Kathy [illegible]

EFFECTS OF FRESHWATER OUTFLOW ON
SAN FRANCISCO BAY BIOLOGICAL RESOURCES

A Report Presented to the
State Water Resources Control Board

by

California Department of Fish and Game

Exhibit 61

April 1, 1983

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

EXECUTIVE SUMMARY

The San Francisco Bay-Delta estuary is one of California's most important aquatic ecosystems. No other area in California can match its rich fisheries potential. It acts as a transition zone between the productive waters of the Pacific Ocean and the nutrient rich flows of the Sacramento and San Joaquin rivers. As such, it is a nursery area for various marine and estuarine species as well as a passageway for several important anadromous fishes. The Bay itself also provides habitat for many resident finfishes, shellfishes, and other invertebrates, mammals, and waterfowl. The value of the aesthetic and therapeutic benefits of fishing, hunting, and other consumptive or non-consumptive uses associated with these resources is difficult to calculate, but there is broad agreement that it contributes significantly to the health and well-being of the State's populace.

Water appropriation and development projects have been and are occurring throughout the Bay watershed. Adequate protection of fish and wildlife resources, in light of such development, requires a thorough knowledge of the freshwater flow needs of San Francisco Bay. The effects of proposed new water development projects on biological resources must be known if those resources are to be protected.

Division 2, Chapter 7 of the Fish and Game Code declares that it is the policy of the State to encourage the conservation, maintenance, and utilization of the living resources of the ocean and other waters under the jurisdiction and influence of the State. This mandate requires the Department to seek to maintain sufficient populations of all species of aquatic organisms. The Department strives to restore any depressed fishery resources shown to be related to reversible causes, such as flow diversions or degraded water quality.

A current concern of the State Water Resources Control Board (SWRCB) is the establishment of appropriate flow standards to protect the beneficial uses (including biological resources) made of water supplies in the Bay-Delta estuary. The Board has set water quality and flow standards which address the outflows needed to protect beneficial uses in the Delta and Suisun Marsh. However, these standards do not specifically address protection of beneficial uses in San Francisco Bay. The State Board is conducting a hearing on water availability in the Sacramento-San Joaquin River system. One subject to be considered is uncontrolled outflows to San Francisco Bay. The SWRCB Prehearing Staff Report states that the Board wishes to receive: (1) a summary of Department of Fish and Game results, thus far, from their "Delta Outflow/San Francisco Bay Study," and (2) an estimate of when the Department of Fish and Game will be able to make at least preliminary recommendations for Bay flow standards. The report further notes that, "an important issue in this hearing is whether the Board should reserve jurisdiction on future permits in such a way as to make it clear that future standards for the Bay may be used in determining the season of water availability in their permits."

This report presents information pertinent to the first issue while Departmental responses to the other issues will be provided in a separate document.

JUSTIFICATION FOR CONCERN

The natural physical distribution system in the Sacramento-San Joaquin River watershed has been altered in order to meet California's water demands. These alterations have changed the flow regimes, which have impacted ecological components of the system. Future alterations may cause additional ecological changes.

Historical Physical Changes

The primary result of flow regime alterations has been a reduction in winter and spring and an increase in summer and fall Delta outflows. These changes have been brought about by water development projects, with the largest being the State Water Project (SWP) and Federal Central Valley Project (CVP). These changes have dampened variation in Delta outflow. The most obvious physical change associated with that dampening is longer periods of increased average salinities.

While regulation has dampened annual variations in flow, substantial unregulated outflows still occur in the winter and spring of all but the driest years. The estuary receives runoff from a drainage basin which covers 40% of California (Conomos 1979). Inflow into the system is highly seasonal and is composed primarily of rain runoff during winter and snowmelt runoff during late spring and early summer. When significant rainfall occurs or unseasonally warm weather melts large snow packs, large unregulated outflows (pulses) move through the system. During wet years daily flows of 7,079 m^3/s (250,000 cfs) or more can reach San Francisco Bay approximately 8-10 days, or sooner, after major storms. For example, during the winter of 1981-82 unregulated, daily peak flows occurred during the months of December (6,229 m^3/s - 220,000 cfs), February (6,485 m^3/s - 229,000 cfs), and April (6,796 m^3/s - 240,000 cfs). If the storm event is intense and of short duration, flows may peak and decrease relatively quickly. These outflow pulses can be described by various flow-related characteristics and have major impacts on the physical-chemical components of the Bay-Delta system.

In addition to dampening outflow variations, diversion projects have decreased total inflows into the estuary. The annual natural flow through the estuary would average about 34 X 10^6 dam^3 (27.6 X 10^6 acre-ft), but diversions upstream from the estuary have halved this amount.

Another hydraulic alteration has occurred because an average of 88% of the inflow to the estuary comes from the Sacramento River, and up to 10,800 cfs of water is at times exported from the Delta. Pumping rates greater than 113 m^3/s (4,000 cfs) (or sometimes larger, depending upon San Joaquin River flows) draw water across the Delta causing reverse or net upstream flows in portions of the San Joaquin, Old, and Middle rivers. Such net upstream flows are typical in the late spring, except in wet years, and in the summer and fall of all years.

Planned Physical Changes

The estuary will be further altered by additional flow reductions caused by the SWP, CVP, and other local projects. DWR estimates that at the 1980 and

2000 levels of development, the annual outflow will be less than 12.3×10^6 dam^3 (10 maf) in 40% and 60% of all years, respectively. Annual outflows less than that occurred in only 10 years between 1922 and 1976.

Current seasonal outflow patterns are also expected to be altered by the year 2000. The greatest changes will be in future dry and normal years (Kelley and Tippets 1977). Unregulated, high Delta outflows will still occur in winter and spring during most of those years, but their magnitude will be significantly reduced and their duration shortened.

Characteristics of unregulated pulse flows may also be altered by future projects. For example, Shasta Lake is the principal water storage facility for the Federal CVP. Since its storage capacity is only 80% of the long-term average annual runoff at the dam site, the enlargement of Shasta Lake is one alternative being considered by water development agencies to develop additional water supplies. U. S. Bureau of Reclamation appraisal-level studies show that "enlargement of Shasta Lake would provide regulation of its total inflows, thereby essentially eliminating flood releases from the dam when downstream Sacramento River tributary runoff is excessively high" (2-Agency Agreement EIR, p. 15). Unregulated flow pulses would still occur downstream of such projects, but the overall characteristics of such flows would be altered significantly.

In addition to the large State and Federal water projects, other smaller, local development projects will cumulatively result in lowered flows into the Bay-Delta system. DWR estimates that by the year 2000, the annual SWP yield could decrease about 740,000 dam^3 (0.6×10^6 acre-ft) as a result of increased use in areas of origin, maturity of CVP contract obligations, and other prior rights.

Potential Ecological Impacts

The hydraulic alterations described above will result in significant ecological changes that may impact beneficial uses in the San Francisco Bay system significantly. Generally, altered flow regimes will affect certain physical components, which in turn can elicit certain biological responses.

Physical Impacts

The best understood physical/chemical factor that is affected by freshwater flows in most estuarine systems is salinity. Salinity levels are determined by mixing of freshwater inflows with saline flows of oceanic origin. River inflow varies widely so it affects salinity variations more than ocean water (Conomos 1979). Reductions in total freshwater flows cause the mixing zone to move upstream, thereby increasing salinities within the estuary.

Uncontrolled outflow pulses affect salinities significantly. Large pulses can cause sudden salinity reductions in localized areas and can also result in marked vertical salinity stratification. Reduction in magnitude or frequency of unregulated pulses would affect the magnitude and frequency of vertical salinity stratification.

In the Bay, nontidal currents are generated by winds and Delta outflow. By averaging velocity data over one or more tidal cycles, one can demonstrate a landward-flowing density current near the bottom and a seaward-flowing current near the surface. Such "gravitational circulation" has been detected in the channels over weekly and bimonthly time scales. Velocities associated with nontidal currents in North Bay are one-tenth those of tidal currents, yet they are important in transporting and cycling particulates in the Bay (Conomos 1979). The magnitude of gravitational circulation is affected by the magnitude of Delta outflow. Since Delta outflow affects are greatest in the central and northern reaches of the Bay, gravitational circulation currents are strongest and most consistent there (Peterson et al. 1975). When high flows move through the system, such currents can be equally strong in South Bay (Roy Walters, USGS, pers. comm.).

Other important physical/chemical factors are nutrients, detritus, and suspended sediment. Generally, the instantaneous concentration (as well as total system loads) of these components in the Bay system is related to Delta outflow. Without considering increases due to waste discharges or agricultural return flow, levels of these components are expected to decline as outflow is reduced, although a simple linear relationship does not exist. The importance of biological recycling, physical resuspension, and human inputs are evident, but knowledge of their relative importance compared to outflow is incomplete. Studies of the relationships between outflow and nutrients are needed to clarify flow-nutrient input relationships in the future.

Potential Biological Responses

Distributions. The most obvious biological response to flow change is altered distribution. Fish can respond by changing location when they are stressed by outflow-related conditions. Distributional changes can be brought about by various flow-related factors.

Salinity is one of the most important factors affecting the spatial and seasonal distributions of various species of fish and macroinvertebrates in estuaries. Most organisms are adapted to a specific range of salinities. If flows change salinities to levels above or below these preferred ranges, those organisms either die or move to other areas where tolerable salinities exist.

Flow reductions affect marine, freshwater, and brackish-water fish differently. For example, within defined boundaries of the estuary, flow reductions cause higher salinity upstream, reducing the amount of habitat available to freshwater fish and compressing their distributions. On the other hand, such flow reductions and salinity increases enlarge the amount of habitat in the estuary favorable to marine species.

Seasonality also complicates this picture. For example, a fish that spawns or grows in certain salinity ranges during spring may not be affected by flow reductions and increased salinities that occur in summer. On the other hand, spring flow reductions would increase salinities and cause the fish to disperse to another area for spawning, which might affect spawning success.

Flows also can affect organism distributions directly, as opposed to indirectly as described above. Larval or young individuals of various marine species can be physically carried to other areas of the system by increased velocities associated with higher flows. Some organisms may be carried downstream to areas where they can feed, grow, and develop. Other groups are transported upstream by density currents near the bottom. As outflows are reduced, this upstream flow also decreases and fewer individual larval forms may be transported upstream.

Abundances. The second significant way that flow changes impact biological resources is by affecting conditions which ultimately alter the abundance of those resources. Such biological responses to flow are much more difficult to document. Generally, the cause and effect relationship between flows and organism abundances operates through a chain of events rather than directly. Usually, other mechanisms that are stimulated or regulated by flows affect short or long-term survival. Some of these mechanisms increase abundance while others lower abundance.

Some flow-related mechanisms include:

1. Salinity Interactions - Flow-induced salinity change is the most obvious mechanism that affects organism abundance. Long-term inflow changes can alter the average salinity of the system, which favors organisms that are most tolerant of those salinity conditions and allows their numbers to increase.

2. Flow-Related Currents and Circulation Patterns - Flows can transplant organisms towards or away from areas where survival can be directly affected. In the case of reduced flows, organism distributions would generally be translated upstream, while increased flows would generally shift distributions downstream. Various environmental factors could either favor or inhibit organism survival and abundance at these new locations. If food is not available, cover is not appropriate, toxic conditions exist, or water diversions are present, overall abundance is likely to be lowered (e.g. salmon fry transported to San Francisco Bay may not survive as well as in the Delta). On the other hand, if the post-transport conditions are suitable, or better than pre-transport conditions, abundances may be enhanced.

   Increased flows may disperse young fish into areas not otherwise available, which results in decreased competition or less predation than that existing where the young fish were earlier concentrated (e.g. young striped bass are carried downstream into Suisun Bay by higher flows). Flows also limit areas that are acceptable for spawning, thereby changing spawning success and subsequent population densities. Finally, flows can sometimes affect the time that various fish are exposed to predation pressure. For example, if flows affect the time period young salmon spend in the system, they may alter salmon abundances by changing the number taken by predators while in the estuary. High flows would move salmon through the estuary, while low flows would slow their migration and allow predators to eat more.

