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SAN FRANCISCO BAY: THE ECOSYSTEM

Further Investigations into the Natural History of San Francisco Bay and Delta With Reference to the Influence of Man

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SUMMARY OF FEDERAL AND STATE WATER PROJECT ENVIRONMENTAL IMPACTS IN THE SAN FRANCISCO BAY-DELTA ESTUARY, CALIFORNIA

JAMES F. ARTHUR, MELVIN D. BALL,
AND SHERYL Y. BAUGHMAN
U.S. Bureau of Reclamation, Mid-Pacific Region
2800 Cottage Way, Sacramento, CA 95825-1898

This paper provides a brief summary of early and post Federal and State water project development and summarizes major changes in physical, chemical, and biological constituents that have occurred as the result of direct water transfer through the Delta (fresh-brackish water portion of the San Francisco Bay-Delta Estuary). Transfer of increasing amounts of Sacramento River water across the Delta channels to the Federal and State water project export pumps in the South Delta over the last 45 years has resulted in several major environmental impacts. A positive impact of water project operations has been the increase in fresh water in many Delta channels during the summer and fall. This increase in fresh water comes from water released from reservoirs to reduce salinity intrusion into the Delta and protect water quality. Most of the negative project-related impacts result from transferring large quantities of water across the Delta in existing channels. The ever-increasing demand for project export water has resulted in net flow reversals during most months of the year in the central and southern Delta. Flow reversal has resulted in: the recycling of large quantities of salt from the San Joaquin Valley back into the valley; scouring of Delta channels; increases in trihalomethane (THM) precursors from Delta sources in export water designated for municipal use; flushing of Delta aquatic habitat resulting from decreased residence times; and entrainment of plankton and various life stages of fish in the project intakes. Other nonproject impacts are mentioned. Potential short- and long-term structural and operational management solutions are also discussed.

This paper provides a brief historical perspective of water development as it relates to the Delta and summarizes major physical, chemical, and biological trends associated with Federal and State water project development in the Delta. The discussion includes our views on specific beneficial and detrimental effects associated with the direct transport of project water through Delta channels. Potential short- and long-term solutions are suggested that may better balance water allocation between environmental, agricultural, and urban needs.

Managing California's water supply has become increasingly difficult as the demand for water escalates. Two-thirds of the State's fresh water originates north of the Delta, while about 70 percent is used south of the Delta. The problem is compounded by the fact that most precipitation occurs during only half of the year – late fall through early spring. Over the last 50 years that the U.S. Bureau of Reclamation's (Reclamation) Central Valley Project (CVP) has operated and the 30 years that the California Department of Water Resources (Water Resources)

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[1] DISCLAIMER. The opinions and conclusions expressed in this paper are those of the authors. They do not represent the official position of the Bureau of Reclamation, a Department of the Interior agency, or the agencies participating in the Interagency Ecological Program for the Sacramento-San Joaquin estuary.

State Water Project (SWP) has operated, there has been a wide range of water year types, including several very wet years in a row (*e.g.*, 1969-71 and 1982-84) to as many as six continuous drought years (*e.g.*, 1987-92).

The two major sources of freshwater inflow to the Delta are the Sacramento River, which enters the Delta from the north, and the San Joaquin River, which enters the Delta from the south (Fig. 1). The area referred to as the Delta includes about 700,000 acres and nearly 700 miles of waterways. About 150 years ago, the Delta consisted of large areas of marshlands and meandering river channels. Since then, the Delta has undergone extensive structural and ecological change.

Levees in the Delta, originally constructed to allow agricultural production on fertile peat soils, are critical to maintaining a system of channels conveying river water to repel salinity and protect water quality for in-Delta use and project exports. The interior of many Delta islands has subsided from 10 to 20 feet below sea level due to peat oxidation resulting from agricultural practices. Levee failures and island flooding occur frequently because many of the Delta levees were not designed or constructed to handle the present differences in elevation between the channels and interior. A major earthquake, high tides combined with strong winds, or a flood could result in catastrophic levee failure and a corresponding loss of a major portion of the State's water supplies.

To provide a dependable water supply for California, most of the major rivers and streams that flow to the estuary have been dammed for flood control, power generation, recreation, and local and out-of-basin water supply. Presently 14 major water entities, in addition to the Federal and State water projects, have reservoirs with capacities exceeding 100,000 acre-feet. The total cumulative storage with date of construction is illustrated in Fig. 2. Currently Reclamation's CVP, the largest water project in California, has a storage capacity of about 8.8 million acre-feet. The SWP has a storage capacity of 3.5 million acre-feet. Thus, a total of about 58 percent of water storage capacity is under Federal and State control. Other major upstream water diversion facilities have a total storage capacity in excess of 9 million acre-feet, representing about 42 percent of the combined capacity in the estuary's drainage basin. Numerous other small water users, with storage capacities under 100,000 acre-feet, also divert water that historically would have flowed to the estuary.

Water diverted to the high-use areas south of the Delta and to the Bay area presently flow directly through existing Delta channels to the Federal and State export facilities. Water began to be moved across the Delta in 1937, with construction of Reclamation's Contra Costa Canal. In the early 1950s, Reclamation constructed the Delta Cross Channel to facilitate water movement from the Sacramento River to its pumping plant near Tracy, in the southern Delta. The Tracy Pumping Plant and the Delta Mendota Canal were completed in 1951, with a total export capacity of 4,600 cfs. The Tracy Fish Collection Facility was completed in 1956.

Ability to divert water out of the Delta was about doubled in 1967 with completion of the Water Resources' Harvey O. Banks Delta Pumping Plant and John E. Skinner Fish Protective Facility. The State's export facility is about 1 mile north of Reclamation's facilities and transports water south via the California

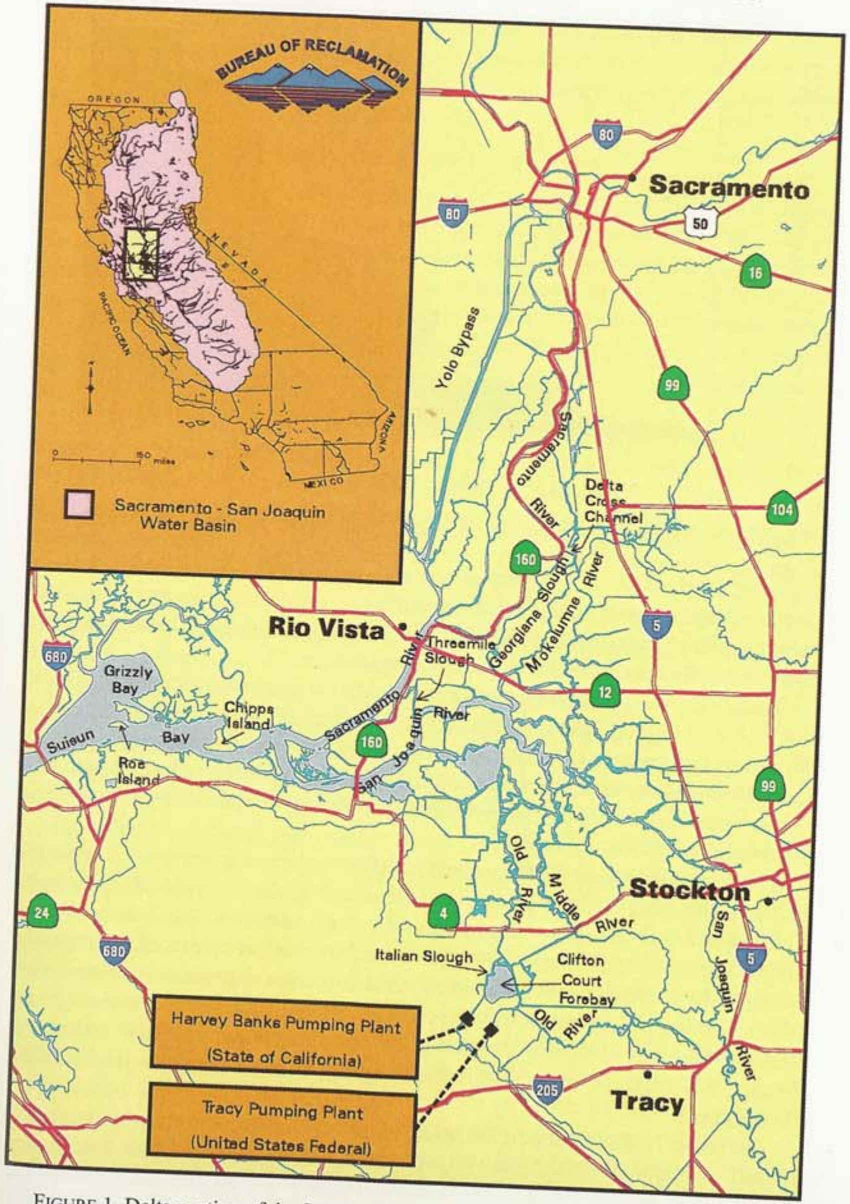

FIGURE 1. Delta portion of the Sacramento-San Joaquin Estuary.

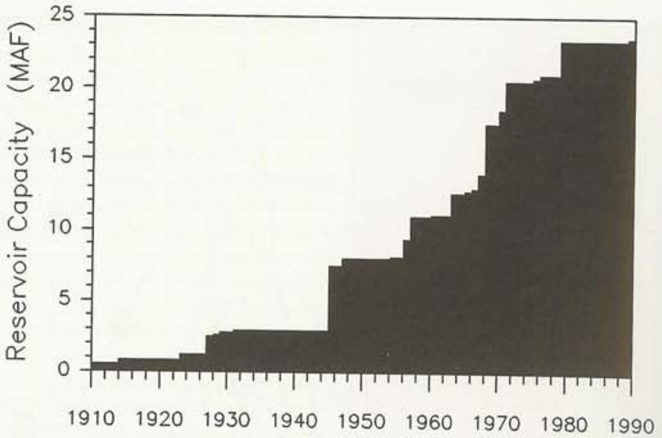

FIGURE 2. Cumulative capacity of selected Central Valley reservoirs. (Obtained from Water Resources.)

Aqueduct and to the Bay area via the South Bay Aqueduct. Banks Pumping Plant has an export capacity of about 10,300 cubic feet per second, but is limited to about 6,400 cubic feet per second under present regulations.

The CVP and SWP have been instrumental in the economic growth of California. About 20 million Californians receive at least part of their water from the Delta. The project reservoirs are multipurpose — providing water for municipal, agricultural, and industrial uses; flood protection during high runoff periods; hydroelectric power generation; various environmental benefits — and are one of the largest sources of recreation in California.

The water projects have also caused major environmental problems. Upstream of the Delta, many of the salmon and steelhead spawning grounds have been blocked and submerged by construction of federal, state, and local dams. Water temperatures, critical for salmon migration and survival, are elevated by reservoir storage. Much of the natural sediment, which has numerous positive environmental impacts, is trapped in reservoirs. Although not the direct result of water projects, much of the natural vegetation, used as habitat along water channels and in the estuary, has been eliminated and replaced by levees to reclaim farmland and for flood control.

The issues in the estuary are complex. Analysis and discussion in this paper are related to major environmental impacts in the Delta that are related to water projects. We believe the greatest negative impacts are largely associated with altered flow patterns and hydrodynamic changes in the Delta resulting from direct transport of CVP/SWP export water through existing Delta channels. Impacts include: reductions in sediment and associated increases in water transparency; recycling of Delta and San Joaquin River salts into the San Joaquin Valley;

additions of Delta-derived organic materials that form THM precursors in water diverted from the upper estuary; and significant alterations of Delta habitat (via decreased residence time and alteration of flow patterns) with corresponding reductions in some fish and their food web.

HISTORICAL PERSPECTIVE

In 1941, Reclamation investigated several alternatives for the present Delta Cross Channel (Carr 1941). At that time the preferred plan included an isolated channel with fish screens at the head. The proposed Delta Cross Channel extended from Freeport along the eastern Delta to the proposed head of the DMC, at that time south of Tracy. This proposed canal was even longer than the Peripheral Canal, recommended later in the 1960s. Following World War II, the Federal water project operators decided to transport water south through natural Delta channels, a decision based strictly on economics.

The actual Delta Cross Channel eventually constructed is only 2 miles long and is used to connect the Sacramento River and Mokelumne River systems. This facility increases the flow exchange out of the Sacramento River to the central Delta-San Joaquin River system and facilitates water delivery to the Federal and State export pumps.

As the Federal export facilities were put on line, it became evident that using the Delta's natural channels for water transfer would create several major environmental problems. Consequently, during the early 1960s, Federal and State agencies formed the Interagency Delta Committee (IDC) to study plans for a joint water transfer facility to the southern Delta (IDC, 1965). Four plans were considered:

- The then-existing and present-day operation using hydraulic barriers;
- A physical barrier (a dam with flood gates and ship locks at Chipps Island);
- Delta waterway control (isolated transfer facility through the central Delta); and
- The Peripheral Canal (isolated channel around the eastern and southern Delta).

The Peripheral Canal plan was selected as the most environmentally sound method of transporting water south. IDC water project biologists, hydrologists, and engineers who had studied the four options for water transfers predicted many of the negative impacts observed today by continued use of a hydraulic barrier to protect project export water transfers, as currently done. Major engineering and environmental studies were initiated in the 1970s to determine how to best construct and operate the Peripheral Canal. However, the plan was not approved by California voters. Work on the Peripheral Canal was canceled after its 1982 defeat at the polls. The lack of a Peripheral Canal, which was designed to solve many of the present environmental problems, has resulted in a stalemate on how to best protect the environment while still exporting water for urban and agricultural uses.

Several alternative Delta water transfer plans have been proposed. One plan called for enlargement of natural Delta channels in the northern and eastern portion of the Delta, without fish protective measures. Installation of channel barriers and a siphon under the San Joaquin River were also evaluated by Water Resources and Reclamation. These plans were part of Senate Bill 1369, which was shelved in 1984 due to a lack of overall support. In cooperation with other agencies and local interests, Reclamation and Water Resources have continued to study structural and water management plans to improve water transport within the Delta.

Numerous legal actions and major events in the Delta that have taken place are summarized in Table 1 (Argent 1989). The intent of all the recent actions and standards has been to protect and/or enhance estuarine resources, including endangered and threatened species. However, we believe that none of these actions directly considered the major cause of the problem — the use of Delta channels to transport water to the export facilities.

Finding an environmentally sound water transfer system is complicated by the complex and dynamic nature of the estuarine biotic community. In addition to the Federal and State water projects, several nonproject factors may be negatively affecting the estuarine food web and fisheries. Although the nonproject impacts have been recognized and discussed for many years, they have been impossible to quantify and difficult to control. Nonproject impacts include: toxicity, introduction of exotic species, entrainment of fish and their food into Delta diversions, illegal take of fish, and direct and indirect dredging effects. Cumulatively, nonproject impacts are clearly having detrimental effects on the estuary's biota, and these impacts should be understood and controlled to the extent possible.

Many alternatives being considered that would significantly enhance environmental resources under the present Delta configuration require reductions in water project exports and corresponding increases in Delta outflow. The consequences of reducing water supply could be devastating to California's economy. We believe some type of isolated water project transfer facility needs to be evaluated as a long-term solution for protecting both water supply and environmental resources.

METHODS AND MATERIALS

This paper uses existing data to summarize major physical, chemical, and biological trends in the San Francisco Bay-Delta estuary since the Central Valley Project (1953) and State Water Project (1968) began exporting water out of the Delta. Where data are available (some flow data extend back to 1930), comparisons are made to pre-project conditions. Most of the information comes from data records collected under the auspices of the Interagency Ecological Program (IEP), formerly the Interagency Ecological Study Program.

The Interagency Ecological Study Program was formed in 1970 via a cooperative agreement between the U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service (FWS), California Department of Fish and Game (Fish & Game), and California Department of Water Resources. Since then, five additional agencies have become members: U.S. Geological Survey, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, State Water Resources Control Board (State Board), and National Marine Fisheries Service. A primary objective of the present Interagency Ecological Program is to collect and evaluate environmental data for the estuary, particularly in regard to the potential impact of water project operations. An overview of all the data collected by each program element can be found in the Interagency Program's *Data Summary Report* (1993).

