State of the Estuary Report 2015

Summary

ECOLOGICAL PROCESSES – Flood Events Indicators Summary

Prepared by Christina Swanson
Natural Resources Defense Council
September 2015

State of the San Francisco Estuary 2015

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What are the indicators?

The State of the Estuary Report uses two indicators to measure and evaluate the frequency, magnitude and duration of ecologically important flood events. The Yolo Floodplain Flows indicator measures seasonal inflows into the Delta 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.

Table 1.

Attribute	**Indicators**	**Benchmarks**
Ecological Processes (Flood Events)	Two indicators measure the frequency, magnitude and duration of: 1) floodplain inundation and flood flows into the Delta (Yolo Floodplain Flows indicator); and 2) high volume flows from the Delta into the Bay (Flood Inflows indicator).	Benchmarks (or reference conditions) are based on: 1) unimpaired flow and flood data records; 2) biological information on floodplain habitat, productivity dynamics, and utilization for spawning, rearing, and outmigration of juvenile salmonids; and 3) current regulatory standards for minimum Bay inflows (i.e., State Water Resources Control Board, 2006 Water Quality Control Plan).

Why are flood events important?

Following winter rainstorms and during the height of the spring snowmelt in the Sacramento-San Joaquin 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. High flows also improve habitat conditions in riverine migration corridors for both adult fish moving upstream as well as young fish moving downstream. 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.

Several factors have had and are having substantial impacts on the frequency, magnitude and duration of high flow, or flood, events into the estuary. 1) 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. This has deprived the estuary and its tributary rivers of regular seasonal flooding, an important physical and ecological process 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. Dams also physically block the flow of sediment, which starves riverine and estuarine wetlands and marshes of the materials they need to sustain (and restore) themselves. 2) 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 of relatively high flows (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. 3) 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, essentially disconnecting the estuary's tributary rivers from their floodplains.

What are the benchmarks? How were they selected?

The benchmarks (or reference conditions) for the two indicators are based on: 1) unimpaired flow and flood data records; 2) biological information on floodplain habitat, productivity dynamics, and utilization for spawning, rearing and migration; and 3) current regulatory standards for minimum Bay inflows (i.e., State Water Resources Control Board, 2006 Water Quality Control Plan).

What are the status and trends of the indicators and Index?

The two flood events indicators show that the frequency, magnitude and duration of floodplain inundation and high volume inflows to the estuary are all too low to drive or support important ecological processes in the lower watershed and estuary. Inundation of the Yolo Bypass is (and has been for decades) too rare, too little and too short to promote primary and secondary productivity, support floodplain spawning, rearing and migration of native fishes, and export sediment, nutrients and organisms to the Delta and estuary. High volume inflow events to the Bay have declined significantly since the 1940s. For the last decade (or two decades), the condition of flood-related ecological process has been "poor" in almost all years.

Table 2.

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 (long term; 1930-2014)**	**Trend since 1990**	**Current condition** (average for last 10 years)
Yolo Floodplain Flows	Not met; goals achieved in 8% of years	Stable (in poor condition)	Mixed	Poor Frequency, magnitude and duration too low to support ecological processes
Flood Inflows	Not met; goals achieved in 12% of years	Decline	Mixed	Poor Frequency and duration of high volume inflows cut by 60-75%

What does it mean? Why do we care?

Floodplain inundation and high volume, flood flows into the estuary are key physical and ecological drivers, stimulating and supporting primary and secondary productivity (creating food for fish and wildlife); transporting sediment (essential for marsh restoration and maintenance, including in the face of sea level rise), nutrients and organisms downstream; and creating spawning, rearing and migratory habitat for fish and wildlife. Man-made reductions in the ecological processes (i.e., from dams and water management operations) measured by these two indicators correspond to declines in food and habitat availability, reduced growth, survival and reproductive success for a number of species, and population declines for a number of fish and wildlife species. In addition to changes in water management operations to selectively restore periodic high volume flood flows to the watershed's and estuary's hydrograph, there are opportunities to manage the Yolo Bypass to create inundated floodplain habitat at lower Sacramento River flows. There is broad agreement that floods and floodplain habitat are important for native fish and wildlife, and that ecosystem restoration and management actions that restore these functions and habitat would likely be effective, but few specific restoration actions have been implemented to date.