3. Flow-Related Nutrient Effects (Fertility) - Nutrient levels may increase with increasing flow thereby enhancing the base of the

food chain. This increased food production can be ecologically translated into better survival and greater organism abundances in the higher trophic levels (e.g. fish or invertebrates).

4. Flows and Pollutants - Water quality constituents in outflow, particularly toxicants, can affect the abundance of organisms in estuaries acutely or chronically. Flows can also mitigate the effects of certain pollutants in the system.

DOCUMENTED FLOW/ECOLOGICAL RESPONSE RELATIONSHIPS

Existing knowledge about the ecological impacts of freshwater flow in estuaries is somewhat limited. However, some understanding of such relationships can be obtained from the literature and from information developed on the San Francisco Bay-Delta system.

Flow/Ecological Relationships In Other Systems

The effect of freshwater flow on biological resources has been documented in estuaries around the world including: Raritan Bay, Chesapeake Bay, St. Margaret Bay, Southern Florida estuaries, the Gulf of Mexico systems, the Columbia River estuary, Strait of Georgia (Vancouver, B.C.), Russian systems, the Nile River estuary, and the Murray River in Australia.

The most comprehensive effort directed to determine the effects of freshwater inflow upon bays and estuaries was conducted on seven estuaries in Texas by the Texas Department of Water Resources. This study resulted in several interesting conclusions: (1) within an individual estuary, different components of the fishery respond differently to seasonal inflow patterns; (2) finfish were negatively correlated with increasing winter inflow, while two shellfish groups correlated positively; (3) responses of taxonomically similar shrimp to flow differed; and (4) inflow responses are unique to individual estuaries.

The Texas study found that, overall, only 31 to 47% of the inflowing surface water can be considered surplus if estuarine subsistence flows are desired. Subsistence flows are defined as flows necessary to minimize annual inflow while meeting salinity standards required to maintain endemic biological community structure in estuaries and to provide for minimal marsh inundation needs (fishery harvest not considered). If flow to meet subsistence levels and to maintain commercial fishery harvest at average 1962 through 1976 historical levels is an objective, up to 100% of the gauged inflow is required in some estuaries. The selection of such objectives in Texas was considered arbitrary.

Investigations in the Gulf of St. Lawrence have centered on primary productivity and nutrient dynamics. Fresh water flowing into St. Margarets Bay was responsible, by direct input and induced offshore upwelling, for 56% of the total nitrogen in the euphotic upper layers. Further, it was found that correlations existed between high inflow levels and the abundance of lobster larvae (*Homarus americanus*) in the Northumberland Strait region of The Gulf. Finally, analysis of commercial harvests from the Gulf of Maine yielded significant correlations (both positive and negative) between certain monthly outflows and subsequent fishery harvests for every species examined.

In the Soviet Union, extensive water development on rivers tributary to the Black, Azov, and Caspian seas has been accompanied by ecological changes such as reduced fishery harvests in the associated estuaries. Primary flow-related causes include: (1) reductions in fish spawning in temporarily flooded lowlands in the lower reaches of some rivers; (2) reductions in nutrient and sediment input important to lower level food chain organisms; (3) overall salinity changes, resulting in replacement of desirable estuarine species by less desirable species; and (4) reductions in outflow-related dilution of pollutants.

Flow/Ecological Relationships In The San Francisco Bay Estuary

Some information on flow/ecological relationships in the San Francisco Bay estuary is available. Some of it has already been documented in the system upstream of Carquinez Strait, while more recent information from the Bay proper is currently being developed in ongoing studies.

Past Investigations

The San Francisco Bay-Delta system has undergone some dramatic changes, and coincidently certain organism populations have declined. For example, the striped bass population has seriously declined, leaving the adult population at one-quarter of what it was 20 years ago and the production of young over the last 5 years at one-third to one-half the expected values. Studies conducted from 1959 to 1976 have shown that young bass survival was directly correlated with outflow and diversions from the Delta, and that variations in young bass survival appears to be important in determining subsequent recruitment to the fishery. However, from 1977 to present, young bass survival has been consistently poorer than expected for the amount of outflow and diversions (Stevens 1979). A State Water Resources Control Board-organized study conducted by the Striped Bass Working Group (1982) revealed several factors that in combination could help explain the reason for the decline and why the population is not recovering. These factors include the following:

1. Phytoplankton production in Suisun Bay and the Western Delta has fallen to extremely low levels.

2. A large source of organic nutrients that could feed young zooplankton (and thus bass) has been eliminated through treatment plant conversion.

3. Diversion projects have resulted in high losses of young bass which has lowered the number of adults available for subsequent spawning.

4. Undesirable levels of toxicants in striped bass may be impacting populations.

5. Adult populations have been reduced to a point where total egg production is only about 10% of what it was 20 years ago. Egg production may be limiting the number of young bass, and subsequently the spawning adults.

The Dungeness crab fishery is one of the most important in the San Francisco Bay region. Landings typically fluctuated between 1 and 8 million pounds, with an average of about 3 million pounds (Skinner 1962), until there was a drastic population decline in the early 1960's. The population has continued at a very low level to the present, thus being a long-term trend rather than a short-term fluctuation. A special study was conducted in order to determine the reasons for this decline and recommend procedures to improve the situation (Dungeness Crab Research Program 1981). The crab decline was found to be most closely correlated with persistent changes in ocean conditions that began 3 years prior to the start of the decline. These changes included increases in water temperature and in the frequency of intensified northward-flowing currents. The ovaries of female crabs were smaller in the warmer water, while hatching success was maximized in colder water. Thus, the long-term effects of warmer water lowered production. Additionally, strong northward-flowing currents have transported early crab larval stages, which are found progressively further offshore as they develop, farther north than usual, making their subsequent inshore movement into the Bay at later stages more difficult. The available evidence does not indicate any relationship between crab declines and Delta outflows.

It was found that juvenile crabs grow faster in San Francisco Bay than in nearshore areas outside the Bay, although the reason remains unknown (Dungeness Crab Research Program 1981). Studies showed that 80% of the 1975 year class entered the Bay complex (Tasto 1979), thus San Francisco Bay appears to be a major nursery area for the Dungeness crab.

White sturgeon abundance has also declined between 1967 and 1974, and then increased from 1974 to 1977, but the total catch has continued to decline. Three potential causes for this decline have been suggested. Degradation of habitat for juveniles may occur due to high diversion rates and low freshwater flows. Low freshwater flows may restrict available habitat or reduce food supplies, while high diversion rates either directly remove fish or disrupt migration patterns. Environmental contaminants, in particular PCB's, which have been found in high levels in adults, may reduce the survival of larval sturgeon and subsequent recruitment. Declines in spawning stock size also may be an important factor in the decline.

These and other studies in the system have identified the following flow-related phenomena: (1) the proportion of young striped bass in downstream nursery areas increases as flow increases (Turner and Chadwick 1972); (2) the opossum shrimp (Neomysis) is hydraulically and behaviorally concentrated in and just upstream of the "entrapment zone," and the zone moves in relation to flow, resulting in changes in this shrimp's distribution (Orsi and Knutson 1979); (3) high river flow controls the distribution and abundance of young salmon, shad, and longfin smelt in the system by dispersing them to downstream areas (Stevens and Miller 1980); (4) in response to large Delta outflows (and subsequent reduced salinities throughout the Bay), Dungeness crabs consolidate in areas of salinity greater than 10 $^{\circ}/oo$ before emigrating out of the Bay (Tasto 1983); (5) species composition of fish in Suisun and Napa Marsh sloughs varies with salinity and flow (Herrgesell et al. 1980); (6) young-of-the-year striped bass abundance indices correlate with flow, and increased survival associated with increased flow has been shown to be a major factor affecting abundance of striped bass recruits 3 years later (Stevens 1977); (7) zooplankton and zoobenthos distributions are correlated most strongly with chlorinity (Painter 1966), which in turn is dependent upon flows; (8) the salinity gradient is very influential in determining the distributions of many (61) species of fish in the Western Delta and San Pablo Bay (Ganssle 1966); (9) high flows and neap tides in South Bay result in increased chlorophyll a levels (Cloern 1982); and (10) Louma and Cain (1979) have found that the rate of freshwater discharge is a primary factor that mitigates the contamination of Macoma balthica in South Bay.

These facts indicate that freshwater flows are a major factor controlling the distribution of aquatic animals in the Bay-Delta system, and that they influence the overall abundance of some animals.

Present Study Results

From 1980 to present, the Four-Agency Delta Outflow/San Francisco Bay Study has carried out a field program to determine the relationship between freshwater flow and fishery resources in the Bay system. To date, the data from this effort has merely been summarized, so data analysis is very preliminary. The information is interesting since it was collected during two different wet years (1980 and 1982) and one dry year (1981). Preliminary findings include:

1. Pacific herring, northern anchovies, longfin smelt, and gobies were the most numerous larval fish collected.

2. Some changes in abundance seem to be related to flow. For example, catches of larval longfin smelt, English sole, and larvae of rare marine species were higher in 1980 and 1982 than in 1981, a low flow year. Adult catches of estuarine species (e.g. longfin smelt, staghorn sculpins, yellowfin gobies, and starry flounders) and marine species (e.g. English sole and speckled sanddabs) were higher in 1980 and 1982, while marine species (e.g. surfperch, jacksmelt, plainfin midshipman, and northern anchovies) were more common in the catches in 1981. Crangon franciscorum, one species of Bay shrimp, was most numerous in 1982, while its abundance was 3.5 times lower in 1981.

3. There is some evidence for larval transport by gravitational circulation. Larval Pacific herring and northern anchovies were in the Western Delta despite the lack of evidence of any spawning activity there. In addition, English sole larval distributions were more widespread during high flow years.

4. The distribution and migrations of all three species of Bay shrimp seems to be correlated with salinity, but other variables have not been included and may modify these findings.

Conclusions

Estuarine research has documented that freshwater flow reductions cause significant biological changes in estuaries of all types. In most cases, changes result from specific responses by organisms to physical conditions such as increased salinities, altered circulation patterns, reduced flood plain inundation, and reduced nutrient input. In some cases, the same flow change favors some organisms, and negatively impacts others. Some biological changes occur only in certain types of systems, while other responses are more general and occur in most estuaries. Distributional change due to flow alteration is a general response, yet it can also be specific to certain systems. Abundance of biological resources can also be altered by flow, but such changes are difficult to document because of obscure "chain-of-event" relationships and difficulties with biological sampling. Therefore, it is not possible to ascertain how general these flow-related abundance changes are, but available information indicates that they may be common and are often species and system-specific. Some of the biological changes associated with flow reduction are continuous functions, while others involve threshold effects. Threshold effects are significant because even small changes in flow can sometimes have major biological effects.

Responses, as described above, have been documented in estuaries around the world; however, it is prudent not to generalize regarding distribution/abundance/flow impacts because of the wide variation in biological response, both on a species and system-specific basis.

FUTURE RESEARCH NEEDS

Before San Francisco Bay flow needs can be determined, more definitive information needs to be obtained. We already know that outflow reductions will affect Bay salinities, but, we must determine if such altered salinities will appreciably affect fish abundances. We also know that some organisms use circulation processes for transportation of their young, but, we need to know the quantitative relationship between outflows and these circulation processes. Further, we need to determine if any observed flow-related circulation changes will impact those organisms known to use currents in the Bay, and if so, whether or not such impacts will be detrimental.

We know that the Bay acts as a nursery area for several important marine species, but, we do not know the overall significance of this function and whether it relates to freshwater flow. For example, English sole larvae and young Dungeness crabs use the Bay while adults do not. The economic and biological importance of Bay-produced sole and crabs is unknown, as is the relationship of flow to such production.

Bay shrimp are an important part of the Bay food chain. They are consumed by striped bass and sturgeon. Environmental conditions in the Bay certainly affect shrimp production, but, the importance of any outflow-related conditions, such as salinities, circulation, and nutrients to shrimp must be determined.

