. Tidal wetland restoration projects for both the Bay and the Delta were obtained from Project Tracker for the years 2015 to 2019 (see details in the methods section below).

Methods

<u>Overall approach</u>

The last comprehensive maps of tidal marshes are from the year 2009 in the Bay and the year 2002 in the Delta. To determine the regional extent of tidal marsh in 2015, the authors of the *2015 State of the Estuary Report* started with the most-recent mapped extent and then added the area of wetlands known to have been opened to tidal action since the maps were developed. The area of recent tidal wetland restoration was determined on a project-by-project basis from public databases, reports, and personal correspondence with project managers. Since no new comprehensive maps of tidal wetlands derived from remotely sensed images have been produced for the Bay or Delta since 2015, this report uses the same approach and updates the regional extent of tidal marsh by adding the area of tidal wetland restoration known to have occurred since the 2015 State of the Estuary report was released.

Methods for determining the mapped extent of tidal marshes are detailed in the 2015 State of the Estuary Report Tidal Marsh Technical Appendix (Safran 2015). Detailed methods for how we updated the extent of tidal wetland restoration since the most recent maps of tidal marshes were developed are provided below.

Determining the extent of recent tidal wetland restoration

This interim indicator builds upon the 2015 effort to establish the acreage of tidal wetlands that have been opened to tidal action since 2009 in the Bay and 2002 in the Delta (the years tidal marshes were last comprehensively mapped). To determine the acres of tidal wetlands that have been restored since 2015, the EcoAtlas Habitat Project Tracker was used to generate a list of projects that meet certain baseline criteria before it was filtered down to a final list. Bay and Delta sites were identified by querying projects within the administrative boundary of Regional Board 2 with a planned habitat type of "Estuarine wetlands" and an event type entry of "Groundwork start" or "Groundwork end" since 2015 (if available). Many projects were missing start and end date information so projects were only excluded if the date was provided and it was outside of the timeframe of interest. The resulting list was compared to the 2015 list of projects and then reviewed and edited by local scientists with knowledge of recent/ongoing restoration efforts (Sandra Scoggin and Liz Duffy, SFBJV; Tim Smith, DWR; Jeremy Lowe, SFEI; Christina Toms, SFBRWQCB; and Cristina Grosso, SFEI). The area of tidal wetland restoration for each site was also provided by Project Tracker (see Table 2).

Acreages of recent tidal wetland restoration were then added to the 2015 regional extent totals to determine the updated extent of mapped tidal marsh and recent tidal wetland restoration. It is important to remember that, although the area of recent tidal wetland restoration is included on the chart of tidal marsh regional extent, not all of this area is yet (or will ever become) tidal marsh. A significant portion of the tidal wetland restoration area is expected to develop into tidal marsh over time, but some percentage of the habitat will remain un-vegetated, either unintentionally or by design. As was the case in 2015, this methodology also assumes that the area of existing mapped tidal marshes has not changed since 2009 in the Bay and since 2002 in the Delta, and that the only possible change in tidal marsh extent comes from intertidal wetland restoration. It will therefore be important to track the progress of these sites and update this indicator once new comprehensive maps of vegetated tidal marshes derived from remotely-sensed images become available. New maps will also allow us to account for changes in the regional extent of tidal marsh due to factors other than tidal wetland restoration, including marsh erosion and progradation, which are both known to have occurred in some places since tidal marshes were last comprehensively mapped (e.g., Beagle et al. 2015). In recent years, advances in image storage and processing have allowed analysts to assess changes in the extent of intertidal wetlands over time from regularly-collected imagery. A recent analysis (Murray et al. 2029) by uses archival Landsat photos to map intertidal flats at annual intervals at a relatively fine resolution. In the future, similar methods could conceivably be employed to map tidal marshes, or the annual maps of intertidal flats could be used to create more refined estimates of the area of tidal wetland restoration that has remained unvegetated (and thus shouldn't count towards the regional extent of tidal marsh). Annual maps of this kind would also allow us to identify locations where marshes are expanding vs.

contracting and quantify the relative contribution of these processes to the overall net change in tidal marsh regional extent.

Determining the regional extent indicator status/score

Throughout this report, a three-tiered “Good—Fair—Poor” system is used to assign a qualitative score to the status of each indicator. With few exceptions, the line between “Good” and “Fair” is set at each indicator’s goal/benchmark and another means is used to establish the line between “Fair” and “Poor.” This interim indicator uses the same scoring system as the 2015 report, which is briefly summarized below.

Rules and thresholds for determining the status of the regional extent of tidal marsh in the Bay are shown in Table 1. The line between “good” and “fair” was set at the 100,000 acre benchmark (see the “Benchmarks” section above) and, without any ecologically sound justification for another value, the line between “fair” and “poor” was simply set at half this amount. Since no quantitative benchmarks were developed for determining the regional extent of tidal marsh in the Delta, we did not develop rules and thresholds for determining the status of the indicator in that region. For now, we assigned the Delta a score of “poor” based on the fact that the current regional extent is less than one half the lowest reference values determined in 2015 (see the “Benchmarks” section above for a description of these reference values). The system for scoring this indicator should be reevaluated in future iterations of this report.

Table 1. Rules employed for determining the status of regional extent of tidal marsh in the Bay. No rules were developed for assigning the status of the indicator in the Delta.

Status	Regional extent	Explanation
Good	>100,000 acres	The indicator receives a score of “good” when it exceeds the 100,000 acre regional goal established by the *Goals Project* (1999).
Fair	50,000-100,000 acres	The indicator receives a score of “fair” when it exceeds one-half of the regional goal.
Poor	<50,000 acres	The indicator receives a score of “poor” when it is less than one-half of the regional goal.

Results

Recent tidal wetland restoration

In the Bay, approximately 1,400 acres of land have been restored to tidal action since 2015 (Table 2). The increase since 2015 in tidal habitat was deemed sufficient to merit an “improving” designation for the Bay regional extent indicator. In the Delta, tidal wetland restoration since 2015 has totaled approximately 440 acres (Table 2). Although small, this increase also merits an “improving” designation.

Table 2. Recent tidal wetland restoration. The areas listed below have been opened to tidal action since the 2015 State of the Estuary report. They are are included as “Tidal wetland restoration between 2015 and 2019” in Table 3 and Figure 1 below.

Recent Restoration Sites	Year Opened to Tidal Action	Planned Area of Tidal Wetland Restoration (Acres)
Bay (Tidal Wetland Restoration Since 2015)		
Corte Madera Marsh Ecological Reserve Restoration - Greenbrae Gas Pipeline Emergency Replacement Project	2015	0.27
Sears Point Wetland and Watershed Restoration Project	2015	970
Bair Island Restoration (Inner)	2015	276
Dotson Family Marsh Restoration	2017	150
Corte Madera Ecological Reserve Expansion and Restoration	2018	5
TOTAL (BAY)		**1401**
Delta (Tidal Wetland Restoration Since 2015)		
Yolo Flyway Farms	2018	300
Decker Island	2017	140
TOTAL (DELTA)		**440**

Total regional extent

Tidal marshes were last comprehensively mapped in the Bay in 2009, at which point there were approximately 45,052 acres total. Since that time, approximately 7,747 additional acres of tidal wetlands have been restored, bringing the total area of mapped tidal marshes plus restored tidal wetlands that could transition into tidal marshes in the Bay to 52,799 acres. In the Delta, there were approximately 7,638 acres of tidal marsh mapped in 2002, with approximately 699 additional acres of tidal wetlands restored since, bringing the total area of mapped tidal marsh plus restored tidal wetlands that could transition into tidal marshes in the Delta to 8,337 acres. These results are summarized in Table 3 and Figure 1 below. Estimates of the regional extent of tidal marsh at earlier dates remain unchanged and are summarized in the 2015 version of this appendix (Safran 2015).

Table 3. Extent of tidal marsh and recently restored tidal wetlands that could transition into tidal marsh (acres).

	Bay	Delta	Total (Estuary)
Most-recent mapped extent of tidal marsh (ca. 2009 for Bay; ca. 2002 for Delta)	45,052	7,638	52,690
Tidal wetland restoration between most-recent mapping (ca. 2009 for Bay; ca. 2002 for Delta) and 2015	6,346	259	6,605
Tidal wetland restoration between 2015 and 2019	1,401	440	1,841
Total (mapped tidal marshes plus subsequent tidal wetland restoration as of 2019)	**52,799**	**8,337**	**61,136**

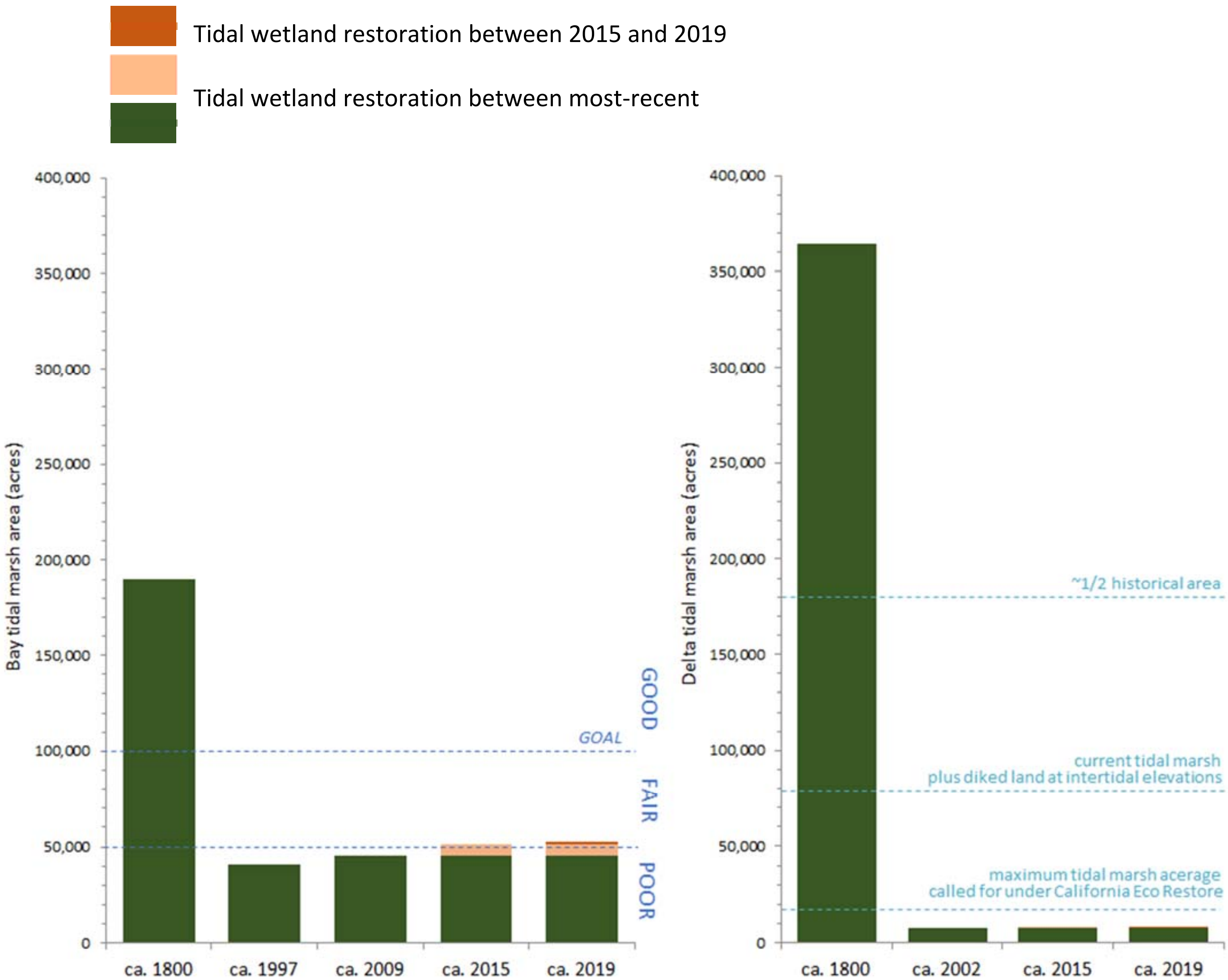

Figure 1. Tidal marsh regional extent in the Bay (left) and Delta (right) over time, including recently restored tidal wetlands that could transition into tidal marsh. Circa 2015 and 2019 extents are calculated by copying the most recent mapped tidal marsh extent (ca. 2009 in the Bay and ca. 2002 in the Delta) and adding the extent of tidal wetland restoration that has occurred since (pink and orange bar segments). Although much of this area is expected to transition into tidal marsh over time, some will remain unvegetated—it is shown to approximate progress since the last comprehensive spatial datasets of tidal marsh extent in the Bay and Delta were developed. Tidal wetland restoration since 2002 in the Delta is included in both the 2015 and 2019 bars, but is essentially too small to be visible at this scale.

Based on the rules described in the methods section, the regional extent of tidal marsh in the Bay is characterized as “fair.” Since it is below 50,000 acres, the ca. 2009 extent of tidal marsh alone qualifies as “poor.” The score of “fair” is based on the ca. 2019 regional extent value (52,799 acres), which combines the mapped area of tidal marsh ca. 2009 with the area of tidal wetland restoration that has occurred since (Table 3), which together exceed the 50,000 acre threshold for “fair” (Table 1). This score is consistent with the ranking of “fair” previously reported for the indicator status in the *State of the Estuary 2015* (SFEP 2015). The regional extent of tidal marsh in the Delta is characterized as “poor,” since, as described in the methods section, the current regional extent is less than one half the lowest reference value utilized in this study. The system for scoring this indicator should be reevaluated in the future once a true benchmark or regional goal is determined.

Peer Review

This work has benefitted from review by Sandra Scoggin and Liz Duffy, SFBJV; Tim Smith, DWR; Jeremy Lowe, SFEI; Christina Toms, SFBRWQCB; and Cristina Grosso, SFEI.

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State of San Francisco Estuary 2019

Technical Appendix

Bay Fish Indicators and Index

Prepared by Christina Swanson
July 2019

I. Background

San Francisco Bay is important habitat for more than 100 fish species, including commercially important Chinook salmon and Pacific herring, popular sport fishes like striped bass and sturgeon, and delicate estuary-dependent species like delta smelt. These fishes variously use the estuary for spawning, nursery and rearing habitat, and as a migration pathway between the Pacific Ocean and the rivers of the estuary's watersheds. Environmental conditions in the estuary—the amounts and timing of freshwater inflows, water temperatures, the extent of rich tidal marsh habitats, and pollution—affect the numbers and types of fish that the Bay can support. Thus, measures of fish abundance, diversity, species composition and distribution are useful biological gauges for environmental conditions in the estuary. A large, diverse fish community that is distributed broadly throughout the Bay and dominated by native species is a good indicator of a healthy estuary.

The Bay Fish Index uses ten indicators to assess the condition of the fish community within the San Francisco Bay. Four of the indicators measure abundance, or "how many?" fish the estuary supports. Two indicators measure the diversity of the fish community, or "how many species?" are found in the Bay. Two indicators measure the species composition of the fish community, or "what kind of fish?" in terms of how many species and how many individual fish are native species rather than introduced non-natives.[1] The final two indicators assess the distribution of fish within the estuary, or "where are the fish?" measuring the percentage of sampling locations where native fishes are found. For each year, the Bay Fish Index is calculated by combining the results of the ten indicators into a single number.

Figure 1. Because the an Francisco Bay is so large and its environmental conditions so different in different areas, the Bay Fish Index and each of its component indicators were calculated separately fro four sub-regions in the estuary: South Bay, Central Bay, San Pablo Bay and Suisun Bay and the western Delta.

Because the estuary is so large and its environmental conditions so different in different areas—for example, Central Bay, near the Golden Gate is essentially a marine environment while Suisun Bay is dominated by freshwater inflows from the Sacramento and San Joaquin Rivers—the types of fishes found in each area differ. Therefore, each of the indicators and the index was calculated separately for four "sub-regions" in the estuary: South Bay, Central Bay, San Pablo Bay and Suisun Bay and the western Delta (Figure 1). For each year and for each sub-region, the Bay Fish Index is calculated by combining the results of the ten indicators into a single number.

[1] Native species are those that have evolved in the Bay and/or adjacent coastal or upstream waters. Non-native species are those that have evolved in other geographically distant systems and have been subsequently transported to the Bay and established self-sustaining populations in the estuary.

II. Data Source

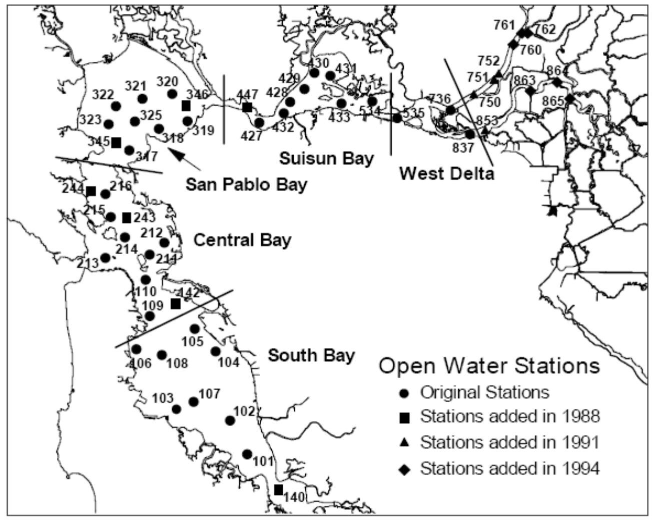

Figure 2. Locations of the sampling stations for the CDFW Bay Study Midwater Trawl and Otter Trawl surveys in the San Francisco Bay. For the Bay Fish Index, only data from the original stations that were sampled continuously from 1980-2017 were used to calculate the indicators for each of the four sub-regions: South Bay, Central Bay, San Pablo Bay and Suisun Bay and the western Delta.

All of the indicators were calculated using data from the California Department of Fish and Wildlife (CDFW) Bay Study surveys, conducted every year since 1980.[2] The Bay Study uses two different types of sampling gear to collect fish from the estuary: a midwater trawl and an otter trawl. The midwater trawl is towed from the bottom to the top of the water column and predominantly captures pelagic fishes that utilize open water habitats. This survey tends to collect smaller and/or younger fish that are too slow to evade the net.[3] The otter trawl is towed near the bottom and captures demersal fishes that utilize bottom and near-bottom habitats and also tends to collect smaller and/or younger fish. Each year, the two surveys sample the same 35 fixed stations in the estuary. These stations are distributed among the four sub-regions of the estuary and among channel and shoal habitats, once per month for most months of the year.[4] In two years, 1994 and 2016, the Midwater Trawl and/or Otter Trawl surveys were conducted during only 6 months or less, compared to the usual 8-12 months per year. Because the sampling period was limited, data from these years were not included in calculation of the indicators and the Bay Fish Index. Information on sampling stations, locations and total number of surveys conducted each year in each of the four sub-regions is shown in Figure 2 and Table 1.

Table 1. Sampling stations and total number of surveys conducted per year (range for 1980-2017 periods, excludes 1994 and 2016) by the CDFW Bay Study Survey in each of four sub-regions of the San Francisco Bay. MWT=Midwater Trawl survey; OT=Otter Trawl survey. See Figure 2 for station locations.

Sub-region	**Sampling stations**	**Number of surveys** (range for 1980-2017 period)
South Bay	101, 102, 103, 104, 105, 106, 107, and 108	64-96 (MWT) 64-96 (OT)
Central Bay	109, 110, 211, 212, 213, 214, 215, and 216	64-96 (MWT) 64-96 (OT)

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[2] Information on the CDFW Bay Study is available at http://www.dfg.ca.gov/delta/projects.asp?ProjectID=BAYSTUDY.

[3] The Bay Study primarily catches fishes that range in size from approximately 1-12 inches (3-30 cm). Other survey programs that monitor fishes in the estuary target smaller or larger fishes (e.g., CDFW 20-mm survey for small juvenile fishes or CDFW creel surveys for adult fishes).

[4] The Bay Study samples more than four dozen stations but the 35 sampling stations used to calculate the indicators are the original sampling sites for which data are available for the entire 1980-2017 period.

San Pablo Bay	317, 318, 319, 320, 321, 322, 323, and 325	64-96 (MWT) 64-96 (OT)
Suisun Bay/Western Delta	427, 428, 429, 430, 431, 432, 433, 534, 535, 736, and 837	87-132 (MWT) 88-132 (OT)

It should be noted that, although the Bay Study Midwater and Otter trawl surveys sample the Bay's pelagic and open water benthic habitats reasonably comprehensively, they do not survey historic or restored tidal marsh or tidal flat habitats where many of the same fish species collected by the Bay Study, as well as other fish species, may also be found. Therefore, results of the Bay Study and of these indicators should not be interpreted to mean that these are the only fishes or fish communities found in the Bay or that these species are found in only these regions of the estuary.

III. Indicator Evaluation

The San Francisco Estuary Partnership's Comprehensive Conservation and Management Plan (CCMP) calls for "recovery" and "reversing declines" of estuarine fish and wildlife but does not provide quantitative targets or goals. However, the length of the available data records, which include the Bay Study surveys used for the indicator calculations here as well as several other surveys, allows for use of historical data to establish "reference conditions."[5] There is also an extensive scientific literature on development, use and evaluation of ecological indicators in aquatic systems and, because San Francisco Bay is among the best studied estuaries in the world, an extensive scientific literature on its ecology.

For each indicator, a "primary" reference condition was established. This reference condition was based on either measured values from the earliest years for which quantitative data were available (1980-1989 for the Bay Study surveys), maximum measured values for the estuary or sub-regions, recognized and accepted interpretations of ecological conditions and ecosystem health (e.g., native v non-native species composition), and best professional judgment. Measured indicator values that were higher than the primary reference condition were interpreted to mean the indicator results met the CCMP goals and to correspond to "good" ecological conditions. For each of the four sub-regions, reference conditions were identically selected but for some indicators their absolute values were calibrated to account for differences among the sub-regions. For example, a reference condition based on historical abundance (i.e., average abundance during the first ten years of the survey) was used to evaluate the abundance indicators but, because overall fish abundance levels differed among the sub-regions, the actual reference abundance level differed among the four sub-regions. In contrast, because the reference condition for the species composition indicators was based the ecological relationship between the prevalence of non-native species and ecosystem and habitat condition, the value of the reference condition was set at the same level for each of the regions, despite the large differences in species composition that already existed between the four sub-regions.

[5] For example, CDFW's Fall Midwater Trawl Survey, conducted in most years since 1967, and Summer Townet Survey, conducted since 1959. However, the geographic coverage of the Fall Midwater trawl and Summer Townet surveys is less extensive than that of the Bay Study and does not extend into all of the four sub-regions of the estuary. Therefore, data from these surveys were less suitable for developing indicators for the entire estuary.

In addition to the primary reference condition, information on the range and trends of indicator results, results from other surveys, and known relationships between fish community attributes and ecological conditions were used to develop several intermediate reference conditions, creating a five-point scale for a range of evaluation results from "excellent," "good," "fair," "poor" to "very poor".[6] The size of the increments between the different evaluation levels was, where possible, based on observed levels of variation in the measured indicator values (e.g., standard deviations) in order to ensure that the different levels represented meaningful differences in the measured indicator values. Each of the evaluation levels was assigned a quantitative value from "4" points for "excellent" to "0" points for "very poor." An average score was calculated for the indicators in each of the fish community attributes (i.e., abundance, diversity, species composition and distribution) and the Bay Fish Index was calculated as the average of these four community attribute scores. Specific information on the primary and intermediate reference conditions is provided in the following sections describing each of the indicators.

Differences among sub-regions and different time periods, and trends with time in the indicators, community attributes, and the multi-metric index were evaluated using analysis of variance and simple linear regression. Comparisons among sub-regions were made using results from the entire 38-year period as well as for the earliest ten-year period (i.e., the reference period; 1980-1989) and the most recent five years (i.e., 2013-2017).[7] Regression analyses were conducted using continuous results for the entire 38-year period for each sub-region.

IV. Indicators

A. Fish Community Attributes

The ten indicators used to calculate the Bay Fish Index assess four different attributes of the San Francisco Bay fish community: abundance, diversity, species composition and distribution (Table 2). Information on indicator rationale, calculation methods, units of measure, specific reference conditions and results is provided in the following sections.

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[6] For example, data from the Fall Midwater trawl and Summer Townet surveys indicate that abundance of fish within the estuary was already in decline by the 1980s. Therefore, for indicator evaluation, abundance levels measured in the 1980s, which were already lower than they have been just ten years earlier, were interpreted to correspond to "good" conditions but not "excellent" conditions.

[7] The indicators were not calculated for 2016 because too few surveys were conducted for the Bay Study. Therefore, the average for the most recent 5 years is calculated with just 4 years of data (2013, 2014, 2015, and 2017).

Table 2. Fish community characteristics and indicators used to calculate the Bay Fish Index.

Fish Community Characteristic	Indicators
Abundance	• Pelagic Fish Abundance • Northern Anchovy Abundance • Demersal Fish Abundance • Sensitive Species Abundance
Diversity	• Native Fish Diversity • Estuary-dependent Fish Diversity
Species Composition	• Percent Native Species • Percent Native Fish
Distribution	• Pelagic Fish Distribution • Demersal Fish Distribution

B. Abundance Indicators

1. Rationale

Abundance (or population size) of native fish species within an ecosystem can be a useful indicator of aquatic ecosystem health, particularly in urbanized watersheds (Wang and Lyons, 2003; Harrison and Whitfield, 2004). Native fishes are more abundant in a healthy aquatic ecosystem than in one impaired by altered flow regimes, toxic urban runoff and reduced nearshore habitat, the usual consequences of urbanization. In the San Francisco Bay, abundances of a number of fish (and invertebrate) species are strongly correlated with ocean conditions immediately outside of the estuary (Cloern et al., 2007; 2010) and freshwater inflow from the estuary's Sacramento and San Joaquin watersheds, which vary widely due to California's climate and but have been reduced and stabilized by water development, flood control efforts, agriculture and urbanization (Jassby et al., 1995; Kimmerer, 2002; and see SOTER 2015 Estuarine Open Water Habitat indicator, and SOTER 2019 Freshwater Inflow Index and Flood Events indicator).

The Bay Fish Index includes four different abundance indicators, each measuring different components of the native fish community within the estuary. The **Pelagic Fish Abundance** indicator measures how many native pelagic, or open water, fish are collected in the Midwater trawl survey. This indicator does not include data for Northern anchovy because, in most years and in most sub-regions of the estuary, northern anchovy comprised >80% of all fish collected in the Bay and obscured results for all other species. **Northern Anchovy Abundance** was measured as a separate indicator, using data from the Midwater trawl survey. Northern anchovy, the most abundant species collected in the Bay, is consistently collected in all sub-regions of the estuary in numbers that are often orders of magnitude greater than for all other species. The **Demersal Fish Abundance** indicator measures how many native demersal, or bottom-oriented, fish are collected by the Otter Trawl Survey. The **Sensitive Fish Species Abundance** indicator measures the abundance of four representative species – longfin smelt, Pacific herring, starry flounder and striped bass[8] – using data from both the Midwater and Otter trawl surveys. All of these species are broadly distributed throughout the Bay and rely on the estuary in different ways

[8] Although striped bass is not native to the Pacific coast, the species was introduced to San Francisco Bay more than 100 years ago and, since then, has been an important component of the Bay fish community. On the North American west coast, the main breeding population of the species is in the San Francisco Bay (Moyle, 2002).

and at different times during their life cycle. Each is relatively common and consistently present in all four sub-regions of the estuary, and all except starry flounder are targets of environmental or fishery management in the estuary. In addition, the population abundance of each of these species is influenced by a key ecological driver for the estuary, seasonal freshwater inflows (Jassby et al. 1995; Kimmerer 2002). Key characteristics of each of the four species are briefly described below

- **Longfin smelt** are found in open waters of large estuaries on the west coast of North America.[9] The San Francisco Bay population spawns in upper estuary (Suisun Bay and Marsh and the Delta) and rears downstream in brackish estuarine and, occasionally, coastal waters (Moyle, 2002). The species was listed as "threatened" under the California Endangered Species Act in 2008.

- **Pacific herring** is a coastal marine fish that uses large estuaries for spawning and early rearing habitat. The San Francisco Bay is the most important spawning area for eastern Pacific populations of the species (CDFG, 2002). Pacific herring supports a commercial fishery, primarily for roe (herring eggs) but also for fresh fish, bait and pet food. In the San Francisco Bay, the Pacific herring fishery is the last remaining commercial finfish fishery.

- **Starry flounder** is an estuary-dependent, demersal fish that can be found over sand, mud or gravel bottoms in coastal ocean areas, estuaries, sloughs and even fresh water. The species, whose eastern Pacific range extends from Santa Barbara to arctic Alaska, spawns near river mouths and sloughs; juveniles are found exclusively in estuaries. Starry flounder is one of the most consistently collected flatfishes in the San Francisco Bay.

- **Striped bass** was introduced into San Francisco Bay in 1879 and by 1888 the population had grown large enough to support a commercial fishery (Moyle, 2002). That fishery was closed in 1935 in favor of the sport fishery, which remains popular today although at reduced levels. Striped bass are anadromous, spawning in large rivers and rearing in downstream estuarine and coastal waters. Declines in the striped bass population were the driving force for changes in water management operations in Sacramento and San Joaquin Rivers and the Delta in the 1980s. Until the mid-1990s, State Water Resources Control Board-mandated standards for the estuary were aimed at protecting larval and juvenile striped bass.

2. Methods and Calculations

The **Pelagic Fish Abundance** indicator was calculated for each year (1980-2017, excluding 1994 and 2016) for each of four sub-regions of the estuary using catch data for all native species except northern anchovy from the Bay Study Midwater Trawl survey. The indicator was calculated as:

$$\text{\# fish}/10{,}000\ m^3 = [(\text{\# of fish})/(\text{\# of trawls} \times \text{av. trawl volume},\ m^3)] \times (10{,}000)$$

[9] In California, longfin smelt are found in San Francisco Bay, Humboldt Bay, and the estuaries of the Russian, Eel, and Klamath rivers.

The **Northern Anchovy Abundance** indicator was calculated for each year (1980-2017, excluding 1994 and 2016) for each of four sub-regions of the estuary using catch data for Northern anchovy from the Bay Study Midwater Trawl survey using the same equation as for pelagic abundance.

The **Demersal Fish Abundance** indicator was calculated for each year (1980-2017, excluding 1994 and 2016) for each of four sub-regions of the estuary using catch data for all native species from the Bay Study Otter Trawl survey. The indicator was calculated as:

$$\# \text{ fish}/10{,}000 \text{ m}^2 = [(\# \text{ of fish})/(\# \text{ of trawls x av. trawl volume, m}^2)] \text{ x } (10{,}000)$$

The **Sensitive Fish Species Abundance** indicator, the abundance of each of the four species was calculated for each year (1980-2017, excluding 1994 and 2016) for each of four sub-regions of the estuary as the sum of the abundances from each of the two Bay Study surveys using the equations below.

$$\# \text{ fish}/10{,}000 \text{ m}^3 = [(\# \text{ of fish})/(\# \text{ of trawls x av. trawl volume, m}^3)] \text{ x } (10{,}000)$$
(for Midwater trawl)

$$\# \text{ fish}/10{,}000 \text{ m}^2 = [(\# \text{ of fish})/(\# \text{ of trawls x av. trawl area, m}^2)] \text{ x } (10{,}000)$$
(for Otter trawl)

The summed abundance for each species was then expressed as a percentage of the average 1980-1989 abundance for that species. The indicator was calculated as the average of the percentages for the four species. Each species was given equal weight in this calculation.

3. Reference Conditions

For the four Abundance indicators, the primary reference condition was established as the average abundance for the first ten years of the Bay Study, 1980-1989. Abundance levels that were greater than the 1980-1989 average were considered to reflect "good" conditions. Additional information from other surveys and trends in fish abundance within the estuary was used to develop several other intermediate reference conditions. Table 3 below shows the quantitative reference conditions that were used to evaluate the results of the abundance indicators.

Table 3. Quantitative reference conditions and associated interpretations for results of the Bay Fish abundance indicators. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Abundance indicators		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>150% of 1980-1989 average	"Excellent," greater than recent historical levels	4
>100% of 1980-1989 average	***"Good," meets CCMP goals***	***3***
>50% of 1980-1989 average	"Fair," below recent historical levels	2
>15% of 1980-1989 average	"Poor," substantially below recent historical levels	1
≤15% of 1980-1989 average	"Very Poor," extreme decline in abundance	0

4. Results

Results of the **Pelagic Fish Abundance** indicator are shown in Figure 3.

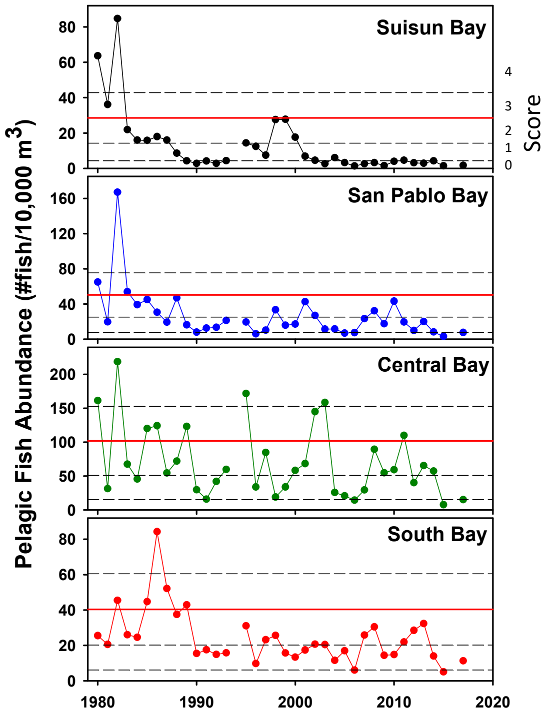

Figure 3. Results for the Pelagic Fish Abundance indicator, expressed as abundance (left Y axis) and score (right Y axis, top panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Abundance of pelagic fishes differs among the estuary's sub-regions.
Pelagic fishes are significantly more abundant in Central Bay than in all other sub-regions of the estuary (Kruskal Wallis One-way ANOVA of Ranks: $p<0.001$, all pairwise comparisons: $p<0.01$). Abundance of pelagic fishes in South Bay is greater than that in Suisun Bay ($p<0.01$) but comparable to that in San Pablo Bay. In 2017, pelagic fishes were nearly 50% more abundant in Central Bay (15 fish/10,000 m^3) than South Bay (11 fish/10,000 m^3), nearly twice as abundant as in San Pablo Bays (8 fish/10,000 m^3), and more than 7 times more abundant than in Suisun Bay (2 fish/10,000 m^3).

Abundance of pelagic fishes has declined in all sub-regions of the estuary.
Pelagic fish abundance declined significantly since 1980 in all sub-regions of the estuary (regression: $p<0.05$ for Central Bay, $p<0.01$ for South and San Pablo Bays, $p<0.001$ for Suisun Bay). For Central Bay, the relatively higher inter-annual variability of pelagic fish abundance reflects the periodic presence of large numbers of marine species such as Pacific sardine. In the last 10 years, pelagic fish abundance declined significantly in Central and San Pablo Bay (regression: $p<0.05$ both tests) and, for all sub-regions pelagic fish abundance in 2015 and 2017 were at near record low levels.

Based on the abundance of pelagic fishes, CCMP goals to "recover" and "reverse declines" of estuarine fishes have not been met.
Both current levels and trends in pelagic fish abundance are well below the 1980-1989 reference period for all sub-regions of the estuary: average pelagic fish abundance levels for the most recent five years (2013-2017) are "poor" in South, Central and San Pablo Bays (39%, 36% and 19% of the 1980-1989 averages, respectively) and "very poor" in Suisun Bay (9%).

Results of the **Northern Anchovy Abundance** indicator are shown in Figure 4.

Abundance of northern anchovy differs among the estuary's sub-regions.
Although northern anchovy are always found in all sub-regions of the estuary, their abundance differs markedly. For the past 38 years, northern anchovy have been more abundant in Central

Bay (mean: 898 fish/10,000 m^3) than all other sub-regions, least abundant in Suisun Bay (15 fish/10,000 m^3), and present at intermediate abundance levels in San Pablo (232 fish/10,000 m^3) and South Bays (275 fish/10,000 m^3) (Kruskal Wallis One-way ANOVA of Ranks: $p<0.001$).

Trends in abundance of Northern anchovy differ in different sub-regions of the estuary.
During the past 38 years, abundance of northern anchovy has been variable but roughly stable in South and Central Bays but declined significantly in San Pablo (regression: $p<0.001$) and Suisun Bays (regression: $p<0.01$). The decline was more abrupt in Suisun Bay, with northern anchovy virtually disappearing from this upstream portion of the estuary: since 1995, northern anchovy population levels in this region of the estuary averaged just 7% of 1980-1989 levels and less than 2% of populations in adjacent San Pablo Bay. This decline is contemporaneous with the establishment of the non-native overbite clam (*Corbula amurensis*) at high densities, the general disappearance of phytoplankton blooms and substantial declines in the abundance of several previously abundant zooplankton species.

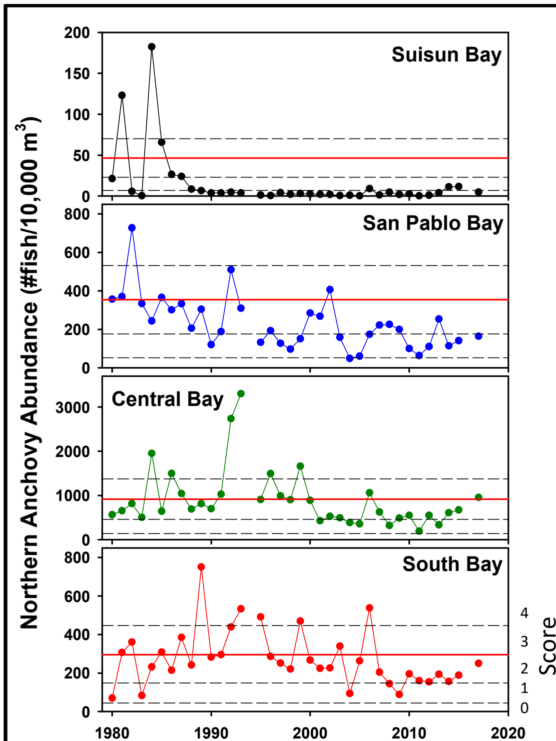

Figure 4. Results for the Northern Anchovy Abundance indicator, expressed as abundance (left Y axis) and score (right Y axis, bottom panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Based on the abundance of northern anchovy, CCMP goals to "recover" and "reverse declines" of estuarine fishes have not been met in the upstream sub-regions of the estuary.
The abundance of northern anchovy, the most common fish in the San Francisco Bay, has declined significantly throughout the upstream regions of the estuary, San Pablo and Suisun Bays, to levels substantially below the 1980-1989 average reference conditions. Average northern anchovy abundance in the most recent five years (2013-2017) are "poor" in Suisun Bay at just 17% of the 1980-1989 average, and "poor" in San Pablo Bay (48%). Although the trends in abundance over the 38-year record, and particularly during the late 1980s and 1990s, are different for Central and South Bays, recent northern anchovy abundance in those regions, "fair" in Central Bay (70%) and "fair" in South Bay (67%), are also too low to meet the CCMP goal. As with demersal fishes, the markedly different trends between the upstream sub-regions (Suisun and San Pablo Bays) and downstream sub-regions (Central and South Bays) suggest that different environmental drivers are influencing northern anchovy in different sub-regions of the estuary: ocean conditions in the downstream sub-regions and watershed conditions, in particular hydrological conditions and planktonic food availability, in the upstream sub-regions.

Results of the **Demersal Fish Abundance** indicator are shown in Figure 5.

