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REPORT

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CLEAN WATER ACT X2 WATER QUALITY STANDARDS

by

Greg D. Sullivan, Ph.D. and Richard A. Denton, Ph.D., P.E.
Contra Costa Water District
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SWRCB April 26-27, 1994 Bay-Delta Standards Workshop CCWD-2

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EXECUTIVE SUMMARY

This report analyzes three important elements of the Clean Water Act X2 standards: (1) the meaning of X2; (2) possible implementation measures for an X2 standard; and (3) additional flow requirements to satisfy an X2 standard. The report suggests modifications which would improve upon the scientific defensibility and effectiveness of the X2 standards. The major findings of this report are outlined below.

It was found that inappropriate conversions between measurements of surface electrical conductivity and practical salinity were used in the development of the X2 standards. The X2 standards as proposed are really more like X1.5 standards.

An extensive analysis was performed to determine estimates of additional outflow requirements of the X2 standards. The "base case" against which additional flow requirements were measured was the 1968-1991 historical period. Analyses were performed using two methodologies: (1) antecedent flow-salinity relations developed by Dr. R.A. Denton; and (2) X2 relations developed by Dr. W. Kimmerer and Dr. S. Monismith. On average the two methodologies gave approximately the same results. Additional outflow requirements are given in table I for five separate analyses:

(1) X2 as a surface EC standard of 2640 μS/cm (2ppt equivalent according to the development of the X2 equation);
(2) X2 as a 3406 μS/cm surface EC standard (2ppt equivalent according to conventional conversion equations);
(3) X2 as a 2ppt (2640 μS/cm surface EC) equivalent flow standard;
(4) X2 as a 2640 μS/cm surface EC standard using a DWRSIM "simulated" base case for 6.0 MAF/year demand;
(5) X2 as a 2ppt bottom salinity standard using the Kimmerer-Monismith X2 equation.

Estimates for additional outflow requirements for a 2ppt standard or equivalent 2640 μS/cm surface EC standard ranged from about 1.0 to 1.3 MAF/year on an overall average basis and 1.5 to 1.85 MAF/year on average in critical years. The equivalent flow standard was found to require about 300 TAF greater additional outflow on average than the 2ppt salinity standard. This can be attributed to (1) the greater ability of the X2 standard to take advantage of the beneficial effects of antecedent wet conditions typical in the first portion of the regulated period as compared to the equivalent flow standard; and (2) the differing ways in which the Roe Island standard was triggered under the two implementation scenarios (the effective averaging period was longer for the salinity standard than for the flow standard). Uncertainty in the estimates of additional flow requirements using Denton's equations was estimated to be about ± 100 TAF for the overall average and ±200 TAF for the averages within year types.

Year Type	Surface EC=2640 μS/cm Standard (Denton equation - historical NDO base case) (TAF)	Surface EC=3406 μS/cm Standard (Denton equation - historical NDO base case) (TAF)	Equivalent Flow Standard (equiv to 2640 μS/cm surface EC) (Denton equation - historical NDO base case) (TAF)	Surface EC=2640 μS/cm Standard (Denton equation - DWRSIM base case at 6.0 MAF demand) (TAF)	Bottom X2 Standard (Kimmerer equation - historical NDO base case) (TAF)
All	1000	850	1300	1000	1100
Critical	1550	1200	1600	1350	1850
Dry	1000	900	1600	800	1200
Below Normal	1000	1250	1900	500	1200
Above Normal	550	350	650	900	400
Wet	900	700	1000	1050	850

Table I. Additional flow requirements of the Clean Water Act X2 standards for the 1968-1991 historical period.

It is suggested that the way in which days are "counted" for credit under the X2 standard be modified. It is proposed that if either (1) the daily average salinity is below 2ppt, (2) the 14-day average salinity is below 2ppt, or (3) the net Delta outflow index is greater than the 2ppt equivalent then the day should count for credit at the appropriate X2 station. This modification would enhance operational flexibility while providing the desired salinity control.

The proposed standards presently vary according to year type. It is suggested that the required number of X2 days vary continuously according to a continuous parameter such as the February-June Sacramento Four River Index using the methodology discussed in chapter 2 of this report. January may also be included in this index to account for antecedent effects of outflow on salinity and an additional factor may be incorporated to account for carryover storage in upstream reservoirs at the end of January. The suggested "sliding scale" approach would result in greater flexibility in water management and better reflect the hydrological state of the Delta estuary.

1. INTRODUCTION

On December 15, 1993 USEPA proposed the following X2 water quality standards as part of their proposed Rule on Bay/Delta Standards.

Number of days (February - June) 2ppt salinity line must be downstream of:			
Year Type	Roe Island* (Port Chicago)	Chipps Island	Confluence (Collinsville)
Wet	133	148	150
Above Normal	105	144	150
Below Normal	78	119	150
Dry	33	116	150
Critical	0	90	150
*Required only after a storm event pushes 2 ppt line downstream of Roe Island			

Table 1.1. EPA Proposed X2 water quality standards.

The purposes of this report are threefold: (1) to assess the meaning of the X2 standards; (2) to estimate additional outflow requirements of the X2 standards under various implementation scenarios; and (3) to suggest modifications to the proposed X2 standards which would improve upon their scientific defensibility and effectiveness.

This report is divided into six chapters: chapter 2 discusses the meaning of the X2 standards; chapter 3 discusses several implementation measures and methods that may be used to estimate additional outflow requirements of the X2 standards; chapter 4 discusses a flow-salinity model developed by Dr. R. A. Denton which is used in the analysis of X2 standard impacts; chapter 5 presents estimates of additional flow requirements under the various implementation scenarios; and chapter 6 suggests modifications to the proposed X2 standards.

2. MEANING OF THE X2 STANDARDS

2.1. X2 in Relation to Surface Electrical Conductivity

To translate bottom salinity to surface salinity information about the vertical salinity gradient in the water column is required. Kimmerer & Monismith (1993) analyzed bottom and surface measurements of salinity for bottom salinities between 1.5 and 2.5 ppt and suggested that for 30-day averaged outflows less than about 6,000 ft^3/s, the difference between top and bottom salinity was about 0.24 ppt and for flows at about 29,000 ft^3/s the difference was about 0.7 ppt. More recently, in an analysis of 1990-1992 USGS data, Monismith (1993) suggested that for bottom salinities near 2ppt the top to bottom salinity difference lies in the range 0 to 0.5 ppt, independent of outflow.

In the development of the X2 equation it was assumed that $S=(2/3)*EC$, where S is salinity in practical salinity units and EC is electrical conductivity in mS/cm. According to this conversion, 2ppt salinity is equivalent to 3000 μS/cm EC. If it is further assumed (as done in the development of the X2 equation) that the top to bottom salinity difference is typically about 0.24 ppt then 2ppt bottom salinity is equivalent to 1.76 ppt surface salinity and 2640 μS/cm EC.

The simple "2/3" equation that was used to convert salinity to EC, however, does not agree with standard conversion equations referenced to 25 °C (by convention, measurements of EC in the Delta are referenced to 25 °C). Figure 2.1.1 shows the relationship between practical salinity and electrical conductivity (EC) at four temperatures using a conversion equation developed by Accerboni and Mosetti. (Walker and Chapman [1973] assessed a number of EC-salinity relations and found the Accerboni-Mosetti equation best suited for accurate conversion.) According to the Accerboni-Mosetti conversion equation, 1.76 ppt surface salinity (2ppt bottom salinity equivalent) corresponds to 3406 μS/cm EC. Since the original X2 equation was developed based on translating surface EC measurements referenced to 25 °C to bottom salinities using the inappropriate "2/3" conversion, the EPA-proposed standards are in fact more like X1.5 standards.

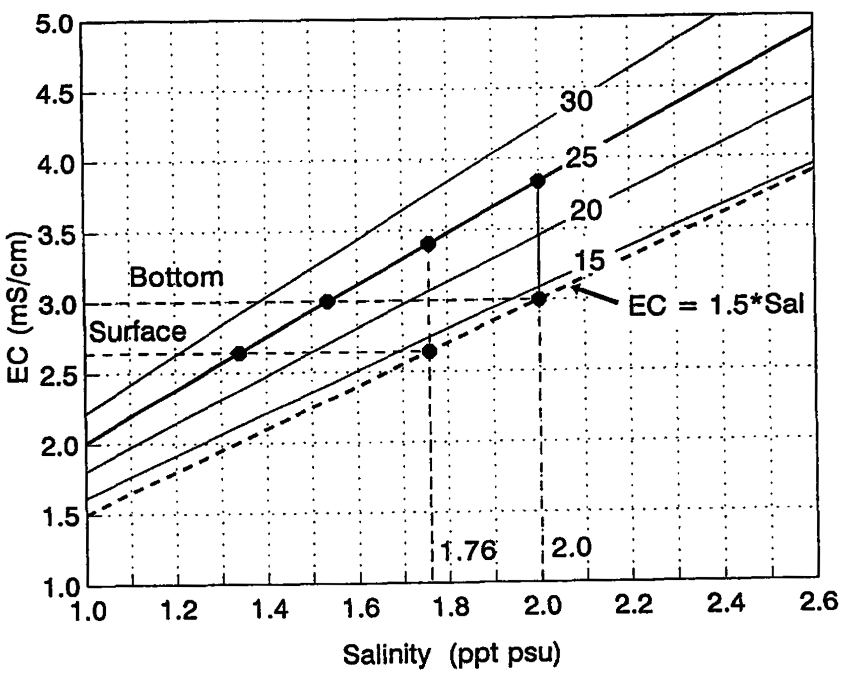

Figure 2.1.1. Conversion from electrical conductivity (EC) to practical salinity using the Accerboni-Mosetti equation. The conversions are shown for four temperatures: 15, 20, 25, and 30 °C.

It is often useful to convert salinity in practical salinity units to approximate concentration of total dissolved solids and chlorides. Figure 2.1.2 shows the relation between total dissolved solids, chloride concentration and practical salinity for seawater. The data plotted are from grab samples from DWR's Municipal Water Quality Investigation Program at Mallard Island and Jersey Point.

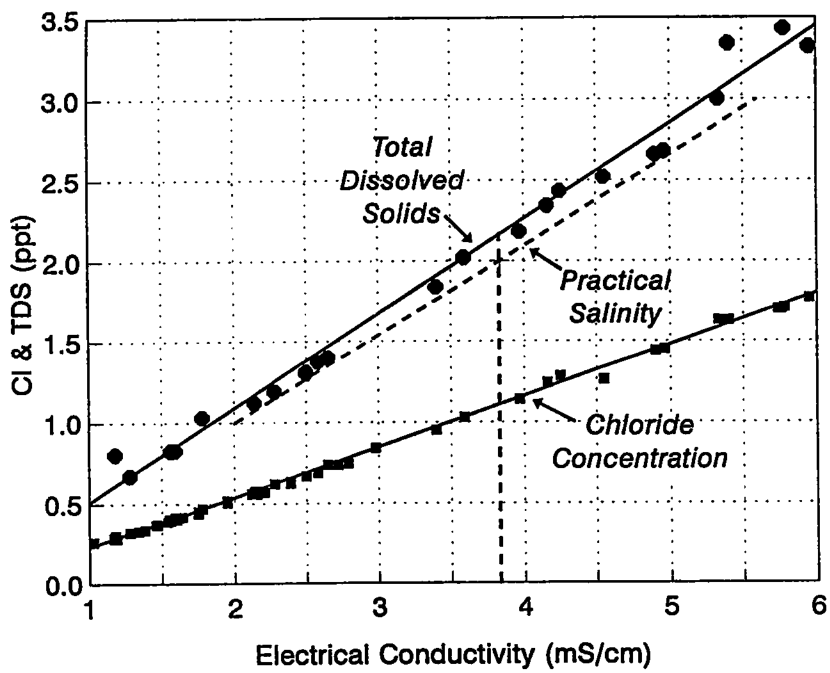

Figure 2.1.2. Total dissolved solids and chloride concentration from DWR grab samples. The dotted line indicates the practical salinity relation of Accerboni- Mosetti referenced to 25°C. The solid lines represent "best-fit" curves.

The distance between X2 stations and Golden Gate Bridge is important in the analysis of the X2 standard. USEPA has assigned nominal values of 64km, 74km, and 81 km, respectively to Roe Island, Chipps Island and the confluence of the Sacramento and San Joaquin Rivers. In the derivation of the X2 equation, however, the positions of the D-1485 surface EC monitoring stations at Port Chicago, Mallard Slough, and Collinsville were defined as 64 km, 75 km, and 81 km, respectively. Variations in the distance from Golden Gate by as little as 0.5 km can have significant effects on the flow requirements. Table 2.1.1 shows steady-state flows required to maintain X2 at several positions (estimates are based on the X2 equation from Kimmerer &

Monismith [1993]).