Other factors, such as pollution, affect fishery abundance in the Bay. We must determine the relative importance of such factors and how they relate to flow-caused impacts. Such an objective necessitates close coordination with other Bay-related studies.

Finally, because of the literature documented, wide variation in biological response, both on a species and system-specific basis, it is necessary to develop flow/resource relationships specifically for San Francisco Bay conditions. Reported amounts of reduction in flow in other systems that caused adverse responses have ranged from 0 to approximately 40%. We have already diverted approximately 50% from the Bay system.

DIRECTION OF PRESENT RESEARCH EFFORTS

Although there is no sharp dividing line between freshwater flow needs for the Bay and other parts of the estuary, most existing relationships between flows and fishery resources have been developed from studies within or upstream of the entrapment zone. There are presently few studies addressing the importance of freshwater flows in the Bay proper. Some efforts are investigating various processes or components of the system that are related to outflow, but only the Four-Agency Delta Outflow/San Francisco Bay Study is making a comprehensive effort to document systemic fishery-flow needs downstream from the entrapment zone. The overall goal of this cooperative study is four-fold: (1) determine how changes in outflow resulting from State and Federal water projects could alter the hydrodynamics and salinity gradients of the estuary; (2) identify those organisms most vulnerable to outflow-related changes; (3) determine how those organisms are likely to react to the projected changes; and (4) recommend flow and salinity standards (or other management strategies) needed to maintain fish and wildlife resources. These goals are being met by conducting one physical and six biological study elements. The physical elements are designed to determine the magnitude, duration, and location of biologically significant variations in hydrodynamics, salinity, suspended solids, and nutrients within the system through analysis of both model and prototype information. The biological elements are all field-oriented and designed to determine the relationships between outflows and distributions and abundances of macroinvertebrates and fish in the Bay. This program began in late 1979 and field work commenced in the Bay in January, 1980. Most of the first 3 years of field data have been processed and entered into the data storage/handling system, but to date only preliminary analyses have been made.

Another major research effort currently underway in the Bay is a program of the U. S. Geological Survey (USGS). The broad goals of these studies of the Bay system are to understand processes and measure rates by which water, solutes, particulate matter, and organisms interact, and to develop and verify conceptual and numerical models of these interactions. A systematic field sampling and laboratory analytical program has been developed during a long-term study (1969-present) of the system. Factors measured include salinity, temperature, dissolved oxygen, carbon dioxide concentration, pH, the abundance of plant nutrients, and the abundance, size, and composition (organic and mineral) of suspended and sedimented particulate matter (such as chlorophyll a concentrations) (USGS 1979). During 1980, USGS combined their efforts with an intensive survey of flow and circulation carried out by the National Oceanic Survey (NOS).

Recently, the program has reduced field data collection and redirected efforts toward data analysis and interpretation. Although this program is not specifically designed to address outflow needs of the Bay, resulting information has applicability to outflow questions.

Another potentially significant Bay research program is the SWRCB Aquatic Habitat Program. The goals of this program are: (1) to assess the health of the aquatic organisms in the Bay related to the effects of water pollutants; (2) to determine the specific causes of any adverse changes in the health of the Bay that appear to be pollutant-related; and (3) to use funds most effectively by coordinating activities of this program with all other monitoring and research activities in the Bay. The program, as yet, has only begun initial efforts in field data collection but long-term studies of hydrodynamics, and local and regional effects of pollution are planned. The plan is based on the premise that aquatic organisms are better indicators of water quality than more traditional physical-chemical measurements. Information collected in this program is needed to distinguish between pollution effects and the effects of flows on natural biological processes being studied in the Four-Agency Delta Outflow Study.

In addition to these large, agency-coordinated studies of San Francisco Bay, other independent or university-related efforts are ongoing. Appendix 2 (pages A-65 through A-77) of the Aquatic Habitat Program-Master Plan For Monitoring the San Francisco Bay-Delta Estuary provides a description of most of these studies. Again, these efforts are not directly involved in determination of Bay flow needs, but information that they obtain will be invaluable in the decision making process.

CHAPTER ONE

HYDROLOGY

The conclusions and recommendations presented in the summary section were based upon extensive literature searches, review of existing research information from San Francisco Bay and other systems, and analysis of new information collected as part of the Delta Outflow/San Francisco Bay Study during 1980-1982. The remainder of this paper will substantiate our conclusions and recommendations by discussing in some detail the information we have generated during research on the topic of Delta Outflow.

DELTA OUTFLOW CHARACTERISTICS

Before discussing Delta outflow, the term must be defined. According to Conomos (1979), San Francisco Bay receives runoff from a 163,000 km^2 (62,934 sq. mile) drainage basin which covers 40% of the land area of California. The main river systems in this basin are the Sacramento and the San Joaquin. The Sacramento provides approximately 88% of the inflow and therefore has a greater influence on the system. Inflow into the Delta from these systems is highly seasonal and is composed of rain runoff during winter and snowmelt runoff during early summer (Conomos 1979). Delta outflow, as used in this paper, is that part of this river inflow that passes from the Delta past Chipps Island into the Bay. Delta outflow is not measured directly but is computed by subtracting estimates of net water consumption in the Delta and Federal and State water exports from the measured inflow to the Delta (Figure 1-1).

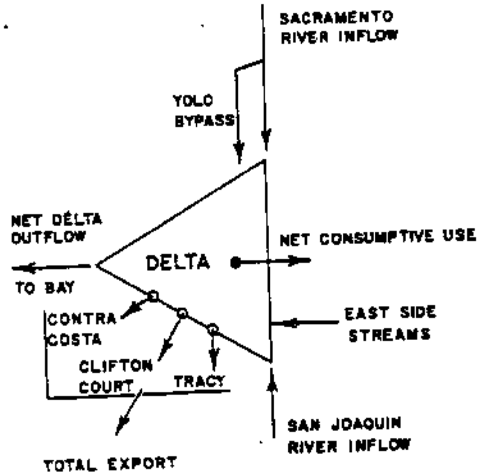


FIGURE 1-1. Schematic Diagram of Delta Water Balance from Conomos (1979).

Non-Delta inflow to the Bay is about 10% of the total inflow. Discharge from rivers such as the Napa and Petaluma are relatively small compared to Delta outflow, and the effects of such inputs are usually masked by those of the larger Delta outflow (Conomos 1979). Other local inputs come from intermittent tributaries and from wastewater discharges into the Bay. Although these non-Delta inflows influence some local environmental conditions (e.g. Coyote Creek in South Bay), the overall ecological significance of such impacts is currently unknown.

When Delta outflows are studied over time, one can observe certain characteristics that typify or describe these flows. Some of these characteristics include volume, velocity, and quality. The quantitative limits or bounds of these characteristics are system specific and are related to factors such as watershed size, weather patterns, bottom types, hydraulic configurations and/or manipulations, inputs, and many more. Over many years of record, outflows demonstrating certain combinations of outflow characteristics occur routinely, and therefore system specific generalizations regarding outflow characteristics can be made. Such a generalization for the San Francisco Bay system follows.

Volume

One of the most descriptive characteristics of Delta outflow is its volume. Volumes are recorded as daily, monthly, or annual averages. On a worldwide basis, the Sacramento River inflow is not large (Table 1-1). Using a 55 year record, Kelley and Tippets (1977) have characterized typical Delta outflows for wet, normal, dry, and critical years. They found that historic monthly Delta outflows (excluding bypass flows) range from approximately 7,500 cfs to 130,000 cfs in wet years and from 7,500 cfs to 18,000 cfs in critical years.

TABLE 1-1. Selected World Rivers Ranked by Discharge (from Hedgpeth 1982).

River (Country)	Rank	Discharge $10^3 m^3$/sec
Amazon (Brazil)	1	175.0
Mississippi (USA)	6	18.0
St. Lawrence (USA, Canada)	16	8.7
Volga (USSR)	17	8.3
Dnieper (USSR)	39	1.3
Sacramento (USA)	46	0.7
Colorado (USA)	49	0.6
Thames (England)	63	0.08

Greater extremes in outflow volume occur on a daily basis. Daily outflows can vary from a negative flow of several thousand cfs to approximately 409,000 cfs (Dec. 23, 1955).

Velocity

Another significant characteristic of Delta outflow is velocity or the speed of water movement, commonly referred to as current. More technically, such currents are called non-tidal currents. Non-tidal currents can be wind driven, tidally induced (residual), or caused by density differences (gravitational or estuarine circulation) or by inflows. Inflows and tidally induced residuals are more or less unidirectional with depth. Wind driven residuals have the surface flow following the wind and a return flow at depth. Density currents are driven by the horizontal density gradient and their strength increases with the depth of the water.

Direct measurement of non-tidal currents in the Bay is very difficult due to the larger ebb and flood tides. However, by averaging velocity data over one or more tidal cycles, one can demonstrate a landward-flowing density current and a seaward-flowing surface current. Such "gravitational circulation" has been defined in the Bay channels, over weekly and bimonthly time scales (Conomos 1979). Existing information suggests that the velocity of non-tidal, outflow-driven currents in North Bay can be as large as 50 cm/s. The density currents are highly variable in space and time. Typical magnitudes are 5-15 cm/s.

More recent velocity information has been developed in 1982 for South Bay by Roy Walters of USGS. He found wind related net horizontal velocities on the order of 20 cm/s for the return flow in the channel while tide induced mean flows were approximately 5 cm/s (Walters, pers. comm.). He found that tidally averaged bottom velocities can reach 15 cm/s in a seaward direction (moving out of South Bay) while surface water is moving into South Bay during large outflow pulses. When such flows subside and Central Bay conditions return to normal, South Bay behaves as a partially mixed estuary and net bottom flows of 5-15 cm/s can be found moving back into South Bay (Walters, pers. comm.).

It is important to recognize that non-tidal current velocities are variable in magnitude and dynamically related to Delta outflows (river discharge), meteorology (Cheng and Conomos 1980), and location in the Bay. They seem small when compared to tidal velocities, yet Conomos (1979) contends that net currents associated with residual circulation have an effect of the same order as tidal diffusion in controlling the water replacement rate in the channels. A table taken from Miller (1982) substantiates the point that there is no dominant water renewal mechanism on an annual time scale (Table 1-2).

TABLE 1-2. Relationship Between Delta Outflow and Water Travel Time in Bay.

Delta Outflow	Time for Water to Travel from Delta to Golden Gate
3,000 cfs with no tides	2 years
3,000 cfs	1½ months
15,000 cfs	2 weeks
100,000 cfs	4 days

Notwithstanding the above discussion, the relative importance of tidal action must be recognized. Although the marked seasonal differences in wind and river inflow alter water mass movement, the basic flow patterns are due to the tides and remain relatively unchanged throughout the year (Conomos 1979). Additionally there is a strong fortnightly variation which is very important. Within the Bay, tidal velocities are strongest in the channels (60-150 cm/s) and weaker in the shoals (up to 35 cm/s). During some periods maximum ebb current speeds of 280 cm/s are typical at the Golden Gate (Conomos 1979). Tidal excursions can be typically about 10 km.

All of these tidal characteristics are modulated as one moves further from the Golden Gate, toward San Pablo and Suisun bays. As one moves upstream the relative importance of flow-related, non-tidal processes becomes more pronounced.

Quality

Delta outflow, like any other water, has quality properties which are affected by many physical and biological processes, and therefore can vary considerably in space and time. In order to categorize these properties as they are most typically found in Delta outflow, it is helpful to compare winter and summer river inflows. Winter is typified by high outflows, and therefore more typical of new inputs into the Bay, while summer flows are quite low and represent recycling processes. Such an analysis has been carried out by Conomos et al. (1979) and most of the following discussion is based upon their work.

Salinity

By definition, Delta outflow is primarily river inflow, and as such, can be considered fresh. However, since the water has passed through the Delta and due to some gravitational mixing as described above, the salinity of outflows reaching the Bay can range from 0 to 10 or 12°/oo. Median salinities of typical winter outflows are approximately 1-2°/oo.

Temperature

Waters associated with winter Delta outflows are usually colder than summer base flows. The cold (10° C) water of these winter flows can slightly depress the ambient Bay water temperatures. Summer base flows are about 20° C.

