DELTA OUTFLOW
AND
SAN FRANCISCO BAY

A Report Prepared for the

Delta Environmental Advisory Committee

of the

California Department of Water Resources

by

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April 1977

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April 28, 1977

TO: ALL DEAC MEMBERS

About six months ago, DEAC asked us to describe the importance of high, unregulated Delta outflows to San Francisco Bay. Bill and I have gathered all of the information we could find and put it together into this report. It is not the last word on this complicated question, but we hope it will serve to stimulate thought and move everyone toward an objective decision.

Unregulated outflow does affect the Bay. We have described some of the ways, but clearly we need to learn more. Our review has led us to conclude that the prudent course is to reserve some portion of the unregulated outflow for the future, and to begin sound research that will determine how much of that reservation is truly needed. Our suggestion for a minimum reservation is one million acre-feet per month for two consecutive winter months. Critical year exceptions would make it more acceptable to the water users.

Our analysis does not include any data gathered during the last two very dry years - in terms of winter outflow, the driest the Bay has ever experienced. The next step should be to tabulate and analyze that important data. The agencies who collected it should be encouraged to do so as soon as possible.

Sincerely,

DW Kelley

Don W. Kelley

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Many scientists and engineers working on this estuary have asked how the future reductions in Delta fresh water outflow, required as California water demands grow, will affect San Francisco Bay (Figure 1). Even the more logical speculations range from descriptions of little significant impact to those of major environmental catastrophy. In the last decade a few engineers and scientists have investigated various aspects of the problem, but no comprehensive study has been done.

This analysis of that question and of what might be done to protect the Bay from damage by Delta outflow reduction has been prepared at the request of the California Department of Water Resources Delta Environmental Advisory Committee (DEAC). It is one of several reports aimed at making California's water development program more environmentally sound.

HOW WILL FRESHWATER OUTFLOWS CHANGE?

Meeting future demands of California agriculture, industry, and municipalities is believed to require both the construction of more reservoirs for the capture and storage of winter runoff, and increased export of water from the Delta. Both will reduce Delta fresh water outflow to the Bay. The California Department of Water Resources (DWR) most recent estimate is that annual Delta outflows in all but above normal and wet years will be less than 5.5 million acre-feet (maf) by 1990 (DWR 1977). In the entire 55 year period for which records are adequate to make such estimates, levels that low are believed to have occurred only twice; in water years 1923-24, and 1930-31 (Table 1). In ordinary dry years, DWR predicts that Delta outflows will by 1990, be reduced to 3.3 maf, and in critical years, to 2.7 maf. Levels this low have never been experienced, but we may approach them in 1976-77.

Figure 2 is DWR's best present estimate of seasonal variations in Delta outflows as they actually occurred in a typical wet, normal, dry, and critical year before major water development projects were built on

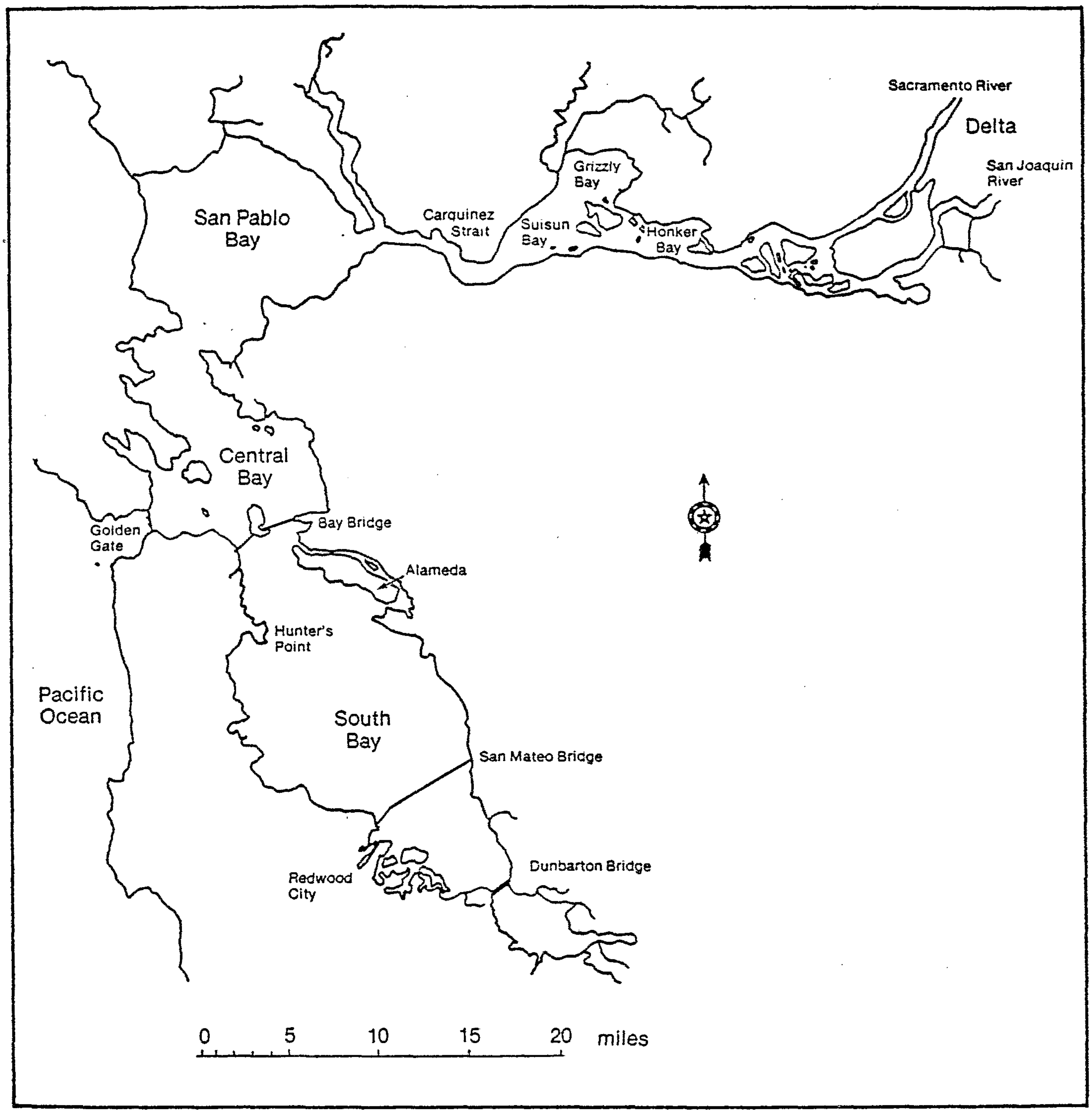

Figure 1 Map of the San Francisco Bay

Table 1. California Department of Water Resources Estimated Historic Delta Outflow
(1000 Acrefeet)

Water Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Total
2122	384	512	1566	1649	4334	3386	3909	5242	3761	791	110	240	25884
2223	468	897	3358	2646	1660	1501	3576	2562	1332	413	70	290	18773
2324	500	439	538	715	1431	581	584	247	-59	-163	-115	29	4727
2425	301	769	1167	1115	6872	2350	4246	3331	1353	213	11	185	21913
2526	388	570	836	1083	4555	1665	3795	1289	210	-82	-67	166	14408
2627	371	2236	2272	2801	8911	4537	5468	3311	2082	359	85	238	32671
2728	508	1452	1359	1716	2539	7252	3989	1955	444	60	8	210	21492
2829	349	711	856	873	1482	1297	1153	1154	565	-17	-18	174	8579
2930	289	322	2297	2151	1931	3570	2088	1394	583	22	7	260	14914
3031	438	535	533	1055	918	1058	424	231	-13	-220	-165	40	4834
3132	170	386	1744	2158	2548	2183	1982	2893	1992	399	-9	110	16556
3233	217	309	577	1007	927	1647	1387	1259	1118	8	-79	112	8489
3334	290	411	1100	2014	1769	1683	1005	391	92	-136	-117	78	8580
3435	207	850	808	2897	1699	3106	7015	4052	2110	234	35	197	23210
3536	459	489	709	3971	7388	3992	3687	2909	1730	256	31	230	25851
3637	356	383	666	900	3710	5211	4163	3708	1805	220	-31	163	21254
3738	469	2041	5508	2635	9296	11918	7328	6918	4800	1360	322	375	52970
3839	629	804	1076	1070	1134	1687	1151	518	54	-131	-105	171	8058
3940	326	326	663	4317	6068	8685	7357	2859	1248	107	18	280	32254
4041	416	685	4014	7412	7832	7901	6830	5011	2762	882	189	263	44197
4142	488	688	3854	5754	8823	3086	5247	4398	3329	833	130	314	36944
4243	539	1010	1950	5692	4486	7194	4405	2831	1568	199	49	235	30158
4344	490	595	747	979	1972	2229	1256	1635	603	11	15	231	10763
4445	341	1072	1474	1268	4629	2584	2197	2535	1479	404	279	438	18700
4546	713	1176	4753	4948	1783	2072	2353	2494	920	253	250	430	22145
4647	526	942	1318	970	1588	2182	1499	669	384	75	131	315	10599
4748	604	736	607	1547	820	1387	3591	3752	2545	427	319	518	16853
4849	608	674	956	911	959	3256	2038	1700	582	158	223	383	13048
4950	379	561	591	1945	3102	2219	2742	2206	1278	265	230	435	15953
5051	635	4324	8293	4973	5112	3367	1817	2166	670	274	316	442	32389
5152	591	953	3101	6862	6048	5529	6186	6520	3941	1080	423	587	41821
5253	575	759	2571	7184	2158	1701	1853	2280	1980	344	188	576	22169
5354	610	880	966	1986	4014	3672	3459	1820	376	59	179	437	18458
5455	531	953	1773	1925	1053	860	780	1191	437	109	139	351	10102
5556	334	601	8449	11896	5540	3987	2407	3674	2139	533	410	703	40673
5657	763	931	880	913	1383	3890	1157	2049	944	141	205	527	13783
5758	1127	1155	1628	2766	10301	6894	9231	4864	3033	732	547	832	43110
5859	769	874	907	1967	3230	1729	645	454	102	149	297	525	11648
5960	318	355	451	826	2824	2087	988	758	252	132	143	305	9439
6061	279	768	1172	944	2284	1715	785	536	231	96	221	305	9336
6162	230	488	966	658	4152	2956	1627	1105	639	166	284	486	13757
6263	2697	971	2135	1442	5448	1820	6110	3262	1159	343	288	772	26447
6364	829	1572	1437	1857	1212	610	531	589	328	186	271	526	10148
6465	475	934	6707	8370	3147	1699	3415	2009	990	352	492	746	29336
6566	898	1543	1893	2714	1948	1509	1127	604	170	195	273	390	13264
6667	396	1308	3636	3750	4366	3342	4512	4434	3672	1440	582	990	32928
6768	1002	990	1212	1548	3018	2392	582	402	216	222	312	360	12646
6869	330	630	1542	7620	9340	5520	4150	3860	2780	786	744	1308	38610
6970	1170	1200	2740	11280	6534	3300	660	648	372	318	474	876	29572
7071	810	1662	5022	3828	2046	1890	2208	1596	1272	708	786	1188	23016
7172	840	834	1440	1273	1314	1092	456	324	186	384	396	648	9192
7273	708	1554	1626	6108	6126	4520	1302	714	438	288	366	678	24438
7374	846	3600	4590	8244	3510	4512	6450	1536	1026	570	774	1266	36924
7475	1146	1404	1686	1105	2545	3056	1760	1611	1298	616	478	737	17442
7576	816	972	1206	600	414	438	456	252	252	264	234	174	6076
55 year Total	31946	54796	115526	170843	205133	176306	161119	122712	69560	17687	11628	23845	1161099
55 year Means	581	978	2078	3106	3693	3206	2929	2231	1265	322	211	434	21111

