San Francisco Bay
Freshwater Inflow Index

INDICATOR ANALYSIS AND EVALUATION

A. Background

San Francisco Bay is the largest estuary on the west coast of the United States. Estuaries, at the interface between rivers and the ocean, are important spawning, nursery and rearing habitat for a host of fishes and invertebrates, migration corridors for anadromous fishes like salmon, steelhead and sturgeon, and breeding and nesting habitat for waterfowl and shorebirds. The amounts, timing, and between- and within-year variability of freshwater inflows into an estuary are the key environmental factors that define the quality and quantity of estuarine habitat (Kimmerer, 2002).

Most of the fresh water that flows into the Bay comes from the Sacramento and San Joaquin River basins, >90% of total freshwater inflow in most years.[1] Smaller streams around the Bay, principally the Napa and Guadalupe Rivers, Alameda, San Francisquito, Coyote, Sonoma Creeks, and many smaller tributaries, contribute the balance. During the past 70 years, freshwater inflows into the Bay have been greatly altered by upstream dams and water diversions (Figure 1). These changes have affected the Bay estuarine ecosystem and plants and animals that depend it.

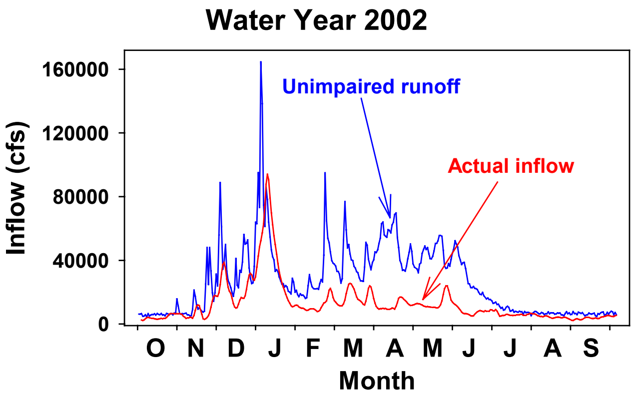

Figure 1. The amounts and timing of freshwater inflow to the Bay have been altered by upstream dams and water diversions. The blue line shows unimpaired runoff from the ten largest rivers of the Sacramento-San Joaquin watershed. The red line shows the actual pattern of freshwater inflow to the Bay from the watershed.

B. Indicators

The Freshwater Infow Index uses six indicators to measure the amounts and degree of alteration of freshwater inflows into San Francisco Bay.

1. Annual Inflow – San Francisco Bay receives most of its freshwater inflow from California's largest watershed, the Sacramento-San Joaquin, which drains 40% of the state. In this watershed, all but one of the major rivers are dammed and much of their water diverted for agricultural or urban use, never reaching the Bay. The Annual Inflow

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[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).

indicator measures the amount of fresh water that flowed into Bay each year, compared to the amount that would have flowed into the Bay under unimpaired conditions.

2. Water Year Type – Runoff and freshwater inflow to the Bay can vary dramatically from year to year, a function of California's temperate climate and unpredictable cycle of droughts and floods. This year-to-year variation in inflow, a key feature of estuaries, drives spatial and temporal variability in the Bay's ecosystem and creates the dynamic habitat conditions upon which Bay fish and invertebrate species depend. The Water Year Indicator compares actual annual inflow with unimpaired annual inflow in terms of water year type. The Water Year Type indicator measures to what degree the water year type experienced by the Bay, as actual inflow, differed from the water year type in the Bay's watershed, measured as unimpaired flows.

3. Spring Inflow – Freshwater inflow during the spring is critically important to many Bay fish and invertebrate species. The amount of inflow affects the estuarine habitat by controlling salinity and the location of the interface between inflowing fresh water and saltwater from the ocean, often measured as X2, the location (in km from the Golden Gate) in the Bay where the salinity of the water near the bottom is 2 ppt (approximately 6% seawater). During the spring, high freshwater inflows, driven by snowmelt in the Bay's main watershed, shift X2 downstream. The Spring Inflow indicator measures the amount of freshwater inflow, as X2, during the spring.

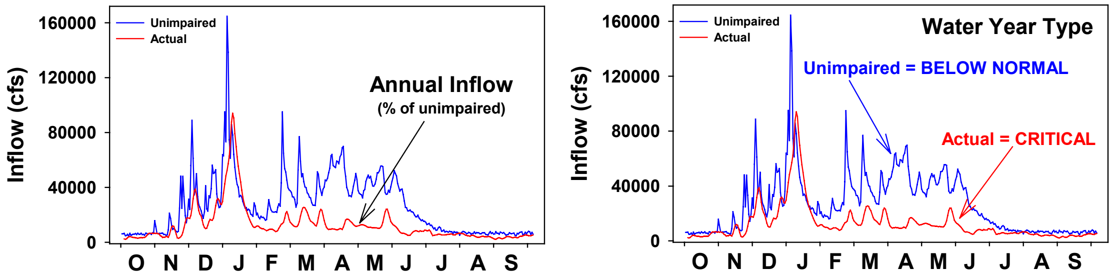
4. Change in Spring Inflow – During the spring, high freshwater inflows create large areas of low salinity habitat in the Bay. Today, large dams on the major rivers of the Bay's watershed capture and store the majority of springtime snowmelt runoff in most years and less fresh water flows into the Bay during this ecologically sensitive period. The Change in Spring Inflow indicator measures the actual amount of spring inflow into the Bay, measured as X2, compared to the amount that would have flowed into the Bay under unimpaired conditions.

5. Seasonal Variation – In the Bay's watershed, runoff varies dramatically throughout the year. Freshwater inflow to the Bay is high during the spring when the winter snowpack melts, and low in the fall and early winter before the first winter rainstorms arrive. This within-year variation in inflow, and the corresponding variation in ecological conditions, is a key feature of estuarine habitats. The Seasonal Variation indicator measures the maximum within-year variation in freshwater inflow, measured as X2, to the Bay.

6. Change in Peak Flow – High, or peak, freshwater inflows to the Bay occur following winter rainstorms and the spring snowmelt. High inflows transport sediment and nutrients to the Bay, increase mixing of Bay waters, and create low salinity habitat in the upstream portions of the Bay, Suisun and San Pablo Bays, conditions favorable for many Bay fish and invertebrate species. The Change in Peak Flow indicator measures the frequency, as number of days, of peak flows into the Bay, compared to the number of days that would be expected based on unimpaired runoff from the Bay's watershed. Peak flow was defined as the 5-day running average of Bay inflow>50,000 cfs.

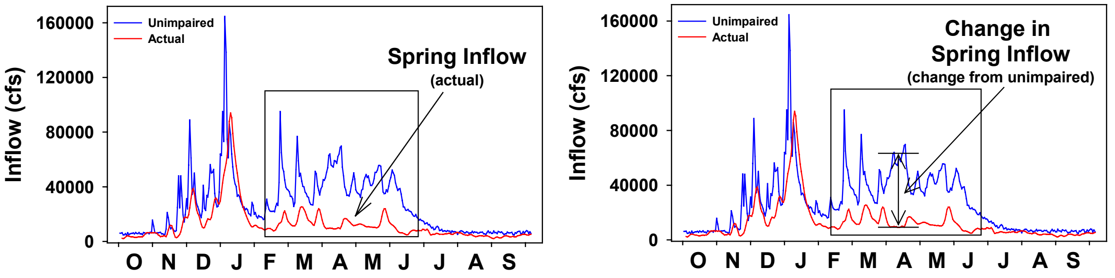
C. Rationale for Indicator Selection

The six indicators were developed to provide a comprehensive picture of Bay inflow dynamics and to capture those aspects of freshwater flow patterns known to drive and control physical, chemical, and biological conditions in estuaries (Figure 2).[2]



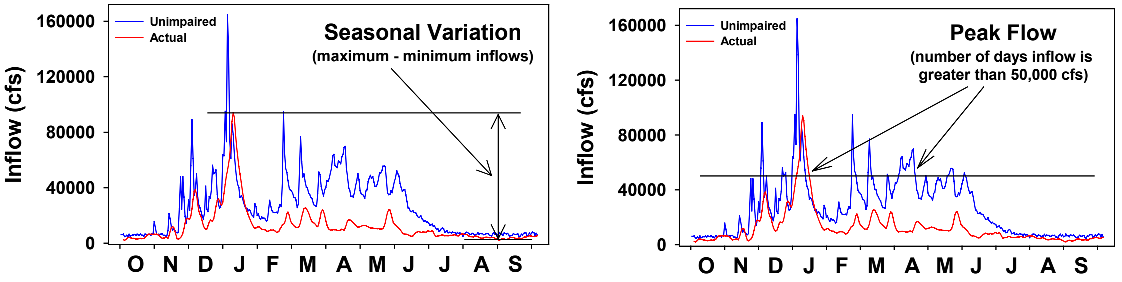
The **Annual Inflow** indicator measures the percentage of freshwater runoff that flows into the Bay

The **Water Year Type** indicator measures alteration in year-to-year variation of freshwater inflow to the Bay.