TABLE 1. Chronology of San Francisco Bay-Delta Estuary

1772	First recorded sighting of the Delta by Fray Juan Crespi and Captain Pedro Farges.
1849	Settlers begin arriving in the Delta region to farm its rich land, one year after the discovery of gold in California.
1861	California Legislature authorizes the Reclamation District Act allowing drainage of Delta lands and construction of sturdier levees to protect the area from flooding.
1914	Passage of the Water Commission Act.
1930	Completion of a comprehensive State Water Plan calling for major transfers of northern California water to the Central Valley.
1940	Contra Costa Canal, the first unit of the federal Central Valley Project (CVP), is completed and use of Delta channels to convey water for export begins.
1944	Completion of Shasta Dam and reservoir as the key feature of the CVP, adding water to Delta channels during naturally low-flow periods.
1951	The State Feather River Project (now State Water Project) authorized by the California Legislature. Diversions from the Delta begin for the CVP's Delta-Mendota Canal.
1959	State Delta Protection Act approved by the state Legislature.
1960	California voters approve the Burns-Porter Act to assist in financing the State Water Project (SWP), including Delta facilities for water conservation, water supply in the Delta, transfer of water across the Delta, flood and salinity control and related functions.
1961	State Department of Water Resources (DWR) initiates the Interagency Delta Committee, consisting of DWR, U.S. Bureau of Reclamation (Bureau) and the U.S. Army Corps of Engineers, to find solutions to Delta problems.
1965	Interagency Delta Committee releases its report which contains a variety of proposals designed to offset adverse effects of increasing use of water from the Delta. The proposal included a plan for a Peripheral Canal.
	DWR officially selects the Peripheral Canal as the Delta water facility of the SWP.
1967	Construction begins of SWP's Clifton Court Forebay.
	Initial diversions begin from the Delta to the California and South Bay aqueducts of the SWP.
1969	U.S. Department of Interior adopts the Bureau's Peripheral Canal Feasibility Report and recommends the project be a joint-use facility of the CVP and SWP with shared costs.
1970	State endorses a joint-use facility, urges Congressional authorization on the condition that Delta water requirements have priority over exports.
1971	State Water Resources Control Board (SWRCB) adopts its Delta Water Rights Decision 1379 establishing water quality standards to be met by both CVP and SWP.
1972	DWR announces that the state is proceeding with planning of the Peripheral Canal as a state-only project.
	First SWP deliveries to souther California.
1973	Delta Environmental Advisory Committee forms. As part of a three-point solution, the committee concludes in January 1977 that a properly designed, built, and operated facility such as the Peripheral Canal is necessary.
	State Department of Fish and Game (DFG) concludes a 10-year study which probes the Delta's problems. Report concludes a Peripheral Canal is the most desirable plan for a Delta water facility.
1974	DWR, DFG, the Bureau, and U.S. Fish and Wildlife Service sign a statement of intent that the agencies will provide protection of fish and wildlife resources in the Delta.
1975	DWR calls for complete reappraisal of alternative possibilities for Delta water management problems.
	U.S. Department of the Interior releases its opinion that the Federal Water Pollution Control Act does not require the Bureau to release water for salinity repulsion in the Delta.

TABLE 1. Chronology of San Francisco Bay-Delta Estuary (*continued*)

	DWR releases a legal opinion stating the Federal Water Pollution Control Act *does* apply to the operation of the CVP.
1977	After reviewing nearly 40 alternative courses of action in the Delta, DWR reaffirms that building the Peripheral Canal is the best answer to Delta problems.
1978	SWRCB issues SWP-CVP Water Rights Decision 1485 regarding CVP and SWP operation to provide water quality control in the Delta.
1979	Secretary of the Interior Cecil D. Andrus announces the CVP will be operated to voluntarily meet state Delta water quality standards (Decision 1485) until legal questions of mandatory federal compliance are resolved. Negotiations proceed between DWR and the Bureau.
	Senator Ruben Ayala introduces Senate Bill (SB) 200 specifying the Peripheral Canal as the Delta transfer facility, not requiring federal participation.
1980	Voters pass Proposition 8 insuring more Delta protection unless SB 200 is defeated.
1982	Voters defeat Proposition 9, which includes the Peripheral Canal SB 200 package, by a 3-2 margin. Northern Californians vote 9-1 against SB 200 and Southern Californians vote 3-2 for the bill.
1983	DWR releases a report analyzing four through-Delta alternatives to the Peripheral Canal.
1984	Attention focuses on Governor Deukmelian's through-Delta plan utilizing natural Delta channels and reconstructed levees. By June "Duke's Ditch" (SB 1369) is shelved.
1986	Congress passes DWR and Bureau historic accord, the Coordinated Operation Agreement (COA).
	California Supreme Court affirms state Court of Appeal ruling (Racanelli decision) strengthening powers of the SWRCB to protect all uses of Delta water and potentially San Francisco Bay.
	DWR and DFG sign Delta Pumping Plant fishery mitigation agreement for direct fish losses.
1987	The SWRCB begins the San Francisco Bay/Sacramento-San Joaquin Delta Estuary Hearing (Bay-Delta Proceedings)
1988	Senate Bill 34 provides $120 million over 10 years for DWR to rebuild levees, enlarge channels and to help reclamation districts make levee improvements.
	Suisun Marsh facilities (tide gates) begin operation to provide water quality for waterfowl protection.
	Construction begins on four additional pumping units at the Delta Pumping Plant.
	An engineering study by the California Urban Water Agencies examines options for improving drinking water quality for users of Delta water.
1991[1]	In May the SWRCB adopts and submits a Bay-Delta water quality plan to the Environmental Protection Agency (EPA).
	In September, EPA disapproves the fish and wildlife objectives.
1994[1]	In January, EPA publishes draft standards in the Federal Register.
	In March, SWRCB commences reviewing requirements of the 1978 and 1991 Bay-Delta plans.
	On December 15, an historic agreement is signed by Federal, State, and special interest groups endorsing a revised Bay-Delta water quality plan. SWRCB releases the draft water quality control plan.

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[1] Items added by Reclamation staff. (From Argent 1989).

Most flow evaluations used data from Water Resources' DAYFLOW model. Data prior to 1978 were hand calculated, and data prior to 1955 used a different calculation for some of the flows due to unavailability of input flows. The five DAYFLOW parameters used in this report are:

- Delta Inflow — Sum of Delta inflows from the Sacramento, San Joaquin, Cosumnes, and Mokelumne Rivers, plus miscellaneous stream flows;
- Exports — Sum of State Water Project, Central Valley Project at Tracy, Contra Costa Canal, and miscellaneous diversions;
- Delta Outflow — Delta inflow minus exports and Delta consumptive depletions;
- Reverse Flow (Qwest) — Delta inflows plus Georgiana Slough and Delta Cross Channel minus exports and 65% of Delta depletions; and
- Percent Diverted — Exports plus depletions/inflow times 100.

It should be noted that Delta depletion is an estimated total for about 1,800 miscellaneous diversions, evaporation, and rainfall, varying weekly but not between years.

As part of the Interagency Ecological Program, Fish and Game conducts several long-term monitoring programs in the estuary. Three were originally established to detect striped bass at different life stages:

- Egg and larval sampling at 30 sites in the Delta and Suisun Bay;
- Young-of-the-year (Y-O-Y) tow-net survey at 30 sites in the Delta and Suisun Bay (not necessarily the same as egg and larval sites); and
- Midwater trawl at 180 sites in the Delta, Suisun Bay, and San Pablo Bay to index striped bass abundance in the fall of their first year.

Other species are also captured in each of these studies. Fish and Game also studies food organism abundance at 50 sites in the Delta, Suisun Bay, and San Pablo Bay (*Neomysis*/zooplankton survey). These data bases were used to examine the biological impacts of project exports.

Analytical tools used for evaluations in this report were SAS, a statistical and graphical analysis system, and ArcInfo, a Geographical Information System software.

RESULTS AND DISCUSSION

We first characterized water project development by examining long-term trends in outflow, inflow, and exports. The impacts on estuarine ecology of through-Delta water transfers are divided into three categories — physical, chemical, and biological. Where data are available and appropriate, we based our analysis of project impacts on major human alterations in the Delta during five periods:

- Prior to 1944 — Before completion of the first large Federal and State dams;
- 1944 to 1951 — After Shasta and Friant dams were in place but prior to significant Federal exports from the Delta;
- 1951 to 1967 — A period of Federal exports only;
- 1968 to 1977 — A period of both Federal and State exports and when State Board Decision 1379 standards were in place; and
- 1978 to 1992 — When State Water Resources Control Board Decision 1485 standards were in place.

Water Project Development

The Federal, State, and local water projects have altered the Delta environment in two major ways. First, Federal and State dams, as well as numerous nonproject diverters upstream of the Delta, have changed the timing and quantity of inflow reaching the Delta. Second, pumping by the two water project export facilities in the southern Delta has changed the magnitude and direction of flow within and through the Delta. The following discussions look at changes in these flows over time.

Delta Outflow

The term "Delta outflow" is used to characterize river discharge from the Sacramento-San Joaquin River basins into Suisun Bay. Historically, Delta outflow has been calculated for net river discharge at the downstream end of the Delta at Chipps Island. Direct measurement of Delta outflow has been impossible because of large tidal flows (peaking near 300,000 cfs at Chipps Island) relative to net river discharge.

Data using different calculations for two periods (1930-1954 and 1955-present) from the DAYFLOW model were combined to provide a continuous record of total annual Delta outflow from 1930 through 1993, as illustrated in Fig. 3. Also indicated in this figure are major changes to the system.

Total annual Delta outflow has been highly variable over the relatively short period of record and is directly related to water year type: wet, above normal, below normal, dry, and critical based on unimpaired flow (as defined by the State Board). On an annual basis, there is no apparent major relationship to human events. Since 1930, both the low and high annual outflows occurred in the last decade. The lowest annual outflow, less than 4 million acre-feet, occurred during the 1977 water year. By far the highest annual outflow, nearly 65 million acre-feet, occurred during the 1983 water year. Although there were some low outflow years from 1928-1934, the longest duration of drought (below-normal water years) occurred from 1987 to the present. Although major changes in Delta outflow resulting from human impacts are not apparent on an annual basis, evaluating seasonal trends in Delta inflow is enlightening.

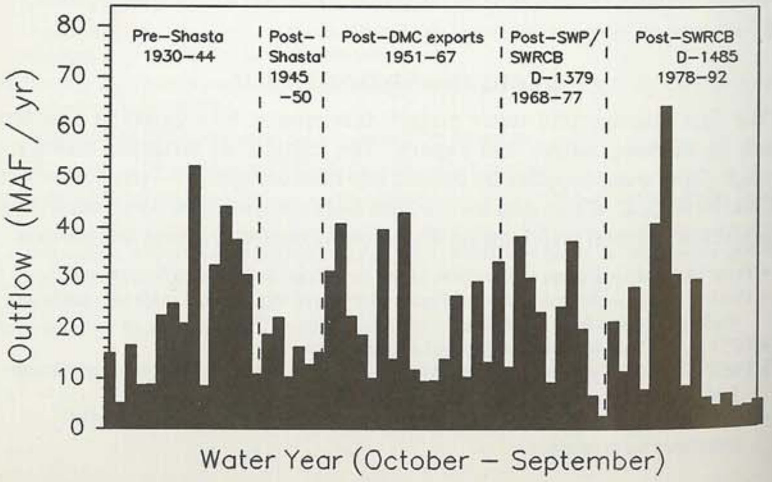

FIGURE 3. Total Delta outflow by water year and periods of major manmade impacts.

Delta Inflow

During the 1955-1993 period when water projects were exporting water, the Sacramento River averaged 84 percent of the total fresh water inflow, the San Joaquin River averaged 13 percent, and the eastern peripheral streams contributed 3 percent. Greater water project impacts occurred in the Delta in the below-normal water years. For the same period and considering only below-normal water years, the Sacramento River averaged 88 percent of the total inflow, the San Joaquin River 10 percent, and the eastside streams only 2 percent.

As the demand for water increased, more large storage reservoirs (Fig. 2) and major delivery systems were built. This was followed by an increase in the quantity of water exported from the Delta and a change in the seasonal pattern and quantity of inflow to the Delta. Since the greatest impacts occur in drier years, only below-normal, dry, and critical water year were used to calculate the changing inflow patterns, 1930-1992 (Fig. 4). Presented are long-term averages for the major manmade changes in the system.

The general trend indicates that year-round Delta inflows were actually lower prior to construction of Shasta Dam until major exports began in the 1950s. Summer and fall inflows have increased especially during the 1951-1992 period because the water projects began exporting water from the Delta. Conversely, winter and spring have been reduced about 40 percent since the State began exporting in 1968 and since Decisions 1379 and 1485 were implemented. However, Delta inflows have become more stable during the spring through fall since exports began.

Water Project Exports

The Federal export pumps have historically been operated on a continuous, 24-hour basis, drawing water directly out of Old River. In about 9 out of 10 years, water in the San Joaquin River is typically pulled into upper Old River and exported by the Federal export pumps. Little of this water reaches the State export pumps located farther downstream. Thus, most of the San Joaquin River flow ends up being pumped back into the San Joaquin Valley.

The balance of water exported by the Federal pumps is Sacramento River water, flowing upstream through the central Delta out of the lower San Joaquin River via Old River and Middle River. During below-normal water years, most of the water throughout the Delta is Sacramento River water. As an illustration, the San Joaquin River may be flowing at 2,000 cubic feet per second, Tracy pumping at 4,000 cubic feet per second; thus, about half of the exported water would be from the Sacramento River.

The State's export pump intake is just north of the Federal intake. Water is drawn from Old River and Middle River into a small regulating reservoir, Clifton Court

Forebay. Unlike Federal export operations, which continuously pump water, the forebay intake gates are generally open only on higher tides (about half the time). The forebay is operated in this manner to allow much of the pumping to be done at night, using off-peak power rates. Opening the gates on higher tides results in nearly all water exported (when San Joaquin River inflow is low) to be of Sacramento River origin via lower Old River, Middle River, and the central Delta. This type of operational scenario also results in large quantities of water being drawn into Clifton Court Forebay over relatively short periods. Arthur (1987) calculated historical export flows based on operations of the radial gates into Clifton Court Forebay, referring to the calculated flows as "instantaneous flow." Typically, actual "instantaneous" export flows are double those reported as daily export flows in DAYFLOW. At times, instantaneous export flows are in excess of 25,000 cubic feet per second, with corresponding large increases in flows and decreased residence times in Old and Middle Rivers.

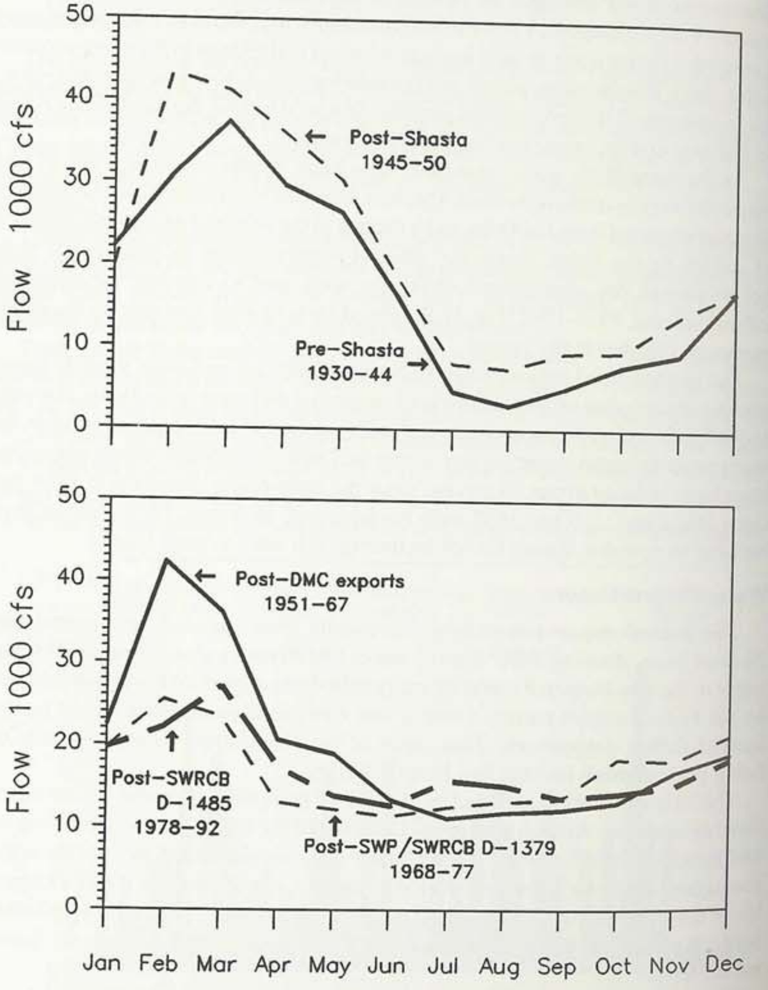

FIGURE 4. Change in average monthly Delta inflows in below average water years for major manmade impacts.