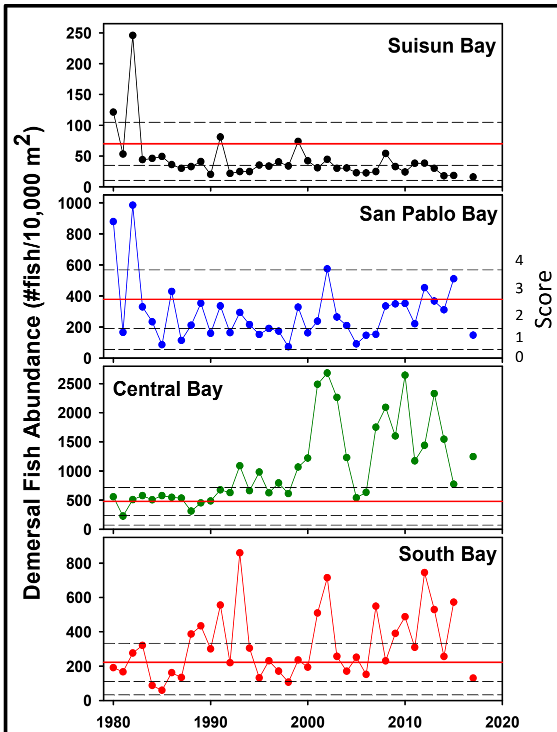

Figure 5. Results for the Demersal Fish Abundance indicator, expressed as abundance (left Y axis) and score (right Y axis, second panel from the top only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Abundance of demersal fish species differs among the estuary's sub-regions.

Demersal fishes are more abundant in Central Bay (1980-2017 mean: 1083 fish/10,000 m^2) than in all other sub-regions of the estuary and least abundant in Suisun Bay (43 fish/10,000 m^2) (Kruskal Wallis One-way ANOVA of Ranks: $p<0.001$). Demersal fish abundance in South (318 fish/10,000 m^2) and San Pablo Bays (290 fish/10,000 m^2) are comparable. In 2017, demersal fishes were more than eight times more abundant in Central Bay (1245 fish/10,000 m^2) than either South or San Pablo Bays (130 and 147 fish/10,000 m^2, respectively), and nearly 80 times more abundant than in Suisun Bay (16 fish/10,000 m^2).

Abundance of demersal fishes has increased in Central Bay but declined in Suisun Bay.

During the past 38 years, abundance of native demersal fishes increased in Central Bay (regression: $p<0.001$) and declined in Suisun Bay (regression: $p<0.01$). In Suisun Bay, abundance of demersal fish has fallen to record low levels; in 2017 the Otter trawl survey collected an average of just 16 fish/10,000 m^2. Demersal fish abundances in South and San Pablo Bays have fluctuated widely but exhibited no significant trend over time. Recent demersal fish abundances (2013-2017 average) were just 29% of the 1980-1989 average in Suisun Bay, slightly lower in San Pablo Bay (88%), and higher in South and Central Bays (168% and 308%, respectively).

Variations in demersal fish abundance in Central and South Bays were driven by multiple species.

In South and Central Bays, higher demersal fish abundances were largely attributable to high catches of Bay goby and Pacific staghorn sculpin, Bay resident species, and plainfin midshipman and two species of flatfishes, seasonal species that use the estuary as nursery habitat but which maintain substantial populations outside the Golden Gate. It is likely that the higher abundance of these species reflected improved ocean conditions.

Based on the abundance of demersal fishes, CCMP goals to "recover" and "reverse declines" of estuarine fishes have been met in all sub-regions except Suisun and San Pablo Bays, the upstream reaches of the estuary.

Both current levels (expressed as the 2013-2017 average) and trends in demersal fish abundance were higher or comparable to the 1980-1989 reference period for all sub-regions of the estuary except Suisun Bay, where demersal fish abundance has decreased significantly and remains "poor" at less than half of recent historical levels. In San Pablo Bay, average demersal fish abundance levels for the most recent five years are roughly comparable to the average during the reference conditions but only "fair" rather than "good." However, demersal fish abundance fluctuates widely in all sub-regions of the San Francisco Bay, suggesting that this indicator may be inadequately responsive to watershed conditions. In addition, the different trends between the upstream sub-regions (Suisun and San Pablo Bays) and downstream sub-regions (Central and South Bays) suggest that different environmental drivers are influencing demersal fish abundance in the different sub-regions of the estuary: ocean conditions in the downstream sub-regions and watershed conditions, in particular hydrological conditions, in the upstream sub-regions.

Results of the **Sensitive Fish Species Abundance** indicator are shown in Figure 6.

Abundances of longfin smelt, Pacific herring, starry flounder and striped bass differ among the different sub-regions of the estuary.

The Bay-wide abundance of the four species was roughly comparable (although starry flounder densities are generally lower than those of the pelagic species), but different species use different sub-regions within the estuary. Longfin smelt and starry flounder are most abundant in San Pablo, Suisun and Central Bays and rare in South Bay. Pacific herring are most commonly found in Central, South and San Pablo Bays and rarely collected in Suisun Bay. Striped bass are mostly collected in Suisun Bay and, to a lesser extent, San Pablo Bay and rarely found in Central and South Bays.

Abundance of sensitive fish species has declined in all sub-regions of the estuary.

During the past 38 years, combined abundance of the four sensitive fish species has declined in all sub-regions of the estuary (regression: $p<0.01$ all sub-regions). For the most recent five-year period (2013-2017), abundance of sensitive fish species in San Pablo Bay is just 16% of that sub-region's 1980-1989 average, 19% in South Bay, 21% in Central Bay, and 34% in Suisun Bay. The higher abundances measured in Suisun Bay in 2008 reflect increases in Pacific herring and starry flounder, species that are relatively uncommon in that sub-region. In each sub-region, most of the decline occurred during the late 1980s and early 1990s and, with the exceptions of a few single years in different sub-regions, the abundance of the four sensitive fish species has remained below 50% of the 1980-1989 average since then.

Abundance declines were measured for most of the species in most sub-regions of the estuary. All of the species except Pacific herring and starry flounder declined significantly in the sub-regions in which they were most prevalent (regression: $p<0.05$ for all species except Pacific herring in Central and South Bays and starry founder in Suisun Bay). Longfin smelt declined in both San Pablo and Suisun Bays (regression: $p<0.05$ both tests), starry flounder declined in South, Central, and San Pablo Bays (regression: $p<0.05$ all tests), striped bass declined in all sub-regions (regression: $p<0.05$ all sub-regions). Pacific herring abundance was variable and did not exhibit significant declines in any sub-region.

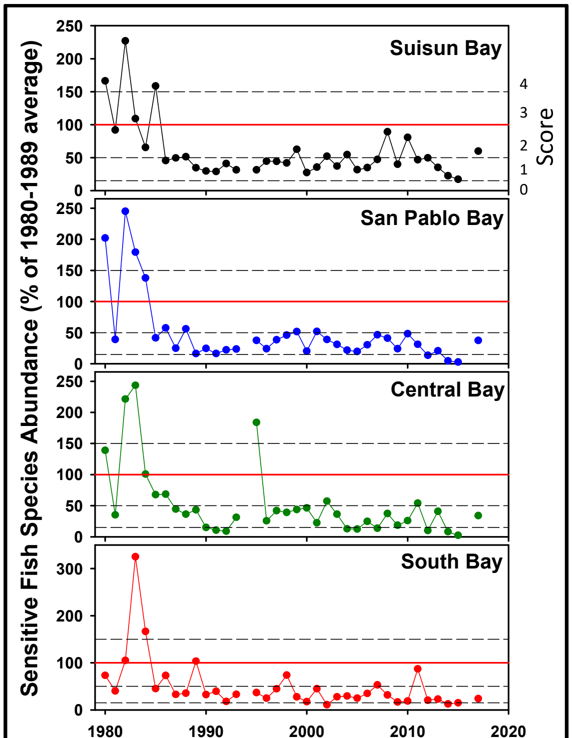

Figure 6. Results for the Sensitive Species Abundance indicator, expressed as abundance (left Y axis) and score (right Y axis, top panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Based on the abundance of sensitive fish species, CCMP goals to "recover" and "reverse declines" of estuarine fishes have not been met in any sub-region of the estuary. The combined abundance of the four estuary-dependent species assessed with this indicator have fallen to levels that are consistently 50% or less than the 1980-1989 average abundance reference condition. Record low sensitive species abundance levels have been measured in each sub-region except South Bay during the past five years (2013-2017). However, sensitive species abundance exhibited high variability during the 1980s, thus recent levels were significantly lower in only South and Central Bay (t-test or Mann-Whitney: $p<0.05$, both tests). Although recent abundance levels in San Pablo and Suisun Bay were markedly lower than during the 1980-1989 reference period, the differences were not statistically significant due to high variability during the 1980s. The significant declines measured for three of the four individual species indicates that population declines of estuary-dependent species span multiple species and all geographic regions of the estuary.

C. Diversity Indicators

1. Rationale

Diversity, or the number of species present in the native biota that inhabit an ecosystem, is one of the most commonly used indicators of ecological health of aquatic ecosystems (Karr et al., 2000; Wang and Lyons, 2003; Harrison and Whitfield, 2004). Diversity tends to be highest in healthy ecosystems and to decline in those impaired by urbanization, alteration of natural flow patterns, pollution, and loss of habitat area.

More than 100 native fish species have been collected in the San Francisco Bay by the Bay Study surveys. Some are transients, short-term visitors from nearby ocean or freshwater habitats where they spend the majority of their life cycles, or anadromous migrants, such as Chinook salmon and sturgeon, transiting the Bay between freshwater spawning grounds in the Bay's tributary rivers and the ocean. Other species are dependent on the estuary as critical habitat, using it for spawning and/or rearing, spending a large portion or all of their life cycles in Bay waters.

Of the more than 100 fish species collected by the Bay Study since 1980, 39 species can be considered "estuary-dependent" species (Table 4). These species may be resident species that spend their entire life-cycle in the estuary, marine or freshwater species that depend on the San Francisco Bay for some key part of their life cycle (usually spawning or early rearing), or local species that spend a large portion of their life cycle in the San Francisco Bay. Just as diversity, or species richness, of the native fish assemblage is a useful indicator of the ecological health of aquatic ecosystems, diversity of the estuary-dependent fish assemblage is a useful indicator for the ecological health of the San Francisco Bay.

Table 4. San Francisco estuary-dependent fish species collected in the CDFW Bay Study surveys.

Estuary-dependent fish species (common names)	
Estuary resident species Species with resident populations in the estuary and/or estuary-obligate species that use the estuary as nursery habitat	**Seasonal species** Species regularly use the estuary for part of their life cycle but also have substantial connected populations outside the estuary
Arrow goby	Barred surfperch
Bat ray	Black perch
Bay goby	Bonehead sculpin
Bay pipefish	California halibut
Brown rockfish	California tonguefish
Brown smoothhound	Diamond turbot
Cheekspot goby	English sole
Delta smelt	Northern anchovy
Dwarf surfperch	Pacific sandab
Jack smelt	Pacific tomcod
Leopard shark	Plainfin midshipman
Longfin smelt	Sand sole
Pacific herring	Speckled sanddab
Pacific staghorn sculpin	Spiny dogfish
Pile perch	Splittail
Shiner perch	Starry flounder
Threespine stickleback	Surfsmelt
Topsmelt,	Walleye surfperch
Tule perch	
White croaker	
White surfperch	

The Bay Fish Index includes two different diversity indicators. The **Native Fish Species Diversity** indicator uses Midwater and Otter trawl survey data to measure how many of the estuary's native fish species are present in the Bay each year. The **Estuary-dependent Fish**

Species Diversity indicator uses data from both surveys to measure how many estuary-dependent species are present each year.

2. **Methods and Calculations**

The **Native Fish Species Diversity** indicator was calculated for each year and for each of four sub-regions of the estuary as the number of native species collected, expressed as the percentage of the maximum number of native species ever collected in that sub-region, using catch data from the Bay Study Midwater and Otter Trawl surveys. The indicator was calculated as:

% of species assemblage = (# native species/maximum # of native species reported) x 100

The **Estuary-dependent Fish Species Diversity** indicator was calculated for each year and for each of four sub-regions of the estuary as the number of estuary-dependent species collected (see Table 4), expressed as the percentage of the maximum number of estuary-dependent species ever collected in that sub-region, using catch data from the Bay Study Midwater and Otter Trawl surveys. The indicator was calculated as:

% of species assemblage =
(# estuary-dependent species/maximum # of estuary-dependent species reported) x 100

3. **Reference Conditions:**

For the two diversity indicators, the primary reference condition was based on the average diversity (expressed as % of the native fish assemblage present), measured for the first ten years of the Bay Study, 1980-1989, and for all four sub-regions combined. Diversity levels that were greater than the 1980-1989 average were considered to reflect “good” conditions. The average percentage of the native fish assemblage present during the 1980-1989 period diversity differed slightly among the four sub-regions for the Native Fish Species Diversity indicator (1980-1989 average: 49%; Suisun Bay diversity was lower than that in the other three sub-regions) and significantly for the Estuary-dependent Fish Species Diversity indicators (1980-1989 average: 72%; Suisun Bay was lowest and Central and South Bay were highest). This approach tended to reflect the relatively lower species diversity observed in Suisun Bay in the indicator results. Table 5 below shows the quantitative reference conditions that were used to evaluate the results of the two diversity indicators.

Table 5. Quantitative reference conditions and associated interpretations for results of the Bay Fish diversity indicators. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Diversity indicators		
Native Fish Species Diversity		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>60% of assemblage present	"Excellent," greater than 1980-1989 average	4
>50% of assemblage present	***"Good," meets CCMP goals***	***3***
>40% of assemblage present	"Fair," below recent historical levels	2
>30% of assemblage present	"Poor," substantially below recent historical levels	1
≤30% of assemblage present	"Very Poor," extreme decline in diversity	0
Estuary-dependent Fish Species Diversity		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>85% of assemblage present	"Excellent," greater than 1980-1989 average	4
>70% of assemblage present	***"Good," meets CCMP goals***	***3***
>55% of assemblage present	"Fair," below recent historical levels	2
>40% of assemblage present	"Poor," substantially below recent historical levels	1
≤40% of assemblage present	"Very Poor," extreme decline in diversity	0

4. Results

Results of the **Native Fish Species Diversity** indicator are shown in Figure 7.

Maximum native species diversity differs among the four sub-regions of the estuary.
The greatest numbers of native fish species are found in Central Bay (96 species) and the fewest are in Suisun Bay (48 species). A maximum of 73 native species have been collected in South Bay and 66 native species have been found in San Pablo Bay.

The percentage of the native fish species assemblage present differs among the sub-regions.
The greatest native species diversity is found in San Pablo and South Bays (medians: 50% and 49%, respectively). Native species diversity in San Pablo Bay is also greater than that in Central Bay (46%). Diversity in Suisun Bay (44%) is comparable to that in Central Bay (Kruskal-Wallis One-way ANOVA of Ranks: $p<0.001$, all pairwise comparisons, $p<0.01$).

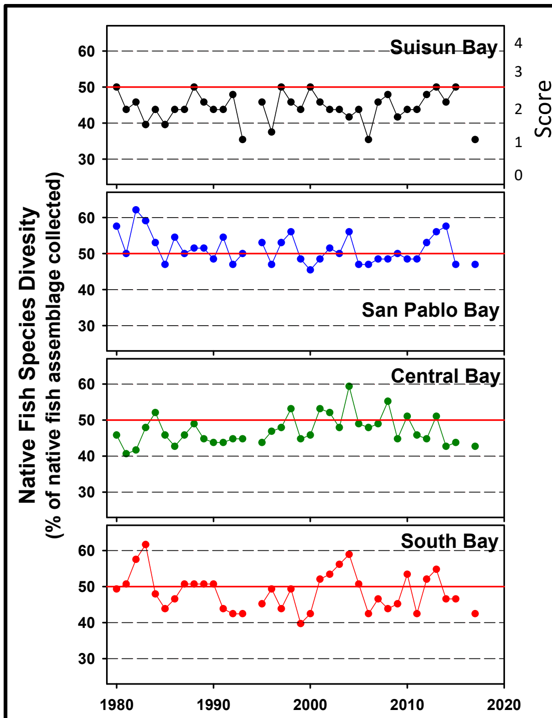

Figure 7. Results for the Native Fish Species Diversity indicator, expressed as percent of assemblage (left Y axis) and score (right Y axis, top panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Native species diversity is relatively stable in all sub-regions.
Over the 38-year period, native species diversity has fluctuated but remained generally stable in all sub-regions of the estuary (regression: all tests, p>0.05). However, in 2017, the percentages of the native species assemblage that were present in each sub-region matched or were close to the lowest levels recorded during the history of Bay Study surveys.

Based on the diversity of the native fish community, CCMP goals to "recover" and "reverse declines" of estuarine fishes have not been fully met in any sub-region of the estuary except San Pablo Bay.
Comparison of average native fish species diversity in the most recent five years (2013-2017) to that measured during the 1980-1989 period shows no significant differences in any sub-region. However, recent diversity levels, 52%, 48%, 45% and 45% in San Pablo, South, Central and Suisun Bays, respectively, have been somewhat lower than the primary reference condition and/or historical conditions for all sub-regions except San Pablo Bay.

Results of the **Estuary-dependent Fish Species Diversity** indicator are shown in Figure 8.

The diversity of estuary-dependent species is lower in Suisun Bay than in other sub-regions of the estuary.
Although roughly the same number of estuary-dependent species are found in each sub-region (38 species in San Pablo Bay; 36 species in Central and South Bays; and 31 species in Suisun Bay), a significantly smaller percentage of the estuary-dependent fish assemblage occurs in Suisun Bay (50% of the assemblage) than in all other regions of the San Francisco Bay (82% in Central Bay; 79% in South Bay; and 69% in San Pablo Bay) (Kruskal-Wallis ANOVA: p<0.001, all pairwise comparisons, p<0.05).

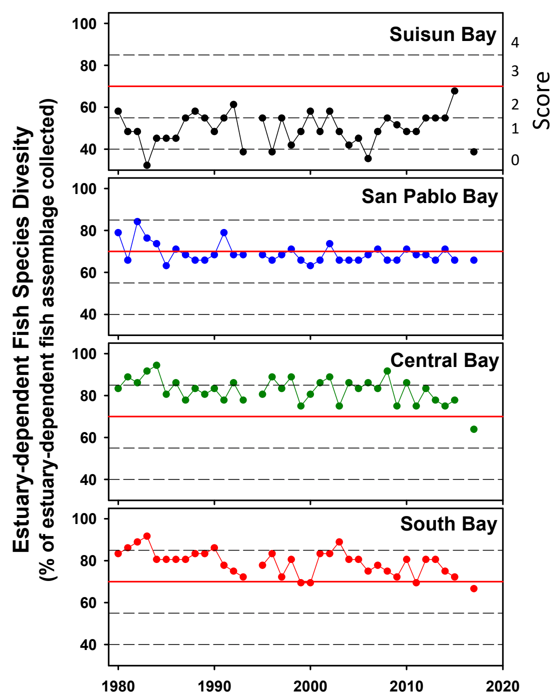

Figure 8. Results for the Estuary-dependent Fish Species Diversity indicator, expressed as percent of assemblage (left Y axis) and score (right Y axis, top panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Diversity of estuary-dependent species is declining in most sub-regions of the estuary.
During the 38-year Bay Study survey period, estuary-dependent species diversity has declined slightly in all sub-regions except Suisun Bay (regression: all tests, p<0.05). Compared to the 1980-1989 period, an average of 4.2 and 3.7 fewer estuary-dependent species were found in Central and South Bays, respectively, in the most recent 5 years (2013-2017). In San Pablo Bay, there were an average of 1.6 fewer estuary-dependent species collected. In 2017, the percentage of the estuary-dependent species assemblage that was collected in the Bay Study surveys was at or near record low levels in all sub-regions of the estuary.

Based on the diversity of the estuary-dependent fish community, CCMP goals to "recover" and "reverse declines" of estuarine fishes have been met in South and Central Bays but not in San Pablo or Suisun Bays.
The percentages of the estuary-dependent fish assemblage that are present, 74%, 74%, 67%, and 54% in Central, South, San Pablo and Suisun Bays, respectively, generally meet or exceed the primary reference condition in all regions except Suisun Bay, where diversity levels are similar to historical levels.

D. Species Composition Indicators

1. Rationale

The relative proportions of native and non-native species found in an ecosystem is an important indicator of ecosystem health (May and Brown, 2002; Meador et al., 2003). Non-native species are most prevalent in ecosystems that have been modified or degraded with resultant changes in environmental conditions (e.g., elevated temperature, reduced flood frequency), pollution, or reduction in area or access to key habitats (e.g., tidal marsh, seasonal floodplain). The San Francisco Bay has been invaded by a number of non-native fish species. Some species, such as striped bass, were intentionally introduced into the estuary; others have arrived in ballast water or from upstream habitats, usually reservoirs.

The Bay Fish Index includes two different indicators for species composition. The **Percent Native Species** indicator uses Midwater and Otter trawl survey data to measure what percentage of the fish species collected in each sub-region of the estuary are native species. The **Percent Native Fish** uses the survey data to measure what percentage of the individual fish collected in each sub-region of the estuary are native species.

2. Methods and Calculations

The **Percent Native Species** indicator was calculated for each year and for each of four sub-regions of the estuary as the percentage of fish species collected in the estuary that are native to the estuary and its adjacent ocean and upstream habitats using the equation below.

% native species = [# native species/(# native species + # non-native species)] x 100

The Percent Native Fish indicator was calculated for each year and for each of four sub-regions of the estuary as the percentage of fish collected in the estuary that are native to the estuary and its adjacent ocean and upstream habitats using the equation below.

% native fish = [# native fish/(# native fish + # non-native fish)] x 100

3. Reference Conditions:

There is an extensive scientific literature on the relationship between the presence and abundance of non-native species and ecosystem conditions and the length of the available data record for the San Francisco Bay allows for establishment of reference conditions. In general, ecosystems with high proportions of non-natives (e.g., >50%) are considered to be seriously degraded. Furthermore, non-native fish species have been present in the San Francisco Bay for more than 100 years; therefore, 100% native fish species is unrealistic. Among the four sub-regions, the 1980-1989 average percentage of native species was 87% and the average percentage of native fish was 90%. For both indicators, Suisun Bay values were lowest. Based on this information, the primary reference condition for both indicators was established at 85%. Percent Native Species and Percent Native Fish levels that were greater than this value were considered to reflect "good" conditions. Table 6 below shows the quantitative reference conditions that were used to evaluate the results of the two species composition indicators.

Table 6. Quantitative reference conditions and associated interpretations for results of the Bay Fish species composition indicators. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Species Composition indicators (Percent Native Species, Percent Native Fish)		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
>95% native	"Excellent," greater than recent historical levels	4
>85% native	***"Good," meets CCMP goals***	***3***
>70% native	"Fair," below recent historical levels	2
>50% native	"Poor," substantially below recent historical levels	1
≤50% native	"Very Poor," extreme decline in abundance	0

4. Results

Results of the **Percent Native Species** indicator are shown in Figure 9.

The percentage of native species in the fish community differs among the four sub-regions of the estuary.
For the past 38 years, non-native species have been most prevalent in Suisun Bay where, on average, 27% of species are non-native (i.e., only 73% of species are native), intermediate and similar in South and San Pablo Bays (13% and 15% non-native, respectively), and the least prevalent in Central Bay (8%) (Kruskal Wallis One-way ANOVA of Ranks: $p<0.001$, all pairwise comparisons, $p<0.001$).

The percentage of native species is declining in most sub-regions.
During the 38-year Bay Study period, the percentage of native species has declined significantly in all sub-regions of the estuary except Central Bay (regression: $p<0.001$, all tests except Central Bay). In South Bay, the percent native species declined from 89% in the 1980-1989 period to 85% in the most recent five-year period (2013-2017). In San Pablo Bay, the percent native species has declined more sharply, from 90% to 82% and in Suisun Bay from 77% to just 68% native species. In 2017, the percentage of the fish species collected in the Bay Study surveys that were native was at or near record low levels in all sub-regions of the estuary.

Trends in the percentage of native species in Bay fish assemblages are driven by declines in the numbers of native species and increases in non-native species.
During the past 38 years, the number of native species in San Pablo Bay declined by an average of 1.2 species and the number of non-native species increased by an average of 3.4 species; in the most recent five years, there were 7.2 non-native species in this sub-region, on average. The

number of non-native species collected in Suisun Bay increased by 3.5 species, from 6.6 to 10 non-native species in the most recent five years. In South Bay, native species declined by one and non-natives increased by one. In Central, the total numbers of native and non-native species changed by less and 0.5 species, on average.

Based on fish species composition, CCMP goals to "recover" and "reverse declines" of estuarine fishes have not been met in Suisun and San Pablo Bays.

Compared to the 1980-1989 period and the biologically based 85% native species primary reference condition, recent measurements (2013-2017) of the percentage of native fish species in the fish community indicate that this characteristic has degraded in both San Pablo Bay (82% native species) and Suisun Bay (68% native species) to levels that do not meet the CCMP goals. In South Bay, the prevalence of native species is also declining but recent levels, 85%, are just at the threshold for "good" conditions to meet CCMP goals.

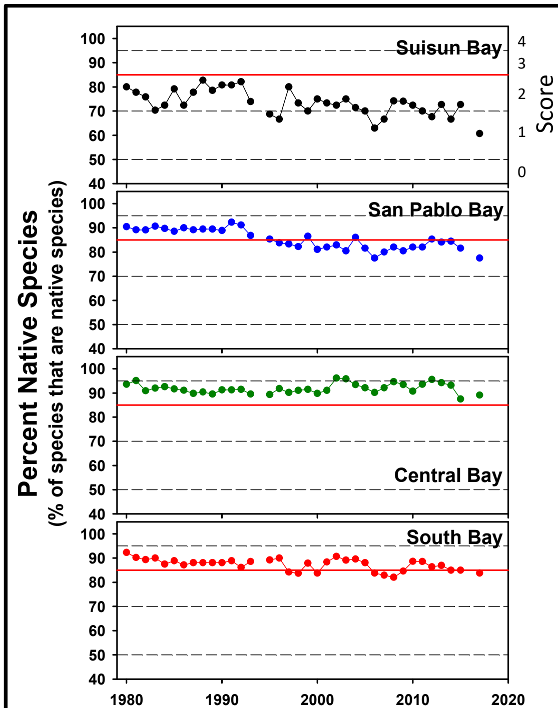

Figure 9. Results for the Percent Native Fish Species indicator, expressed as percent native species (left Y axis) and score (right Y axis, top panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Results of the **Percent Native Fish** indicators are shown in Figure 10.

The percentage of native fish in the fish community differs among the four sub-regions of the estuary.

For the past 38 years, non-native fish have dominated the Suisun Bay sub-region, where in most years less than 50% of fish collected are natives (1980-2017 average: 48%). Non-native fish are rare in the other three sub-regions. Central Bay has the lowest prevalence of non-native fishes, 0.1%. Percentages of non-native fish in South and San Pablo Bays are intermediate and comparable at 1.6% and 2.5% respectively (Kruskal Wallis One-way ANOVA of Ranks: $p<0.001$, all pairwise comparisons, $p<0.001$).

Trends in the percentage of native fish differ among the sub-regions.

The percentage of native fishes is declining in the Suisun and South Bay sub-regions of the estuary but not in Central or San Pablo Bays (regression: $p<0.01$, both tests). In Suisun Bay, the percent native fish declined from 63% in the 1980-1989 period to just 47% in the most recent five-year period. In 2017, just 19% of the fish collected in Suisun Bay were natives. Percent native fish declined in South Bay from more than 99% to 97%. Increases in the numbers of non-native fish in South Bay in 2007 and 2008 were largely attributable to higher catches of two non-natives, striped bass and chameleon goby.

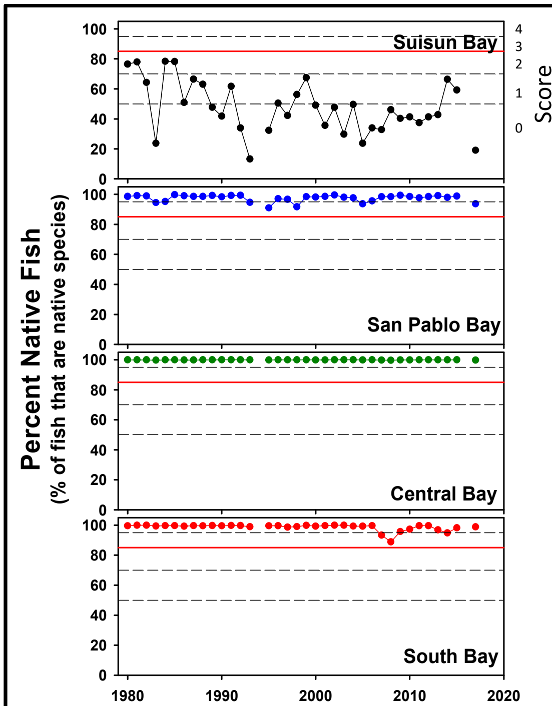

Figure 10. Results for the Percent Native Fish indicator, expressed as percent native fish (left Y axis) and score (right Y axis, top panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Based on fish species composition, CCMP goals to "recover" and "reverse declines" of estuarine fishes have been met in all sub-regions of the estuary except Suisun Bay.

In all sub-regions of the estuary except Suisun Bay, native fish comprise the vast majority of the fish community, exceeding 95% of the total fish present in nearly all years. In Suisun Bay, the percentage of the fish community that is comprised of non-native fish is extremely high and increasing, indicating that the condition of this region of the estuary is poor and deteriorating.

E. Distribution Indicators

1. Rationale

The distribution of native fishes within a habitat is an important indicator of ecosystem condition (May and Brown, 2002; Whitfield and Elliott, 2002; Nobriga et al., 2005). Native fishes may be excluded or less abundant in degraded habitats with unsuitable environmental conditions and/or those in which more tolerant non-native species have become established. The Bay Fish Index includes two indicators to assess the distribution of native fishes within the estuary. The **Pelagic Fish Distribution** indicator uses Midwater trawl survey data to measure the percentage of the survey's sampling stations at which native species were regularly collected. The **Demersal Fish Distribution** indicator uses Otter trawl survey data to make a similar measurement for bottom-oriented native fishes.

2. Methods and Calculations

The **Pelagic Fish Distribution** indicator was calculated for each year and for each of four sub-regions of the estuary as the percentage of Midwater trawl survey stations at which at least one native fish was collected in at least 60% of the surveys conducted in that year.

> **Pelagic Fish Distribution** =
> (# survey stations with native fish in 60% of surveys)/(# survey stations sampled) x 100

The **Demersal Fish Distribution** indicator was calculated identically using Otter trawl survey data.

3. Reference Conditions:

There is an extensive scientific literature on the relationship between the presence and abundance of non-native species and ecosystem conditions. The length of the available data record for the San Francisco Bay allows for establishment of "reference conditions." For the two Distribution indicators, the primary reference condition was established based on the number of stations sampled by the Bay Study surveys (8-12 stations per sub-region; therefore the maximum resolution of this indicator is limited to 8-13% increments depending on sub-region) and the average percentage of stations with native species present for the first ten years of the Bay Study, 1980-1989 (~96%). Distribution levels that were greater than the reference condition were considered to reflect "good" conditions. Table 7 below shows the quantitative reference conditions that were used to evaluate distribution indicators.

Table 7. Quantitative reference conditions and associated interpretations for results of the Bay Fish distribution indicators. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Distribution indicators (Pelagic Fish, Demersal Fish)		
Quantitative Reference Condition	**Evaluation and Interpretation**	**Score**
100% of stations	"Excellent," greater than recent historical levels	4
>80% of stations	***"Good," meets CCMP goals***	***3***
>60% of stations	"Fair," below recent historical levels	2
>40% of stations	"Poor," substantially below recent historical levels	1
≤40% of stations	"Very Poor," extreme decline in abundance	0

4. Results

Results of the **Pelagic Fish Distribution** indicator are shown in Figure 11.

The percentage of Midwater trawl survey stations that regularly have native fish differs among the four sub-regions of the estuary.
For the past 38 years, native fish have been consistently present at nearly all Midwater trawl survey stations in all sub-regions of the estuary except Suisun Bay. During the 1980-2017 period, native fish were present, on average, at 97-100% of survey stations in South, Central and San Pablo Bays. In contrast, native fish were present in only an average of 74% stations in Suisun

Bay (Kruskal Wallis One-way ANOVA of Ranks: $p<0.001$, Suisun v all other sub-regions; $p<0.05$).

Trends in the distribution of native pelagic fish differ among the sub-regions.

The percentage of survey stations with native fish was stable in all sub-regions of the estuary except Suisun Bay. In Suisun Bay, distribution of native fishes declined significantly from 88% of stations (1980-1989) to 59% in the most recent five years (2013-2017) (Mann-Whitney Rank Sum test; $p<0.01$; regression: $p<0.001$). This decline in distribution occurred abruptly in 2003; since 2003, native pelagic fish have been consistently present at only 59% of stations, on average, compared to being present at 84% of stations during the first 23 years of the survey. Native fish were most frequently absent from survey stations located in the lower San Joaquin River and the western region of Suisun Bay.

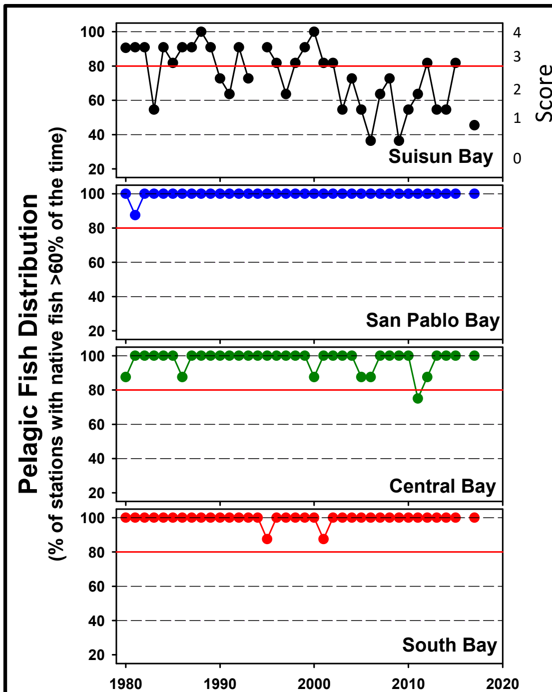

Figure 11. Results for the Pelagic Fish Distribution indicator, expressed as percent of stations (left Y axis) and score (right Y axis, top panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Based on native pelagic fish distribution, CCMP goals to "recover" and "reverse declines" of estuarine fishes have been fully met in all sub-regions of the estuary except Suisun Bay.

In all regions of the estuary except Suisun Bay, native pelagic fish are regularly collected at all Midwater trawl survey stations. In contrast, native fish are increasingly absent from the western region of Suisun Bay, the most upstream region of the estuary, suggesting that the condition of this region of the estuary is deteriorating.

Results of the **Demersal Fish Distribution** indicator are shown in Figure 12.)

The percentage of Otter trawl survey stations that regularly have native fish differs among the four sub-regions of the estuary.

For the past 38 years, native fish have been consistently present at nearly all Otter trawl survey stations in all sub-regions of the estuary except Suisun Bay. During the 1980-2017 period, native fish were present, on average, at 98-100% of survey stations in South, Central and San Pablo Bays. In contrast, native fish were present in only an average of 72% stations in Suisun Bay (Kruskal Wallis One-way ANOVA of Ranks: $p<0.001$, Suisun v all other sub-regions; $p<0.05$).

Trends in the distribution of native demersal fish differ among the sub-regions.

The percentage of survey stations with native fish was stable in all sub-regions of the estuary except Suisun Bay (regression: $p<0.001$). In Suisun Bay, distribution of native fishes declined briefly but significantly in the early 1990s, from 88% of stations (1980-1991) to just 61% of stations (1992-1994), and then recovered to 85% (1995-2000). In 2001, distribution declined again and, even with the relatively high level in one year (2008), it has remained significantly lower since then, 59% on average (t-test: $p<0.001$ for 1980-2000 v 2001-2017). For the most recent five years (2013-2017), native demersal fish have been present at 50% of stations and, in 2017, just 27% of stations, the lowest distribution level on record. Similar to pelagic fish, native demersal fish were most frequently absent from survey stations located in the western region of Suisun Bay.

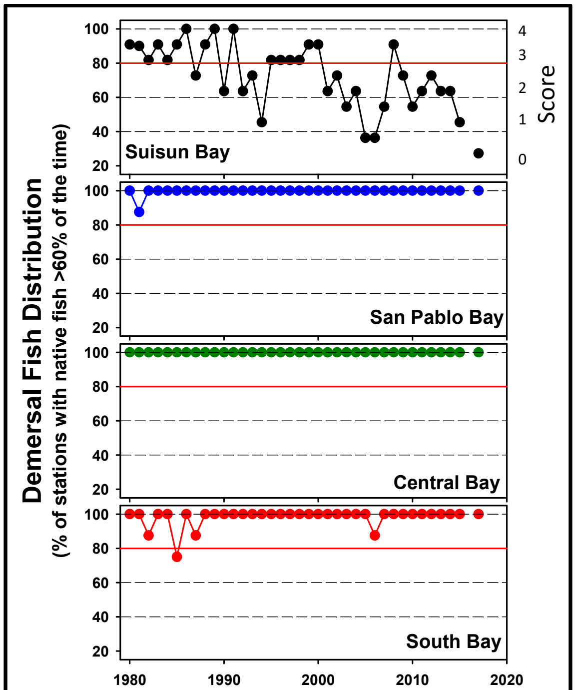

Figure 12. Results for the Demersal Fish Distribution indicator, expressed as percent of stations (left Y axis) and score (right Y axis, top panel only for example), for 1980 to 2017. The horizontal red line shows the primary reference condition. The horizontal dashed lines show the other reference conditions used for evaluation.

Based on native demersal fish distribution, CCMP goals to "recover" and "reverse declines" of estuarine fishes have been fully met in all sub-regions of the estuary except Suisun Bay.

In all regions of the estuary except Suisun Bay, native demersal fish are regularly collected at all Otter trawl survey stations. In contrast, native fish are increasingly absent from the western region of Suisun Bay, the most upstream region of the estuary, suggesting that the condition of this region of the estuary is deteriorating.

V. Bay Fish Index

The Bay Fish Index aggregates the results of the four abundance indicators (Pelagic Species, Demersal Species, Northern Anchovy, and Sensitive Species), two diversity indicators (Native Species and Estuary-dependent Species), two species composition indicators (Percent Native Species and Percent Native Fish) and the two distribution indicators (Pelagic Fish and Demersal Fish Distribution).

A. Index Calculation

For each year and for each sub-region, the Bay Fish Index is calculated by combining the results of the ten indicators into a single number. First, results of the indicators in each fish community attribute (i.e., abundance, diversity, species composition and distribution) were combined by averaging the quantitative scores of each of the component indicators. Within each fish community attribute, each indicator was equally weighted. Next the average scores for each fish community attribute were combined by averaging, with each fish community attribute equally weighted. An index score greater than or equal to 2.5, which reflects at least two community attributes with average scores greater than 3, was interpreted to represent “good” conditions and an index score less than 0.5 was interpreted to represent “very poor” conditions.

B. Results

Results of the four component metrics (Abundance, Diversity, Species Composition, and Distribution) and the Bay Fish Index for each sub-region are shown in Figures 13-16 (following pages).

The Bay Fish Index differs among the four sub-regions of the estuary.
For the 38-year survey period, the Bay Fish Index was equally high in the Central Bay (1980-2013 average: 3.1) and South Bay (3.0), lowest in Suisun Bay (1.5), and intermediate in San Pablo Bays (2.8) (Kruskal Wallis One-way ANOVA of Ranks: all pairwise comparisons, $p<0.05$; Central=South>San Pablo>Suisun). For the most recent five years (2013-2017), the pattern among the sub-regions was similar: the average index was 3.0, 2.8, 2.6, and 1.1 for Central, South, San Pablo and Suisun Bays, respectively. Lower index values for Suisun Bay at the beginning of the survey period were attributable to lower diversity (i.e., smaller percentages of the sub-region’s species assemblage were present) and species composition (i.e., high prevalence of non-native species and non-native fish).

Trends in the Bay Fish Index differ among the sub-regions.
During the 38-year survey period, the Bay Fish Index has declined significantly in all sub-regions of the estuary (regression 1980-2017: $p<0.05$ all sub-regions). The overall condition of the fish community in Suisun Bay has declined from “fair” in the early 1980s (1980-1989 average: 2.2) to consistent “poor” conditions since the 1990s. This decline was driven by significant declines in abundance, species composition and distribution (regression: all tests, $p<0.001$). In San Pablo Bay, the Index has declined, from mostly “good” conditions in the early 1980s to periodically “fair” conditions since the mid-2000s; this decline is largely attributable to significant declines in abundance and species composition (regression: $p<0.05$, both tests). The declines in the Index in South and Central Bays, while significant, were not as severe and conditions of the fish community remained “good” in all years.