Suspended Particulate Matter

Delta outflow contributes the bulk of the suspended inorganic particles to the Bay and also some of the organic particles (particularly plant fragments and freshwater phytoplankton). The remainder of the organic materials comes from the ocean, sewage effluents, substrate resuspension, and in situ biological production. Typical concentrations of suspended particulate matter in winter related outflows are approximately 50 mg/l. According to Davis (1982), the total suspended solids input into the Bay in 1978 due to outflow alone was about 1,900 million kilograms. This number is very approximate and surely varies from year to year, but the important point is that outflows are a significant source of suspended particulate matter.

Oxygen

Davis (1982) notes that oxygen production by plants and oxygen from the atmosphere are the main sources of oxygen to the Bay. The oxygen level in outflow does not influence the Bay oxygen levels.

Nutrients

Conomos *et al*. (1979) state that the three major sources of markedly differing nutrient concentrations in the Bay are Delta outflow, Golden Gate exchange (ocean water), and sewage inflow from South Bay waters. They note that on the basis of Bay-wide distributions, South Bay sewage is believed to be the major source of phosphate, ammonia, and nitrate + nitrite to the southern reach of the Bay. Delta outflow is the major source of these nutrients as well as silicate to the northern reach (e.g. San Pablo Bay). Some nutrients are also supplied to North Bay by ocean exchange.

In terms of total volume the winter input of all nutrients from Delta outflows is at least 10 times greater than total input from summer flows. However, much of this total input may be carried out the Golden Gate by these high flows. Davis (1982) estimates that outflow contributes approximately 12 million kilograms of total nitrogen and about 3 million kilograms of phosphorus to the Bay per year. Ocean and sewage inputs are seasonally constant and their temporal variations are usually insignificant compared to Delta inputs (Conomos *et al*. 1979). Even though sewage additions of nutrients to the Bay are large, the fact that the Bay is naturally nutrient-rich precludes detection of changes in the biota resulting from these additions. Typical concentrations of selected nutrients in winter Delta outflows are presented in Table 1-3.

TABLE 1-3. Typical Concentrations of Selected Nutrients in Winter Delta Outflows (Data Taken From Conomos *et al*. 1979).

Nutrient	Winter Outflow Concentration (µg-atoms/liter)
Silicate	250.0
Phosphate	2.5
Nitrate + Nitrite	22.0
Ammonia	2.5

Pollutants

Since Delta outflow drains from a significant part of the state, it is reasonable to assume that it carries many elements or chemicals considered to be pollutants.

The list of potential pollutants is so long and diverse that no attempt to completely list those present in outflow will be made. Further, relatively few consistent monitoring programs have been carried out so that existing knowledge regarding pollutant levels in outflow is sketchy at best. The major types of pollutants or toxicants potentially present in outflow include heavy metals, pesticides, herbicides, PCB's, and selected organics.

Heavy metal loadings are sometimes expressed as a composite parameter known as equivalent heavy metals (EHM) (Russell <u>et al</u>. 1982). EHM is the sum of arsenic, cadmium, chromium, copper, lead mercury, nickel, silver, and zinc after the mass of each has been weighted by its chronic toxicity relative to that of chromium. As such, it is used as an approximation of environmental significance of these metals (Russell <u>et al</u>. 1982). Russell <u>et al</u>. (1982) state that in 1800, Delta outflow was responsible for nearly all of the heavy metals in the Bay. Today, they say, the Bay receives one-third more EHM than in 1800, but now surface runoff matches the Delta contribution. Obviously outflow still provides a significant amount of metals to the Bay.

Finally, it is important to note that even though Delta outflow acts as a source of pollutants, it is also most likely a driving force that removes biologically available metals from the Bay (Luoma and Cain 1979).

Other Outflow Characteristics

When Delta outflow hydrographs for selected water years are plotted, other outflow characteristics become apparent (Figure 1-2). Throughout most years, several specific quantifiable "outflow pulses" periodically occur. These pulses appear as spikes or peaks which are greater than base flows. Pulses can be described in terms of volume, velocity, and quality as discussed above, but they also have characteristics of duration, timing, and consistency.

<u>Duration</u>

The length of time during which a periodic outflow pulse occurs can be defined as its duration. As expected, durations of outflow pulses in the Bay system are related to the magnitude of watershed storms, intensity of snowmelt, or reservoir release schedules. In the Bay system, the duration of outflow pulses is most closely related to outflow volumes. Generally, pulses with a maximum rate of less than 32,000 cfs have a duration between 5 and 10 days, while durations of outflow pulses greater than 32,000 cfs range from 10 to 50 days (Figure 1-2). Sometimes high flow pulses have short durations (see October and February, '62-'63, Figure 1-2) while other high flow pulses have longer durations (see January and February, '79-'80; February and March, '74-'75; January-March, '57-'58, Figure 1-2). Further, the duration of pulses occurring in spring-summer is usually long and continues over at least 3 months in most years.

<u>Timing</u>

The temporal distribution or timing of outflow pulses in the Bay system is variable, yet they generally occur during winter and spring months due to watershed

FIGURE 1-2. Daily Delta Outflows For Selected Water Years (Data From DWR).

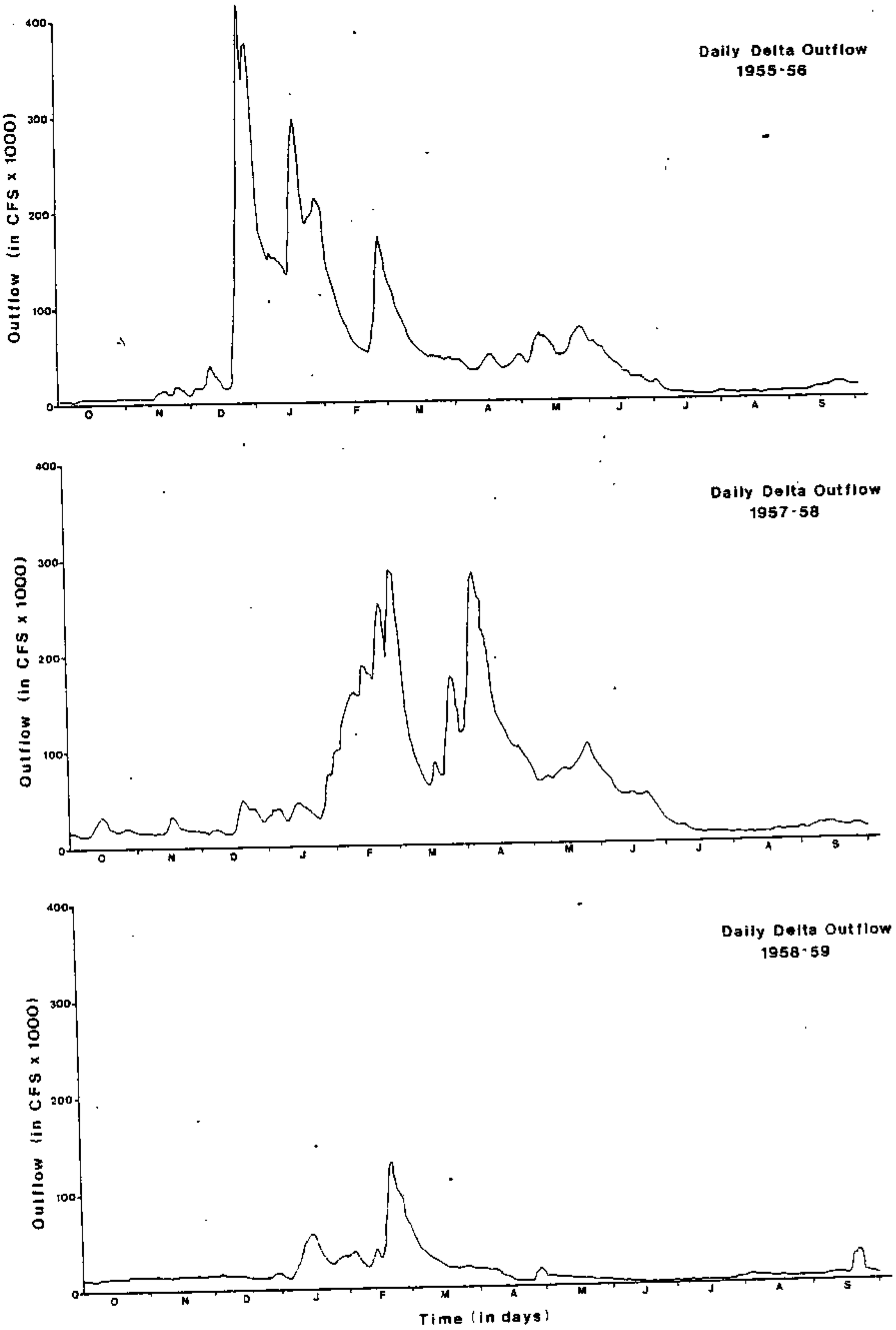


FIGURE 1-2. (Cont'd.)