The **Spring Inflow** indicator measures the amount of freshwater inflow during the spring.

The **Change in Spring Inflow** indicator measures the difference between actual and unimpaired inflow during the spring.



The **Seasonal Variation** indicator measures the within-year variation in freshwater inflow to the Bay.

The **Change in Peak Flow** indicator measures the frequency of high flows into the Bay.

Figure 2. The six indicators of the Freshwater inflow Index measure the amounts and degree of alteration of freshwater inflow to the Bay from the Sacramento-San Joaquin watershed.

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[2] The daily inflow shown in the graphs use DAYFLOW Delta outflow for the "actual", and the unadjusted 10-river daily unimpaired runoff for "unimpaired" (see methods and calculations section). The 10 river runoff would have likely have been attenuated by the time it reached the Bay, which would reduce short flow spikes in winter and increase the duration of high flows in winter and spring. There is no calculated daily unimpaired Bay inflow and the graphs above are for illustrative purposes only, to show the general impact of reservoirs and exports on Bay inflow.

Collectively, the indicators examine three broad categories of Bay freshwater inflow dynamics: 1) total annual flow; 2) spring flow; and 3) within-year variation in flow. Within each of these categories, one indicator evaluates the "status", or condition of Bay inflow, and the other measures the degree of "alteration" in that condition, compared to natural or historic (i.e., pre-development) conditions. The indicators were also designed to evaluate Bay inflow conditions in the context of the large year-to-year variations of freshwater runoff (i.e., water year type, see below) typical of the multiple watersheds that supply fresh water to the Bay. Therefore, for some indicators, either the measurement or the evaluation criteria was normalized according to water year type to account for this large inter-annual variation in Bay flow dynamics. The relationships of these factors among the six indicators are outlined in Table 1 below.

Table 1. General characteristics of the Freshwater Inflow Index indicators.

Indicator	Category	Status vs Alteration	Normalized for water year type
Annual Inflow	Annual flow	Alteration	No
Water Year Type	Annual flow	Status	Yes
Spring Inflow	Spring flow	Status	No
Change in Spring Inflow	Spring flow	Alteration	Yes
Seasonal Variation	Within-year variation	Status	No
Change in Peak Flow	Within-year variation	Alteration	Yes

D. Methods and Calculations

Because the majority of inflow to the Bay is provided by the Sacramento-San Joaquin watershed, the six indicators of the Freshwater Inflow Index were calculated using data from Sacramento and San Joaquin River inflows only. The indicators were calculated for each year[3] using data from California Department of Water Resources (DWR) DAYFLOW model and unimpaired flow datasets provided by DWR. DAYFLOW is a computer program developed in 1978 as an accounting tool for calculating historical Delta outflow and other internal Delta flows.[4] DAYFLOW output is used extensively in studies by State and federal agencies, universities, and consultants. DAYFLOW output is available for the period 1930-2002.

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[3] Flow indicators were calculated for each water year. The water year is from October 1-September 30.

[4] More information about DAYFLOW is available at www.iep.ca.gov/dayflow.

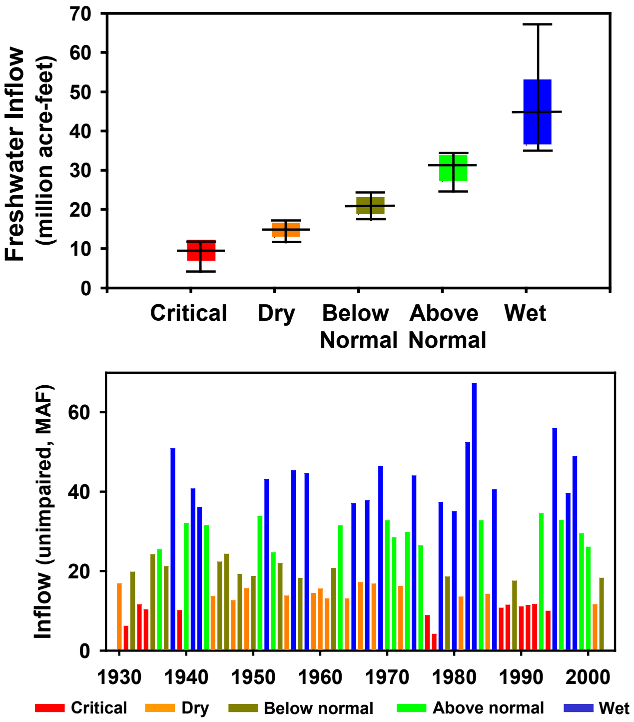

Figure 3. Freshwater inflow to the Bay varies from year-to-year. For comparisons among years, the amounts of runoff are categorized as "water year types", based on frequency of occurrence. The top panel shows average inflow amounts for each year type (average: horizontal line; standard deviation: colored box; and range: vertical line). The bottom panel shows unimpaired inflow from 1930-2002, with each bar colored to indicate year type.

Water Year Type: Several of the indicators were calculated to account for the large year-to-year variations in rain and snow precipitation in the Sacramento-San Joaquin watershed. We classified each year as one of five water year types: wet, above normal, below normal, dry, and critical.[5] Using values for unimpaired outflow calculated by DWR (see below), year types were established based on frequency of occurrence during the period of 1921-1994, with each year type comprising roughly 20% of all years.[6] The range of flows measured for each year type (Figure 3) was then used to assign year types to all years after 1994.

Unimpaired Inflow: For several of the indicators, DAYFLOW results, which report modeled "actual" flow conditions, were compared with estimates of "unimpaired" flow, the amounts of freshwater that, under the same hydrological conditions but without the effects of dams and diversions upstream of the Bay, would have flowed into the Bay (see Figure 1). Unimpaired Bay inflows were estimated using two data sources: 1) unimpaired runoff data from the ten largest rivers in the Sacramento-San Joaquin watershed[7] (available for 1921-2002 and provided by a variety of agencies and compiled by DWR), and 2) DWR's unimpaired Delta outflow calculation (available for 1921-1994).[8] Because the 10-river unimpaired flow

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[5] Despite use of the term "below normal", this year type includes the median, with half of all years receiving more runoff and the other half of years receiving less runoff.

[6] Terminology for the five year types follows that used by state and federal water management agencies although, for water management purposes in the Sacramento and San Joaquin basins, water year types are determined using other factors, such as the previous year's precipitation, as well as than frequency of occurrence.

[7] Sacramento, Feather, Yuba, American, Cosumnes, Mokelumne, Stanislaus, Tuolumne, Merced, and San Joaquin Rivers calculated at the foothill-valley boundary.

[8] The DWR unimpaired Delta outflow represents the watershed runoff absent dams and diversions with current land uses and does not represent the “natural” Delta outflow, because it does not account for changes in natural watershed runoff characteristics that have occurred in the past 150 years due to vegetation conversion, channelization and other land use alterations. The cumulative effect of those changes in the Central Valley means that the DWR unimpaired Delta outflow is probably about 3 million acre-feet too high on average and that the average annual runoff from the 10 rivers was closer to what the Delta outflow was under natural conditions (see TBI 1998 From the Sierra to the Sea: the Ecological History of the San Francisco Bay watershed, pp. 2-72). The DWR unimpaired Delta outflow also would

estimate does not include flows from smaller west and east side streams such as Stony, Cache, Battle and Butte Creeks, it tended to underestimate flows during wet years when these and other streams contribute substantial amounts of runoff. To provide unimpaired inflow values for the 1995-2002 period for which DWR estimates were not available, we developed a correction factor to be applied to the 10-river estimate by comparing the 10-river and DWR estimates for the 1930-1994 period.[9] This correction was then applied to the 10-river estimates for the entire period of record. This estimate of unimpaired flow was then reduced to make the amount closer to what the Delta outflow would have been under natural conditions by accounting for alterations in land use, including the loss of millions of acres of riparian and wetland vegetation that consumed a fraction of river flows (TBI, 1998).[10]

Pre-dam Inflow: For some of the indicators, DAYFLOW results were compared to DAYFLOW results from 1930-1943, the period prior to the completion of major dams in the watershed. This approach was used primarily for those indicators that were calculated from daily flow data rather than annual or monthly flow totals.

X2 as an indicator of freshwater inflow: Freshwater inflow into the Bay affects the estuarine habitat by controlling the salinity of the Bay and the location of the interface between inflowing fresh water and saltwater from the ocean, often designated as X2, the location (in km from the Golden Gate) where the salinity of the water near the bottom of the Bay is 2 ppt (approximately 6% seawater). High freshwater inflows cause the Bay to become less salty and move X2 downstream, closer to the Golden Gate. During periods of low inflow, saltwater encroaches into the Bay and X2 moves upstream, occasionally reaching locations upstream of the confluence of the Sacramento and San Joaquin Rivers in the Delta. Bay inflows and X2 are highly correlated (Jassby et al., 1995) therefore, for some of the indicators, Bay inflows were measured as X2 rather than in units of flow.