X2 (km)	Q (ft^3/s)	X2 (km)	Q (ft^3/s)	X2 (km)	Q (ft^3/s)
63.5	30470	73.5	13000	80.5	7160
64.0	29200	74.0	12460	81.0	6860
64.5	27980	74.5	11940	81.5	6580

Table 2.1.1 Steady-state flows required to maintain X2 at various locations. Flows are determined using the X2 equation from Kimmerer & Monismith (1993).

2.2. Historical Perspective on X2 Attainability

An analysis was performed using two different methodologies to determine the number of days the X2 standards (treated as an equivalent surface EC of 2640 μS/cm) were met historically for the period, 1930-1992, at Port Chicago, Chipps Island, and Collinsville. The first methodology used Denton's antecedent flow-salinity relations (discussed in chapter 4) to determine salinity as a function of time at the three stations. The second methodology used the X2 equation (discussed in chapter 4) to determine X2 as a function of time. In both cases, historical DAYFLOW estimates of net Delta outflow were used. The historical number of days the X2 standards were met are given in table 2.2.1.

	Port Chicago		Chipps Island		Collinsville		Annual
Water Year	Gave days	X2 days	Gave days	X2 days	Gave days	X2 days	40/30/30 Index
1930	72	91	144	143	150	150	5.90
1931	0	0	73	70	101	98	3.66
1932	127	145	151	151	151	151	5.48
1933	18	0	150	150	150	150	4.63
1934	19	16	101	100	120	113	4.07
1935	131	150	150	150	150	150	6.98
1936	140	149	151	151	151	151	7.75
1937	135	137	150	150	150	150	6.87
1938	150	150	150	150	150	150	12.62
1939	19	0	103	102	130	126	5.58
1940	132	141	151	151	151	151	8.88
1941	150	150	150	150	150	150	11.47
1942	150	150	150	150	150	150	11.27
1943	135	142	150	150	150	150	9.77
1944	41	22	143	142	151	151	6.35
1945	114	135	150	150	150	150	6.80

Water Year	Port Chicago Gave days	Port Chicago X2 days	Chipps Island Gave days	Chipps Island X2 days	Collinsville Gave days	Collinsville X2 days	Annual 40/30/30 Index
1946	127	132	150	150	150	150	7.70
1947	41	26	110	109	145	141	5.61
1948	91	81	146	139	151	151	7.12
1949	72	74	141	140	150	150	6.09
1950	103	119	150	150	150	150	6.62
1951	109	123	146	146	150	150	9.18
1952	151	151	151	151	151	151	12.38
1953	101	115	150	150	150	150	9.55
1954	113	117	139	139	150	148	8.51
1955	0	0	118	104	150	144	6.14
1956	142	151	151	151	151	151	11.38
1957	53	50	146	145	150	150	7.83
1958	150	150	150	150	150	150	12.16
1959	41	39	79	79	118	115	6.75
1960	33	34	121	111	137	132	6.20
1961	38	19	87	86	135	132	5.68
1962	67	68	143	137	150	150	6.65
1963	108	125	150	150	150	150	9.63
1964	7	8	74	71	142	140	6.41
1965	95	124	150	150	150	150	10.15
1966	20	33	113	110	129	123	7.16
1967	145	150	150	150	150	150	10.20
1968	54	49	81	81	122	120	7.24
1969	150	150	150	150	150	150	11.05
1970	58	68	91	97	148	144	10.40
1971	57	68	150	150	150	150	10.37
1972	0	0	64	62	93	88	7.29
1973	69	82	124	123	150	146	8.58
1974	96	119	150	150	150	150	12.99
1975	84	105	150	150	150	150	9.35
1976	0	0	0	0	63	52	5.26
1977	0	0	0	0	0	0	3.09
1978	114	125	141	142	150	150	8.65
1979	44	47	121	108	143	137	6.67
1980	77	93	151	151	151	151	9.04
1981	19	0	79	76	133	108	6.21
1982	137	150	150	150	150	150	12.72
1983	150	150	150	150	150	150	15.29
1984	60	68	92	89	151	151	10.00
1985	0	0	39	31	110	99	6.47
1986	84	85	139	138	150	150	9.93
1987	0	0	51	30	96	91	5.83
1988	0	0	7	0	52	28	4.63
1989	24	0	45	37	111	104	6.13
1990	0	0	0	0	38	9	4.81
1991	5	0	36	14	59	37	4.21
1992	11	0	48	41	82	78	4.07

Table 2.2.1. Number of days X2 standards were met using: (1) Denton's antecedent flow-salinity relations; (2) Kimmerer-Monismith X2 equation.

Figure 2.2.1 shows the number of days salinity is 2ppt or less at Chipps Island for the period, 1930-1992, as a function of the Sacramento River 40-30-30 index. The solid dots represent data from 1964 to 1976, the interval selected by SWRCB (SWRCB letter to EPA November 15, 1993) as representing the recommended protection period required under the Clean Water Act (late 1960s to early 1970s). The solid line represents a least squares linear fit to the 1964 to 1976 data for values of the runoff index less than 12 MAF.

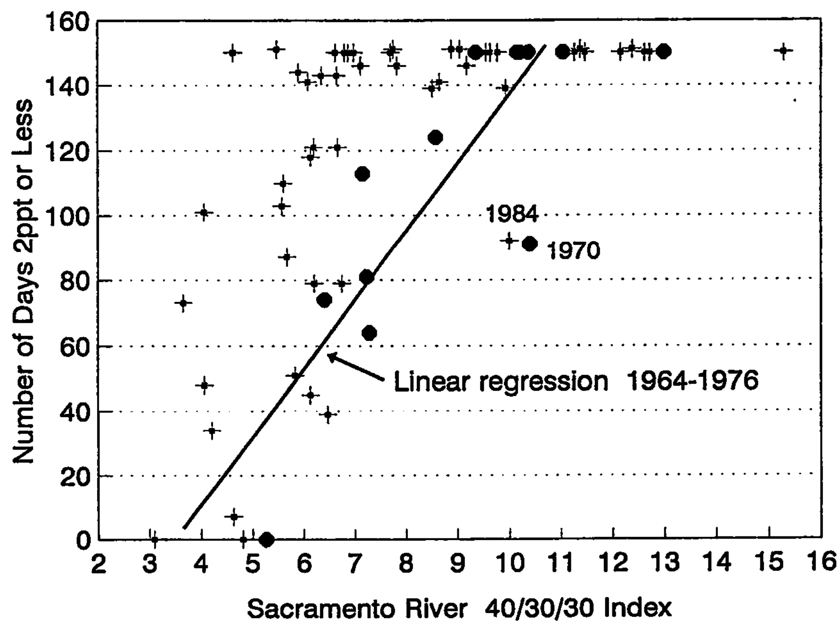

Figure 2.2.1. Relation between the number of X2 days at Chipps Island and the Sacramento River 40-30-30 index for the period, 1930-1992. Solid dots represent the period, 1964-1976. The solid line represents a least squares linear fit through the 1964-1976 data.

Figures 2.2.2, 2.2.3, and 2.2.4 show the number of days salinity is less than or equal to 2ppt at Roe Island, Chipps Island, and Collinsville, respectively, as a function of the February through June Sacramento Four River Index. The February through June Sacramento Four River Index is chosen here as it is more representative of the water available to meet the X2 standards than the full Sacramento Four River Index (October through September) or the 40-30-30 index. The data in figures 2.2.2 to 2.2.4 are categorized into four historical periods: (1) 1930-1939 (pre-projects), (2) 1940-1967 (start of construction of CVP and from 1951 onwards CVP on-line), (3) 1968-1975 (representative of EPA's period of recommended protection), (4) 1976-1992. The period before initial operations of the CVP (1930-1939) has the greatest number of X2 days, as expected. The number of X2 days in the recent period, 1976-1992, is similar to the number of X2 days in the EPA-targeted late 1960s to early 1970s period at similar levels of the February-June Sacramento Four River Index.

The number of X2 days in figures 2.2.2 to 2.2.4 is highly correlated with both inflow into the Delta system (quantified by the February-June Sacramento Four River Index) and total diversions. As diversions increase for a given level of the Sacramento Four River Index the net Delta outflow decreases and the number of X2 days decreases. The parameter which best determines the number of X2 days from February through June is the February-June net Delta outflow. Figure 2.2.5 shows the good correlation between X2 days at Chipps Island and the February-June net Delta outflow for the extended period, 1930-1992. (Anomalies still exist, e.g. 1970, a year in which the timing of outflow was skewed relative to other years with similar net February-June outflow.) NDO, however, cannot be used as a predictive index to define a sliding scale because Delta outflow is dependent on project operations.

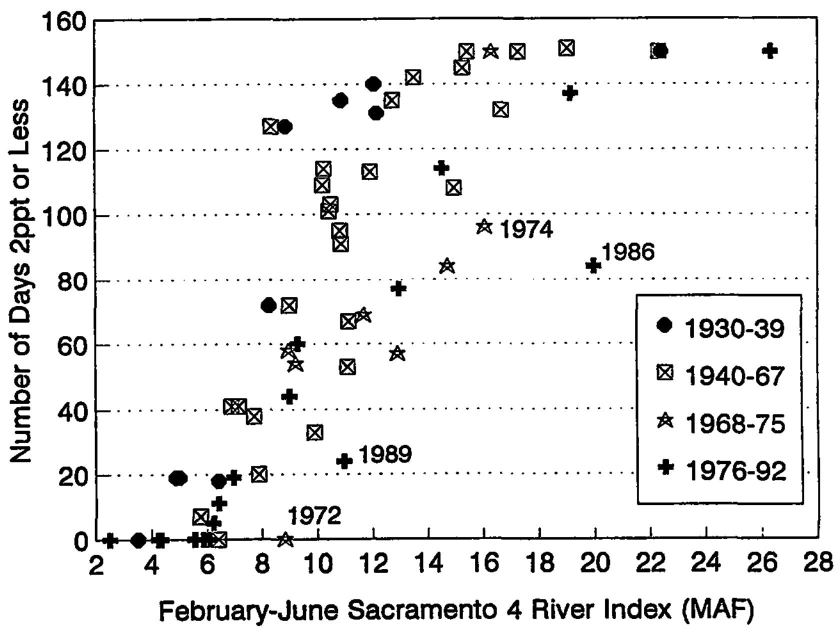

Figure 2.2.2. Relation between the number of X2 days at Roe Island and the February-June Sacramento Four River Index for the period, 1930-1992.

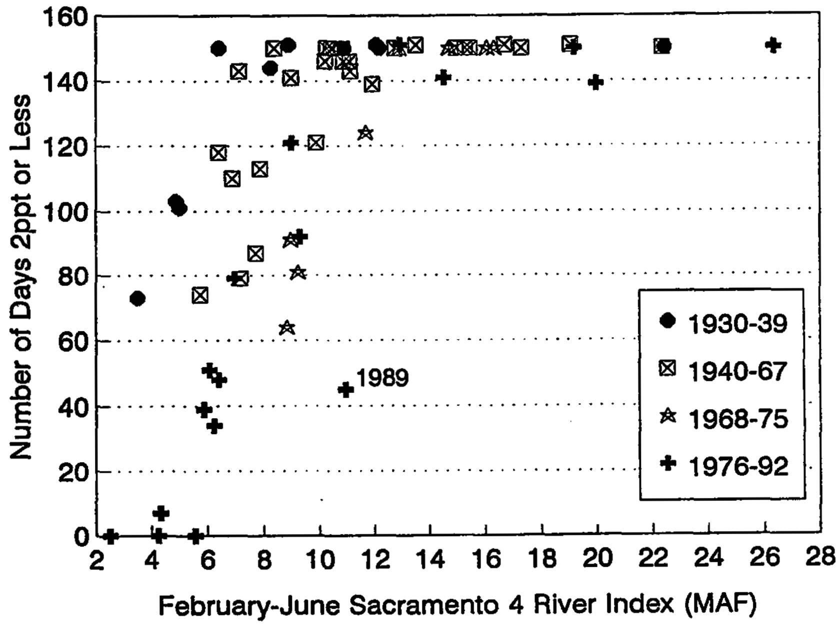

Figure 2.2.3. Relation between the number of X2 days at Chipps Island and the February-June Sacramento Four River index for the period, 1930-1992.