State of the Estuary Report 2015

Technical Appendix

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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 1930-2014, although data for Yolo Bypass flows are only available for 1940-2014.[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.

[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.

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.

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

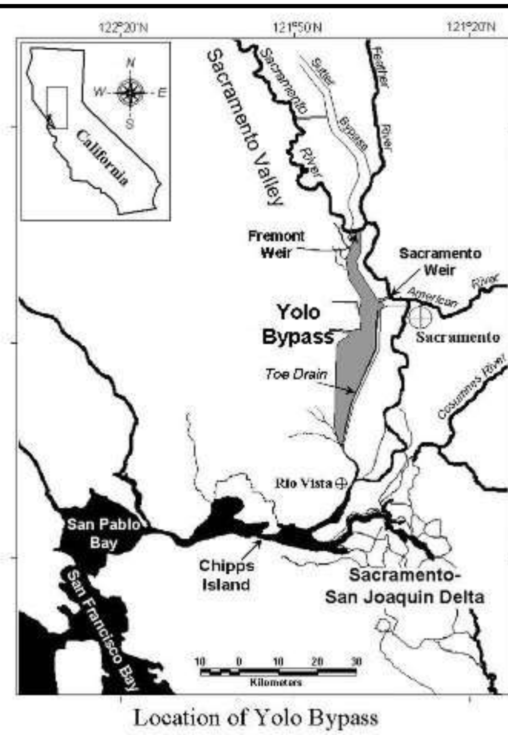

Figure 1. Location of the Yolo Bypass. Source: http://www.americanrivers.org/initiative/floods/projects/yolo-bypass-and-the-fremont-weir

the weir and water flows into the Bypass, inundating up to 60,000 acres of shallow floodplain habitat.

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 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]

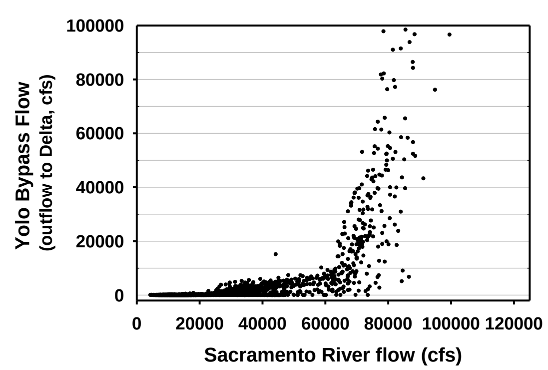

Figure 2. The relationship between Sacramento River flows and Yolo Bypass inflows to the San Francisco Estuary. Data source: California Department of Water Resources, Dayflow.

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

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[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.

[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.

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.

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 years 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 75 years, the Yolo Bypass has flooded and discharged flows greater than 10,000 cfs for 45 days during the late winter and spring in an average of only 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 conditions 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 54% of years and for at least two months in 26% of years. The last time the Yolo Bypass flooded with >10,000 cfs for at least 45 days was eight years ago, in 2006. Based on frequency of occurrence, floodplain flow and habitat conditions have been consistently poor or very poor.