Monthly outflows of 1 to 4 MAF. Monthly outflows of more than 4 MAF.

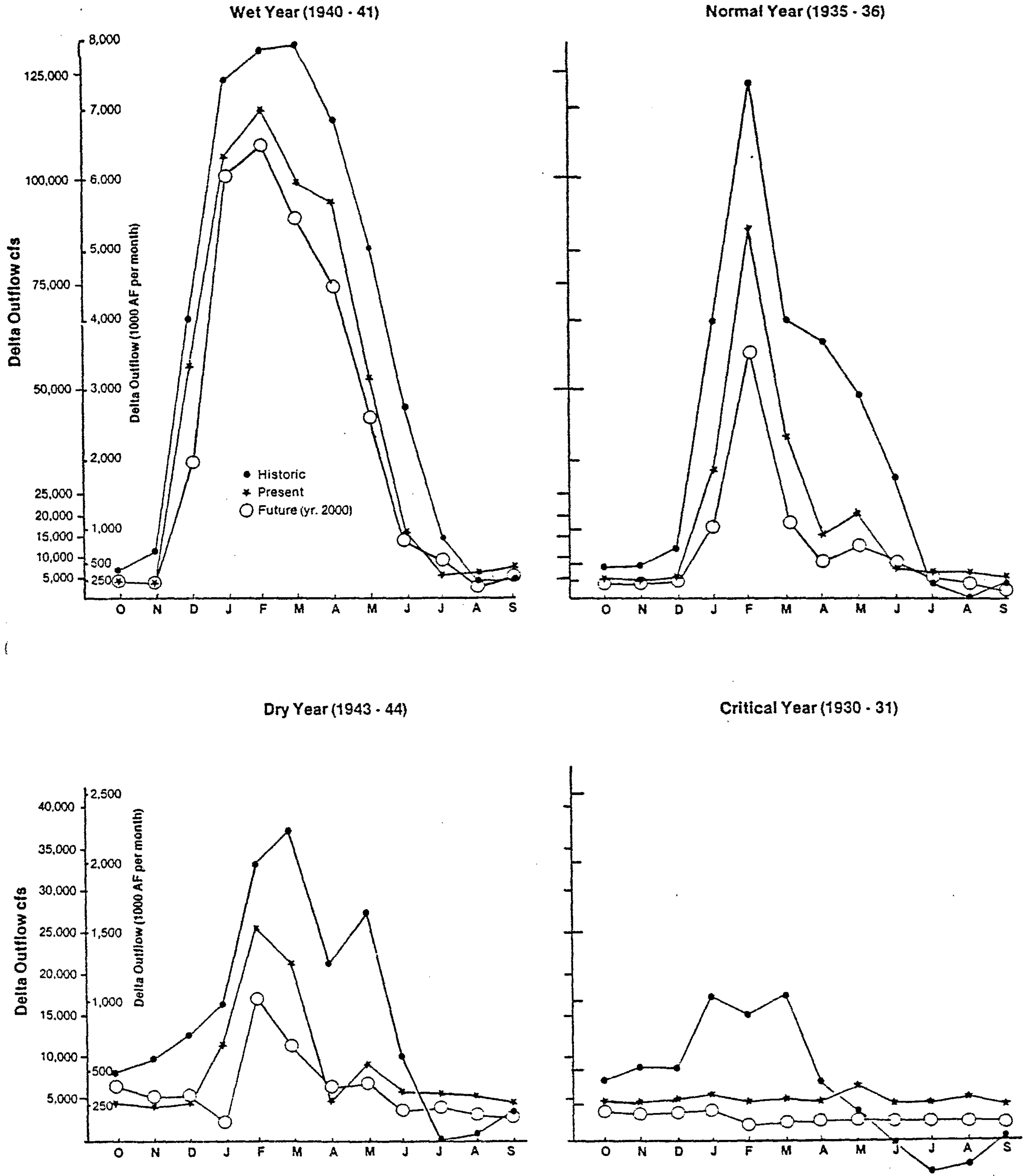

Figure 2 Delta outflow to the San Francisco Bay as it actually was during four recent years, how it would have been if present levels of Delta input and export had occurred in those years, and how it is expected to change under proposed water development plans. Note that the Delta outflow scales for "Dry" and "Critical" years is different from the "Wet" and "Normal" year scales. Delta outflow is given as cubic feet per second and, in parentheses, as thousands of acre feet per month. (Data from Roos 1976 and DWR 1977)

the system, what those outflows would have been with the present level of development, and what they would have been with the dams and Delta exports planned for the year 2000. Future wet years will retain their basic characteristics of large unregulated winter and spring outflows. Critical year outflows will change little. As we are seeing this year, enough reservoirs have already been built above the Delta and Delta exports are already high enough to capture most of the runoff in critical years. It is in future dry and normal years that we will see the greatest changes. The high Delta outflows that still occur in winter and spring of such years will be greatly reduced and shortened. Table 2 is DWR's most recent estimate of what Delta outflows would have been like from 1921-1971 under 1990 conditions of upstream storage and Delta export.

What will be the result? In this report we will discuss five important environmental factors that are greatly influenced by high Delta outflows into the Bay: salinity concentrations, salinity stratification, nutrient supplies, turbidity, and finally biological productivity.

SALINITY

During a mean tidal cycle 1.5 million acre-feet (maf) of seawater, 25 percent of the Bay's total volume flows in and back out through the Golden Gate. That immense amount of seawater mixes with freshwater that enters largely as Delta outflow to form a long salinity gradient. During each summer, as Delta outflows are reduced, that gradient moves upstream to the western edge of the Delta. It is kept out of the Delta by releases of water stored in the Central Valley Project (CVP) and State Water Project (SWP) reservoirs upstream. Fall or winter rains increase Delta outflows and push the salinity gradient downstream again - to a location depending on the magnitude and duration of unregulated Delta outflow. Seasonal changes during a normal and a dry year are shown and compared with Delta outflows in Figure 3.

Table 2. California Department of Water Resources estimated Delta outflows that would have occurred with 1990 levels of upstream storage and diversion.[1]

(1000 Acre-feet)