E. Evaluating Results and Grading

For each indicator, upper and/or lower reference conditions, corresponding to "excellent" and "very poor" ecological conditions, were established. Reference conditions were based on unimpaired inflow, pre-dam inflow, known relationships between inflow and a biological response such as fish population abundance or survival, recognized and accepted interpretations of estuarine inflow conditions and ecosystem health, and best professional judgment. The range of the indicator results from the upper and lower reference conditions was subdivided into five categories, corresponding to letter grades A through F. Each letter grade also corresponded to a "grade point", ranging from 0 (for F) to 4 (for A). The Index was calculated as the "grade point average" of the component

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tend to overestimate winter and spring flows and underestimate the late spring, early summer flows due to the loss of the large flood basins that acted as large natural reservoirs. The cumulative effects of the land use alterations on the upland watersheds are relatively minor, and the unimpaired 10-river flow is a satisfactory representation of runoff into the Central Valley.

[9] The correction factor, in annual acre-feet of water, that was added to the 10-river unimpaired flow estimate was: [-4211000+0.3237(10-river)].

[10] The correction factor varied with water year type. Critical: -1,000,000 acre-feet (AF); Dry: -2,000,000 AF; Below normal: -3,000,000 AF; Above normal: -4,000,000 AF; Wet: -5,000,000 AF.

indicators, and is reported as a **Grade** (i.e., A-F) and a **Score** (i.e., the grade point average expanded to a 100-point scale using a multiplication factor of 25).

F. Indicator Analysis

Indicator 1. Annual Inflow

Methods and Calculations: The Annual Inflow Indicator measures the amount of fresh water that flows into Bay each year compared to the amount that would have flowed into the Bay under unimpaired conditions. The indicator is calculated as:

Annual Inflow (% of unimpaired) = [(Actual inflow/unimpaired inflow)*100].

The Annual Inflow Indicator was not normalized for year-to-year variations in water year type.

Grading and Evaluation: The upper reference condition was set at 88.5%, a level at which the amount of unimpaired flow diverted before reaching the Bay is nearly twice the average percent diverted measured during the pre-dam period. The lower reference condition (i.e., the break point between a D and an F grade) was set at 50%, a level at which only half of all runoff from the watershed reaches the Bay. For the other grade levels, the range between 50 and 100% was divided into four equal increments of 12.5%.

Annual Inflow Indicator

Reference condition	Inflow (% of unimpaired)	Rationale for reference conditions	Ecological condition	Grade point	Grade
Upper	$\geq$88.5	Upper reference condition was set at 88.5%, a level at which the amount of unimpaired flow diverted was more than two times the average diverted during the pre-dam period. Lower reference condition was set at 50%. Intermediate grade interval based on a linear scale.	Excellent	4	A
	75-<88.5		Good	3	B
	62.5-<75		Fair	2	C
	50-<62.5		Poor	1	D
Lower	<50		Very poor	0	F

Results:

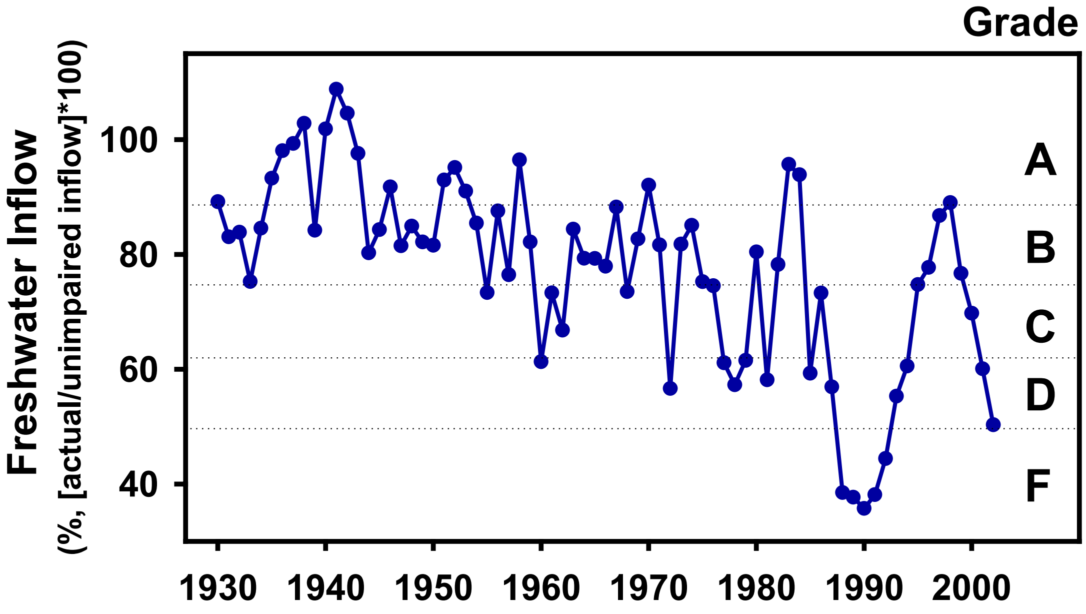

Figure 4. Changes in the Annual Inflow indicator from 1930 to 2002. The indicator measures the percentage of unimpaired runoff that flowed into the Bay.

Annual Inflow	Grade (2002)	Trends Long-term (1930-2002)	 Short-term (1998-2002)
In 2002, only 50% of total runoff flowed into the Bay	D	↓ (declining)	↓ (declining)

The percentage of total annual runoff, or unimpaired flow, that reaches the Bay has declined (Figure 4).

. Freshwater inflows to the Bay have declined significantly during the past sixty years, since Shasta Dam on the Sacramento River was completed. The greatest decline occurred since the early 1970s, after the California Aqueduct was completed to Southern California and several large dams were completed in the Sacramento and San Joaquin River watersheds. During the pre-dam period (1930-1943), an average of 93% of total runoff flowed into the Bay. During the 1987-1992 drought, less than 42% of total runoff flowed into the Bay. During the subsequent sequence of wet years (1995-2000), inflows increased to an average of 79% but, in the following drier years, inflows again declined. In 2002, only 50% of total runoff flowed into the Bay.

Freshwater flows into the Bay declined in all water year types. Freshwater inflow, as percentage of unimpaired inflow, has declined by an average of 0.6% per year (regression, $p<0.01$, all year types) (Figure 5). Even in wet years, Bay inflows have been cut by an average of 20% since 1967, when Oroville Dam was completed.

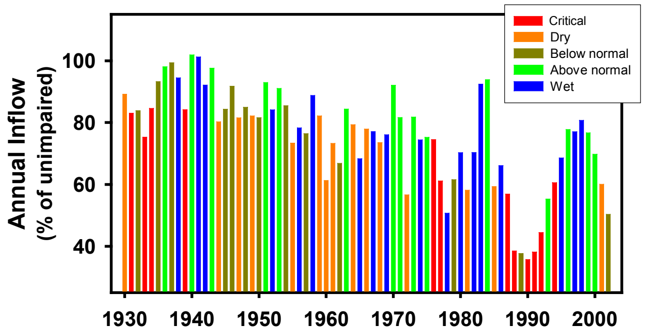

Figure 5. Annual inflow (% of unimpaired), 1930-2002. Each bar is a single year and, for that year, unimpaired water year types are represented by the different colors.

The largest reductions in freshwater inflow occurred in dry and critically dry years. Since Shasta Dam was completed, an average of only 51% of critical year runoff reached the Bay. Following closure of Oroville Dam, Bay inflows in dry and below normal years were further significantly reduced, from 77% (1944-1967, average) to 62% (1968-2002, average) in dry years and from 82% (1944-1967) to 50% (1968-2002) in below normal years (t-test, $p<0.05$, both year types).

Indicator 2. Water Year

Methods and Calculations: The Water Year Indicator compares actual annual inflow with unimpaired annual inflow in terms of water year type. The indicator measures to what degree the water year type experienced by the Bay, as actual inflow, differed from the water year type in the Bay's watershed, measured as unimpaired flows. This indicator was normalized for water year type, i.e., for each year, the indicator was evaluated based on the expected ranges of unimpaired inflow for that year's water year type. For calculation of the indicator, five reference intervals were established:

1) Range of the reference interval = mean unimpaired inflow to the upper range of inflow for that water year type
2) Range = mean inflow minus 1 standard deviation (SD) for that water year type to mean unimpaired inflow for that water year type
3) Range = upper range value for the next drier water year type to the mean inflow minus 1 standard deviation (SD) for that water year type
4) Range = lower range value for the next drier water year to upper range value of the next drier water year type
5) Range = upper range value for water year type that is two year types drier than the unimpaired water year type to the lower range of the water year type that is two year types drier than the unimpaired water year type.