Based on Bay Fish Index, CCMP goals to “recover” and “reverse declines” of estuarine fishes have been met in the Central, South and San Pablo Bay sub-regions, but not in Suisun Bay.
The overall condition of the fish community is “good” in the Central and South Bays, the most downstream regions of the estuary. In San Pablo Bay, the condition of the fish community is “good” or, in some years, “fair.” In contrast, in Suisun Bay, the most upstream region of the estuary most directly affected by watershed degradation, alteration of freshwater inflows and declines in the quality and quantity of low-salinity habitat, the fish community is in “poor” condition. These declines in the Bay Fish Index are largely driven by declines in fish abundance (all four sub-regions), increasing prevalence of non-native species (South, San Pablo and Suisun Bays), and declines in the distribution of native fish within the sub-region (Suisun Bay).

C. Summary and Conclusions

Collectively, the ten indicators and the Bay Fish Index provide a reasonably comprehensive assessment of status and trends San Francisco Bay fish community. The results show substantial geographic variation in both the composition and condition of the fish community within the estuary and in the response of specific indicators over time. Table 8 below summarizes the indicator and Index results by sub-region. In addition, the following general conclusions can be made:

1. The San Francisco Bay fish community differs geographically within the estuary in fish community composition, fish abundance, and trends in various attributes of its condition over time.
2. Different indicators show different responses over time, some demonstrating clear declines in condition over time, others no change, and a few increases. In some cases, the same indicators measured in different sub-regions of the estuary show different responses over time. These results suggest that different physical, chemical or biological environmental variables (or combinations of these variables) influence the fish community response in different sub-regions.
3. Overall condition, as measured individually by the fish indicators and by the Bay Fish Index for the community response, is poorest in the upstream region of estuary, Suisun Bay; best in Central Bay, the region most strongly influenced by ocean conditions and with a predominantly marine fish fauna; and intermediate in San Pablo and South Bays. However, over the 38-year period of record for these indicators, the condition of the fish community is declining in all sub-regions of the estuary.
4. Even 38 years ago, the condition of the fish community in Suisun Bay was poorer than in all other sub-regions of the estuary. The fish community was less diverse with relatively lower percentages of the native fish assemblage present, and dominated by high percentages of non-native species.
4. The abundance of pelagic fishes in the estuary (which include Northern anchovy and most of the sensitive species measured in those two indicators) has shown the greatest changes over time, indicating this component of the fish community has low resilience and/or is tightly linked to just one or a few environmental drivers that have also experienced substantial change in conditions during the sampling period.

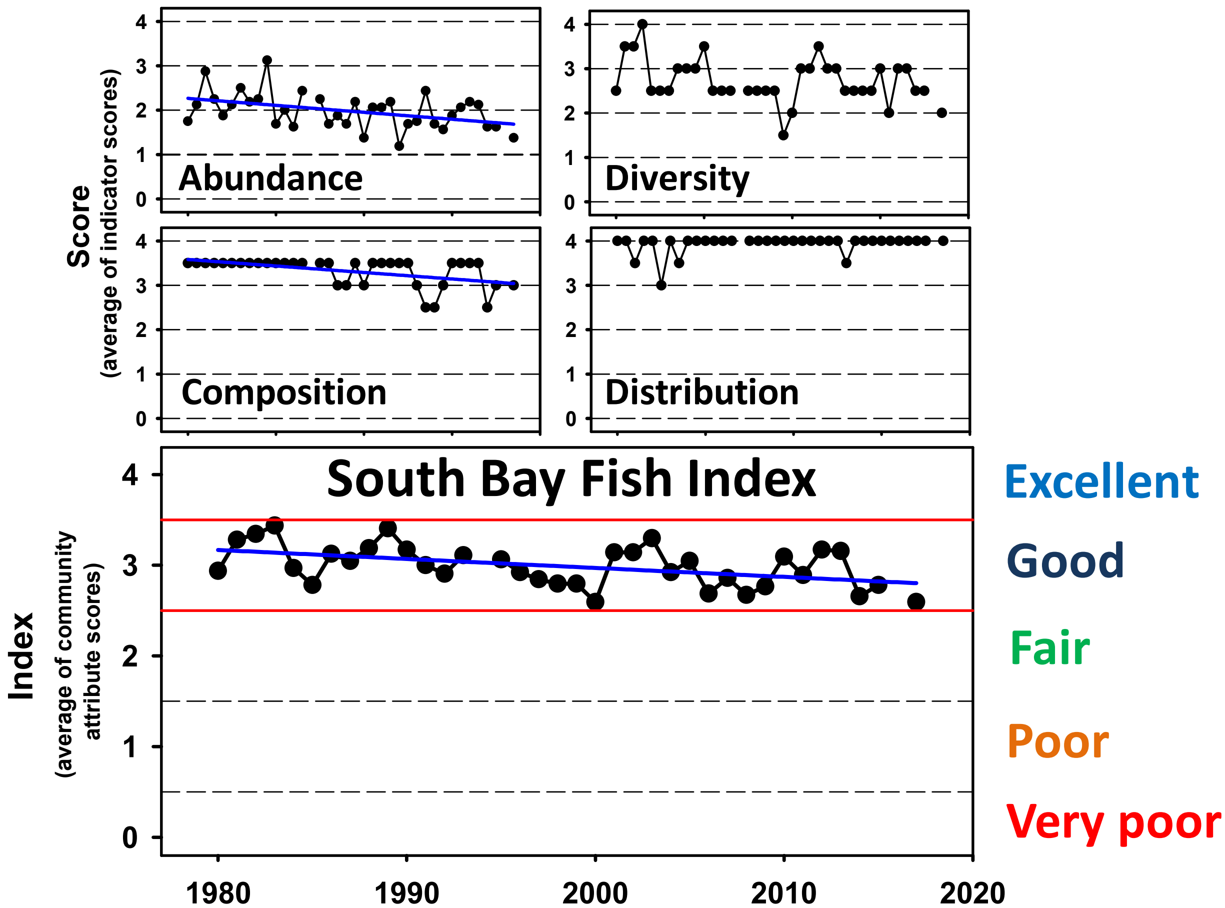

Figure 13. Results for the Bay Fish Index for South Bay for 1980 to 2017. The top four panels show results for the four fish community attributes, expressed as average scores. The large bottom panel shows the Index, calculated as the average of the scores of the four component community attributes. For those results with a significant trend over time, the regression line is shown in blue. For the Index graph, the horizontal red lines and dashed lines show the reference conditions and Index evaluation.

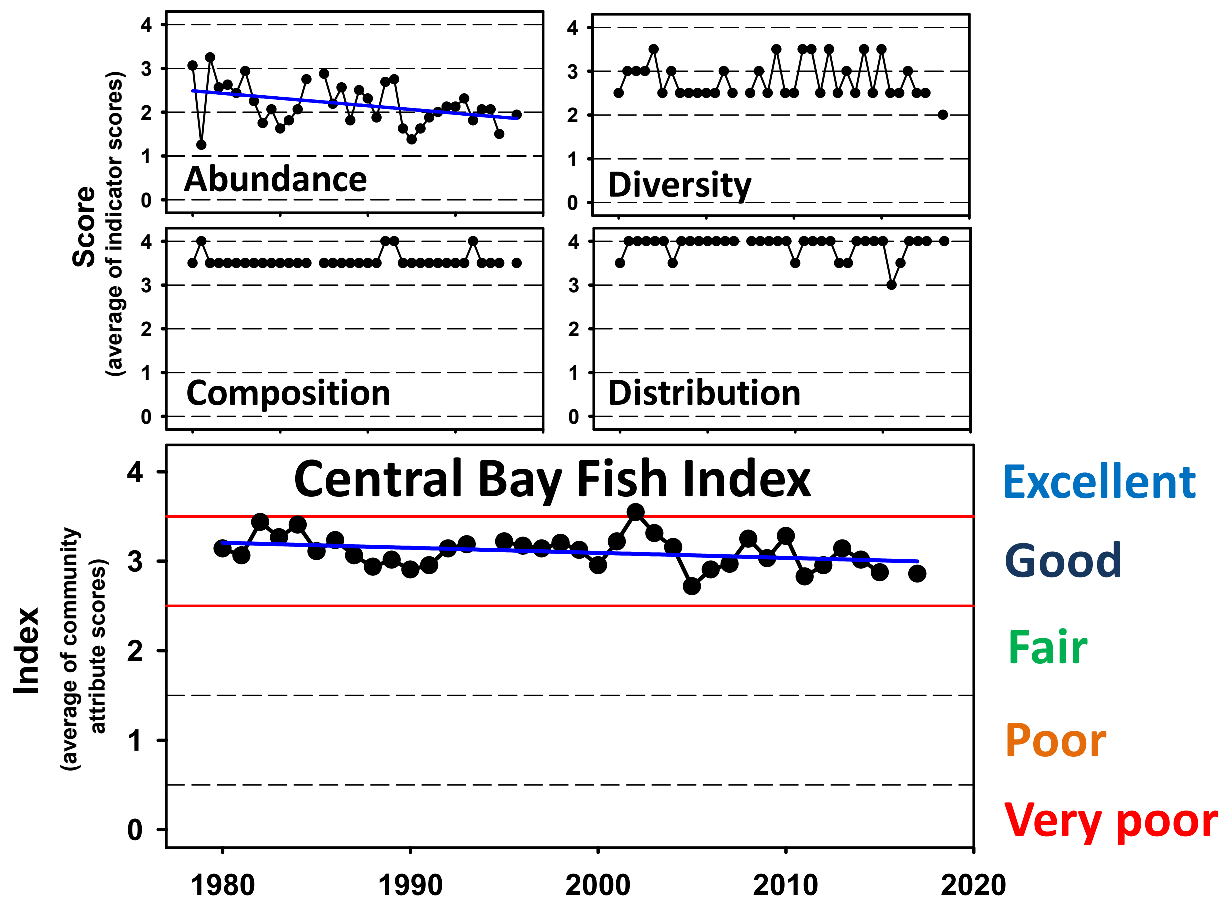

Figure 14. Results for the Bay Fish Index for Central Bay for 1980 to 2017. The top four panels show results for the four fish community attributes, expressed as average scores. The large bottom panel shows the Index, calculated as the average of the scores of the four component community attributes. For those results with a significant trend over time, the regression line is shown in blue. For the Index graph, the horizontal red lines and dashed lines show the reference conditions and Index evaluation.

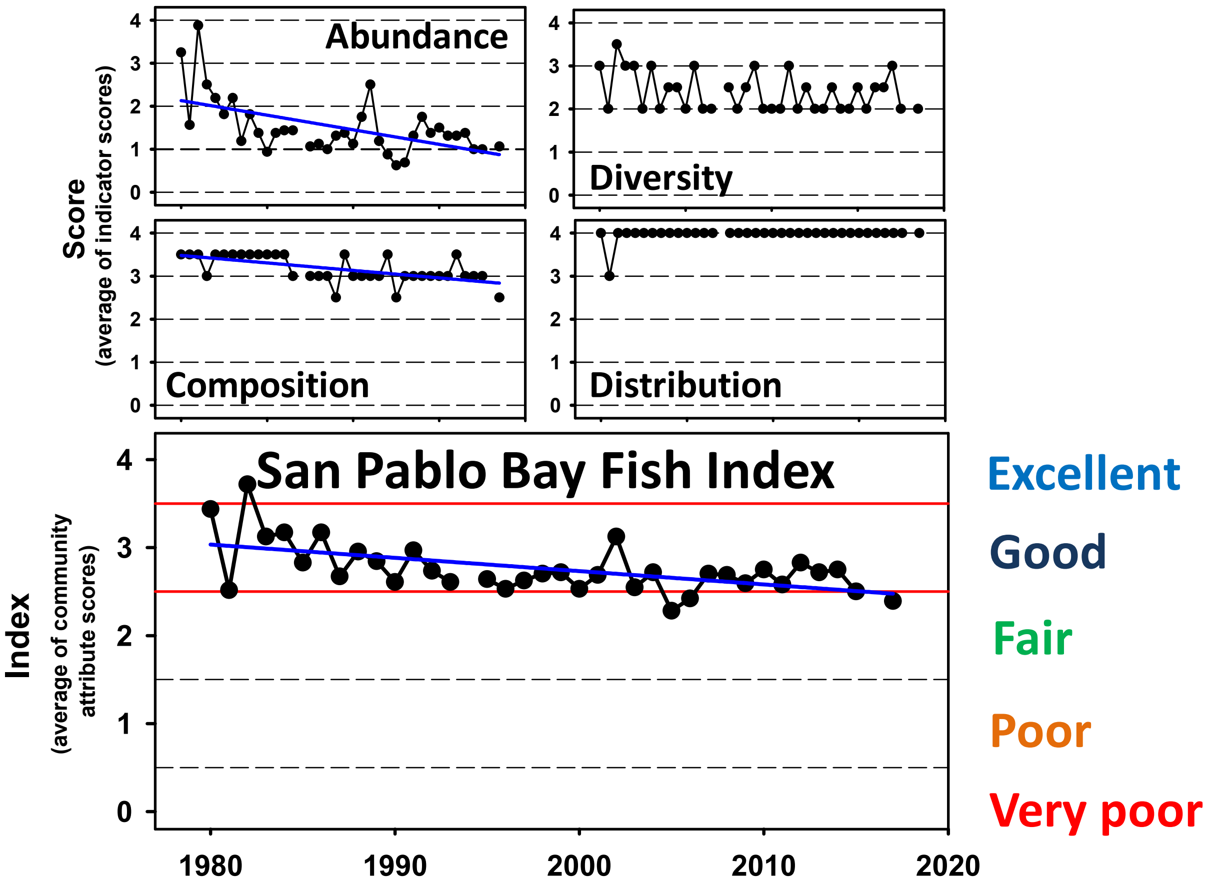

Figure 15. Results for the Bay Fish Index for San Pablo Bay for 1980 to 2017. The top four panels show results for the four fish community attributes, expressed as average scores. The large bottom panel shows the Index, calculated as the average of the scores of the four component community attributes. For those results with a significant trend over time, the regression line is shown in blue. For the Index graph, the horizontal red lines and dashed lines show the reference conditions and Index evaluation.

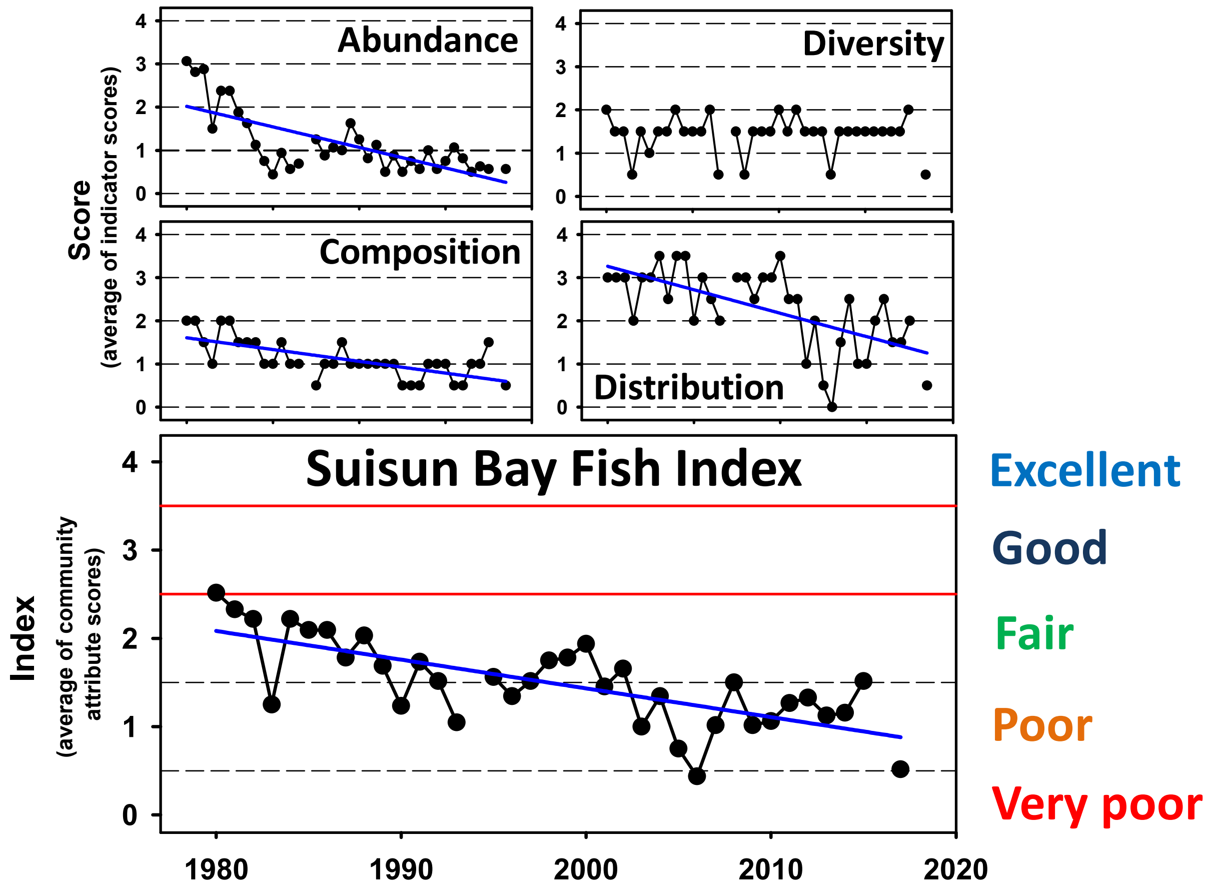

Figure 16. Results for the Bay Fish Index for Suisun Bay for 1980 to 2017. The top four panels show results for the four fish community attributes, expressed as average scores. The large bottom panel shows the Index, calculated as the average of the scores of the four component community attributes. For those results with a significant trend over time, the regression line is shown in blue. For the Index graph, the horizontal red lines and dashed lines show the reference conditions and Index evaluation.

Table 8. Summary of results for the ten Bay Fish indicators (grouped by color for the fish community attributes) and the Bay Fish Index.

Indicator	CCMP Goals Fully met if goal achieved in >67% of years since 1990 Partially met if goal achieved in 33-67% of years Not met if goal achieved in <33% of years	Trend since 1990	Current condition (average for last 5 years)
Pelagic Fish Abundance	Not met in any sub-region	Stable at low levels	Poor (South, Central, San Pablo) Very Poor (Suisun)
Northern Anchovy Abundance	Not met in any sub-region	Stable at low levels (Suisun, San Pablo) Declining (South, Central)	Fair (South, Central) Poor (San Pablo, Suisun)
Demersal Fish Abundance	Fully met (Central) Partially met (South) Not met (San Pablo and Suisun)	Stable (South, San Pablo, Suisun) Increasing (Central)	Excellent (South, Central) Fair (San Pablo) Poor (Suisun)
Sensitive Species Abundance	Not met on any sub-region	Stable at low levels	Poor (all sub-regions)
Native Fish Diversity	Not met in any sub-region	Stable	Good (San Pablo) Fair (South, Central, Suisun)
Estuary-dependent Fish Diversity	Fully met (South, Central) Not met (San Pablo, Suisun)	Stable	Good (South, Central) Fair (San Pablo) Poor (Suisun)
Percent Native Species	Fully met (Central) Partially met (South) Not met (San Pablo, Suisun)	Stable (South, Central) Declining (San Pablo, Suisun)	Good (South, Central) Fair (San Pablo) Poor (Suisun)
Percent Native Fish	Fully met (South, Central, San Pablo) Not met (Suisun)	Stable (South, Central, San Pablo) Fluctuating (Suisun)	Excellent (South, Central, San Pablo) Poor (Suisun)
Pelagic Fish Distribution	Fully met (South, Central, San Pablo) Partially met (Suisun)	Stable (South, Central, San Pablo) Declining (Suisun)	Excellent (South, Central, San Pablo) Poor (Suisun)
Demersal Fish Distribution	Fully met (South, Central, San Pablo) Partially met (Suisun)	Stable (South, Central, San Pablo) Declining (Suisun)	Excellent (South, Central, San Pablo) Poor (Suisun)
Bay Fish Index	**Fully met (South, Central and San Pablo)** **Not met (Suisun)**	**Stable (South, Central, San Pablo)** **Declining (Suisun)**	**Good (South, Central, San Pablo)** **Poor (Suisun)**

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State of the Estuary Report 2019

Technical Appendix

Fish Assemblage Health Indicators for the Upper San Francisco Bay Estuary, including Suisun Bay, Suisun Marsh, and Delta

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and Jonathan Rosenfield, Ph.D., San Francisco Baykeeper

I. BACKGROUND

Evaluations of “health” at the species or population level of biological organization require assessment of different attributes of viability, including abundance, diversity, spatial distribution, and productivity (McElhany et al. 2000). Although these attributes influence each other, they each reveal different and somewhat independent information about a populations’ conservation status. Developing conceptual analogs for these species-level attributes of viability can provide insight into the “health” of ecological communities and species assemblages. Tracking changes in and interactions among a suite of these indicators of assemblage health through time can increase understanding of fish assemblage dynamics and the drivers of those dynamics. Several fish-based indices have been developed to assess ecological quality of estuarine systems; indices commonly include species richness (diversity), abundance, fish condition, and nursery function (productivity) as metrics (Perez-Dominguez et al. 2011).

The San Francisco Estuary Partnership’s State of the Bay report (2011) developed 10 indicators that reflected the health of the pelagic fish assemblage in the larger San Francisco Bay complex (including San Francisco Bay-proper, South San Francisco Bay, San Pablo Bay and Suisun Bay). Although the State of the Bay report (hereafter, SOTB 2011) developed indicators for Suisun Bay, it did not develop indicators of fish assemblage dynamics for many parts of the upper Estuary. The upper Estuary includes Suisun Marsh, the largest brackish marsh on the west coast of North America (CDWR 2014 – http://www.water.ca.gov/suisun/) and the Sacramento-San Joaquin Delta (hereafter, the “Delta”), a tidal freshwater region east of the confluence of California’s two longest rivers. Together Suisun Marsh and the Delta comprise unique habitats in the largest inland estuary on the west coast of North America and serve as home to more than 55 species of fish. In the past 150 years major changes to the upper Estuary’s habitats and patterns of freshwater flow have affected the region’s fish assemblages (The Bay Institute 2016; 2019), as has introduction and invasion of this area by numerous non-native species (Matern et al. 2002; Light and Marchetti 2007).

SOTB (2011) synthesized pelagic fish sampling data from one long-term survey of the Bay’s fish assemblage (the California Department of Fish and Wildlife’s Bay Study) to develop indicators that portrayed long-term patterns in fish abundance, diversity, species composition, and spatial distribution from the Golden Gate to Suisun Bay. In addition, SOTB focused on indices of sub-strata of the fish assemblage (e.g., habitat guilds or trophic guilds) to gain further insight into ecological dynamics of the Bay and the forces driving those dynamics.

The Delta, Suisun Bay, and Suisun Marsh (collectively, the upper Estuary) are important habitats for native fish, including those that may inhabit the nearshore ocean, Bay, and/or Central Valley rivers during other parts of their life cycles. Here, indicators of native abundance and species composition (native vs. introduced) for the upper Estuary were developed for three major habitat types in this region – marsh, deep open water, and shallow, unvegetated waters – to compliment the Bay Fish Index from SOTB

(2011). These indicators enable evaluation of broad changes in fish abundance and species composition, two important attributes of the condition of the fish assemblage.

The 2015 State of the Estuary report developed synthetic metrics of population dynamics and diversity (indicators) of the fish assemblage of the entire Estuary, including the embayments of the San Francisco Bay complex. Like its predecessors (SOTB 2011, SOTER 2015), this State of the Estuary Report presents fish indicators with the expectation that such indicators, correctly designed, can represent multi-species responses to major changes that have occurred in the Estuary and its watershed during the period for which sampling data are available. However, no single indicator is capable of providing a full picture of "health" for ecosystems or even fish assemblages in any region of the Estuary; indeed, factors operating beyond the geographic area of the upper Estuary (e.g. the Central Valley or the nearshore ocean) influence the abundance and diversity patterns described here. Additional indicators, focusing on other attributes of assemblage health, may be needed to relate ecological mechanisms local to the upper Estuary to patterns in the local fish assemblage.

Development of fish assemblage indicators for the upper Estuary was guided by the approach taken in SOTB (2011). Fidelity to that approach (as revised and updated) maximizes the potential to gain a comprehensive understanding of the fish assemblage dynamics across the Estuary as a whole. However, the dominant environments of the upper Estuary are very different physically from the brackish or near marine pelagic environments that dominate much of the San Francisco Bay complex that were the subject of SOTB (2011). The ratio of pelagic habitats to edge (littoral) plus bottom (benthic) habitats is much lower in the upper Estuary than in the San Francisco Bay complex as a whole; for example, the Delta-proper was historically dominated by myriad sloughs (which have now been simplified into a network of channels) that featured extensive shallow water habitat at their edges and productive benthic habitats as well. Because there is interest in restoring shallow, sub-tidal habitats and complex sloughs in the Delta (e.g., California Resources Agency's EcoRestore program), measuring the health of the fish assemblage in the Delta should, to the extent possible, be sensitive to fish that specialize in these shallow, edge and bottom habitats. Also, Suisun Marsh, which neighbors the Delta-proper, is: (a) an ecosystem of great significance; (b) not covered by previous Bay indicators; and (c) somewhat representative of the types of habitats that once existed and may be restored in the Delta. Thus, it makes sense to add indicators of fish assemblage dynamics in Suisun Marsh to this section of the State of the Estuary report.

Why were these indicators chosen?

A suite of indicators of the Delta's fish assemblage was considered with the goal of capturing assemblage-level analogs to the species-level attributes of viability defined by McElhany et al. (2000). In order to be regarded as "healthy", fish assemblages in the upper Estuary should reveal good or excellent levels of:

- Abundance (numbers of native fish)
- Inter-specific diversity, including
    - number of species (richness)

    - distribution of abundance across species (diversity)
    - native species richness vs. non-native species richness
- Intra-specific diversity, including
    - life history diversity (e.g. time and size of migration, alternate life history strategies)
    - phenotypic and behavioral diversity
- Spatial distribution
- Productivity, including
    - life-stage specific survival rates
    - condition (weight/length, etc., e.g. Kimmerer et al. 2005)

Indicators for most of these attributes have not been developed here, but their development in future iterations of this report is recommended.

There are several challenges with interpreting available data for indicators of assemblage health. Several long-term data sets are available for the Delta (Table 1). For the purposes of indicator development, an ideal monitoring program would catch different age classes of all fish species with equal efficiency, over a wide spatial area, year-round, over a long time period, with consistent monitoring methods. No such sampling program exists – each of the existing programs was designed for particular purposes and not to measure or evaluate the health of the entire Delta fish assemblage. All the programs have different sampling biases specific to their respective programs (e.g. associated with sampling gear, detection probabilities, highly mobile species, as well as short- and long- term habitat variation). Even the San Francisco Bay Study (used in the SOTB 2011), which was designed to monitor the health of the entire fish assemblage, did not sample the entire spatial extent of the upper Estuary until recently. Also, this program only samples benthic and pelagic environments. Analyses by the United States Fish and Wildlife Service (USFWS) Delta Juvenile Fishes Program and the Interagency Ecological Program (IEP) have begun to evaluate changes in detection probabilities in selected monitoring programs over time (Mahardja et al. 2017).

To capture the range of different habitats sampled in the upper Estuary across the longest time-series possible, long-term data from three community sampling surveys were analyzed: California Department of Fish and Wildlife's Fall Midwater Trawl (FMWT), the US Fish and Wildlife Service's Juvenile Fishes Program (Beach Seine), and University of California at Davis's Suisun Marsh Fish Survey (Otter trawl). These are not the only sampling programs in the Delta but, taken together, these three sampling programs provide a geographically diverse view of fish assemblage abundance and diversity in a range of habitats over multiple decades (Tables 1 and 2, Figure 1).

Table 1. Comparison of several sampling programs for Upper Estuary Fish Indicators (information adapted from Honey et al. 2004)

Survey	Period of Record (colors = new stations added)	Sampling time during the year	Geographic coverage (colors correspond to "period of record" when new stations added)	Habitat type sampled	Effectively samples body sizes	Consistent methods, gear, and locations	Sampling effective for:	Existing detection probability assessment	Other notes
Fall Mid-water Trawl	1967 1990 1991 2009 2010	Sep-Dec	Western Delta Channels Edge of N. Sac Northern/eastern N. Sac Channel Cache slough	Nearshore channel, open water	>40mm	Generally	**Designed for**: Age-0 Striped Bass **Captures**: Juvenile pelagic	No	Limited to one season, changes in distribution could appear to be abundance changes.
SF Bay Study	1980 1998 1988, 1991, 1994	Year round	Entire estuary, limited sampling in the north, east and south Delta South Suisun Bay San Joaquin River Channel and Delta	Channel, open water & benthic	>40mm	Some sampling missing from late '80s to early 90's	Two gears deployed **Designed for**: Fish and invertebrate assemblage **Captures**: Variety, otter trawl samples demersal fish, in open water	No	Does not sample the northern, eastern and southern Delta well.
Summer Townet	1959 2011 2009	June and then flexible ~August	Southern Delta well, Added channel in north Same as 2011 (2010 skipped)	Benthic	<390 mm Larval fish, juvenile delta smelt	Timing different, gear the same	**Designed for:** age 0 Striped Bass **Captures**: Pelagic, young striped bass	No	Irregular start and end dates, short sampling period in summer.
Salvage	1957 - Tracy 1968 - Skinner	Year round	Two locations South Delta	NA	Juvenile to adult of some species	Yes	**Designed for:** Enumerating entrainment, medium to large fish	No	Single location sampling, dependent on water export, not all fish identified.
Suisun Marsh Fish Survey	1980 1994	Year round	Suisun Marsh eastern Suisun Marsh	Benthic, marsh	Juvenile to adult of some species	Some change in sites, methods and gear relatively consistent	**Designed for:** Marsh habitat, demersal fish **Captures:** May capture pelagic fish in some sloughs	No	Problems with large and small sloughs for pelagic fish.
Delta Juvenile Fish Sampling	1976. 1990's 2002	Year round (more consistent after 1995)	Entire Delta Larger extent Site on the San Joaquin	Littoral zone, floodplain, open water in three locations	<25 mm Juvenile to Adult of some species (smaller fish than 25mm caught, but ID suspect)	Number of locations changed, methods generally consistent	**Designed for:** Salmon fry and cyprinids **Captures:** Most small to medium sized fish (<~150mm) in the littoral zone	Yes (not published)	Year round only since 1992 Boat ramp sites may bias results, problems with inter-annual comparisons of catch trends ID of fish less than 25mm suspect

Table 2. Sampling programs used as data sources for calculation of for Upper Estuary Fish Indicators in different regions and habitats of the Delta and Suisun Marsh.

<table>
<tr><td></td><td colspan="3">Habitats</td></tr>
<tr><td>Region</td><td>Marsh/Demersal</td><td>Pelagic</td><td>Littoral</td></tr>
<tr><td>Suisun Marsh</td><td colspan="2">UC Davis Suisun Marsh Fish Survey (Otter Trawl)</td><td></td></tr>
<tr><td>Suisun Bay</td><td></td><td rowspan="2">CDFW Fall Midwater Trawl</td><td></td></tr>
<tr><td>Central-Western Delta</td><td></td><td rowspan="3">U.S. Fish and Wildlife Service Delta Beach Seine</td></tr>
<tr><td>Northern Delta</td><td></td><td></td></tr>
<tr><td>Southern Delta</td><td></td><td></td></tr>
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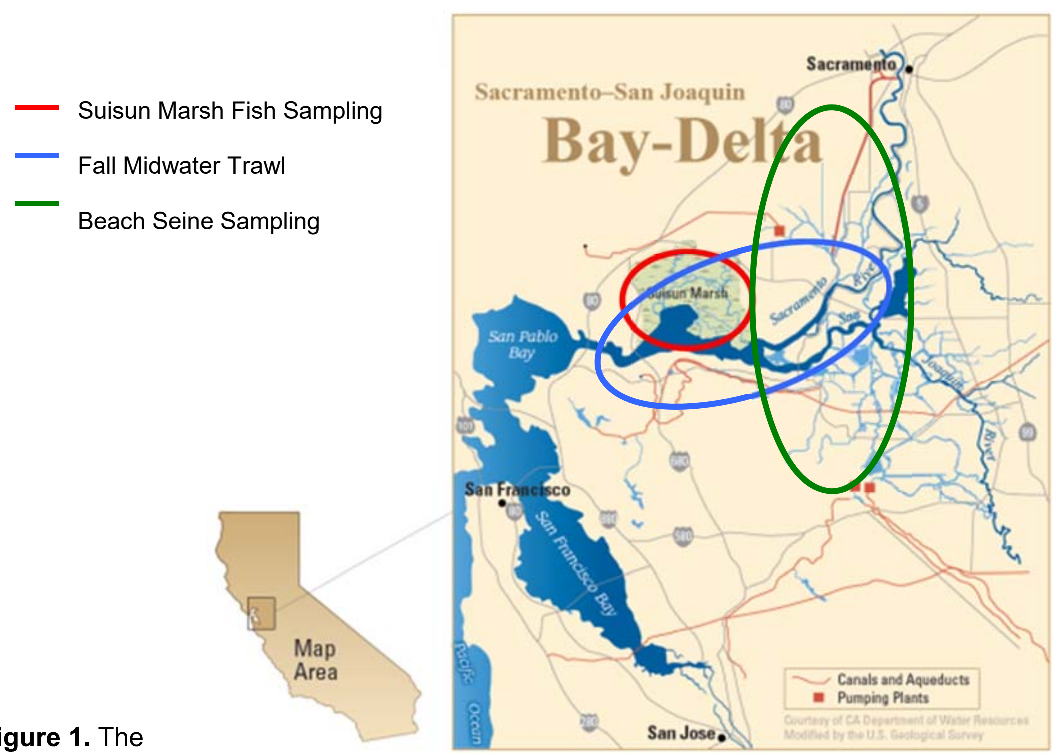


Figure 1. The Sacramento-San Joaquin Bay-Delta is where Central Valley Rivers meet the larger San Francisco Bay Estuary complex. Because the upper estuary is so large and contains a variety of habitats, the indicators of fish assemblage health in this area were calculated from three sampling programs that use different methods to survey several habitats and regions of the upper estuary (Image accessed 1/12/14 at http://ca.water.usgs.gov/news/2012/SanFranciscoBayDeltaScienceConference.html).

We prioritized development of indicators of fish abundance and community composition for the upper Estuary (Table 6). Future iterations of the SOTER report should incorporate data from other long-term sampling programs. Data from additional sampling programs may help complete and unify the abundance and species composition indices presented here and they are necessary for developing additional indices that can link fish assemblage health in the upper Estuary to local ecosystem processes (e.g., productivity, spatial distribution, guild-specific evaluations, etc.).

The SOTB (2011) provided fish abundance indicators for pelagic, demersal, and sensitive fish species. Additionally, these indicators were measured separately within each of four regions. Here, separate indicators of abundance and assemblage diversity were produced for marsh species, pelagic species of the Delta's open channels, and littoral species in Suisun Marsh and the Delta-proper. Where appropriate, within each sampling program/habitat type, separate indices were produced to characterize sub-regions designated by the Interagency Ecological Program (IEP; Figure 2). Results for the different sub-regions were compared to determine whether data could be combined among regions within a sampling program (i.e. to determine whether regional trends were consistent). Due to the non-overlapping strengths and weaknesses of the different sampling programs available for this analysis (Table 1, Table 2), no effort was made to aggregate all indicators into a single index of fish assemblage health in the upper Estuary.

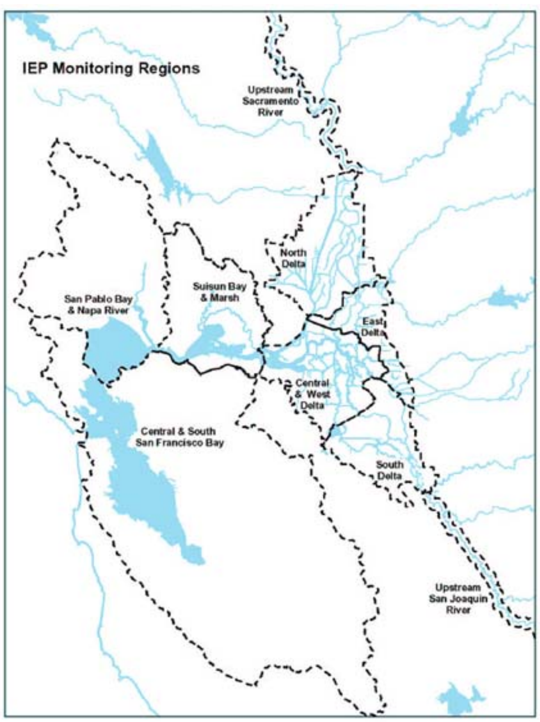


Figure 2. The Interagency Ecological Program's San Francisco Estuary Monitoring Regions (Figure from Honey et al. 2004, p. 6).

How were proposed indicators vetted with experts?
The methods used to calculate the SOTER (2015) indicators of health for the fish assemblage of the upper Estuary were presented to, and sequentially peer-reviewed by, a group of experts in this region's fishes and fish sampling programs. Additional input was received from data administrators for the various sampling programs. A list of reviewers who provided input and direction through small group discussion, one-on-one discussions and written comment is provided below.

Name	**Agency/Organization**
Randall Baxter	California Department of Fish and Wildlife
Matt Dekar	United States Fish and Wildlife Service
Sam Harader	Delta Science Council
Daniel Huang	Delta Science Council
Kristopher Jones	California Department of Water Resources
Joseph Kirsch	United States Fish and Wildlife Service
Teejay O'Rear	University of California, Davis
Ted Sommer	California Department of Water Resources
Jonathon Speegle	United States Fish and Wildlife Service
Hildie Spautz	California Department of Fish and Wildlife
Christina Swanson	Natural Resources Defense Council
Susie Tharatt	United States Fish and Wildlife Service
Darcy Austin	Delta Stewardship Council

II. DATA SOURCES

Suisun Marsh abundance and species composition indicators.
Suisun Marsh Fish Survey (Otter Trawl, UCD).
Suisun Marsh indicators were calculated with data collected by the Suisun Marsh Fish Survey (Moyle et al. 2014). The survey has been conducted monthly since 1979 in Suisun Marsh, sampling 17 sites consistently since 1980 (Figure 3, Tables 1 and 3); four additional sampling locations (which were not sampled as consistently in early years) were included in the data set as they provided greater spatial coverage, but did not materially affect long-term trends in catch-per-unit-effort data (T. O'Rear, personal communication). An otter trawl was used to sample primarily benthic, and pelagic fishes across the spatial extent of the Marsh in large and small sloughs; net tows in large sloughs lasted for 10 minutes and in small sloughs, for 5 minutes (https://watershed.ucdavis.edu/project/suisun-marsh-fish-and-invertebrate-study). Because the size of the net (1m x 2.5m opening) was large relative to the width and depth of some sloughs it samples, this survey samples most of the water column in some areas – thus, these data provided a relatively good indication of fish occupying open water habitats in smaller Marsh sloughs.

This sampling program provided data from a critically important ecosystem, adjacent to the Delta-proper that is included in many discussions of "Delta" habitat restoration (e.g. the Bay Delta Conservation Plan). The habitats present in the Marsh, though modified, are similar to those that would have existed in the historical Delta and those that may be restored in a future Delta. The Suisun Marsh Fish Survey has been particularly effective at sampling native species that rely on shallow, marsh habitats (e.g., splittail (*Pogonichthys macrolepidotus*), tule perch (*Hysterocarpus traski*) and at detecting new invaders to the estuary ecosystem (Matern et al. 2002). Thus, data from this system are critical to any long-term assessment of the upper Estuary's fish assemblage. On the other hand, the Suisun Marsh Survey did not provide a comprehensive image of the Delta fish assemblage's health because it only sampled in the Marsh and therefore focused on species that are common in marsh slough habitats. Also, like any fish community sampling program, the Suisun Marsh Survey gear and methodology only reliably captured fish within a particular size range (generally ~35mm-250mm).

Figure 3. Locations of stations that have been sampled consistently by UC-Davis' Suisun Marsh Fish Survey. Map created by Amber Manfree. Fish assemblage indicators for Suisun Marsh were calculated from the Suisun Marsh Fish Survey data.