WATER YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
2122	387	329	566	323	2074	1429	512	1817	1159	400	202	195	9393
2223	254	262	2043	1715	727	250	683	635	565	400	202	196	7932
2324	250	195	203	154	280	169	184	191	183	191	191	184	2375
2425	191	184	232	154	2109	343	715	758	565	399	202	195	6047
2526	202	195	203	199	1794	169	930	369	231	240	202	195	4929
2627	203	594	267	709	5782	1739	2225	1308	833	614	202	326	15802
2728	407	349	356	363	953	5921	871	758	565	399	202	196	11240
2829	203	203	216	154	275	169	315	238	192	191	190	183	2529
2930	191	184	212	635	186	1250	399	416	231	240	202	196	4342
3031	202	196	203	221	139	169	183	191	183	191	191	184	2253
3132	190	183	426	577	517	169	232	440	232	239	202	196	3603
3233	202	196	203	266	139	169	183	277	184	190	191	183	2383
3334	191	183	213	305	264	169	184	191	184	190	190	184	2448
3435	190	183	191	1180	167	1251	2136	912	565	399	202	195	7571
3536	203	196	203	1051	3522	1066	584	758	565	399	202	196	8945
3637	246	195	220	209	1817	2535	652	635	565	399	202	196	7871
3738	238	463	2737	1222	7452	9642	3526	4015	2491	615	202	334	32937
3839	630	327	337	154	329	294	398	315	183	190	190	183	3530
3940	191	184	190	1032	2429	6131	3353	758	564	399	202	196	15629
4041	228	196	1995	6051	6534	5641	4611	2585	856	615	202	326	29840
4142	405	328	2839	4776	7859	1037	2796	2332	1555	615	202	334	25078
4243	406	426	688	4933	3055	5071	1317	942	833	614	202	326	18813
4344	400	327	339	161	1036	706	398	420	231	239	202	196	4655
4445	203	196	240	154	2468	1429	398	636	565	399	202	196	7086
4546	278	196	3266	2279	678	738	398	759	565	399	202	196	9954
4647	225	195	202	154	280	909	398	297	232	239	202	196	3529
4748	202	195	202	154	173	261	1206	1228	720	400	202	195	5138
4849	203	195	215	154	139	2381	398	415	232	240	202	196	4970
4950	203	195	202	401	1055	842	538	966	564	399	202	195	5762
5051	277	2523	5364	3893	3411	1330	398	894	833	614	202	327	20066
5152	449	330	1756	4856	4213	3791	3467	4229	2572	615	202	345	26825
5253	829	328	1744	5674	959	866	683	1376	1287	615	202	326	14889
5354	390	327	338	754	2570	2498	1907	758	565	399	202	196	10904
5455	203	195	633	676	366	188	398	424	232	239	202	196	3952
5556	203	196	5625	9300	4452	1572	758	2618	1424	615	202	326	27291
5657	640	327	337	154	1082	2415	398	1134	564	400	202	196	7849
5758	218	213	634	2186	10212	6502	6041	2704	2191	615	202	337	32055
5859	648	326	337	1020	2561	595	398	297	231	239	202	196	7050
5960	202	195	202	173	1007	946	398	401	320	239	202	195	4480
6061	203	205	203	218	1261	575	398	321	231	239	202	195	4251
6162	203	195	202	153	2905	897	398	635	565	399	202	195	6949
6263	1343	196	680	681	3629	1306	4897	1489	833	614	202	326	16196
6364	337	492	337	619	144	169	398	362	298	240	202	196	3794
6465	203	196	4509	6469	1093	524	2535	1180	833	614	202	350	18808
6566	407	563	404	1049	1040	1128	399	402	321	240	202	196	6351
6667	203	256	1612	3020	2680	3337	3147	3158	2662	721	203	339	21338
6768	560	327	339	940	3311	1892	398	402	321	240	202	196	9128
6869	202	196	675	7012	7078	2951	2827	4241	1866	615	202	352	28217
6970	658	328	2133	12781	4466	1844	398	402	321	245	202	327	24105
7071	395	494	3654	2309	862	2766	724	1572	1091	615	202	346	15030
50 YEAR TOTALS	16298	15658	51227	93777	114534	90041	62098	54561	36154	19816	10032	11926	576112
50 YEAR MEAN	326	313	1025	1876	2291	1801	1242	1091	723	396	201	239	11524

[1] Estimates assume Delta transfer facility, Four-Agency fish agreement, and mid-valley canal. They are preliminary data subject to revision.

Monthly outflows of 1 to 4 MAF.

Monthly outflows of more than 4 MAF.

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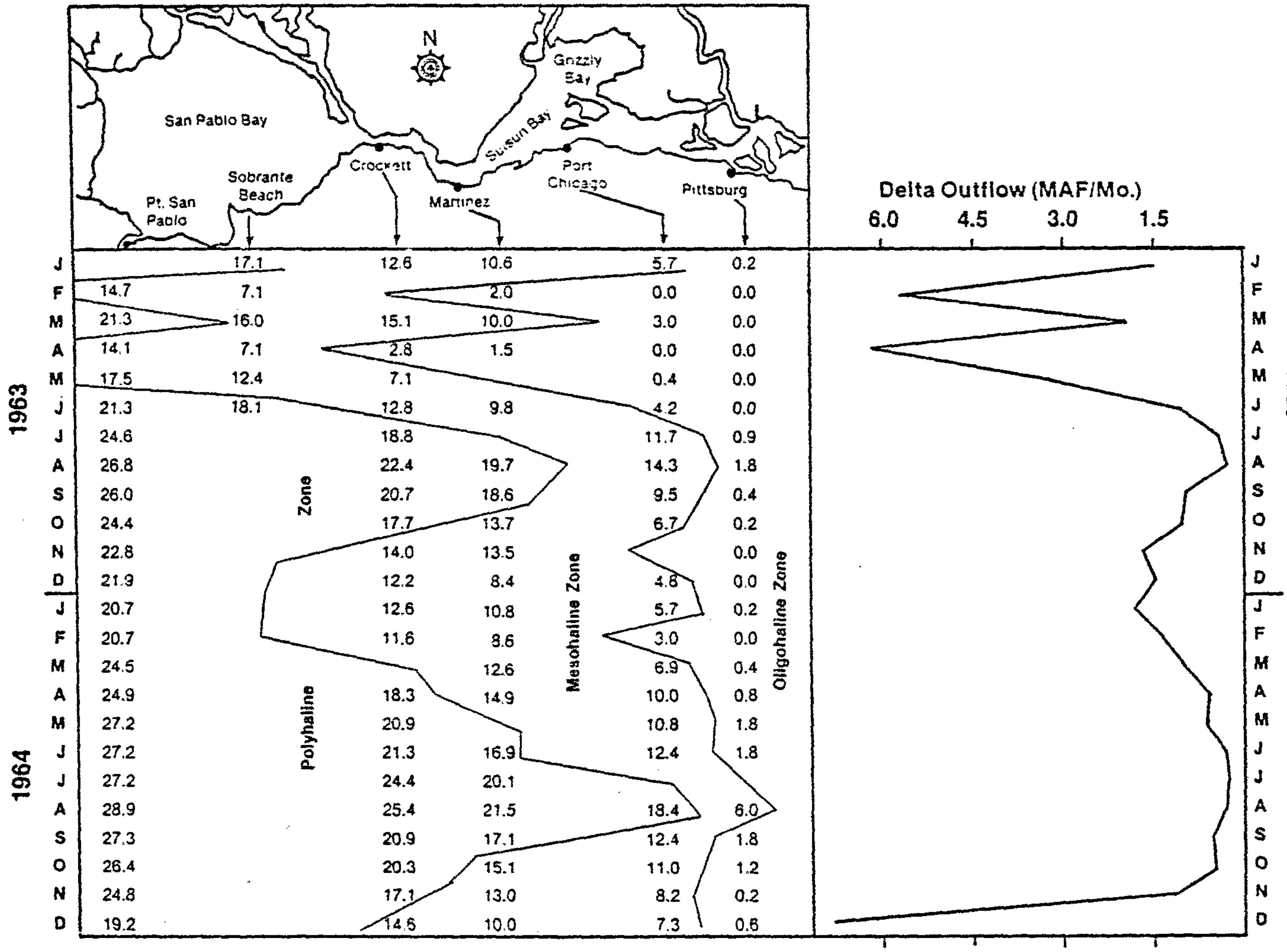

Figure 3 Changes in surface salinity (parts per thousand) and Delta outflow during a "normal" and a "dry" year. Salinity data is from Kelley (1966). Outflow data from Roos (1971).

The tongue of fresh and brackish water which has nearly always invaded San Pablo, often Central, and sometimes South San Francisco Bay in winter, will do so much less frequently under 1990 conditions of greater upstream storage and diversion. The salinity gradient will tend to be stabilized in Suisun Bay, remaining there year-round in about one-fifth of the years. In such years and in summer and early fall of all years, salinities will depend on the regulated outflows required by the State Water Resources Control Board.

SALINITY STRATIFICATION

The high winter outflows of freshwater from the Delta tend to flow on top of the heavier saltwater of San Francisco Bay. Tides and winds mix the two, but when outflows are large enough this mixing is incomplete and the Bay is said to be partly "stratified". Such salinity stratification has always occurred in Suisun, San Pablo, and Central San Francisco Bays for several months of nearly all winters, and has at times extended well into South San Francisco Bay during periods of very high runoff. how high?

This salinity stratification creates circulating currents through the estuary which transport suspended and dissolved materials downstream near the surface, and surprisingly enough, upstream near the bottom. Both surface and bottom currents move back and forth with the tides, of course, but on flood tides currents are stronger near the bottom and on ebb tides they are stronger near the surface. Current velocities are faster, and residence times of any transportable materials in any one location are much shorter, than if the fresh and saltwater were completely mixed and there was a simple back and forth but net seaward movement of the mix with changing tides. Such circulation has been named as important for flushing pollutants (McCulloch, et al., 1970), for controlling basic biological productivity (Arthur, 1975; Ball, 1975), and for transporting and distributing larval invertebrates, fish, and their food supplies (Pritchard, 1951; Cronin, 1967).

How much outflow is required to stratify the Bay? Obviously, different amounts are needed in the different reaches of the Bay. The information described below leads us to believe that reasonable estimates of the minimum monthly outflows needed for stratification are 4 maf in South Bay and 1 maf in Central and San Pablo Bays. Suisun Bay is stratified with much lower outflows, the sort provided by summer releases from upstream reservoirs to keep salinity out of the Delta.

South Bay

One of the first studies of San Francisco Bay stratification was done by scientists of the US Geological Survey in South Bay (McCulloch, et al.,1970). They found that extremely high Delta outflows (7.3 million acre-feet in January, 1969, and 9.3 million acre-feet in February) reduced surface salinities in South San Francisco Bay from a fall normal near 30 parts per thousand (ppt) to between 8 and 12 ppt (Figure 4). USGS scientists believe that these extremely large freshwater outflows created a net surface current flowing towards the Bay's southern or landward end and a net bottom current flowing seaward. They believe that these currents lasted until March, by which time Delta outflows had decreased to about 5.5 million acre-feet per month. The salinity of Central Bay was then higher than that of South Bay. The tides carried this water of higher salinity into South Bay and the current patterns reversed, i.e., bottom currents moved southward toward the landward end of the Bay and surface currents moved northward toward the Golden Gate. The USGS scientists believe this new circulation pattern lasted from March through May as monthly Delta outflows decreased from 5.5 to 3.9 maf.