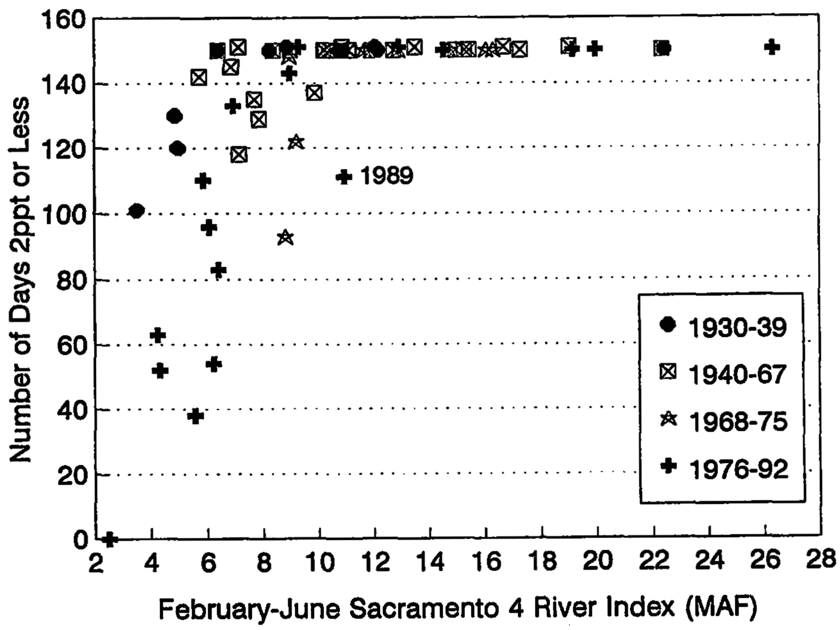

Figure 2.2.4. Relation between the number of X2 days at Collinsville and the Sacramento Four River index for the period, 1930-1992.

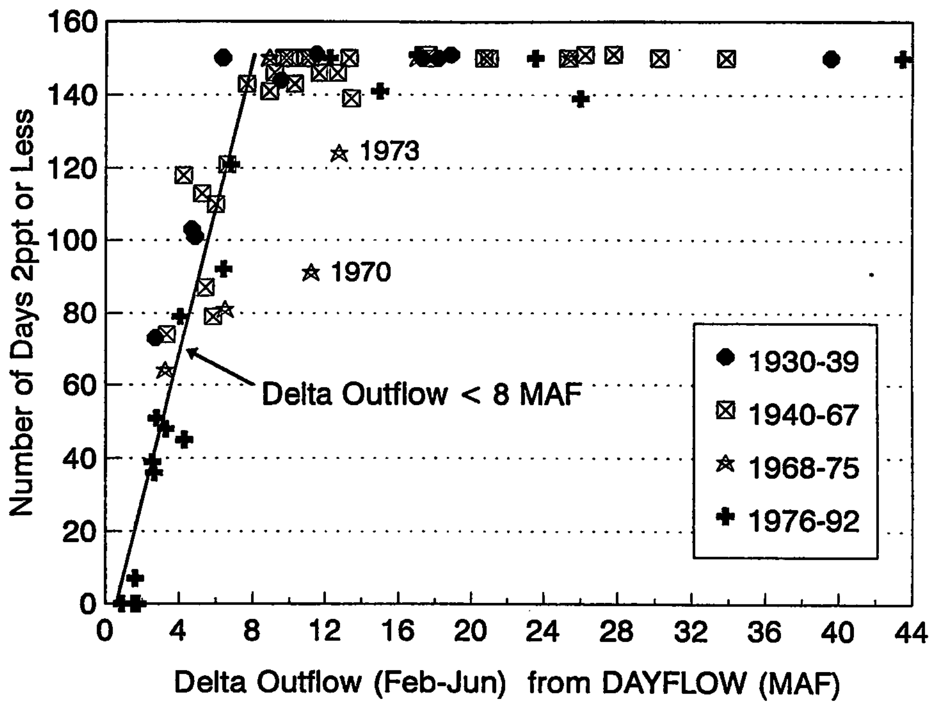

Figure 2.2.5. Relation between the number of X2 days at Chipps Island and the February-June net Delta outflow for the period, 1930-1992.

2.2.3 Sliding Scale Approach to X2 Standards

EPA has recommended a level of protection for San Francisco Bay and the Delta similar to that which existed during the late 1960s and early 1970s. In developing the X2 standards, however, EPA used a longer period, 1940-1975, to determine the X2 day requirements for specified year types. This longer period was deemed necessary to ensure sufficient data for the analysis. EPA used the 40-30-30 Sacramento River Index to categorize water years into one of five water year types (wet, above normal, below normal, dry, and critical) and averaged the data within each category. In essence, EPA's methodology reduced the data from 36 years to four points: the average number of X2 days during wet, above normal, below normal, and dry years (the period, 1940-1975, contained no critical years).

It is recognized that the 40-30-30 index, which was developed as part of the SWRCB D-1630 process to define water year availability over a full water year (October-September) may not be representative of the salinity regime in Suisun Bay for the period, February-June; e.g. the 40% component of the 40-30-30 index is the sum of monthly unimpaired runoffs for April-July and July runoff cannot affect salinity in the previous period, February-June. Similarly, unimpaired runoff in October, November, and December that is not stored in upstream reservoirs will not significantly effect salinity in the February-June period. EPA has considered using other indices than the 40-30-30 index to define the X2 day requirements (Issue #1, USEPA 1994, p.834). One alternative EPA has considered is to modify the 40-30-30 split of the April-July runoff, October-March runoff, and the previous water year's index. A somewhat better approach may be to use the sum of the monthly runoffs for the period, February through June, as this most directly affects salinity in the Delta and Suisun Bay. This index may be further refined by including January to account for antecedent effects of outflow on salinity and/or including an additional factor to account for carryover storage in upstream reservoirs at the end of January.

To determine appropriate X2 day requirements historical X2 attainability may be plotted versus the February-June runoff index. This enables analysis of periods such as 1955-1975 (21 points), 1964-1975 (12 points), or 1968-1975 (8 points) to address EPA's Issue #5 (USEPA 1994, p.839) which deals with the determination of the appropriate historical reference period for developing target number of X2 days. Figure 2.3.1 shows X2 days at Roe Island for a period compatible with the required level of protection, 1968-1975, along with a least squares linear fit. The data plotted in figure 2.3.1 and in figures 2.2.2 to 2.2.4 suggest that since a simple linear equation reasonably fits the data use of a higher order polynomial appears unwarranted. Also shown in figure 2.3.1 are the number of X2 days required under the proposed X2 standards. There is some overlap in required number of days because the water year types for the proposed standards are based on the 40-30-30 index rather than a February through June runoff index. The proposed X2 standards tend to require significantly greater number of days of compliance than the least squares linear fit through the 1968-1975 data.

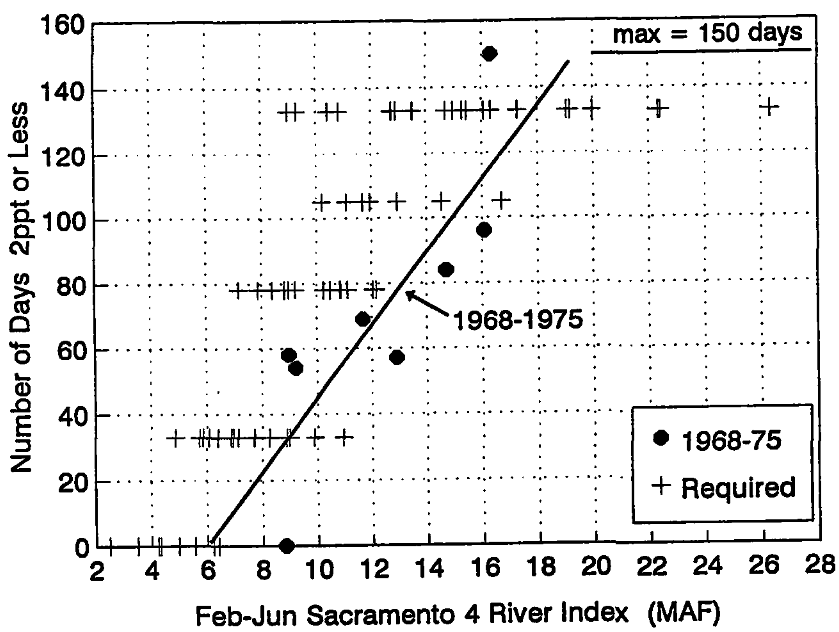

Figure 2.3.1. Number of X2 days at Roe Island for the period, 1968-1975. The solid line represents a least squares linear fit through the data. The crosses represent the required number of days under the EPA-proposed X2 standards.

Figure 2.3.2 shows the number of X2 days at Chipps Island for the period, 1968-1975, along with a least squares linear fit. Data for which the February through June index was greater than 14 MAF were not included in the least squares linear fit since they were at the maximum number of days (150 days). EPA's extrapolation to set a critical year standard (the period 1940-1975 used by EPA contains no critical years) appears to have overstated the necessary level of protection at Chipps Island. The linear fit through the 1968-1975 data shown in figure 2.3.2 suggests that very few days of 2 ppt or less would be required at Chipps Island during critical years for appropriate protection. The proposed below normal and above normal year X2 day requirements also appear to be overstated.

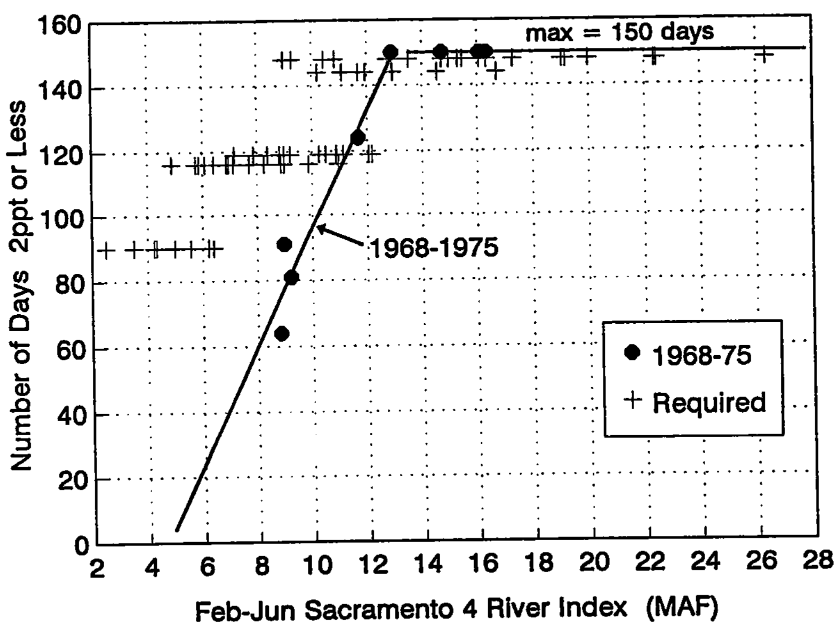

Figure 2.3.2. Number of X2 days at Chipps Island for the period, 1968-1975. The solid line represents a least squares linear fit through the data for values of the February-June Index less than 14 MAF. The crosses represent the required number of days under the EPA-proposed X2 standards.

Figures 2.2.2, 2.2.3, and 2.2.4 indicate that the least squares linear fits are sensitive to the choice of historical period. Figure 2.3.3 shows X2 days at Chipps Island for the period, 1955 through 1992, with linear fits for the periods, 1955-1976, 1968-1975, and 1968-1992. Prior to

1968 (pre-SWP) there were fewer diversions upstream of the Delta and less exports and the number of days of X2 compliance were correspondingly higher. The linear fit for 1955 through 1976 therefore reflects the correspondingly higher ratio of Delta outflow to unimpaired runoff relative to the period, 1968-1975. It is interesting to note that including the period, 1976 through 1992, with the period of desired level of protection, 1968-1975, results in only a small change to the least squares linear fit.

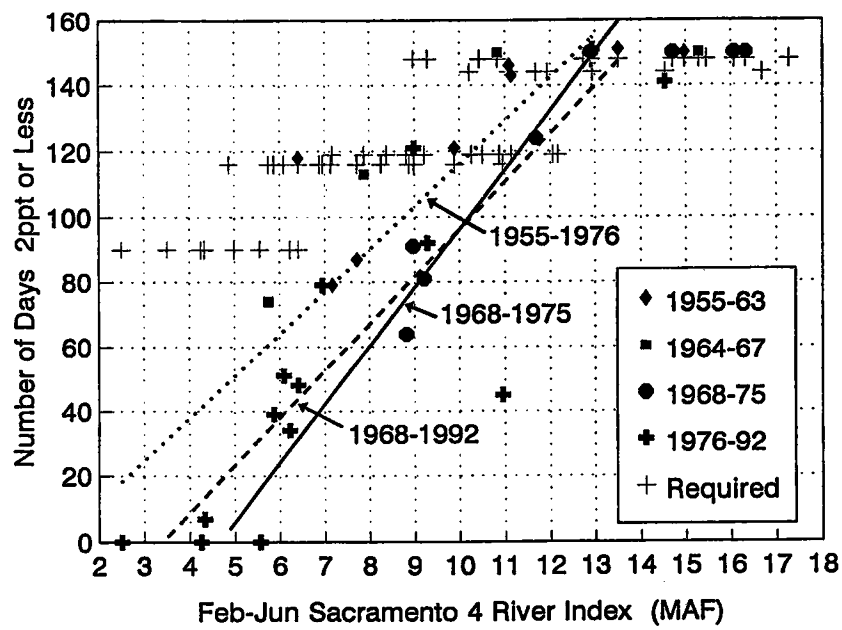

Figure 2.3.3. Number of X2 days at Chipps Island for the period, 1955-1992. The solid line represents a linear fit through the data for 1968-1975; the dashed line represents a linear fit through the data for 1968-1992; the dotted line represents a linear fit through the data for 1955-1976.