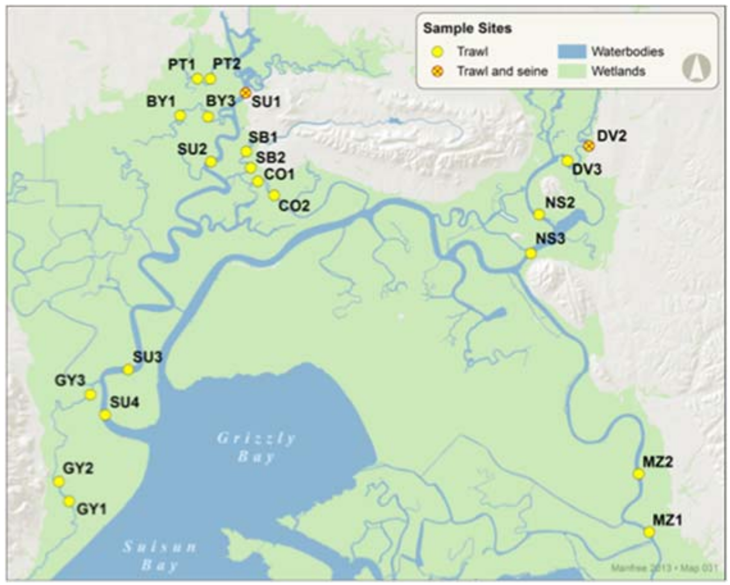


Table 3. Suisun Marsh Fish Survey sampling stations and total numbers of surveys for the 1980-2018 period of record used to calculate indicators (data from UCD Suisun Marsh Fish Survey Otter Trawl; provided by T. O'Rear). Catch per trawl indicators were based on data from 21 sites (despite the fact that only 17 were sampled consistently) following the reporting protocol of the Suisun Marsh Survey. Annual trends in CPUE are not affected by the inclusion of the four sites that were sampled less consistently (T. O'Rear, personal communication).

Region	Sampling Stations	Number of Surveys
Suisun Marsh	BY1, BY3, CO1, CO2, DV2, DV3, GY1, GY2, GY3, NS2, NS3, MZ1, MZ2, PT1, PT2, SB1, SB2, SU1, SU2, SU3, and SU4	8,403

Beach Zone abundance and species composition indicators.

Delta Juvenile Fishes Program (Beach Seine, USFWS).

This survey program sampled littoral habitat throughout the spatial extent of the Delta-proper, throughout the year (Figure 4, Table 1 and 4) and was originally designed to sample juvenile salmon. Fish were caught in a seine that is 15.2m wide as it was pulled manually through shallow water (<1.3m) areas that have little bottom vegetation or obstructions (http://www.fws.gov/stockton/jfmp/Docs/Data%20Management/1214/Metadata%20(Updated%20September%2009,2014).doc). These habitats, and fish that specialize in them, are usually sampled ineffectively by gear towed behind a boat. Data were collected weekly or bi-weekly since 1976. Because year-round, monthly sampling became consistent in 1995, only data from 1995 onward were used in constructing indicator time trends from this data set. In order to develop a comprehensive image of dynamics in the Delta's fish assemblage, findings from this survey must also be considered in the context of other surveys, because sampling only occurred in the littoral zone and the gear captures fish efficiently only within a certain (species-specific) body size range (generally ~30mm-200mm).

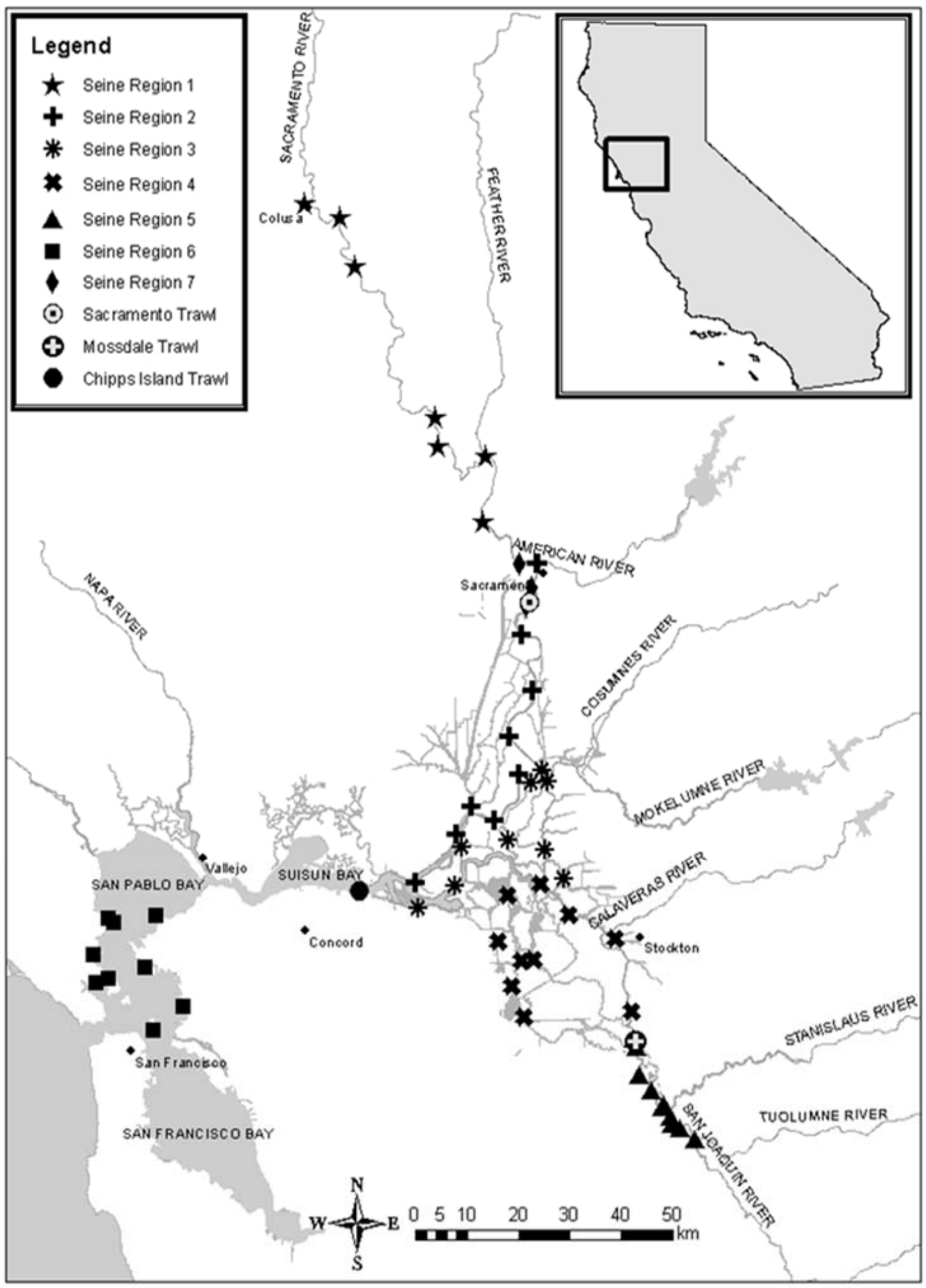


Figure 4. Sampling station locations of the USFWS Beach Seine Survey used to calculate Delta Beach Zone fish indicators. Only 1995-2018 data from four IEP regions, *North, East, South and Central-West) were used. Map from USFWS Delta Juvenile Fishes Program (http://www.fws.gov/stockton/jfmp/Docs/Data%20Management/12-14/Metadata%20(Updated%20September%2009,2014).doc).

Table 4. Delta Beach Zone sampling stations and total numbers of surveys for the 1995-2018 period of record used to calculate the indicators (USFWS Delta Juvenile Fishes Program, Beach Seine Survey, data provided by J. Speegle). *Indicates that the station is a substitute location for a station that was not accessible at the survey time.

Regions from the Delta Beach Seine Survey	Sampling Stations	Number of Surveys (1995-2018)
North Delta	**SR043W** **SR049E** **SR057E** **SR014W** **SR062E** **SR055E** **SR055A*** **SS011N**	7434
East Delta	**XC001N** **GS010E** **SR017E** **DS002S** **SR024E** **LP003E** **SF014E**	6331
South Delta	**SJ063W** **SJ063E*** **OR014W** **SJ041N** **SJ051E** **SJ068W** **SJ072E*** **SJ070N*** **OR003W** **SJ032S** **SJ026S** **SJ056E** **OR019E** **OR001X*** **SJ074W** **SJ074A*** **OR023E** **WD002W** **WD002E*** **SJ058W** **SJ058A*** **SJ058E***	8386

	MR010W MR010A* SJO56E	
Central-West Delta	SJ001S MK004W TM001N SJ005N SR012W* MS001N MS001A* SR012E	5283

Upper Estuary Pelagic Zone abundance and species composition indicators.
*Fall Midwater Trawl (midwater trawl, CDFW)***.**
This survey sampled open-water, pelagic species in the upper Estuary (San Pablo Bay to the western Delta) every month from September through December at fixed sampling locations (Figure 5; Table 1 and Table 5). Methods were relatively consistent over a long time period (since 1967); however, within the upper Estuary, many new sites were added since 1967. In addition, because the Fall Midwater Trawl (FMWT) only sampled during one season and did not sample littoral or benthic habitats that form a relatively large proportion of available space for fish in the upper Estuary, these data did not present a comprehensive picture of the entire fish assemblage in this region. On the other hand, the fact that the FMWT sampled pelagic waters of Suisun Bay and the Central-West Delta for such an extended period means that these data provided an excellent complement to results for Suisun Bay recorded by the Bay Study (e.g., this State of the Estuary Report; SOTB 2011).

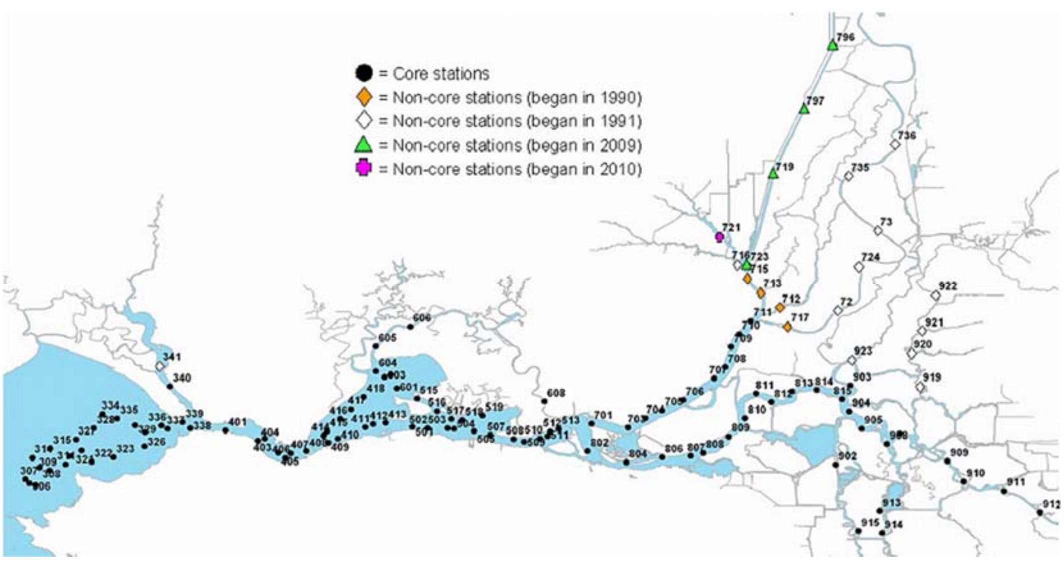


Figure 5. Locations of the sampling stations for the CDFW Fall Midwater Trawl survey used to calculate the Upper Estuary Pelagic Zone Fish Indicators. Only data from core stations, collected 1967-2018, in Suisun Bay and the Central-West Delta were used for calculations (Map from http://www.dfg.ca.gov/delta/data/fmwt/stations.asp).

Table 5. Sampling Stations and total numbers of surveys for the 1967-2018 period of record used to calculate Pelagic Zone Indicators (data from CDFW Fall Midwater Trawl, accessed at ftp://ftp.dfg.ca.gov/).

Regions from Upper Estuary Open Water	Sampling Stations	Number of Surveys (1967-2018)	Years Excluded from Analysis for Partial Sampling
Suisun Bay	401, 403-418, 501-505, 507-513,515-519, 601-606, 608	7896	1969-1972 and 1976 (Limited sampling) 1974 and 1979 (no sampling)
Central and West Delta	701, 703-711, 802, 804, 806-815, 902-906, 908-915	5880	1969 – 1973, 1975 and 1984 (Limited sampling) 1974 and 1979 (no sampling)

III. INDICATOR EVALUATION

Evaluating indicator trends in ecosystem health requires establishing reference conditions (*what value was the indicator in the past?),* designating thresholds (*what would be considered "good" or "poor"?),* and assessing the significance of any trends (*how does the current condition compare to the established thresholds*; Perez-Dominguez et al. 2011). Reference conditions may include "primary" reference conditions that reflect indicator status in a known historical period (SOTB 2011) or aspirational objectives – specific, measureable, achievable, relevant, and time-bound (S.M.A.R.T.) articulations of recovery goals. The San Francisco Estuary Partnership's Comprehensive Conservation and Management Plan (CCMP, SFEP 2007) calls for "recovery" and "reversing declines" of estuarine fish and wildlife but does not provide quantitative objectives that would allow for indicators to be referenced to desired outcomes. Thus, the indicators developed here are benchmarked to "primary reference conditions" (SOTB 2011) calculated from historical data. The primary reference conditions provide a scale against which improvement or deterioration can be evaluated. Identification of a primary reference condition does not indicate that such a condition is the desired state for the Estuary's fish assemblage; rather it provides a retrospective baseline with which one can evaluate the direction and relative magnitude of change.

For each indicator, primary reference conditions were established based on the earliest data available for each of the sampling programs studied, maximum measured values for the upper Estuary or sub-region, recognized and accepted interpretations of ecological conditions and ecosystem health (e.g., native versus non-native species composition), and/or best professional judgment. Wherever possible, indicator scoring was accomplished using methods equivalent or parallel to those used in SOTB (2011). In the case of abundance indicators, scores were calibrated to account for differences in absolute values of indicators among the sampling programs or sub-regions. The reference conditions for the assemblage composition indicators were based on the ecological relationship between the prevalence of non-native species and ecosystem and habitat condition (SOTB 2011). For these assemblage composition indicators, the value of the reference condition associated with a particular score (e.g., “good”, “poor”) was maintained in the upper Estuary at the same level as identified in SOTB (2011).

Following SOTB (2011), five intermediate reference conditions were created to provide a scale for assessing deviations from the primary reference condition. In order to ensure that the different levels represented meaningful differences in the measured indicator values, the range of indicator values assigned to each intermediate reference conditions was based on observed levels of variation in the measured indicator values. For each indicator, an assessment of current status was based on indicator trends and the average score of the most recent 5 years of the data set.

IV. INDICATORS

The following indicators were calculated for three regions of the Upper Estuary.

Table 6. Fish community characteristics and indicators calculated.

Fish Community Characteristics	Indicators
Abundance (Natives)	• Suisun Marsh native fish abundance • Pelagic Zone native fish abundance Regions: Central-West Delta and Suisun Bay • Beach Zone native fish abundance Regions: North, South, East, Central-West Delta
Species composition	• Percent Native Fish • Percent Native Species
Food Web Productivity (All fish)	• Suisun Marsh sum of standardized total fish abundance • Pelagic Zone sum of standardized fish abundance Regions: Central-West Delta and Suisun Bay • Beach Zone sum of standardized fish abundance Regions: North, South, East, Central-West Delta

A. Abundance Indicators
1. Rationale

The most obvious measure of fish abundance is a simple index of the number of fish caught. Abundance of native fish can be an indicator of aquatic ecosystem health (see full explanation in the SOTER Fish Technical Appendix 2015 and Wang and Lyons 2003, Harrison and Whitfield 2004).

Because the Estuary’s fish assemblage is influenced by processes affecting fish production elsewhere (upstream in the Central Valley’s rivers or in the nearshore ocean), caution should be used in relating these abundance indices to local ecosystem processes. Additional indicators (e.g. spatial distribution, survival/productivity) will be useful for connecting trends in fish abundance to ecological drivers occurring within the Delta. For example, we constructed species composition indicators, which highlight the proportion of native to non-native species, to compliment the total abundance indicators. Studying both trends in native fish abundance and assemblage composition may help to reveal ecological changes underlying changes in total abundance. This approach tracks that employed by SOTB (2011) for its abundance indicators.

Limitations and future amendments to the abundance indicators
Catch-per-unit-effort (e.g. fish/trawl, fish/volume) is a measure of fish abundance that standardizes, within sampling programs and habitats, for variation in sampling effort across years. Use of this density metric as an indicator of total abundance relies on numerous assumptions. For example, use of the CPUE metric assumes that the density measured by the sampling program is representative of an "average" density across the region and habitat being sampled; if fish are more or less aggregated around sampling stations than they are throughout the area represented by those sampling stations, the relationship of CPUE to total abundance may be inaccurate. This is especially true if sampling stations are not chosen randomly for each sampling set or across years, as is the case with most fish sampling programs in this estuary. Also, average CPUE for all fish says nothing about the type of fish being caught, nor fish biomass. Because these are synthetic indicators, they also obscure particular relationships and trends that are occurring within sub-sets of the fish assemblage (e.g. individual species trends). Finally, as mentioned above, changes in indicators are not necessarily indicative of mechanistic drivers *within* the region being sampled, as migratory fish species' populations may be responding to conditions elsewhere in their life cycle. However, fish density (and abundance) does represent a snapshot of conditions experienced by fish and other species in the sampling zone at a given time. Therefore, CPUE metrics present a partial picture of the status of the local fish assemblage.

Future iterations of the SOTER should consider creating separate abundance indices for different ecological guilds (e.g., resident, nursery dependent, migratory fish, or sensitive species) to provide a more focused view of population trends within these different ecological groups. SOTER (2015) segregated abundance into native vs. non-native species and analyzed differences in trends across these two groups; this is one example of the additional information to be gained by studying subsets of the entire assemblage. Indicators that would present a more comprehensive view of ecosystem health when combined with abundance and diversity indices should be explored. For example, indicators of within Delta survival and spatial distribution may provide greater insight into local ecosystem processes affecting fish distribution. Also, measuring abundance as biomass would more accurately represent fish productivity and carrying capacity in the sampling zone.

2. Methods and Calculations, Assumptions, and Uncertainties

Methodology for constructing fish abundance indicators in this report followed SOTER (2015), which drew upon methodology described in SOTB (2011).

Suisun Marsh Fish Abundance Indicator

The Suisun Marsh Abundance Indicator was calculated as catch per trawl for each year (1980-2018):

fish/trawl = [native fish caught in year-x]/[trawls year-x]

This monitoring program did not provide estimates of the volume of habitat sampled but maintained a relatively consistent sampling protocol over the sampling period; thus, standardizing effort by the number of trawls was deemed appropriate (Matern et al 2002; T. O'Rear, personal communication, 2014). Data from sampling locations (n=17-21) that have been sampled throughout all or most of the sampling program (1980-2018) were used here (Table 4). Although there are ecological gradients, e.g. salinity, in the Marsh that might affect fish diversity and abundance (and the sampling program distinguishes between small sloughs and large sloughs), we analyzed the Marsh as one ecological unit without sub-regions.

Delta Beach Zone Fish Abundance Indicator

Delta Beach Zone Fish Abundance Indicators were produced for each of four, pre-determined IEP regions in the Delta (Figures 2 and 4). The sampling localities included in each region are identified in Table 4. Within each region, an abundance index was calculated as (1995-2018):

fish/10,000 m^3 = [native fish caught in year-x] / [total volume sampled in year-x] x(10,000)

The volume sampled was calculated as: (seine length x seine width x seine depth)/2 (http://www.fws.gov/stockton/jfmp/Docs/Data%20Management/12-14/Metadata%20(Updated%20September%2009,2014).doc). Because monthly sampling became routine in 1995, we constructed abundance indicators for only 1995-2018 using data from every month of the year. Native fish abundance in each of the Delta Beach Zone regions displayed broadly similar patterns (Figure 9); however, although the scores between regions were mostly well-correlated (Table x); the North Beach Zone pattern was only marginally correlated with two other regions. As a result, the Native Fish Abundance Indicator was scored and displayed separately for each region of the Delta.

Upper Estuary Pelagic Zone

Upper Estuary Pelagic Zone Abundance Indicators were calculated using data from the Fall Midwater Trawl program, which samples fixed stations in the upper Estuary from September-December (Figure 5; Stevens 1977). We divided sampling stations into two IEP regions, Suisun Bay and the Central-West Delta and calculated a separate indicator for each region; sampling results from San Pablo Bay were excluded from our analyses. Sampling locations in each region are identified in Table 5. Within each region, an abundance index was calculated as (1967-2018):

fish/10,000 m^3 = [(native fish caught in year-x)/(total trawls in year-x * tow volume m^3)] *(10,000)

Sampling locations in the Delta-proper have been added to the FMWT several times over the program's existence (Table 1; Honey et al. 2004); however, in order to maximize the length of the time series, we restricted the sites used to create our abundance indicators to those that were sampled continuously in the years 1967-2018 ("Core 1" stations). Abundance indicators were not calculated in years where sampling effort (number of trawls) was much less (<68%) than the long-term modal average of trawls. Years included in our calculations are described in Table 5.

Total catch was divided by actual tow volume for 1985-2018 to produce a catch-per-unit-effort value for each year. Tow volume was not measured consistently for years prior to 1985; so, for this earlier sampling period annual catch was divided by the mean tow volume from the 1985-2018 period and, we also displayed annual catch by the 25^{th} and 75^{th} percentiles of 1985-2018 tow volume to bracket our estimated CPUE. Assumptions regarding average tow volume in the time series pre-1985 did not have any effect on scoring of this indicator (see, results section).

Reference Conditions

Wherever possible, the 1980-1989 average index value was used as the primary reference condition for abundance indicators. This is consistent with the Bay fish indicators (SOTB 2011). In the SOTB (2011), the 1980-1989 average is considered "good", recognizing that some fish populations were already in decline by the 1980's. A five-tier scale rates annual average CPUE over time from "very poor" to "excellent". Any individual year in the record may be compared to the reference condition and scored. Following production of SOTER 2015, data errors were detected which affected the calculation of reference conditions. These errors may have arisen in the official data or during transmission or processing. Data and quantitative reference conditions presented here have been corrected to reflect the latest official data.

Suisun Marsh

The 1980-89 average catch per trawl was established as the primary reference condition for this data set. These were the earliest years for which data was available. Following SOTB (2011), the 5-tiered scoring system was developed for other intermediate reference conditions as described in Table 7.

Table 7. Quantitative reference conditions and associated interpretations for the Suisun Marsh Fish Abundance Indicator.The average score during the primary reference period, which corresponds to "good" conditions, is in bold and all other reference conditions are calculated from that value (e.g. "excellent" is 150% of the 1980-1989 value). [Data management errors in calculating this indicator for SOTER 2015 were corrected here; thus, reference condition thresholds have changed slightly from those depicted in SOTER 2015].

Abundance Indicators Suisun Marsh Catch Per Effort (Data: UCD Suisun Marsh Fish Survey, Otter Trawl)			
Quantitative Reference Condition	**Interpretation**	**Low End of Range**	**High End of Range**
>150% of the 1980-1989 Average	Excellent	>23.1	N/A
>100% of the 1980-1989 Average	**Good**	**>15.4**	**23.1**
>50% of the 1980-1989 Average	Fair	>7.7	15.39
>15% of the 1980-1989 Average	Poor	>2.31	7.69
<15% of the 1980-1989 Average	Very Poor	N/A	<2.31

Delta Beach Zone

The Beach Zone was not consistently sampled year-round until 1995. Average CPUE from 1995-2004 was established as the primary reference condition for the Delta Beach Seine sampling program. The primary reference condition, during this period was assigned a "poor" score to match the average score of the Suisun Marsh and Pelagic Zone abundance indicators during the same period. Following SOTB (2011), the 5-tiered scoring system was developed for other intermediate reference conditions. Evaluation thresholds for these scores are described in Table 8.

Table 8. Quantitative reference conditions and associated interpretations of the results of the Delta Beach Zone fish abundance indicator. For each region in the Delta, the average of the primary reference condition, which corresponds to "poor" conditions, is in bold. The primary reference condition was rated "poor" to correspond to scores for the Pelagic and Marsh abundance indicators during 1995-2004.

Abundance Indicators Delta Beach Zone Catch Per Effort (Data: USFWS Delta Juvenile Fishes Program, Beach Seine Survey)			
North Delta			
Quantitative Reference Condition	**Interpretation**	**Low End of Range**	**High End of Range**
> 150% of Good	Excellent	> 27976	NA
> (1995-2004 Average / 15%)	Good	> 18650	27976
> 50% of Good	Fair	> 9325	18650
> **1995-2004 Average**	**Poor**	**> 2798**	**9325**
< 1995-2004 Average	Very Poor	< 2798	NA
East Delta			
Quantitative Reference Condition	**Interpretation**	**Low End of Range**	**High End of Range**
> 150% of Good	Excellent	> 27127	NA
> (1995-2004 Average / 15%)	Good	> 18084	27127
> 50% of Good	Fair	> 9042	18084
> **1995-2004 Average**	**Poor**	**> 2713**	**9042**
< 1995-2004 Average	Very Poor	< 2713	NA
South Delta			
Quantitative Reference Condition	**Interpretation**	**Low End of Range**	**High End of Range**
> 150% of Good	Excellent	> 9619	NA
> (1995-2004 Average / 15%)	Good	> 6412	9619
> 50% of Good	Fair	> 3206	6412
> **1995-2004 Average**	**Poor**	**> 962**	**3206**
< 1995-2004 Average	Very Poor	< 962	NA
Central-West Delta			
Quantitative Reference Condition	**Interpretation**	**Low End of Range**	**High End of Range**
> 150% of Good	Excellent	> 19852	NA
> (1995-2004 Average / 15%)	Good	> 13235	19852
> 50% of Good	Fair	> 6617	13235
> **1995-2004 Average**	**Poor**	**> 1985**	**6617**
< 1995-2004 Average	Very Poor	< 1985	NA

Pelagic Zone of the Upper Estuary

The 1980-89 average catch per effort was established as the primary reference condition for this data set. Following SOTB (2011), the 5-tiered scoring system was developed for other intermediate reference conditions as described in Table 9.

Table 9. Quantitative reference conditions and associated interpretations for the results of the Upper Estuary Pelagic Zone Fish Abundance Indicator. The average during the primary reference condition, which corresponds to "good" conditions, is in bold. [Data management errors in calculating this indicator for SOTER 2015 were corrected here; thus, reference condition thresholds have changed slightly from those depicted in SOTER 2015]

Abundance Indicators Pelagic Zone Catch Per Effort (Data: CDFW Fall Midwater Trawl)			
Central-West Delta			
Quantitative Reference Condition	**Interpretation**	**Low End of Range**	**High End of Range**
>150% of the 1980-1989 Average	Excellent	>12.1	NA
>100% of the 1980-1989 Average	**Good**	**>8**	**12.1**
>50% of the 1980-1989 Average	Fair	>4	8
>15% of the 1980-1989 Average	Poor	>1.2	4
<15% of the 1980-1989 Average	Very Poor	NA	<1.2
Suisun Bay			
Quantitative Reference Condition	**Interpretation**	**Low End of Range**	**High End of Range**
>150% of the 1980-1989 Average	Excellent	>113.5	NA
>100% of the 1980-1989 Average	**Good**	**>76**	**113.5**
>50% of the 1980-1989 Average	Fair	>37.8	76
>15% of the 1980-1989 Average	Poor	>11.3	37.8
<15% of the 1980-1989 Average	Very Poor	NA	<11.3

3. Abundance Results

Suisun Marsh

Native fish abundance in Suisun Marsh declined over the period of record but have rebounded slowly since the mid-1990's (Figure 6). Levels detected in the first few years of the survey were "excellent" or "good", but became consistently "fair" or "poor" during the late 1980's and early 1990's. Over the last five years, conditions reflected in the indicator have improved from from "poor" to "fair".

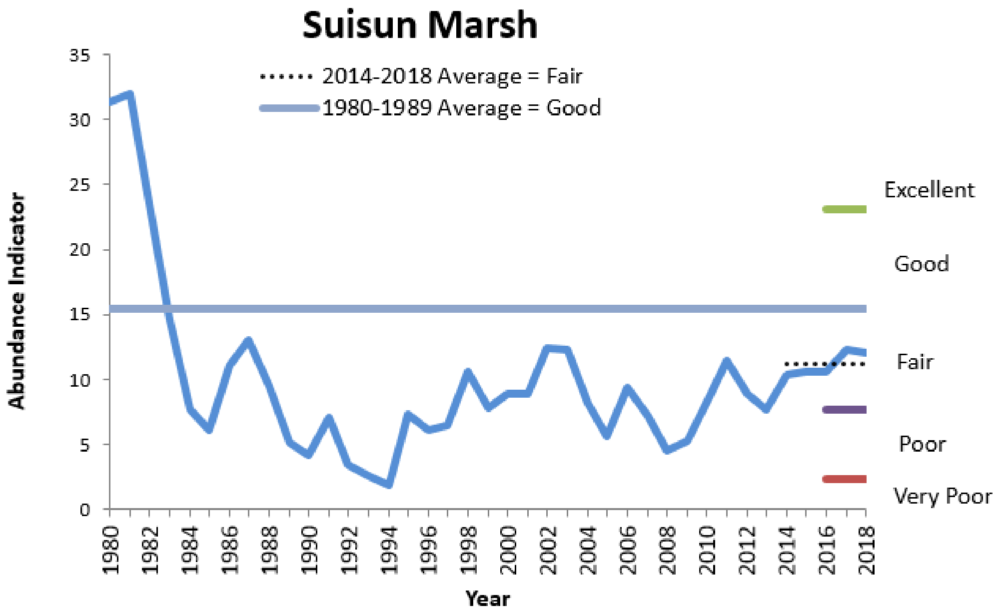


Figure 6. Suisun Marsh Fish Abundance Indicator from 1980-2018. Over the period of record the abundance indicator has declined from “excellent” to “poor” in the mid-1990’s; the recent five-year average improved to “fair”. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 7). The primary reference condition (1980-1989 average), indicated by a light blue horizontal line, represents a “good” score. The dotted line, representing the 2014-2018 average, reveals that the Suisun Marsh native fish abundance is “fair”.

Upper Estuary Pelagic Zone

Native fish abundance in the Pelagic Zone has declined dramatically over time, with recent averages reflecting “very poor” condition of the fish assemblage in this habitat. Small differences were detected in the native fish assemblage abundance patterns between the two regions sampled in the Pelagic Zone – Suisun Bay (Figure 7) and the Central-West Delta (Figure 8). Native fish abundance indicators in both regions have declined dramatically through the period of record, although the timing and pattern of decline differ somewhat between regions. The abundance indicator in Suisun Bay followed a trend that was broadly similar to that seen in Suisun Marsh abundance; abundance of native fish scored “excellent” in the early years of the survey and even in the earliest years of the primary reference period (1980-1989). Abundance indicator scores declined rapidly just prior to the onset of the 1987-1994 drought in Suisun Bay and rebounded in the late-1990’s. The indicator declined persistently through the early 2000’s and remains in “very poor” condition (as it was in SOTER 2015) despite an increase in 2017.

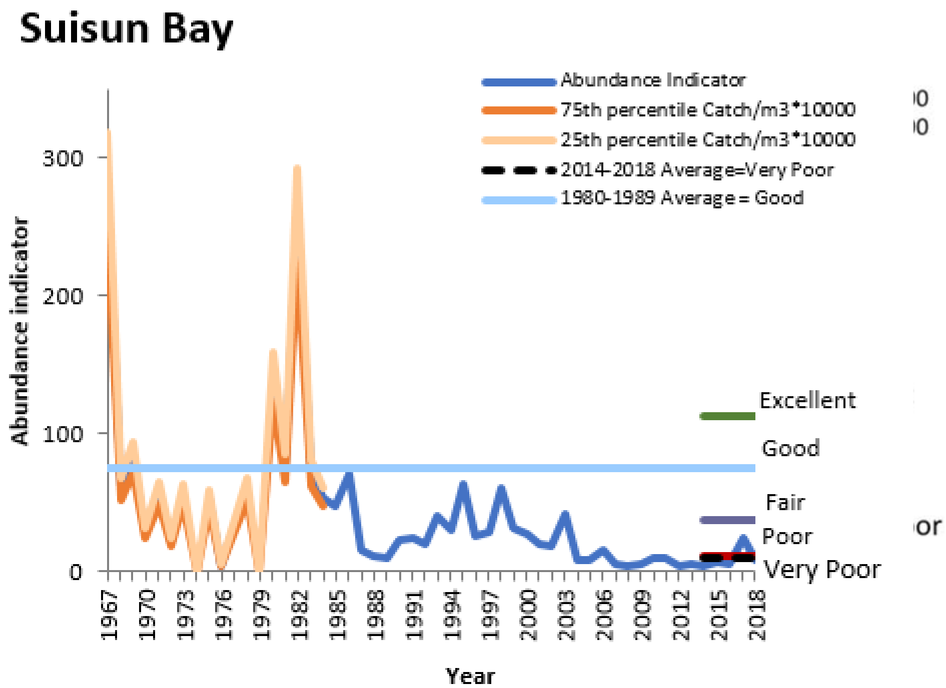


Figure 7. Upper Estuary Pelagic Zone Native Fish Abundance Indicator for the Suisun Bay region from 1967-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 9). The primary reference condition (1980-1989 average) is indicated by a light blue horizontal line. The dashed line represents the 2014-2018 average. Native fish abundance in the Pelagic Zone of Suisun Bay is “very poor”. Volume sampled was not recorded consistently during 1967-1984 period; thus, in order to calculate catch-per-unit-effort (CPUE, i.e., per volume sampled) for this period, we estimated volume sampled using the 25th, and 75th percentile values of volume sampled between 1985-2018; the effect of different sampling volume estimates are shown in peach and pink lines respectively.

Abundance trends in the Central-West Delta Pelagic Zone are different in degree from those described for the Suisun Bay Pelagic Zone and Suisun Marsh. Here, the abundance index appeared to be somewhat stable throughout the 1980’s and early 1990’s. Both, the increase in the late 1990’s (to “good”) and the precipitous decline in abundance after the early 2000’s (except in 2011) were consistent with patterns seen in Suisun Bay and Suisun Marsh. The average of the most recent five years indicates that the pelagic fish assemblage in this area remains in “very poor” condition.

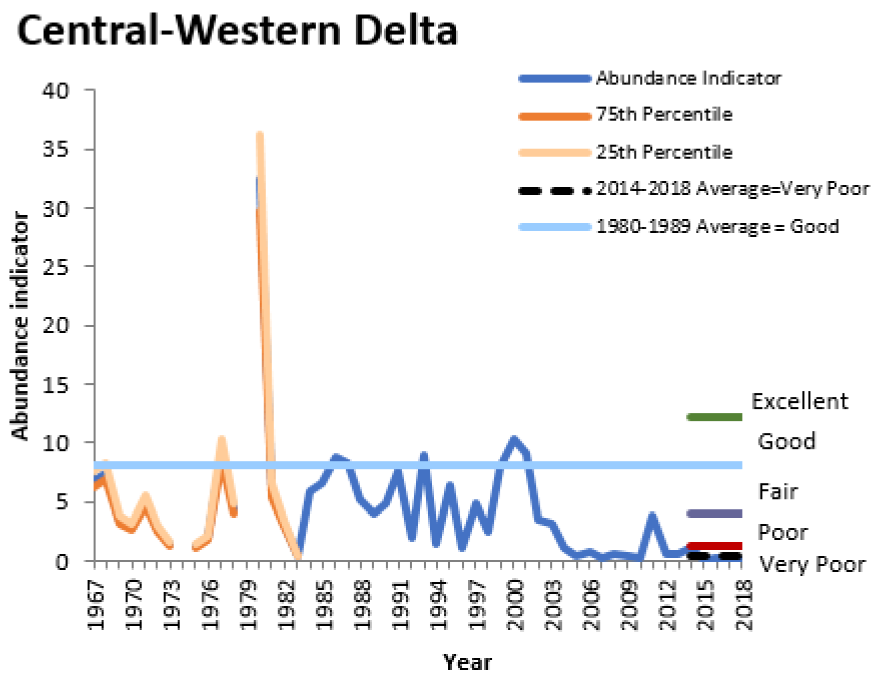


Figure 8. Upper Estuary Pelagic Zone Native Fish Abundance Indicator for the Central-West Delta region from 1967-2018. There has been a rapid decline in native fish abundance since the year 2000, except in 2011. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 9). The primary reference condition (1980-1989 average) is indicated by a light blue horizontal line. The dashed line represents the 2014-2018 average and shows that native fish abundance in the Pelagic Zone of the Central-Western Delta is “very poor”.

Delta Beach Zone

Native abundance conditions in the Delta Beach Zone were similar in four regions. Trends in native fish abundance were similar in across Delta Beach Zone (Figure 9; Table 10); however, the trends in fish abundance in the North Delta are not strongly correlated with those in other regions. Delta Beach Zone region scores are plotted separately for greater resolution of patterns within the individual regions; a combined score for the Delta Beach Zone as a whole (not shown) produced similar patterns and current scores as when the regions were considered separately.

Abundance of native fish species has been “poor” or “very poor” in all regions of the Delta Beach Zone for most of the last 24 years (Figure 10); the current score is “very poor” in all regions except the North Delta, where the indicator is “poor”.

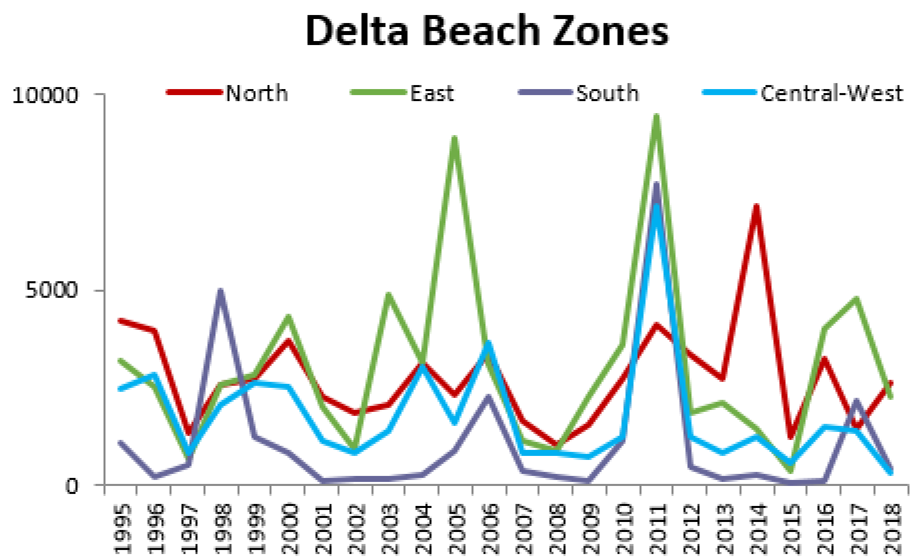


Figure 9. Comparison of native catch per unit effort for four Delta Beach Zone regions. Trends for native fish abundance were similar (see correlation matrix below) for most regions and exhibited different patterns than for total fish abundance

Table 10: Correlation values for comparison of trends between North, East, South and Central-West Delta Beach Zones. Asterisks indicate significant relationships (* = p <0.05, ** = p<0.001). The North Beach Zone is only correlated with the Central-West Zone.