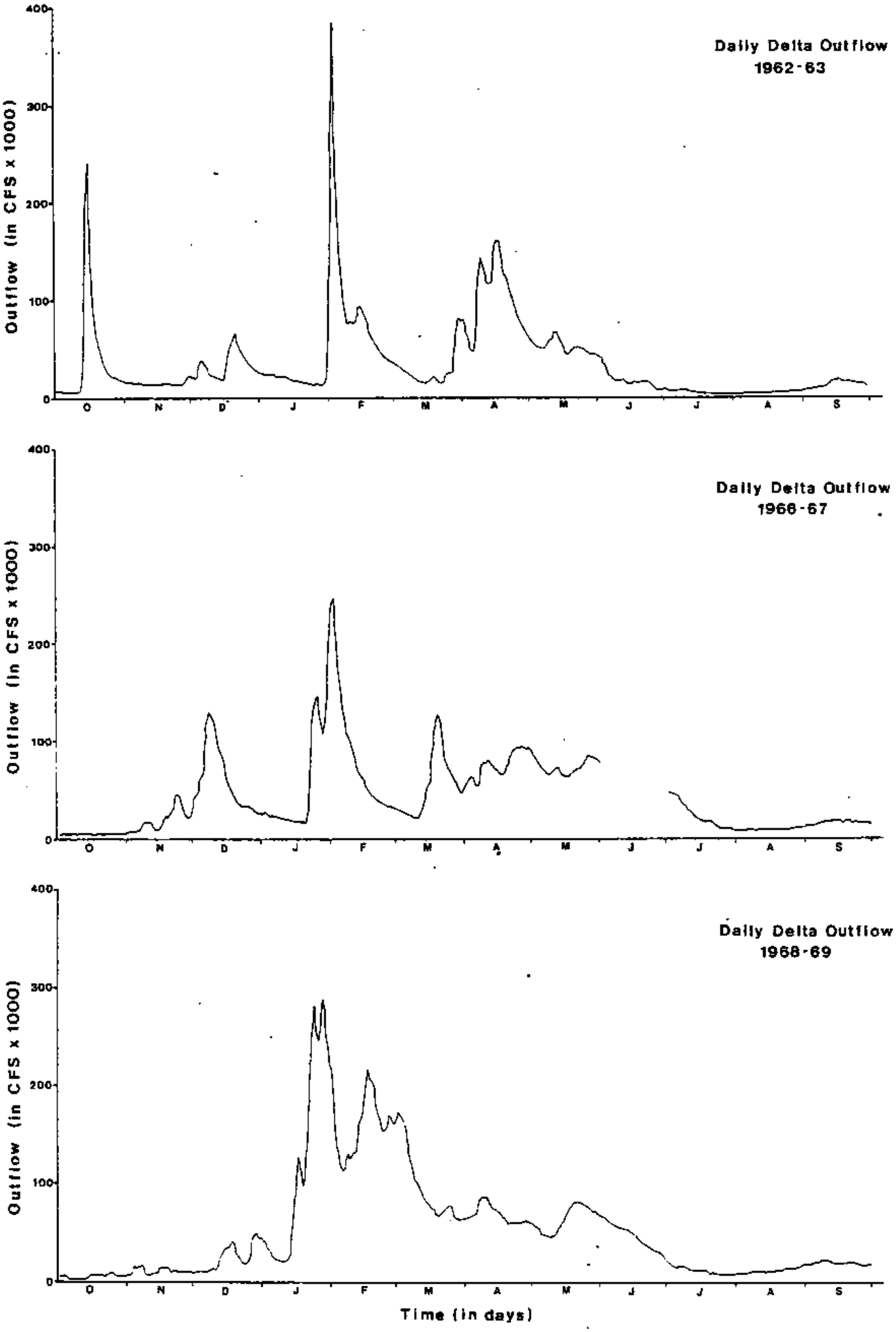
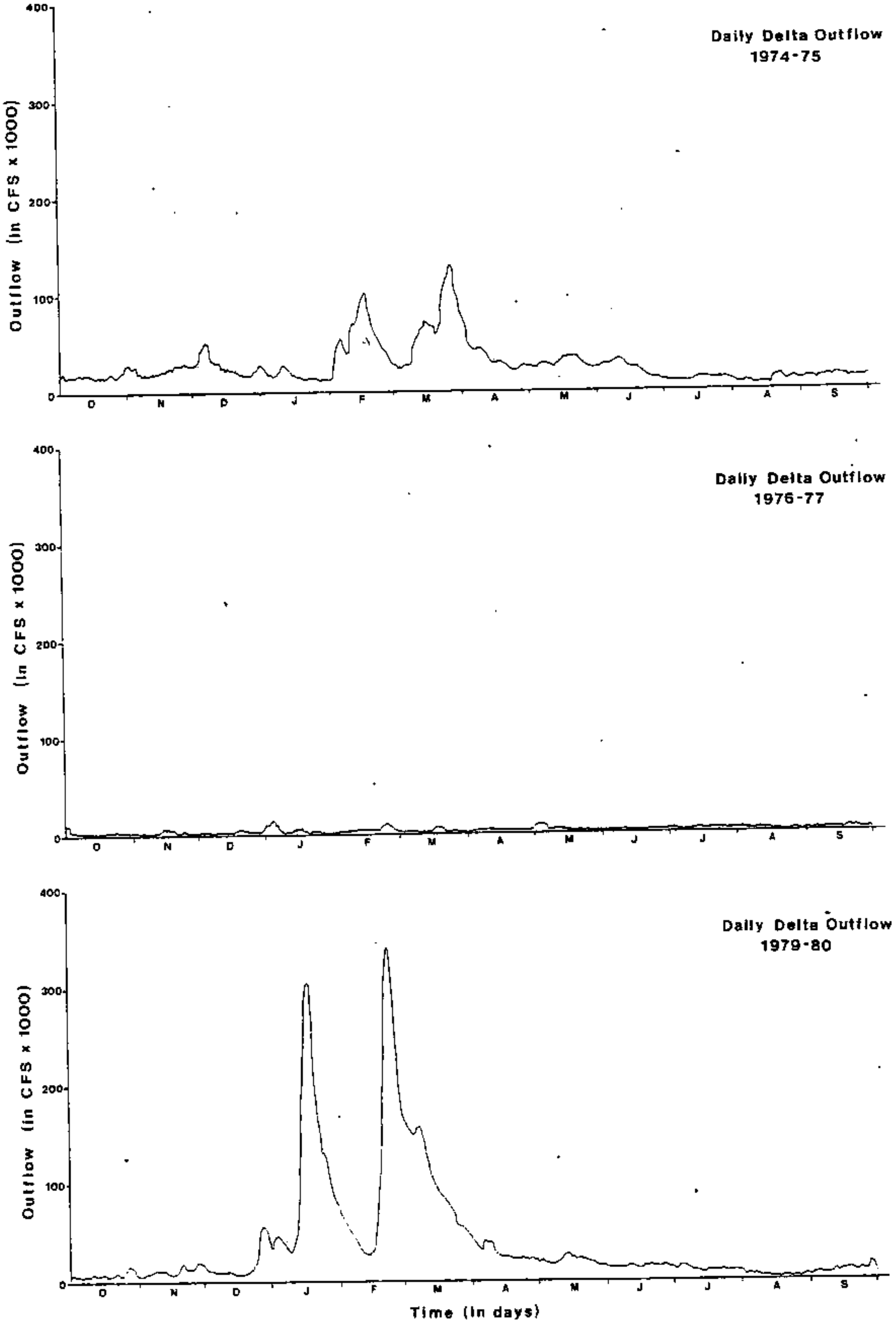


FIGURE 1-2. (Cont'd.)



storms, spring snowmelt, or dam releases. Pulses occurring during the fall (Oct-Dec) are usually small with maximum discharges below 50,000 cfs. Exceptions to this pattern do occur (Figure 1-2). Large pulses have occurred in October ('62-'63) and December ('66-'67). The largest outflow pulses usually occur in winter (Jan-Mar), but major outflows occurred during April, 1958 and 1963 (Figure 1-2). Spring (Apr-Jun) pulses during most years tend to be moderate in volume (20,000 to 85,000 cfs, Figure 1-2). Significant outflow pulses are notably absent during the summer months, although exceptions occur. During September, 1959, an outflow 25,000 cfs greater than base flows occurred (Figure 1-2).

Frequency

Outflow pulses have occurred essentially every year. The only exception has been during the drought year 1976-77, but even then there were noticeable rises and falls in outflow (see early January, late February, and early May -Figure 1-2).

A DWR analysis performed for the Draft EIR for the proposed additional pumping units at the Delta Pumping Plant summarizes information on the consistency of pulse occurrence during the 24 year period 1955-1979. They found that during this period there was an average of six events per year. Further they found small events occurred more consistently than large, although there were at least 27 large occurrences during the 24 year period (Table 1-4).

TABLE 1-4. Size, Number, and Volume of Outflow Events During the Period 1955-1979 (From DWR 1982).

Size	Number of Events	Cubic Metres per Second	Cubic Feet per Second
Small	64	283.2 to 707.9	10,000 to 25,000
Medium	53	707.9 to 2,832	25,000 to 100,000
Large	27	> 2,832	> 100,000

HISTORICAL AND PRESENT DELTA OUTFLOWS

During the last 70 years, annual Delta outflows have been quite variable (Figure 1-3). They ranged from about 3.16 dam^3 (2.6 maf) during water year 1976-77 to 65.2 dam^3 (52.9 maf) during 1937-38. The 55 year mean for the period 1922-1977 is 26.0 dam^3 (21.1 maf).

As mentioned earlier, estimates of outflow are derived from inflow to the Delta, consumptive use within the Delta, and export from the Delta. The relationship between these factors has been altered by water development activities. Inflows into the Delta have been reduced by construction of upstream reservoirs (e.g. Shasta in 1944), increased consumptive uses in the basin, and exports from the

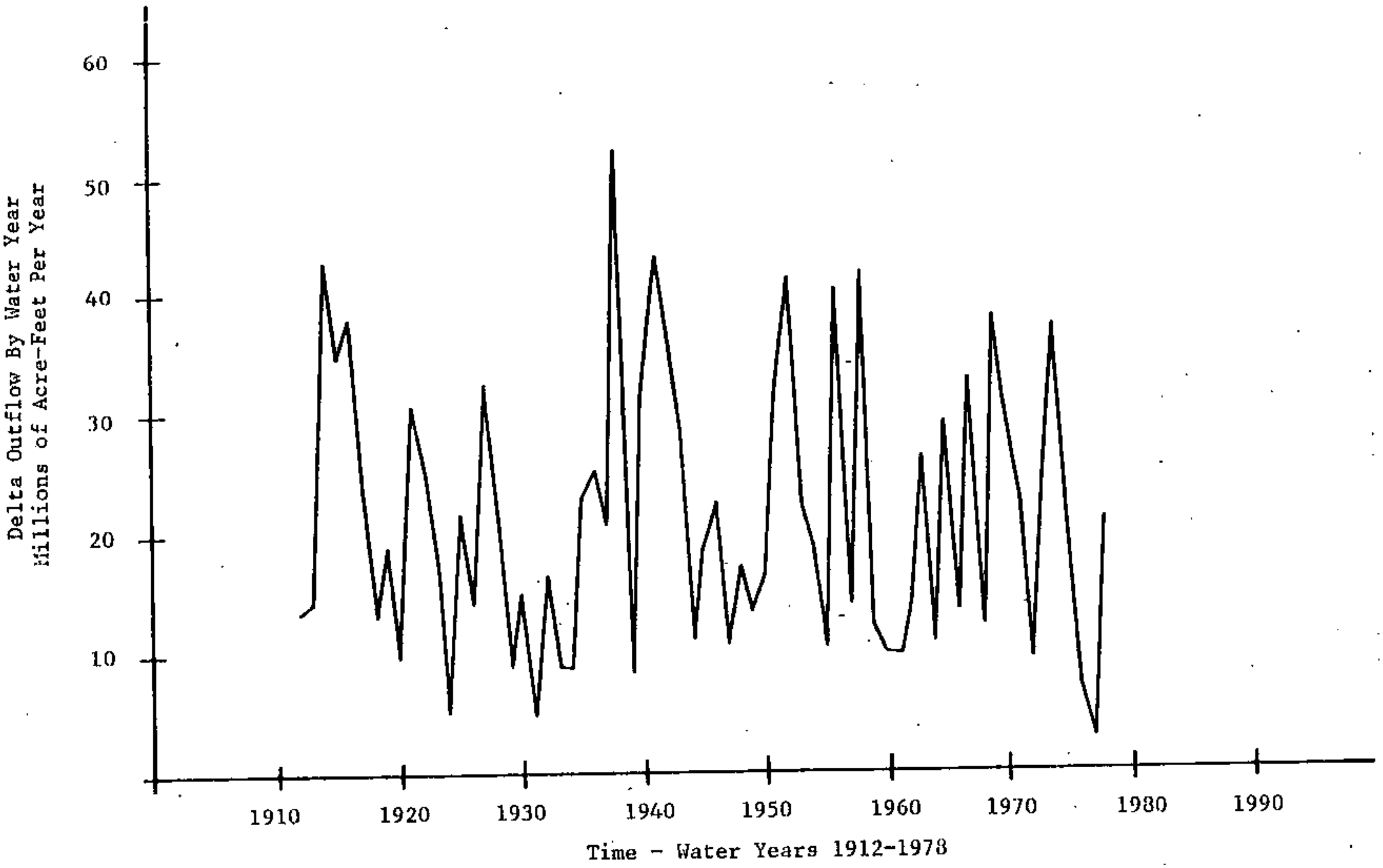


FIGURE 1-3. Historical Outflow From the Sacramento-San Joaquin Delta at Chipps Island (Computed) (From Rumboltz 1979).

Delta through the SWP and CVP. The overall impact has been a decrease in the total amount of freshwater that reaches San Francisco Bay. However, the precise magnitude of this reduction has been masked by variable, large scale, cyclical rainfall patterns that have occurred throughout the years and by the methods used to calculate changes. For example, a USBR pre- and post-Shasta Reservoir construction outflow analysis (Rumboltz 1979) found that from 1912 to 1944, when Shasta construction was completed, the average annual outflow was 25.3 dam^3 (20.5 maf) while the post-construction average was 26.4 dam^3 (21.4 maf). This result shows the "masking effect" of averaging data when cyclical weather patterns occur in the system. It suggests outflows were not affected by project construction, yet post-project diversions from the Delta and increasing in-basin uses obviously decreased Delta outflow.

A more meaningful way to look at changes in outflow from historical to present conditions is to analyze data for given years from simulations of with and without project conditions (Table 1-5). Such an analysis shows that for most months during all water year types, the current Delta outflows are lower than historical (without development) levels. It also should be noted that the relative importance of these reductions varies by year type (Table 1-5). For instance, proportional reductions are more severe during dry and critical years than in wet or normal years.

Another significant recent change has occurred in seasonal outflow patterns. Present outflows are higher during the summer months (Jul-Sept) than they were historically. This is due to retention of winter flows in reservoirs and subsequent release in summer for export from the Delta and for the protection of beneficial uses in the Delta.