The proposed X2 day requirement at Collinsville is 150 days for all water year types. Figure 2.3.4 shows the number of X2 days at Collinsville for the period, 1964-1992. There were only two years during 1968-1975 when the number of X2 days was significantly less than 150 days. However, the data from the longer period, 1964-1992, suggest that in critical years (beyond the range of conditions in the 1968-1975 period) some relaxation in the proposed X2 day requirements may be warranted.

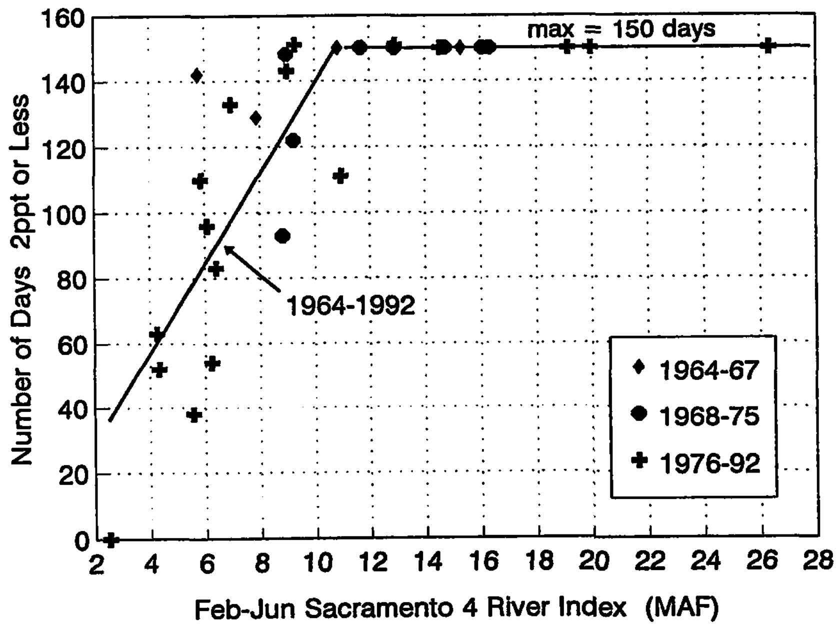

Figure 2.3.4. Number of X2 days at Collinsville for the period, 1968-1975.

In summary, the data presented in figures 2.2.1-2.2.5 and in figures 2.3.1-2.3.4 suggest that a sliding scale methodology based on linear fits to data for individual years provides an effective way to define day requirements for the X2 standard. An index based on the February-June Sacramento Four River Index appears to correlate well with the historical number of X2 days. Because the number of X2 days depends both on the runoff index and on the total amount of diversions from the system, an X2 standard based on a linear sliding scale equation would in effect impose a limit on the amount of total diversions from the whole watershed for the February-June period. While the period, 1968-1975, has been used to illustrate the sliding scale methodology, alternate periods may be selected, such as 1964-1976.

3. ASSESSING IMPACTS OF X2 WATER QUALITY STANDARDS

3.1. Implementation Scenarios

EPA's proposed X2 water quality standards may be implemented in a number of different ways. Under one possible implementation scenario the 2 ppt bottom salinity standard may be converted to a surface salinity standard measured in terms of electrical conductivity; under another scenario the 2ppt bottom salinity may be converted to an equivalent steady-state flow. In addition, the requirements for the number of days X2 is downstream of Collinsville, Chipps Island, and Port Chicago may be modified to reflect a continuous variation with some parameter, such as an index based on February-June runoff, which indicates the hydrologic state of the system (table 1.1 shows EPA's proposed discrete variation with year type).

3.2. Methods of Analysis

The additional outflow requirements of the X2 water quality standards may be examined under various implementation scenarios using two different methodologies. The first methodology employs Denton's antecedent flow-salinity relations (discussed in chapter 4); the second methodology employs Kimmerer & Monismith's X2 equation (discussed in chapter 4). The first methodology involves calculating salinity in the Delta system for a given hydrology and determining the additional outflow required to meet the X2 standards; the second methodology involves calculating the X2 location in the Delta and determining the additional outflow to meet the X2 standards.

The hydrologic "base" case against which additional flow requirements are measured may be defined in one of two ways: either (1) as measured, historic outflows over the period, 1968-1991, a period during which both the CVP and SWP were in operation; or (2) as "simulated" outflows using a procedure such as the planning model, DWRSIM, over a longer period which ideally might represent the outflows that would have occurred if present day standards were in place with a present day level of development. Although it is recognized that using historic outflows for the period, 1968-1991, does not account for possible re-operation of the projects or additional standards which have been implemented recently, the historic data set does provide a reasonably accurate representation of the range of daily fluctuations over this period. The outflows from DWRSIM, on the other hand, are expressed as monthly averages; daily estimates must be inferred. Moreover, DWRSIM uses an empirical procedure to calculate operational flows which does not always produce verifiable results. (Denton & Sullivan 1993 discuss improving DWRSIM's accuracy by incorporating Denton's flow-salinity relations into DWRSIM.)

The uncertainty in DWRSIM (more specifically the MDO "carriage water" component of DWRSIM) is illustrated in figure 3.1. Here Denton's antecedent flow model predicted salinities are compared to DWRSIM-predicted salinities and measured salinities for the period, 1967 through 1990. The average fractional error (defined as the standard deviation of the fractional error in a single monthly-average salinity prediction) is about 50% using Denton's antecedent flow methodology, whereas it is about 380% using DWRSIM. Given the uncertainty associated with DWRSIM, the historic net Delta outflow data set is selected as a more representative "base-case" against which to measure additional flow requirements of the X2 standards.

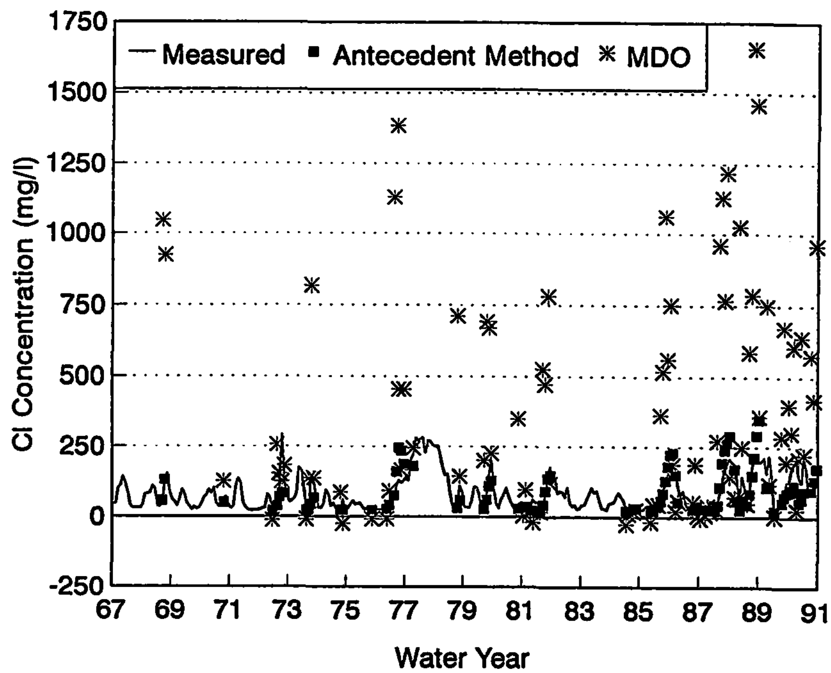

Figure 3.1. Measured and predicted monthly-averaged salinity at Rock Slough. Predictions are based on: (1) Denton's antecedent flow method; and (2) steady-state relations from the "carriage water" model, MDO, used in DWRSIM.

4. ANTECEDENT FLOW-SALINITY MODEL

Empirical antecedent flow-salinity relations have been developed that were motivated by simple results from one-dimensional dispersion theory (Denton, 1993a). The relations can be used directly to predict salinity at locations in the Delta given the prior time-history of net Delta outflow, or inverted to predict the flow required over some time interval to produce a given salinity.

4.1 A Simple Flow-Salinity Relation

Consider the simple case of a one-dimensional estuary in which flow quantities vary only with longitudinal position and time. In this case the tidally-averaged advection-dispersion equation for salinity transport is given by

$$A\frac{\partial S}{\partial t} - Q\frac{\partial S}{\partial x} = \frac{\partial}{\partial x}KA\frac{\partial S}{\partial x} , \qquad (1)$$

where A(x) is the estuary cross-sectional area, S(x,t) is the concentration of salt, Q(x,t) is the volumetric flowrate, K is the longitudinal dispersion coefficient, x is distance in the longitudinal direction (increasing in the upstream direction), and t is time (Denton 1993a). The problem may be further simplified by assuming that the area, A, longitudinal dispersion coefficient, K, and flowrate, Q, are independent of longitudinal position. Boundary conditions may be selected as constant ocean salinity, S_o, at $x=0$, and constant upstream river salinity, S_b, at $x=\infty$. For Q independent of time, the steady-state solution to this problem is

$$S = (S_o - S_b)e^{-Qx/KA} + S_b . \qquad (2)$$

Of course in natural environments, such as the San Francisco Bay-Delta estuary, the above assumptions may need modification. In particular, the tidally-averaged flowrate, Q, can fluctuate significantly on time scales ranging from days to months, and the estuary geometrical configuration can be tremendously complex. Geometrical complexities notwithstanding, a modified form of equation (2) is considered for use in modeling unsteady salinity response to variations in Q. At a fixed position, a relationship of the form

$$S(t) = (S_o - S_b)e^{-\alpha G(t)} + S_b \qquad (3)$$

is considered, where G(t) is a functional of the flow time-history (antecedent flow), and α, S_o, and S_b are empirically determined constants which can vary with position.

4.2 Antecedent Outflow G(t)

Consider a relation for the functional, G, of the form

$$\frac{dG}{dt} = \frac{(Q - G)G}{\beta} , \qquad (4)$$

where β is an empirically determined constant which can vary with position. (This formulation is similar to a relation used by Harder 1977.) In equation (4), β/G may be thought of as an effective time-constant, τ, which determines the rate of approach of G to Q; equation (4) implies that the system response is relatively quick when G is large and relatively slow when G is small.

4.3 Parameter Estimation

Practical application of equation (3) and equation (4) requires that four constants be determined from field measurements for each Delta location of interest. In practice, the determination of empirical constants from measurements of Q and S may be done as follows. β may first be determined by choosing the value which best moves the measurements of S onto a single line in the S-G plane. S_b can then be determined by locating the horizontal asymptote of the single line as $G \rightarrow \infty$. Here S_b represents the background salinity at high flowrates (large Q) from sources upstream and within the Delta, not from seawater intrusion. The remaining two parameters, S_0 and α can be determined by minimizing the deviation between model estimated S and measured S, subject to some defined weighting system (some range of S or G may be more important than another for a particular application). The parameter estimation procedure is illustrated in figures 4.1(a) and 4.1(b). In figure 4.1(a), 14-day average salinity is shown versus 14-day averaged net Delta outflow (Q). By selecting an appropriate value for β, the data from figure 4.1(a) can be moved onto a single line in the S-G plane as shown in figure 4.1(b). The parameters, S_o, S_b, and α, are determined from the "best-fit" line shown in figure 4.1(b).