To evaluate changes in exports, the 1951-1992 period (following the start of Delta-Mendota Canal exports) was subdivided into the applicable periods (Fig. 5). As expected, total exports have increased as demands have increased over the years. In the earlier years, Delta exports peaked in the summer, with minimal amounts pumped in the winter. After the State export pumps came on-line in 1968, in addition to the increase in total pumping, the monthly variation in pumping has been reduced. Part of the year-round increase in exports was made possible by construction of reservoirs south of the Delta such as San Luis and other offstream storage reservoirs, which allow storage of high winter flows.

With a greater quantity of water being transported across the southern and central Delta to the export pumps, channel residence times have decreased. As discussed later, we believe this has resulted in increased flushing of pelagic (open water), food chain and fish habitat in the Delta.

Physical Impacts

Relating physical impacts to biological impacts is not simple. The timing and location of the biological life stage being evaluated, relative to the area of influence, is critical. Evaluating the impacts of water project export pumping on the fate of a particular life stage of a fish is further complicated by constantly changing flows — flows that determine where an organism is transported. At a given export rate,

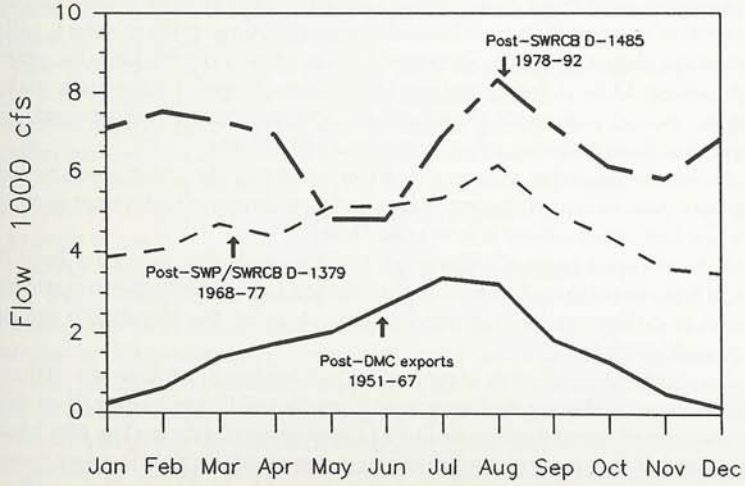

FIGURE 5. Change in average monthly Delta exports in all water year types for major manmade impacts.

impacts can be quite variable, depending on flows in the Sacramento and San Joaquin Rivers relative to the export rate being evaluated. Thus, the net transport rates of suspended materials or organisms are dependent on the interaction of varying streamflows in 700 miles of waterways; ocean water intrusion; agricultural, municipal, and industrial Delta entrainments; and water project export rates plus other factors such as toxins. Understanding the basic hydrodynamic flow regime in the Delta is essential to evaluating biological and chemical interactions related to flow.

Hydrodynamics

Over the past 50 years, several numerical and physical models have been developed that are driven primarily by differences in stage between areas. These models have provided a general understanding of flow patterns in the Delta, but information on specific net flow rates in the various channels and sloughs requires further field verification. Actual measurements of flow in key channels and diversion points have been difficult and limited over the years; however, recent technological advances now allow us to obtain continuous measurement of net channel flow and direction over extended periods. Some of this new technology is used in our analysis. In attempting to understand the Federal and State water project impacts on the fisheries, it is important to understand the changes they have caused to net Delta flow patterns.

Sacramento River System. A conceptual schematic of typical net flow patterns before and after the water projects began exporting water out of the Delta is illustrated in Figs. 6A and 6B. Prior to water project exports (or during very high San Joaquin River inflows under present conditions), all net flows in the major open channels were toward the Pacific Ocean (Fig. 6A). However, a typical Delta flow pattern under lower flow condition since the water projects began exporting shows flow reversals in some of these channels as Sacramento River water is pulled toward the pumps (Fig. 6B). Sacramento River water is diverted into the central and southern Delta at three locations: Delta Cross Channel; Georgiana Slough, a natural channel immediately downstream from the Delta Cross Channel; and Threemile Slough, several miles downstream of Rio Vista.

As mentioned earlier, Sacramento River water can also move south through Sherman Lake or around Sherman Island under conditions of high export pumping and low San Joaquin River inflow to the Delta.

A Reclamation study (Collins *et al.* 1992) suggests that flow rates from the Sacramento River to the Delta Cross Channel and Georgiana Slough are primarily driven by differences in stage and tidal phase between the Sacramento and San Joaquin Rivers.

San Joaquin River System. In most years, San Joaquin River flows are relatively low compared to flows in the Sacramento River. Part of the San Joaquin River splits downstream of where it enters the Delta to form upper Old River (Fig. 6B). Under conditions of high exports, a relatively large portion of this flow is drawn toward the Federal and State export intakes north of Tracy. Much of the San Joaquin River flow not drawn off at upper Old River continues downstream in the main channel, is intercepted, and is drawn south to the export facilities via lower Old River, Middle River, and smaller channels (how the water enters the export facilities is discussed in greater detail in the section on water project exports).

San Joaquin River flow not diverted to the export pumps continues downstream past the head of Old River to Stockton. In low-flow years, the San Joaquin River flow often reverses in this area, with net flow being upstream. Water Resources places a rock barrier at the head of Old River in many years during the early fall to return positive downstream flow in that reach, which assists upstream migration of adult salmon. The Old River barrier also helps to reduce the annual dissolved oxygen sag in the Stockton area. The problem is caused by settling of organic sediments and discharges from the municipal waste treatment plant in the Stockton Ship Channel and turning basin.

The treatment plant was upgraded in 1979, to provide tertiary treatment during the late summer-early fall canning season. At the same time, New Melones Reservoir (Reclamation) was completed and Stanislaus River flow releases to the San Joaquin River flow were reallocated. This combination has greatly improved dissolved oxygen levels and allowed upstream fall migration of salmon. However, in recent dry years, the rock barrier has also been installed in the spring to reduce diversion of downstream migrating salmon smolts to the export facilities, enhancing their survival.

The authors believe the cause of the most serious environmental impacts results from direct diversion of water out of southern Delta channels. This method of diversion both lowers the quality of export water and negatively affects estuarine fish and their food web. These impacts are mainly the result of reversal of net nontidal flows that occur to varying degrees throughout the San Joaquin River system of the western, central and southern Delta. For this evaluation, the term "reverse flow" is used to describe flow conditions when net nontidal streamflow direction is opposite of pre-project flows.

To estimate the extent of flow reversal, Water Resources staff adds together all Delta inflows, then subtracts 65% the Delta depletion and project export pumping. A negative number signifies net flows calculated to be reversed; a positive number signifies net downstream flows. We must emphasize that Qwest (estimate of net flow in the lower San Joaquin River) is a calculated value and does not represent actual flows, although it may provide reasonable estimates of net flows for periods of a month or more.

Another consideration is the effect of spring and neap tides on net flow in the lower San Joaquin River. Several years ago, Water Resources (Chung, pers. commun.) estimated that an approximate 4,000 cubic foot per second net flow, upstream or downstream, is attributable to spring and neap tides. The net flow (non-tidal) direction is upstream during spring tides and downstream during neap tides. In other words, the Delta is filling and emptying on about a 2-week cycle. This neap/spring cycle becomes increasingly important relative to salinity intrusion and standards during periods of low net outflow and high water demand. Neap/spring tidal conditions are not factored into the Qwest calculation and under

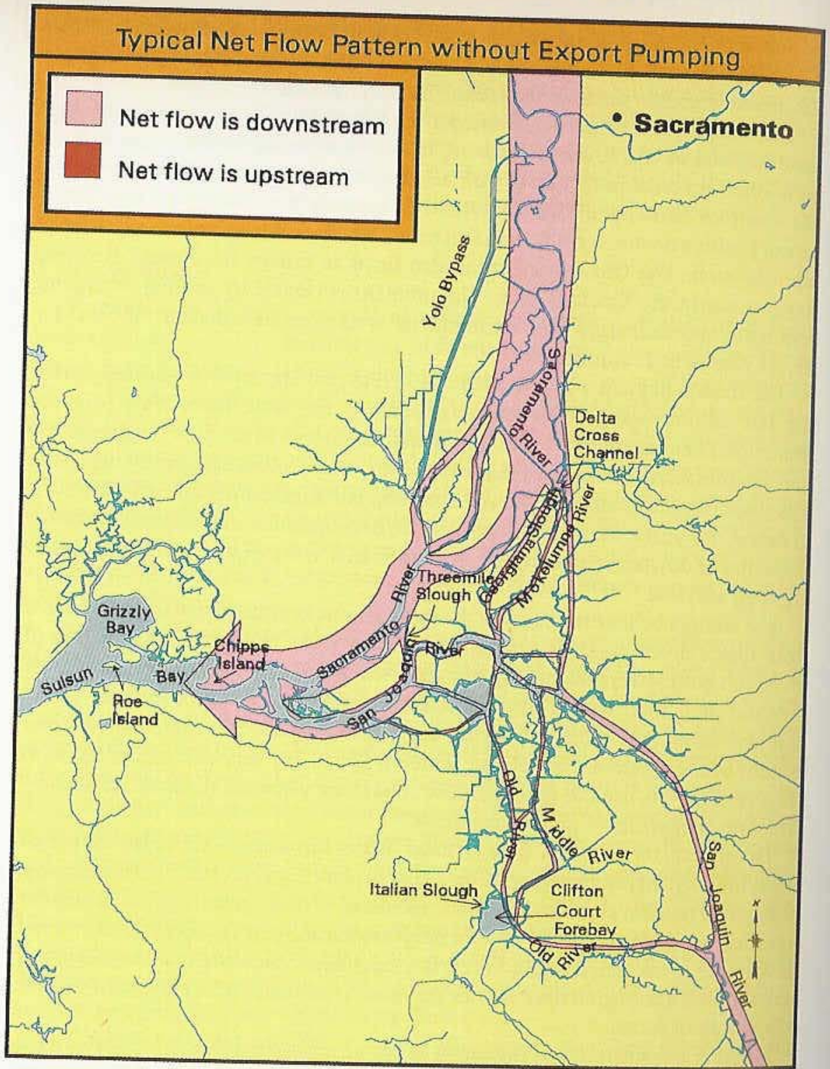

FIGURE 6A. Net flows in the Sacramento-San Joaquin Delta Estuary under low inflow conditions without export pumping.

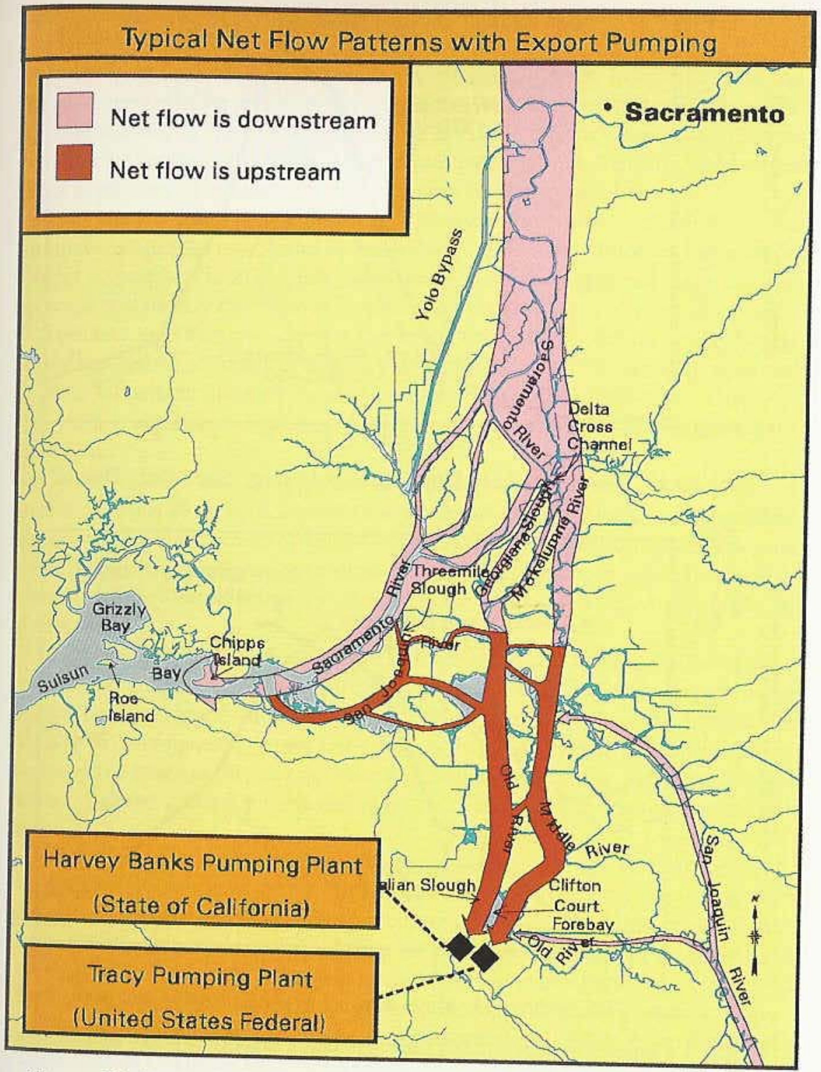

FIGURE 6B. Net flows in the Sacramento-San Joaquin Delta Estuary under low inflow conditions with export pumping.

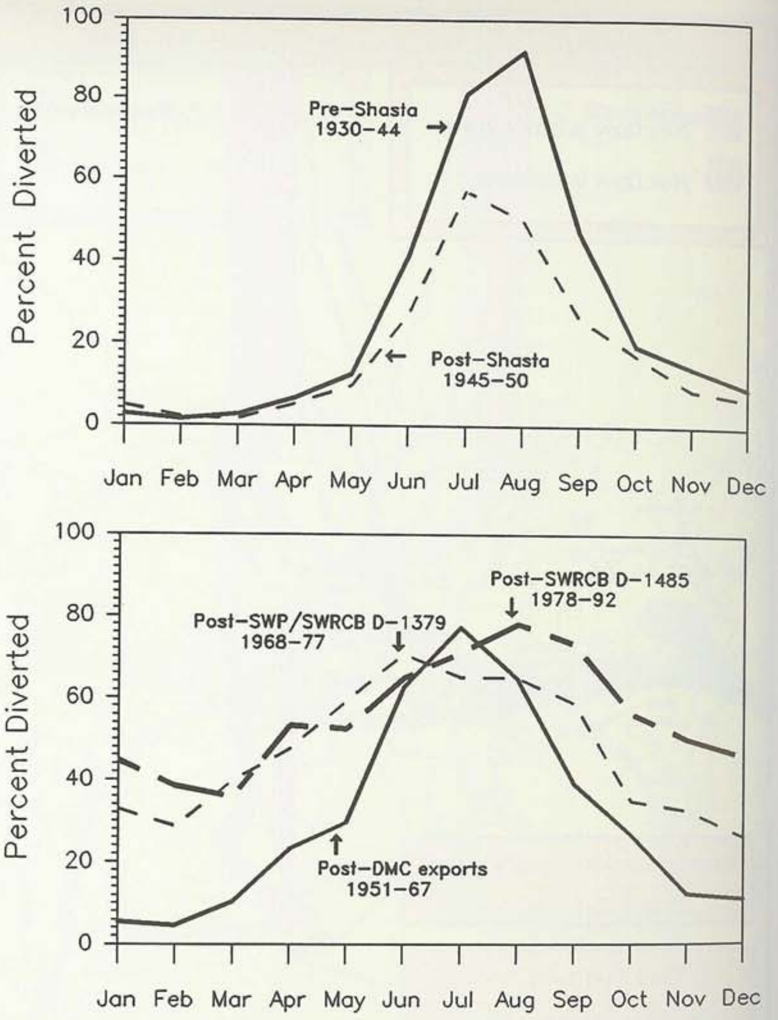

FIGURE 7. Change in average monthly percent of inflow diverted in below average water years for major manmade impacts.

low streamflow conditions (discussed later) often dominates hydrodynamic transport. Periods of sustained high westerly winds can also affect filling of the Delta.