Pearson Correlation Matrix	North	East	South	Central -West
North	1.00			
East	0.185	1.00		
South	0.173	0.572**	1.00	
Central-West	0.416*	0.641**	0.771**	1.00

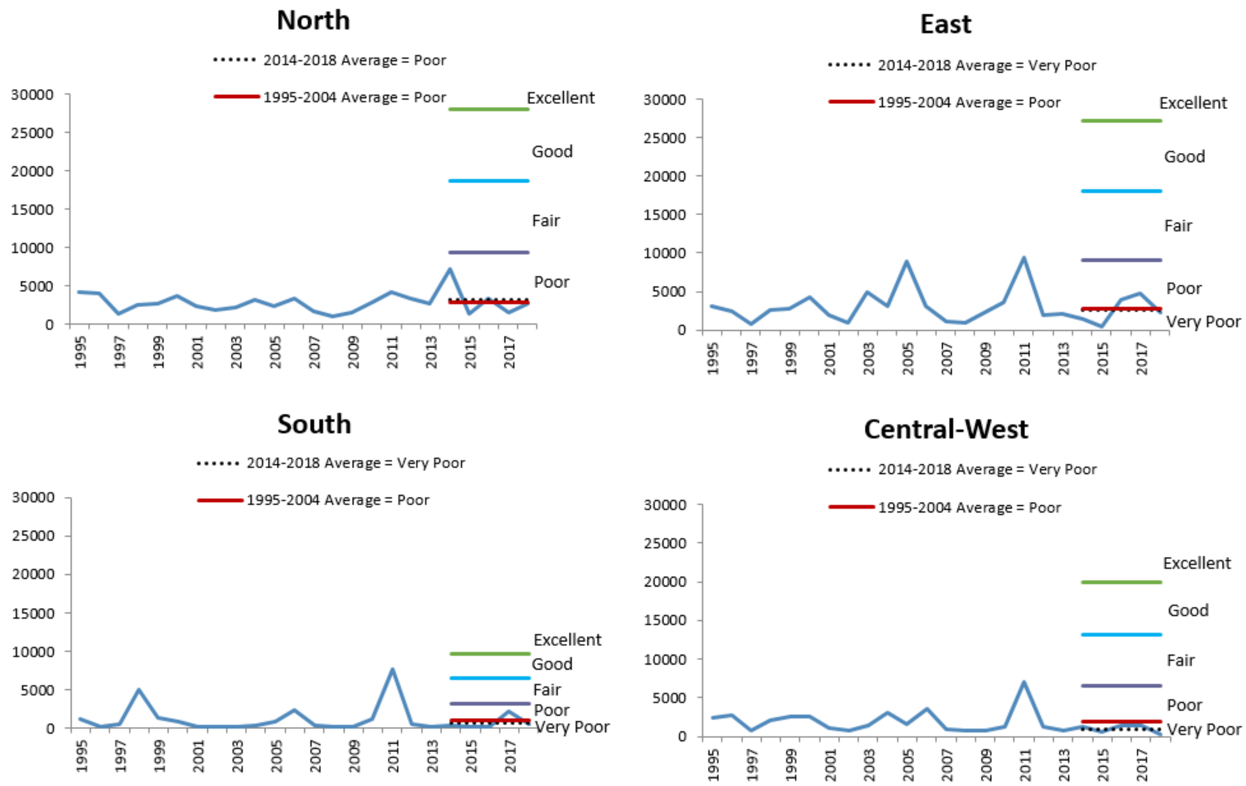


Figure 10. Delta Beach Zone Native Fish Abundance Indicator for each of four Delta Beach Zone regions**.** Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 8). The primary reference condition (1995-2004 average) was considered to be “poor” based on averages calculated from Suisun Marsh data and Pelagic Zone abundance indicators during that same time period. The dotted line represents the 2014-2018 average, indicating that native fish abundance in the North Zone remains “poor”, whereas it has become “very poor” in the rest of the Delta Zones.

Summary of Beach Zone Abundance and Diversity Trends

Taken together, the Beach Seine data reveal that abundance of native fish in the shallow, shoreline waters of the Delta has become “very poor”, and in the North Zone remains “poor” in recent years. All Delta Beach Zones exhibited an increase in native fishes in 2011, and a slight increase in 2017.

5. Summary of Abundance Results

Abundance of fishes in the Pelagic Zone and Suisun Marsh decreased substantially since the early 1980’s and the decline accelerated in the early part of this century; the native fish abundance indicator of Suisun Marsh appears to be improving slowly. Abundance of native species in the Delta Beach Zone has remained “Poor” or “Very Poor” during most of the period of record. *Although results for individual species are not reflected in the abundance indicator, it is worth noting that recent surveys, in 2018 and 2019, have failed to detect and endemic species, Delta Smelt and abundance of several other individual pelagic species are at or near record low levels. Based on abundance, the CCMP goals to recover and* *reverse declines of estuarine fishes (SFEP 2007) have not been met in the upper Estuary region.*

B. Species Composition Indicators:

1. Rationale

An indicator for species composition was developed for SOTB (2011) based on work by May and Brown (2002) and Meador et al. (2003) who found that the relative proportions of native and non-native species in an ecosystem are important indicators of ecosystem health. SOTB (2011) states:

> *"Non-native species are most prevalent in ecosystems that have been modified or degraded with resultant changes in environmental conditions (e.g., elevated temperature, reduced flood frequency), pollution, or reduction in area or access to key habitats (e.g., tidal marsh, seasonal floodplain). The San Francisco Estuary has been invaded by a number of non-native fish species. Some species, such as striped bass, were intentionally introduced into the estuary; others have arrived in ballast water or from upstream habitats, usually reservoirs."* [p. 176]

As with the abundance indicators, it is important to note that indicators of assemblage composition are not necessarily tied to local processes as many species in a particular region may have spawned or reared in distant habitats – it is possible that, to some degree, the relative abundance or diversity of non-native species to native species reflects "propagule pressure" from other environments in the Central Valley.

As with the SOTB (2011), two different indicators for species composition were calculated:

- Percent Native Species reflects the *species richness* of native and non-native fishes in a given region.
- Percent Native Fish reflects the percentage of *individual fish* collected in each sub-region of the Estuary that were native species.

2. Methods and Calculations, Assumptions, and Uncertainties

In general, the same methodology for constructing species composition indicators was applied to each of the upper Estuary fish data sets (representing different sampling programs and major habitats). Differences among the sampling programs required some modification of methods for each sampling program.

A **Percent Native Species Indicator** was calculated for each year in each sampling program/sub-region as the percentage of fish species collected in the upper Estuary that are native to the Estuary, as follows:

% native species = [native species richness /(native species richness + non-native species richness)] x 100

A **Percent Native Fish Indicator** was calculated in each year in each sampling program/sub-region as the percentage of total individual fish collected in the Estuary that are native to the Estuary and its adjacent ocean and upstream habitats, using the equation below:

% native fish = [native fish individuals/(total individual fish caught)] x 100

For each sampling program, the years incorporated into the composition indicators were the same as those described for their respective abundance indicators (see above).

3. Reference Conditions

Primary reference conditions for the assemblage composition indicators were the same as those used in SOTER (2015). These reference condition scores were based on inference from ecological literature and there was no compelling justification to use a different scoring system for the upper Estuary than had been used in the pelagic waters of the lower Estuary. The average percent native fish for the primary reference period, 1980-1989, (~85%) in the lower Estuary, was judged to be "good" (SOTB 2011). Index values where native fish represents less than 50% of total catch were judged to represent highly degraded conditions (SOTB 2011). Suisun Bay was reported to have lower percentages of native fish relative to total catch than other regions of the Bay (SOTB 2011). See Table 11 for quantitative reference conditions used here and in (SOTB 2011).

Table 11. Quantitative reference conditions and associated interpretations for the results of the Fish Species Composition Indicators (Percent Native Fish and Percent Native Species) for Suisun Marsh, Delta Beach Zone and Upper Estuary Pelagic Zone.

Quantitative Reference Condition	Interpretation	Low End of Range	High End of Range
>95%	Excellent	>95	N/A
>85%	Good	>85	95
>70%	Fair	>70	85
>50%	Poor	>50	70
≤50%	Very Poor	N/A	<50

4. Results of Species Composition

Suisun Marsh

The Percent Native Fish indicator is currently "poor" in Suisun Marsh, a slight increase from from its primary reference condition (1980-1989 average).

The 1980-1989 average percentage of native fish in total catch for the Suisun Marsh Survey was 45.0%. This means that the primary reference condition for Suisun Marsh (the earliest records from regular sampling) was "very poor" (Figure 11, Table 11). In the most recent 5 years, the percentage of native fish improved from "very poor" (as reported in SOTER 2015) to 51%, or "poor".

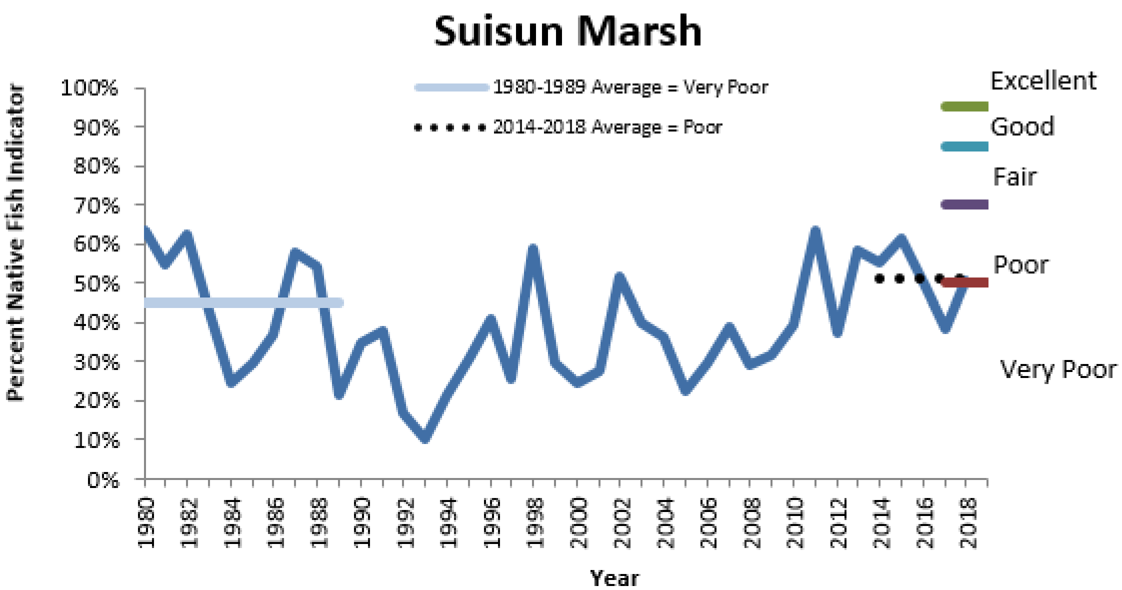


Figure 11. Changes in the relative abundance of native fish (Percent Native Fish Indicator) in Suisun Marsh from 1980-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 11). The primary reference condition (1980-1989 average) is indicated by a light blue horizontal line. The dotted line represents the 2014-2018 average. The primary reference condition and recent five-year averages (45% and 51% respectively), are an indication that the relative abundance of native fishes has increased in recent years, but remains "poor".

The Percent Native Species indicator is currently "poor" in Suisun Marsh; this reflects an improvement from "very poor" in SOTER 2015.

The 1980-1989 average percentage of native species detected in the Suisun Marsh Survey was 51%. This means that the baseline conditions for Suisun Marsh (the earliest records from regular sampling) rated "poor" (Figure 12, Table 11). In the most recent five years (2014-2018), the percentage of native fish species has remained similar (52%), meaning that the proportion of native species has not declined further in Suisun Marsh, but is "poor".

In addition to plotting the percent native species, the raw number of native vs. introduced species over the time series was compared (Figure 13) in an effort to assess whether changes in sampling effort (changes in trawl number) across years affected the total number of species detected. Native and non-native species richness was not significantly correlated and did not appear to respond to differences in the number of trawls conducted in the early years of the survey.

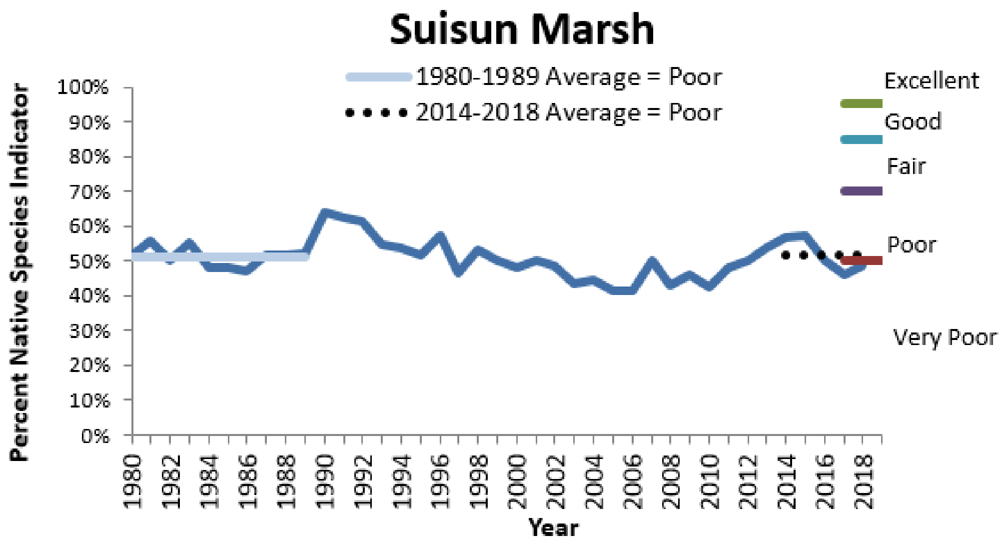


Figure 12. Changes in the Percentage of Natives Species Indicator in Suisun Marsh from 1980-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 11). The primary reference condition (1980-1989 average) is indicated by a light blue horizontal line. The dotted line represents the 2014-2018 average. Reference period averages and recent five-year averages are similar (51.1% and 51.7%, respectively, of species detected in the Suisun Marsh Survey are native). The early reference condition average represented "poor" health and last five-year average indicates that current conditions are "poor".

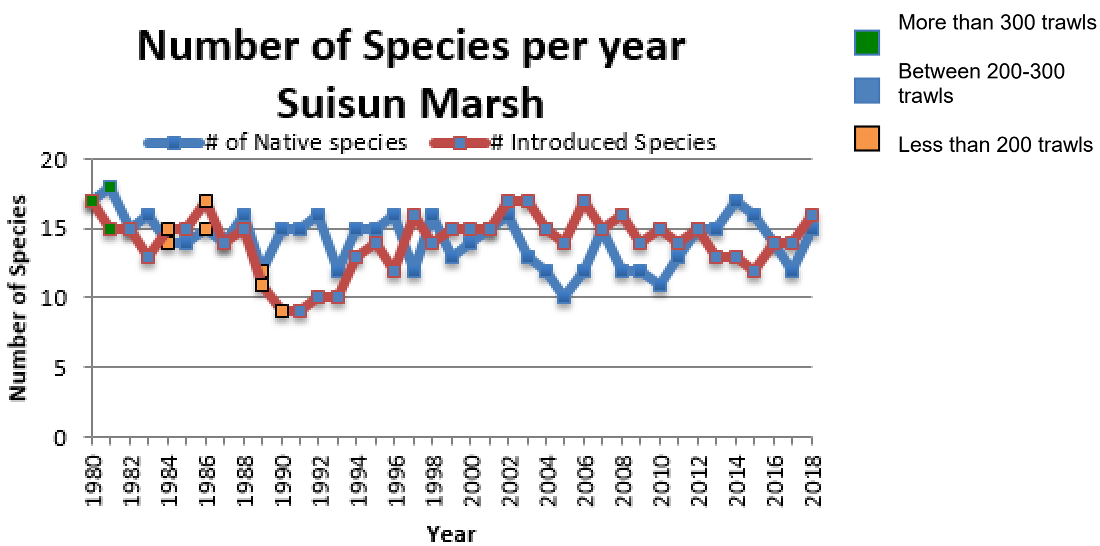


Figure 13. Comparison of native and non-native species richness through time was not correlated in Suisun Marsh. Native species richness has declining slowly, but increased in 2018, whereas non-native species richness has increased since 2015. Colored boxes indicate changes in sampling effort (number of trawls) in

some years. No relationship between the number of trawls and the richness of native and non-native species or the native/non-native relationship was detected.

Upper Estuary Pelagic Zone

Suisun Bay*. *The percentage of native fish represented in the pelagic assemblage of Suisun Bay was "poor", indicating no change in score between the primary reference condition (1980-1989 average) and the average of the last 5 years. The 1980-1989 average percentage of native fish in total catch of Suisun Bay was 65.6%. This means that the primary reference condition for Suisun Marsh (the earliest records from regular sampling) was "poor" (Table 11). In the most recent 5 years, the percentage of native fish in the total catch declined slightly (to 63%), but this too indicates that assemblage health is "poor" (Figure 14). The indicator varied widely over the period of record from "good" to "very poor".

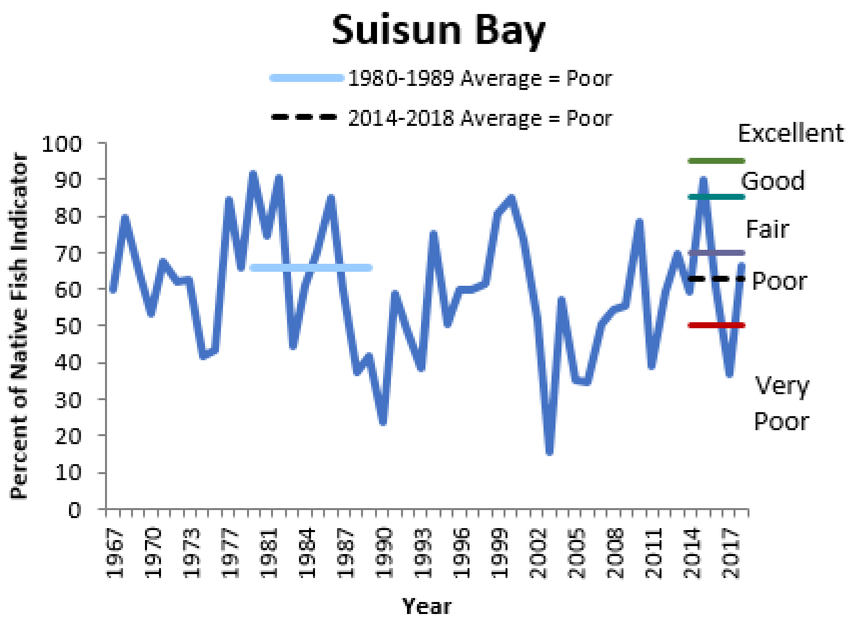


Figure 14. Changes in the relative abundance of native to non-native fish (Percent Native Fish Indicator) for the Pelagic Zone of Suisun Bay from 1967-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 11). The primary reference condition (1980-1989 average) is indicated by a light blue horizontal line. The dotted line represents the 2014-2018 average. Reference period averages and recent five-year averages are similar (65.6% and 63% respectively). Both the early reference condition average and last five-year average reflect "poor" health of the fish assemblage in this region of the upper estuary.

The percentage of native species in the pelagic assemblage of Suisun Bay was "fair" representing little change from its primary reference condition (1980-1989). In both the reference period and the last 5 years, slightly less than two-thirds of the species were native (74%, Figure 15). There is no indication that variation in sampling effort in the early years of the program affected total or relative richness scores. Over the period of record the indicator varied between “fair” and “poor”.

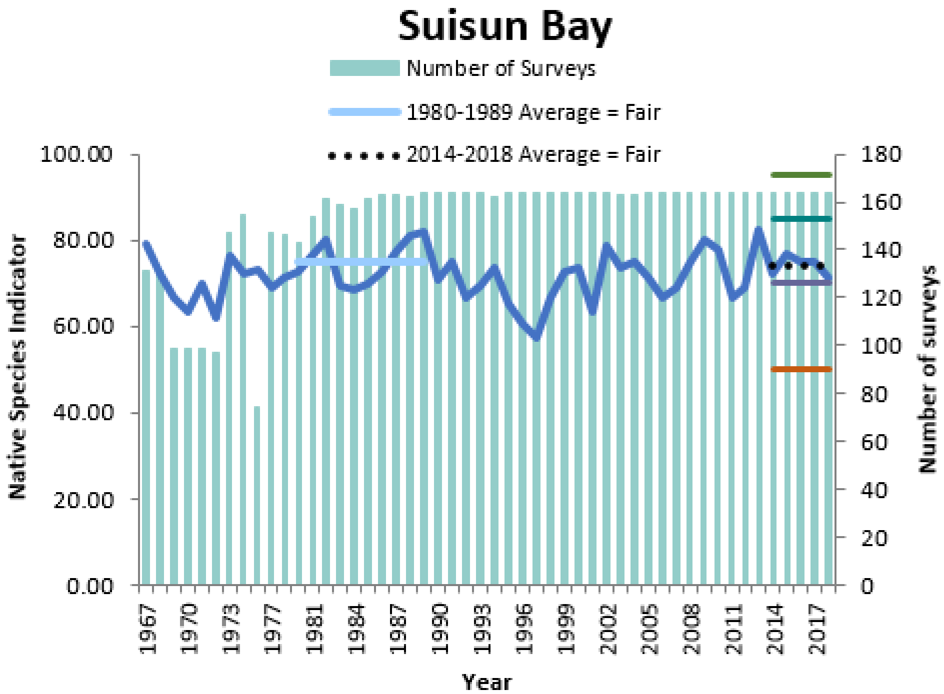


Figure 15. Changes in the Percent Native Species Indicator for the Pelagic Zone of Suisun Bay from 1967-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 11). The primary reference condition (1980-1989 average) is indicated by a light blue horizontal line. The dotted line represents the 2014-2018 average. The reference period and recent five-year averages are similar (75% and 74% respectively) indicating that the relative richness of native species remains “fair” in this region of the upper estuary. There was no significant correlation between the number of species detected and the number of surveys conducted (r=-0.007, p=0.96).

Central-West Delta. The percentage of native fish represented in the pelagic assemblage of the Central-Western Delta has remained “very poor” and continued to decline in recent years. The indicator has remained solidly below 50% throughout most of the time series (Figure 16). Native species richness reached a peak in 2011, but has averaged declined markedly over the past 5 years, reflecting a “very poor” score.

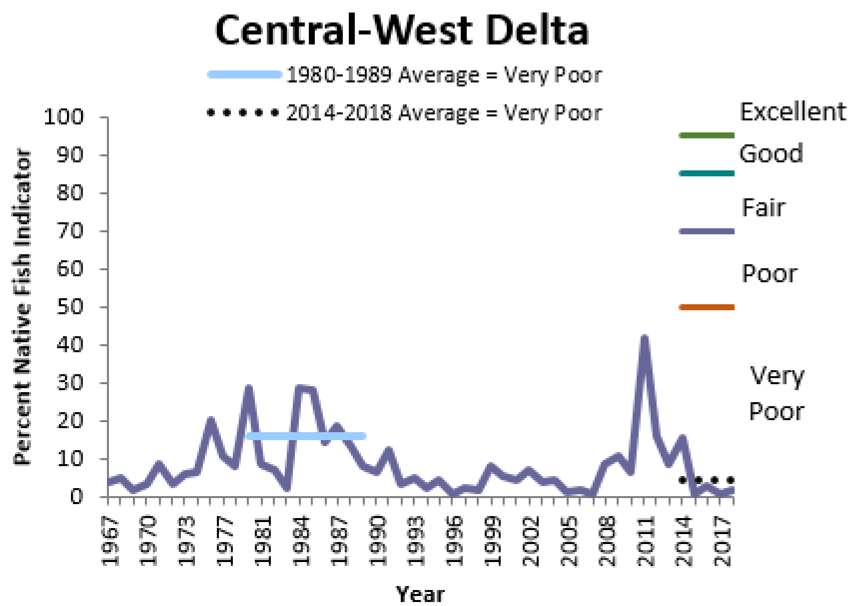


Figure 16. Changes in the Percent Native Fish Indicator for the Pelagic Zone of the Central-West Delta from 1967-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 11). The primary reference condition (1980-1989 average) is indicated by a light blue horizontal line. The dotted line represents the 2014-2018 average. Recent 5-year average has declined well-below the reference period average, indicating that the relative richness of native species remains “very poor” and has continued to decline in this region.

The percentage of native species in the pelagic assemblage of the Central-West Delta declined following the primary reference period (1980-1989), this indicator was most recently “very poor”. In the reference period native species made up about half (54%) of the total species caught by the FMWT pelagic sampling program when it sampled in the West Delta (Figure 17). In the last 5 years, the quantitative indicator score was 48%, on average; this reflects “very poor” status of native species relative richness in the Central-West Delta.

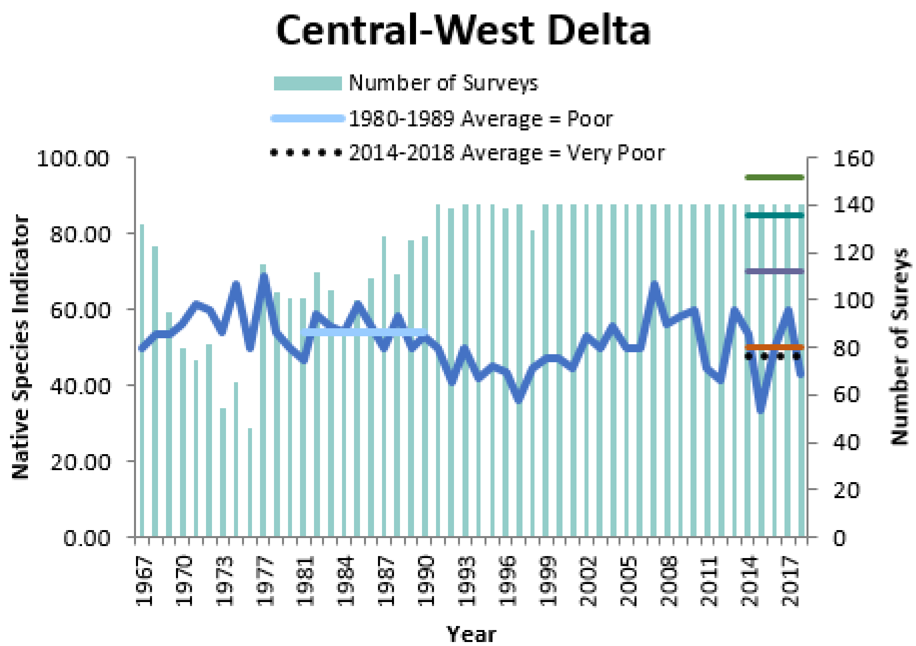


Figure 17. Changes in the Percent Native Species Indicator for the Pelagic Zone of the Central-West Delta from 1967-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 11). The primary reference condition (1980-1989 average) is indicated by a light blue horizontal line. The dotted line represents the 2014-2018 average. Reference period averages and recent five-year averages are different. Conditions in the reference period (54% native species) were "poor" but the average of the most recent five years (48% native species) was "very poor", as it was in SOTER 2015. There was no significant correlation between the number of species detected and the number of surveys conducted (r=0.10, p=0.51).

Delta Beach Zone.

The percentage of native fish and native species in all regions of the Beach Zone assemblage of the Delta was "very poor" in both the primary reference condition and in recent years. The percentage of native fish has declined in all regions during the last 5 years. Peak percentages were driven largely by high numbers of juvenile Sacramento splittail (Figure 18). Native species have declined steadily in all Delta regions throughout most of the period of record (Figure 19).

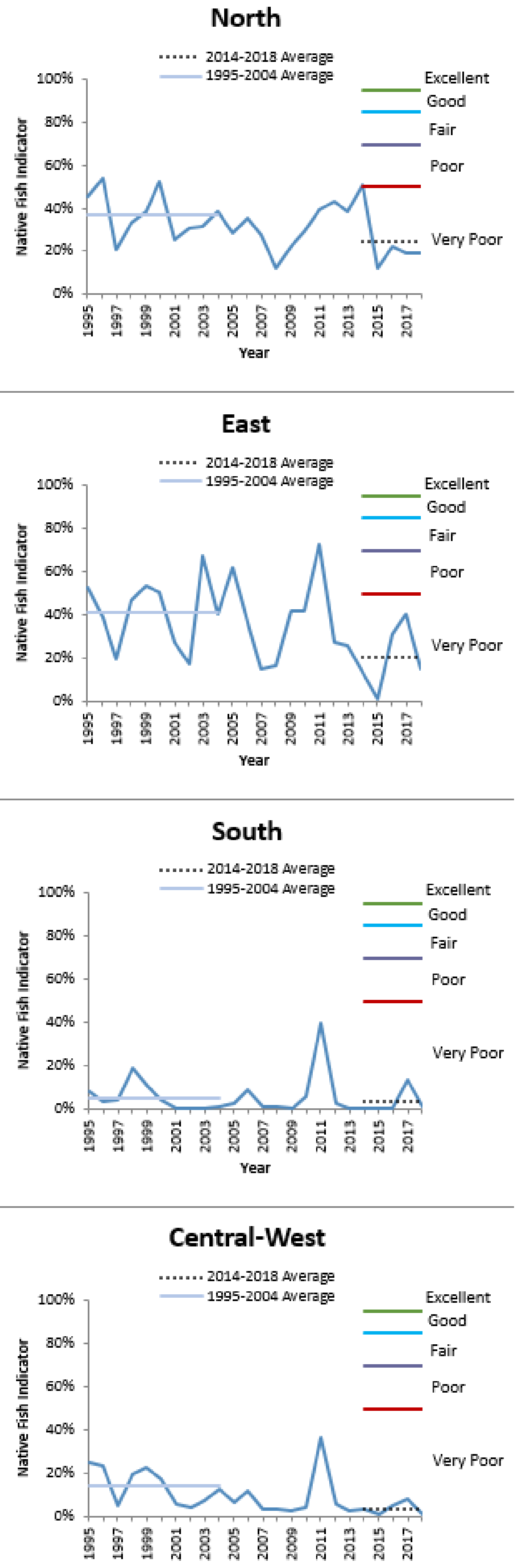


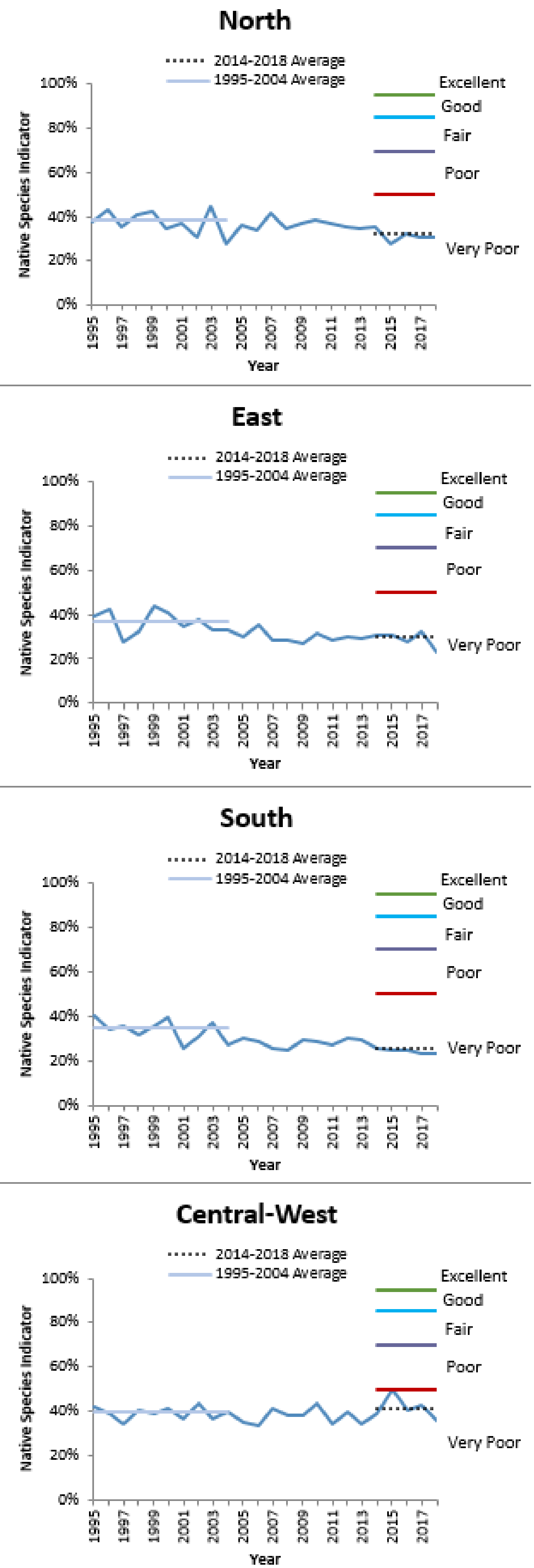
Figure 18. Changes in the relative abundance of native fish (Percent Native Fish Indicator) for the Delta Beach Zones from 1995-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 11). The primary reference condition (1995-2004 average) is indicated by a light blue horizontal line. The green dotted line represents the 2014-2018 average.

The primary reference condition for North, East, South and Central-West was “very poor” (37%, 42%, 5%, and 15% respectively). The 2014-2018 averages remained “very poor” in all regions of the Delta Beach Zone (25%, 21%, 3% and 4% respectively).

Figure 19. Changes in the Percent Native Species Indicator for the Delta Beach Zones from 1995-2018. Short horizontal colored lines indicate scoring thresholds assigned to this indicator (see Table 11). The primary reference condition (1995-2004 average) is indicated by a light blue horizontal line. The dotted line represents the 2014-2018 average.

The primary reference condition for native species richness North, East, South and Central-West was “very poor” (39%, 37%, 35%, and 39% respectively) and the 2014-2018 averages remained “very poor” (32%, 30%, 26%, and 42% respectively).

No significant correlations between the number of species detected and the number of surveys conducted were detected (e.g. in the South Delta; r=0.16, p=0.50 in the original analysis of these indicators (SOTER 2015)).



V. SUMMARY

Collectively the results of fish indicators for the upper Estuary provide insight into a few key attributes of fish assemblage health. **Although no synthetic index of our measures of assemblage health was constructed, it is clear that the fish assemblage in the upper Estuary is generally in "very poor" condition (Table 12).** Trends in the relative diversity of native fish in Suisun Marsh and pelagic habitats of Suisun Bay have been stable slowly improving; these may be exceptions to the generally very poor condition of the Upper Estuary Fish assemblage.

Table 12. Summary of Results relative to the CCMP goals to "recover" and "reverse" declines of estuarine fishes for the fish indicators in the Upper San Francisco Estuary.

Indicator	Region (Sub-region if trends are different)	CCMP Goal Met	Evaluation		Trend
			Reference Period	Short-Term (last five years)	Over the Period of Record
Native Fish Abundance	Suisun Marsh	No	Good	Fair	Decline
	Suisun Bay Pelagic	No	Good	Very Poor	Decline
	Central-West Delta Pelagic	No	Good	Very Poor	Decline
	Delta Beach Zone	No	Poor	Very Poor	Decline
Percent Native Fish	Suisun Marsh	No	Very Poor	Poor	Improving
	Suisun Bay Pelagic	No	Poor	Poor	Stable
	Central-West Delta Pelagic	No	Very Poor	Very Poor	Stable
	Delta Beach Zone	No	Very Poor	Very Poor	Decline
Percent Native Species	Suisun Marsh	No	Poor	Poor	Stable
	Suisun Bay Pelagic	No	Fair	Fair	Stable
	Central-West Delta Pelagic	No	Poor	Very Poor	Decline
	Delta Beach Zone	No	Very Poor	Very Poor	Stable

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State of the San Francisco Estuary 2019
Technical Appendix

Beneficial Floods Indicator

Prepared by Christina Swanson
March 2019

I. Background and Rationale

The San Francisco Estuary receives more than 90% of its freshwater inflow from the California's two largest rivers, the Sacramento River flowing from the north and the San Joaquin River from the south (Kimmerer 2002). Following winter rainstorms and during the height of the spring snowmelt in this vast watershed, the estuary's tributary rivers may flood, spilling over their banks to create ecologically important floodplain habitat and sending high volumes of fresh water into the estuary. These seasonal high flows drive multiple ecological processes including: primary and secondary production in inundated floodplains and the upper estuary; downstream transport or organisms, sediment, and nutrients to the Bay; creation of spawning and rearing habitat for a numerous fish species; and mixing of Bay waters and creation of productive brackish, or "low-salinity," habitat in the Bay's upstream Suisun and San Pablo regions (Jassby et al. 1995; Sommer et al. 2001; Kimmerer 2002, 2004; Schemel et al. 2004; Feyrer et al. 2006a, b; del Rosario et al. 2013). All of these provide conditions favorable for many native fish, invertebrate and other wildlife species. High flows, as well as rapid increases in flows, are also important triggers for reproduction and movement for many estuarine fishes and for anadromous species like salmon that migrate between the ocean and rivers through the estuary. Just as high flows into the Bay create large areas of low salinity habitat, they also improve habitat conditions in riverine migration corridors for both adult fish moving upstream as well as young fish moving downstream.

In the Estuary's Sacramento-San Joaquin watershed, several factors have had and are having substantial impacts on the frequency, magnitude and duration of high flow, or flood, events into the estuary. First, flows in most of the Bay's largest tributary rivers have been greatly altered by dams, many of which built for the purpose of reducing downstream flooding and to store the mountain runoff for later use and export to other regions in the state. These upstream water management operations have deprived the estuary and its tributary rivers of an important physical and ecological process, regular seasonal flooding, that we now know is an essential component of the health of the estuary, its watershed and the plants and animals that depend on these habitats. Further, by physically blocking the flow of sediment, these dams are also starving riverine and estuarine wetlands and marshes of the materials they need to sustain (and restore) themselves. Second, large amounts of water are extracted from the rivers and the Delta upstream of the Bay. Collectively, these diversions can remove large percentages of the total flow (as well as nutrients, primary production and plankton), even during relatively high flow (see Freshwater Inflow Index). This reduces the amount of fresh water that flows into the estuary and can decrease inflow to levels below important thresholds for floodplain inundation, habitat creation and sediment transport. And finally, the lower reaches of the estuary's largest tributary rivers, the Sacramento and San Joaquin Rivers, are confined by man-made levees that prevent or restrict inundation of adjacent floodplains during high flow events. Thus, even under high flow conditions, adjacent floodplains that would have been inundated if there were no levees are not. In essence, many of the estuary's tributary rivers have been disconnected from their floodplains, reducing or eliminating creation of ecologically important floodplain habitat.

The State of the Estuary Report uses two indicators to measure and evaluate the frequency (or "how often?"), magnitude ("how much?") and duration ("how long?") of ecologically important flood events. The Yolo Floodplain Flows indicator measures seasonal inflows into the Delta (the upstream region of the San Francisco Estuary) from the Yolo Bypass, the large, partially managed floodplain immediately upstream of the Estuary in the lower Sacramento River basin. The Flood Inflows indicator measures flood events in terms of high-volume freshwater inflows to the Bay from the Delta and the Sacramento-San Joaquin watershed.

II. Data Source

Each of the indicators was calculated for each year using daily freshwater inflow data from the California Department of Water Resources (CDWR) DAYFLOW model (Delta inflow from the Yolo Bypass, QYOLO, for the Yolo Floodplain Flows; Delta outflow, QOUT, for Flood Inflows to the Bay; and Sacramento River flow at Freeport, QSAC, for calibration and development of reference conditions for the Yolo Floodplain Flows indicator). DAYFLOW is a computer model developed in 1978 as an accounting tool for calculating historical Delta outflow, X2 and other internal Delta flows.[1] DAYFLOW output is used extensively in studies by State and federal agencies, universities, and consultants. DAYFLOW output is available for the period 1930-2018, although data for Yolo Bypass flows are only available for 1940-2018.[2] Additional information on unimpaired Sacramento River flows and Delta outflow (or Bay inflow), used to inform development of reference conditions and interpret indicator results, was from CDWR's California Central Valley Unimpaired Flow dataset.[3]

III. Indicator Evaluation and Reference Conditions

The San Francisco Estuary Partnership's Comprehensive Conservation and Management Plan's (CCMP) goals for "increase[ing] freshwater availability to the estuary", "restor[ing] healthy estuarine habitat" and "promot[ing] restoration and enhancement of stream and wetland functions to enhance resiliency and reduce pollution in the Estuary" are non-quantitative. However, examination of unimpaired flow and flood data records as well as biological information on floodplain habitat, productivity dynamics, and utilization for spawning, rearing and juvenile salmonid outmigration provide useful information for establishing ecologically relevant threshold levels and reference conditions for flood frequency, magnitude and duration.

For each indicator and its frequency, magnitude and duration component metrics, a primary reference condition, the quantitative value against which the measured value was compared, was established. Measured values that were higher than the primary reference condition were interpreted to mean that aspect of flood flow conditions met the CCMP goals and corresponded to "good" ecological conditions. Specific information on the primary reference condition and additional intermediate reference conditions is provided below for each indicator.