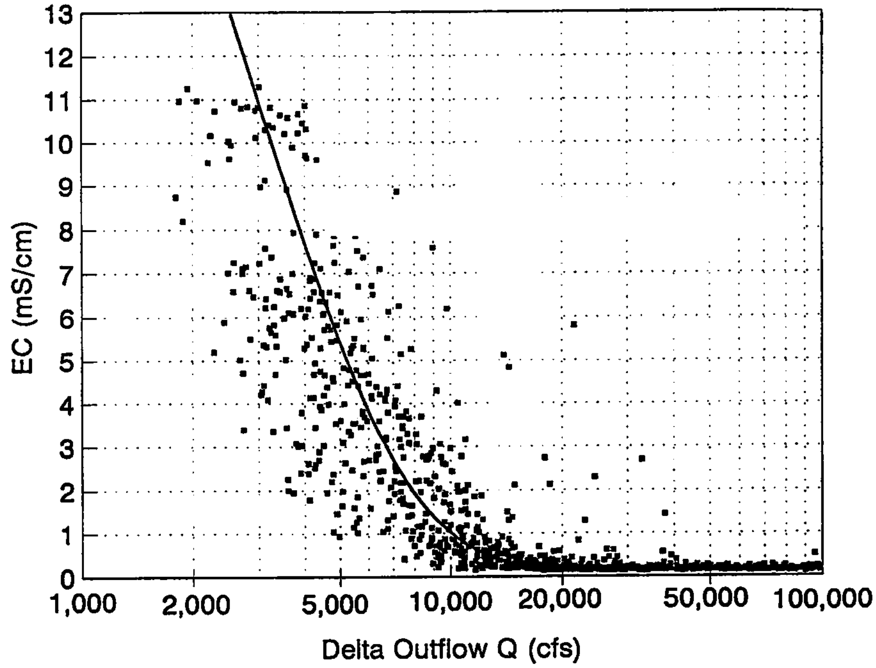

Figure 4.1(a). 14-day average salinity at Collinsville as a function of 14-day average net Delta outflow (Q). The data shown are for water years 1968 through 1986.

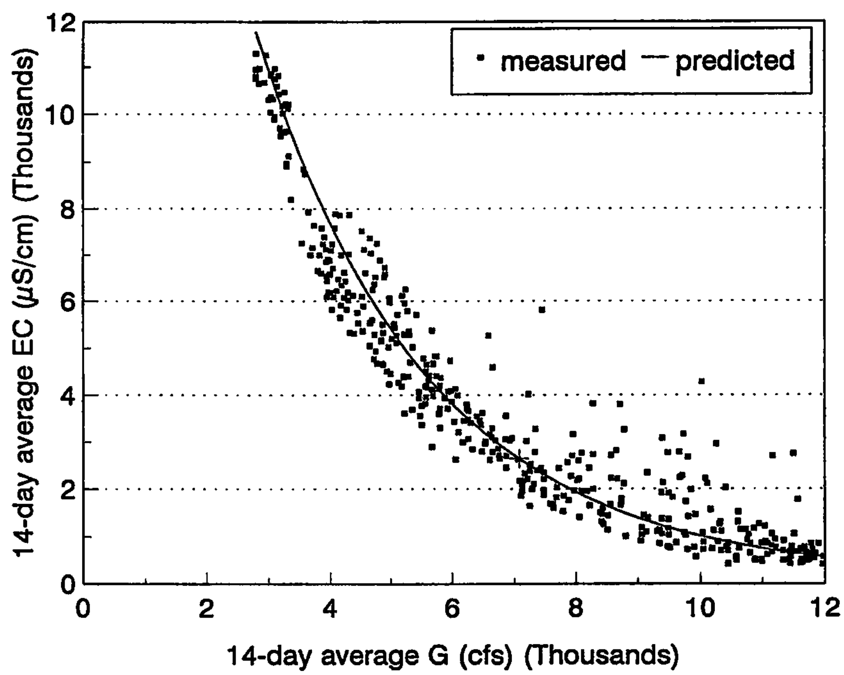

Figure 4.1(b). Predicted and measured 14-day average salinity at Collinsville. The solid line is the salinity predicted using Denton's antecedent flow relations and overall "best-fit" parameters from table 4.1 (below). The cross indicates the model prediction at EC=2640 μS/cm using locally "best-fit" parameters in the vicinity of EC=2640 μS/cm.

Figures 4.2 and 4.3 show 14-day average salinity at Chipps Island and Port Chicago, respectively, as functions of G. The lines shown in each figure represent "best-fit" exponentials from equation (3). Overall "best-fit" parameters at Port Chicago, Chipps Island, and Collinsville are given in table 4.1 below.

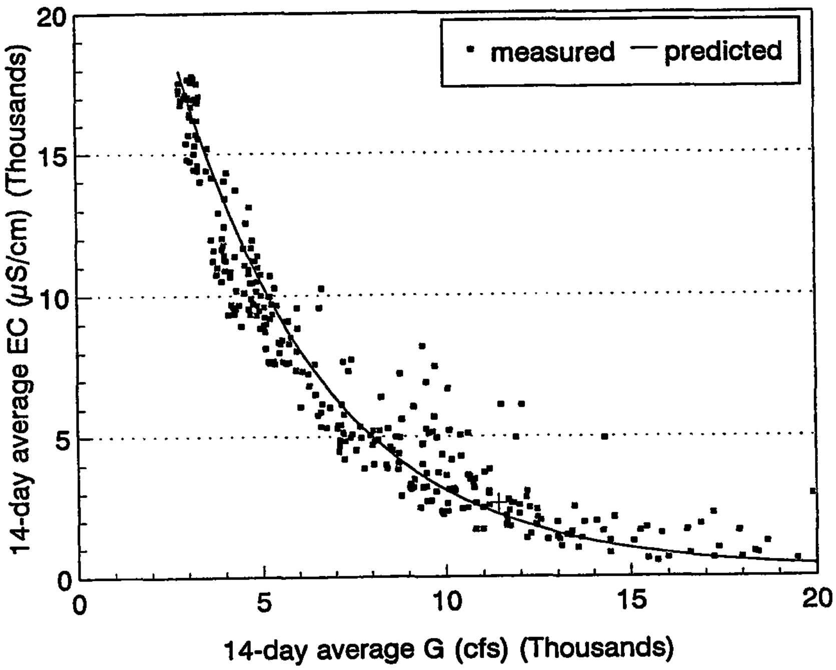

Figure 4.2. Predicted and measured 14-day average salinity at Chipps Island. The solid line is the salinity predicted using Denton's antecedent flow relations and overall "best-fit" parameters from table 4.1. The cross indicates the model prediction at EC=2640 μS/cm using locally "best-fit" parameters in the vicinity of EC=2640μS/cm.

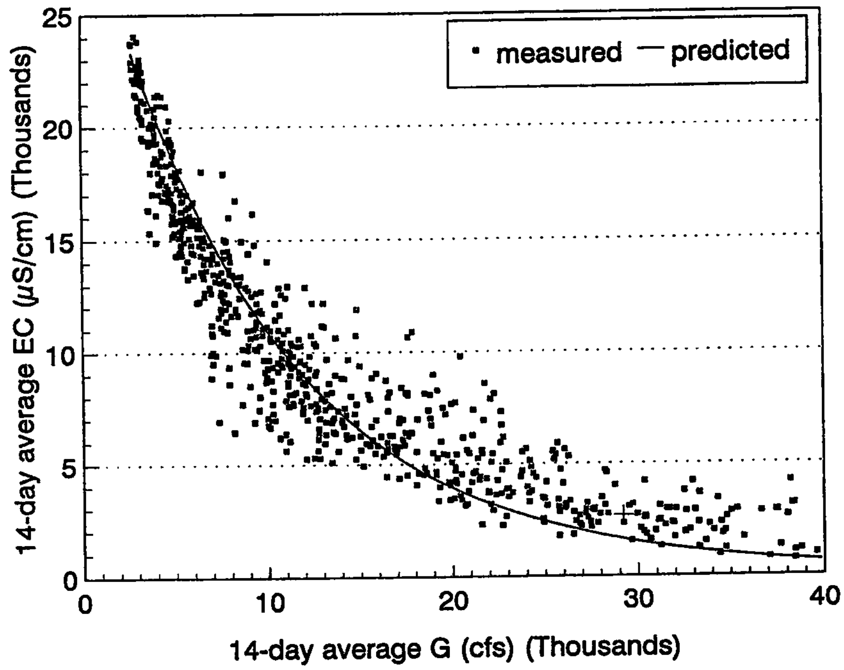

Figure 4.3. Predicted and measured 14-day average salinity at Port Chicago. The solid line is the salinity predicted using Denton's antecedent flow relations and overall "best-fit" parameters from table 4.1. The cross indicates the model prediction at EC=2640 μS/cm using local "best-fit" parameters in the vicinity of EC=2640 μS/cm.

Location	β (ft^3) ($x10^{10}$)	S_b (μS/cm) ($x10^2$)	α $(ft^3/s)^{-1}$ ($x10^{-4}$)	S_o (μS/cm) ($x10^4$)
Port Chicago	1.26	1.7	1.05	3.1
Chipps Island	1.50	1.8	2.5	3.6
Collinsville	1.50	1.5	3.6	3.2

Table 4.1. "Best-fit overall" antecedent flow model constants.

In assessing impacts of X2 standards focus is centered on the salinity equivalent of 2ppt. According to the conversion employed in the development of the X2 equation (see discussion in chapter 2) 2ppt bottom salinity is equivalent to about EC=2640 μS/cm at the surface. "Best-fit" antecedent flow model parameters for salinity in the vicinity of 2640 μS/cm differ slightly from the overall "best-fit" parameters. The crosses shown in figures 4.1(b), 4.2, and 4.3 indicate Denton's antecedent model prediction at EC=2640 μS/cm using locally "best-fit" parameters in the vicinity of EC=2640 μS/cm.

4.4 Uncertainty in Denton's Antecedent Flow Model Predictions

Predictions of salinity at Collinsville, Chipps Island, and Port Chicago using Denton's antecedent flow model are shown alongside field measurements in figures 4.4-4.6. The salinities shown have been averaged over 14-day intervals to remove spring-neap tide-induced salinity variations since net Delta outflow (Q) estimates do not account for spring-neap variations.

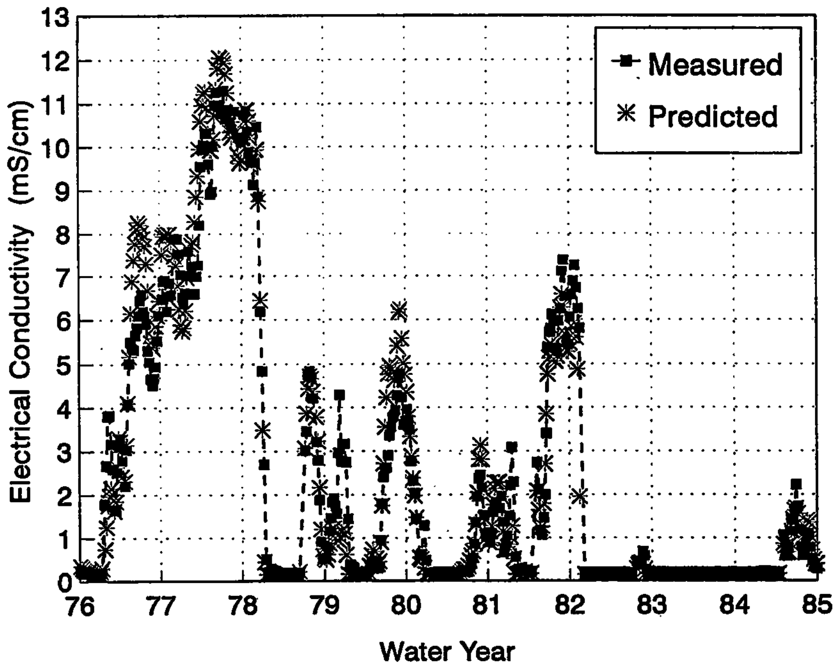

Figure 4.4. Measured and predicted 14-day average salinity at Collinsville for the period, 1976-1985. The stars represent predictions using Denton's antecedent flow model. The squares joined by dashed lines represent field-measured salinities.