For evaluation of long-term trends of water project reservoir releases and export pumping impacts on net flow patterns in the Delta, we examined the phenomenon of reverse flows using diverse data sets:

- Percent of Delta inflow diverted by project exports;
- Acoustical velocity measurements in Old River and Middle River;

- Reverse flows (Qwest) in the lower San Joaquin River; and
- Upward looking Doppler profile data obtained near Antioch in 1994.

Percent of Delta Inflow Diverted. The percent of Delta inflow diverted has changed greatly as the result of the Federal and State water project operations. The percent diverted is computed by summing Delta inflows and subtracting channel depletions plus Federal and State export pumping. For this analysis, we assumed Delta depletions to be constant between years for the period of record.

The data indicate about a 30 percent decrease in percent diverted during the summer comparing pre-Shasta to post-Shasta conditions (prior to Delta water project exports) (Fig. 7). Since Delta depletions were assumed constant, this decrease was largely the result of increased summer inflows via reservoir releases.

The data also demonstrate that the percent diverted in the fall/winter/spring period has increased from less than 10 percent in the 1930-1950 period to an excess of 30 to 60 percent diverted under more recent conditions, 1968-1992. There has also been a significant increase in the percent diverted as water demands have increased.

Comparison of the summer period indicates that the percent diverted has increased about 20 percent since the late 1940s, when the projects began upstream reservoir storage and Delta diversion. However, the post-project percent diverted is still lower than pre-Shasta conditions. Overall, there has been a shift from a high percent of inflow being primarily diverted in the summer to a year-round high rate of diversion.

Comparison of Delta inflows (Fig. 4) with percent diverted (Fig. 7) shows there has actually been a decrease of inflows in winter and spring, even though water exports have increased with time. Winter inflows prior to the State exporting water (1930-1967) are generally in the same range. After 1968, winter and spring inflows decreased as much as 50 percent, while demands increased (Fig. 5). December and January inflows generally remained constant, even though exports increased over time.

We draw two conclusions from the data presented in Figs. 4, 5, and 7. First, since the water projects began diverting water from the Delta, much greater quantities of water are being transported across the central Delta to the export pumps. At the same time, inflows during the winter and spring have decreased and summer/fall inflows have increased. Less inflow and higher pumping have caused much shorter residence time and consequent flushing of habitat in areas critical to certain fish and their food web. Second, implementation of State Water Resources Control Board standards has not improved conditions in this part of the estuary, as intended.

Acoustical Velocity Measurements in Old and Middle Rivers. In 1987, as part of the Interagency Ecological Program, the Geological Survey installed AVMs (acoustical velocity meters) in lower Old and Middle Rivers (about halfway between the lower San Joaquin River and the export facilities). Combining Old River and Middle River AVM measurements (USGS, open file) into monthly averages, the data were plotted against total export pumping and San Joaquin River inflow at Vernalis to determine if there was a relationship. The results demonstrate

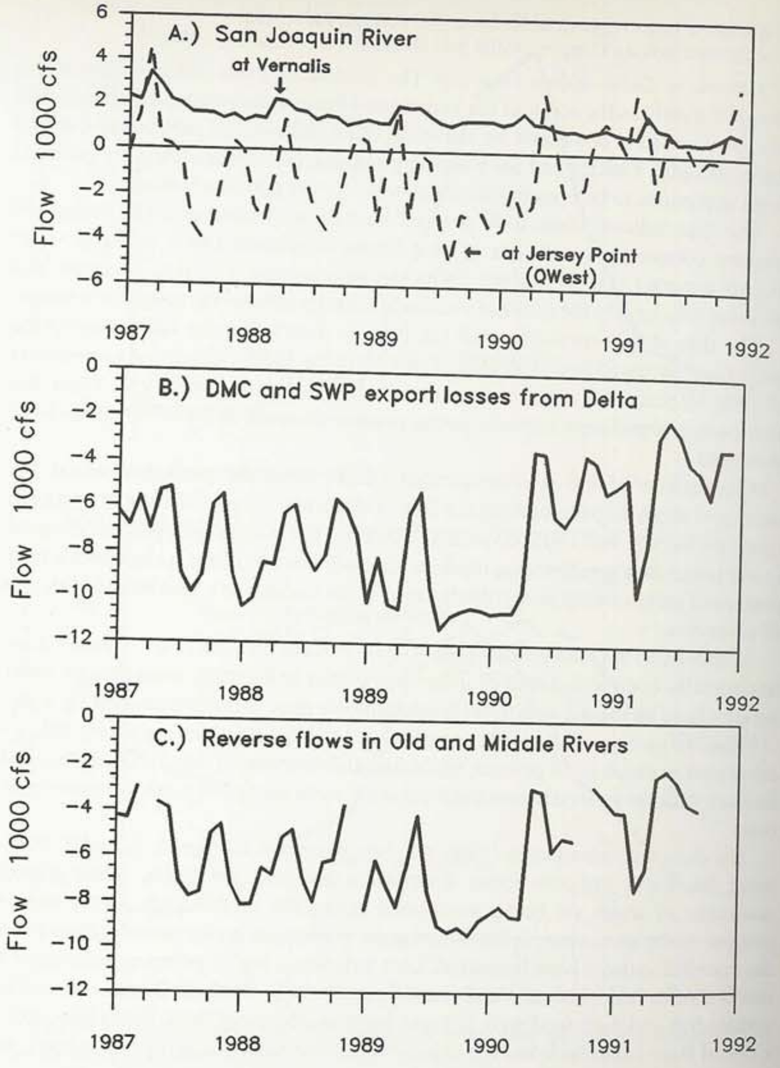

FIGURE 8. Monthly average flows: (A) San Joaquin River at Vernalis; (B) DMC and SWP exports; and (C) sum of Old and Middle River UVM measurements. (USGS data).

that over a 5-year period, 1987-1991, flows were always toward the export pumps (Fig. 8). Average net flows for both rivers were generally greater than -3,000 cfs and, at times, exceeded -9,000 cfs. Under the low San Joaquin inflow occurring in those drought years, the export pumping greatly influenced net nontidal flows in Old and Middle Rivers.

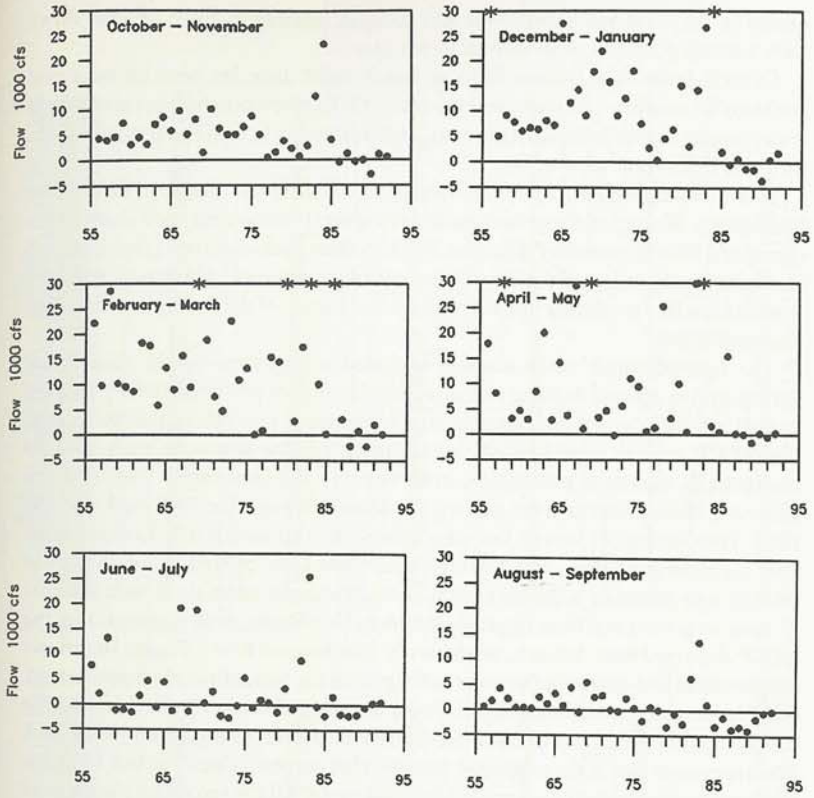

FIGURE 9. Average bimonthly net nontidal flow (QWest) computed for Jersey Point.

Lower San Joaquin River. Calculated flows at Jersey Point (Qwest), averaged for 2-month intervals, were graphed to show long-term trends (Fig. 9). The reference line, zero, means there is neither upstream nor downstream net flow. Negative or reverse flows are upstream in the lower San Joaquin River, positive flows are downstream.

The data indicate that net flows generally have been positive over the 35-year period of record from October through May, with a few exceptions in very dry years. Highest positive flows generally occurred during the high runoff months, December through May.

Net flows are most often negative during June through September, with the exception of a few wet years. Average monthly reverse flows first occurred in the 1950s, during June and July, a few years after the Delta-Mendota Canal started exporting water. In the mid-1970s, after the State Water Project had been operating a few years, mean monthly reverse flows in August and September became the rule except in very wet years. Since the last drought, starting in 1987, reverse flows have become common in all months of the year.

Overall, in the San Joaquin River at Jersey Point there has been an increased tendency in net flow reversal since the early 1970s corresponding to increases in water project export demands. However, high variability in water year types makes the trend difficult to ascertain.

Direct Measurements of Net Flows in the Lower San Joaquin River. The Interagency Ecological Program conducted a special entrapment zone study in the spring of 1994. The primary objective was to collect hydrodynamic (physical) and biological information under low Delta outflow conditions. The study area was from Suisun Bay to slightly upstream of the confluence of the Sacramento and San Joaquin Rivers.

The hydrodynamic study element included deployment by the Geological Survey of five upward-looking acoustic Doppler current profiler (ADCP) sensors, as well as other current and water quality instruments throughout the study area. The ADCP sensors were located about 1 meter off the bottom at each site and continuously measured horizontal current velocity and direction at 1-meter depth intervals. Measurements were taken from March through the first week of June 1994. The Geological Survey low pass filtered the continuous data to remove the tidal component of flow, which allows these data to be plotted as long-term net velocity and direction in the horizontal at 1-meter depth intervals at each site.

Data were obtained from Geological Survey (Jon Burau, pers. commun.) for the ADCP deployed near Antioch, on the lower San Joaquin River. Figure 10a shows net current at five depths in the water column over the 3-month deployment period. Bin 1 is the measured residual velocity near the channel bottom 2 meters above the bed, and bin 11 is near-surface residual current measured 13 meters above the bed. The uppermost plot is the measured (nonfiltered) current velocity at bin 11 and is provided to show clearly the spring/neap tidal cycle. All the velocities shown have been rotated into the direction of the prevailing channel, known as the principal direction. Therefore, net flows (shown as sticks) that are drawn above the zero line (positive) represent up-estuary residual currents. Conversely, sticks that are drawn below the zero line (negative) represent net currents that are directed down-estuary toward Suisun Bay.

The net residual flow data clearly demonstrate continuous upstream net flows in the lower third of the water column over the entire 3-month study period. Net residual flows in the upper two-thirds of the water column were downstream. This pattern was consistent during a number of spring and neap tidal cycles. Also noteworthy is that Corps of Engineers current-meter data collected between Collinsville and Rio Vista (Fig. 10b) demonstrated that during this same period the net bottom-to-surface flow was downstream in the lower Sacramento River (Jon Burau, personal communications).

The circulation pattern observed at Antioch occurred during a period of relatively low Delta outflow and low water project exports. We are not certain of the cause of the circulation pattern. However, suspended materials including organisms that spend time in the lower portion of the water column are affected by

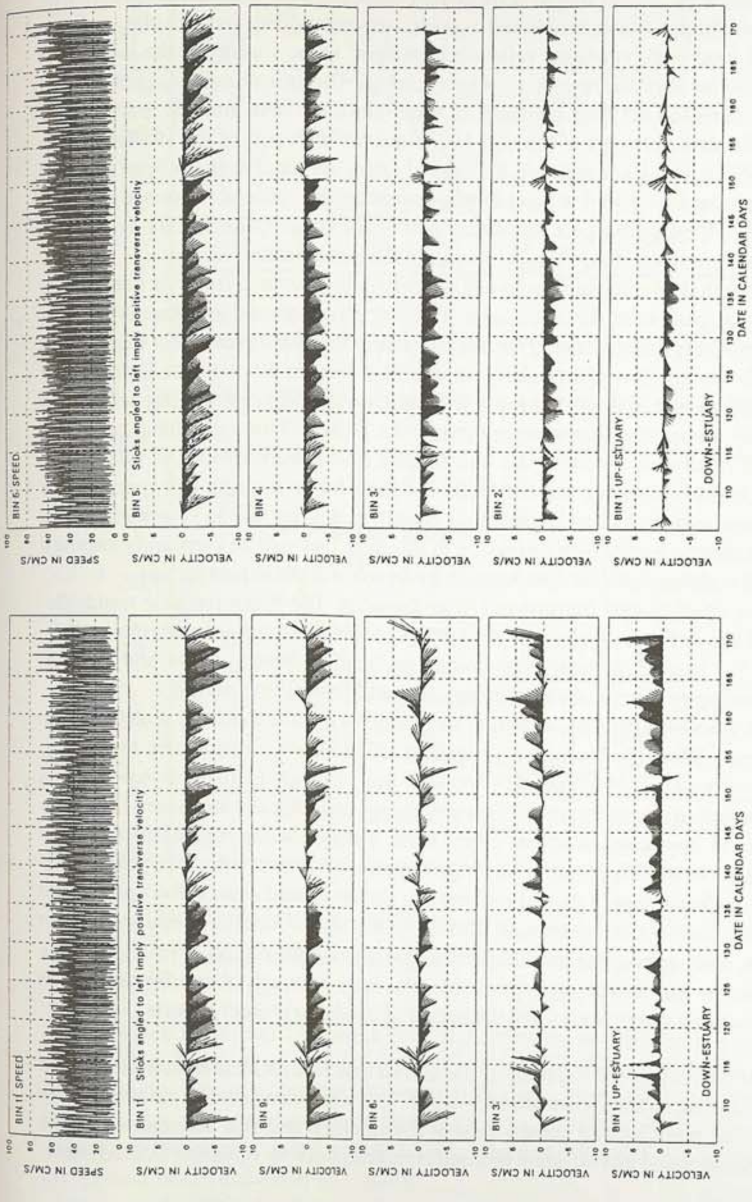

FIGURE 10. (A) Acoustic Doppler current profiler data at San Joaquin River near Antioch. USGS data (Jon Burau). (B)Acoustic Doppler current profiler data at Sacramento River near Emmaton. USGS data (Jon Burau).

residual currents at this site and could have been transported upstream into the Delta. Further studies are warranted.

In summary, the available information indicates that during periods of low inflow and high Delta demands and exports, suspended particles, including pelagic fish and food-web organisms influenced by flow, in the vicinity of the lower San Joaquin River may be drawn to the export pumps. The data strongly suggest a trend toward increased net flow reversals as water demands have gone up, particularly during the drought years of the mid-1970s and the latter part of the 1980s through early 1990s. Residence times in the central Delta have increasingly been reduced as more water is required to meet demands. We believe reduced residence time has resulted in the flushing of a significant part of the estuary's habitat for organisms requiring a long residence time to maintain their abundance.

Although there are valid technical concerns about reverse flows as denoted by Qwest, *i.e.*, peak tidal flows are large (150,000 cfs) compared to net reverse flows (0 to -5,000 cfs), we believe QWest is still a very important factor. For example, if streamflows are low (particularly in the San Joaquin River) and Delta water demands are high, salinity intrusion will increase and organisms being actively or passively transported downstream through the Delta will have greater exposure to in-Delta diversions in lower Old and Middle Rivers. Furthermore, if this occurs when Qwest is negative and the Delta is filling due to a spring tide, particles or organisms may be moved upstream or remain in this part of the system. Because there is about a 6-mile tidal excursion in this area, they will be constantly exposed to the diversions from the San Joaquin River towards the export pumps.