The following winter the USGS measured the salinity of South Bay on December 19, following a month of Delta outflows that totaled 1.2 maf. They found no stratification. South Bay salinities top to bottom were

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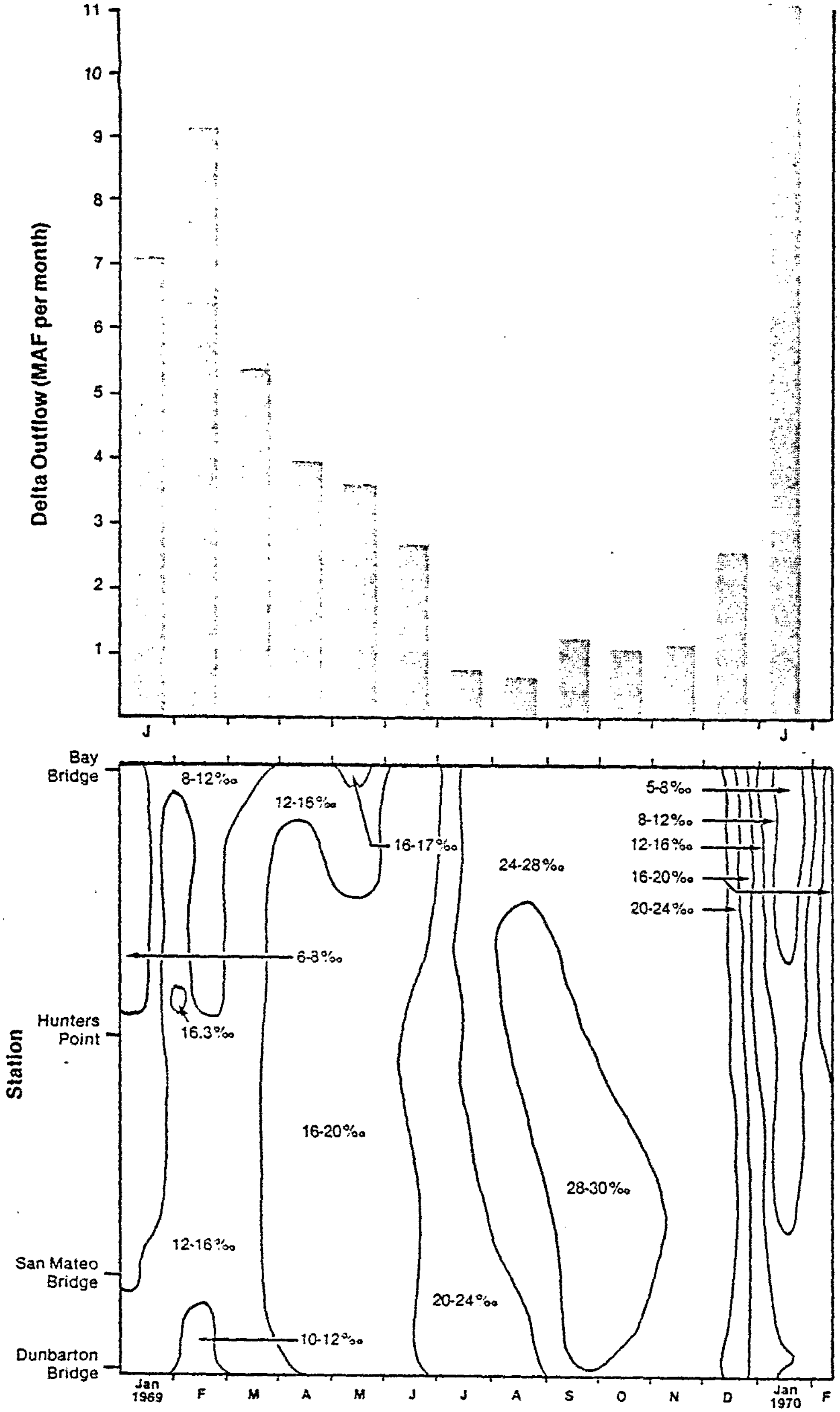

Figure 4 Total monthly Delta outflow (upper) and corresponding changes in surface salinity in the South Bay (lower) during the period from January 1969 to January 1970. Salinity figure redrawn from McCulloch, et al. 1970, Delta outflow data from Dept. of Water Resources (1976).

uniformly about 25 ppt (Figure 5). Following the December 19 measurements, Delta outflows increased and on January 27, 1970 the second set of measurements showed the northern half of South Bay to be stratified. The total Delta outflow for the previous thirty days had amounted to 11 maf.

The USGS data suggests that stratification of even the northern part of South Bay does not occur unless surface salinities there are reduced below about 20 ppt. Comparison of average surface salinity measurements collected at Alameda over a 5 year period with Delta outflows (Figure 6) is evidence that Delta outflows greater than 4 maf are required to accomplish that. Much higher flows, probably near 7 maf per month, are probably required to stratify the south half.

Outflows of 4 maf or more actually occurred during at least one month in 55 percent of the last 55 years (Table 1). The combination of upstream storage reservoirs and Delta diversions is now capable of reducing the occurence of such high outflows to only one-third of the years. DWR's operation studies predict that planned future construction of upstream reservoirs and increases in Delta exports would further reduce the frequency and duration of such very high flows only slightly (Table 3). It appears that the major reductions in frequency and duration of stratified circulation in South Bay were made possible by construction of the big reservoirs built for flood control and irrigation storage in the Sacramento-San Joaquin Valleys between 1940 and 1965. No one knows how these changes have affected South Bay's ecology. Because salinity stratification historically occurred there irregularly only in about half the years, it may never have played a significantly beneficial role in South Bay.

Central Bay

Central Bay salinities are just a few parts per thousand below seawater salinities during the summer when Delta outflows are usually controlled at about 4000 cfs.

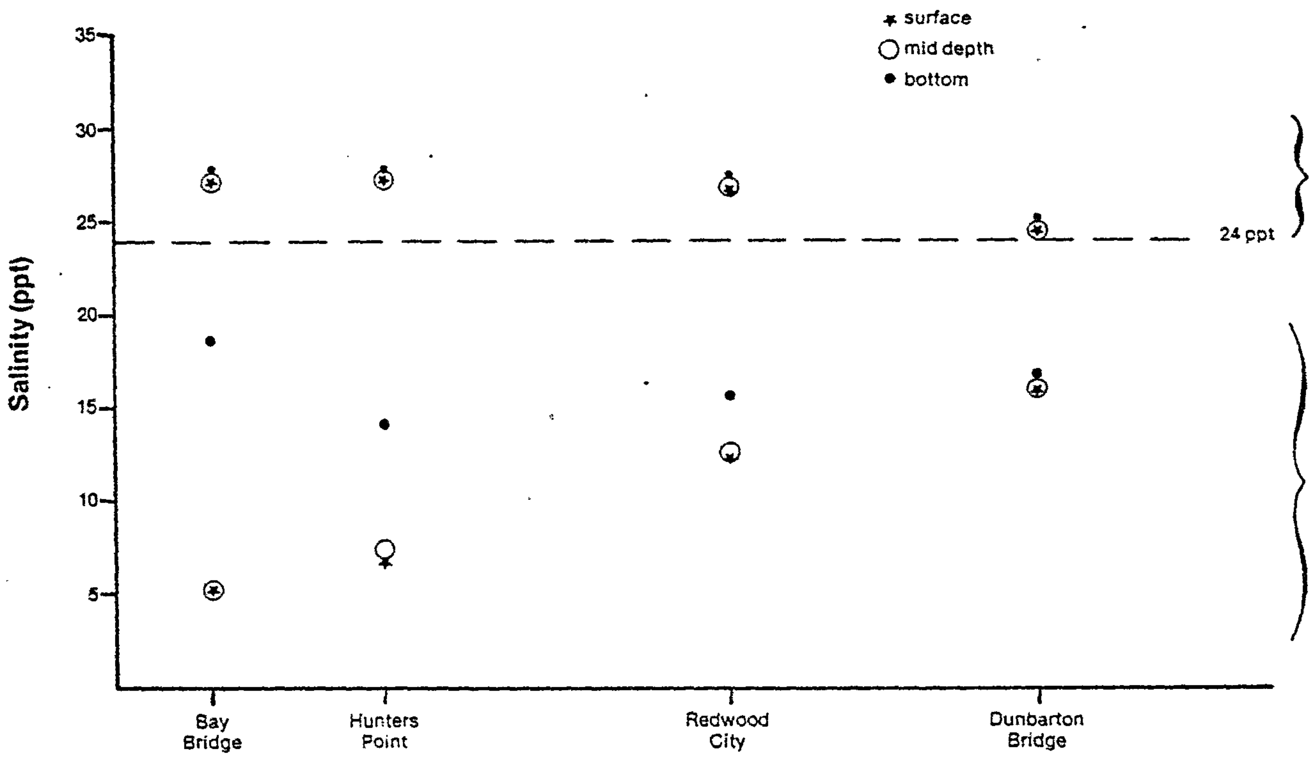

Figure 5 Salinities measured in South San Francisco Bay on December 19, 1969 and January 27, 1970. All the salinity values on Dec. 19 are above 24 ppt and there is no evidenced stratification. On January 27, when the previous 30 day outflow had been about 11 million acre-feet the northern half of South Bay was stratified. The salinity data is from McCulloch, et al. (1970) and outflow data from Roos (1971).

