State of San Francisco Bay 2011
Appendix H

ECOLOGICAL PROCESSES – Flood Events Indicator
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 flows of fresh water into the estuary. These seasonal high flows transport organisms, sediment, and nutrients to the Bay, increase mixing of Bay waters and create productive brackish, or "low-salinity" water habitat in the Bay's upstream Suisun and San Pablo regions, conditions favorable for many native fish and invertebrate species (Kimmerer 2002). 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 (see Estuarine Open Water Habitat indicator), they also improve habitat conditions in riverine migration corridors for both adult fish moving upstream as well as young fish moving downstream.

In the Bay's Sacramento-San Joaquin watershed, several factors have had and are having substantial impacts on the frequency, magnitude and durations of high flow events into the estuary. First, flows in most of the Bay's largest tributary rivers have been greatly altered by dams (see Freshwater Inflow Index). Many of these dams were built for the purpose of reducing flood events and to store the mountain runoff for later use and export to other regions in the state. However, 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, the effects of climate change on flows in the watershed are already detectable and are predicted to increase. With warmer temperatures, increasing proportions of the precipitation in the watershed comes as rain, which runs off immediately, rather than snow, which melts later in the season. In the rivers and the Bay, the result is more frequent but shorter duration high flow events earlier in the year driven by rain runoff rather than the long duration spring snowmelt flood flows of the past. Third, 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, even during of relatively high flow (see Freshwater Inflow Index). This reduces the amounts of fresh water that flow into the estuary and can decrease inflows to levels below important threshold for habitat creation and sediment transport.

The Flood Events indicator uses three measurements to assess the frequency, magnitude and duration of flood events and high inflows to the estuary.

II. Data Source

The Flood Events indicator was calculated for each year using daily freshwater inflow data (referred to as "Delta outflow") from the California Department of Water Resources (CDWR) DAYFLOW model. 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 1930-2010.

III. Methods and Calculations

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

For each year, frequency was measured as:

> # of years in the past decade (i.e., ending with the measurement year) with freshwater inflows >50,000 cubic feet per second (cfs)[2] for more than 90 days during the year.

For each year, magnitude was measured as:

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

For each year, duration was measured as:

> # days during the 90 days of highest inflow that inflow>50,000 cfs.

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 Indicator Evaluation and Reference Conditions section below.

VI. 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 historical flow and flood data records provide useful information for establishing ecologically relevant threshold levels and reference conditions for flood frequency, magnitude and duration.

Selection of the inflow threshold for a flood events, defined as the 5-day running average of freshwater inflow>50,000 cfs, was based on three 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; 2) examination of DAYFLOW data also suggested that this inflow level corresponded to substantial inflows to the Delta from the Yolo Bypass, the main flood management overflow channel for the estuary's largest tributary, the

[1] More information about DAYFLOW is available at http://www.water.ca.gov/dayflow
[2] Freshwater inflow levels were measured as the 5-day running average of "Delta outflow."

Sacramento River; and 3) flows of this magnitude shift the location of low salinity habitat[3] downstream into Suisun and upper San Pablo Bays (depending on antecedent conditions), providing favorable conditions for many estuarine invertebrate and fish species. Examination of "pre-dam" flow data (1930-1943, before major storage and flood control dams were constructed on the estuary's main tributary rivers in the Sacramento-San Joaquin watershed), indicated that flood flow conditions occurred in 57% of years with median durations of 95 days per year of flows>50,000 cfs. Therefore, the frequency reference condition was set at five years out of 10 years (50%) and the duration reference condition at 90 days per year. Measured values that were above these reference conditions were interpreted to correspond to "good" conditions. An additional "lower" reference condition was established to denote "poor" conditions. Measured values that were between the two reference conditions were interpreted to correspond to "fair' conditions. Table 1 shows the reference conditions and associated interpretations for the indicator metrics.

Results of indicator and its component measurements were analyzed using analysis of variance and simple linear regression to identify differences among different time periods and trends with time.

V. Results

Results of the three component measurements of the Flood Events indicator are shown in Figure 1.

The frequency of occurrence of flood events has declined (Figure 1, top panel).
Frequency of occurrence of high inflow flood events in the San Francisco Estuary 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 2010, the estuary experienced only one year (2006) with a flood event.

Flood magnitude has not changed (Figure 1, middle panel).
Flood magnitude, as measured by average inflows during the 90 days with highest inflows per year, is highly variable and, over the 81-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 64,697 cfs during the last two decades and not significantly different (Mann-Whitney Rank Sum test, $p>0.24$). High inflows during the most recent decade are somewhat lower, 48,003 cfs on average, bit not significantly different (t-test, $p>0.1$)

The duration of flood events has not changed (Figure 1, bottom panel).

[3] 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.

The number of days per year with inflows above the flood threshold is also highly variable and, over the 81-year data record has not changed significantly (regression, $p>0.15$). However, compared to the "pre-dam" period (1930-1943), which had an average of 82 days per year of inflows above the flood threshold, floods during the most recent decade (2001-2010) are significantly shorter, at just 27 days per year (t-test, $p<0.05$). In 2010, a year with median hydrological conditions, there were only 9 days with inflows >50,000 cfs.

Results of the Flood Events indicator are shown in Figure 2.