For each year, actual inflow was compared to the reference intervals and then calculated as the proportional difference between the actual inflow and the upper range value of the appropriate reference interval. These reference intervals were also used as the grading intervals (see below).

Grading and Evaluation: For each water year type, reference conditions and grade intervals were based on the reference intervals used for the indicator calculation above.

Water Year Type Indicator

Reference condition	Alteration in Water Year Type (UF=unimpaired flow)	Ecological condition	Grade point	Grade
Upper	≥mean UF	Excellent	4	A
	mean UF - >mean-1SD UF	Good	3	B
	mean-1SD UF - > upper limit UF next drier water year type	Fair	2	C
	upper limit UF next drier water year type – > lower limit UF next drier water year type	Poor	1	D
Lower	< lower limit UF next drier water year type	Very poor	0	F

Results:

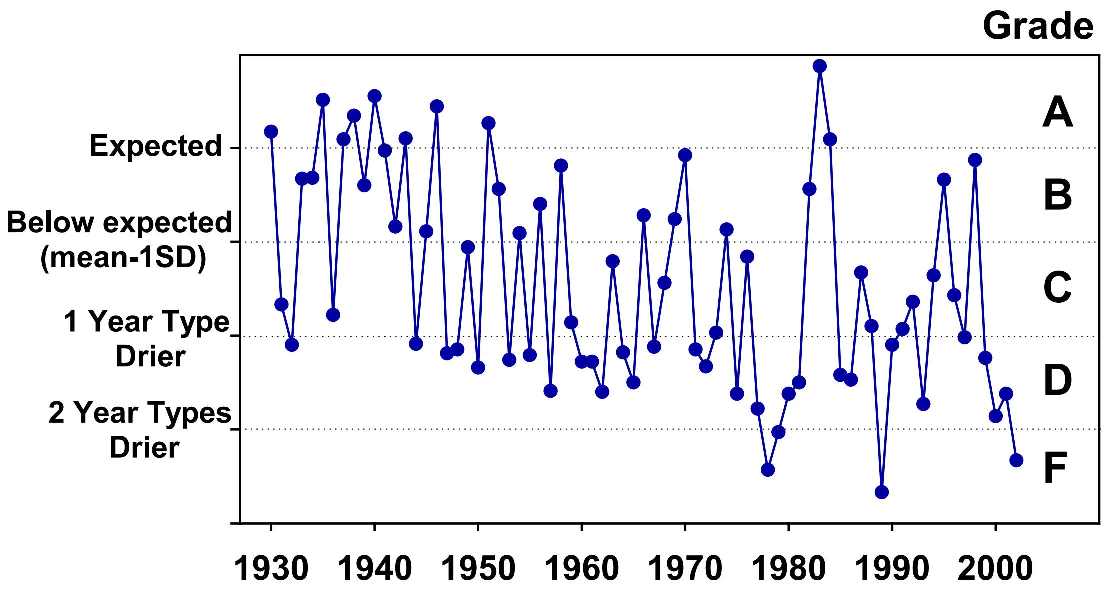

Figure 6. Changes in the Water Year Type indicator from 1930-2002. The indicator compares annual inflow with unimpaired annual inflow in terms of water year type.

Water Year	Grade	Trends	
	(2002)	Long-term (1930-2002)	Short-term (1998-2002)
In 2002, the Bay was two water types drier than expected	F	↓ (declining)	↓ (declining)

Reductions in freshwater inflow have resulted in drier annual conditions in the Bay than would be expected compared to the water year type measured in the watershed (Figure 6). Since the 1940s, the Bay was at least one water year type drier than expected in more than half of all years (Figures 6 and 7). Between 1960 and 2002, the Bay was subjected to ten anthropogenically-induced critically dry years, in addition to the eight critical years measured during that period in the watershed. In 2002, although it was a below normal year in the watershed (i.e., a "median" year), for the Bay it was a critically dry year, two water year types drier than expected.

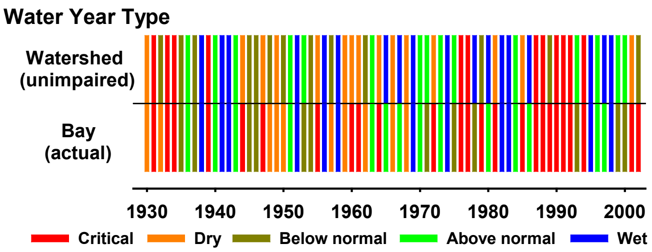

Figure 7. Alterations in water year type, 1930-2001. Each bar is a single year and, for that year, water year type is represented by the different colors. Top panel shows water year type for the Bay's watershed. Bottom panel shows water year type in the Bay.

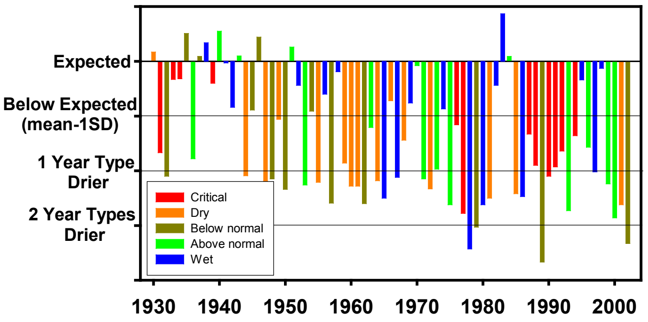

Figure 8. Alterations in water year type, 1930-2002. Each bar is a single year and, for that year, unimpaired water year type are represented by the different colors.

Since the late 1960s, even above normal and wet years have been altered to at least one water year type drier in the Bay.
Between 1930 and 1967, when the last major dam in the Sacramento River watershed was completed, most years in which Bay inflows were reduced enough to change the Bay's water year type were either critical or dry years (Figure 8). Since 1967, 59% of the years in which Bay year type was reduced were either above normal or wet, suggesting that water management operations in recent years are disproportionately affecting wetter year types.

Year-to-year variability in annual inflows has been reduced.
Since the 1960s, frequency of critically dry years in the Bay has increased 100%, to 42% of all years. Frequency of wet years has been cut in half. In eleven of the past 21 years (1981-2002), the Bay received the same amounts of water that would be expected in a critically dry year.

Indicator 3. Spring Inflow

Freshwater inflows during the spring provide important spawning and rearing habitat for many Bay fishes and invertebrates (Kimmerer, 2002). For a number of species, population abundance and/or survival are strongly correlated with the amounts of inflow the Bay receives during the spring and the location of X2 (Figure 9). Abundance and/or survival are higher when X2 is located downstream in the Bay, closer to the Golden Gate (e.g., X2=50) compared to years in which X2 is located further upstream (e.g., X2=90).

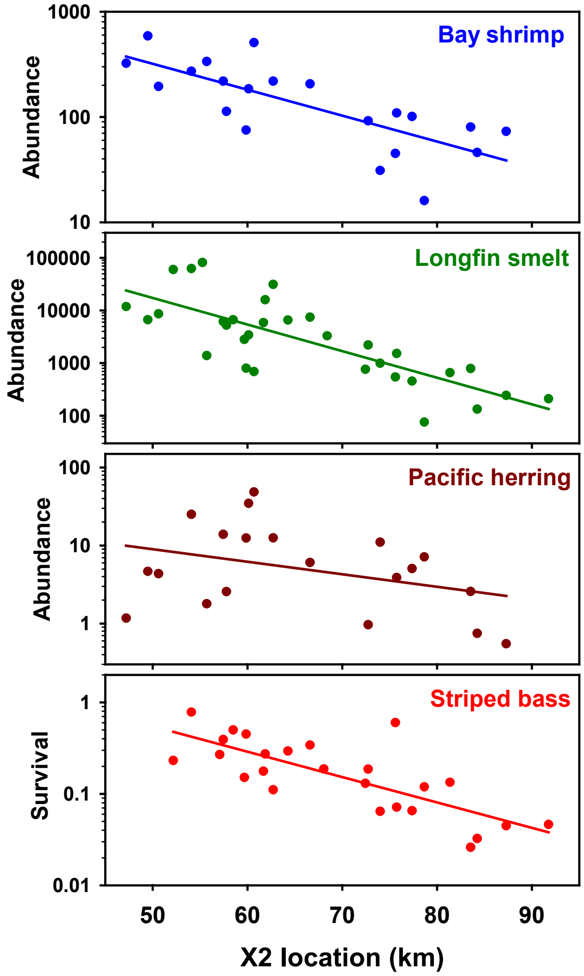

Figure 9. Population abundance and survival of selected Bay fish and invertebrates species in relation to spring (February-May) inflows, expressed as X2 (location of the 2 ppt isohaline, km from the Golden Gate).