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[1] More information about DAYFLOW is available at www.iep.ca.gov/dayflow.
[2] Dayflow data for Yolo Bypass discharges, as compared to other potentially applicable data on Sacramento River flow or stage, Yolo Bypass inflows or inundation levels, was selected for calculation of this indicator based on the long record, completeness and quality of the data, as well as its easy accessibility.
[3] This report is available at: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spprtinfo/dwr_2007a.pdf.

Effects of Water Year Type on Flood Flows and the Indicators: Runoff from the Sacramento-San Joaquin watershed can vary dramatically from year to year, a function of California's temperate climate and unpredictable occurrences of droughts and floods. Even in the current system, in which flows are highly altered by dams and water diversion, high volume flood flows are larger and occur for more frequent and longer durations in wet years compared to drier years. However, for evaluation of these two indicators, water year type was not considered. Instead the indicators measure actual flow conditions for each year, and those measured levels are compared to a single reference condition that does not vary with water year type. Therefore, measured values for frequency, magnitude and duration of flood flows and the evaluation results relative to ecological condition and ecological services provided by flood flows (i.e., “good” v “poor”) are lower in dry years (and multi-year droughts) than in wetter years. (In contrast, the Peak Flows indicator of the Freshwater Inflow Index measures changes in the number of days of flood flows compared to unimpaired flow conditions that have been normalized to account for difference in water year type.)

IV. Indicators

A. Yolo Floodplain Flows indicator

1. Rationale

The Yolo Bypass is a designated floodway located west of the Sacramento River and north of the Delta (Figure 1). The bypass conveys flood flows from the Sacramento Valley, including the Sacramento River, Feather River, American River, Sutter Bypass, and westside streams, directly into the northern Delta at Cache Slough. Inundation of the Yolo Bypass is largely controlled by the Fremont Weir (completed in 1924), located on the Sacramento River: during high flow events, the Sacramento River overtops the weir and water flows into the Bypass, inundating up to 60,000 acres of shallow floodplain habitat.

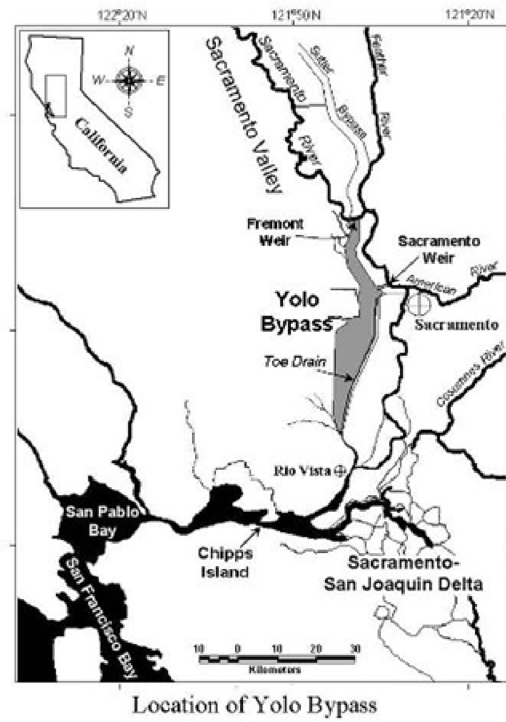

Figure 1. Location of the Yolo Bypass. Source: http://www.americanrivers.org/initiative/floods/projects/yolo-bypass-and-the-fremont-weir

In the Sacramento-San Joaquin watershed, floodplain habitat is most ecologically valuable during the later winter and spring, the period when high flows would typically occur (see Freshwater Inflow Index, Figure 2). In addition to its high primary and secondary productivity, many species use floodplain habitat for spawning, rearing and migration (Sommer et al. 2001; Schemel et al. 2004; Feyrer et al. 2006a, b; del Rosario et al. 2013).[4] Proposals for managed restoration of seasonal floodplain habitat by modifying the Fremont weir to allow more frequent

[4] The references cited here are only some of the extensive published research on the Yolo Bypass. A comprehensive list and web links to access these and other articles is available at: http://www.water.ca.gov/aes/yolo/yolo_pubs.cfm.

flooding of the Yolo Bypass are prominent elements of Bay-Delta ecosystem restoration planning efforts and species protection plans but none have been implemented yet.

2. Methods and Calculations

The Yolo Floodplain Flows indicator uses three component metrics to assess the frequency, magnitude and duration of occurrence of flood flows from the Yolo Bypass into the San Francisco Estuary during late winter and spring of each year.

Frequency was measured as:

> # of years in the past decade (i.e., ending with the measurement year) with Yolo Bypass flows >10,000 cubic feet per second (cfs) for >45 days during February-June period.[5]

Magnitude was measured as:

> average Yolo Bypass flow (cfs) for the 45 days of highest flows during the February-June period.

Duration was measured as:

> total # days during the February-June period with Yolo Bypass flows >10,000 cfs.[4]

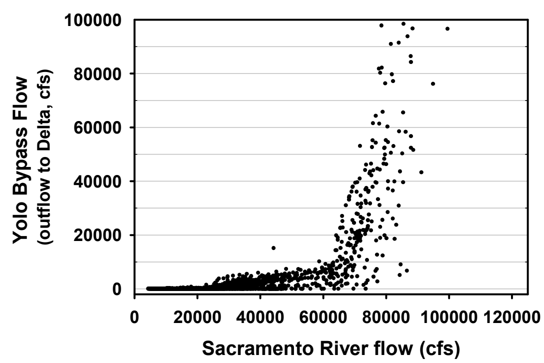

Figure 2. The relationship between Sacramento River flows and Yolo Bypass inflows to the San Francisco Estuary. Data source: California Department of Water Resources, Dayflow.

The late winter-spring period was used based on biological studies that demonstrate the ecological importance of floodplain habitat during this period (Sommer et al. 2001; Schemel et al. 2004; Feyrer et al 2006b; del Rosario et al. 2013). The Yolo Bypass flow level of >10,000 cfs was established based on examination of the relationship between Sacramento River flows and Yolo Bypass flows, which indicated that this level of Yolo Bypass flows, which corresponds to Sacramento River flows of approximately 60,000 cfs, is a threshold at which Yolo Bypass flows increased markedly with relatively small increases in Sacramento River flow (Figure 2). The time period of 45 days was based on the time needed for reproduction of splittail, a native floodplain spawner, including access the floodplain, spawning, egg incubation and larval rearing and migration downstream to the Delta (Sommer et al. 1997; Feyrer et al. 2006b). It is likely that, following an initial inundation event and Yolo Bypass flows >10,000, the Yolo Bypass remains inundated for some days after outflows from the floodplain fall below the 10,000 cfs threshold and reference condition used of the indicator metrics; therefore flood events that meet the (non-consecutive) 45 day reference condition threshold may in fact inundate the Yolo Bypass for more than 45 days.

[5] Neither the 45-day period used as part of the reference conditions or nor the count of numbers of days with Yolo Bypass flows >10,000 cfs used in metric calculations required that these days be consecutive.

For each year, the Yolo Floodplain Flows indicator was calculated by combining the results of the three measurements into a single number by calculating the average of the measurement "scores" described in the Reference Conditions section below.

3. Reference Conditions

The primary reference conditions for the component metrics of the Yolo Floodplain Flows indicator were established as Yolo Bypass flow magnitude of >10,000 cfs for at least 45 days during the February through June period in at least 3 out of 10 years. The bases for the 10,000 cfs and 45 days primary benchmarks are described above. The primary reference condition for frequency was based on an ecological objective to provide spawning habitat for splittail and outmigration and rearing habitat for young salmonids with a return period, 3 out of 10 years, that was relevant to the species' population dynamics.[6] Yolo Bypass flows that met or exceeded these benchmarks were considered to reflect "good" conditions and meet the CCMP goals. Additional information on Yolo Bypass flows under actual flow conditions (Figure 2), unimpaired Sacramento River flows, and primary and secondary productivity dynamics on the floodplain (e.g., Schemel et al. 2004) was used to develop the other intermediate reference condition levels. Table 1 below shows the quantitative reference conditions that were used to evaluate the results of the component metrics for the Yolo Floodplain Flows indicator.

Table 1. Quantitative reference conditions and associated interpretations for results for each of the three component metrics of the Yolo Floodplain Flows indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Yolo Floodplain Flows				
Quantitative Reference Conditions			**Evaluation and Interpretation**	**Score**
Frequency	**Magnitude**	**Duration**		
≥5 years out of 10	>20,000 cfs	>60 days	"Excellent," similar to unimpaired conditions	4
≥3 years out of 10	***>10,000 cfs***	***>45 days***	***"Good," meets CCMP goals***	***3***
≥2 years out of 10	>5,000 cfs	>15 days	"Fair"	2
≥1 year out of 10	>2,000 cfs	>5 days	"Poor"	1
0 years out of 10	≤2,000 cfs	≤5 days	"Very Poor," chronic absence of floodplain habitat	0

[6] Splittail live for 5 to 7 years and can spawn in multiple years (Sommer et al. 1997). Chinook salmon typically return to spawn as 2- to 4-year old fish; therefore creation of floodplain migration habitat in 3 of 10 years would provide benefit to approximately one third of the salmon population (more information available at: http://www.nmfs.noaa.gov/pr/species/fish/chinook-salmon.html.

4. Results

Results of the Yolo Floodplain Flows indicator are shown in Figures 3 and 4.

The frequency of creation of inundated floodplain habitat in the Yolo Bypass is low (Figure 3, top panel).
During the past 79 years, the Yolo Bypass has flooded and discharged flows greater than 10,000 cfs for 45 days during the late winter and spring in 8 years, on average just one year out of 10 years (10% of years; range 0-20% of years). For a 15-year period from 1968 to 1982, the Yolo Bypass never flooded to the primary reference condition levels. Based on the relationship between Sacramento River flows and Yolo Bypass flows (Figure 2), this is much less frequent than the Yolo Bypass would have flooded under unimpaired conditions (and with the current Fremont Weir configuration), when it would have flooded with at least 10,000 cfs of flow for at least one month in half of all years and for at least two months in a quarter of all years. The last time the Yolo Bypass flooded with >10,000 cfs for at least 45 days was eight years ago, in 2017. Based on frequency of occurrence, floodplain flow and habitat conditions have been consistently poor or very poor.

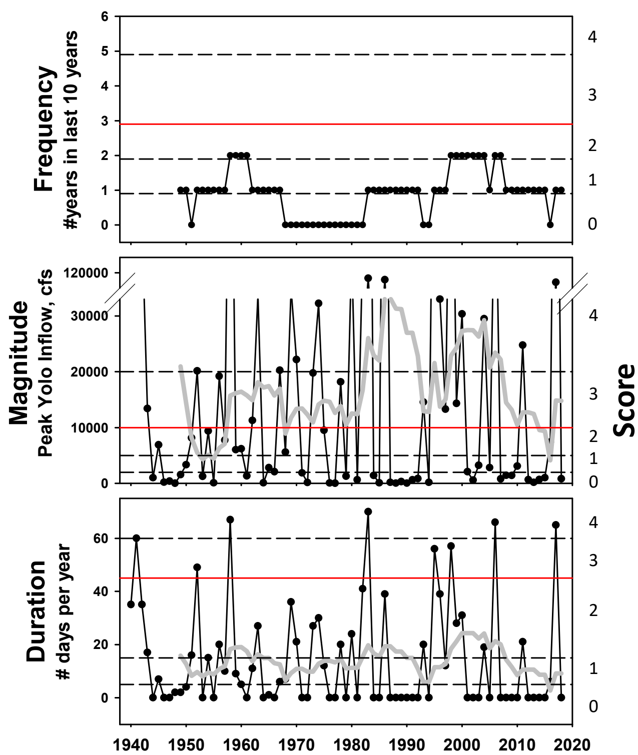

Figure 3. Results of the frequency (top panel), magnitude (middle panel) and duration (bottom panel) component metrics of the Yolo Floodplain Flows indicator. Score is shown on the right Y axis. Each point shows the result for that year and, for the magnitude and duration metrics, the heavy solid grey line shows the 10-year running average. The horizontal red and dashed lines show the reference conditions for each metric and the numeric score is shown on the right Y axis.

The magnitude of flood flows from the Yolo Bypass is variable and has not changed over time (Figure 3, middle panel).
Floodplain inundation, as measured by the magnitude of flood flows from the Yolo Bypass is highly variable and, over the 79-year data record, has not changed significantly (regression, p>0.9). Since 1940, average flood flows from the Yolo Bypass have been greater than 10,000 cfs in 38% of years. The highest flows from the Yolo Bypass occurred in 1983, 1986 and 2017, when the 45 days of highest floodplain discharge to the Delta averaged more than 100,000 cfs. The last time average Yolo Bypass flood flows were greater than 100,000 cfs was in 2017. In 2018, a median year,[7] the average of the highest 45 days of late winter-spring flows from the Yolo Bypass was just 826 cfs.

[7] Median water years have unimpaired flows that are in the middle quintile of years (i.e., 40% to 60%).

The duration of flood flows from the Yolo Bypass is low in most years (Figure 3, bottom panel).

Flood flows in excess of 10,000 cfs have occurred for more than 45 days in only 8 of the past 79 years (10% of years). In 36 of 79 years (46% of years) there were no days with Yolo Bypass flood flows greater than 10,000 cfs. The duration Yolo Bypass flood flows is lower than would have occurred under unimpaired conditions: based on unimpaired Sacramento River flows, the Yolo Bypass would flood with monthly average flows greater than 10,000 cfs for at least one month in most years and at least two months a quarter of years. Flood flow duration is highly variable and has not changed over time (regression, p>0.5). The last time flood flows exceeded 10,000 cfs for 45 days was in 2017. In 2018, Yolo Bypass flows never exceeded 10,000 cfs during the late winter or spring seasons.

Results of the Flood Events indicator, which combines the results of the frequency, magnitude and duration metrics, are shown in Figure 4.

Floodplain flows on the Yolo Bypass are too rare, too low and too short to support ecological processes.

Although Yolo Bypass flows exceed the 10,000 cfs reference condition threshold in more than a third of years, the duration of those flows is too short to stimulate and support ecological processes and produce ecologically valuable floodplain habitat, as they are defined by the reference conditions established for this indicator. As a result, the frequency of occurrence of "good" floodplain conditions is too low to support important ecological processes in the upstream reaches of the San Francisco Estuary and provide environmental benefits on a relevant timeframe to the population dynamics of floodplain-dependent species. Based on the indicator, the ecological and habitat conditions provided by Yolo floods flows have been "poor" or "very poor" in 70% of years.

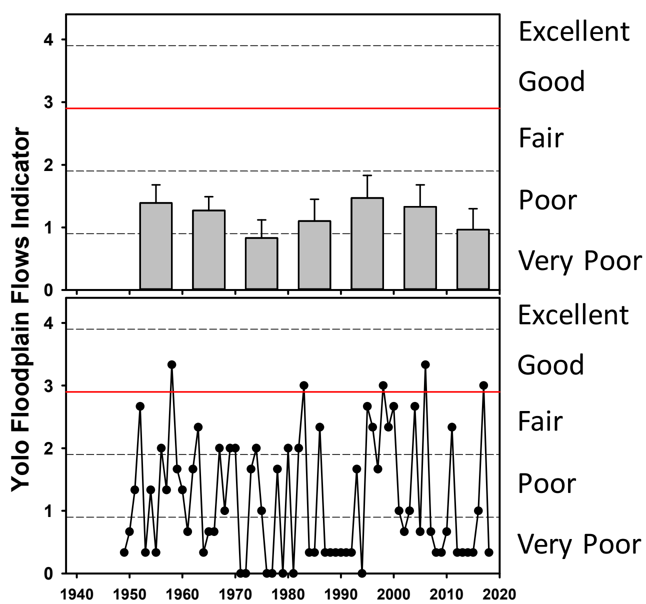

Figure 4. Results for the Yolo Floodplain Flows indicator, which combines the results of the frequency, magnitude and duration component metrics (Figure 3) for 1949 to 2018. The top panel shows results as decadal averages±1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red and dashed lines show the reference conditions and the indicator evaluation categories are at right.

Based on the Yolo Floodplain Flows indicator, CCMP goals to restore healthy estuarine habitat and function have not been met.

For the past 79 years, the frequency, magnitude and duration of inundation the Yolo Bypass and creation of floodplain habitat immediately upstream of the estuary, have been insufficient to provide ecologically important conditions for primary and secondary productivity, and spawning, downstream migration and rearing of estuarine and anadromous fishes. Since the early 1990s, when the CCMP was implemented, flood conditions have been "good" in only 3 years (10% of years) and have been "very poor" in 14 years (48% of years).

B. Flood Inflows indicator

1. Rationale

High volume, flood inflows of fresh water to the San Francisco Bay occur following winter rainstorms and during the spring snowmelt. Flood inflows transport sediment and nutrients to the Bay, increase mixing of estuarine waters, and create low salinity habitat in Suisun and San Pablo Bays (the upstream reaches of the estuary), conditions favorable for many estuary-dependent fish and invertebrate species. In rivers and estuaries, flood flow events are also a form of "natural disturbance" (Kimmerer 2002, 2004; Moyle et al., 2010).

2. Methods and Calculations

The Flood Events indicator uses three component metrics to assess the frequency, magnitude and duration of occurrence of high inflow, or flood events, in the San Francisco Estuary each year.

Frequency was measured as:

> # of years in the past decade (i.e., ending with the measurement year) with Bay inflows >50,000 cubic feet per second (cfs)[8] for more than 90 days during the year.

Magnitude was measured as:

> average inflow (cfs) during the 90 days of highest inflow in the year.

Duration was measured as:

> # days with Bay inflow>50,000 cfs.

High volume, flood flow was defined as the 5-day running average of actual daily freshwater Bay inflow>50,000 cfs. Selection of this threshold value was based on two rationales: 1) examination of DAYFLOW data suggested that flows above this threshold corresponded to winter rainfall events as well as some periods during the more prolonged spring snowmelt; and 2) flows of this magnitude shift the location of low salinity habitat, or X2[9], downstream to 50-60 km upstream of the Golden Gate into Suisun and upper San Pablo Bays (depending on antecedent conditions), driving primary and secondary productivity and providing favorable conditions for many estuarine invertebrate and fish species (Jassby et al. 1995; Kimmerer 2002, 2004).

For each year, the Flood Events indicator was calculated by combining the results of the three measurements into a single number by calculating the average of the measurement "scores" described in the Reference Conditions section below.

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[8] Freshwater inflow levels were measured as the 5-day running average of "Delta outflow."

[9] The location of low salinity habitat in the San Francisco Estuary is often expressed in terms of X2, the distance in km from the Golden Gate to the 2 ppt isohaline.

3. Reference Conditions

The primary reference conditions for the component metrics of the Flood Inflows indicator were established as Bay inflow (or Delta outflow) magnitude of >50,000 cfs for at least 90 days during the water year in at least 4 out of 10 years. The basis for the 50,000 cfs benchmark is described above. The primary reference conditions for frequency and duration were based on examination of unimpaired Bay inflows (or Delta outflows) that showed that an average of 5 out of 10 years (51% of years) had four or more months with average flows >50,000 cfs and an additional 13% of years had three months of flows of this magnitude. Bay inflows that met or exceeded these benchmarks were considered to reflect "good" conditions and meet the CCMP goals. Additional information on unimpaired Bay inflows and current regulatory standards for seasonal Bay inflows was used to develop the other intermediate reference condition levels. Table 2 below shows the quantitative reference conditions that were used to evaluate the results of the component metrics for the Flood Inflows indicator.

Table 2. Quantitative reference conditions and associated interpretations for results for each of the three component metrics of the Flood Inflows indicator. The primary reference condition, which corresponds to "good" conditions, is in bold italics.

Flood Inflows				
Quantitative Reference Conditions			Evaluation and Interpretation	Score
Frequency	Magnitude	Duration		
≥6 years out of 10	>100,000 cfs	>120 days	"Excellent," similar to unimpaired conditions	4
4 or 5 years out of 10	***>50,000 cfs***	***>90 days***	***"Good," meets CCMP goals***	***3***
2 or 3 years out of 10	>30,000 cfs	>45 days	"Fair," similar to current regulatory standards	2
1 year out of 10	>10,000 cfs	>10 days	"Poor," below current regulatory standards	1
0 years out of 10	≤10,000 cfs	≤10 days	"Very Poor," Bay inflows "flatlined"	0

V. Results

Results of the Flood Inflows indicator are shown in Figures 5 and 6.

The frequency of occurrence of flood events has declined (Figure 5, top panel).
Frequency of occurrence of high inflow flood events in the San Francisco Bay has declined significantly (regression, $p<0.001$). The first major decline occurred during the 1940s and 1950s, coincident with completion of large storage and flood control dams on the estuary's largest rivers, with frequency falling from an average of 5.8 years out of 10 years with floods in the 1940s (1939-1949) to an average of 1.7 flood years per decade in the 1950s and 1960s. Frequency declined again in the 1970s, 1980s and early 1990s, dropping to an average of just 1.3 flood years per decade (1970-1994). Frequency increased slightly during the late 1990s, concurrent with an unusually wet sequence of years, but then declined again in the 2000s. For the past three decades, flood frequency conditions have been consistently "poor." In the decade ending in 2018, the estuary experienced only one year (2017) with a flood event that met the primary reference condition.

Flood magnitude has not changed (Figure 5, middle panel).

Flood magnitude, as measured by average inflows during the 90 days with highest inflows per year, is highly variable and, over the 89-year data record, it has not changed significantly (regression, $p>0.5$). High inflows during the "pre-dam" period (1930-1943) were somewhat higher at 80,361 cfs, on average, compared to the average 54,360 cfs for the last two decades but not significantly different (Mann-Whitney Rank Sum test, $p=0.08$). High inflows during the most recent decade (2009-2018) are similar, 53,698 cfs on average, and not significantly different than pre-dam levels (t-test, $p=0.21$).

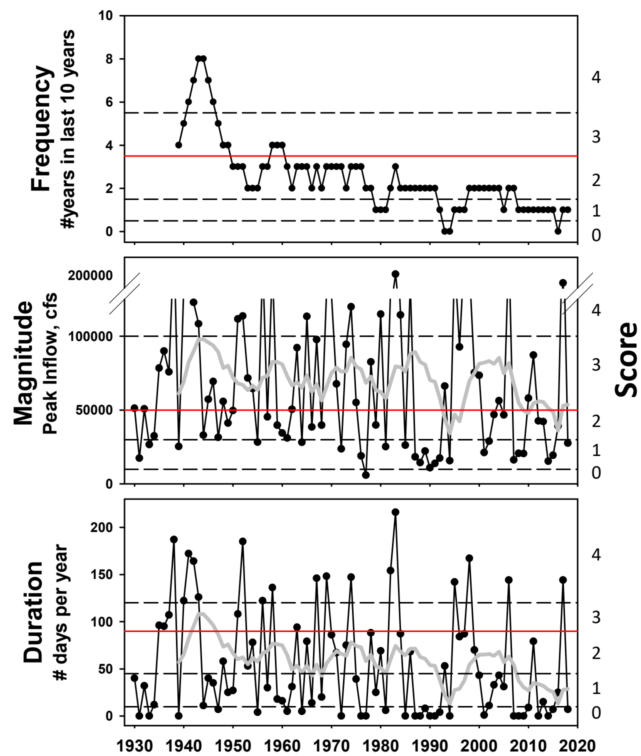

Figure 5. Results of the frequency (top panel), magnitude (middle panel) and duration (bottom panel) component metrics of the Flood Inflows indicator. Score is shown on the right Y axis. Each point shows the result for that year and, for the magnitude and duration metrics, the heavy solid grey line shows the 10-year running average. The horizontal red and dashed lines show the reference conditions for each metric and the numeric score is shown on the right Y axis.

The duration of flood events has declined (Figure 5, bottom panel).

The number of days per year with inflows above the 50,000 cfs flood threshold is also highly variable. Prior to construction of the major dams in the estuary's watershed (the pre-dam period, 1930-1943), high inflows occurred for an average of 82 days per year, significantly more often than during the last decade (2009-2018) when there was an average of just 29 days per year (t-test, $p<0.05$). Regression analysis also suggests this decline, although due to the variability of data, the decline is not statistically significant (regression, $p=0.074$). In 2018, a median year, there were just 7 days with inflows >50,000 cfs.

Results of the Flood Inflows indicator, which combines the results of the frequency, magnitude and duration metrics, are shown in Figure 6.

High inflow flood conditions have declined.

Results of the indicator reveal a steady and significant decline in high inflow, flood event conditions in the Bay (regression, $p<0.001$), from a roughly equal mix of "good," "fair" and "poor" conditions prior to the 1960s to mostly "fair" and "poor" conditions by the 1980s. Conditions improved during the late 1990s, during a sequence of unusually wet years but declined again in the 2000s. Since 2001, conditions have been "poor" or "very poor" in all but four years. "Good" flood inflow conditions occurred only in 2006 and 2017, respectively the 2nd and 7th wettest years in the 89-year data record. Declining flood event conditions were driven by the decline in flood duration, which has fallen by more than 65% (pre-dam years compared to last decade) and the resultant decline in the frequency of flood events that met the primary reference condition criteria, which has fallen more than 80%.

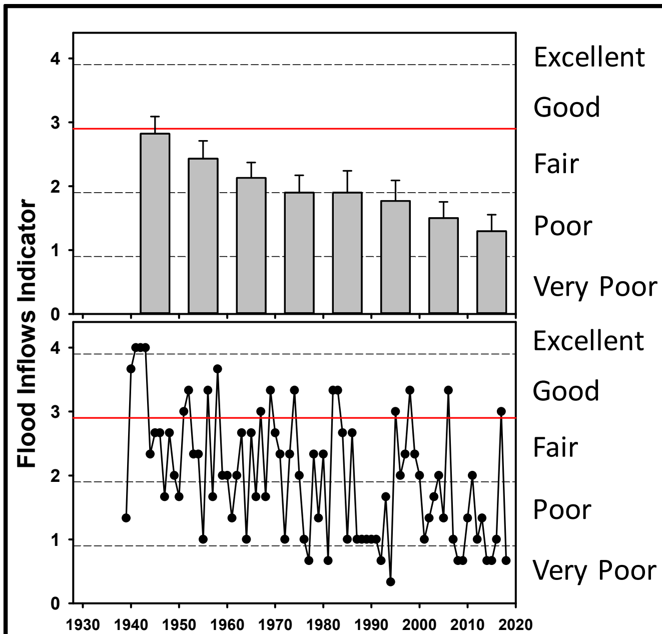

Figure 6. Results for the Flood Inflows indicator, which combines the results of the frequency, magnitude and duration component metrics (Figure 5) for 1939 to 2018. The top panel shows results as decadal averages$\pm$1 SEM (and for nine years for 2010-2018) and the bottom panel shows results for each year. The horizontal red and dashed lines show the reference conditions and the indicator evaluation categories are at right

Based on the Flood Inflows indicator, CCMP goals to restore healthy estuarine habitat and function have not been met.

The indicator shows that, for the past five decades, flood inflow conditions, an important physical and ecological process in the Bay, have been mostly "fair" or "poor." Since the early 1990s, when the CCMP was implemented, flood conditions have been "good" in only four years (14% of years) and have been "poor" or "very poor "in 64% of years.

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State of the Estuary Report 2019

Technical Appendix

Urban Water Use

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TECHNICAL APPENDIX: URBAN WATER USE

CONTEXT

Potable (not recycled) surface and ground water use by the communities and farms in and around San Francisco Bay-Delta Estuary totals about 2.1 million acre-feet per year (maf/yr). A little more than half of that amount or about 1.1 maf/yr is used by the residents, businesses, institutions, and industries in the urban and suburban communities and the other half is for irrigated agriculture. About 0.9 maf/yr or 90% of the agriculture use is in the Delta, supplied by withdrawals from Delta channels, the remaining agricultural use - 0.1 maf/yr- primarily occurs in the North Bay, Eastern Alameda and Contra Costa Counties, and southern Santa Clara Valley, supplied mainly by groundwater. About 0.84 maf/yr or about 75% of the Estuary's urban or municipal water use is in the cities and towns in the watersheds surrounding the San Francisco Bay (designated as the Bay region).[1] Most of Bay region's urban water supply – nearly 75% on average- is imported, both directly from the Delta and upstream from Sierra rivers with smaller amounts from the Russian River and Lagunitas Creek; as a result the Bay region is more reliant on imported water than any other region in the state. Less than 10% is surface water from local Bay-draining (non-Delta) watersheds, such as the Napa River and Alameda, Coyote, Los Gatos and San Mateo Creeks. The remaining 15% is from groundwater, which is a locally significant supply source to urban users in the Santa Clara and Livermore Valleys, and in Fremont and the North Bay. Non-potable recycled water is a small (about 5%) but growing supply source in the Bay region.

About 0.27 maf/yr or 25% of the Estuary's urban water use is from the larger cities and communities within and adjacent to the Delta's Secondary Zone and Suisun Marsh, including the City of Sacramento, and is designated as the Delta-Suisun region. Over 80% of the supply for those communities comes from the diversion of surface water, including the Sacramento and San Joaquin Rivers in the Delta and from the tributaries of those rivers upstream of the Delta (American, Mokelumne, Stanislaus, and Calaveras). Groundwater is an important supply for some of these communities including Stockton, Brentwood, Sacramento, and Discovery Bay.

Using less water (conservation) and using water more efficiently by reducing the amount of water needed for any activity while still accomplishing the goals of that activity (e.g. toilet flushing, irrigation) has many actual and potential benefits for the Bay Area including:

- Reduces the financial and energy costs of treating, heating and transporting water
- Reduces the need to develop new supplies;
- Reduces pollutant loads from irrigating lawns, gardens and crops;
- Reduces the vulnerability of supplies to disruption by earthquakes, droughts, floods, rising sea level, and regulatory requirements to protect endangered species.
- Reduces the demand on already-over-drawn supply sources, potentially leaving more water to maintain the habitats, living resources, and ecological processes of the Bay and its watersheds

The 2015 SOTER assessed urban water in the midst of an extended and severe Statewide drought, which resulted in mandatory reductions in urban use for nearly one year. Although greater precipitation and runoff in recent years have eliminated mandatory conservation, conserving water is still a priority for urban water

[1] The terms "urban" and "municipal" water use are used interchangeably and refers to the use by communities and municipalities that are supplied by public water districts and private water companies in contrast to the rural areas that are primarily self-supplied with groundwater.

suppliers and the State. Another drought is inevitable and this water use indicator will show whether urban water users have learned the lesson of the recent drought and made conservation a way of life.

INDICATOR

This indicator assesses the region's water use and the efficiency of that use over time. Because of differing data availability, the urban water use indicator for the San Francisco Bay-Delta Estuary is separated into two regions- the Bay region and the Delta-Suisun region. The Bay region indicator measures both the total water use and just the residential water use portion (single and multi-family) in two ways: the annual potable volume in acre-feet; and the per-person use in gallons per day (gpcd or per capita use), as was done for the 2015 SOTER. [2] The per capita use is the water use volume divided by the population. The 1986-2017 period of assessment for the Bay is long enough to evaluate how the region's urban use is affected over time by population growth, climate, plumbing codes, conservation measures and economic conditions. 1986 is just prior to the 1987-92 drought, the longest duration drought experienced by the Bay Area. Major plumbing code changes were also instituted in the early 1990's. From 2007 to 2009 the region experienced a 3-year dry period and economic downturn and from 2012-2016 experienced another prolonged drought.

New for 2019, the Delta -Suisun region indicator only measures the total urban water use and the total per capita use since 2005; residential use data prior to 2005 was not consistently measured in all 10 of the assessed retailers; In 2005, only 20% of the City of Sacramento service connections were metered. The total use for the 10 retailers was also not consistently available from the readily accessible data sources prior to 2005. The 2005-2017 period of assessment for the Delta-Suisun region captures the changes in water use due to the economic downturn and recent drought.

This indicator measures the consumption of the water used inside and outside of the residences, businesses, and industries in the Bay Area. The total water use is measured as the potable supply delivered into the retailer's system and includes the unaccounted water, including losses in the distribution system. The residential water use is metered prior to entering the single or multi-family residence and would include leaks and losses between the street and the residence. The metered supply into the system and the metered residential use does not measure the total water footprint, which is the volume of water that is required to produce all the goods and services that are consumed and which is many times greater than the direct consumption.[3]

Residential use, which includes both single family and multi-family residences, consists of indoor uses (waste elimination, washing clothes and dishes, bathing, drinking) and outdoor uses (irrigation and cleaning). Commercial users can have both an indoor and outdoor component, depending on the nature of the business while industrial users are primarily using water indoors for a manufacturing process including energy generation. Residential use is the factor most directly controlled by individuals and families, whose decisions to use water more efficiently in and around the home can collectively create large-scale benefits.

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[2] Measures of potable or drinkable water do not include recycled water.

[3] The average yearly water footprint of an American is about 655,000 gallons per year or about 18 times greater than the 36500 gallons per year or the roughly 100 gallons per day the average Bay Area resident consumes through the water supply system. Water footprints of all nations for the period 1997 - 2001 have been first reported Chapagain, A.K. and Hoekstra, A.Y. "Water footprints of nations". *Value of Water Research Report Series No. 16* (UNESCO-IHE)

Residential per capita use is sometimes used to compare water use within and across watershed boundaries or among water agencies.[4] Total per capita use measures, along with the residential use, different proportions of commercial, industrial, and institutional uses by the different municipalities and thus make the comparisons across boundaries and what individuals use less accurate. The total municipal per-capita use for the Bay and Delta regions, however, is a reasonable indicator of how the region as a whole is managing its water supplies over time and is also the metric that is used to assess compliance with State legislation that establishes urban water use targets.

DATA SOURCES

All of the Bay Area municipal water suppliers measure the water use of their customers in order to bill them based upon the volume of use. The retail water suppliers separate the customers into different sectors or types of use, often distinguished by the size and type of water meter. Residential water use is normally accounted for separately from commercial, industrial, institutional and dedicated landscaping use. Residential customers are usually separated into single family and multi-family accounts and must be combined to derive the total residential use. The water suppliers generally report the water use on a monthly or bi-monthly basis in gallons or cubic feet or occasionally acre-feet. For this indicator the volume of annual water use is compiled in acre-feet per year. An acre-foot is equal to 325,851 gallons.

This indicator also requires population data in order to calculate the per-capita use. Water suppliers also report their population, which is usually derived from census data although sometimes the population is estimated based upon the number of customer accounts.

Annual water use data for the entire 1986-2017 period is available from water suppliers that serve about 93% of the 6.65 million people that reside in the municipalities in the local Bay-draining watersheds. Total municipal and residential water use and population data for the 1986-2017 period were compiled for Contra Costa Water District (CCWD), East Bay Municipal Utilities District (EBMUD), Alameda County Water District (ACWD), San Francisco Public Utilities District (SFPUC), Zone 7 Water Agency (Zone 7), Santa Clara Valley Water District (SCVWD), Bay Area Water Supply and Conservation Agencies (BAWSCA- an association of the water agencies that wholesale water from the SFPUC), Marin Municipal Water District (MMWD), and the City of Napa (Napa). Table 1 lists the agencies, the type of service provided (wholesale or retail or both), the geographic region served, population, and the sources of water. Municipalities and areas not included because data back to 1986 was not available include Novato, Petaluma, Sonoma Valley, Napa Valley communities not including City of Napa, Vallejo, American Canyon, and Suisun City; the combined population of these areas in 2014 is about 450,000.

For the Delta-Suisun region, 2005-2017 data were compiled for 1.2 million people in the Delta or Delta-adjacent water service areas in the incorporated communities of Benicia, Brentwood, Discovery Bay, Fairfield, Lathrop, Sacramento, West Sacramento, Stockton, and Tracy. Table 4 lists the agencies, the type of service provided, the geographic region served, population, and the sources of water. The incorporated communities of Suisun City and Rio Vista were not included (total population of about 40,000) and the unincorporated communities of Mountain House Freeport, Clarksburg, Hood, Courtland, Locke, Collinsville, Walnut Grove, and Isleton, that were not included total about 15,000. Figure 5 demarcates the included communities on a map

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[4] This assumes that the agencies are defining the single family and multi-family residential customer class similarly, which is not always true. E.g some agencies separate mobile home parks and dedicated landscaping meters at multi-family complexes.

of the Delta-Suisun regions. Appendix XXX provides more detail on the Delta-Suisun communities that were chosen to include in the region.

Data for the 1986-2017 period for the Bay region and 2005-2017 for the Delta-Suisun region was obtained directly from the water suppliers, from reports that the suppliers produce, and the state agencies and associations to which they report their data. The specific sources include:

1. Directly from the following suppliers: EBMUD, SFPUC, MMWD, BAWSCA, Napa, CCWD, Zone 7, SCVWD (prior
2. Fiscal-year data compilations for the Bay Area Water Agencies Coalition (BAWAC- a coalition of the major Bay Area water agencies); some of these data were superseded by data obtained directly from suppliers)
3. Department of Water Resources Public Water System Survey (PWSS).[5]
4. State Water Resources Control Board Electronic Annual Reports for Large Drinking Water Systems
5. California Urban Water Conservation Council (CUWCC) database
6. Urban Water Management Plans (UWMP) for selected suppliers

The water use data reported by retail suppliers to the PWSS, the Drinking Water Program and the CUWCC is not always consistent with the data for the same year contained in agency reports including the BAWAC report and their Urban Water Management Plans. These inconsistencies were brought to the attention of the suppliers who provided the water use directly to us.

METHODS AND CALCULATIONS

The average daily water use per person – gallons per capita per day (gpcd) – is calculated by converting the reported monthly, bi-monthly or annual residential water use data into gallons, dividing by the appropriate number of days to get a daily use and then dividing that result by the population using that water to get the gallons per capita per day (gpcd). It is assumed for purposes of this calculation that only the population reported to reside within the service area of the district consumes the residential water and that visitors to the area are consuming water from non-residential accounts (i.e. commercial or institutional accounts).[6] For certain water service districts, reliable population data were not available, and city population data were scaled to the populations within service areas based on ratios from previous years where data were available.

BENCHMARKS, TARGETS, AND REFERENCE CONDITIONS

As noted above, in order to evaluate how the Bay Area urban use is affected over time by climate, plumbing codes, conservation measures and economic conditions, water use was assessed beginning in 1986. 1986 is just prior to the 1987-92 drought, the longest drought experienced by Bay Area municipalities and prior to major plumbing code changes instituted in the early 1990's and is used as a reference condition in Table 3 from which to measure changes in total water use, population, and per-capita use. Due to limited data availability in the Delta-Suisun region, 2005 is used as a reference condition in Table 6.

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[5] The PWSS are available up through 2012. Beginning in 2013, DWR no longer requested suppliers to submit a PWSS and monthly water use data is reported by suppliers to the Drinking Water Program database housed at the State Water Resources Control Board.

[6] It is possible that some of the visitors using the water in the municipalities are using residential water (e.g. bed and breakfasts, other short-term rentals) but that there is no way of determining that for this project. If visitors are using residential water in significant quantities then the gpcd will be somewhat lower.

Benchmarks used to evaluate progress on this indicator are based on state legislation goals articulated in the 2009 Water Conservation Act (SBX7-7), and the State Water Board's 2015 and 2016 drought emergency regulations. For the Bay region the goal of 125 gallons by 2020 represents a reduction from a baseline for the whole Bay region. For the Delta-Suisun region, the goal of 180 gallons represents a 20% reduction in the per-capita use from a baseline, population-weighted for the 10 agencies evaluated in this region. The second benchmark derives from the 2015 and 2016 drought regulations to reduce urban use statewide by 25% translated by the State Water Board for each urban water supplier separately to reduce their total volumetric use from their 2013 level. Required reductions in the Bay region in the 2015 drought ranged from 8% for San Francisco to 36% for Hillsborough. Required reductions in the Delta-Suisun region ranged from 20% for multiple communities to 32% for Discovery Bay. The individual supplier reductions translated to a Bay region 2015 drought reduction target of 18% and a 27% reduction in the Delta-Suisun region. Applying this 18% reduction to the 2013 Bay Area urban water use of 937,000 results in a reduction target of about 768,000 ac-ft for a 12-month period. This value is not a compliance target but is useful as a benchmark for water use in 2015. [7]

The Water Conservation Act of 2009, Senate Bill x7-7 (2009 Act) established a goal of reducing urban per-capita water use from a baseline usage by 20% by 2020 with an interim goal of a 10% per-capita reduction by 2015. This first legislatively-proscribed urban water use target in California provides that targets can be calculated by one of four methods. A water supplier can choose the method to establish its target, which is described in Methodologies for Calculating Baseline and Compliance Urban Per Capita Water Use, Feb 2011, available on the DWR web site http://www.water.ca.gov/wateruseefficiency/sb7/ established for tracking the implementation of the legislation. The Method 3 target is ninety-five percent of the applicable hydrologic region target derived from the State's 20x2020 Water Conservation Plan.[8] The benchmark for the total per-capita metric, based upon 95% of the region's target of 131 gpcd, is currently 125 gpcd for 2020 and 137 gpcd for 2015.[9] These benchmarks are shown in Figure 2 to assess progress for the region, although they are not meant to be used to determine 2009 Act compliance.