Delta Outflow and Entrapment Zone Location. The hydrodynamic trends described above for the Delta may also affect conditions in the downstream embayments. We limited our analysis to long-term trends in Delta outflow and location of the entrapment zone, an area of significant biological importance.

Water development in California, including the Federal and State water projects has greatly altered mean monthly trends of Delta outflow. To evaluate the trends, outflow from 1930-1992 (period of record) was subdivided into the five periods of major events using only the below-normal, dry, and critical water years (Fig. 11).

Prior to operation of Shasta Dam, Delta outflow during midsummer, on the average, was slightly negative in August during below-normal water years. Generally, outflows were highest for all months (below normal years) after completion of Shasta Dam but before exports started. Following the onset of combined project exports, early spring into late fall became the low outflow period. Overall, average outflows in the winter and spring months have been cut about 50 percent in below-normal water years since the period of combined project exports (1968-present).

Outflows affect the location of the entrapment zone, which occurs in the area where surface salinities are about 1-6 ppt. The entrapment zone is an area where suspended particles and certain food-web organisms and fish concentrate as the result of chemical/physical and biological interactions with estuarine hydrodynamics.

In the 1960s, the U.S. Geological Survey conducted a study in San Francisco Bay in which surface and bottom drifters were released at different points in the estuary (Conomos *et al.* 1970). Many of the bottom drifters released in San Francisco Bay moved a considerable distance upstream. These data provided strong evidence that net upstream bottom flow caused by gravitational circulation (induced by differences in density between fresh water and salt water) was a prominent component of circulation in this estuary.

In the early 1970s, Reclamation theorized that observed phytoplankton, certain

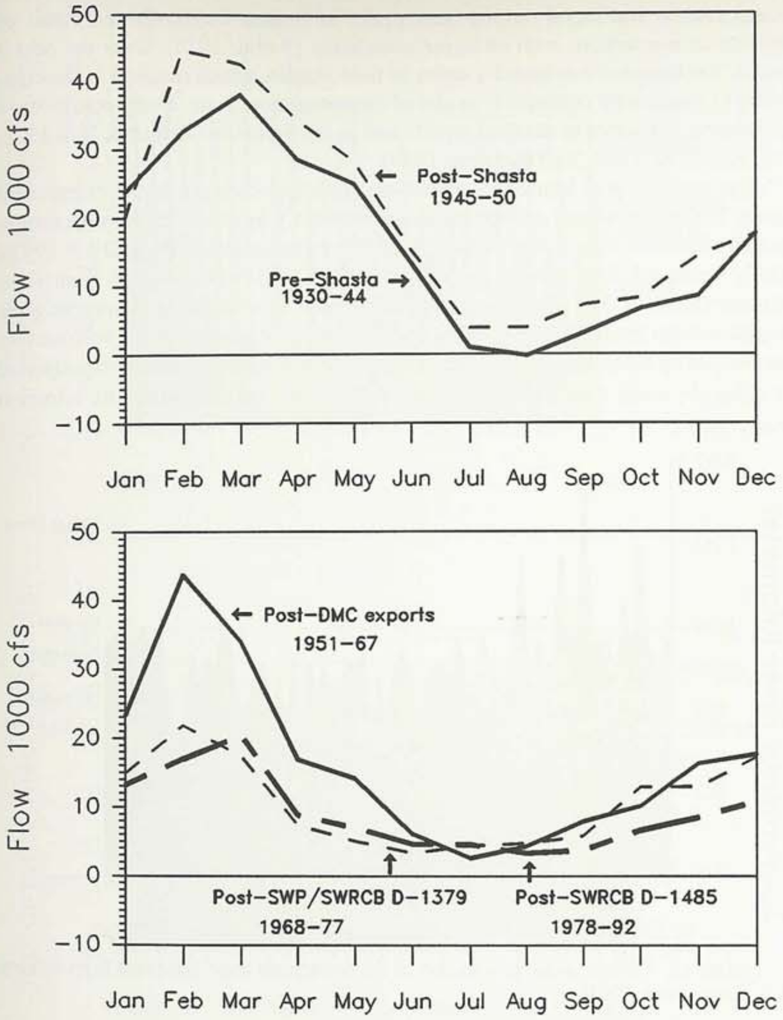

FIGURE 11. Change in average monthly Delta outflows in below average water years for major manmade impacts.

zooplankton, and larval striped bass peaks in Suisun Bay were the result of biological interactions with estuarine circulation (Arthur 1975). Over the next 5 years, Reclamation conducted a series of field studies, which resulted in development of the present conceptual model of the entrapment zone. Study results were published in a series of detailed reports and in the literature (Arthur & Ball 1978, 1979a, 1979b; 1980; Ball & Arthur 1979).

Our analysis was limited to evaluating historical changes in the entrapment zone. Maximum annual entrapment zone intrusion was obtained from maximum salinity intrusion records for 1920-1978 presented in the *Delta Atlas* (DWR 1993). Daily mean tidally averaged location for 1968-1992 was obtained from Russ Brown (Jones and Stokes), which used a model to calculate entrapment zone location from mean daily water project salinity records and the X2 relationship developed by Kimmerer (1992). The computed mean monthly values were adjusted 3 miles (½ mean tidal excursion) upstream to represent the maximum intrusion each month.

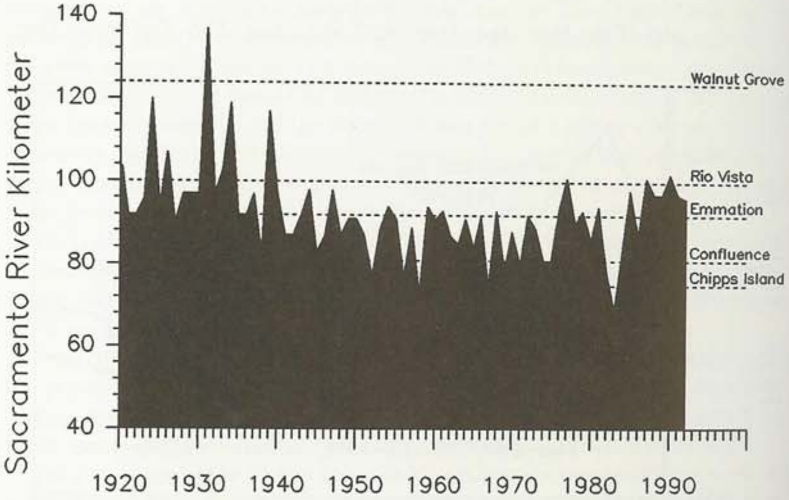

FIGURE 12. Yearly maximum intrusion of the entrapment zone estimated from salinity data (Delta Atlas, 1993).

The period of maximum easterly intrusion of the entrapment zone during 1920-1992 occurred during drought years prior to completion and operation of Shasta Reservoir (Fig. 12). From the mid-1940s (after completion of Shasta Dam) to the early 1970s, intrusion was held to a minimum. During drought years after the mid-1970s, intrusion increased, but not to the levels of the pre-Shasta years.

Mean monthly entrapment zone intrusion was also evaluated. Using the relationship between Jones and Stokes data and mean monthly Delta outflow, approximate locations for earlier years were developed (Fig. 13). The breaks in the data are for years when mean monthly Delta outflow was negative for up to three consecutive months. In those cases, the regression would not predict a location, and a circle with a cross was placed at the top of the graph. The main conclusions are that maximum intrusions have not been as great as prior to Shasta, however, since the mid-1970s, high-intrusion periods have been of longer duration. This same period is when reverse flows in the lower San Joaquin River (QWset) have become increasingly negative for August and September.

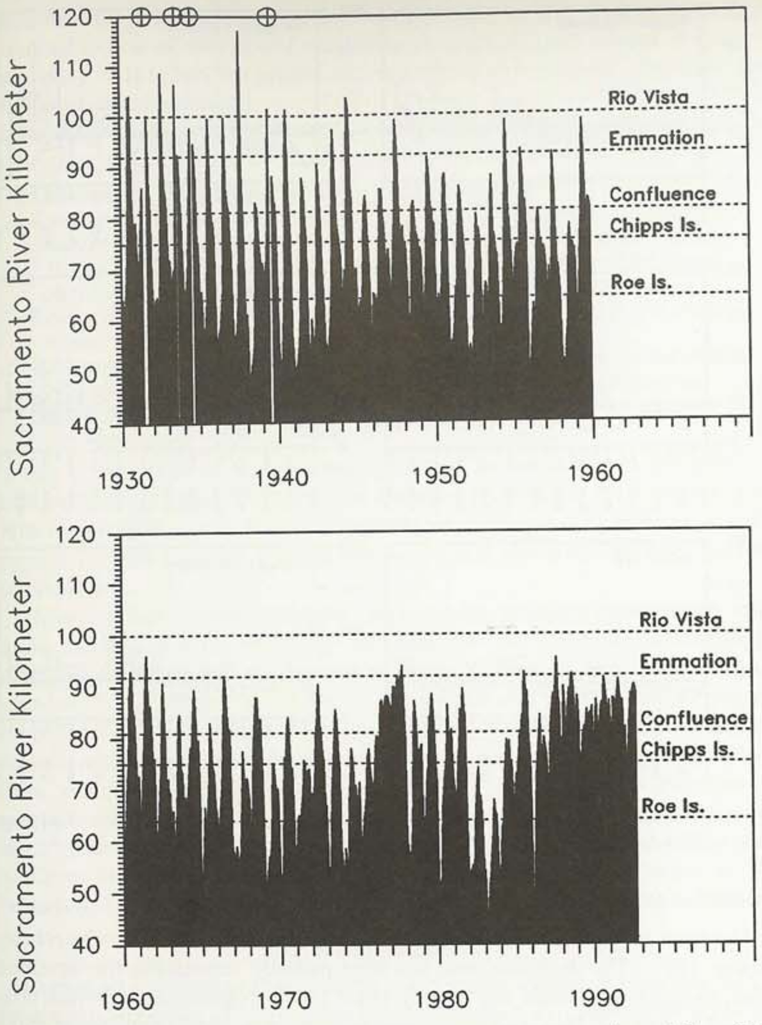

FIGURE 13. Average monthly location of the entrapment zone estimated from Delta outflow.

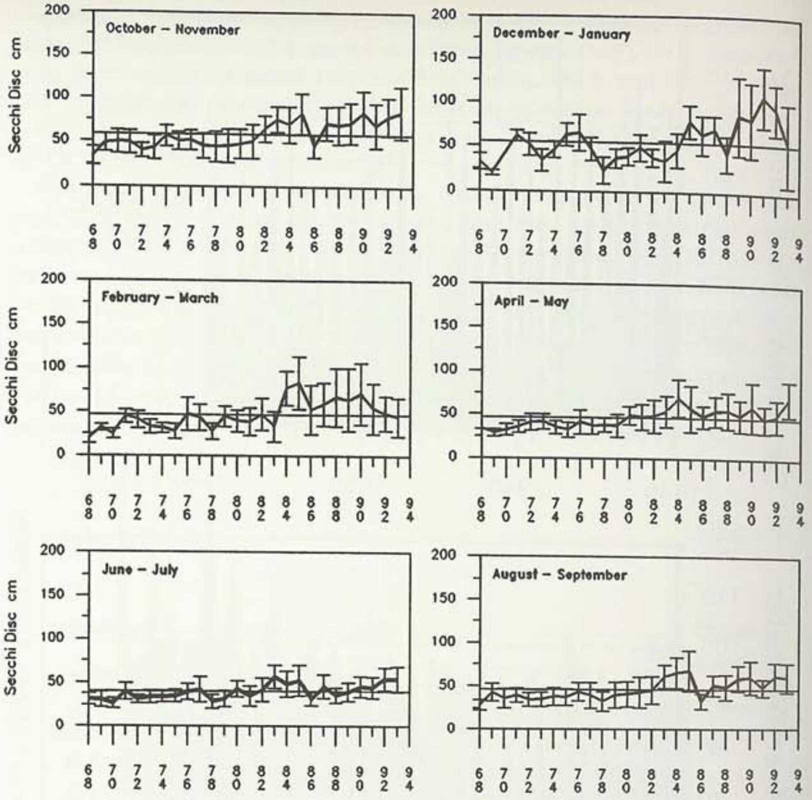

FIGURE 14. Average bimonthly water transparency (std dev.) showing mean of all years in the western and central Delta.

Suspended Sediments

The water projects have decreased the load of suspended sediment to the estuary (Arthur 1987). The decreased load has been partially responsible for increased water transparency within the estuary (Ball 1987). Numerous reservoirs constructed by Federal, State, and local agencies have trapped sediments. Some of the fine silts and clay particles, however, manage to pass through the reservoirs, depending on the water residence time.

Water transparency measurements in the western/central Delta have indicated a significant clearing trend since the mid-1970s (Fig. 14). During intense blooms in the mid-1980s, water transparency in the area would often drop by 50 percent in less than a month as phytoplankton levels peaked.

The clearing trend for water transparency was greater for the western/central Delta than for the inflow water of the Sacramento River in the northern Delta.

Water transparency in Suisun Bay area has also experienced a major increase since the mid-1980s. There were two main reasons for this. First, there was an extended period of very low flow during the drought, and second, the newly introduced Asian clam has greatly reduced phytoplankton levels. The clam also filters suspended sediments.

There are several possible causes or combination of causes for this clearing trend in the estuary, five of which were discussed by Ball (1987):

- Sediments are being trapped in Central Valley reservoirs;
- Scouring below the reservoirs removed the suspended sediment deposited in the beds of valley river systems as a result of hydraulic mining (banned in the late 1880s), and now the suspended materials have been washed out of the system, allowing the stream bed to return to a pre-hydraulic mining condition;
- Resuspended sediments in the Delta shoals and channels are being lost to export pumping;
- Sediments that cycle between the Delta and downstream bays with the entrapment zone and two-layered flow circulation are being lost to export pumping, and
- Agricultural practices on the valley floor have changed, resulting in a reduction of suspended sediments to the rivers.

One consequence of this clearing appears to be the increased intensity and dominance of phytoplankton blooms by *Melosira granulata* in the western/central Delta region (Ball 1987). This diatom produces taste and odor problems in water supplies destined for municipal and industrial use. It also is not desirable food for zooplankton.

There are many unanswered questions involving sediment resuspension, relocation, and loss from the estuary by entrainment to the export pumps through the reverse flow patterns in the lower San Joaquin River system. Sediments are constantly being settled, resuspended, and translocated by tides, wind, and net streamflows. During periods of high flows, the upstream estuarine areas are scoured, and the sediments move downstream. In the summer, under low streamflows, sediments are resuspended in the bays by wind and tidal action, move upstream with two-layered flow circulation patterns, and are redeposited in the adjacent shoals. This was documented in the upper estuary in the mid-1970s when the Corps of Engineers added iridium (a tracer) to dredge spoil dumped in San Pablo Bay. Later that year, iridium was found upstream in Suisun Bay sediments.

Chemical Impacts

Human actions that can alter estuarine water quality include: actions that change the quantity or quality of water within the Sacramento-San Joaquin drainage basin; unregulated agricultural returns; municipal, industrial, and unregulated discharges within the Delta and San Francisco Bay; airborne pollutants and water project exports. Water quality in this estuary is generally good (DWR annual reports to SWRCB, 1975-present) relative to many estuaries throughout the world. Many of the historical problems, such as the low dissolved oxygen and smell that were characteristic of South Bay into the 1970s, have largely been eliminated through regulatory actions and improvements in waste water treatment. Recent actions by the U.S. Environmental Protection Agency, San Francisco Bay Regional Water

Quality Control Board, and others to form the San Francisco Estuary Institute continue to address concerns involving various toxicants within the estuary.

Delta Water Quality

Water quality concerns in the estuary have changed over time. For example, a major potential water project impact identified in State Water Resources Control Board Decision 1379 hearings in 1967-68 was massive algal blooms. University experts testified that the projects would remove sediment via export pumping and increase nutrients via discharge through the proposed San Luis Drain, resulting in massive algal blooms throughout the system.