High inflow flood event conditions have declined.
Results of the indicator reveal a steady and significant decline in high inflow flood event conditions (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 81-year data record. Declining flood event conditions were driven almost entirely by the significant drop on flood frequency, which has fallen more than 75%.

Based on the Flood Events indicator, CCMP goals to restore healthy estuarine habitat and function have not been met.
The indicator shows that, for the past five decades, flood event conditions, an important physical and ecological process in the estuary, have been mostly "fair" or "poor." Since the early 1990s, when the CCMP was implemented, flood conditions have never been "good" and have been "poor" in 67% of years.

VI. Peer Review

The Flood Events indicator builds upon the methods and indicators developed by The Bay Institute for the 2003 and 2005 Ecological Scorecard San Francisco Bay Index and for the San Francisco Estuary Partnership Indicators Consortium. The Bay Institute's Ecological Scorecard was developed with input and review by an expert panel that included Bruce Herbold (US EPA), James Karr (University of Washington, Seattle), Matt Kondolf (University of California, Berkeley), Pater Moyle (University of California, Davis), Fred Nichols (US Geological Survey, ret.), and Phillip Williams (Phillip B. Williams and Assoc.). The versions of the Flood Events indicator presented in this document was reviewed and revised according to the comments of Bruce Herbold and Peter Vorster (The Bay Institute).

VII. References

Kimmerer, W. J. 2002. Physical, biological, and management responses to variable freshwater flow into the San Francisco Estuary. Estuaries 25:1275-1290.

Table 1. Quantitative reference conditions and associated interpretations for results of the three Flood Events indicator metrics. The primary reference condition, which corresponds to “good” conditions, is in bold.

Flood Events Indicator			
Metric	**“Good”** **Score=3**	“Fair” Score=2	“Poor” Score=1
Frequency	**>5 years out of 10 years**	>2 years out of 10 years	≤2 years out of 10 years
Magnitude	**Inflow>100,000 cfs**	Inflow>50,000 cfs	Inflow≤50,000 cfs
Duration	**>90 days**	>45 days	≤45 days

Figure 2. Changes in the frequency, magnitude and duration of occurrence of flood events in the San Francisco Estuary, from 1930-2010. Black lines and symbols show the annual Index values, solid red line shows the 10-year running average for the Index. Horizontal dashed lines shows the reference conditions and associated interpretations.

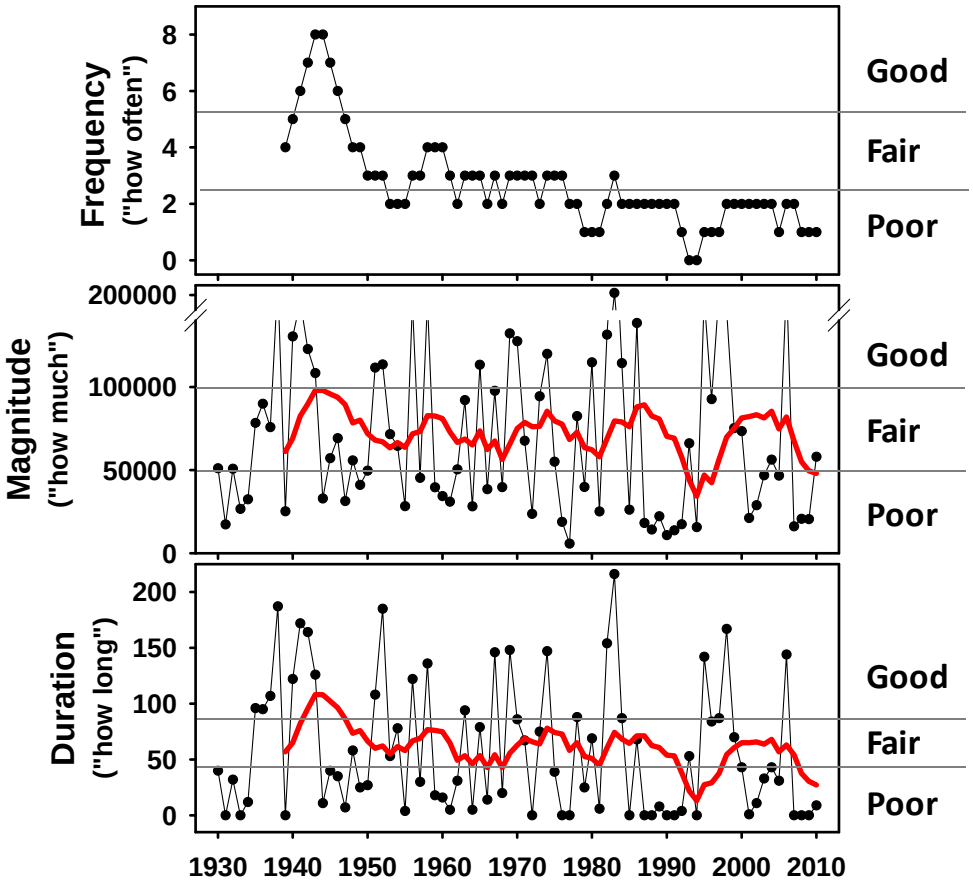

Figure 3. Changes in the Flood Events indicator from 1939-2010. Black lines and symbols show the annual indicator values, solid red line shows the 10-year running average for the indicator. Horizontal dashed lines shows the reference conditions and associated interpretations.