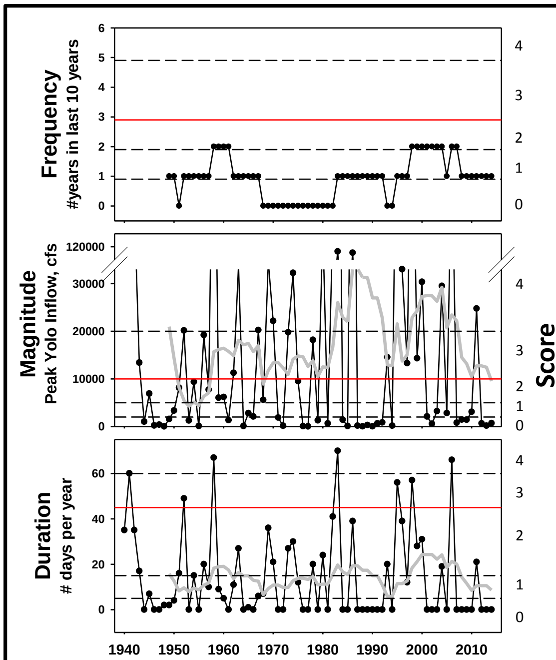

Figure 3. Results of the frequency (top panel), magnitude (middle panel) and duration (bottom panel) component metrics of the Yolo Floodplain Flows indicator. Score is shown on the right Y axis. Each point shows the result for that year and, for the magnitude and duration metrics, the heavy solid grey line shows the 10-year running average. The horizontal red 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 75-year data record, has not changed significantly (regression, $p>0.5$). Since 1940, average flood flows from the Yolo Bypass have been greater than10,000 cfs in 39% of years. The highest flows from the Yolo Bypass occurred in 1983 and 1986, when floodplain discharge to the Delta exceeded 10,000 cfs for several months. The last time average Yolo Bypass flood flows were greater than 10,000 cfs was in 2011. In 2014, a critically dry year, the average of the highest 45 days of late winter-spring flows from the Yolo Bypass was less than 700 cfs.

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 7 of the past 75 years (9% of years). In 34 of 75 years (45% 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 2006. In 2014, 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 the 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.

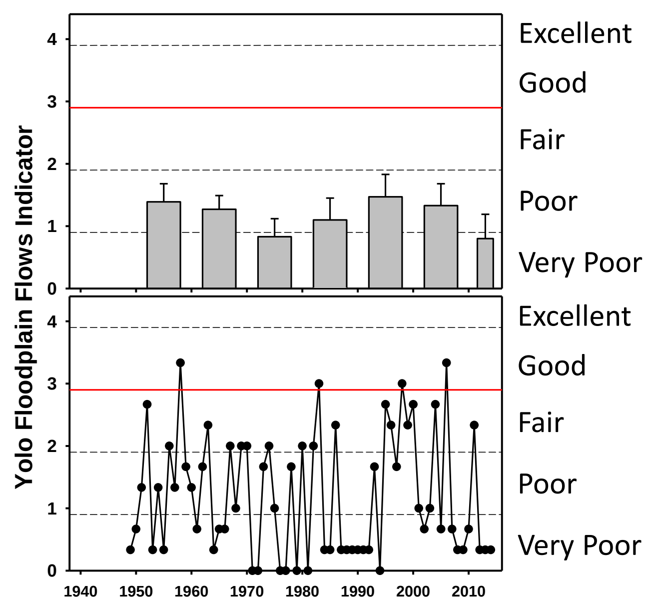

Figure 4. Results for the Yolo Floodplain Flows indicator, which combines the results of the frequency, magnitude and duration component metrics (Figure 3) for 1949 to 2014. The top panel shows results as decadal averages±1 SEM (and for five years for 2010-2014) and the bottom panel shows results for 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 75 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 2 years (8% of years) and have been "very poor" in 13 years (52% 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)[7] 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 during the 90 days of highest inflow that 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 downstream to 50-60 km[8] 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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[7] Freshwater inflow levels were measured as the 5-day running average of "Delta outflow."

[8] 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 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 2014, the estuary experienced only one year (2006) with a flood event that met the primary reference conditions.