Methods and Calculations: The Spring Inflow Indicator measures the amounts of freshwater inflow into the Bay during the spring. Inflow is expressed in terms of X2, the location of the 2 ppt isohaline in km from the Golden Gate. Bay inflows and X2 are strongly correlated (Jassby et al., 1995). The indicator was calculated as average X2 from daily X2 values for the February 1-June 30 period. Daily X2 is calculated as:

$$X2\ (d_i) = 10.16 + 0.945(X2,\ d_{i-1}) - 1.487(\log[\text{outflow},\ d_i])$$

where d_i is the current day,
d_{i-1} is the previous day,
outflow is in cubic feet per second (cfs).

The Spring Inflow Indicator was not normalized for year-to-year variations in water year type.

Grading and Evaluation: Reference conditions for the Spring Inflow Indicator were based on known relationships between X2 and species abundance and survival (see Figure 9) and the maximum and minimum seasonal locations measured for spring X2 during both the pre-dam (1930-1943) and total 72-year record for which data are available. For most species for which abundance or survival data have been related to X2, abundance and/or survival are maximized when spring X2 is approximately 50-60 while low abundance and/or survival are measured when spring X2 approaches 80-90. Abundance and/or survival increase by two- to five-fold for each 10-km decrease (i.e., movement downstream) of X2. Prior to major dam construction in the watershed, maximum X2 location measured during critically dry years was 74 km (average of three critical years). Therefore, X2<55 was set as the upper reference condition (i.e., the break point between and A and a B grade), and X2≥85 was set as the lower reference condition (i.e., the break point between a D and an F grade).

Spring Inflow Indicator

Reference condition	X2 (km from Golden Gate)	Rationale for reference conditions	Ecological condition	Grade point	Grade
Upper	<55	Upper reference condition was set at X2=55. Lower reference condition set at X2=85. Intermediate grade interval based on a linear scale with 10-km increments.	Excellent	4	A
	55-<65		Good	3	B
	65-<75		Fair	2	C
	75-<85		Poor	1	D
Lower	≥85		Very poor	0	F

Results:

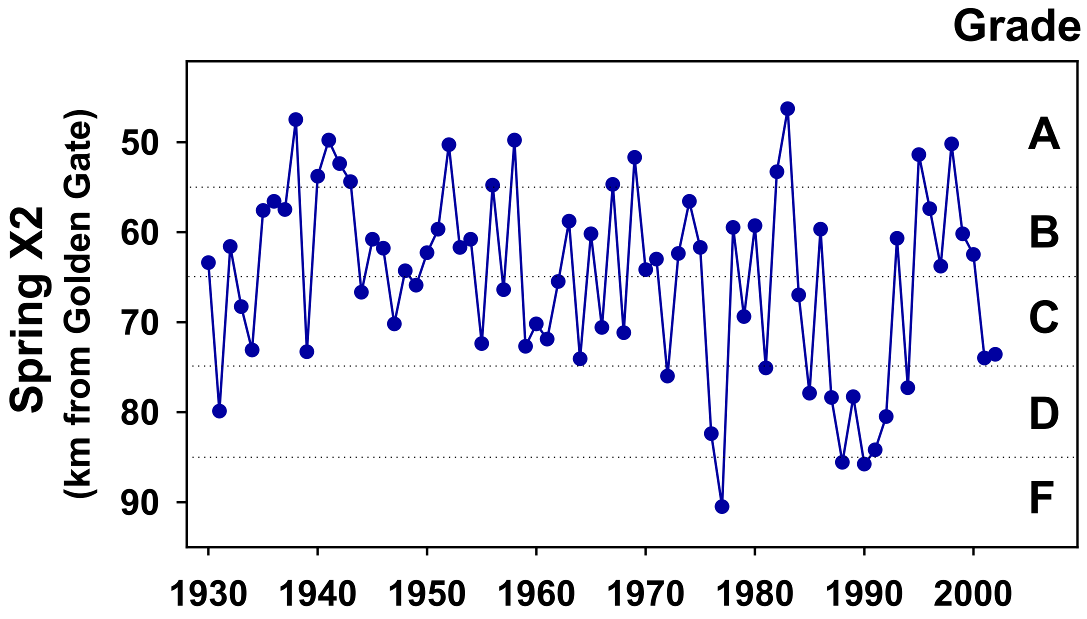

Figure 10. Changes in the Spring Inflow indictor from 1930-2002. The indicator measures X2, the location of "low salinity" habitat, during the spring.

Spring Inflow	**Grade**	**Trends**	
	(2002)	Long-term (1930-2002)	Short-term (1998-2002)
In 2002, spring inflows were low and X2 location was unfavorable for Bay fish and invertebrates	C	↔ (fluctuating)	↓ (declining)

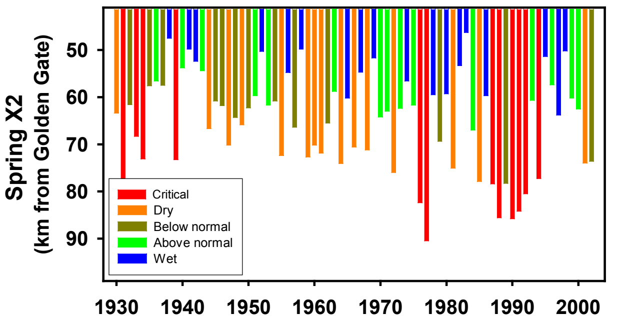

Figure 11. Spring X2 (km from Golden Gate), 1930-2002. Each bar is a single year and, for the year, unimpaired water year type is represented with the different colors.

Spring inflows are highly variable, a result of large year-to-year variations in runoff and water management operations that store and divert flows upstream of the Bay (Figures 10 and 11). Prior to the 1970s, spring X2 values rarely exceeded 75. Since then, spring X2 has been shifted upstream as far 90 km, creating ecological conditions that are very unfavorable to many Bay species (see Figure 9). During the 1987-1992 drought, spring X2 remained upstream of 75 km for seven consecutive years, a period that also saw severe population declines among many Bay species (see Fish Index). In 2002, X2 was located at 74 km, a value typical for critically dry years prior to water development within the Bay's watershed.

Indicator 4. Change in Spring Inflow

Methods and Calculations: The Change in Spring Inflow Indicator measures the actual amount of spring inflow into the Bay (February 1- June 30), compared to the amount that would have flowed into the Bay under unimpaired conditions. Inflow was measured as X2 and the change in spring inflow was expressed as the change in X2 (i.e., movement upstream, in km). This indicator was normalized by water year type to account for the effects of the large year-to-year variations in spring flows typical in the Sacramento-San Joaquin watershed. Actual X2 was calculated as the mean of daily spring X2 values (see Spring Inflow Indicator methods and calculations above). Unimpaired X2 values were calculated for each water year type using two methods: 1) DAYFLOW results for pre-dam spring inflows; and 2) monthly unimpaired flows (February-June, calculated from the 10-river unimpaired flows estimates).[11] The two estimates of unimpaired X2 were very similar but, for the purpose of simplicity, the pre-dam based estimate was selected for calculation for the indicator. Change in X2 (km) was calculated as:

Change in X2 (km) = Pre-damX2 for that year type – Actual X2.

Grading and Evaluation: For each water year type, the upper reference condition was set as the mean pre-dam spring X2 location (or 0 km change in X2). For each year type, the interval size was set at 5 km, more than twice the within-water year type variation (standard deviation) measured for unimpaired X2 values (calculated from monthly unimpaired flows).

Change in Spring Inflow Indicator

Reference condition	Change in X2 (km shifted upstream)	Rationale for reference conditions	Ecological condition	Grade point	Grade
Upper	≥0	Upper reference condition was set at 0 km change in X2. Lower reference condition set at 15 km upstream movement of X2. Intermediate grade interval based on a linear scale.	Excellent	4	A
	0-<5		Good	3	B
	5-<10		Fair	2	C
	10-<15		Poor	1	D
Lower	≥15		Very poor	0	F

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[11] Monthly X2 (m_i) = 122.2 + 0.3278(X2, m_{i-1}) – 17.65(log[outflow, m_i]), where m_i is the current month, m_{i-1} is the previous month, outflow is in cubic feet per second (cfs).