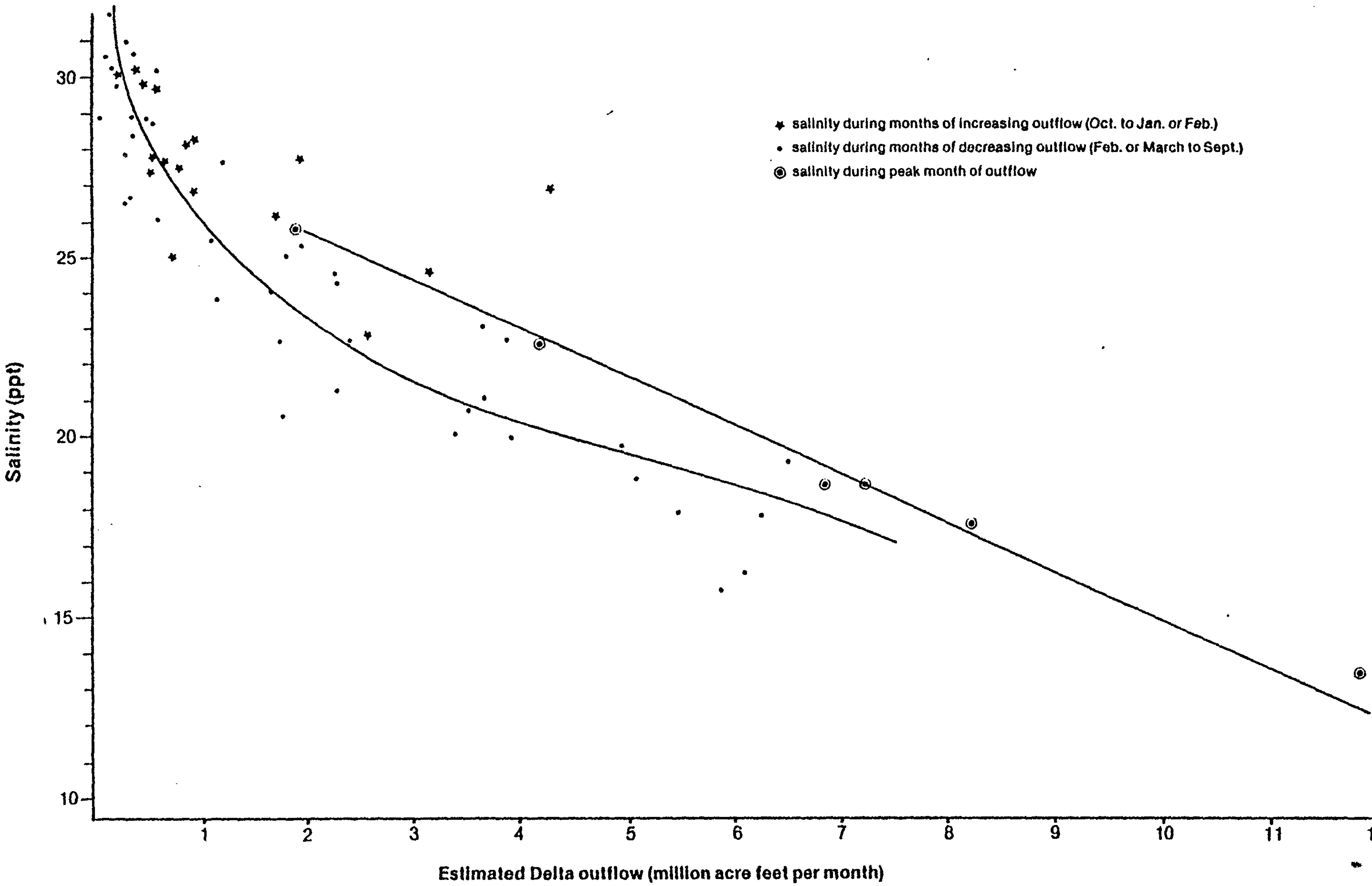

Figure 6. Average monthly surface salinity measured at Alameda compared with the estimated total Delta outflow for the same month (1951-56). The curves were fitted by eye, no curve for increasing outflow data (✱) was drawn. Salinity data was presented in McCulloch et al., 1970. Delta outflow data from Roos (1971).

Table 3. Percent of months during 33 year period (1921-54) in which monthly Delta outflows exceeded 7 and 4 maf or would have exceeded those levels under historic, present (1980), and future (1990) conditions of upstream storage and diversion.

Outflow (maf/month)	Historic <1 maf export	1980 6.0 maf export	1990 8.4 maf export
4 to 7	8.9	5.8	3.8
> 7	4.0	1.0	1.3

At such times, there is usually only a 1 ppt or so difference between surface and bottom. As Delta outflows increase in late fall or winter, surface salinities are reduced more than bottom salinities (Figure 7). Outflows of one million acre-feet per month established surface and bottom salinity differences of 2-4 ppt and outflows of 4 maf per month increased these differences only to 5-7 ppt. Clearly, Central Bay is not easy to stratify.

There is some evidence however, that even small surface/bottom salinity differences cause net upstream bottom and net downstream surface currents. In the fall of 1956 when Delta outflows were 10,800 cfs and surface/bottom salinity differences in Central Bay were only 1 ppt, the US Corps of Engineers measured a slight net upstream current near the bottom and a slight net downstream current near the surface (Peterson et al., 1975).

More evidence resulted from the US Geological Survey (Conomos, et al., 1971) release of seabed drifters into the ocean outside of Golden Gate bi-monthly from March 1970 thru March 1971. Most were subsequently recovered in Central and San Pablo Bay. Monthly Delta outflows during that year ranged from 3.3 to 0.3 maf, and during the entire period the seabed drifters moved upstream. The high spring and winter flows seemed to cause more persistent bottom drifting further upstream into Central Bay and San Pablo Bay, but some drifters moved up there at all flows.

The upstream movement of seabed drifters during low summer flows occurred during a period of active salinity intrusion, however, and is not evidence that such movements would occur during a winter of such low controlled flows.

San Pablo Bay

San Pablo Bay, with its high exchange of water with Central Bay and its shallowness and its high wind,

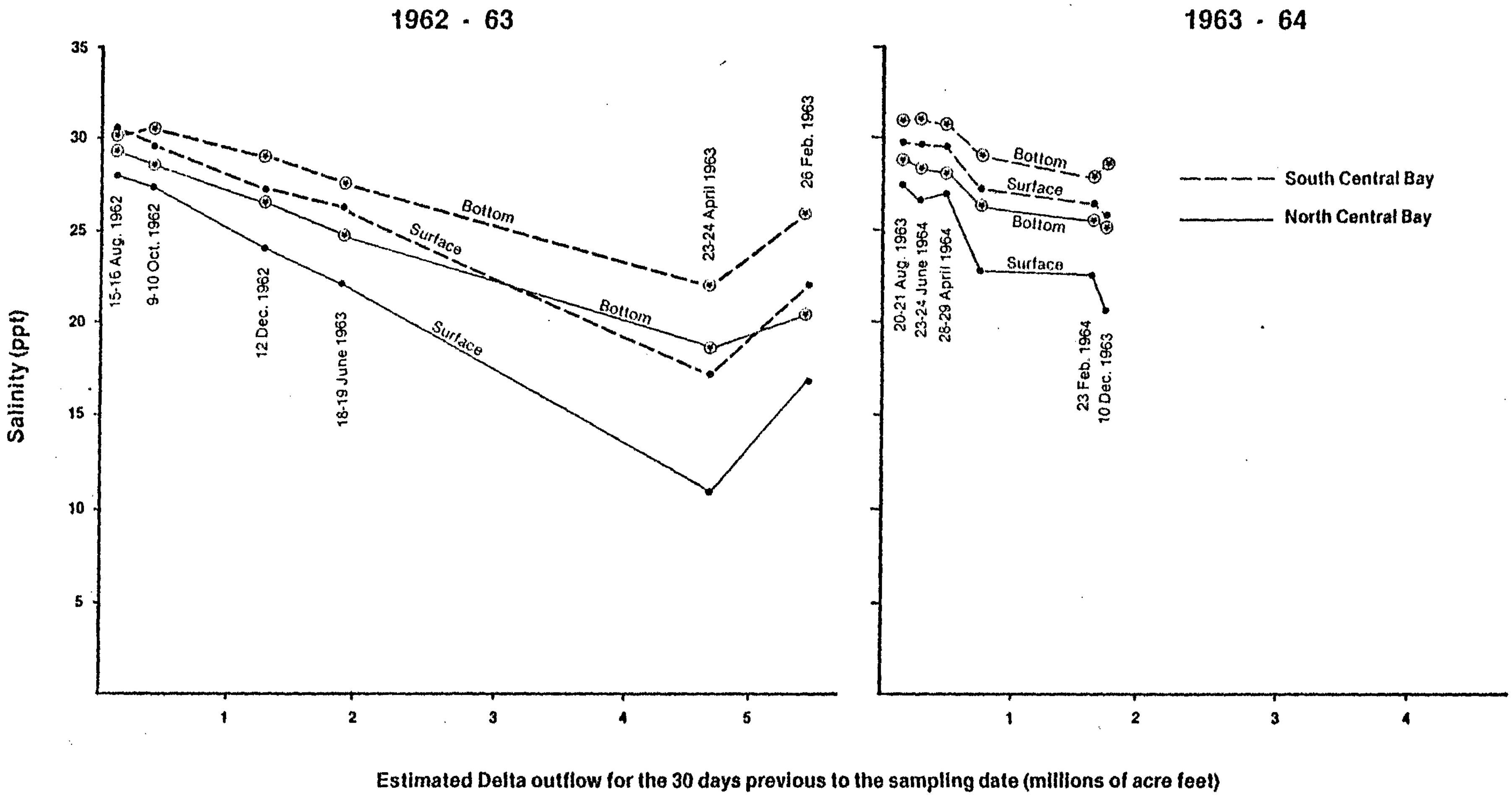

Figure 7. Mean of surface and bottom salinities measured at HH and LL tidal periods in northern and southern Central Bay graphed against Delta outflow. Salinity data is from Storrs, et al (1964, 1965) and outflow data was estimated from Dept. of Water Resources and US Bureau of Reclamation records (12 Dec 1962 is a mean of HL and HH tides).

is an area where the forces opposing stratification are truly great. The Sanitary Engineering Research Laboratory (SERL) studies in 1961-62 and 1962-63 showed the east-west salinity gradient in San Pablo Bay to be fairly steep until Delta outflows approached 1 maf per month, and the surface and bottom salinity differences to be usually no greater than in Central Bay (Figure 8). SERL measured bottom/surface salinity differences ranging from 3 to 10 ppt following outflows of about 1.5 maf for a month.