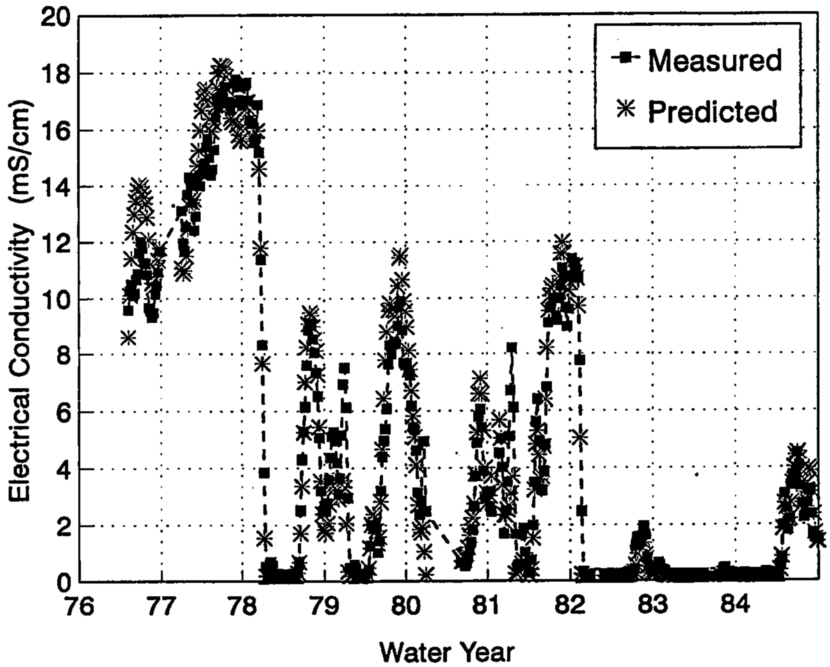

Figure 4.5. Measured and predicted 14-day average salinity at Chipps Island for the period, 1976-1985. The stars represent predictions using Denton's antecedent flow model. The squares joined by dashed lines represent field measured salinities.

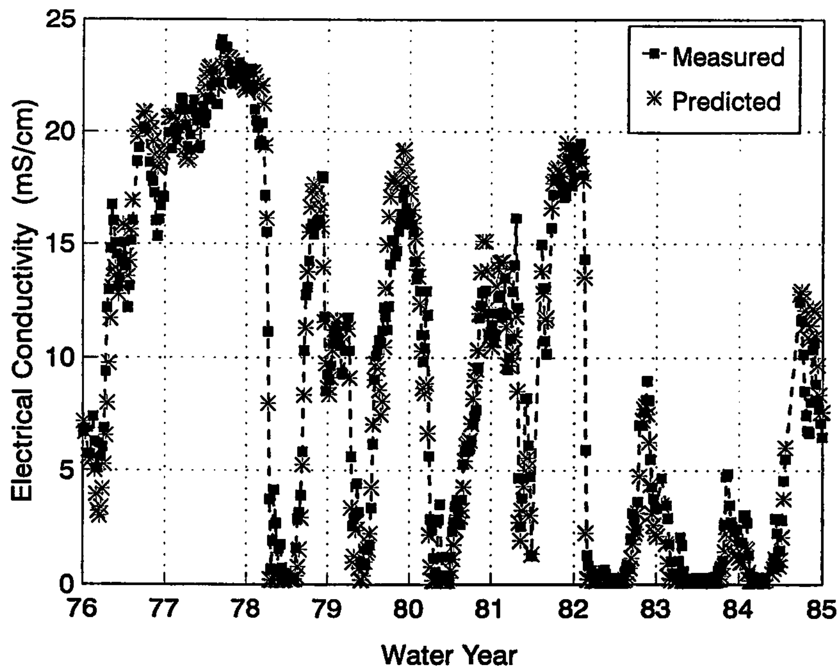

Figure 4.6. Measured and predicted 14-day average salinity at Port Chicago for the period, 1976-1985. The stars represent predictions using Denton's antecedent flow model. The squares joined by dashed lines represent field measured salinities.

A quantitative estimate of uncertainty in a single 14-day average salinity prediction may be determined from the standard deviation of the difference between predicted and measured salinity values. For the periods shown in figures 4.4, 4.5, and 4.6 at Collinsville, Chipps Island, and Port Chicago, respectively, the fractional error in a single 14-day average salinity prediction using Denton's antecedent flow model is 25%, 25%, and 20%, respectively. Some portion of this error can be attributed to errors in estimates of net Delta outflow which rely on somewhat uncertain estimates of Delta consumptive use.

4.5. Comparison to X2 Equation

The Kimmerer-Monismith daily X2 equation is given by

$$X2(t) = 10.16 + 0.945\,X2(t-1) - 1.487\,logQ(t), \qquad (5)$$

(Kimmerer & Monismith [1993]) where X2(t) is the position of the 2ppt isohaline at time t, X2(t-1) is the position of the 2ppt isohaline at time t-1, Q(t) is the calculated value of net Delta outflow in ft^3/s, and t is time expressed in days. Equation (5) may also be expressed in the equivalent form

$$X2(t_n) \approx -1.487\sum_{i=1}^{n}(.945)^{n-i}\ logQ(t_i) + 184.7, \qquad (6)$$

valid for large times after the starting time of the model (the dependence on the initial value of X2 is insignificant after several months). It is interesting to compare equation (6) which predicts X2 as a function of the antecedent flows and equations (4) and (5) which predict salinity at a fixed position as a function of the antecedent flows. As noted in chapter 4.2, the time constant for the system in Denton's model, β/G, implies that the system responds quickly to changes in flow when G is large and more slowly when G is small. Equation (6), on the other hand, implies that the system response is independent of the flow (the multiplicative factors of the antecedent flows in equation 6 are constant and independent of the flows). The importance of the differing time constants becomes apparent when examining the operations necessary to meet the X2 standards according to the two models, as discussed in chapter 5.

Flow requirements under steady-state conditions (X2[t]=X2[t-1]) for 2ppt at Collinsville, Chipps Island, and Roe Island from equation (5) are given in table 4.3. Also shown in table 4.3 are equivalent steady-state flow requirements for EC=2640 μS/cm based on Denton's antecedent flow model using "best-fit" parameters in the vicinity of EC=2640 μS/cm from table 4.2.

Station Name	Location (km)	Steady-State Flow Required - X2 equation (ft^3/s)	Steady-State Flow Required - Denton antecedent flow equation
Roe Island	64	29,200	29,220
Chipps Island	74	12,460	11,400
Collinsville	81	6,860	7,080

Table 4.3. Flow equivalents to 2ppt bottom salinity based on: (1) Kimmerer-Monismith X2 equation; (2) Denton antecedent flow model for EC=2640 μS/cm using "best-fit" parameters in the vicinity of 2640 μS/cm.

5. ANALYSIS OF ADDITIONAL WATER REQUIREMENTS OF X2 STANDARDS

Analyses of additional flow requirements of the X2 standards were performed for three implementation scenarios: (1) X2 as a surface salinity standard of EC=2640 μS/cm (2ppt equivalent in development of X2 equation); (2) X2 as a surface salinity standard of EC=3406 μS/cm (2ppt equivalent using conventional conversion equations); and (3) X2 as an equivalent flow standard using equation (5). Periods of analysis using DAYFLOW historical estimates of net Delta outflow were as follows: (I) 1930-1950 (pre-projects); (II) 1951-1967 (CVP on-line); and (III) 1968-1991 (CVP and SWP on line). Analyses were performed using Denton's antecedent flow methodology described in chapter 4 under implementation scenarios 1, 2, and 3 for periods I, II, and III. For comparison, an analysis of period III under scenario 1 using DWRSIM's base case outflow at 6 MAF/year and 7 MAF/year demand was performed using Denton's antecedent flow method. An analysis of period III under implementation scenario 1 using historical flows was also performed using the X2 equation.

5.1 Assumptions in Analysis

The following assumptions were made in the analysis of the X2 water quality standards:

1. Year type was established using the 40-30-30 criteria as defined in State Water Resources Control Board Draft D-1630.

2. Roe Island salinity was assumed equivalent to Port Chicago salinity.

3. Confluence salinity was assumed equivalent to Collinsville salinity.

4. 2ppt salinity 1m from the bottom of the channel floor was assumed equivalent to 1.76 ppt at the surface. The conversion used in the development of the X2 equation gave that 1.76 ppt was equivalent to EC=2640 μS/cm at 25°C; the Accerboni-Mosetti conversion equation (see chapter

2) gave that 1.76 ppt was equivalent to EC=3406 μS/cm at 25°C.

5. DAYFLOW estimates of historical NDO were used to establish the "base case."

6. Salinity requirements and trigger criteria were assumed to be based on a minimum 14-day running average to account for spring-neap tidal variations; since the net Delta outflow (NDO) estimates did not account for spring-neap variations (in a sense some degree of spring-neap averaging was already implied in NDO estimates), the salinity criterion and trigger were treated as daily standards.

7. Steady-state flows equivalent to X2 were determined using the X2 equation, as given in table 4.3. Since NDO estimates did not account for spring-neap tidal variations, the equivalent flow standards were treated as single-day average standards.

8. The Chipps Island standard was enforced for the first N_{CHP} days of the period, February 1 through June 30, where N_{CHP} is the Chipps Island day requirement given in table 1.1.

9. Once the Roe Island (Port Chicago) standard was triggered (salinity fell below the threshold level), the Roe Island standard was met for the next N_{PC} days, where N_{PC} is the day requirement for Port Chicago given in table 1.1, or until June 30, whichever came first.

10. No assumptions were made about water availability; estimates of additional outflow requirements were based solely on required increases in NDO.

11. No restrictions were placed on the maximum daily additional flow.

12. In analyses using the X2 equation the minimum flow was set to 316 ft^3/s; i.e., values of NDO less than 316 ft^3/s were set to 316 ft^3/s (as done in the development of the X2 equation).

13. In analyses using the X2 equation "ramping" was used where unrealistically large increases in outflow would be required to move X2 downstream (e.g., the X2 equation predicted that it would require in excess of 300 million ft^3/s outflow to move X2 from Collinsville to Chipps Island in one day). Ramping gradually increased the flows 20 days ahead of time to avoid unrealistically large flows.

5.2. Additional Flow Requirements

Chapters 5.2.1, 5.2.2, and 5.2.3 give estimates of additional flow requirements for surface EC standards of 2640 μS/cm, 3406 μS/cm, and for an equivalent flow standard for the periods, 1968-1991, 1951-1967, and 1930-1950, respectively. Analyses were performed using Denton's antecedent flow-salinity equations using historical estimates of net Delta outflow as the "base case." Section 5.2.4 gives estimates of additional flow requirements using a DWRSIM "simulated" base case. Section 5.2.5 gives estimates of additional outflow requirements using the X2 equation.

There are three primary reasons for the differences in additional outflow requirements between the X2 equivalent flow standard and the 2640 μS/cm surface EC standard: (1) the way in which the Roe Island standard is triggered; (2) differences in effective averaging periods; and (3) differences in conversion of EC=2640 μS/cm to equivalent flow using the X2 equation and using Denton's antecedent flow relations. The large differences in water years 1972, 1985, and 1987 are due to the triggering criterion at Roe Island: under the single-day NDO implementation scheme the Roe Island standard is triggered in 1972, 1985, and 1987, whereas under the surface salinity implementation scheme the 14-day average EC does not fall below the threshold value and the Roe Island standard is not triggered. In water years 1968, 1981, and 1988 there are two causes for the differences in additional flow requirements: (1) the effects of large prior flows (antecedent conditions) are taken into account in the surface salinity implementation, but not in the single-day NDO implementation; (2) approximately 1,000 cfs additional flow is required to meet the Chipps Island standard calculated from the X2 equation as compared with the (zero-biased) Denton antecedent flow relation.

Differences between the surface EC standard of 2640 and 3406 μS/cm are due to the reduction in flow required to meet 3406 μS/cm as compared to 2640 μS/cm. On average the 2640 μS/cm standard requires 150 TAF more outflow for all years and 350 TAF more outflow in critical years. There is the possibility, however, that the 3406 μS/cm standard could require increased outflow in a particular year. This in fact happens in 1972 when the Roe Island criterion is triggered under the 3406 μS/cm standard whereas it is not under the 2640 μS/cm standard.

The analysis of flow requirements using the DWRSIM "simulated" base case suggests that at a demand level of 6 MAF/year the calculated additional flow requirements are similar to those calculated using the historic NDO base case. Difficulty in assessing the DWRSIM "simulated" base case, however, arises because of the extra water released in the MDO "carriage water" model in DWRSIM to meet other Delta standards above that necessary in reality in some instances and in other instances inadequate releases. This can be seen in figure 3.1 which shows the large uncertainty (almost 400% on average) in MDO predictions of salinities at Rock Slough.

Estimates of additional flow requirements determined using Denton's antecedent flow-salinity relations and Kimmerer & Monismith's X2 equation are comparable on average. On a year-by-year basis, though, there can be significant differences due to the differing time-responses of the models. This is particularly important at the beginning of February when the preceding period is dry. For example, if X2 were at Collinsville on January 31 and had to be moved to Chipps Island in one day, Denton's relations predict that the required single-day flow is about 100,000 ft^3/s, whereas the X2 equation predicts that the required flow is 350,000,000 ft^3/s. Clearly the latter figure is physically unrealistic as this is over 1000 times greater than the typical tidal flow and saline water would be immediately flushed out to the sea. When considering time scales on the order of days and relatively large shifts in X2, results using the X2 equation must be viewed carefully. To avoid physically unrealistic predictions in the analyses, flows were increased gradually over 20 days using the X2 equation when relatively large shifts in X2 were required over a small span of time.