Results:

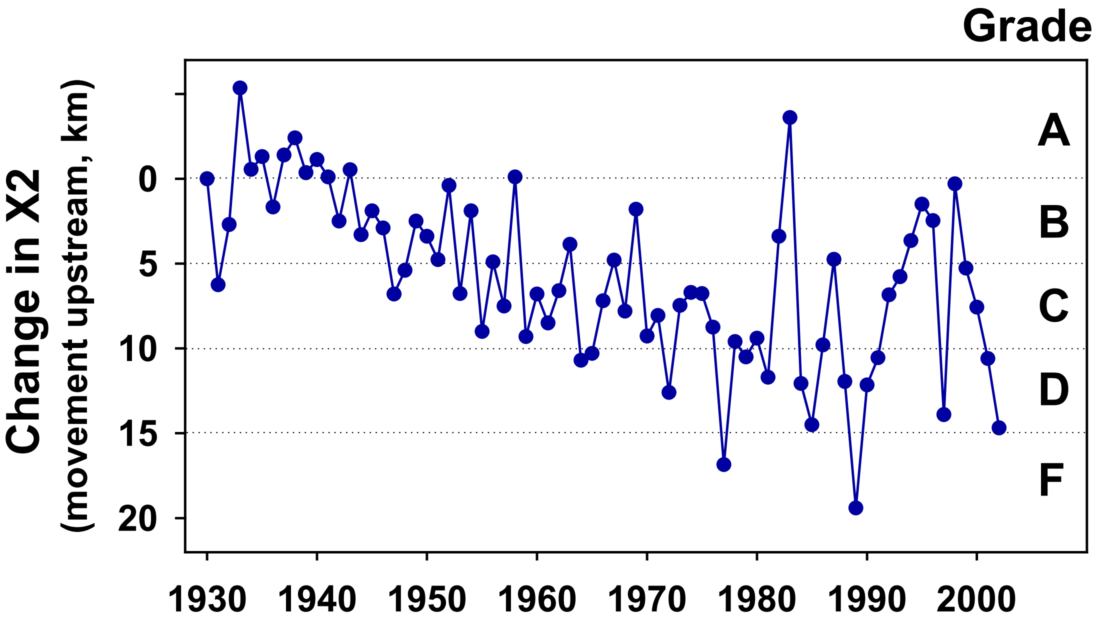

Figure 12. Changes in the Change in Spring Inflow indicator from 1930-2002. The indicator measures the upstream movement of X2, the location of "low salinity" habitat, during the spring.

Change in Spring Inflow	**Grade**	**Trends**	
	(2002)	Long-term (1930-2002)	Short-term (1998-2002)
In 2002, X2 was shifted nearly 15 km upstream	**D**	↓ (declining)	↓ (declining)

Reductions in spring flows have shifted X2 upstream in the Bay (Figure 12). Upstream movement of spring X2 has increased over time.

Between 1940 and 1989, spring X2 steadily and significantly increased (regression, $p<0.01$), shifting as much as 20 km upstream of its predicted (i.e., pre-dam) position. The greatest upstream movements of spring X2 occurred in 1977 and 1989, both times in the second or third year of multi-year droughts. In 2002, spring X2 was nearly 15 km further upstream than predicted based on pre-dam runoff.

Spring X2 has been shifted upstream in all water year types.

Although the largest upstream shifts in X2 have occurred in some critically dry years, substantial upstream movement occurs in all year types (Figures 13 and 14). Since 1967, when the last major dam in the Sacramento River basin was completed, spring X2 has been shifted upstream by similar amounts (10.8 km, on average) during critical, dry and below normal years (ANOVA, p>0.2).

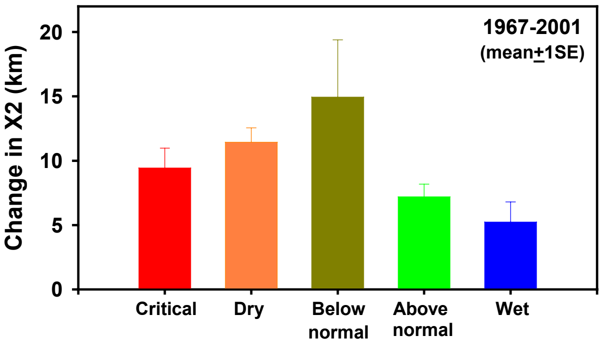

Figure 13. Mean (±1 SE) upstream movement of spring X2 in each water year type during the 1967-2001 period.

New Bay-Delta water quality standards for X2[12], implemented in 1995, have not markedly reduced the upstream movement of spring X2.

In 1995, new water quality standards specified springtime X2 locations based on hydrology in the Bay's main watershed. Since then, in the three above normal and three wet years, upstream movement of X2 (i.e., change in X2) has not been significantly different from values measured for those water year types between 1967 and 1994 (t-test, p>0.05, both year types). In 2001, the first dry year since establishment of the new standards, spring X2 was shifted 10.6 km upstream, compared to an average of 11.6 km in the four dry years between 1967 and 1995. In 2002, a below normal year, spring X2 was nearly 15 km farther upstream than predicted and more than 2 km upstream of the location required by the 1995 Water Quality Control Plan X2 standards (although the standards were not technically violated, see Stewardship Index, "Extra" Bay Inflows indicator).

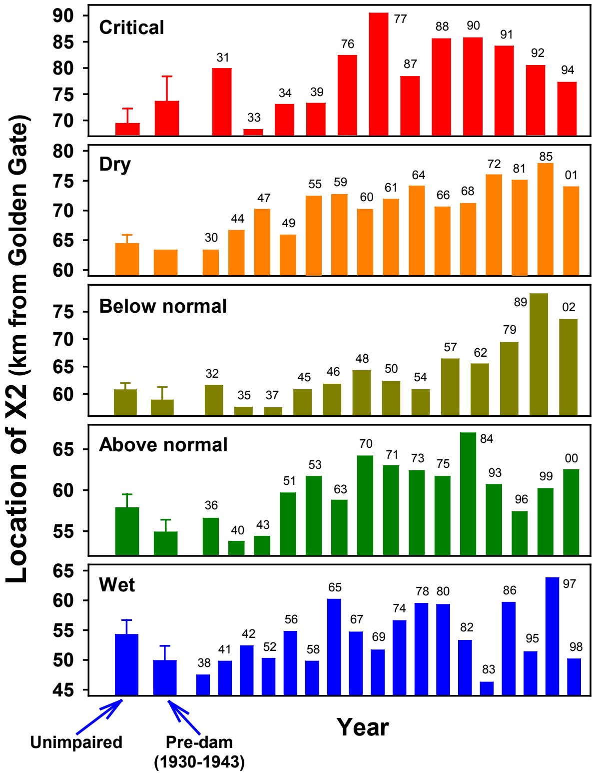

Figure 14. Location of spring X2 (km from Golden Gate) in each water year type, 1930-2002. Mean (±1SD) unimpaired X2 and mean pre-dam X2 (mean±1SD) are also shown for each year type. The number above each bar is the year (shown as last two digits).

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[12] In 1995, the State Water Resources Control Board issued D-1641, the Water Quality Control Plan for the San Francisco Bay-Delta, requiring freshwater inflows to the Bay sufficient to maintain X2 at specific locations for specific numbers of days each month during the spring, dependent on hydrology in the Sacramento-San Joaquin watershed.

Indicator 5. Seasonal Variation

Methods and Calculations: The Seasonal Variation Indicator measures the maximum within-year variation in freshwater inflow to the Bay. Inflow was measured using daily X2 and, for each year, the indicator was calculated as:

Seasonal Variation (difference in X2, km) = maximum X2 – minimum X2.

Pre-dam values for this indicator did not vary with water year type, therefore the indicator was not normalized by water year type.

Grading and Evaluation: Pre-dam values for the Seasonal Variation Indicator were 50±8 km (mean±1SD) and did not vary among the water year types. Therefore, the upper reference condition was set at this mean value minus 1 standard deviation (SD) (i.e., 42 km). The increment for each grade level was set at 1 SD (i.e., 8 km).

Seasonal Variation Indicator

Reference condition	Within-year difference in X2 (km)	Rationale for reference conditions	Ecological condition	Grade point	Grade
Upper	≥42	Upper reference condition was set at the mean-1SD of within-year variation in X2 measured for pre-dam years. Grade increment was set at 8 km, equivalent to the standard deviation of within-year variation measured for pre-dam years.	Excellent	4	A
	34-<42		Good	3	B
	26-<34		Fair	2	C
	18-<26		Poor	1	D
Lower	≥18		Very poor	0	F

Results:

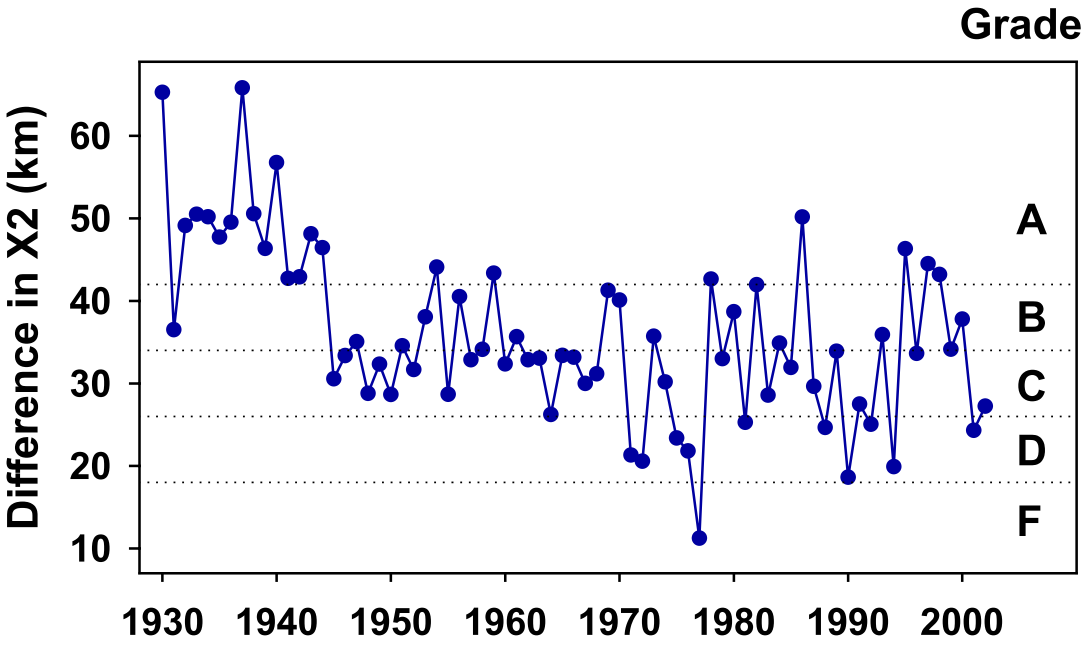

Figure 15. Changes in the Seasonal Variation indicator from 1930-2002. The indicator measures the maximum within-year variation in inflows, with inflow measured in terms of X2.

Seasonal Variation	Grade (2002)	Trends Long-term (1930-2002)	Trends Short-term (1998-2002)
In 2002, within-year variation in outflow was moderately low	C	↓ (declining)	↓ (declining)

Seasonal variation in freshwater inflows to the Bay declined abruptly following closure of Shasta Dam (1943) (Figure 15).

Compared to pre-dam conditions, seasonal variation in inflows have been reduced by nearly 40%, to an average of 33 km (difference between maximum and minimum X2). In 2002, seasonal variation was reduced by 46% compared to pre-dam levels.

Seasonal variation has been reduced in all water year types.
Maximum within-year variation in Bay inflow has been significantly reduced in all year types except wet years (ANOVA and t-tests, p<0.05, all year types except wet) (Figure 16). Reductions in seasonal inflow variation were most pronounced in critical and dry years. Only in wet years did seasonal variation values approach values measured prior to major dam construction in the watershed.

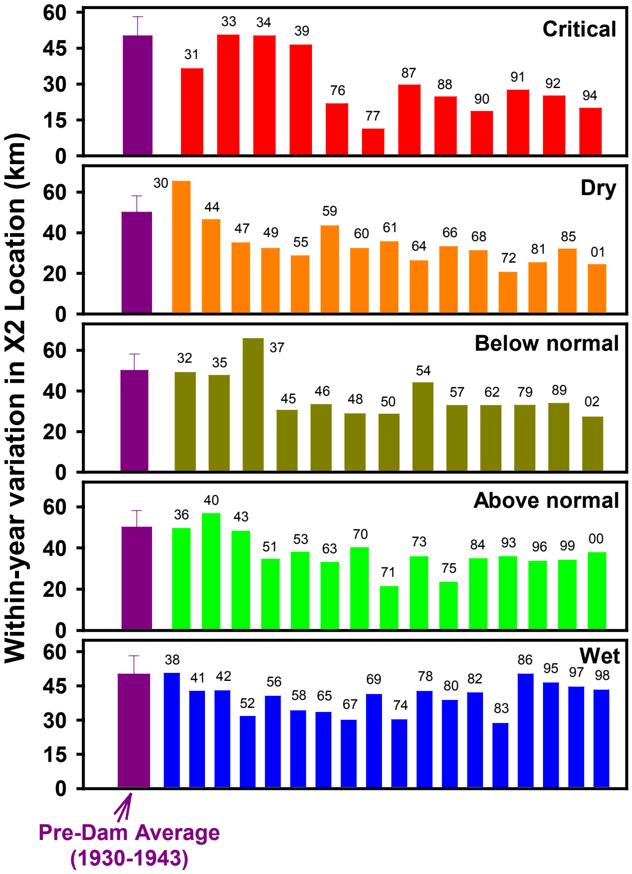

Figure 16. Maximum within-year differences in daily X2 locations in each water year type, 1930-2002. Mean (±1SD) pre-dam variation in X2, which did not differ among the water year types, is also shown as the purple bars. The number above each bar is the year (shown as last two digits).

Reductions in seasonal flow variations resulted from increases in late summer and fall inflows to the Bay.
Prior to construction of upstream dams and water export facilities in the Delta, freshwater inflows into the Bay during the late summer and fall were low and X2 was typically located far upstream of the Sacramento River-San Joaquin River confluence. Since then, water management operations that release stored water for agricultural use and, by the late 1950s, for export from the Delta to the San Joaquin Valley and southern California, have increased summer and fall Bay inflows. Increased freshwater inflows, necessary to maintain low salinities in the Delta so exported water was usable for irrigation and drinking water, shifted summer and fall X2 significantly further downstream into the Bay (regression, p<0.05) (Figure 17). Despite significant changes in spring X2 location (see Spring Inflow and Change in Spring Inflow Indicators), neither minimum nor average daily annual X2 values have changed significantly (regression, p>0.05, both tests) during the 72-year period of record.

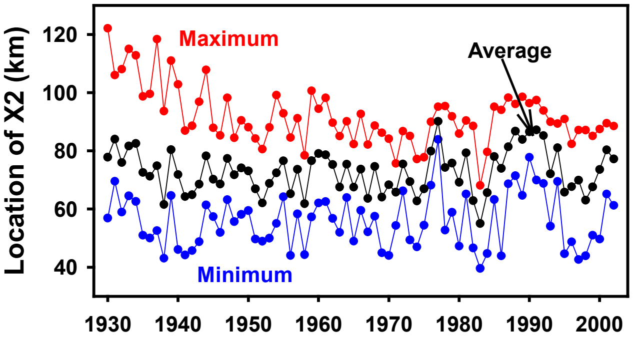

Figure 17. Maximum, minimum daily X2 locations and average annual X2 location, 1930-2002.

Indicator 6. Change in Peak Flow

Methods and Calculations:

The Change in Peak Flow indicator measures the frequency of high, or peak, inflow events in the Bay. Peak flow was defined as the 5-day running average of Bay inflow>50,000 cfs. Selection of this threshold value was based on two rationales: 1) flows of this magnitude shift X2 location downstream to 50-60 km (depending on antecedent conditions), providing favorable conditions for many Bay invertebrate and fish species (see Spring Flow Indicator); 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 Bay's responses to another aspect of seasonal flow variation in its watershed. The indicator is calculated as the difference between the actual number of days of peak flow per year and the number of days of peak flow per year that would have occurred under unimpaired or pre-dam inflow conditions:

Peak flow (days) = # days peak flow (actual) - # days peak flow (unimpaired).

Daily unimpaired flow data were not available therefore, to predict number of days of peak flow per year under these conditions, a polynomial regression was developed based on pre-dam data (Figure 18).[13] Water Year 1983, the year with the highest annual unimpaired inflow on record and during which flows were minimally affected by water management operations (see other indicators), was also included in this regression analysis to provide a high unimpaired inflow value and anchor the regression. This indicator is normalized by water year type to account for the large year-to-year variations in flows.

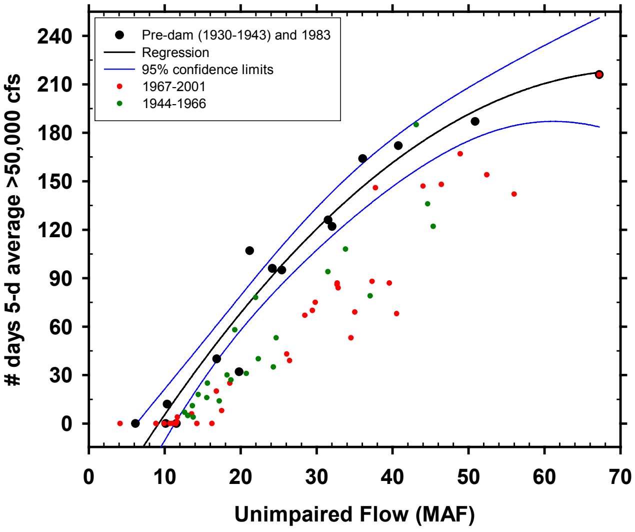

Figure 18. Actual (symbols) and predicted (regression line and confidence limits) numbers of days of peak flows per year. This graph was used to establish reference conditions for grading the Peak Flow Indicator (see below).