RESULTS

Figures 1 and 2 and Table 3 document the fluctuation and eventual overall decline in total water use and per-capita use in the San Francisco Bay region in the 1986-2017 period. Consistent with the trends in coastal California, the Bay region used significantly less potable water in 2017 than in 1986 - about 0.3 million acre-feet (maf) or 28% less- despite more than a 1.6 million or a 32% increase in population over the same period. The combination of decreased use and increased population means that water is used more efficiently on a per-capita basis, the 108 gpcd in 2017 is nearly half of the 200 gpcd 30 years ago. The residential volumetric water use showed similar, but modestly lower percentage decreases in water use compared to the total water use reflecting the investments by industry, commercial entities, and institutions in water efficiency and their use of recycled water. A sampling of the 2018 total water use of some of the larger water agencies in the Bay

[7] The emergency regulations proscribe compliance for the 9-month period from June 2015 to February 2016.

[8] The 20 by 2020 Water Conservation Plan follows from the 2008 governors executive order requiring state agencies to develop a plan to reduce statewide per capita urban water use by 20 percent by the year 2020.

[9] The 131 gpcd regional target is reported in the 2010 UWMP for SFPUC. According to Peter Brostrom, DWR water use efficiency section chief, The SBx7-7 target for the San Francisco Bay hydrological region is not a fixed number but that for purposes of this assessment the 131 gpcd can be used (pers com, Sept 10, 2015)

region (SFPUC, EBMUD, CCWD, San Jose Water Co, Marin Municipal, Alameda County Water District) indicates that the total water use was the same or modestly higher (1% to 3%). The variation in water use is largely explained by the climatic differences between the cooler Bay-side versus the warmer inland areas and residential lot size differences between the smaller lots in the older cities and larger lots in the newer suburbs; SFPUC and CCWD represent the two extremes in the Bay Area with a greater than two-fold difference in the total and per-capita water use. Variations in water use are also reflective of the relative proportion of the different types of uses- residential versus non-residential uses and variations within the commercial and industrial sectors- in the region. For example Santa Clara and Contra Costa Counties have more water-using industry than Marin or Napa Counties. The water use trends over time also reflect the relative growth patterns in the region in the past 30 years. Residential growth has been proportionally much greater in the warmer inland areas of Eastern Alameda and Contra Costa Counties than in the inner Bay Area and is reflected in the increase of residential water use in the water districts serving those areas. The per-capita total and residential use, however, has decreased in all areas with the greatest reductions in the areas with higher outdoor water use.

Although the water use in the Delta-Suisun region was evaluated over a much shorter time period, 13 years (2005 to 2017) compared to the 32 years in the Bay region, Figures 3 and 4 and Table 6 also show the same trend of increasing population, decreasing total water use and increased efficiency as indicated by the 31% decrease in per-capita use. The available data reported to the State Water Board indicates that the total water use in 2018 increased by 4% to 7 % in some of the faster growing South Delta communities such as Brentwood, Tracy and Lathrop but stayed virtually the same in the larger communities of Sacramento, Stockton and Fairfield.

The benchmark of a 20% reduction in per-capita use by 2020 was achieved in the Bay and Delta-Suisun regions in 2014 and has been significantly exceeded since then, suggesting that new legislative standards for increased water use efficiency are achievable. The two regions achieved their 2015 and 2016 drought reduction targets and many communities in the regions significantly exceeded their targets. The 8% increase in total water use in the two regions since 2016 is due to both population and economic growth as well as increases in outdoor water use after the drought, particularly in the hotter inland regions where outdoor water use represents a larger fraction of the total use (about 50% of the total use). Despite recent increases in total water use, dramatic gains in the efficiency of water use are permanent because of existing regulations and plumbing standards, and should continue given technological progress on appliance and industrial efficiency and transformations of landscapes to lower potable water use. A sign of the progress is that the Bay regions per-capita residential water – encompassing both indoor and outdoor use- is close to 60 gpcd, or within 10% of the legislatively proscribed standard to achieve 55 gpcd for indoor-only residential use by 2024. Many of the coastal communities are already lower than the indoor standard indicating that the new standards should be achievable in the Bay region. The success in meeting existing benchmarks and emerging requirements will require new measures of progress.

THREATS & CHALLENGES

Responding to increasing extremes of wet and dry years, recurring drought and warming temperatures, population growth and greater stresses on freshwater-dependent ecosystems will require still more efficiency and less dependence on imported water. The Bay Area faces the additional challenge of accommodating population growth. Every new person, family, or business presents increasing demand for new supply at a time when the region remains more vulnerable than ever to the warming climate. The Bay Area is still highly dependent on imports from watersheds reliant on shrinking natural snow storage. The warming climate will also increase outdoor water use, which currently represents about 40% of the total urban use in the region and offers the greatest potential for additional water savings. Efficiency improvements need to go beyond traditional conservation measures that reduce potable water use, however. Improvements must also encompass greater use of locally derived non-potable sources such as recycled wastewater and the on-site reuse of gray water, rainwater, and stormwater. The ongoing drought is stimulating behavioral changes in how we use water. Whether this collective action will lead to permanent reductions in urban water use and an increase in freshwater flows to the Bay and through rivers and streams — flows vital to fish and ecosystem health — remains to be seen.

Table 1: Major Water Agencies in the San Francisco Bay Region

Agency	Type	County / region served	2017 Population	Primary sources of water
Alameda County Water District (*ACWD*)	Retail	South Alameda	351,000	SWP, SFPUC, and ground water
Bay Area Water Supply and Conservation Agencies (*BAWSCA*)[1]	Association	San Mateo, north Santa Clara, south Alameda	1,824,411 (874,415)[2]	SFPUC, SWP, CVP, local surface and ground water
Contra Costa Water District (*CCWD*) (includes treated and wholesale service areas)	Retail and Wholesale	North, central, and east Contra Costa	494,285	CVP, and direct diversion from the Delta
East Bay Municipal Utility District (*EBMUD*)	Retail	North Alameda, north and central Contra Costa	1,426,000	Mokelumne River and local surface water
Marin Municipal Water District (*MMWD*)	Retail	South and central Marin	189,900	Lagunitas Creek, and Russian River surface water
City of Napa	Retail	Napa	87,797	SWP, local surface water
San Francisco Public Utilities District (*SFPUC*)	Retail and Wholesale	San Francisco	874,228	Tuolumne River and local runoff in Alameda and San Mateo County
Santa Clara Valley Water District (*Valley Water*)[3]	Wholesale	Santa Clara	1,956,598	SFPUC, SWP, CVP, local surface and ground water
Zone 7 of the Alameda County Flood Control and Water Conservation District (*Zone 7*)	Wholesale and Retail	East Alameda	255,170	SWP, local surface and ground water

[1] BAWSCA does not deliver water but is an association of the 26 cities, water districts and other agencies that purchase all or a portion of their water from the City and County of San Francisco (SFPUC) Hetch Hetchy water system.
[2] BAWSCA includes ACWD and agencies that are part of Valley Water. The bracketed number represents the 2015 population *excluding* those entities.
[3] Valley Water population includes South County

Table 2- Total and Residential Water Use for the San Francisco Bay Region

	Year	Population Served	Total Use		Residential Use	
			Acre-feet	GPCD	Acre-feet	GPCD
	1986	4,926,783	1,095,075	198	589,835	107
Drought Period	1987	4,979,501	1,115,781	200	589,065	106
	1988	5,037,887	1,054,355	187	544,857	97
	1989	5,104,278	947,070	166	514,297	90
	1990	5,161,134	981,503	170	514,416	89
	1991	5,194,112	859,548	148	450,112	77
	1992	5,248,028	876,048	149	482,453	82
	1993	5,319,206	908,995	153	514,013	86
	1994	5,363,939	957,448	159	531,947	89
	1995	5,394,104	961,710	159	542,424	90
	1996	5,450,714	1,016,822	167	572,912	94
	1997	5,522,039	1,066,884	172	600,685	97
	1998	5,598,163	1,009,597	161	563,015	90
	1999	5,668,259	1,060,497	167	596,470	94
	2000	5,750,656	1,090,438	169	612,620	95
	2001	5,817,604	1,093,009	168	621,477	95
	2002	5,849,746	1,089,017	166	619,335	95
	2003	5,869,093	1,059,250	161	634,344	96
	2004	5,922,332	1,082,049	163	641,958	97
	2005	5,950,543	1,031,193	155	612,521	92
	2006	5,997,222	1,030,924	153	616,989	92
Dry Period and Recession	2007	6,062,945	1,060,596	156	631,236	93
	2008	5,940,947	986,819	148	587,079	88
	2009	5,978,758	906,759	135	534,628	80
	2010	5,987,069	864,667	129	514,350	77
	2011	6,043,340	875,742	129	509,677	75
Drought	2012	6,105,964	897,884	131	543,926	80
	2013	6,177,981	937,375	135	556,250	80
	2014	6,240,291	819,718	117	484,223	69
	2015	6,289,903	718,030	102	410,582	58
	2016	6,361,929	735,499	103	416,103	58
	2017	6,461,421	794,289	110	450,001	62
Percent Change (%)		31%	-27%	-45%	-24%	-42%

Table 3: Total and Residential Water Use in 2017 for Individual Agencies in the San Francisco Bay Area

Agency	Population change since 1986	2017 Water Use			Change in water use 1986-2017		Per capita water use		Change in *per capita* water use 1986-2017	
		Total (AF[4])	**Residential (AF)**	**Resid. % of total[5]**	**Total % change**	**Residential % change**	**Total** (GPCD)	**Resid.** (GPCD)	**Total % change**	**Residential % change**
Alameda County Water District (*ACWD*)	+47%	40,871	23,994	59%	-10%	-21%	104	61	-38%	-46%
Bay Area Water Supply and Conservation Agencies (*BAWSCA*)[6]	+31%	224,343	125,373	56%	-21%	-22%	110	61	-40%	-22%
Contra Costa Water District (*CCWD*)	+ 60%	96,400	51,730	54%	-28%	+7%	174	93	-55%	-33%
East Bay Municipal Utility District (*EBMUD*)	+26%	183,492	103,842	57%	-23%	-24%	115	65	-39%	-39%
Marin Municipal Water District (*MMWD*)	+14%	24,555	16,321	66%	-25%	-21%	113	77	-36%	-30%
City of Napa	+33%	12,413	7,601	61%	-4%	-6%	126	77	-28%	-29%
San Francisco Public Utilities District (*SFPUC*)[7]	+19%	69,511	42,305	61%	-39%	-24%	71	43	-48%	-36%
Zone 7 Alameda County (*Zone 7)*	+128%	39,556	22,644	57%	+47%	+26%	138	79	-36%	-45%

[4] Units: AF = acre-feet (325,831 US Gal., or 1233.48 m^3); GPCD = gallons per capita per day
[5] Residential water use as % of total water use not including recycled water
[6] BAWSCA values are for the Fiscal Year and include ACWD and agencies that are part of SCVWD.
[7] SFPUC values are based on annual changes from recent PWSS data and scaled to match overlapping years in the 2015 SOTER.

Table 4: Water Agencies in the Delta-Suisun Region

Agency	Type	City / region served	2017 Population	Primary sources of water
City of Benicia	Retail	Benicia	28,000	Sacramento River/North Bay Aqueduct; Putah Creek (Solano Project); local surface (Lake Herman)
Brentwood	Retail	Brentwood	61,383	Groundwater; Delta diversion from Rock Slough
Discovery Bay	Retail	Discovery Bay	15,000	Groundwater
City of Fairfield	Retail	Fairfield	110,065	Sacramento River/North Bay Aqueduct; Putah Creek (Solano Project)
City of Lathrop	Retail	Lathrop	23,384	Stanislaus River purchases; groundwater
City of Sacramento	Retail & Wholesale	Sacramento	493,025	Sacramento and American Rivers; groundwater
City of Stockton	Retail	Stockton	175,530	Calaveras, Stanislaus, and Mokelumne River purchases; Delta diversion; groundwater
California Water Service - Stockton	Retail	Stockton	172,105	Calaveras and Stanislaus River purchases; groundwater
City of Tracy	Retail	Tracy	91,051	CVP; Stanislaus purchases; groundwater
City of West Sacramento	Retail	West Sacramento	53,082	Sacramento River diversions

Table 5- Total Water Use for the Delta-Suisun Region

	Year	Population Served	Total Use	
			Acre-feet	GPCD
	2005	1,101,817	281,502	228
	2006	1,111,662	280,333	225
Dry Period and Recession	2007	1,122,211	301,639	240
	2008	1,133,067	286,051	225
	2009	1,140,188	265,086	208
	2010	1,154,833	252,794	195
	2011	1,153,292	249,327	193
Drought	2012	1,156,604	256,113	198
	2013	1,166,913	264,486	202
	2014	1,173,137	224,134	171
	2015	1,186,947	194,263	146
	2016	1,207,153	200,485	148
	2017	1,222,625	215,802	158
Percent Change (%)		11%	-23%	-31%

Table 6: Total Water Use in 2017 for Individual Agencies in the Delta-Suisun Region

Agency	**Population change since 2005**	**2017 Water Use (AF[8])**	**Change in water use 2005-2017 % change**	**Per capita water use (GPCD)**	**Change in *per capita* water use 2005-2017 % change**
City of Benicia	+4%	4,629	-21%	148	-24%
Brentwood	+34%	9,873	-2%	144	-27%
Discovery Bay	+1%	2,842	-23%	169	-24%
City of Fairfield	+10%	20,043	-14%	163	-21%
City of Lathrop	+83%	4,168	+32%	159	-28%
City of Sacramento	+11%	93,813	-32%	170	-39%
City of Stockton	-1%	29,314	-15%	149	-15%
CWS - Stockton	+5%	23,246	-23%	121	-27%
City of Tracy	+16%	16,352	-9%	160	-22%
City of W Sacramento	+32%	11,519	-22%	194	-41%

[8] Units: AF = acre-feet (325,831 US Gal., or 1233.48 m^3); GPCD = gallons per capita per day

Figure 1

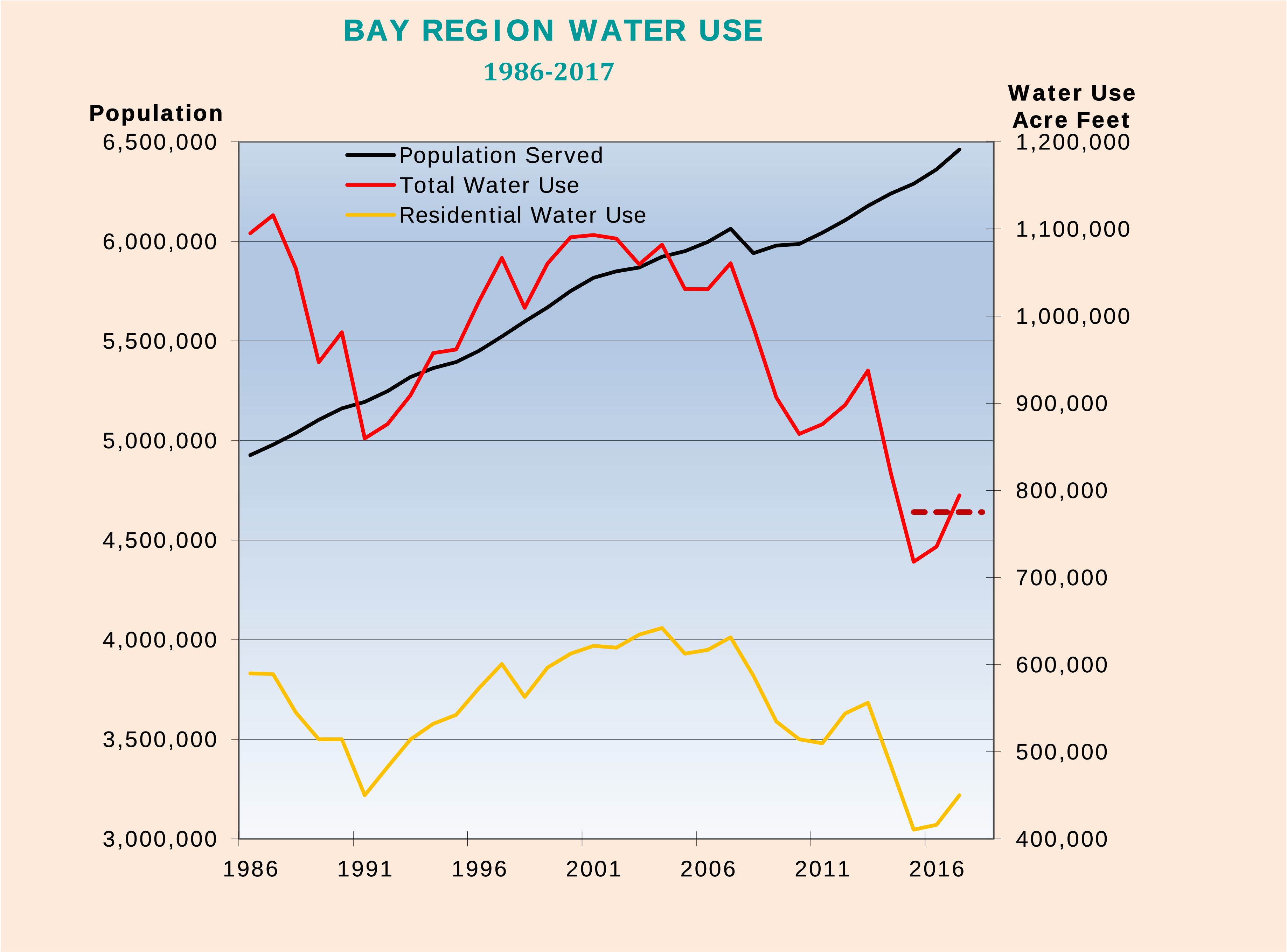
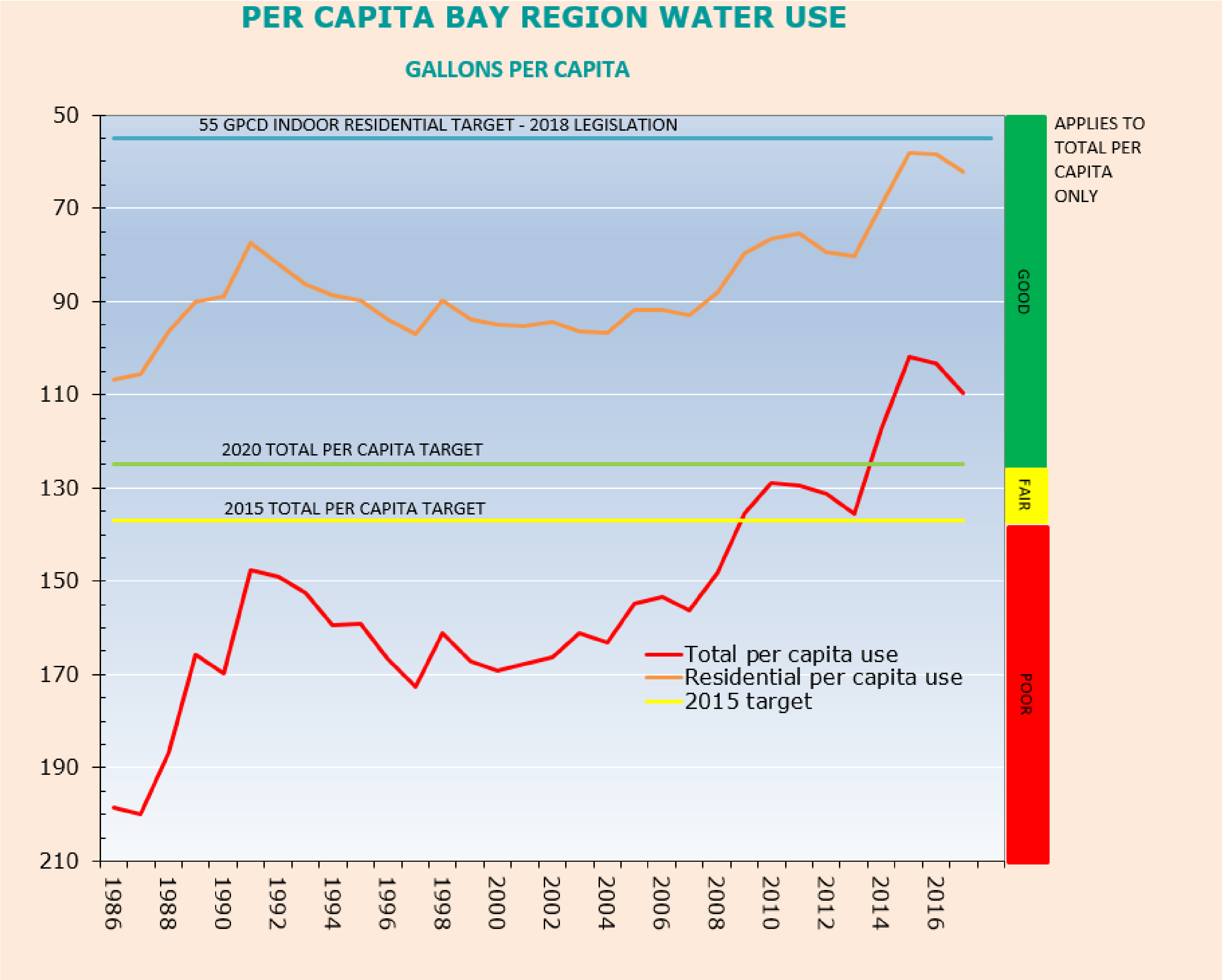

BAY REGION WATER USE
1986-2017
Population
Water Use
Acre Feet
Population Served
Total Water Use
Residential Water Use
6,500,000
6,000,000
5,500,000
5,000,000
4,500,000
4,000,000
3,500,000
3,000,000
1,200,000
1,100,000
1,000,000
900,000
800,000
700,000
600,000
500,000
400,000
1986
1991
1996
2001
2006
2011
2016

Figure 2



PER CAPITA BAY REGION WATER USE
GALLONS PER CAPITA
55 GPCD INDOOR RESIDENTIAL TARGET - 2018 LEGISLATION
2020 TOTAL PER CAPITA TARGET
2015 TOTAL PER CAPITA TARGET
Total per capita use
Residential per capita use
2015 target
GOOD
FAIR
POOR
APPLIES TO TOTAL PER CAPITA ONLY
50
70
90
110
130
150
170
190
210
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016

Figure 3

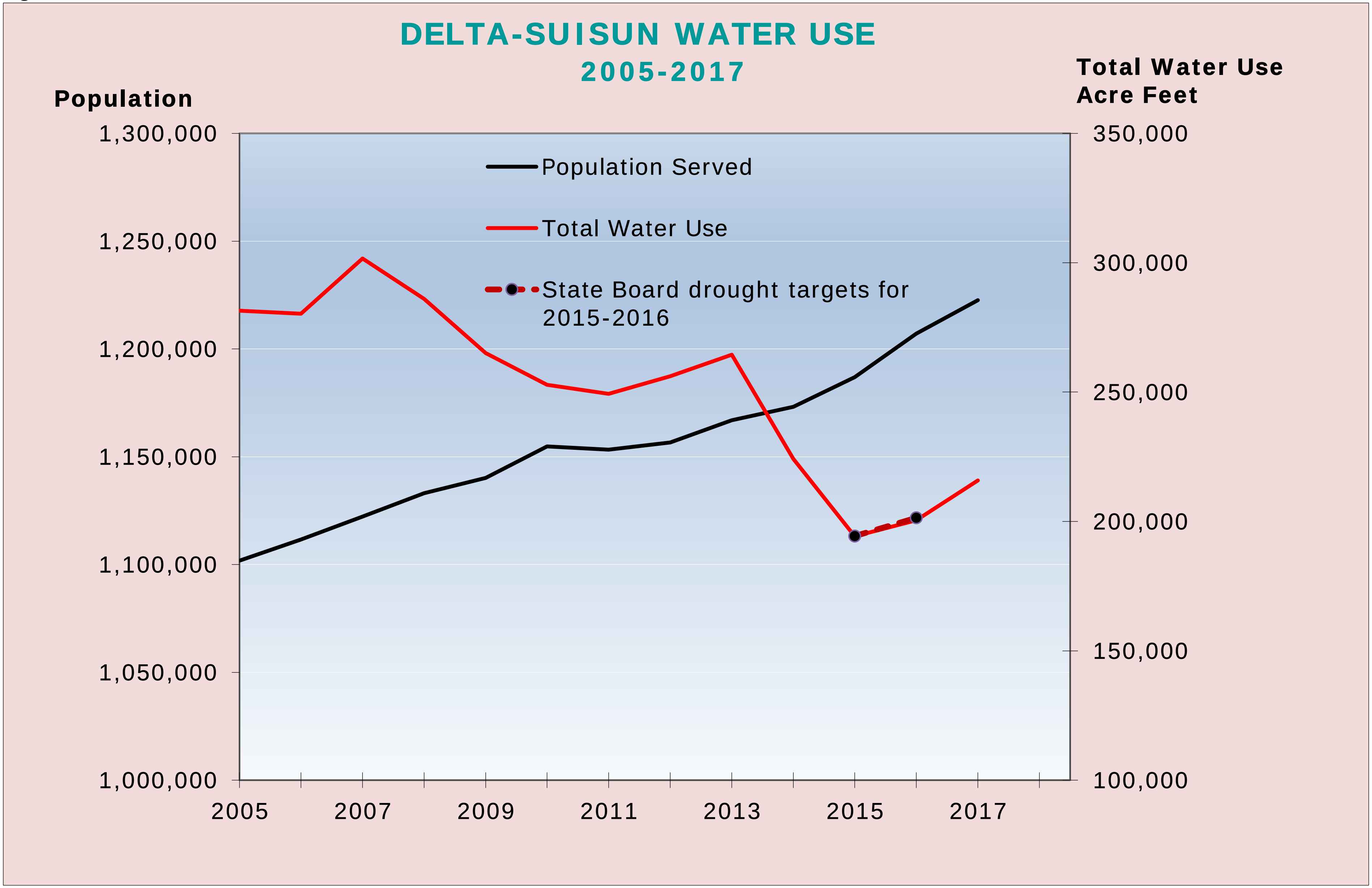
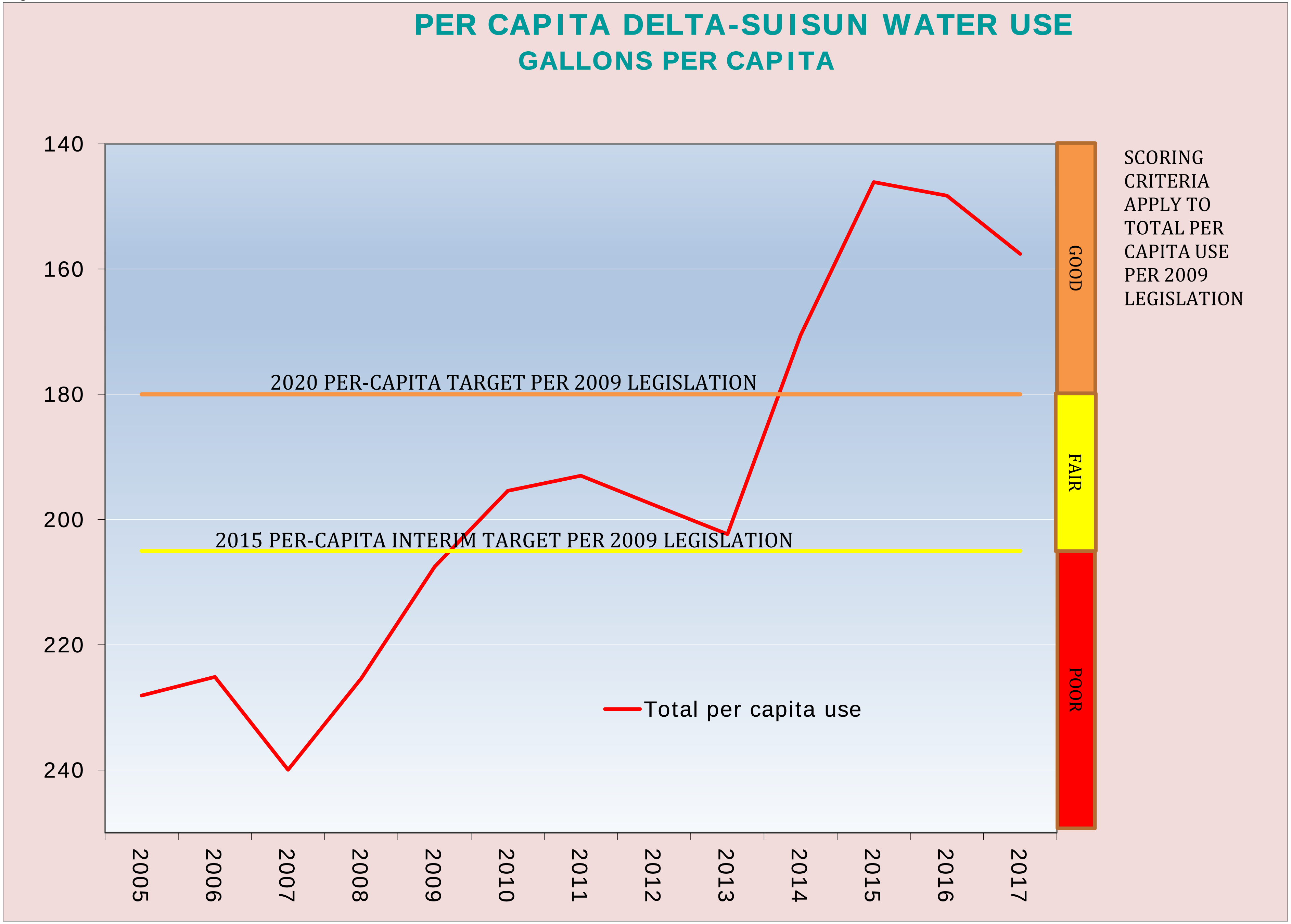
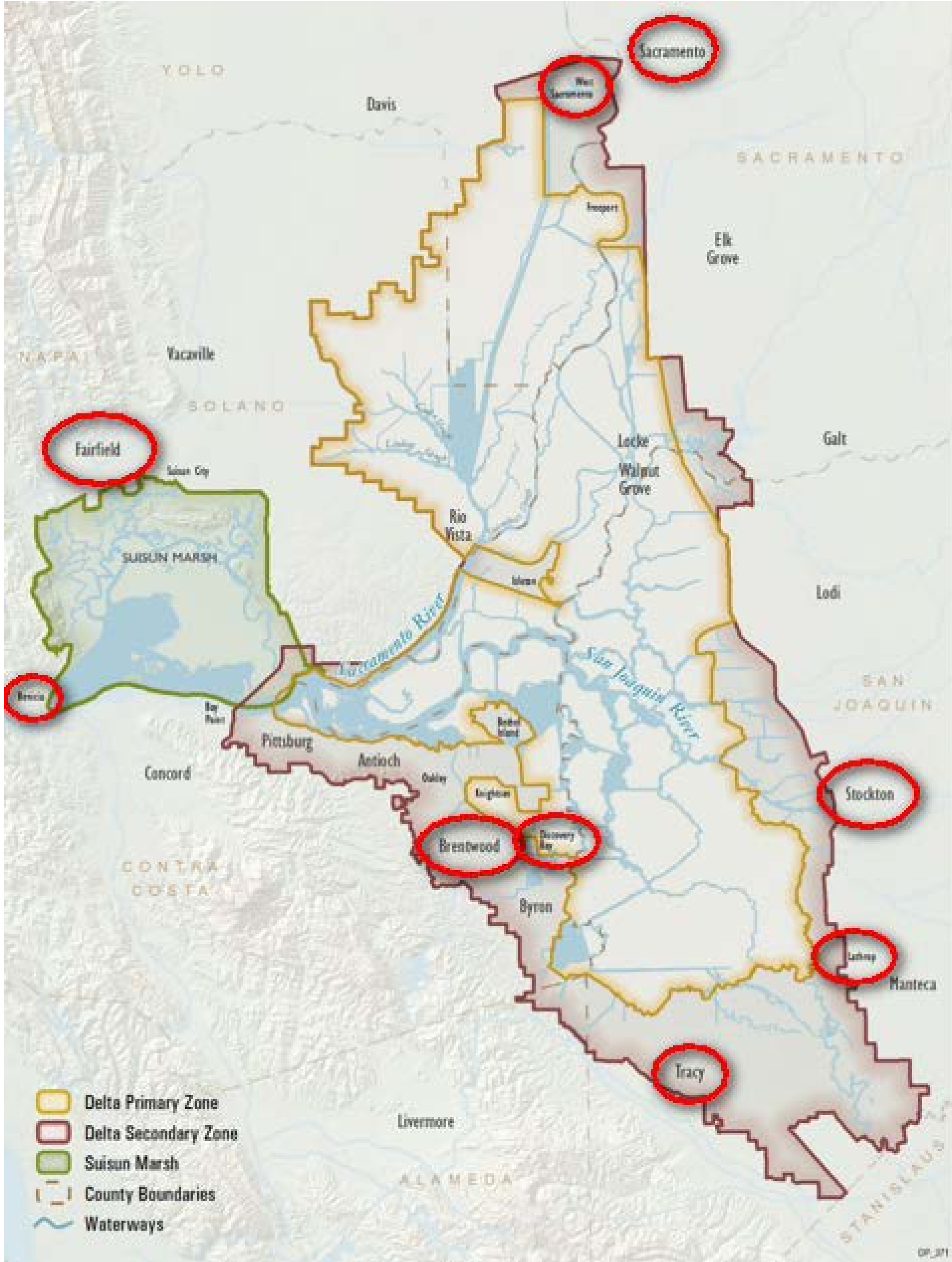

DELTA-SUISUN WATER USE
2005-2017
Population
Total Water Use
Acre Feet
1,300,000
1,250,000
1,200,000
1,150,000
1,100,000
1,050,000
1,000,000
350,000
300,000
250,000
200,000
150,000
100,000
2005
2007
2009
2011
2013
2015
2017
Population Served
Total Water Use
State Board drought targets for 2015-2016

Figure 4



PER CAPITA DELTA-SUISUN WATER USE
GALLONS PER CAPITA
140
160
180
200
220
240
2020 PER-CAPITA TARGET PER 2009 LEGISLATION
2015 PER-CAPITA INTERIM TARGET PER 2009 LEGISLATION
Total per capita use
GOOD
FAIR
POOR
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
SCORING CRITERIA APPLY TO TOTAL PER CAPITA USE PER 2009 LEGISLATION

Figure 5- Map from Delta Plan highlighting the 10 retailers assessed in the Delta-Suisun Region (Stockton has two retailers)



State of the Estuary Report 2019

Technical Appendix

Emerging Indicator: Subsided Lands

Prepared by Matt Benjamin
San Francisco Estuary Institute

Brief Description
This emerging indicator measures the amount of land in the Estuary at elevations below the average daily high tide but diked off from tidal action, and categorizes land uses and elevations within these areas. This metric highlights the status and trend of land subsidence in tidally disconnected areas of the Bay and Delta and provides insight into flood risk at a regional scale.

Preliminary Indicator Status and Trend
Metrics for scoring the status of subsided lands in the Estuary have not yet been developed. However, the amount of land that has been disconnected from tidal action in the Estuary is extensive — there is currently more area protected by levees in the Bay and Delta than what remains connected to the tides. In the Bay, most tidally disconnected areas remain in wetlands, aquatic habitat types, and salt ponds, which limits further subsidence. Agriculture predominates in the Delta, which increases the likelihood of further subsidence.

Brief Scientific Interpretation
The subsided lands emerging indicator measures the amount of formerly tidal lands in the San Francisco Bay and Sacramento-San Joaquin River Delta that have been disconnected from tidal action. It categorizes disconnected areas by land use type and severity of land subsidence. These metrics serve as important indicators for flood risk and habitat restoration potential in the regions. Severely subsided lands with heavy human activity, such as urban development and agriculture, present an increasing flood risk as sea levels rise, groundwater levels change, and rainfall patterns shift with climate change. In some cases, less subsided lands present opportunities to restore tidal habitats in the Estuary, where only a small fraction of the historical tidal habitat remains.

Subsidence is less severe in the Bay than in the Delta, and subsided lands largely remain wetted in the Bay. The majority of the Delta, meanwhile, has subsided more than ten feet below the height of the average daily high tide (Mean Higher High Water) and is largely used for agriculture, placing these areas at risk of further subsidence. Subsidence exposes human lives and assets at risk of flooding from various sources, and interventions will be increasingly necessary to protect human activities on subsided lands moving forward. The Estuary also has significant potential for restoring tidal marsh, but increasing subsidence may limit opportunities into the future.

Background and Rationale
Historically, the San Francisco Bay and Sacramento-San Joaquin River Delta provided some of the most extensive tidal wetland habitat on the West Coast of North America. Central California contained over 100 estuaries with wetland habitat, yet the Bay and Delta contained 99% of the region's wetland area (Brophy et al. 2019). However, today, much of the Estuary's formerly tidal lands have been diked off for human uses. In the Bay, levees were primarily constructed around large tracts of tidal lands to construct salt ponds, while lands in the Delta were largely diked off to allow for agriculture on its fertile lands. In Suisun Bay, grouped with the San Francisco Bay in this analysis, duck ponds constitute the major land use in formerly tidal lands. These land use changes have signified major losses in habitat for wetland-dependent animals and corresponded with population declines for some species (Robinson et al. 2014). At the same time, they have made room for a productive agricultural system, booming cities, and other human uses in the Estuary.

The low elevation of formerly intertidal and subtidal lands places them at increased risk of flooding due to breached levees, rising groundwater, and rainfall. As sea levels rise, rainfall patterns shift with climate change, and land subsides,these risks are becoming increasingly pressing. Particularly in formerly tidal and subtidal lands that are now dry for most or all of the year, soil sediments undergo compaction and oxidation that results in the land's surface sinking (Shirzaei and Bürgmann 2018). These effects are generally less severe or absent from land uses that maintain water above soils, such as managed ponds. Subsidence not only increases flood risk, but also leads to carbon emissions as soils degrade. Lands that have subsided significantly (i.e., around 10 feet below MHHW or more) are difficult to restore to tidal habitat.

Changes in elevation can indicate the degree to which key biophysical processes, such as sediment deposition and marsh accretion, are occuring. These processes allow mudflats and tidal marshes to maintain their elevations relative to the tide, and can mitigate risk from storm surge, erosion, and sea level rise, thus contributing to shoreline resilience. Where tidal disconnection has halted these processes, land subsidence may lead to significant increases in flood risk. Interventions may be necessary to maintain certain land uses in deeply subsided areas, and restoration may be a preferable alternative to maintaining such land uses in some cases. Elevation is thus an integral part of the health of the Estuary, and elevation changes will serve as important indicators of the region's resilience to imminent global changes.

Methods
To identify areas at or below tidal elevations that are now disconnected from tidal action in the San Francisco Bay and Sacramento Delta, we first assembled topography and bathymetry datasets for the region. We relied primarily upon the California Department of Water Resource's 2012 Bay-Delta topobathy synthesis, and used DWR's 2012 synthesis to fill gaps in the data. In eight areas in the South and San Pablo Bays where the resulting topobathy raster reported

inaccurate bathymetry values for salt ponds, we corrected the inaccuracies using expert opinion for depth values. The local elevation of MHHW was derived from AECOM (2016) for the Bay and Seigel and Gillenwater (2018) for the Delta. We then subtracted mean higher high water values from the assembled topobathy data raster to determine areas at or below mean higher high water. We converted this elevation dataset into polygon format to identify areas connected and disconnected from tidal inundation. To correct for possible false connections, we erased from these polygons berms, embankments, engineered levees, floodwalls, shoreline protection structures, transportation structures, and water control structures as mapped by the San Francisco Bay Shore Inventory (2016) for the Bay and the California Levees Database (2015) for the Delta. To correct false disconnections, we manually added connections for areas visibly connected to the tides based on aerial imagery. After applying these corrections, we dissolved contiguous polygons and classified the polygon that included the mouth of the Bay as tidally connected and all other polygons as disconnected. We used the Bay Area Aquatic Resources Inventory (2017) as a final corrective measure to locate misidentified tidal ecosystems and reclassify associated polygons as connected to the tides. We reclassified elevations in tidally disconnected areas into two categories: areas between zero and ten feet below MHHW, and areas over ten feet below MHHW. This distinction roughly corresponds with the depth at which restoration to tidal marsh becomes logistically infeasible.