5.2.1. 1968-1991; NDO Base Case; Denton Antecedent Flow Methodology

Average Annual Additional Outflow

Year Type	Number of Years in Sample	Additional Flow (TAF) 2640 μS/cm Standard	Additional Flow (TAF) 3406 μS/cm Standard	Additional Flow (TAF) Flow Standard
All	24	1000	850	1300
Critical	5	1550	1200	1600
Dry	4	1000	900	1600
Below Normal	3	1000	1250	1900
Above Normal	3	550	350	650
Wet	9	900	700	1000

Year-by-Year Additional Outflow Summary

Year	Year Type	EC=2640 μS/cm Standard		EC=3406 μS/cm Standard		Flow Standard	
		Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)
1968	BN	ON	1060	ON	760	ON	1460
1969	W	ON	0	ON	0	ON	0
1970	W	ON	2880	ON	2370	ON	3090
1971	W	ON	790	ON	420	ON	860
1972	BN	OFF	810	ON	2130	ON	3020
1973	AN	ON	1220	ON	920	ON	1400
1974	W	ON	410	ON	200	ON	490
1975	W	ON	300	ON	20	ON	320
1976	C	OFF	1330	OFF	1010	OFF	1570
1977	C	OFF	2470	OFF	2090	OFF	2150
1978	AN	ON	90	ON	10	ON	230
1979	BN	ON	1130	ON	840	ON	1260
1980	AN	ON	370	ON	170	ON	380
1981	D	ON	1090	ON	750	ON	1450
1982	W	ON	0	ON	0	ON	10
1983	W	ON	0	ON	0	ON	0
1984	W	ON	2560	ON	2090	ON	2750
1985	D	OFF	650	OFF	420	ON	1940
1986	W	ON	1330	ON	1010	ON	1460
1987	D	OFF	920	ON	1420	ON	1910
1988	C	OFF	1190	OFF	910	OFF	1540
1989	D	ON	1290	ON	930	ON	1090
1990	C	OFF	1330	OFF	1020	OFF	1560
1991	C	OFF	1340	OFF	1040	OFF	1300

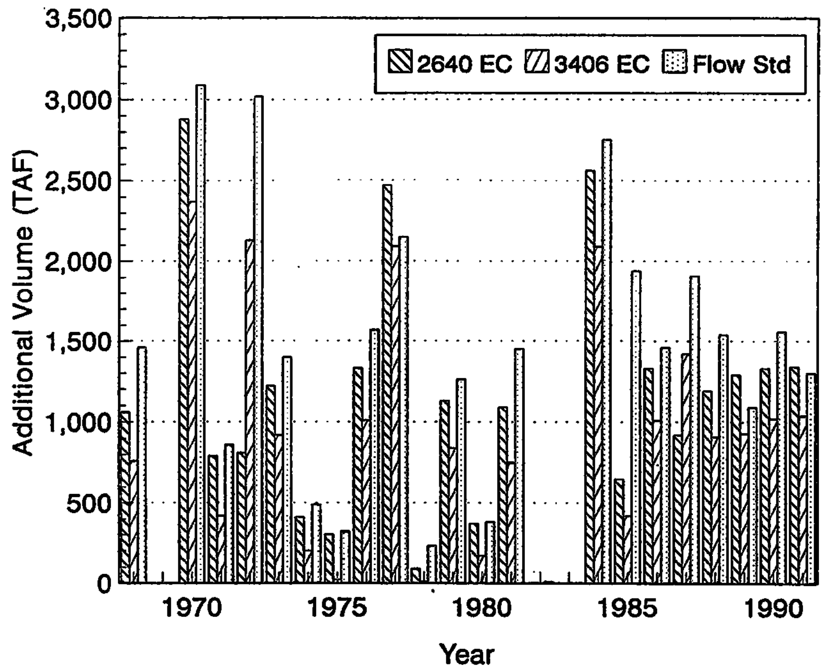

Figure 5.2.1.1. Additional outflow requirements of X2 standards for the period, 1968-1991, using Denton's antecedent flow-salinity relations based on: (i) EC=2640 μS/cm standard; (ii) EC=3406 μS/cm standard; (iii) equivalent flow standard.

5.2.2. 1951-1967; NDO Base Case; Denton's Antecedent Flow Salinity Methodology

<u>Average Annual Additional Outflow</u>

Year Type	Number of Years in Sample	Additional Flow (TAF) 2640 μS/cm Standard	Additional Flow (TAF) 3406 μS/cm Standard	Additional Flow (TAF) Flow Standard
All	24	450	250	600
Critical	5	0	0	0
Dry	4	500	300	900
Below Normal	3	800	500	1050
Above Normal	3	400	250	600
Wet	9	200	100	250

Year-by-Year Additional Outflow Summary

Year	Year Type	EC=2640 $\mu S/cm$ Standard		EC=3406 $\mu S/cm$ Standard		Flow Standard	
		Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)
1951	AN	ON	90	ON	20	ON	210
1952	W	ON	0	ON	0	ON	0
1953	W	ON	630	ON	340	ON	700
1954	AN	ON	80	ON	40	ON	280
1955	D	OFF	170	OFF	100	ON	940
1956	W	ON	0	ON	0	ON	0
1957	AN	ON	1060	ON	720	ON	1280
1958	W	ON	0	ON	0	ON	0
1959	BN	ON	1480	ON	1100	ON	1880
1960	D	ON	430	ON	280	ON	700
1961	D	ON	470	ON	240	ON	700
1962	BN	ON	150	ON	60	ON	160
1963	W	ON	460	ON	260	ON	570
1964	D	ON	920	ON	580	ON	1190
1965	W	ON	410	ON	190	ON	460
1966	BN	ON	860	ON	420	ON	1170
1967	W	ON	20	ON	0	ON	40

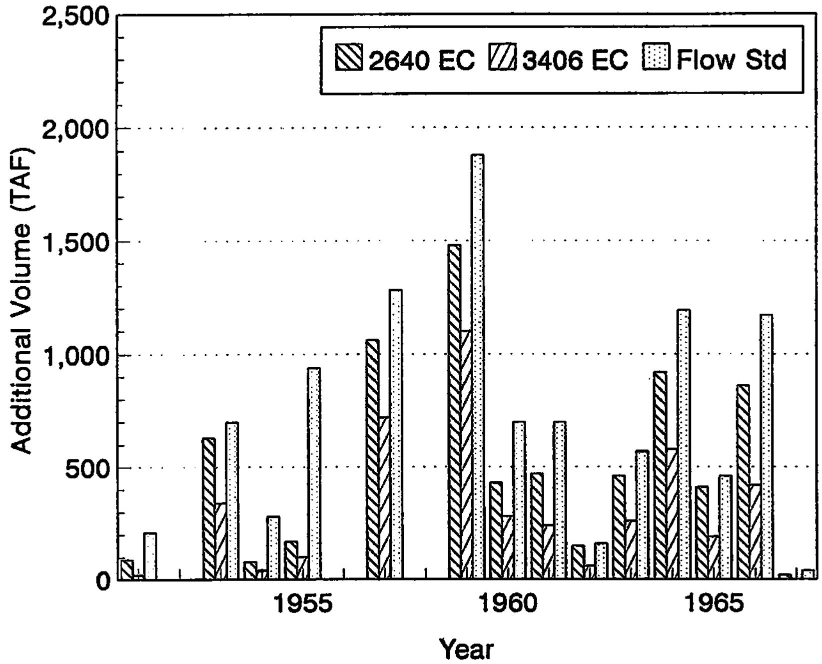

Figure 5.2.2.1. Additional outflow requirements of X2 standards for the period, 1951-1967, using Denton's antecedent flow-salinity relations based on: (i) EC=2640 μS/cm standard; (ii) EC=3406 μS/cm standard; (iii) equivalent flow standard.

5.2.3. 1930-1950; NDO Base Case; Denton's Antecedent Flow Salinity Methodology

Average Annual Additional Outflow

Year Type	Number of Years in Sample	Additional Flow (TAF) 2640 μS/cm Standard	Additional Flow (TAF) 3406 μS/cm Standard	Additional Flow (TAF) Flow Standard
All	24	100	50	200
Critical	5	350	250	450
Dry	4	150	100	350
Below Normal	3	50	0	100
Above Normal	3	0	0	0
Wet	9	0	0	0

Year-by-Year Additional Outflow Summary

Year	Year Type	EC=2640 μS/cm Standard		EC=3406 μS/cm Standard		Flow Standard	
		Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)
1930	D	ON	90	ON	0	ON	50
1931	C	OFF	680	OFF	530	OFF	920
1932	D	ON	50	ON	0	ON	70
1933	C	OFF	0	OFF	0	OFF	10
1934	C	OFF	340	OFF	260	OFF	440
1935	BN	ON	60	ON	0	ON	80
1936	BN	ON	40	ON	0	ON	70
1937	BN	ON	0	ON	0	ON	0
1938	W	ON	0	ON	0	ON	0
1939	D	ON	580	ON	330	ON	1190
1940	AN	ON	0	ON	0	ON	0
1941	W	ON	0	ON	0	ON	0
1942	W	ON	0	ON	0	ON	0
1943	W	ON	0	ON	0	ON	40
1944	D	ON	110	ON	50	ON	250
1945	BN	ON	20	ON	0	ON	60
1946	BN	ON	0	ON	0	ON	20
1947	D	ON	250	ON	100	ON	490
1948	BN	ON	0	ON	0	ON	90
1949	D	ON	0	ON	0	ON	70
1950	BN	ON	210	ON	110	ON	230

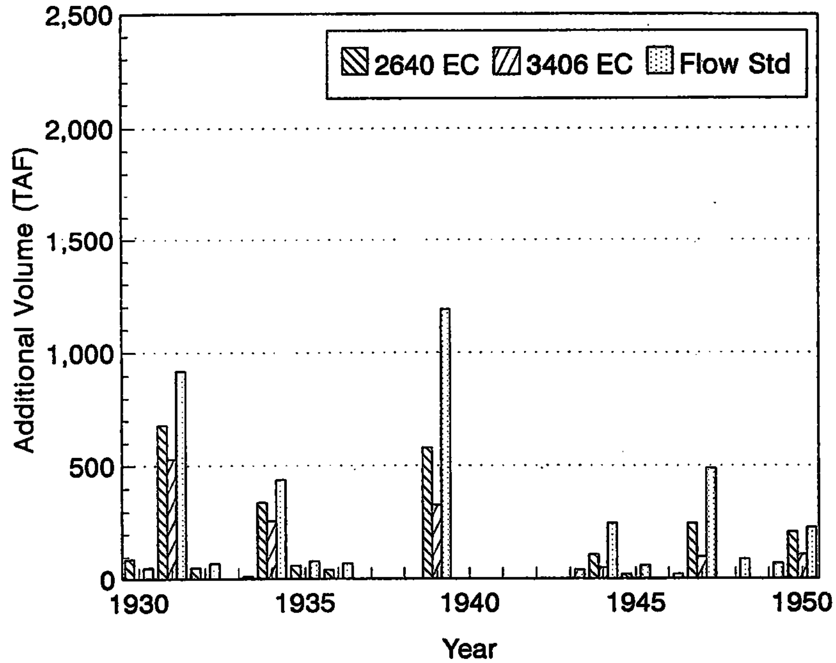

Figure 5.2.3.1. Additional outflow requirements of X2 standards for the period, 1930-1950, using Denton's antecedent flow-salinity relations based on: (i) EC=2640 μS/cm standard; (ii) EC=3406 μS/cm standard; (iii) equivalent flow standard.