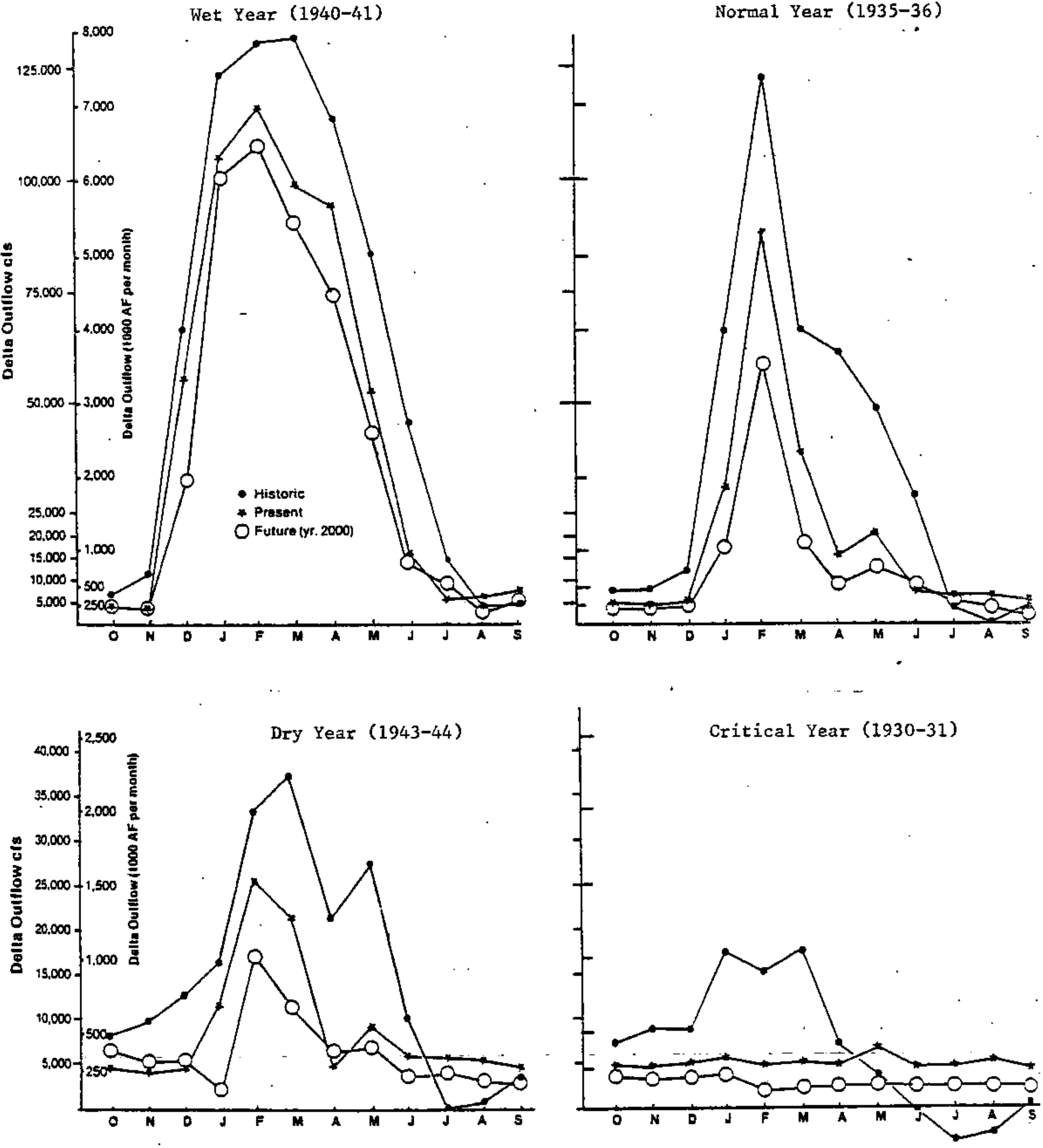
FUTURE DELTA OUTFLOWS

DWR has recently estimated that annual Delta outflows in dry and critical years will be less than 6.8 dam^3 (5.5 maf) by 1990 (Kelley and Tippets 1977). (Since 1922, about a third of all years have been dry or critical.) During the 55 year period between 1921-1976, levels that low occurred only twice; in water years 1923-24 and 1930-31 (Kelley and Tippets 1977). After 1990, "ordinary" dry year flows will be reduced to 4.1 dam^3 (3.3 maf) and critical year flows to 3.3 dam^3 (2.7 maf).

Seasonal outflow patterns also will continue to be altered (Figure 1-4). In the future, wet years will retain their basic patterns; large winter and spring flows. Critical years will change little, except that already low outflows will be reduced a little further. However, the greatest changes will be in future dry and normal years - 56% of the time (Kelley and Tippets 1977). High Delta outflows will still occur in winter and spring during those years, but their magnitude will be significantly reduced and their duration shortened.

Month	Wet (About 32% of all years)		Normal (About 36% of all years)		Dry (About 20% of all years)		Critically Dry (About 12% of all years)	
	Without Development	Current	Without Development	Current	Without Development	Current	Without Development	Current
October	6,000 to	3,000	7,000 to	4,000	7,500 to	5,000	3,000 to	3,000
November	11,000 to	6,000	8,000 to	5,000	10,000 to	5,000	5,000 to	4,000
December	65,000 to	40,000	10,000 to	6,000	12,000 to	6,000	9,000 to	3,500
January	120,000 to	100,000	65,000 to	23,000	17,500 to	6,000	17,000 to	5,500
February	140,000 to	120,000	125,000 to	90,000	42,000 to	22,000	17,000 to	3,200
March	130,000 to	100,000	65,000 to	24,000	43,000 to	12,000	27,000 to	3,200
April	115,000 to	80,000	62,000 to	14,000	25,000 to	8,000	23,000 to	4,200
May	80,000 to	45,000	47,000 to	17,000	30,000 to	6,500	20,000 to	4,000
June	45,000 to	18,000	23,000 to	10,000	11,000 to	4,000	18,000 to	3,100
July	14,000 to	10,000	3,000 to	7,500	0 to	7,500	500 to	3,000
August	3,000 to	8,000	1,000 to	7,500	0 to	7,500	1,300 to	6,000
September	3,000 to	6,000	2,000 to	6,000	3,500 to	5,000	1,800 to	3,200

TABLE 1-5. Comparison of Delta Outflow - Outflow Without Water Development Compared to Outflow With Current Development and Standards (All in Monthly Average cfs) (From Miller 1982).



Wet Year (1940-41)

Normal Year (1935-36)

Dry Year (1943-44)

Critical Year (1930-31)

FIGURE 1-4. Delta Outflows to the San Francisco Bay as it Actually was During 4 Recent Years, How it Would Have Been if Present Levels of Delta Input and Export had Occurred in Those Years, and How it is Expected to Change Under Proposed Water Development Plans (From Kelley and Tippets 1977).

PROJECTED CHANGES IN OUTFLOW CHARACTERISTICS AND ENVIRONMENTAL CONDITIONS

Since future Delta outflows will be reduced below present levels, it is instructive to project what will happen to typical outflow characteristics and then determine how these changed characteristics will change the physical/chemical environmental conditions of the Bay system. First the projected changes of outflow characteristics will be discussed.

Changes In Outflow Characteristics

Volume

With increased upstream storage and diversion from the Delta, it is obvious that the volume of outflows will be decreased from those that would be present in the absence of future development. Storage projects will alter seasonal outflow patterns by decreasing winter and spring volumes and increasing summer-fall flows.

Velocity

Overall reductions in Delta outflow can affect water movement in the Bay system. Reduction of outflows would raise salinity in the northern reach of the Bay. This would decrease the salinity gradient in most of that area and hence reduce the strength of estuarine circulation. However, the gradients would be steeper at the eastern end of the northern reach so there may be stronger density flows there. The net effect is that the northern reach is more dependent upon tidal dispersion for water renewal. Hence, longer mixing time-scales would occur.

In South Bay, a low level of tidal dispersion (including tidally induced residual currents) operates over most of the year. However, the big exchanges with Central Bay are due to density currents. With reduced outflows, the salinity in Central Bay is increased and the strength of the density currents is reduced.

Quality

It is likely that some outflow quality parameters will be altered if overall quantities of outflow are reduced. Predictions about the exact nature of these changes and the speed with which they will occur must be classified in the realm of "intelligent speculation" until we know more about magnitudes of flow reduction (Goldman 1970).

Salinity of Outflows. The salinity of Delta outflows will probably increase since the relative proportion of drainage (or return flows) would increase as fresh (unused) water diversions or upstream uses increase. Even though serious changes in salinity of the Bay would result due to increased ocean salinity intrusion, the salinity of the outflow itself may only increase slightly.

Temperature. The temperatures of reduced flows might be altered slightly when compared to those associated with higher flows, since temperatures and velocities are related. Inland temperature extremes, where outflows originate, are greater than in the Bay area. Lower velocities associated with lower flows would increase residence time and therefore expose those flows to greater periods of ambient air temperature influences. The result could be outflows with slightly cooler winter temperature and slightly warmer summer temperatures.

Suspended Particulate Matter. Reduced flows will result in lower concentrations of suspended particulate matter entering the Bay. Reduced flows would be exposed to increased Delta and river residence times, and therefore would allow more matter to settle out. Krone (1966) has treated this subject extensively and provided projections of annual suspended sediment in outflow from the Delta to the Bay system under various flow conditions (Figure 1-5). The effect of such reductions on suspended sediment concentrations in the Bay is the subject of considerable debate. The debate evolves from uncertainties as to the relative roles of input and resuspension of sediments within the Bay in determining suspended sediment concentrations, particularly in the summer.

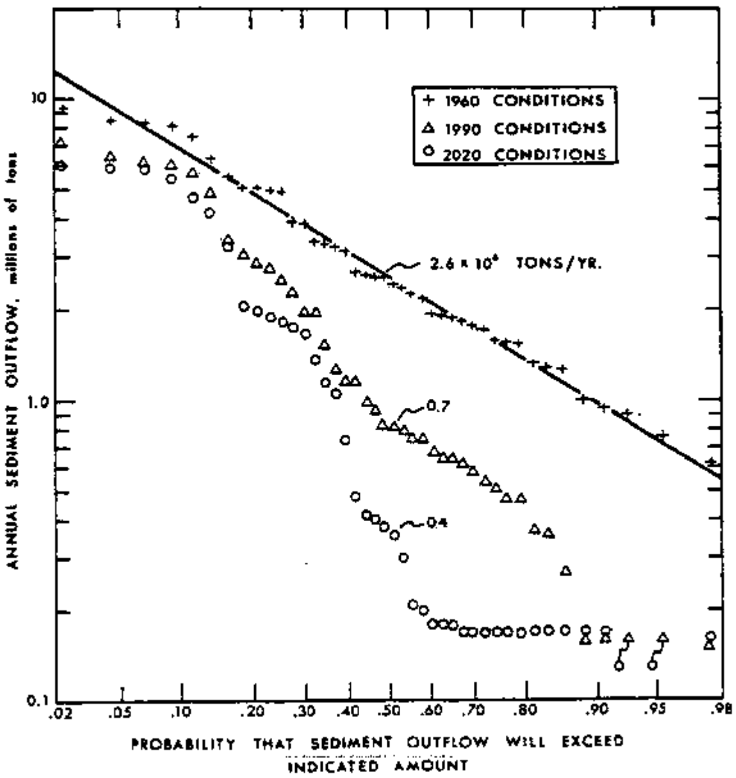


FIGURE 1-5. Annual Suspended Sediment Outflow From the Delta to the Bay System (From Krone 1966).

Oxygen. Since the oxygen levels in outflow do not seem to influence the Bay, flow reduction should not affect dissolved oxygen in the Bay directly. Oxygen levels could be affected indirectly if flows affect phytoplankton production or BOD levels.