The Decision 1379 hearings resulted in formation of the Interagency Ecological Study Program and development over the next 10 years of phytoplankton and water quality models, with accompanying field studies. Although some of proposed impacts proved to be correct (*e.g.*, water transparencies have increased as sediments have been removed from the system), others did not (*e.g.*, additional nutrients may not cause higher phytoplankton production). Today's major concern is too little phytoplankton as the result of the introduced clam. Toxins are also of some concern to the food web in the Delta, but a direct cause-and-effect relationship has yet to be established.

Reservoir releases have prevented extreme salinity intrusion during drought years, such as occurred prior to Shasta Dam. The increased flow of fresh water through the Delta to the export pumps has provided a flushing action for water quality in the Delta. However, for this paper we have concentrated on what we believe are the two most important negative water quality impacts of exporting project water out of the natural Delta channels — namely, recycling of salts and additions of trihalomethane (THM) precursors.

Recycling of Salts

Salt buildup on San Joaquin Valley agricultural lands as a result of evapotranspiration and poor drainage has been a major problem since farming began. Historical civilizations have been lost as a consequence of salt buildup and today it is still a major problem worldwide. The west side of California's San Joaquin Valley is an area of high salt buildup resulting from poor drainage. In portions of the valley, one solution has been to drain the salts to the San Joaquin River (FWPCA 1967 and 1968; DWR 1965 and 1969; and Interagency San Joaquin Valley Drainage Program 1990). San Joaquin River salt loads combined with substantial agricultural return flows from Delta islands are recycled back into the valley by the water project export pumps.

As part of Reclamation's testimony in the SWRCB Decision 1630 hearings, Arthur (1987) evaluated salt loads entering and leaving the Delta via the water project export pumps. Among other things, these data indicated that:

- Central Valley Project exports generally had higher salt concentrations than the State Water Project, indicating interception of San Joaquin River water via upper Old River;

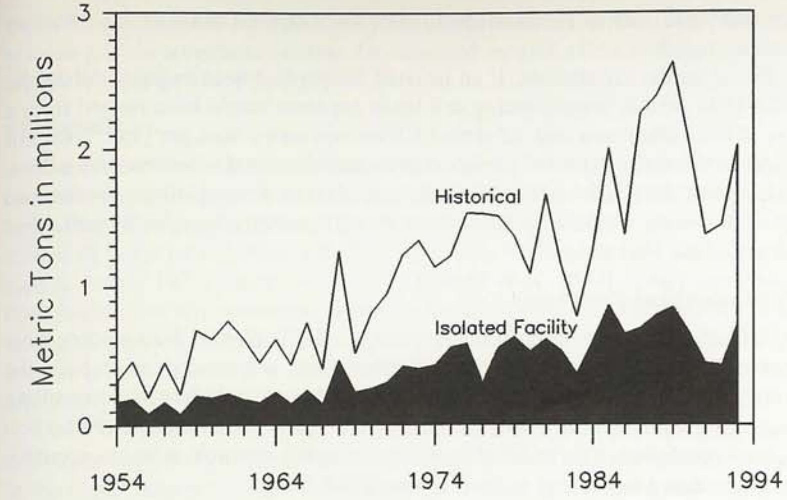

FIGURE 15. Annual combined SWP/CVP salt load exported vs. the possible salt load with an isolated facility diverting at Greens Landing on the Sacramento River. (Calculated from daily salinity and flow data.)

- Salt loads were generally higher at both export facilities in the summer/fall period, particularly in below-normal water years; and
- The salt load being recycled back into the San Joaquin Valley by the export pumps often exceeded the salt load entering the Delta via the rivers and streams (up to 300 percent).

Arthur concluded from these data that much of the salt load that was in excess of river inflow loads probably originated from Delta island return flows. Ocean-derived salt also contributes to the salt load leaving the Delta via the project export pumps. However, the projects are required to meet State Water Resources Control Board salinity standards at varying locations downstream of the pumps in the San Joaquin River, which reduces the amount of ocean salt diverted at the pumps.

A comparison was made between actual CVP/SWP export salt loads observed (1954-1993) with what would have occurred if an isolated transfer facility had been in place (Fig. 15). Annual historical export salt loads were calculated by converting mean daily records of specific conductance to total dissolved solids and multiplying the concentration by the daily export rate to determine annual loads. Projected salt loads for an isolated transfer facility were derived using mean daily data for the Sacramento River at Greens Landing near Hood (proposed diversion site for the Peripheral Canal) and multiplying by the daily export rates to obtain an annual load.

Total annual salt loads exported via the Delta-Mendota Canal ranged from about 0.2 million to 0.7 million metric tons per year in 1954-1967, increasing since 1968 to a peak of about 2.7 million metric tons per year in 1989. The increase is the result of increased water demand and export capacity when the SWP export pumps came on line in 1968. Periods of lower annual salt loads are generally associated with very wet years, such as 1982 and 1983, when water demand and salt concentrations are relatively low.

Based on the calculations, if an isolated facility had been in place during the 1954-1994 period, corresponding salt loads exported would have ranged from a low of 0.2 million to a high of almost 0.8 million metric tons per year. Total salt loads for the entire period of project exports was estimated to be about 45 million metric tons. Total salt load for the same period, if from an upstream Sacramento River diversion, would have been about 16 million metric tons, or 35 percent of the actual salt load exported.

Trihalomethane Precursors

Trihalomethanes are disinfection byproducts (DBP) formed during water processing at municipal treatment plants. Chlorine and chloramines have been the preferred disinfectant because of lower cost and high effectiveness in controlling bacterial growth in water distribution systems. New Environmental Protection Agency regulations have resulted in utilities initiating research on more expensive water treatment technology to limit DBPs (DWR 1994).

Delta waters, southern Delta in particular, have elevated concentrations of organic matter and bromides, which contribute to the formation of DBPs. Water diverted by the State Water Project, Central Valley Project, and Contra Costa Water District are generally higher in organic matter, bromide, and other mineral salts than water from the northern Delta. Sea water has been identified as the major source of bromides in the southern Delta.

Studies conducted in the 1980s (DWR 1994) documented sources of organic materials being exported by the Central Valley Project and State Water Project. These included streamside vegetation, decaying crop residues, algae, and sewage. The largest source appears to be the region's soils. Delta islands, consisting of high peat deposits, are constantly being eroded. Seasonal farming activities affect the amount of organic matter leached and drained from island soils, which eventually discharges into the Delta channels. These return flows are largely unregulated, and no treatment is required to remove organic materials (or any other substance) at the source of the discharge.

THMs would largely be eliminated (as would treatment problems and expenses incurred by municipal treatment plants south of the Delta) if Sacramento River water were not directly transported through the Delta.

Biological Impacts

When biological sampling was first initiated in the 1960s, abundance levels of important food-web organisms — phytoplankton, zooplankton, and many fish species — were relatively high in the Delta and Suisun Bay. These included periods of below-normal water years when the entrapment zone was located in the western Delta. In the early 1970s, the abundance of striped bass and certain food chain organisms began to decline in the Delta, followed by a further decline during the 1976-77 drought. After the initial Delta decline, abundance of striped bass and certain entrapment zone organisms began to decline in Suisun Bay. The Delta/Suisun Bay decline continued after implementation of Decision 1485 and became greatly accentuated during the extended drought of the 1980s (Herbold *et al*. 1992; Monroe & Kelly, 1992).

Phytoplankton

We believe the Federal and State water projects have had major impacts on estuarine phytoplankton (the primary producers at the base of the aquatic food web). Phytoplankton dynamics in the Delta and Suisun Bay have been extensively evaluated in the past (Arthur & Ball 1978, 1979a, 1979b, 1980; Ball 1977, 1987; Ball & Arthur 1979; Cloern *et al.* 1983; Stewart *et al.* 1984). Conclusions have been mainly that phytoplankton blooms in the Delta tend to occur when net flows through the central Delta drop, creating long residence times. Since the early 1970s, with increased water export through the Delta, the duration of bloom conditions has greatly declined.

Under the same conditions of Delta inflow and diversions from the Delta, recent evaluations by Jassby & Powell (1994) and Jassby (1995) of chlorophyll and flow in the upper estuary suggest that primary production in the Delta and supply of phytoplankton to the entrapment zone would be greater if the water were diverted from the upper Delta and not through the Delta. Such isolated diversion conditions would enhance the upper estuarine food web.

Phytoplankton growth dynamics in Suisun Bay and the entrapment zone have been studied and reviewed more extensively (previously referenced). Results of these studies and evaluations have all concluded that phytoplankton abundance is enhanced when the entrapment zone location is centered at the upstream end of Suisun Bay. This entrapment zone location retains entrapped phytoplankton adjacent to the shallow productive shoals, where adequate levels of light stimulate highest production levels. Longer duration of low outflows have moved the entrapment zone upstream into the lower San Joaquin River. Phytoplankton in this area are subject to less light causing lower production rates and also loss to entrainment caused by the export pumps.

The accidental introduction of the Asiatic clam, *Potamocorbula amurensis*, first observed in 1986, has had a devastating effect on the food web in areas of the estuary where the clam has become abundant (Nichols *et al.* 1990). Since 1987, in the Suisun Bay area and upstream to the freshwater boundary, the clam has reduced phytoplankton levels by more than an order of magnitude. Evaluations of the clam's filtering rate, assimilation efficiencies of phytoplankton and bacterioplankton, and their impact on the food web were studied by Hollibaugh & Werner (1991).

The major decline in phytoplankton abundance in Suisun Bay and the entrapment zone in recent years appear to have been caused by introduced species. However, the State and Federal water project operations are also impacting phytoplankton levels in Suisun Bay and the entrapment zone by flushing much, if not most, of the phytoplankton standing crop in the San Joaquin River portion of the Delta out the export canals. Based on our understanding of the estuary, we believe this is caused by:

- Increased flushing of Delta habitat (via reduced residence times);
- Delta entrainments; and
- Net reverse flow in the lower San Joaquin River, which increases the exposure of organisms to diversions leading to the export pumps and reduces the amount of phytoplankton being transported downstream and out of the Delta.

Zooplankton

Zooplankton are near the base of the food web and are consumed by larger zooplankton, immature fish, and some mature fish. Many species of zooplankton have also declined in recent years. For our analysis, we evaluated water project impacts on their abundance by reviewing zooplankton trends recently compiled by Obrebski *et al.* (1992) and Kimmerer (1992).

Obrebski examined the abundance trends (1972-1988) of 20 species of zooplankton in several families during spring, summer, and fall for distribution relative to salinity and for changes in geographical distribution (Obrebski *et al.* (1992). The more marine species (occurring downstream of the entrapment zone) with the exception of *Acartia* sp. had no downward trend in abundance. In the fall of 1987 *Acartia* sp. numbers declined by nearly one order of magnitude following the introduction of the Asian clam, *Potamocorbula amurensis*. This suggests that the water projects had little or no impact on their abundance.

Kimmerer (1992) evaluated the *Neomysis* sp. and *Eurytemora* sp. data relative to entrapment zone location as related to Delta outflow. He compared abundance differences in the entrapment zone between the Sacramento River side with similar differences up the San Joaquin River side (at locations relative to the confluence, Emmaton, and Jersey Point) for similar levels of outflow. In general, the declines were much greater in the lower San Joaquin River than in the lower Sacramento River, particularly for *Neomysis* sp., which have a much longer generation time.

Kimmerer also calculated losses of these species to export entrainment using a simple dilution model and concluded no significant loss. We believe the fact that modeling the loss as he did without incorporating the effects of two-layer flow and pumping mainly on higher tidal phases would not yield valid results.

We also believe the data relate well to what one would expect if reverse flows in the San Joaquin River had a negative impact on abundance. With the farthest upstream location for the entrapment zone, there was a slightly lower peak abundance for *Eurytemora* sp. but a drop in *Neomysis* sp. abundance of nearly an order of magnitude. Also, for both species the peak was in slightly higher salinity water (1.5 ppt higher), suggesting entrainment losses from the upstream end of their habitat range. The other significant observation was that when the entrapment zone was below Chipps Island, concentrations of both species were much higher in the San Joaquin River above the confluence than at equal distances up the Sacramento River. The opposite occurred (concentrations were much lower in the San Joaquin River) when the entrapment zone location was above the confluence. This effect was even more pronounced when the entrapment zone was above Emmaton.

When the entrapment zone is below Chipps Island, the net advective downstream flow in the Sacramento River is greater than in the San Joaquin River, and zooplankters tend to be flushed farther downstream. When the entrapment zone is upstream of the confluence and farther on, up to Emmaton, in the Sacramento River, the entrapment zone concentrates the two species, with opposing net bottom flows acting on their net vertical swimming behavior.

The opposite occurs in the lower San Joaquin River. Net bottom flows in the San Joaquin River (with similar upstream entrapment zone locations as the Sacramento River) are different under present conditions of export pumping. With high export pumping, the net flows are toward the central Delta and the export pumps. This results in net upstream movement and a dilution effect on organisms that concentrate in the entrapment zone.

Orsi (1986) observed that *Neomysis* sp. move up vertically in the water column during the day only on flood tides. The surface waters travel faster than the bottom waters. This characteristic of their swimming behavior also would accelerate their upstream movement in the San Joaquin River under reverse flow conditions. This also further explains the major decline in *Neomysis* sp. abundance when the entrapment zone is located above the confluence, and there is higher export pumping.

Fish

Information amassed over the years by the Interagency Ecological Program and others documenting water project impacts on estuarine fish is voluminous and extensive. For example, for many years Fish and Game has related striped bass abundance and survival to a combination of Delta outflow and export pumping. Results have been presented in a number of hearings, scientific publications, and Interagency Ecological Program reports (Turner & Chadwick 1972; Chadwick *et al.* 1977; Stevens 1979, 1980; Stevens *et al.* 1985; IESP 1987; Turner 1992). Most recently, Fish and Game developed a striped bass model for the Decision 1630 hearings (Kholherst *et al.* 1992) based on 20 years of data used to predict adult striped bass levels that would be obtained at various Delta outflows and export levels.

The U.S. Fish and Wildlife Service has also evaluated water project operations on salmon migration and survival. Studies based on the release of marked salmon smolts at various locations in the Delta, with subsequent recaptures (of a small percentage) at Chipps Island to determine survival rates, have documented many of the problems caused by directly diverting water from the Delta. These studies have indicated, among other things, that salmon diverted off the mainstem Sacramento or San Joaquin Rivers within the Delta have higher mortality rates than salmon smolts not diverted by water project operations (Fish & Wildlife Service, 1992).

Thousands of pages have been written over the years relating to the impacts of water project operations on the estuarine biota. This includes testimony presented in the various State Water Resources Control Board Bay-Delta hearings (D1379; D1485; D1630), numerous Interagency Ecological Program reports, scientific publications, and project planning evaluations. Therefore, we have limited our evaluation of biological impacts to a few examples of direct water project entrainment, changes in distribution and abundance of several fish species and a zooplankter that were historically abundant in the Delta, and modeling results evaluating water project operations on biological transport in the Delta.

Fish Entrainment. Both the Central Valley Project and State Water Project screen out most fish longer than about an inch prior to exporting water from the Delta. Louvers are used to direct fish to holding tanks, where they are counted and trucked to release sites in the Delta. Food web organisms, fish eggs, and larvae are essentially pumped out of the Delta via the Delta-Mendota Canal and the California Aqueduct.

For this evaluation, fish salvage records from the project fish facilities were obtained for 1978-1991. Also included in our analysis are total entrainment losses based on estimated predation losses.

Water Resources and Fish and Game have been conducting predation tests in Clifton Court Forebay over the last several years. Marked hatchery-reared salmon smolts were released near the entrance to Clifton Court, and the numbers captured at the fish screens were recorded. Losses were presumably the result of predation by striped bass and other predators. Predation losses were estimated at about 75 percent for Clifton Court. Although no field verification has been conducted, biologists have assigned a prescreen loss rate of 15 percent for the CVP intake.

Based on the these tests, Fish and Game has developed a correction factor for predation and louver efficiency at both the CVP and SWP that is applied to actual salmon salvage measurements to obtain entrainment numbers. The correction factor (for salmon) for the CVP is 0.568 and for the SWP is 4.33. However, predation and screen efficiency tests have not been done on other species because of insufficient larval fish for testing. Understanding the limitations, we assumed for this analysis that the predation loss estimates are applicable to the other species evaluated.