5.2.4. Comparison of DWRSIM Base Case and NDO Base Case; 1968-1991; Denton Antecedent Flow Methodology

Average Annual Additional Outflow

Year Type	Number of Years in Sample	Additional Flow (TAF) NDO Historical Base Case	Additional Flow (TAF) DWRSIM Base Case 6 MAF Demand	Additional Flow (TAF) DWRSIM Base Case 7 MAF Demand
All	24	1000	1000	1100
Critical	5	1550	1350	1500
Dry	4	1000	800	800
Below Normal	3	1000	500	750
Above Normal	3	550	900	950
Wet	9	900	1050	1200

Year-by-Year Additional Outflow Summary

Year	Year Type	NDO Historical Base Case		DWRSIM Base Case (6 MAF Demand)		DWRSIM Base Case (7 MAF Demand)	
		Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)
1968	BN	ON	1060	ON	750	ON	960
1969	W	ON	0	ON	0	ON	0
1970	W	ON	2880	ON	2480	ON	2980
1971	W	ON	790	ON	1720	ON	1900
1972	BN	OFF	810	OFF	130	OFF	370
1973	AN	ON	1220	ON	1480	ON	1540
1974	W	ON	410	ON	770	ON	780
1975	W	ON	300	ON	880	ON	1000
1976	C	OFF	1330	OFF	960	OFF	1380
1977	C	OFF	2470	OFF	1930	OFF	1970
1978	AN	ON	90	ON	220	ON	230
1979	BN	ON	1130	ON	680	ON	980
1980	AN	ON	370	ON	1010	ON	1090
1981	D	ON	1090	ON	600	OFF	300
1982	W	ON	0	ON	90	ON	90
1983	W	ON	0	ON	0	ON	0
1984	W	ON	2560	ON	2330	ON	2690
1985	D	OFF	650	OFF	370	OFF	510
1986	W	ON	1330	ON	1350	ON	1580
1987	D	OFF	920	OFF	780	OFF	1050
1988	C	OFF	1190	OFF	1040	OFF	1270
1989	D	ON	1290	ON	1350	ON	1440
1990	C	OFF	1330	OFF	1440	OFF	1480
1991	C	OFF	1340	OFF	1440	OFF	1480

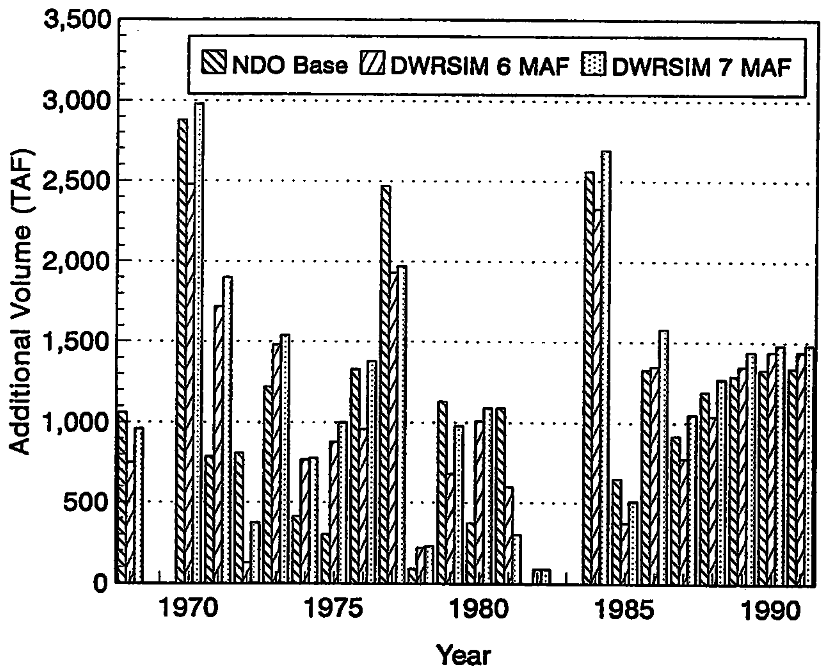

Figure 5.2.4.1. Additional outflow requirements of X2 standards for the period, 1968-1991, using Denton's antecedent flow-salinity relations based on: (i) NDO historical base case; (ii) DWRSIM base case. X2 standard is implemented as EC=2640 μS/cm standard in both cases.

5.2.5. Comparison of Denton's Antecedent Flow Salinity Analysis and X2 Equation Analysis

Average Annual Additional Outflow

Year Type	Number of Years in Sample	Antecedent Flow-salinity analysis	X2 Equation Analysis
All	24	1000	1100
Critical	5	1550	1850
Dry	4	1000	1200
Below Normal	3	1000	1200
Above Normal	3	550	400
Wet	9	900	850

Year-by-Year Additional Outflow Summary

Year	Year Type	Antecedent Flow-Salinity Analysis		X2 Equation Analysis	
		Roe Island Trigger	Increased Outflow (TAF)	Roe Island Trigger	Increased Outflow (TAF)
1968	BN	ON	1060	ON	1630
1969	W	ON	0	ON	0
1970	W	ON	2880	ON	2600
1971	W	ON	790	ON	450
1972	BN	OFF	810	OFF	820
1973	AN	ON	1220	ON	1010
1974	W	ON	410	ON	220
1975	W	ON	300	ON	320
1976	C	OFF	1330	OFF	1570
1977	C	OFF	2470	OFF	2720
1978	AN	ON	90	ON	20
1979	BN	ON	1130	ON	1210
1980	AN	ON	370	ON	160
1981	D	ON	1090	OFF	510
1982	W	ON	0	ON	0
1983	W	ON	0	ON	0
1984	W	ON	2560	ON	2430
1985	D	OFF	650	OFF	860
1986	W	ON	1330	ON	1600
1987	D	OFF	920	OFF	1250
1988	C	OFF	1190	OFF	1460
1989	D	ON	1290	ON	2190
1990	C	OFF	1330	OFF	1740
1991	C	OFF	1340	OFF	1640

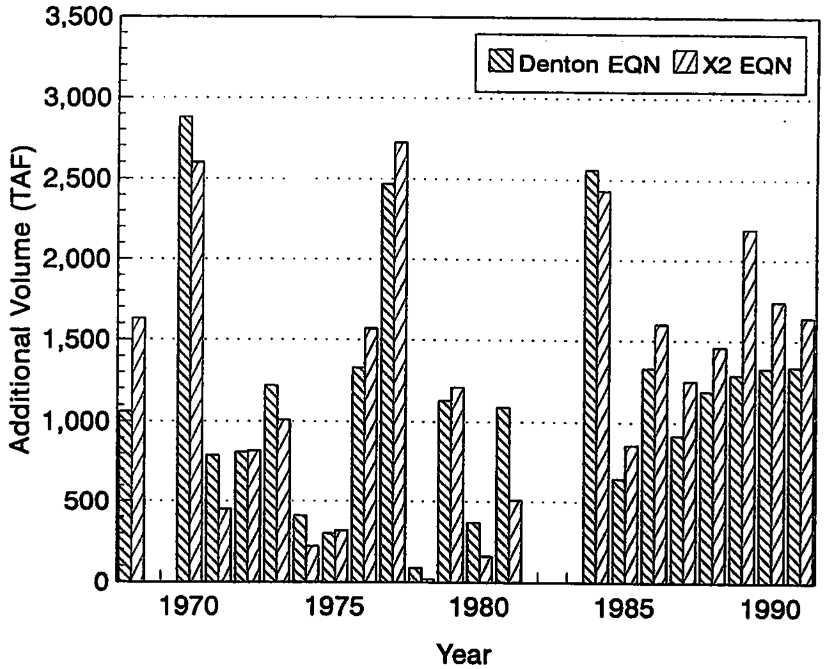

Figure 5.2.5.1. Additional outflow requirements of X2 standards for the period, 1968-1991, using: (i) Denton's antecedent flow-salinity relations; (ii) X2 equation. The X2 standard is implemented as an EC=2640 μS/cm standard in both cases.

5.3. Uncertainty in Estimates of Required Additional Outflow

An error analysis was conducted to determine the level of uncertainty associated with estimates of additional outflow using Denton's antecedent flow model for the period, 1968 to 1990. Field measurements of salinity were used to determine errors in the flow-salinity model predictions. The error analysis was restricted to the flow range and season range relevant to the proposed X2 water quality standards.

The error in a salinity prediction was defined as the difference between the value predicted using equation (3) in chapter 4.1 and the field-measured value. The error in S could also be converted to an equivalent error in G, the G error providing an estimate of the error in the prediction of additional flow required to meet X2 salinity requirements. The error in G was defined as the difference between the value predicted from equation (4) in chapter 4.2 and the value which would yield the measured salinity based on equation (3) in chapter 4.1. Time-averaging over 14-day intervals was employed since measured salinities were influenced by spring-neap tides not accounted for in estimates of NDO. The difference between the 14-day average predicted G and the 14-day average "measured" G gave the average error over a 14-day interval. This difference represented the overprediction or underprediction of flow required to meet X2 standards.

The error analysis was performed for the period, February 1 to June 30, from 1968 to 1990. The error in the additional outflow for a particular year was defined as the sum of the error in G from February 1 to June 30 multiplied by the time interval. Since the error in G was only defined where (i) salinity data existed, and (ii) G was in the range relevant to the proposed X2 standards, the summation in some years was only over a sub-interval of the February 1 to June 30 time period. In cases where estimates were not defined over the full period, the error over the sub-interval was multiplied by the ratio of the total time period to the sub-period (giving a somewhat conservative estimate of error since the sub-period error would not, in general, be perfectly correlated with the full period error). Where the error was undefined for greater than half the full period, the additional outflow error for that year was undefined. Additional outflow error estimates for the period, 1968 to 1990, are shown in figure 5.3.1.

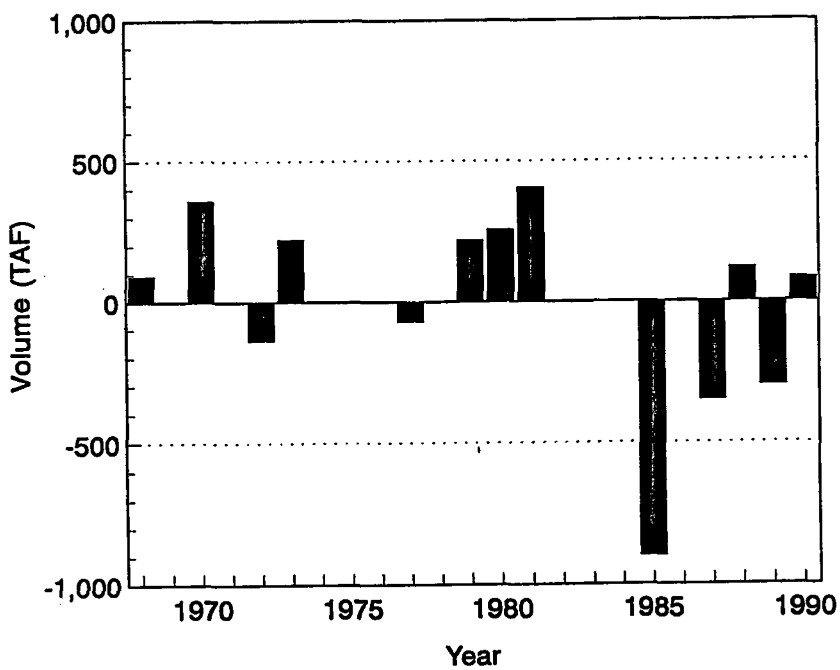

Figure 5.3.1. Error in annual additional outflow estimates, 1968-1990 (defined only for years with sufficient data). Positive error indicates an overprediction of additional outflow; negative error indicates an underprediction of additional outflow.

The standard deviation of the yearly additional outflow errors gave an estimate of the uncertainty in annual additional outflow for any particular year. For the 1968 to 1990 period, the standard deviation of the annual additional outflow error was approximately 330 TAF. The uncertainty in the average additional outflow over a period of N years was then $330/\sqrt{N}$ (assuming the annual errors were uncorrelated); for the period, 1968-1990, the uncertainty in average additional outflow was 70 TAF for all years, 150 TAF for critical years, 150 TAF for dry years, 200 TAF for below normal years, 200 TAF for above normal years, and 100 TAF for wet years (uncertainty in the latter 5 averaging periods rounded to the nearest 50 TAF). As discussed earlier, a portion of these errors can be directly attributed to errors in estimates of net Delta outflow and additionally to inaccuracies in measurements of EC.

6. PROPOSED MODIFICATIONS TO X2 STANDARDS

The following three modifications are suggested for the X2 standards:

1. Allow for greater flexibility in the way in which days can be counted for credit under the X2 standards. The day should count for credit if either: (i) the daily average surface EC is less than the 2 ppt bottom salinity equivalent; (ii) the 14-day average surface EC is less than the 2ppt bottom salinity equivalent; or (iii) the net Delta outflow index is greater than the 2ppt equivalent. This provision would enhance operational flexibility while providing the desired salinity control.

2. Modify the number of required X2 days to reflect conditions during a specified target period using a continuous index such as the February-June Sacramento Four River Index. January may also be included in this index to account for antecedent effects of outflow on salinity and an additional factor may be incorporated to account for carryover storage in upstream reservoirs at the end of January. Modifications should be done using the methodology discussed in chapter 2. This would result in greater flexibility in water management, better reflect the hydrological condition of the estuary, and better represent conditions that existed in the targeted period.

3. As discussed in chapter 2 inappropriate conversions between practical salinity units and EC were used in the development of the X2 standard. It is suggested that either the 2ppt bottom salinity standard be referred to as X1.5 or the surface EC equivalent be set to 3406 μS/cm (rather than 2640 μS/cm) which is the appropriate 2ppt equivalent.

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