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 85-year data record, it has not changed significantly (regression, $p>0.5$). High inflows during the "pre-dam" period (1930-1943) were, on average, 80,361 cfs compared to 68,408 cfs during the last two decades and not significantly different (Mann-Whitney Rank Sum test, $p=0.39$). High inflows during the most recent decade (2005-2014) are somewhat lower, 51,416 cfs on average, but not significantly different than pre-dam levels (t-test, $p=0.16$).

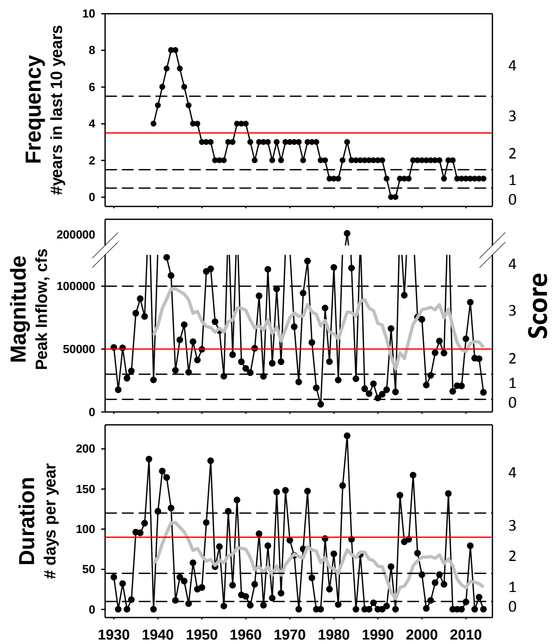

Figure 5. Results of the frequency (top panel), magnitude (middle panel) and duration (bottom panel) component metrics of the Flood Inflows indicator. Score is shown on the right Y axis. Each point shows the result for that year and, for the magnitude and duration metrics, the heavy solid grey line shows 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 (2005-2014) when there was an average of just 28 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, $p=0.075$). In 2014, a critically dry year, there were zero 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" in all years except 2006, the 6th wettest year in the 85-year data record, 2011, also a wet year, and 2004. Declining flood event conditions were driven by the decline in flood duration, which has fallen by more than 60% and the resultant decline in the frequency of flood events that met the primary reference condition criteria, which has fallen more than 75%.

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 three years (12% of years) and have been "poor" in 68% of years.

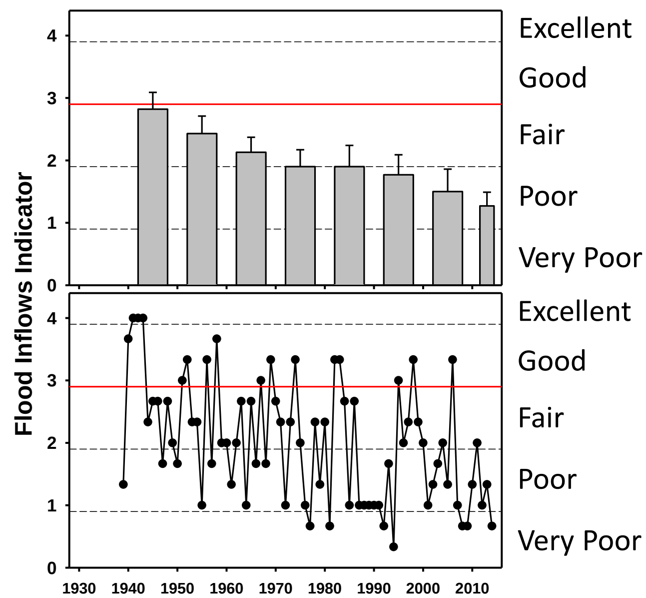

Figure 6. Results for the Flood Inflows indicator, which combines the results of the frequency, magnitude and duration component metrics (Figure 5) for 1939 to 2014. The top panel shows results as decadal averages±1 SEM (and for five years for 2010-2014) and the bottom panel shows results for each year. The horizontal red and dashed lines show the reference conditions and the indicator evaluation categories are at right

VI. References

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