The US Corps of Engineers measured bottom/surface salinity differences of 3 or 4 ppt at an outflow of 10,600 cfs following a month of outflow totaling about 0.7 maf, but were unable to detect any net upstream movement in the lower depths (Peterson et al., 1975).

The USGS seabed drifters again provided the most useful evidence about currents. Many traveled upstream into San Pablo Bay throughout the year, but they stopped short of Carquinez Strait.

Carquinez Strait

In an early review of the effects of upland discharge on estuarine hydraulics, Simmons (1955) of the US Corps of Engineers described the vertical distribution of flow in Carquinez Strait during a Delta outflow of about 25,000 cfs. He concluded that the predominant flow in the east end of this narrow deep strait was downstream at all depths and that at the west end of the strait the predominant flow was downstream in the upper 35 percent of the water column and upstream in the lower 65 percent.

Scientists of the US Geological Survey analyzed US Corps of Engineers unpublished data to show that surface/bottom salinity differences in western Carquinez Strait were 4-5 ppt at Delta outflows ranging from 11000 to 35000 cfs (Peterson et al., 1975). Throughout that range, net currents above mid-depth flowed downstream while below mid-depth they flowed upstream. Flows of 81,000 cfs reduced all salinities to near zero and eliminated the upstream bottom flows.

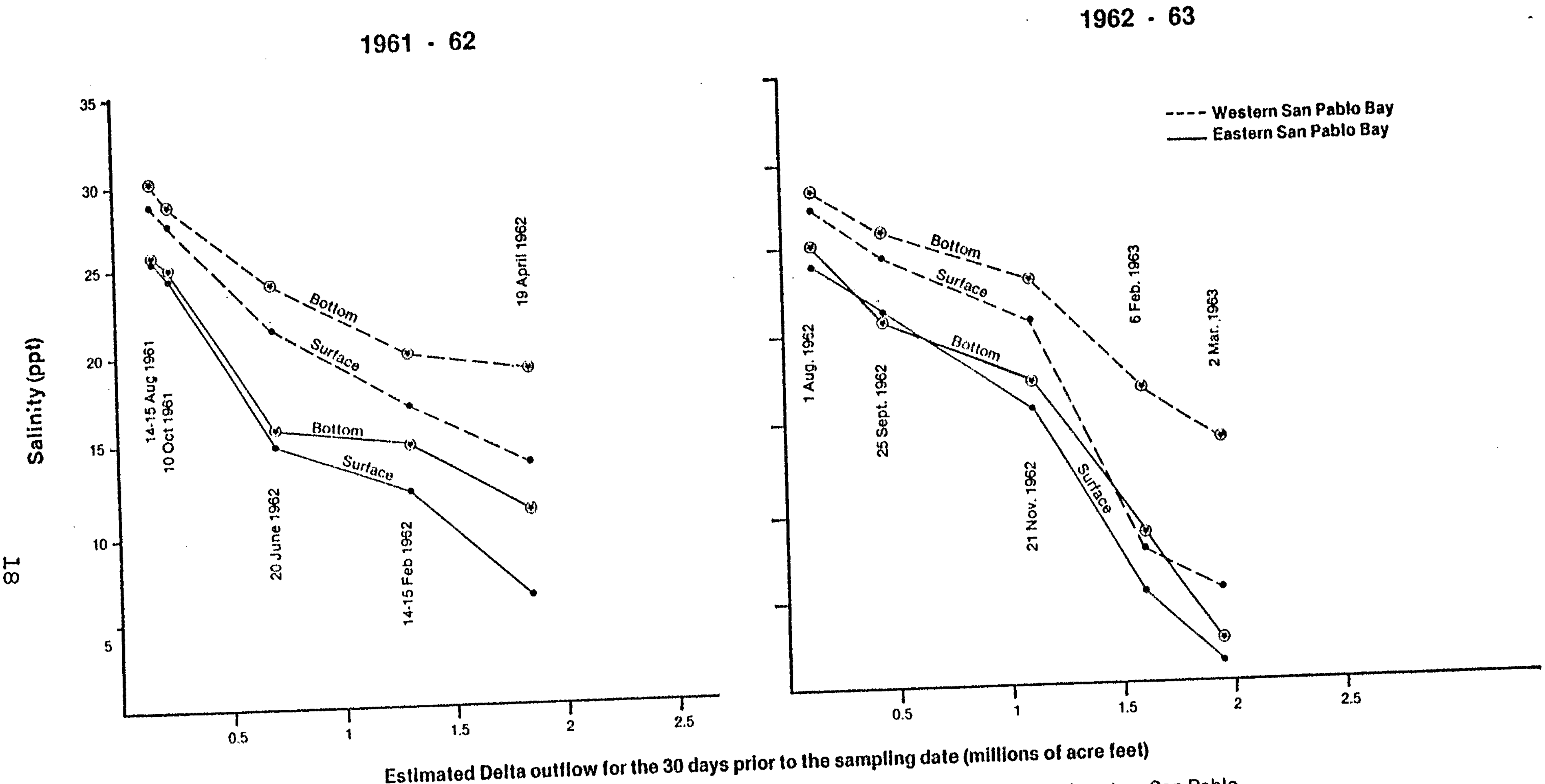

Figure 8 Mean of surface and bottom salinities measured at HH, HL and LL tidal periods in western and eastern San Pablo Bay graphed against Delta outflow. Salinity data is from Storrs, et al., (1963, 1964) and outflow data is from Dept. of Water Resources and U.S. Bureau of Reclamation records.

Suisun Bay

Suisun Bay is stratified even during low summer outflow, and the circulation patterns and resulting biological phenomena that result from such stratification have been well studied in recent years (Conomos and Peterson, 1975; Arthur, 1975; Ball, 1975; Peterson and Conomos, 1975; Rumboltz, Arthur, and Ball, 1976). Outflows much above 1 maf per month destratify upper or eastern Suisun Bay by converting it to essentially freshwater from top to bottom (Figure 9). The western end is well stratified at flows ranging from 4.5 maf to 0.6 maf per month and perhaps even less.

Effect of Outflow Reduction on Stratification

The information we have reviewed is evidence that South Bay is not stratified until Delta outflows approach at least 4 maf per month. We have already noted that flows that high never occurred regularly, that their frequency and duration have already been significantly reduced and that further major reduction is not planned. South Bay will continue to stratify only for short periods in very wet years.

Central, San Pablo, and Suisun Bays are another story. The information we have reviewed is evidence that in Central and San Pablo Bays even 2-4 ppt difference in salinity of bottom and surface water does cause a two layered net flow with bottom water moving upstream and surface water going down.

During periods of salinity intrusion differences of even less than 2 ppt may cause a two layered flow. Delta outflows of about 1 maf per month appear necessary to create the 2-4 ppt bottom/surface salinity differences. Until there is more evidence, we believe it unrealistic to believe that the two layered flow and circulation patterns associated with it occur in Central and San Pablo Bay when Delta outflows are less than 1 maf per month. The best evidence we have that such outflows are enough to do so is that during the fall of 1970 when Delta outflows were increasing from an August flow of 0.5 maf to a November flow of 1.6 maf, seabed drifters moved in through the Golden Gate and upstream through Central