Average monthly entrainment records at the fish protective facilities for all fish species, 1978-1991, are summarized in Fig. 16. Most entrainment of fish occurs during May through August. Overall, entrainment at the SWP is many times higher than at the CVP fish facilities.

Entrainment peaks of all species combined (Fig. 16a) correspond to periods with high percent of inflow diverted (Fig. 7). Obviously, many fish species are highly susceptible to Delta export entrainment and export during this period.

Entrainment records for some key fish species indicate peaks occur in different periods. Chinook salmon entrainment, for example, is high from April through June, with a pronounced peak in May (Fig. 16c). Delta smelt (Fig. 16d) were abundant from May through July, with the peak in June. Striped bass, on the other hand, peak in June (Fig. 16b) and represent nearly all of the total entrainment estimates illustrated in Fig. 16a.

Export salvage records provide a good picture of when fish present in the Delta are susceptible to water project entrainment. Species of concern need to be evaluated relative to their time of maximum exposure to the export pumps and corrective actions should be taken to minimize their losses.

Effects on Distribution and Abundance. To evaluate the possible impacts of

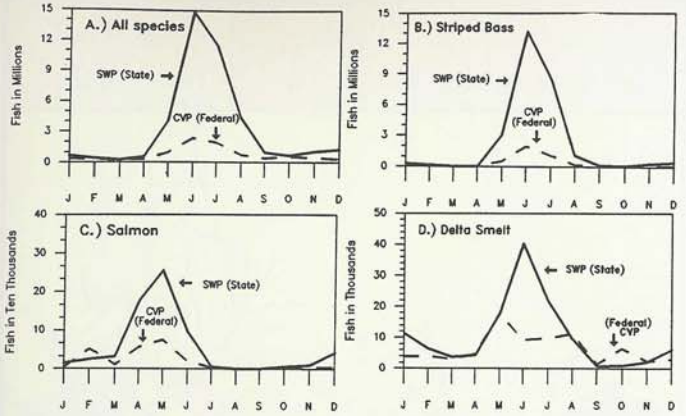

FIGURE 16. Average yearly entrainment of juvenile and adult fish at the DMC and SWP export facilities: (A) all species; (B) striped bass; (C) salmon and (D) Delta smelt.

through-Delta water transport on the biota, we examined long-term trends in the distribution and abundance of several zooplankters and key fish species that have experienced major declines in recent years. Three example species first began to decline in the Delta prior to their overall systemwide decline. *Trichocerca* sp. is a rotifer whose peak abundance historically occurred in the central and southern Delta. Striped bass, the focus of Fish and Game studies over the last 30 years, has the most complete data record. Delta smelt was listed as threatened in 1993. Salmon were not evaluated because their life history indicates they only pass through the Delta in a relatively short time on their outmigration to the ocean.

Reclamation's geographical information system (GIS) was used to graphically display changes in long-term average abundance and distribution of the three example species throughout the estuary prior to and following their decline. For example, GIS was used to plot the average concentration of *Trichocera* sp. (plotted as circles in Figures 17a-b) prior to its decline, 1967-1976, and following its decline, 1977-1992. These data illustrate a major reduction of this rotifer in the central and southern Delta and in the upstream end of Suisun Bay. We believe this major decline is at least partly attributable to reduced residence times and Delta entrainment resulting from direct transport of project water through Delta channels.

Although the timing of the decline for the two fish species differed (1981-1992 for delta smelt and 1977-1992 for striped bass), both species experienced little pre- to post-decline differences in average abundance on the Sacramento River side of the western Delta (Figs. 18a-c, 19a-c). The major declines in average abundance for both species occurred on the San Joaquin River side of the western, central, and southern Delta and the southern edge of Suisun Bay (although all of Suisun Bay showed a significant decrease). Again, we feel these observations are the results of

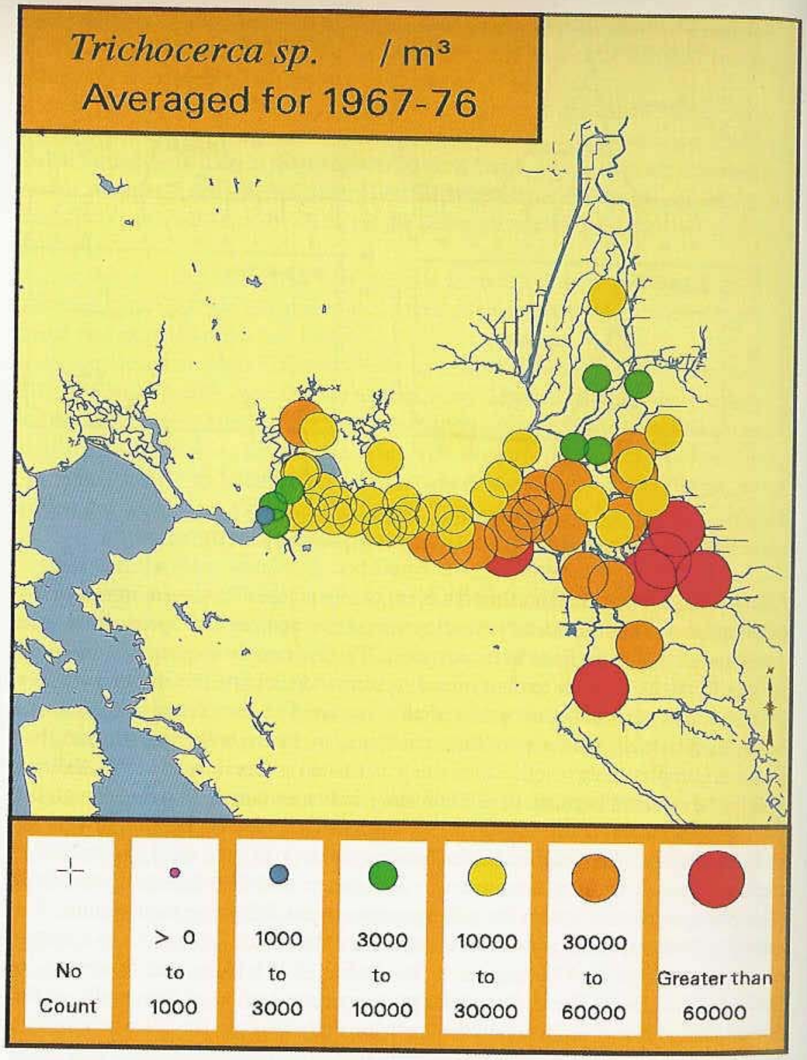

FIGURE 17A. Average density of the rotifer, *Trichocerca* sp., for each station of zooplankton survey prior to decline. Data from California Department of Fish and Game.

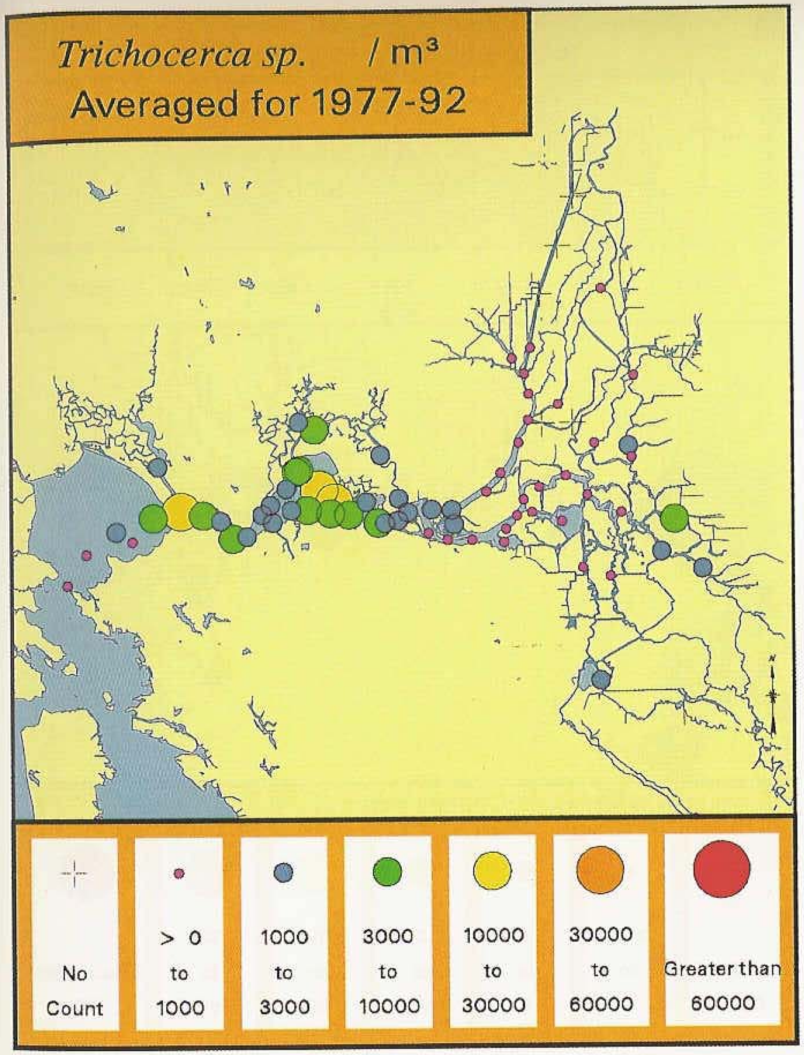

FIGURE 17B. Average density of the rotifer, *Trichocerca* sp., for each station of zooplankton survey following decline. Data from California Department of Fish and Game.

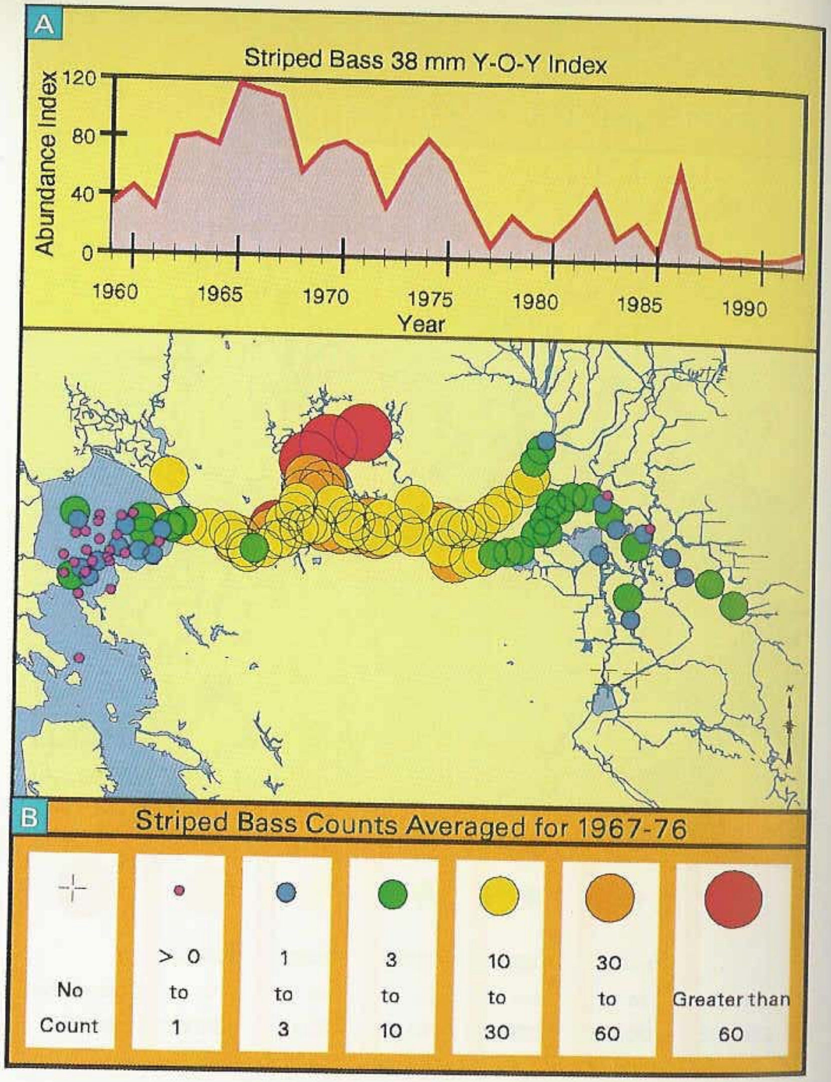

FIGURE 18(A/B). (A) Yearly Y-O-Y striped bass index from summer townet survey depicting declining abundance. (B) Average counts per station from midwater trawl survey prior to decline. Data from California Department of Fish and Game.

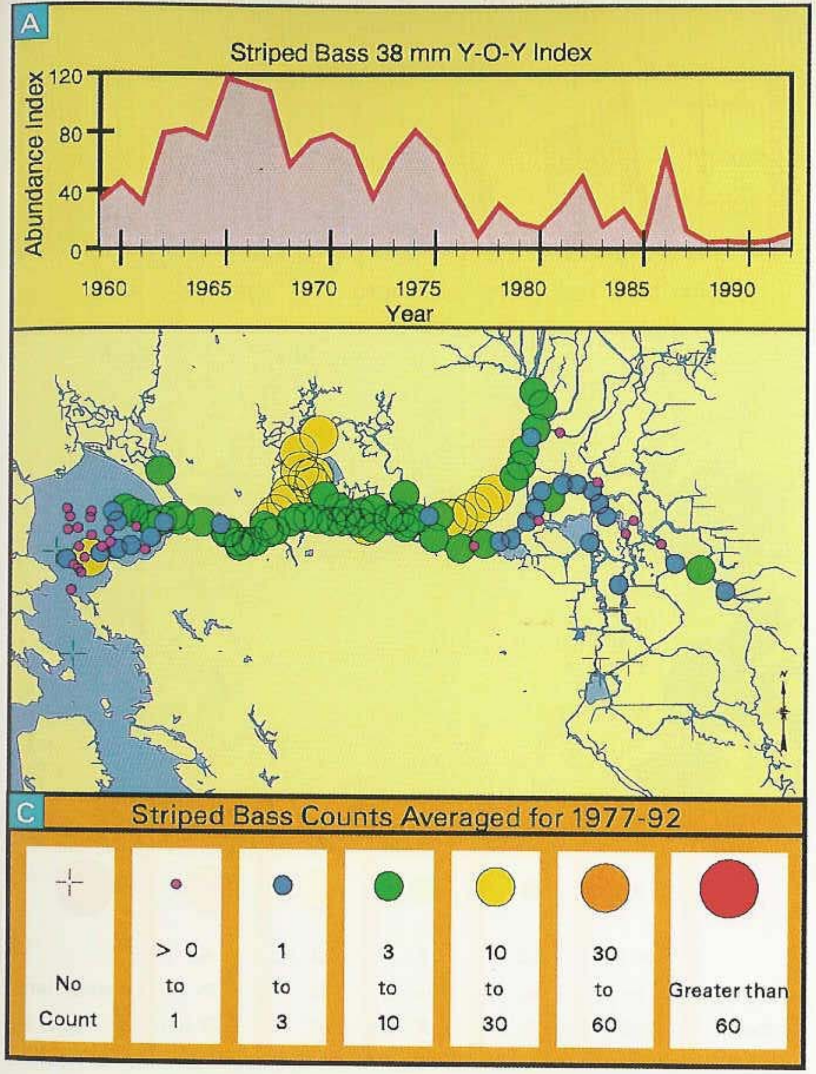

FIGURE 18(A/C). (A) Yearly Y-O-Y striped bass index from summer townet survey depicting declining abundance. (C) Average counts per station from midwater trawl survey following decline. Data from California Department of Fish and Game.