Grading and Evaluation:

The reference conditions for each water year type were based on predicted number of days of peak flow per year, estimated using the polynomial regression developed from pre-dam and 1983 data and the regression's 95% confidence limits (see Figure 18 above). Over most of the range of unimpaired inflows, the maximum value for the 95%

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[13] Days of peak flow = -68.52 + 7.95(UF) – 0.06(UF^2), where UF is unimpaired inflow; n=15, r^2=0.9524,.

confidence interval was 15 days, therefore this was set as the grading interval. For each year type, the upper reference condition was set as the predicted (mean) number of peak flow days per year minus the 95% confidence limit (15 days). Because of the large variation in numbers of days in peak flow among water year types and in particular the relatively few peak flow days predicted to occur in critical and dry years, this grading scale was biased towards disproportionately high grades to those type of years (see 2001 Change in Peak Flow grade for an example of this bias). Thus a high grade may not always indicate that desirable flow conditions occurred in critical or dry years, when relatively few periods of high peak flow occurred historically, but simply that the degree of peak flow alteration was minimal.

Change in Peak Flow Indicator

Reference condition	Difference in days of peak flow (days)	Rationale for reference conditions	Ecological condition	Grade point	Grade
Upper	≥mean-15	Upper reference condition was set at the predicted number of days (mean) minus 15 days. Grade increment was set at 15 days, equivalent to the average value of the 95% confidence limits of the prediction.	Excellent	4	A
	mean-15-< mean-30		Good	3	B
	mean-30-< mean-45		Fair	2	C
	mean-45-< mean-60		Poor	1	D
Lower	≥60		Very poor	0	F

Results:

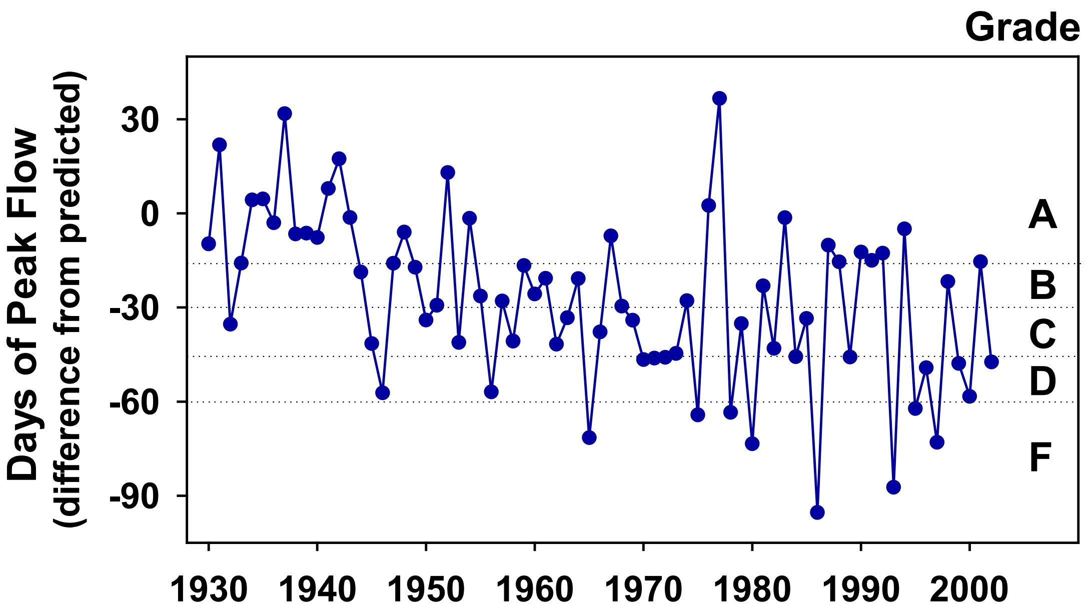

Figure 19. Changes in the Change in Peak Flow indicator from 1930-2002 The indicator measures the reduction in the number of days of peak flow (>50,000 cfs) between actual and unimpaired inflow conditions.

Peak Flow	Grade	Trends	
	(2002)	Long-term (1930-2002)	Short-term (1998-2002)
In 2002, a below normal year, only 11 days of peak flow were measured in the Bay, less than the 58 days predicted	D	↓ (declining)	↔ (fluctuating)

The frequency of peak flows in the Bay has declined (Figure 19).
Peak flow frequency (as number of days per year) declined immediately following completion of the Shasta Dam on the Sacramento River (1943). Since then, the number of days of peak flow the dropped by an average of 33 days per year (average calculated for 1944-2002). For all water year types except above normal years, the reduced number of peak flows days since 1943 has remained relatively constant (regression, $p>0.05$ for all year types except above normal). For above normal years, the number of peak flow days has continued to decline (regression, $p<0.04$), suggesting water management operations in recent years may be disproportionately impacting wetter years. For the most recent five-year period (1998-2002), the Bay received an average of 38 fewer days of peak flow than expected. In 2002, a below normal year in which 58 days of peak flow were predicted, only 11 days of peak flow were measured.

Reductions in peak flow frequency were most pronounced in intermediate water year types. In dry, below normal and above normal years, the numbers of peak flow days were reduced, on average, by 73, 47, and 41%, respectively (Figure 20). In dry years, nearly all of the already rare peak flows days have been eliminated.

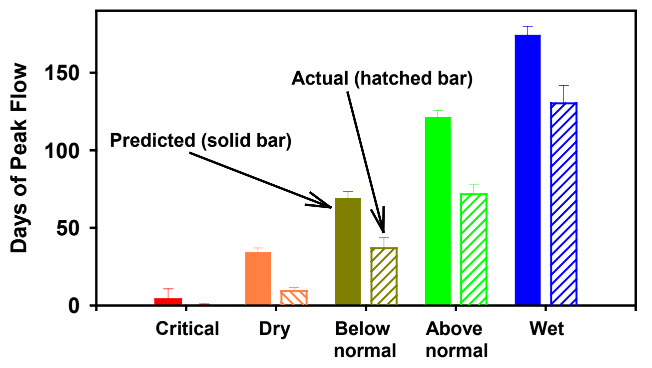

Figure 20. Comparison of predicted and actual numbers of peak flow days for each water year type, 1944-2001.

G. Freshwater Inflow Index

The Freshwater Inflow Index aggregates the results of the Annual Inflow, Water Year Type, Spring Inflow, Change in Spring Inflow, Seasonal Variation, and Change in Peak Flow indicators.

The Freshwater Inflow index declined between 1943 and 2002 (Figures 21 and 22). Between 1943 and 2002, the health of the Bay as measured by the amounts and timing freshwater inflow from its largest watershed declined significantly (regression, $p<0.001$). During the pre-dam period, the average score was 88, significantly greater than that measured during the most recent five-year period (1998-2002), which averaged 52 (t-test, $p<0.001$). The lowest scores were measured during the 1987-1992 drought, averaging just 35 for the six-year period. Following the drought, freshwater inflow conditions improved, largely the result of a sequence of relatively wet years (1995-2000). However, since 1998, the index has steadily and significantly declined (regression, $p<0.05$).

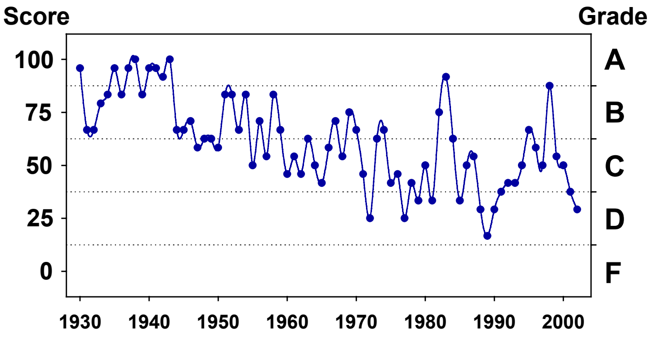

Figure 21. The Freshwater Inflow Index aggregates the results of the Annual Inflow, Water Year Type, Spring Inflow, Change in Spring Inflow, Seasonal Variation, and Change in Peak Flow indicators.

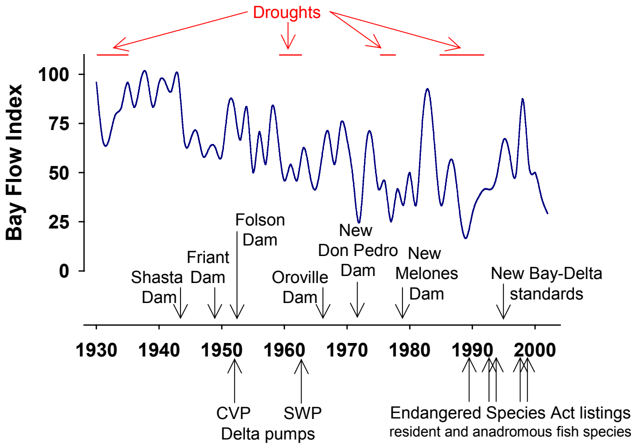

Figure 22. During the past 73 years, a period which included four major droughts, the Bay's vast watershed was transformed by dams and diversions. The Bay Freshwater Inflow Index tracks the effects of upstream water development on the freshwater inflow dynamics of the estuary.

H. References

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