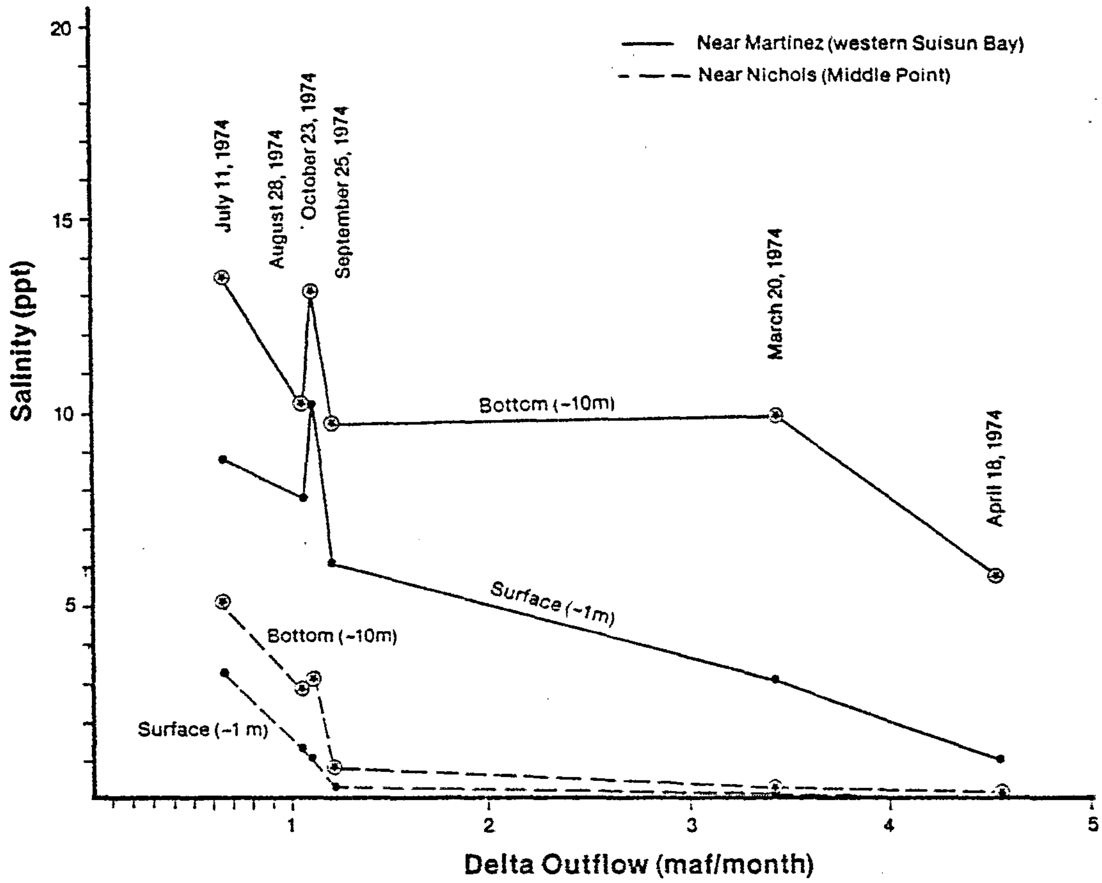

Figure 9 Surface and bottom salinity measurements taken in western Suisun Bay at Martinez and in upper Suisun Bay at Port Chicago during 1976 plotted against Delta outflow (Data are from DWR and USBR, 1976).

Bay. Because Delta outflows were increasing during this period the drifters could not have moved upstream with a general intrusion of seawater as they could have during the low flows of the previous summer. They had to move with bottom currents resulting from the sort of circulation patterns associated with stratification.

The DWR historical outflow estimates from 1921-22 through 1975-76 are that outflows greater than 1 maf per month usually occurred throughout the winter and spring until June (Table 1). Because of upstream reservoirs and Delta exports, they now occur much less frequently in April and May but still almost always occur from December through March. DWR's predictions are that by 1990 upstream storage and Delta exports will have increased so that winter outflows of 1 maf will not occur in any month in 20 percent of the years (Table 2). During a drought period like that which occurred from 1928-29 to 1934-35 they will not occur at all. During such years, Central and San Pablo Bays will not receive what we have defined as enough water for the winter stratification.

Suisun Bay, which usually destratifies as it freshens with high winter outflows, will in such years remain stratified all winter.

NUTRIENT SUPPLIES

Dissolved nitrogen, phosphorus, silica, and other nutrients necessary for phytoplankton production reach San Francisco Bay in sea water entering the Golden Gate, in local runoff, in the discharge of waste treatment plants, and in Delta outflow. Future reductions in Delta outflows will reduce nutrient contributions while future waste discharges and agricultural drainage will increase them. The San Francisco Bay Basin Plan estimates that increases in agricultural drainage and waste produced by a growing human population would more than offset losses of essential nutrient supplies that have historically entered the Bay as Delta outflow (State Water Resources Control Board 1975). It is beyond the scope of this study

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to analyze that conclusion, but we have examined two nutrient sources that might not be so easily replaced - silica and organic detritus.

Silica

Silica is of great importance because large quantities of it are used to produce the hard shells of diatoms, the free floating organisms that make up 90 percent or more of the Bay's phytoplankton (Storrs, et al., 1966; Scrivani, 1975), and because much of it is supplied by Delta outflow (Table 4).

90%?

In years of normal rainfall Delta outflow supplies between two and three times the amount of silicate contributed from both ocean currents and waste discharge. Ocean currents entering the Bay on flood tides, provide a relatively constant low concentration of silicate, whereas Delta contribution is greatest during winter high Delta outflow. During the winter and spring months, when outflow is high, Suisun and San Pablo Bay silicate levels are higher than those of Central and South Bay levels. Summer and fall silicate levels throughout the Bay are usually low: about equal to ocean concentrations.

Future reductions in Delta outflows are bound to reduce the winter and spring concentrations of silicate in Suisun and San Pablo Bays, especially in dry years, and will probably reduce the concentrations in Central Bay and the north end of South Bay during wet years.

Detritus

Leaf and plant fragments washed into streams provide a fertile substrate for microorganisms that eventually decompose them. Such "detritus" is the principal energy source driving the ecosystem of most running

Table 4. Monthly silicate contributions to San Francisco Bay. Numbers are estimated millions of pounds. /1

DELTA CONTRIBUTION

Outflow rate		Silicate
mean cfs per month	millions of acre-feet per month	
2000	0.12	4.7
5000	0.30	11.8
20000	1.20	47.1
50000	3.00	118.1
100000	6.00	236.2
150000	9.00	354.3

OCEAN CONTRIBUTION

26.4

WASTE DISCHARGE CONTRIBUTION

2.0

/1 Adapted from Conomos and Peterson (1975) who reported average freshwater silicate concentration as 300 µg atoms/l (about 18 mg/l) and ocean water silicate concentrations as 30 µg atoms/l (about 1.8 mg/l).

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streams and rivers where currents are too fast for phytoplankton growth.

J.H. Day's extensive studies of South African estuaries have led him to conclude that organic detritus is the main source of basic food in the Knysna Estuary (Day 1967), and Odom and de la Cruz (1967) showed it to be the chief link between primary and secondary production in small Georgia estuaries. In most large estuaries of this continent, phytoplankton is a major primary producer but detritus may also play an important role.

Large amounts of organic detritus are often observed by biologists making collections with fine mesh nets or water samplers near the bottom of the Delta and the Bay, but no direct measures of it have been made. It is reasonable to assume that large quantities of detritus of terrestrial origin are supplied to the Bay during high outflow periods and that major reductions in Delta outflow will reduce that supply.

SUSPENDED SEDIMENT AND TURBIDITY

Professor R.B. Krone (1966) has predicted that the future reductions in Delta outflow will reduce suspended sediment concentrations and Bay turbidity. His concern is that such reductions may reduce the ability of San Francisco Bay to assimilate pollutants and that increased transparency could permit undesirable growths of phytoplankton or other algae.

Delta outflow is the major source of suspended sediment in the Bay. More than three-quarters of it enters along with large winter and early spring flood flows and the highest suspended solid and turbidity levels occur during these periods. The large winter and spring flows carry some of the new sediment into Central and even South Bay or out to the ocean, but much of it begins to aggregate in the upper part of the salinity gradient and initially settles in shallows of Suisun and San Pablo

Bays. Wind and wave action resuspends such deposits from shallow areas while tidal currents, which are strong throughout the Bay, scour and resuspend it from deeper water. The finer resuspended sediments are transported to the ocean or deposited in areas where resuspension forces are low, leaving coarser compacted sediments on the bottom (Krone, 1976). Such deposits are less easily resuspended and Krone is concerned that reduced outflow will not only reduce suspended sediment contributions but also the amount of material resuspended from the bottom.

This resuspension of sediment is the most important process maintaining Bay turbidities in late spring through fall, and the US Corps of Engineers has estimated that about 15 times as much material is resuspended each year as actually enters the Bay with river inflow (US Corps of Engineers, 1975). Obviously any change influencing resuspension could have a great impact on Bay suspended sediment concentrations and turbidity.

Using USBR predicted Delta diversion rates of 8.4 maf and estimates of future outflow reduction, and assuming that sediment input to the Bay would be reduced by the same percentage as freshwater Delta outflow, Krone (1966) estimated a reduction by 60 to 77 percent in low inflow years and 36 percent on the average. Kennedy (1970) suggested this method overestimated sediment reduction because the contribution of sediment to the Bay occurs primarily in a few months in the winter when a smaller proportion of Delta outflow would be diverted. Kennedy then used a monthly diversion rate to calculate the potential sediment loss as roughly from 44 to 66 percent in low water years. During normal or high water years, when diversion rates are lower, relative to Delta outflow, the difference between the two estimates is much less.

The US Corps of Engineers (1975) have provided some useful data that may help us understand what such reductions mean. They compared suspended solids and transparency measurements made during a four year period

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of three subnormal and one normal year with similar measurements made during a five year period of higher outflows (Table 5). Using Krone's method, we estimate the mean annual sediment input during the drier period was about 64 percent of what it was during the wetter period. Comparable suspended sediment levels were 50 percent in Central Bay, 58 percent in San Pablo Bay and 79 percent in Suisun Bay. Transparencies were higher during the dry period.

This limited data supports the belief that outflow reductions may well cause major reductions in suspended solids and turbidity, especially in Central Bay and San Pablo Bay where resuspension of previously settled sediments is the more important factor.

It should be noted that while salinity stratification and the bottom currents created by it may have a significant effect on resuspension, the data in Table 5 would not show that effect. Outflows during even the dry years during which these measurements were made averaged 14.2 maf, and were high enough to maintain such currents throughout the winter in all reaches but South Bay.

BIOLOGICAL EFFECTS

The flora and fauna living in San Pablo, Central, and South Bays are mostly species that can tolerate sea-water salinities. Ganssle (1966) collected 40 species of fish in San Pablo Bay, 31 of which were basically marine forms. Anglers fishing from the shore or from piers around the edge of the Bay catch ocean fishes, primarily surf-perches, Embiotocidae, staghorn sculpin *Leptocottus armatus*, and starry flounders *Platichthys stellatus*, or anadromous fish like the striped bass *Morone saxatilis*, that lives its adult life in saltwater.

The edges of these bays support large beds of the eastern soft shell clams *Mya arenaria*, and Japanese littleneck clams *Tapes semidecussata*, the bay mussel *Mytilus edulis*, and many other species found in both marine and estuarine environments elsewhere.

Table 5. Historical Mean Suspended Solids Concentrations and Transparencies of Water During Years of Above and Below Normal Delta Outflow.