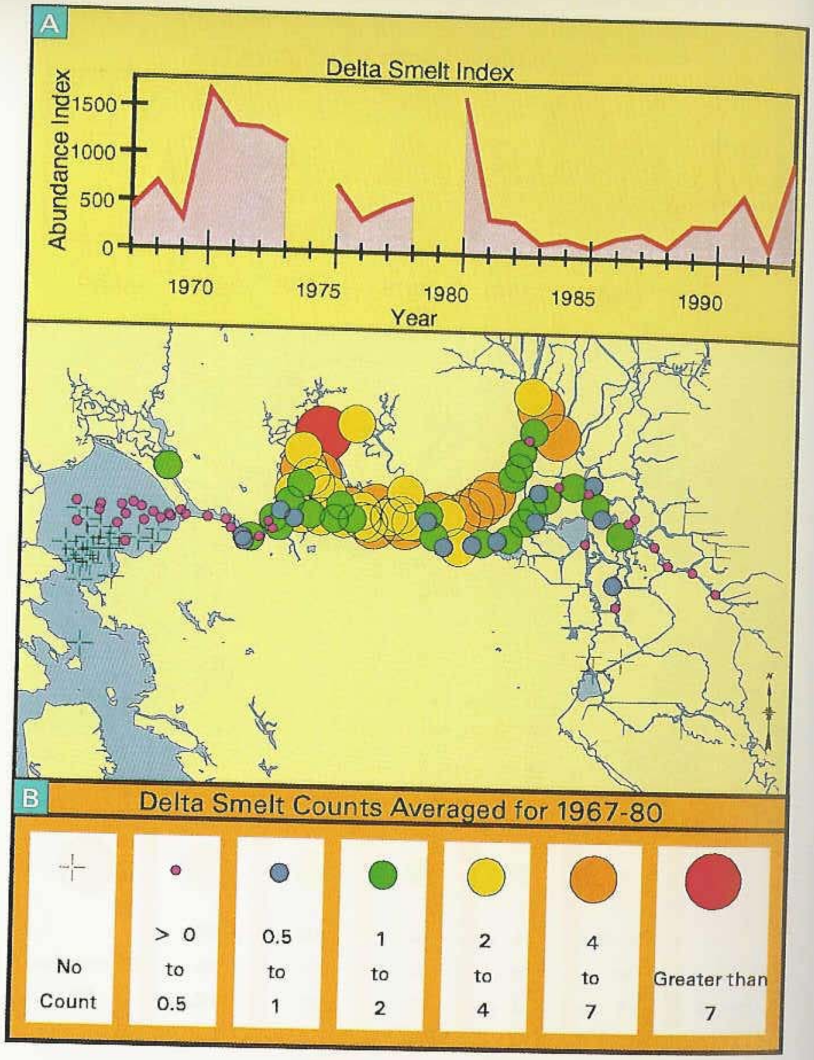

FIGURE 19(A/B). (A) Yearly delta smelt index from fall midwater trawl survey depicting declining abundance. (B) Average counts per station from midwater trawl survey prior to decline. Data from California Department of Fish and Game.

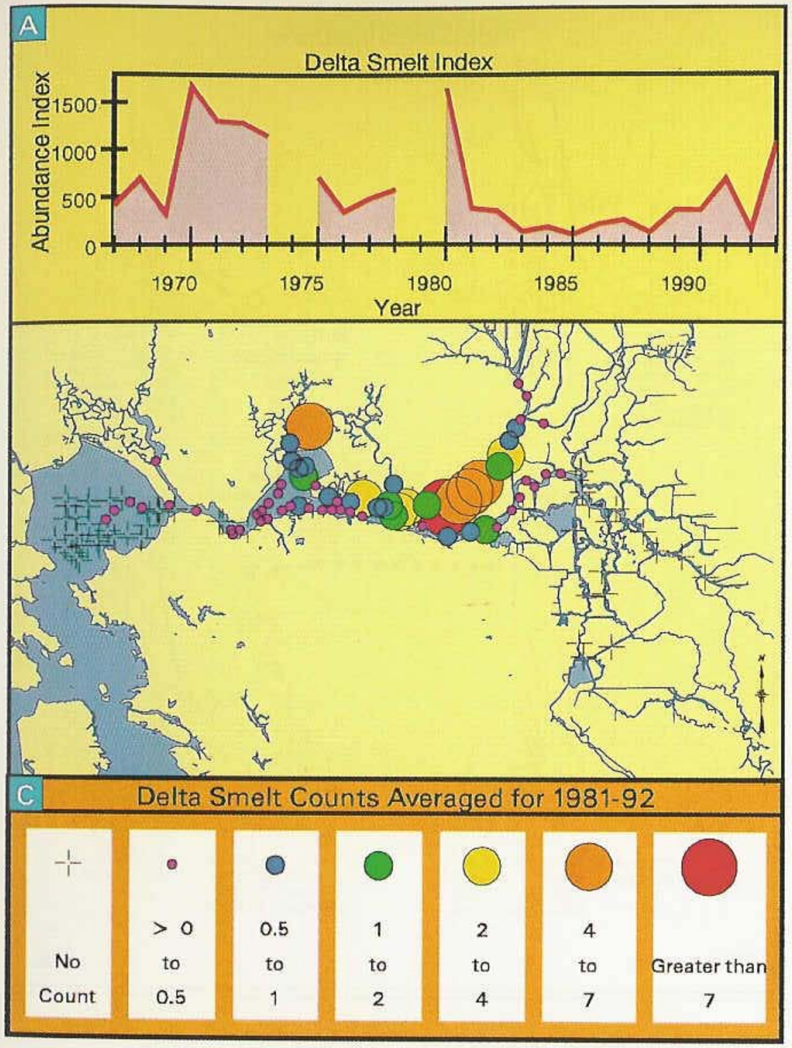

FIGURE 19(A/C). (A)Yearly delta smelt index from fall midwater trawl survey depicting declining abundance. (C) Average counts per station from midwater trawl survey following decline. Data from California Department of Fish and Game.

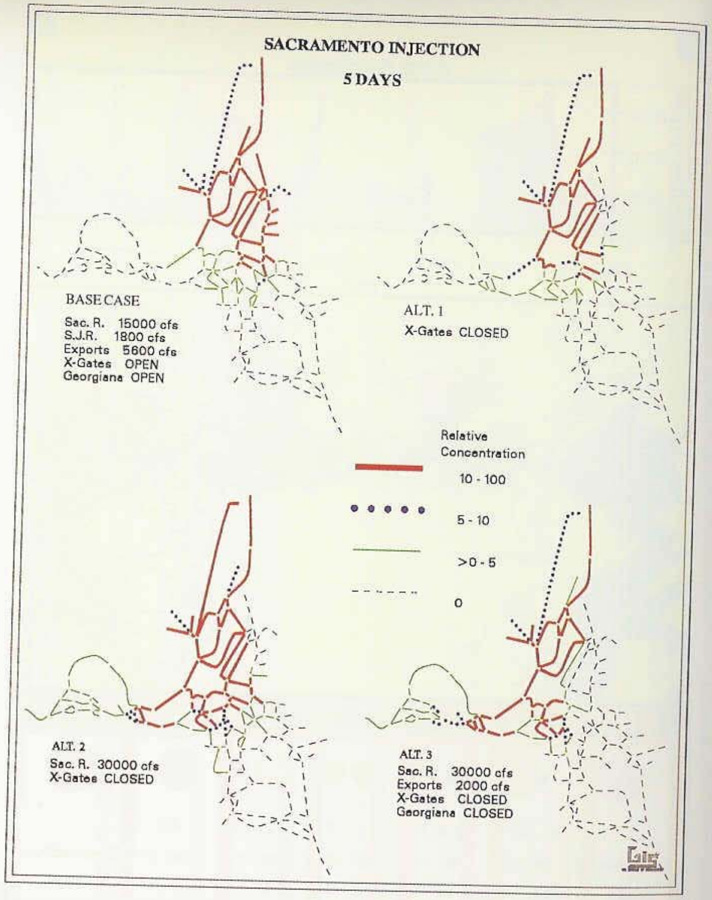

FIGURE 20A. Numeric model estimates of fish transport in the Delta under different management alternatives at 5 days.

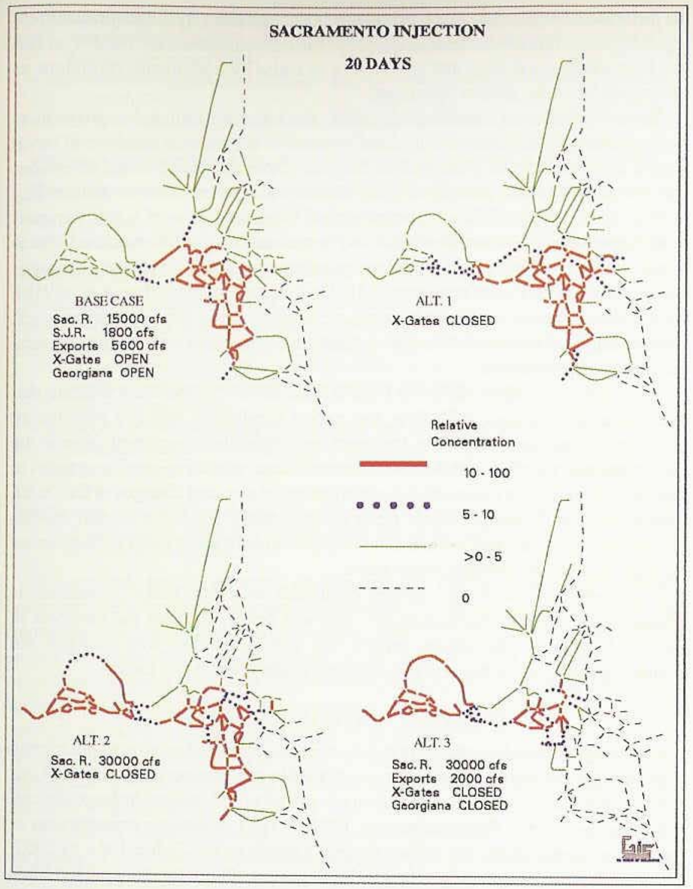

FIGURE 20B. Numeric model estimates of fish transport in the Delta under different management alternatives at 20 days.

the process discussed throughout this paper. Although these dynamic physical/biological interactions are difficult to quantify, further evaluations are needed on fish and food chain organisms that are subject to Delta hydrodynamic conditions as influenced by water project operations.

Numeric Transport Modeling. In 1989, Reclamation initiated a program to evaluate management options that could be taken to enhance the transport of larval striped bass through the Delta (where they are exposed to unscreened diversions and the project export pumps) to their downstream nursery area in Suisun Bay (Arthur *et al.* 1990, 1991a). A component of these studies used a salt transport model developed by Wong (Reclamation) to evaluate several physical and operational alternatives that would enhance downstream transport of striped bass eggs and larvae when they were most exposed to Delta entrainment (Arthur *et al.* 1991b). As a base case for the model evaluations, we chose average flow and export levels observed under Decision 1485, which were then compared over time to several management alternatives.

The results (examples shown in Figs. 20 and 21 for two periods) indicate that under average Decision 1485 flow and export conditions, salt and presumably planktonic organisms subject to transport are primarily transported toward the export pumps via Old and Middle Rivers. These modeling results appear to substantiate trends we observed in our evaluation of physical changes in the Delta. Comparisons with other available Delta hydrodynamic and salt transport models yielded similar results and indicated net transport toward the export facilities under average (and below-average) water years.

As a result of the model studies conducted thus far, Water Resources is developing a "particle tracking model" that will better represent the transport of biota in the Delta. The authors believe this will be the best tool available for evaluating short- and long-term management alternatives in the Delta.

SUMMARY AND CONCLUSIONS

Our analysis included long-term trends of project impacts based on major human alterations in the Delta. Where data are available and appropriate, we based our analysis of project impacts on major changes: prior to 1944, before the large Federal and State dams were first constructed; 1944 to 1951, following construction of Shasta and Friant Dams but before Federal exports in the Delta; 1951 to 1967, period of Federal exports only; 1968 to 1977, period of both the Federal and State exports and when Decision 1379 standards were in place; and 1978 to 1992, when Decision 1485 standards were in place.

Trends indicate that water project operation has impacted Delta hydrodynamics in below-average water years in the following ways:

- Since Delta exports began, outflows have been reduced but more stable from the spring through fall;
- Delta inflows have increased in the summer and fall;
- Winter and spring inflows have decreased;
- Percent of Delta inflow diverted has been much higher in the winter, spring, and fall since the combined SWP and CVP exports;

- Reverse flows in the lower San Joaquin, Old, and Middle River systems show increased duration during the extended drought and have occurred at increased frequency in recent years;
- Maximum entrapment zone intrusion into the Delta occurred most frequently prior to Shasta Dam;
- Least entrapment zone intrusion occurred following Shasta Dam construction until the mid-1970s; and
- Summer entrapment zone intrusions have been of greater duration since mid-1970s.

The effect of water project operations on water chemistry has resulted in:

- A major recycling and addition of salts into the San Joaquin Valley; and
- The addition of THM precursors, generated in Delta water, to urban water supplies.

Water project impacts on the estuarine biology have included:

- Increased suspended sediments being diverted;
- A corresponding increase in water transparency in the Delta;
- Increased intensity of *Melosira granulata* phytoplankton blooms (causing taste and odor problems and being a poor food source) in the western Delta apparently resulting from increased water transparency and hydrodynamic conditions created by operations;
- Reduction of food-web organisms from the Delta to Suisun Bay due in part to increased reverse flows and losses to project and Delta entrainment;
- Peak entrainment of fish by the water projects occurs during periods of high percent inflow diverted; and
- Declines of several key species (examples present: striped bass, Delta smelt, and *Trichocerca* sp. in the San Joaquin River side of the Delta, resulting in further declines in Suisun Bay.

We conclude that the observed declines in some fish and food chain organisms are most likely the result of some combination of: changes in flow patterns and transport in the lower San Joaquin River and central Delta (toward the water project export facilities); flushing of available central and southern Delta habitat (due to decreased residence time); and Delta islands and water project entrainment. These factors are exacerbated during below-normal water years. Directly exporting water through the Delta is much more of a problem than the amount of water exported. We believe a properly designed and operated isolated diversion facility with appropriate upstream monitoring and fish screening facilities would largely restore the Delta as good habitat.

In addition, exporting water directly out of the southern Delta results in the recycling of salts from the San Joaquin Valley, plus adding additional salts from Delta islands and ocean sources to the San Joaquin Valley. Forty years of exporting water with a high salt load has greatly added to major environmental and agricultural problems in the valley. An upstream isolated water diversion facility would have reduced the salt load by about 65 percent.

Organic materials, largely originating from Delta island discharge sources, form THM precursors. THM precursors are a major problem to urban water users that soon will require expensive treatment to remedy. Transporting water from upstream of the Delta would largely reduce this problem.

POTENTIAL SOLUTIONS

The estuary is a complex, highly dynamic system, that is under constant change. Numerous factors, some of which have been summarized in this paper, are also negatively affecting the estuarine water quality and biota. The focus of this paper, however, has been on the Federal and State water projects and how they impact the estuary.

The evidence for negative impacts of water project diversions in the Delta is indisputable and has been recognized and documented over the last 30 years. The early project engineers and biologists recognized the potential problems with direct water transfer through the Delta and predicted the general environmental impacts observed today. The question is more than when and how much do exports have to be reduced under the present system to prevent problems related to fish and water quality. We believe the preponderance of available information indicates that by continuing the direct transfer of water through natural Delta channels as presently done, there is probably no level that does not create some problems. Thus, *how* water is diverted is more of a problem than the quantity diverted.

Numerous advances have been made in technology and techniques to continuously monitor different fish life stages and flows in the Delta since the proposal to construct the Peripheral Canal was defeated on the 1982 referendum. Use of a new particle tracking model being developed by DWR as well as Delta and Suisun Bay 1-dimensional and 3-dimensional hydrodynamic models being developed by the IEP, combined with specific fish and water quality studies, will give project planners much better tools to assess alternatives before implementing any solution. For example, continuous monitoring of early fish life stages upstream of the Delta Cross Channel could provide sufficient warning to close the gates until peaks of fish are past the diversion point. There have also been advances in "fish friendly" methods of diverting water and fish screen technology.

Studies to assess all available options that will optimize resources levels while balancing all the beneficial uses in California are essential before any major changes are made in the system. The official position of the Department of the Interior and, thus, the Bureau of Reclamation is that *all* potential solutions to the Delta problems will be fully evaluated. On December 15, 1994, Reclamation and other Federal and State agencies involved in the Bay/Delta signed an agreement to provide a Bay/Delta Protection Plan (CAL/FED). CAL/FED, working with other interested parties, has provided the standards that are to be adopted by the State Water Resources Control Board in the next few months. These standards are expected to provide short-term measures to reduce the decline in fish abundance. Among other things, the Bay/Delta water quality plan requires evaluation of alternative facilities to transport water through the Delta.

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