Nutrients. While the total input of dissolved nutrients will decrease as flow volumes decrease, concentrations of dissolved nutrients such as phosphate, nitrate, and ammonia in outflow may increase as flow volumes decrease. This speculation is based upon the fact that manmade input of dissolved nutrients will continue at present (or increased) levels, and therefore lower flow volumes would result in greater concentrations. On the other hand, particulate matter may be less and thus organic nutrients tied up in particulate form could be reduced by increased settling. Concentrations of nutrients such as silicate, which originates from lithogenous sources (weathering of rocks), may remain the same, since their origin is in the upper watersheds in areas where storage or diversion effects are not felt as severely.

Pollutants. The relationship between concentrations of pollutants in outflow and reduced outflow volumes is uncertain, but if flows are reduced and pollutant inputs from all sources remain the same or increase, one would expect the remaining flows reaching the Bay to carry greater pollutant concentrations. Russell et al. (1982) state the following: "Although Delta outflow quantity is a controversial subject today, quality of the outflow will also be an issue in the 1980's. The population of the Sacramento-San Joaquin Valley is expected to increase by more than 20% over the next 10 years. The additional load of municipal wastewater pollutants combined with pesticides, nutrients, and salts from the agricultural return flows will further burden the Bay..." Such comments imply that as total flows decrease, pollutant concentrations in remaining outflows will increase.

Duration of Outflow Pulses

Reductions in overall outflow through storage or diversion will alter the duration of certain outflow pulses. If flow reductions occur due to reservoir storage, the duration of certain pulses could be increased. For example, if reservoirs are at or above flood control reservation levels, peak outflows could be held back and released when local runoff downstream subsides. This would result in outflow pulses with diminished peaks and longer duration. On the other hand, flow reductions due to diversion could reduce the duration of some flow pulses. This relationship can be shown hypothetically (Figure 1-6). A given level of outflow reduction due to either cause (storage or diversion) will obviously affect different sized pulses by differing proportions. Smaller pulses will be affected proportionally more than large events. The daily operations studies necessary to quantify the significance of such changes have not been made.

Timing of Outflow Pulses

Since the temporal occurrence of outflow pulses in the Bay depends primarily upon storms in the watershed, it is unlikely that occurrence patterns would be

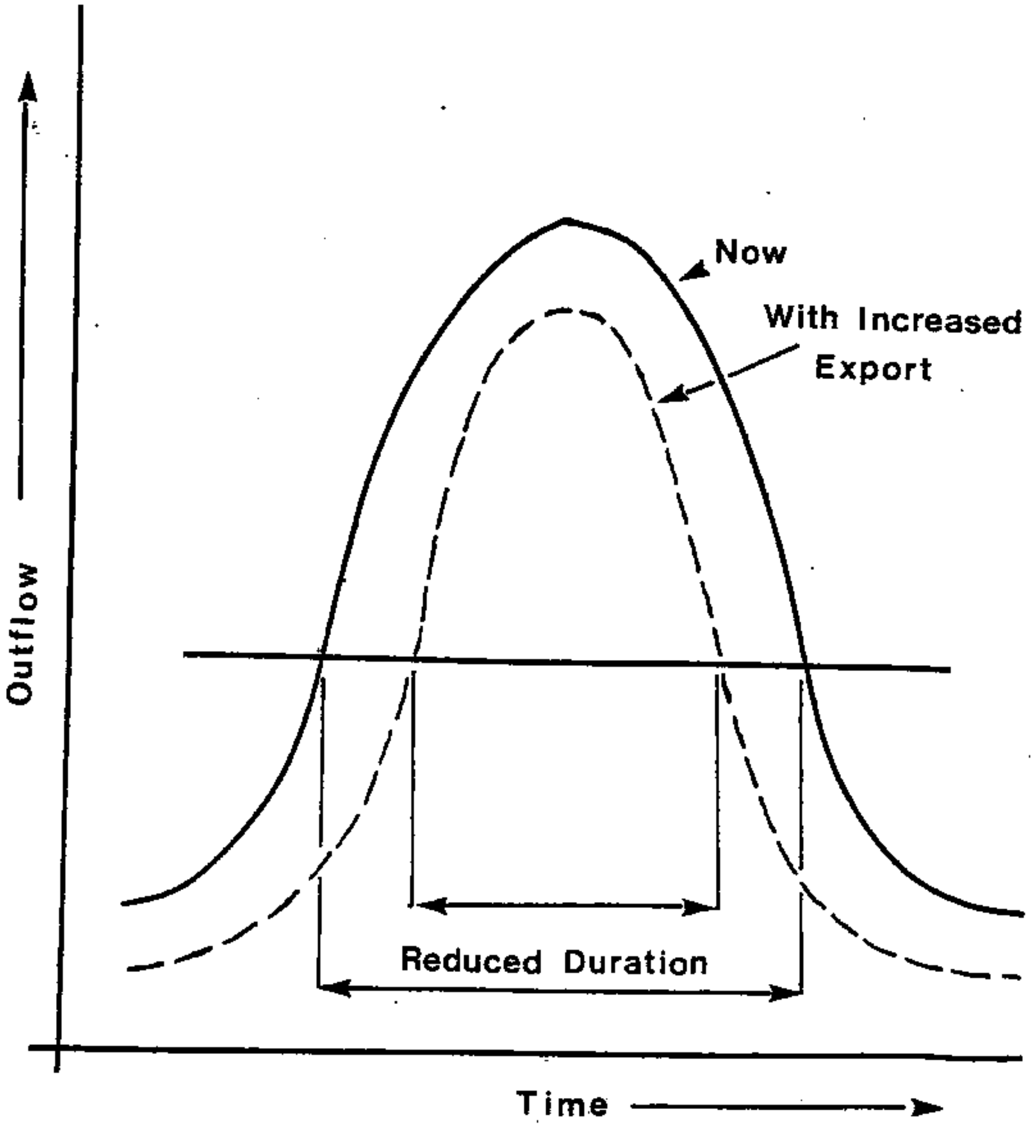


FIGURE 1-6. Graphic Depiction of Changes in Duration of Outflow Pulses Under Two Export Conditions.

significantly affected by flow reductions. However, some pulses could be affected. Low volume pulses that move through the system today may be completely eliminated when diversion or storage rates are increased in the future. In other words, pulses that are defined as "unregulated" today will be "regulated" by future project expansions and/or management procedures.

Frequency

Flow reductions to the system would also affect the frequency of outflow pulses in the Bay. This point was made in a DWR analysis developed for a Draft EIR for the proposed additional pumping units at the Harvey O. Banks Delta Pumping Plant. Defining an event as 283.2 m^3/s (10,000 cfs) and using present development level operation studies to analyze data for the 24 year period 1928 to 1934, this analysis found that by adjusting flows for the full 291.7 m^3/s (10,300 cfs) daily diversion capability of a second intake at Clifton Court Forebay, there would be thirteen (13) less events than would have occurred historically, after the unit was installed. Obviously, the more storage is increased the greater the reduction in the pulses of any given frequency will be.

Changed Outflow Characteristics and Their Effect on Physical/Chemical Environmental Conditions in the Bay

Changes in outflow characteristics will affect the physical/chemical conditions of the Bay system. Those environmental conditions most responsive to outflow changes include: a) salinity, b) temperature, c) current patterns and velocities, and d) nutrients, detritus, and solids.

Salinity

Salinity levels in the Bay are inversely related to the levels of Delta outflow (Figure 1-7). During periods of high inflow, near-surface salinities in the Bay decrease and the Bay becomes fresher. When inflows decrease, the exchange from the ocean becomes more influential and the Bay environment becomes saltier. During summer periods, evaporation can cause salinities to increase above those of the seawater flowing in and out of the Bay. Delta outflows vary widely, and while tidal action varies little, ocean salinities vary only by about $3^{o}/oo$ (Conomos 1979). Hence, outflows play the dominant role in controlling salinity variations in the Bay.

Long term reductions in annual outflows would increase the average salinity of the Bay. Such long term salinity changes due to changes in annual outflow patterns have already been documented in the upper estuary (Rumboltz 1979). Average chloride levels at Collinsville have doubled (400 mg/l to 800 mg/l) during the month of April and have increased by 100 mg/l during May (300 mg/l to 400 mg/l). June salinities at Collinsville have also increased since 1960.

The longitudinal salinity gradient that is set up due to mixing of seawater and fresher Delta outflows is an important feature of the Bay salinity field. The northern reach of the Bay has a longitudinal salinity gradient varying from less than $1^{o}/oo$ at the Delta to $32^{o}/oo$ at the Golden Gate (Conomos 1979).

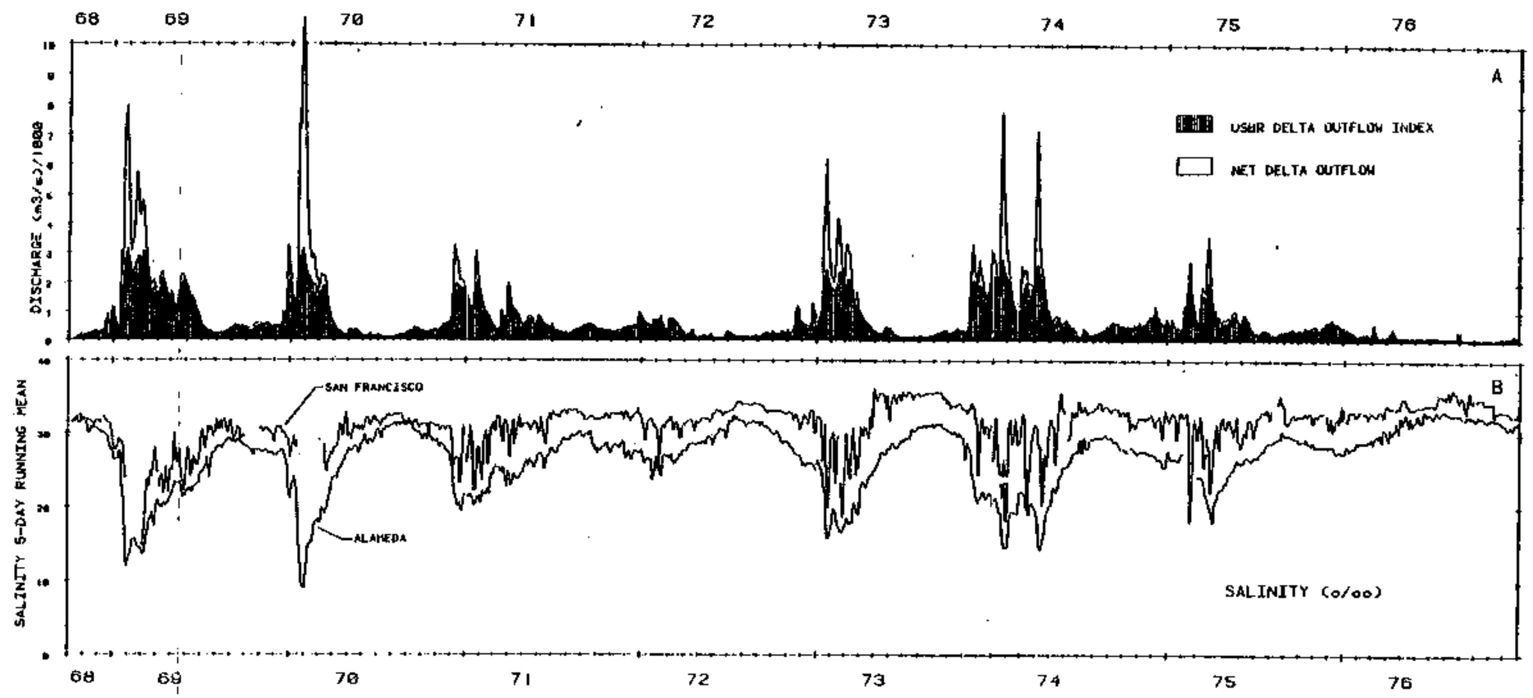


FIGURE 1-7. Daily Delta Outflow (A) and Surface Salinity at Alameda and San Francisco (Fort Point) (B) for 1968 Through 1976 (From Conomos 1979).