Years of Measurement Delta Outflow	1970-75 22.1 maf suspended solids mg/l	(transparency in feet)△1	1960-64 14.2 maf suspended solids in mg/l	(transparency in feet)△1
South Bay	--	(2.4)	42	(2.7)
Central Bay	36	(4.2)	18	(4.6)
San Pablo Bay	77	--	45	(1.6)
Suisun Bay	82	(0.78)	65	(0.90)

△1 Transparencies are the maximum depth at which an eight wide diameter white plate (Secchi disc) can be seen from the surface.

Both Felice (1958) and Painter (1966) describe a rather abrupt and distinct difference between benthic fauna of San Pablo and Suisun Bays as a "distinct faunal break" in eastern Carquinez Strait. Marine and estuarine animals predominate west of this and estuarine and freshwater forms to the east.

The marine benthic animals are kept below Carquinez Strait by what has always been a regular winter invasion of freshwater which many of them cannot tolerate for long.

The fishes, the shrimps, and the crabs are relatively motile compared to the benthic animals and their distribution and migrations throughout the estuary vary with dry or wet years. Ganssle (1966) sampled fish with small mesh trawls and gill nets throughout 1963 and 1964, the years for which outflow and the salinity information is shown in Figure 3. In the drier 1964, both Pacific herring Clupea pallasi, and Northern anchovies Engraulis mordas, migrated farther upstream; the herring clear into Suisun Bay. The young of bay shrimp appeared in Suisun Bay earlier and in greater numbers in 1964. Market crabs which had been almost totally absent in 1963 were common in San Pablo Bay in 1964 and present even in western Suisun Bay. We can be almost certain that the distribution of the Bay's biota will change in the future - that marine forms will more often be farther up the estuary.

It is harder to predict future changes in the concentrations or production of plankton, and in the size of other invertebrate and fish populations. Figure 10 is a very simple conceptual model illustrating how some of the changes we have discussed in this report are related to one another and to the ultimate production of benthic fauna, crabs, shrimps, and fishes. It shows that the planned reductions in the frequency and duration of large unregulated Delta outflows will increase salinity and reduce stratification. This will reduce the peculiar circulation that occurs in estuaries when they are stratified or partially stratified. An important identifiable change here will be a reduction in upstream bottom currents.

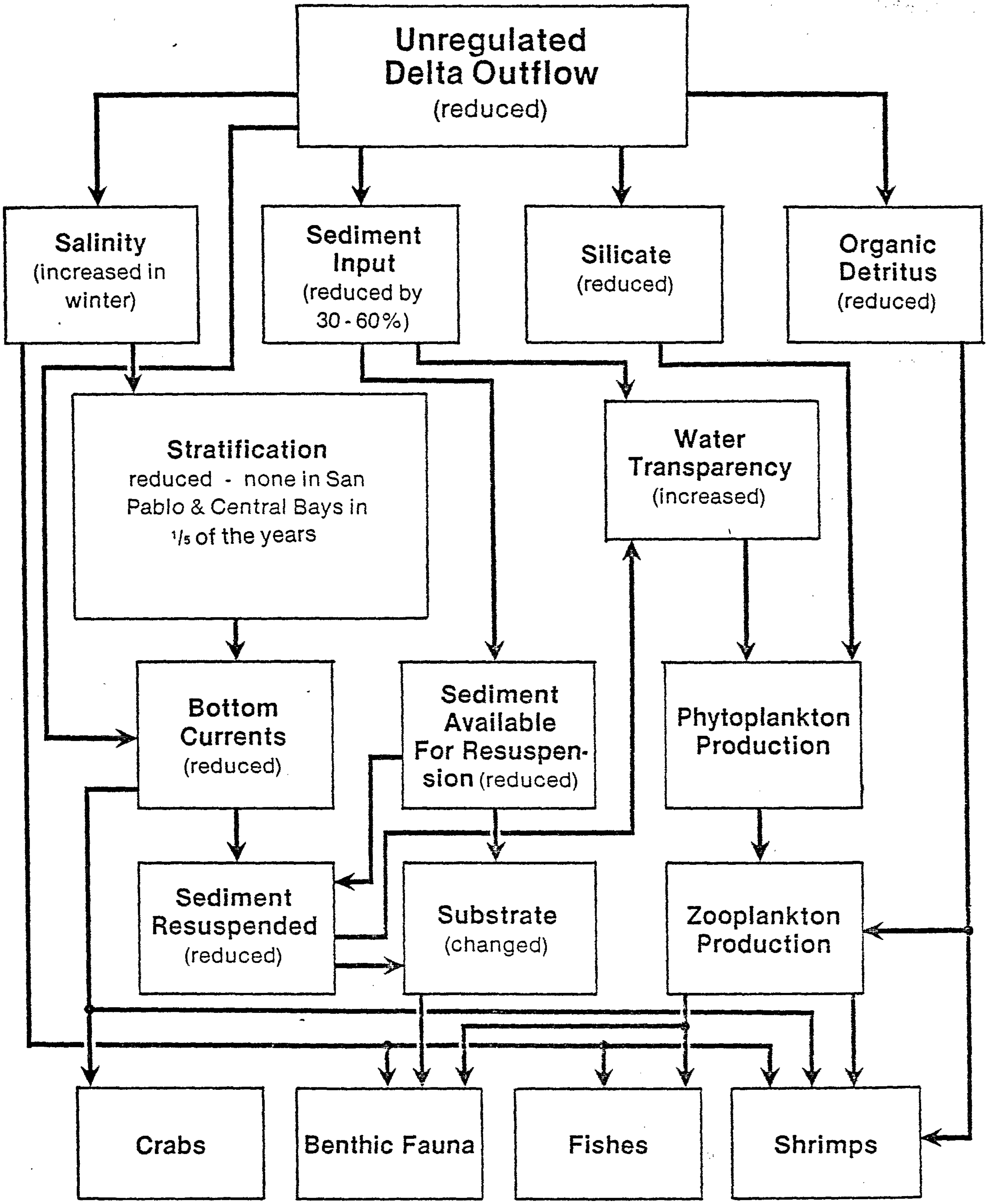

Figure 10 Conceptual model of factors affected by unregulated Delta outflow.

The reduction of unregulated outflow will at the same time lower the contribution of inorganic sediment and organic detritus to the Bay. That will likely increase water transparency during the winter and will reduce the amount of sediment deposited and available to be later resuspended. The reduction in those deposits combined with the reduction of bottom currents that resulted from reduced salinity stratification will probably cause additional increases in water transparency during the summer.

The increased water transparency will certainly affect phytoplankton production and the available evidence we have seen combined with the experience of the last two years, suggests that it most likely will be reduced. This may also result from reductions in the silicate and other inorganic nutrients which are direct results of the reduced Delta outflow. Zooplankton which feed on phytoplankton and organic detritus will also be affected. Our model illustrates that most of these factors can be expected to influence benthic fauna, crabs, shrimps, and fishes. No one knows what specific changes will occur.

Crabs and some shrimps spawn in or near ocean salinities, in the lower reaches of estuaries or in the outside oceans, but the young are reared upstream in the brackish water. The reductions in bottom currents may interfere with their upstream migration. It is an oversimplification to say that elimination of salinity stratification will eliminate these migrations, but it is foolhardy to believe they will not be affected.

It is likely that future years will see Central Bay, San Pablo Bay, and, in the summer, Suisun Bay less turbid and their substrates firmer. The distribution of benthic fauna and perhaps the fish that feed on them may well change. The effect of outflow reduction on phytoplankton is not predictable with existing knowledge beyond saying that we have found no reason to expect major undesirable increases in algae or other plant growth. We believe it more reasonable to expect a reduction in algae and zooplankton production and in biological productivity but cannot even guess to what degree. The Bay will probably be as esthetically attractive as ever, perhaps more so as the bottom becomes firmer and waters clear somewhat. We assume of course that pollution will be prevented and the shoreline will be protected from damage by filling, etc.

The major risk ahead is to anadromous fishes. Their migrations through and above the estuary have historically been timed to coincide with subsequent periods of good spawning and egg hatching conditions upstream and with production of large food supplies for young as they move downstream through their nursery areas. High outflows of fresh water into the Bay play important roles in transporting fish and maintaining these food supplies. Changes in those outflows as great as we expect almost certainly will be reflected in the migrations and survival of salmon, steelhead, shad, striped bass, and sturgeon. It will require a heroic effort by scientists and engineers to preserve large populations of these fishes in the face of these changes and other changes we can expect in their environment upstream.

RECOMMENDATIONS

1. A RESERVATION OF WINTER OUTFLOW - We think the risk to the Bay and especially to anadromous fish is great enough to require some reservation of high unregulated Delta outflows - so that water will be available if future research or experience proves it is needed. Our estimate is that 1 maf for 2 consecutive months is the smallest amount that could be reasonably called a useful reservation. Less would probably not create or maintain in Central and San Pablo Bays the circulating currents so characteristic of estuaries. We believe that two months is a minimum period in which to expect the changed physical and chemical conditions that accompany the higher outflow to be put to good use by phytoplankton, zooplankton, other invertebrates, and fishes.

Our experience with this estuary and our review of the work done in other estuaries has given us a healthy respect for the wide variation and durability of estuarine ecosystems. But there is a limit - our suggestion is that 1 maf for two consecutive months is a minimal reservation to set on winter outflow until we know more.

2. RESEARCH - The research needed to define the effects of future outflows on the Bay and to help solve any problems that may result should be started soon, and should be a joint responsibility of the State Water Project, Central Valley Project and others who have or will significantly reduce Delta outflows.

The first step in planning that research should be to collect and analyze the information gathered during the last two years of unprecedented low Delta outflows. When properly analyzed, that information will tell us much about what is and what is not relevant to study.

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