We tabulated land uses within disconnected areas using land use data from three sources: the Delta Landscapes Project (2014), Bay Area Aquatic Resources Inventory (2017), and National Land Cover Dataset (2016). For a detailed explanation of the crosswalk used to consolidate land use classes from these three data sets, see the detailed methodology for the shoreline indicator. From the classifications used in the shoreline indicator, we further consolidated land uses into four categories. We grouped managed wetlands, managed ponds, water, slope and depressional wetlands, marsh, seasonal wetlands, and mudflats into a wetlands, aquatic habitat types, and salt ponds group, and we consolidated woody riparian habitats and undeveloped land into a terrestrial habitat types class. Urban development and agriculture remained as distinct classifications.

Given that this analysis relied on spatial datasets produced prior to 2019, the results do not necessarily reflect the current or state of tidal wetland restoration in the Estuary. Future restoration projects were not incorporated into the analysis.

Results

Over half the area of the San Francisco Bay and Sacramento-San Joaquin River Delta is now disconnected from the tides. The most severe land subsidence in tidally disconnected areas occurs in the Delta, where most lands are now ten feet or more below tidal elevation. In the Bay, most tidally disconnected lands remain between zero and ten feet below tidal elevation (Fig. 1). Overall, most of the Estuary's tidally disconnected lands occur in the Delta, where over 85% of the area is diked off (Fig. 2). Agriculture serves as the primary land use in the Delta across subsidence levels. Nearly 20,000 acres of urban development occurs on subsided lands in the

Bay and Delta, primarily in areas with less than ten feet of subsidence (Figs. 3 & 4). Most subsidence lands in the Bay are in the wetlands, aquatic habitat types, and salt ponds land use class. Much of this area refers to duck ponds and other managed wetlands in Suisun Bay (Figs. 3 & 4).

Discussion

Extensive modifications to Bay and Delta wetlands have produced the tidally disconnected lands at and below tidal elevation that are prevalent today. These modifications were particularly comprehensive in the Delta, the majority of which is no longer connected to tidal action. Today, many areas with heavy human activity (e.g., urban and agricultural areas) are at increasing flooding risk due to land subsidence, sea level rise, and climate change. Maintaining and protecting these land uses in these areas will require significant intervention. In some of these areas it could be more cost-effective (and beneficial for the environment) to restore tidal habitats or convert them to habitat types that reduce the rate of subsidence. Many large-scale restoration projects have already occured in formerly disconnected areas and others are currently underway. Future repetitions of this analysis will gauge how well wetland restoration, as well as other interventions like sediment augmentation, change elevations in the region.

Figures

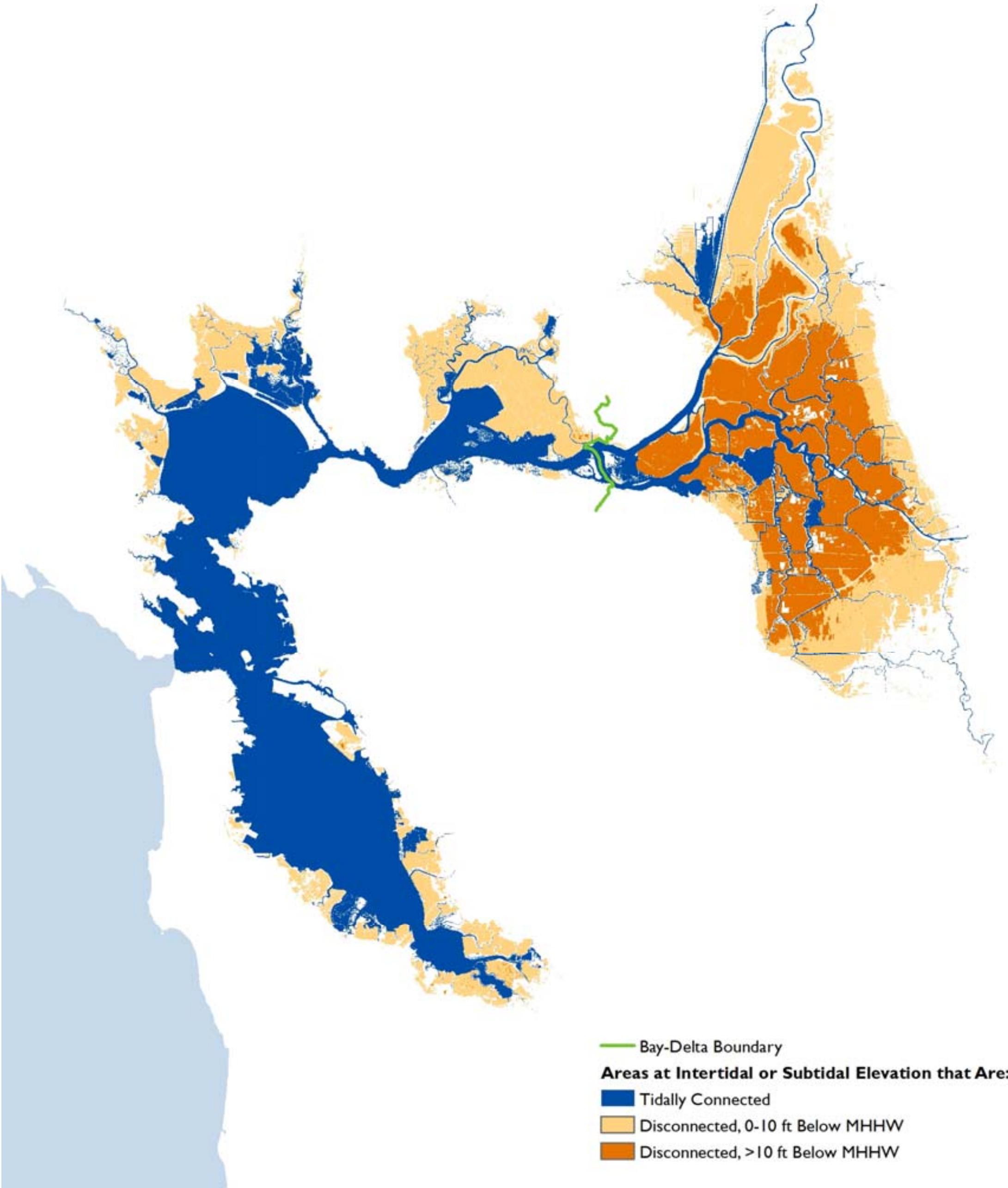


Figure 1: *Severity of land subsidence in areas disconnected from the tides but below mean higher high water elevation. Green line indicates the boundary used to distinguish between the Bay and the Delta in this analysis. Note that Suisun Bay is considered part of the San Francisco Bay.*

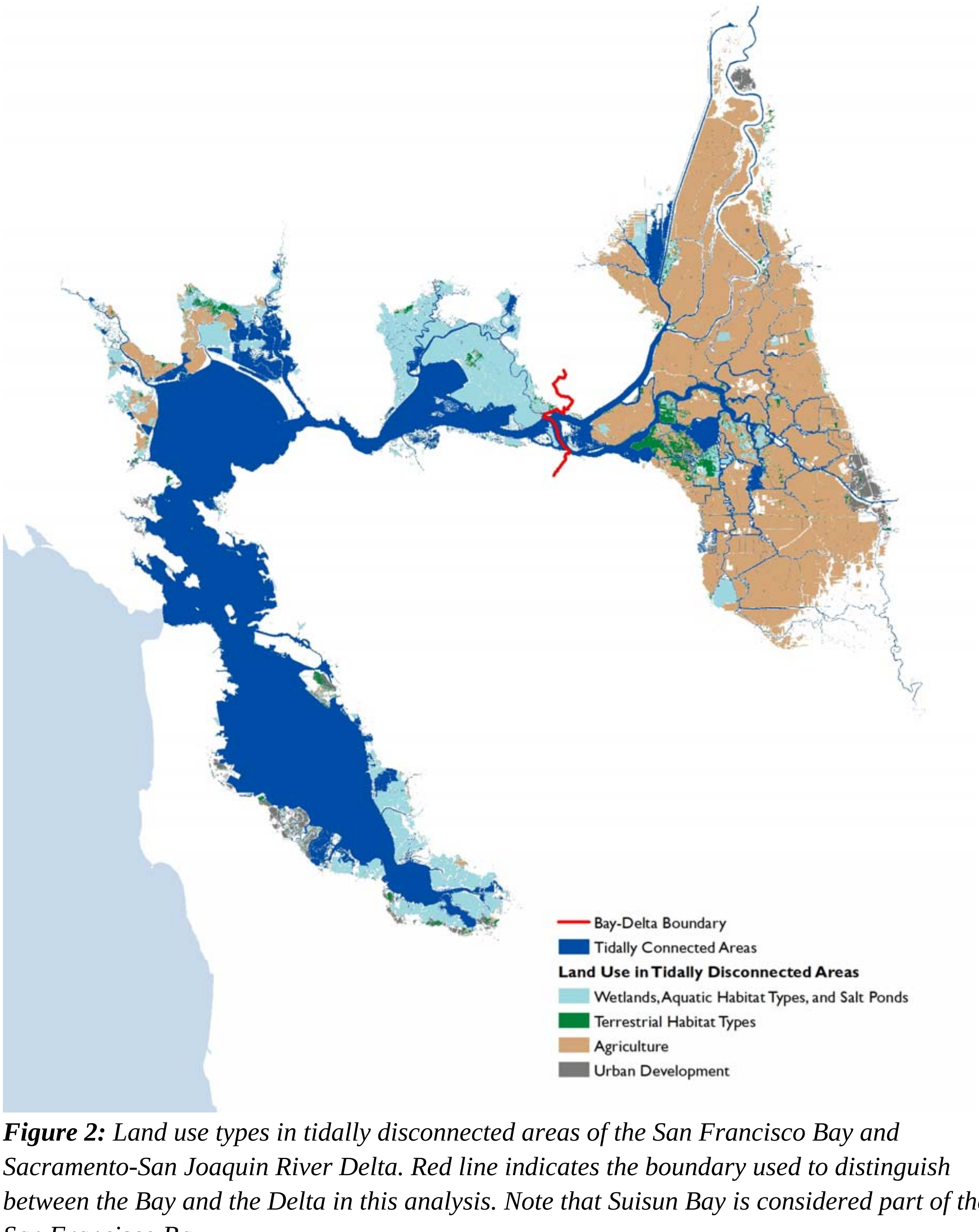


Figure 2: *Land use types in tidally disconnected areas of the San Francisco Bay and Sacramento-San Joaquin River Delta. Red line indicates the boundary used to distinguish between the Bay and the Delta in this analysis. Note that Suisun Bay is considered part of the San Francisco Bay.*

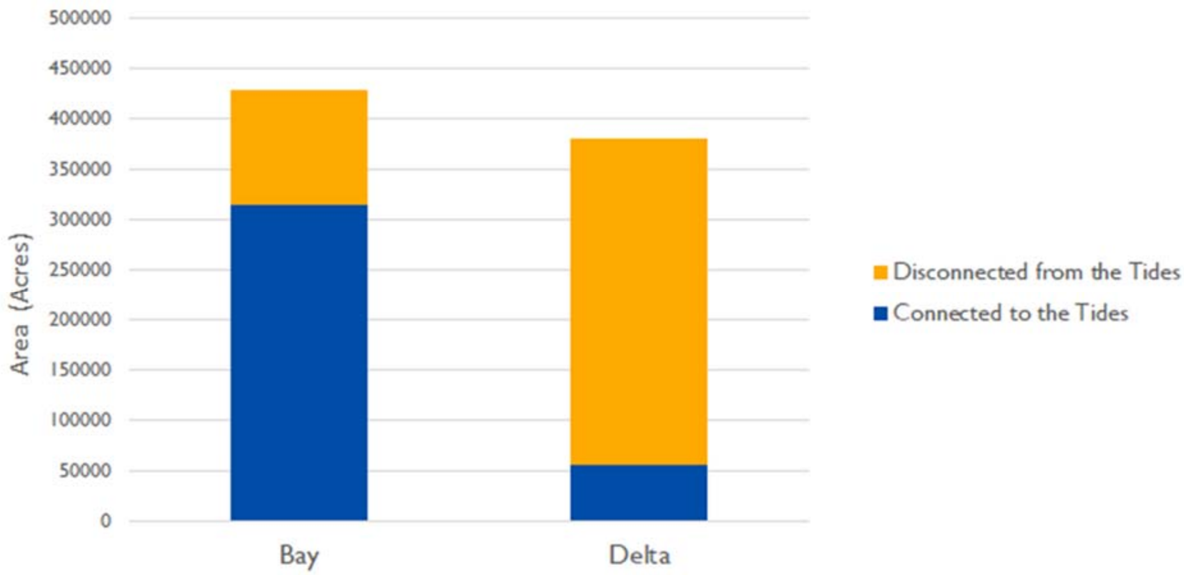


Figure 3: *Area of land in the Bay and Delta at or below MHHW and connected or disconnected from tidal action.*

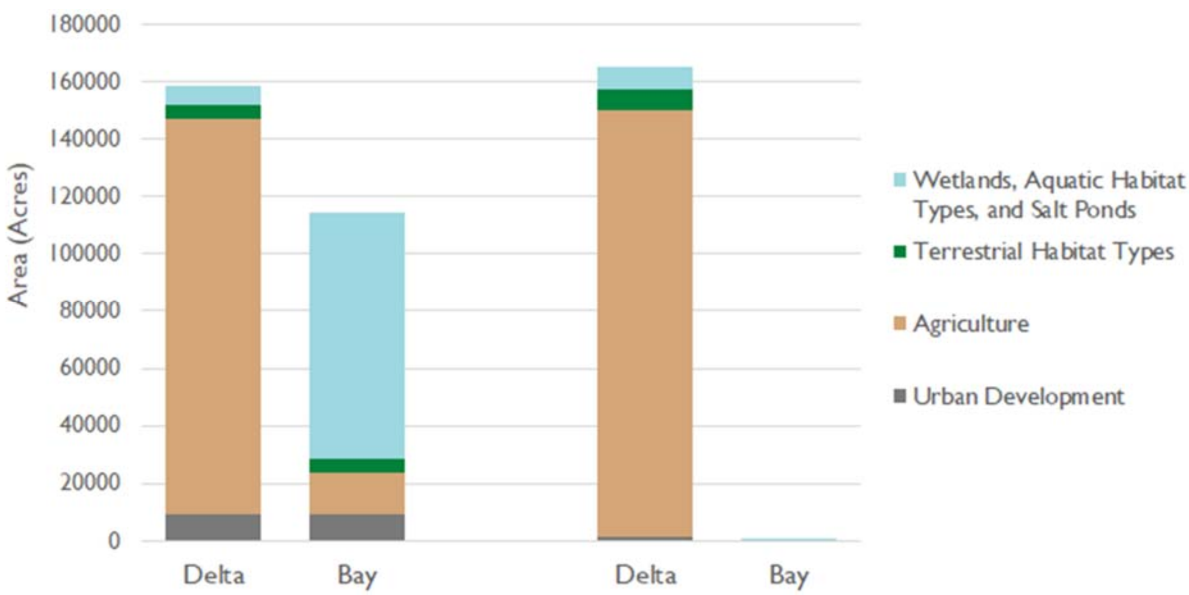


Figure 4: *Land use breakdown of areas between zero and ten feet below MHHW and more than ten feet below MHHW in the Delta and Bay. Data corresponds with that displayed in Fig. 2.*

Works Cited

Brophy, Laura S., et al. "Insights into estuary habitat loss in the western United States using a new method for mapping maximum extent of tidal wetlands." *PloS one* 14.8 (2019): e0218558.

Robinson, April, et al. *A Delta Transformed: Ecological Functions, Spatial Metrics, and Landscape Change in the Sacramento-San Joaquin River Delta*. San Francisco Estuary Institute, 2014, *A Delta Transformed: Ecological Functions, Spatial Metrics, and Landscape Change in the Sacramento-San Joaquin River Delta*.

Shirzaei, Manoochehr, and Roland Bürgmann. "Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area." *Science Advances* 4.3 (2018): eaap9234.

State of San Francisco Estuary 2019

Technical Appendix

Emerging Indicator: Shore Resilience

Prepared by Katie McNight
San Francisco Estuary Institute

Background and rationale

Because they are more flexible and able to adapt to change, natural shores like beaches and tidal marshes are more resilient to flooding than hardened, engineered shores. Even in leveed areas, integrating appropriate semi-natural features can make the shore more resilient. Diked wetlands, for example, can slow or halt subsidence and support wildlife, although they tend not to be as resilient as fully natural systems. Emerging climate adaptation strategies take this into account by incorporating natural and semi-natural features into designs for future shore projects. This emerging indicator categorizes the Estuary's heterogeneous shore to provide an example of how the potential for resilience could be tracked over time using a repeatable, low-cost approach. The categories used in this indicator are intended to demonstrate a spectrum of resilience from relatively low (developed and agricultural land) to intermediate (diked and managed wetlands) to relatively high (ecosystems subject to key land-surface processes, like flooding and sediment dynamics).

Methods

Step 1: We define the shore in the Bay and Delta as where the land meets the water; the boundary that exists between a levee or a foreshore of marsh and the open water of the Bay-Delta Estuary.

We utilize the same approach to evaluate the regional extent of natural features along the shore for the Bay and the Delta, but differences exist in the datasets and data processing methods used. We use different mapping techniques to delineate the Bay and Delta shore and crosswalk land cover and habitat datasets to create a regional layer. The Bay shore was delineated using the latest Bay Area Aquatic Resources Inventory (BAARI version 2.1, largely based on 2009 imagery) (SFEI-ASC 2017a) data by merging channels, tidal flats, and open water habitat extents and extracting the boundary. The resultant Bay shore extends up major creeks draining to the Bay and delineates the foreshore of marshes. The Delta shore was delineated using data from the CA Department of Fish and Wildlife's Vegetation Classification and Mapping Program (VegCAMP, Hickson and Keeler-Wolf 2007) by merging tidally connected channels with open water habitats and extracting the boundary.

Step 2: We use a 100-meter landward buffer to evaluate the percent of natural features located along the shore. This width threshold reflects the average minimum marsh width needed in the Bay to attenuate 100-year incident waves down to 0.3m (1ft) in height before waves reach the back edge of the marsh. The same width threshold was used to create a buffer along the shore in the Delta even though wind-waves are not a major issue there. Though somewhat arbitrary, this buffer distance may still be useful in tracking progress on semi-natural features that protect shore infrastructure and reduce subsidence in the Delta.

Step 3: Along the Bay shore, between the Golden Gate to Broad Slough, Bay Area Aquatic Resources Inventory (BAARI, SFEI 2017a) and National Land Cover Database (NLCD, Homer et al. 2015) datasets were used to classify the 100-meter shore by land cover type. In the Delta, upstream of Broad Slough and within the legal Delta boundary, we combined California Aquatic Resources Inventory data (CARI, SFEI 2017b), VegCAMP data (Hickson and Keeler-Wolf 2007), and NLCD (Homer et al. 2015) data to classify the shore by land cover type. We then crosswalked these four land cover datasets into land use categories associated with different levels of shore resilience. More resilient land use categories included marshes, managed ponds, and managed wetlands. Less resilient land use categories included urban development and agriculture. Land use types that could not easily be categorized were grouped together as "other/resilience not categorized". Results are reported by total percent area of each category type within the 100-m shore for the Bay and the Delta.

Next steps to refine or expand this approach could include:

- Incorporating Bay Shore Inventory data (SFEI 2016) to better understand shore frontage characteristics (i.e. stretches of shoreline that have a beach, wetland, or other natural or semi-natural feature in front of it, that are not captured in the 100-m landward buffer);

- Developing visual tools to communicate this approach to a broad audience (i.e. conceptual diagrams in plan view visualizing landward buffer with breakdown of habitat extents);

- Defining a system to score resilience between natural and semi-natural shore features based on existing widths as compared to desired widths to perform a certain function;

- Excluding places within the shore buffer at elevations higher than a specified sea level rise projection (i.e. steep shores that are not vulnerable to near-term sea level rise);

- And refining the "other/resilience not categorized" areas within the 100-m shore to capture the potential for resilience of additional natural or semi-natural land cover types such as riparian vegetation.

Data gaps, limitations, and other considerations include:

- Differences in the resolution of data (e.g. coarseness of NLCD data) and the age by which the data was derived (e.g. SFEI-ASC 2017 data based largely on 2009 NAIP imagery), could impact the scale at which interpretations of this indicator can be made.

- The nature by which the Delta shore was derived through using channel and open water polygons may overestimate the amount of semi-natural features within the Delta since the delineated shore follows creek channels. A more simplified shore may better represent the extent of these features, although such a dataset was not available at the time of this study.

- The intent of this indicator is to be cost effective and repeatable in order to track changes to the shore over time. Therefore, the timing of which the input datasets (i.e. BAARI, in this instance) will be updated is an important consideration to determine how often this indicator can be reproduced. This consideration will be a significant factor in determining the efficacy of this indicator.

- Major differences result in the overall composition of the shore within the Bay and Delta depending on the shore definition used. Therefore, it is important to consider how the shore delineation may impact the overall results.
- An integrated and standardized dataset of shore feature types (e.g., berms, levees) and corresponding elevations for the full Bay-Delta shore is needed to capture a more nuanced categorization of shore resilience. Such a dataset was mapped for the Bay in 2016 but does not extend to the Delta. Although different levee layers exist throughout the Delta, a comprehensive data layer is needed to better evaluate the potential for resilience throughout the full Bay-Delta Estuary.

References:

Hickson D, Keller-Wolf T. 2007. Vegetation and land use classification and map of the Sacramento-SanJoaquin River Delta. Report prepared for Bay Delta Region of California Department of Fish and Game, Sacramento, CA.

Homer, C., J. Dewitz, S. Jin, G. Xian, L. Yang, P. Danielson, J. Coulston, N. Herold, J. Wickham, and K. Megown. 2015. Completion of the 2011 National Land Cover Database for the Conterminous United States - Representing a Decade of Land Cover Change Information. Photogrammetric Engineering and Remote Sensing 81:346-354.

SFEI (San Francisco Estuary Institute). 2016. San Francisco Bay Shore Inventory: Mapping for Sea Level Rise Planning. San Francisco Estuary Institute-Aquatic Science Center, Richmond, CA.

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State of San Francisco Estuary 2019

Technical Appendix

Emerging Indicator: Urban Green Space

Prepared by Matt Benjamin
San Francisco Estuary Institute

Brief Description

The emerging indicator quantifies the amount of publicly accessible green space that exists per resident in residential areas across the Estuary. It incorporates data from two metrics: the acreage of public parks within a half mile (approximately a ten-minute walk) of each point in the region, and the number of people who live within a half mile of this park area. The ratio of these metrics approximates the amount of benefit residents of different areas in the Estuary can derive from green space.

Nearby urban green space correlates with various measures of mental, physical, and social health. However, green space is often inequitably distributed and provides disproportionate benefits to wealthy communities. While cities surrounding the San Francisco Bay and Sacramento-San Joaquin Delta have a relatively large amount of green space, it is generally located in or near wealthier neighborhoods. Comparing green space per person in disadvantaged communities to green space in the Estuary as a whole illuminates disparities in park benefits across communities. Tracking changes in this disparity will help communities and environmental planners ensure that all residents can benefit from accessing the outdoors.

Preliminary Indicator Status

Metrics for scoring the status of urban green space in the Estuary have not yet been developed. However, park access is high in the San Francisco Bay and Sacramento-San Joaquin Delta regions as compared to other urban areas in the United States. In San Francisco, Oakland, Sacramento, San Jose, and many other cities around the Estuary, more than three quarters of residents live within a ten-minute walk of a public park - more than 20% higher than the national average (Trust for Public Land 2018). There is a median of 91 square feet of park per person across the Estuary. However, publicly accessible green spaces are not equitably distributed across the Estuary. Within disadvantaged communities, there is a median of 61 square feet of park per person. This gap suggests a disparity in the benefits that disadvantaged and non-disadvantaged communities can derive from parks.

Background and Rationale

Various studies have linked green space with aspects of human health in urban areas (Kondo et al. 2018). City parks, tree-lined streets, gardens, and other forms of urban nature can provide recreational opportunities while simultaneously mitigating urban heat and improving air quality (Nowak & Heisler 2010). Visitors to urban parks benefit from improved mood, attention, and other measures of mental and physical health (Kondo et al. 2018). Green space also provides various benefits for local biodiversity and mitigates urban runoff.

As the populations of the San Francisco Bay and Sacramento-San Joaquin River Delta areas rapidly expand, tracking the availability of urban green space will illuminate how effectively parks in the region provide benefits to human health. Specifically comparing green space access in disadvantaged communities to the Estuary overall will help communities and planners ensure that there is equity in distribution of benefits.

Past studies have examined the distribution of parks in the region and areas with limited access. The Trust For Public Land, for example, has mapped areas in the various cities of the Estuary that are within a ten-minute walk of public parks and identified areas that lack local parkland (Trust for Public Land 2018). However, the analysis for this emerging indicator is novel in calculating nearby parkland per person. It incorporates two measurements to produce a park area per person metric: the acreage of public parks within a half mile of each point in the region, and the number of people who live within a half mile of this park area. The indicator compares park per person values between disadvantaged communities and the Estuary as a whole to illuminate disparities that exist in green space access.

Methods

Our preliminary study area included all areas within the San Francisco Bay watershed boundary and the Sacramento Delta legal boundary. We used Metropolitan Transportation Commission city boundaries (2014) and included in the study area the entire extent of all cities with boundaries that at least partially extend into the Bay or Delta boundaries. We then refined our extent to only developed areas by clipping the boundary to areas designated as “residential” and “commercial/industrial/institutional” in the Association of Bay Area Governments (ABAG) 2005 land use dataset.

To calculate park area per person, we first calculated population density in a ten-by-ten meter grid covering the study area. We used American Community Survey (ACS) 2017 population estimates for census block groups for this calculation. We clipped census block group polygons to ABAG 2005 residential and commercial/industrial/institutional parcels, then calculated the number of ten-by-ten meter cells within each resulting polygon and divided the ACS census block group populations by this number of cells (Figure 1).

We subsequently used the California Protected Areas Database to identify publicly accessible ("open" or "restricted" access) parks within and surrounding the urbanized area of the estuary. We used the focal statistics tool in ArcMap v10.7 to calculate the park area within a half mile of every point in the ten-by-ten meter grid (Figure 2). We divided the population density raster by this nearby park area raster, then used focal statistics once again to calculate the number of people accessing each point in each park. We used focal statistics a final time to find, for each point in the urban area, the number of people accessing parkland in the surrounding half mile. We ultimately divided nearby park area by the number of people accessing nearby parkland to ascertain the park area per person at each point in the study area (Figure 3).

We calculated the median nearby park per person value for the entire urban area using the zonal statistics tool in ArcMap, then did so for disadvantaged communities for comparison. We included in our analysis disadvantaged communities as identified by California Senate Bill 535 (updated June 2018), the California Department of Water Resources (updated 2016) and communities of concern as identified by the Metropolitan Transportation Commission (updated 2018). SB535 designates communities as disadvantaged based on pollution, population health statistics, and socioeconomic factors. The Department of Water Resources does so based on median household income, and MTC does so based on income, minority status, and six other socioeconomic variables.

It is important to note that this analysis does not paint a full picture of park access. We used raw distances, not walking distances along streets and paths, to calculate distances from parks. In reality, barriers exist that make parks less accessible to residents in some areas. Furthermore, parks vary in quality and the health benefits they confer upon visitors, but we treat all parkland as equal in this analysis.

Results & Discussion

Residents of neighborhoods in the Bay and Delta near the urban boundary, adjacent to both the estuary and the uplands, benefit from large amounts of nearby park area per person. This result extends from the large area of parkland adjacent to the urban boundary and these areas' low populations relative to the urban core. People who live near major urban park chains, such as the Coyote Creek Parkchain in San Jose, likewise enjoy large areas of park within a half mile relative to their populations - a consequence of the high concentration of green space compared to what exists in the rest of the urbanized Estuary.

Residents of urban areas in the San Francisco Bay and Sacramento Delta regions have a median of 91 square feet of nearby park per person (Figure 4). Residents of disadvantaged communities have a median of 61 square feet - lower than approximately 62% of residents of the overall urban area. This disparity likely has significant ramifications for the physical and mental health of residents of disadvantaged communities, who are less likely to reap the air quality and restorative benefits of urban green space.

Figures

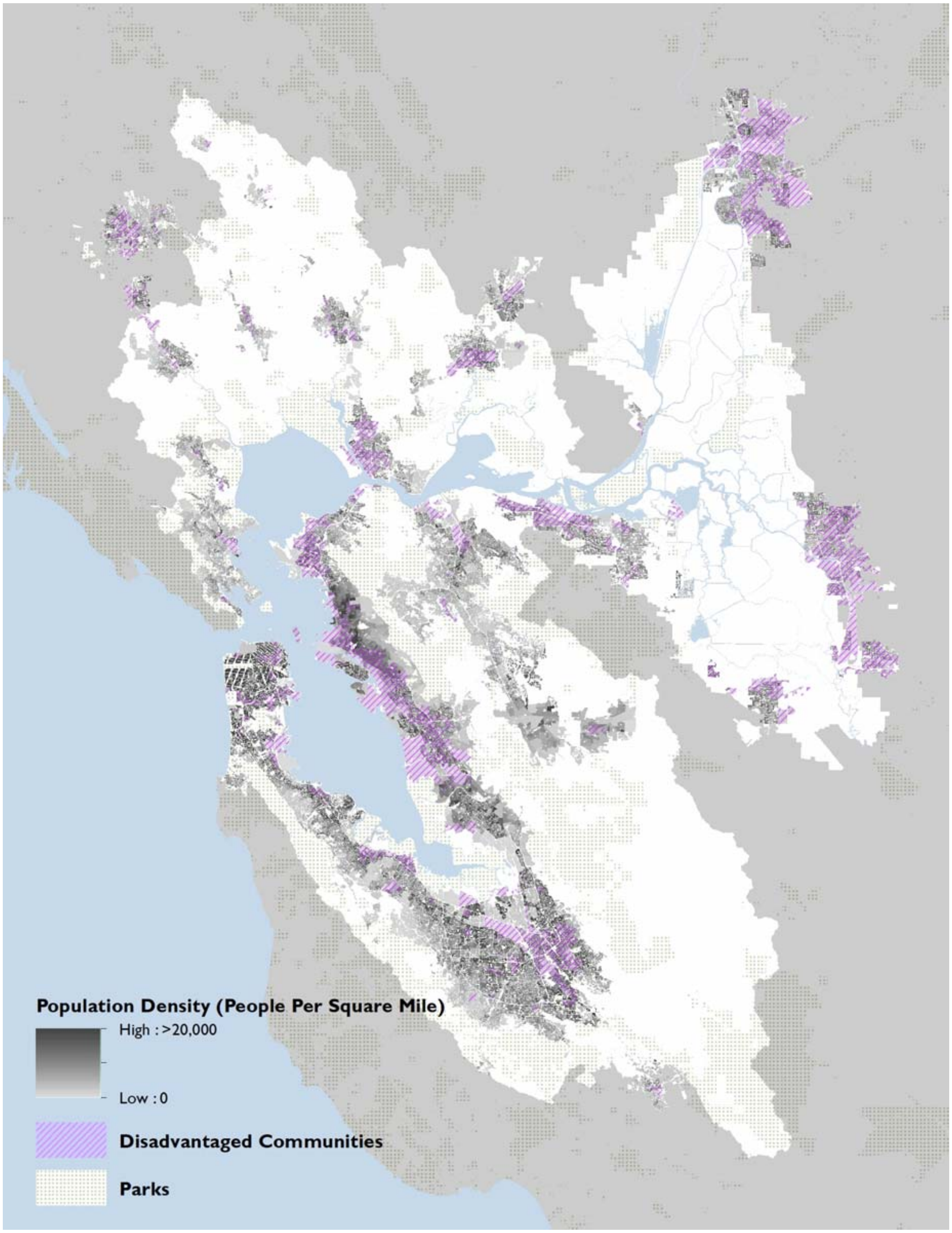

Figure 1: *Population density in urban areas surrounding the San Francisco Bay and Sacramento-San Joaquin River Delta.*

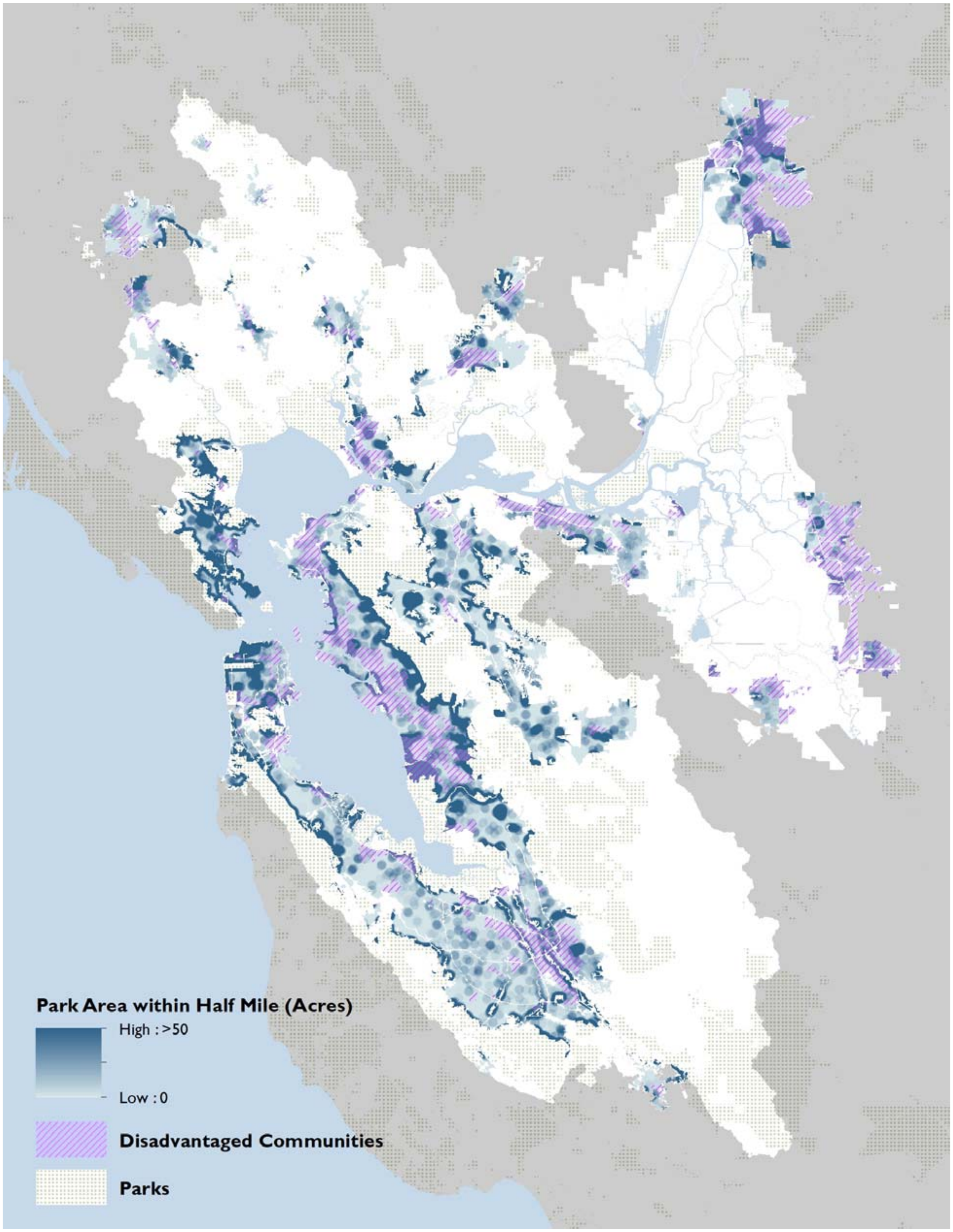

Figure 2: *Total park area within a half-mile of each point in residential areas of the Estuary.*

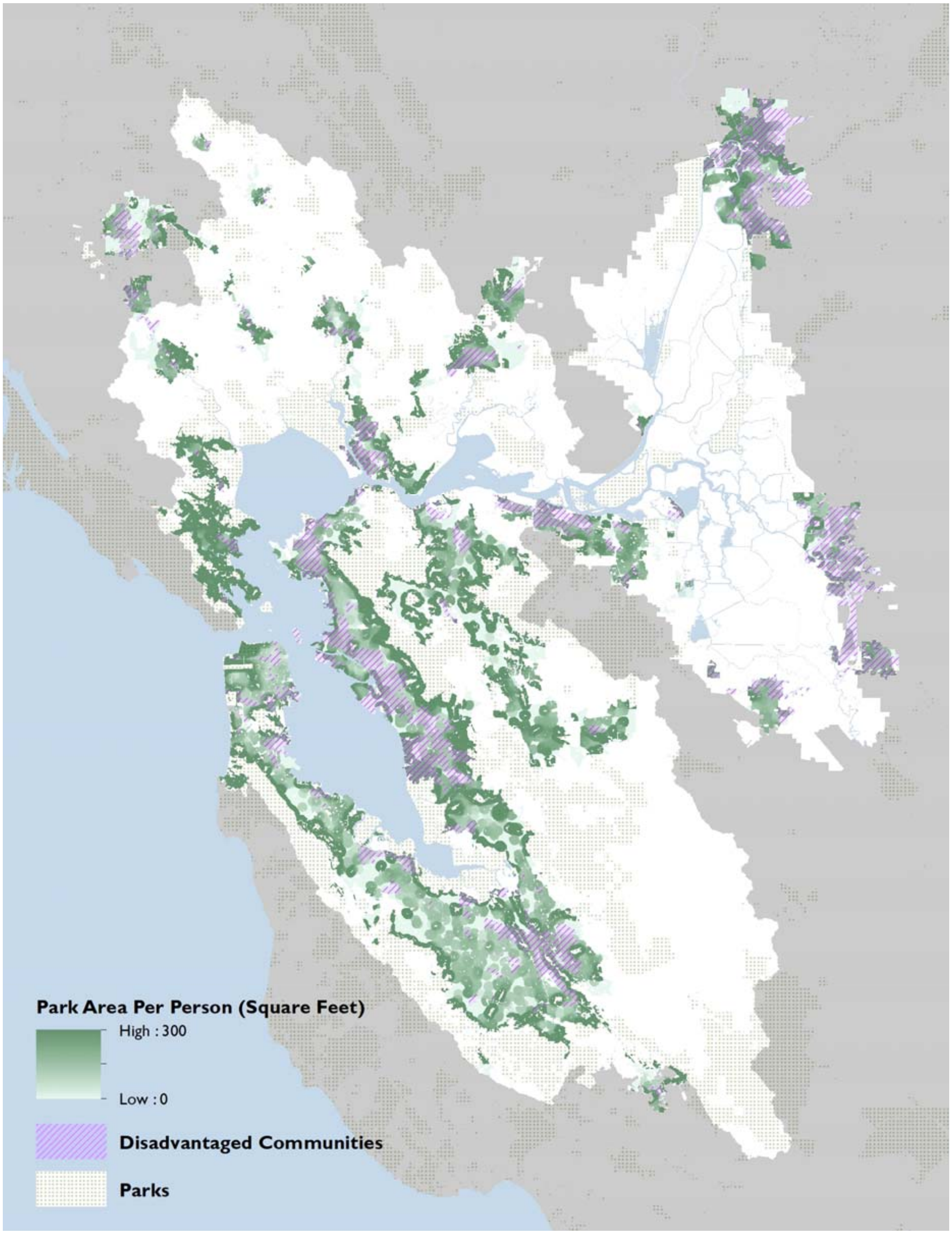

Figure 3: *Park area within a half mile per person. This map incorporates data from Figures 1 and 2 to approximate park access at various points across the Estuary.*

Figure 4: *Park area per person in disadvantaged communities in the Estuary versus park area per person in the urbanized Estuary overall.*

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