During the summer, as Delta outflows are reduced, the gradient becomes stronger. As fall or winter rains increase Delta outflows, the maximum salinity gradient is pushed downstream again. The distance it is moved depends upon the magnitude and duration of the outflow events (Kelley and Tippets 1977).

Kelley and Tippets (1977) have projected that the maximum salinity gradient will tend to be stabilized in Suisun Bay in dry and critical years under 1990 conditions. By then, upstream storage and diversion will cause the maximum gradient to remain there year round in about one-fifth of the years. Reduced flows also compress the distance over which the salinity gradient extends.

Salinity stratification is another important aspect of freshwater flow/salinity relationships. High winter outflows flow on top of ocean derived saltwater. Tides and winds usually mix the two, but during large outflows this mixing is less complete and the Bay becomes stratified. Vertical salinity gradients in the system typically have differences of $5^{o}/oo$ during winter and $3^{o}/oo$ during summer (Conomos 1979). During high outflows vertical differences of more than $10^{o}/oo$ have been recorded (Conomos 1979). Long-term reductions in flow would tend to reduce the amount of salinity stratification.

Temperature

The effects of outflow temperature changes on the entire heat budget of the Bay are unknown and may be minor, since air temperature is the dominant factor controlling water temperatures.

Current Patterns and Velocities

Delta outflow is directly related to circulation and mixing in the Bay. Higher outflows result in more rapid net circulation and more intensive mixing of the water mass (Conomos 1979). The net movement of a water parcel downstream through the system is greatly enhanced by Delta outflows (Figure 1-8). Gravitational circulation also is modified by changes in freshwater flow (Walters and Gartner pre-publication MS).

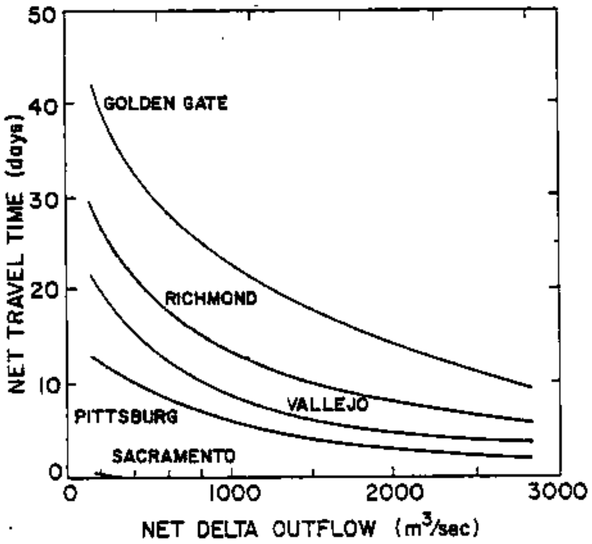


FIGURE 1-8. Net Travel Time of a Water Parcel From Sacramento to Various Locations in the Northern Reach as a Function of "Daily Delta Outflow," Modified After J. B. Gilbert and Assoc. (1977) (From Conomos 1979).

The above information shows the intricate relationship between outflows and water movement in the Bay. Even though the basic instantaneous flow patterns are tidally induced and remain relatively unchanged throughout the year, changes in outflow would reduce the magnitude and occurrence of various components of the net current regime. Flow reductions would probably alter the magnitude and occurrence of upstream-moving bottom mean currents, downstream-moving mean non-tidal surface currents, and vertical currents. This is a simplistic summary and the actual changes in these patterns would be extremely difficult to document because of the complexity of such processes. However, best scientific projections support the fact that such changes would take place. For a technical treatment of flow/circulation processes in the Bay, the reader is referred to Peterson *et al.* 1975; Fischer and Kirkland 1978; Conomos 1979; Cheng and Casulli 1982; Cheng and Walters 1982; Walters and Gartner pre-publication MS).

Nutrients and Suspended Particulates

The role of freshwater flows as an important source of nutrients has been documented in many estuaries including: Peel-Harvey Estuary, Western Australia (McComb *et al.* 1981); Bay of Brest, France (Monbet *et al.* 1981); Rhode River Estuary, Maryland (Correll 1981); and Charlotte Harbor, Florida (Fraser and Wilcox 1981). In all of these cases high input of nutrients was associated with periods of high inflow.

Inflow is not the only source of nutrients to estuaries. The ocean and sewage effluents also contribute, but are relatively constant sources throughout the year. Other processes regulate the cycling of nutrients in San Francisco Bay, but these processes and rates which control supply and removal are seasonally modulated by Delta outflow (Conomos *et al.* 1979).

Delta outflow is a major source (4×10^6 metric tons per year - Davis 1982) of suspended particulates (small particulates, usually less than 0.1 mm in diameter) to the northern reach of the Bay. Particulate sediment loads in the Bay increase as flows increase and 80% of the sediment inputs are received in the winter (Davis 1982). Some of these particles break down and add nutrients to the system, while others (silts or clays) block light or act to remove phosphorus, heavy metals, and organic insecticides from the water (Goldman 1970).

The critical point of these facts is that outflows provide a contribution to the nutrient and sediment budgets of the Bay system. Any reductions in outflow will reduce the input of nutrients, detritus, and sediments by some increment proportional to the concentration in that outflow and the amount of reduction. For example, using data provided by Kelley and Tippets (1977) it can be shown that a mean reduction in monthly outflow from 4,247 m^3/s (150,000 cfs) to 56 m^3/s (2,000 cfs) reduces the monthly silicate contribution to the Bay from 354.3 million pounds to 4.7 million pounds. Likewise, Krone (1979) predicts that flow reductions will reduce sediment inflow into the Bay. Recycling processes, increased waste discharges, wind-related resuspension, tidal action, and exchange with the ocean all modify the effect of flow-caused reductions in nutrients and suspended solids on phytoplankton production in the Bay. As a result flow reductions probably will not cause proportional reductions in phytoplankton production. In fact, planned flow reductions may not affect phytoplankton production in the Bay significantly. Effects on phytoplankton production may be more noticeable in the ocean, as most of the nutrients entering the estuary ultimately end up in the ocean.

Mitigating Factors

The previous discussion on flow and its effect on the physical/chemical environment of the Bay is somewhat speculative and simplified. There are many complicating factors which could mitigate the influence of outflows in the Bay system. Two of these factors are previous flows and location in the Bay.

Previous Flows

The magnitude, timing, and duration of previous flows can greatly influence the level of impact of any outflow pulse. For example, increases in outflow have a more marked effect on the salinity of the Bay when these increases are preceded by a prolonged dry period, than when they are preceded by high outflow conditions (SWRCB 1978). Since some circulation is related to salinity differences (gravitational circulation), previous conditions influence circulation changes resulting from (or caused by) flow changes. The first large flow pulse of the season (usually December) would, therefore, impact salinity conditions in the Bay more than following events. Later pulses would certainly influence salinity conditions, but the magnitude of change would be less. The relative impact of other outflow characteristics could also be affected by previous flows.

Location In Bay

There are at least four distinct reaches in San Francisco Bay: (i) Suisun Bay, (ii) San Pablo Bay, (iii) Central Bay, and (iv) South Bay. The impact of any given outflow pulse on environmental conditions in these reaches is not the same. The relationship between flows, magnitude of environmental effect, and location is plotted conceptually in Figure 1-9. The effect of a low outflow on the salinity, stratification (circulation), temperature, or nutrient and sediment levels in the Suisun reach would be greater than effects in Central Bay. Higher outflows would cause greater changes in these parameters at all locations, while effects would be proportionally greater at upstream areas (e.g. slope of line in Figure 1-9 increases).

Flows also affect environmental conditions in the southern reach, but greater flows are needed to induce changes there. This point can be made by looking at the effects of outflow on salinities in South Bay (Table 1-6). Salinities in the reach are profoundly affected only after outflows reach a threshold level of about 1120-2800 m^3/s (40,000-99,000 cfs). The significant point is that the same flows that can effect all other reaches of the Bay may affect South Bay little.

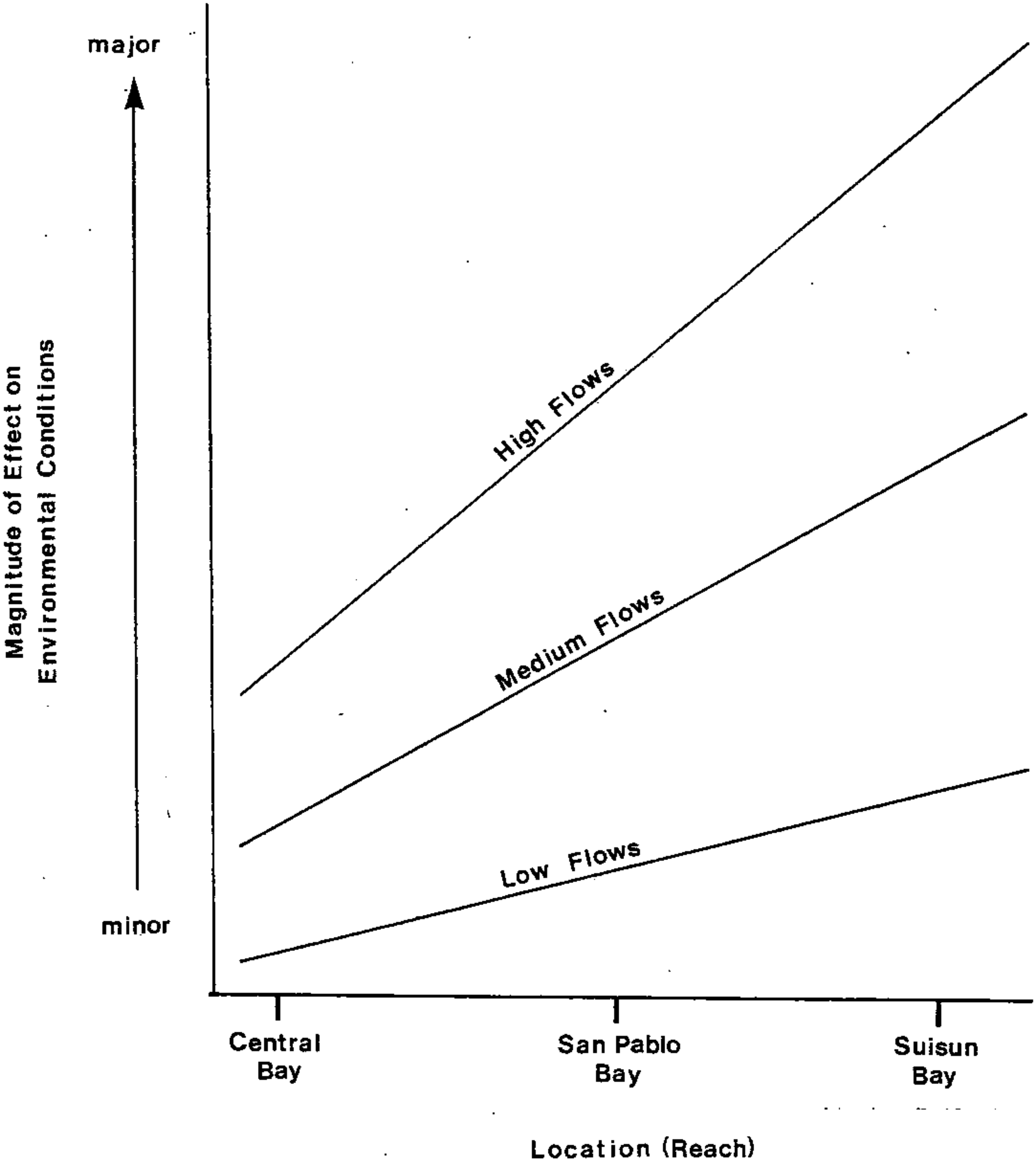


FIGURE 1-9. Conceptual Relationship Between Bay Reach, Magnitude of Effect, and Outflows to the Bay.

TABLE 1-6. The Effects of Various Net Delta Outflows (NDO) on the Salinity Field on the Southern Reach (From Conomos 1979).

Delta Outflow[a] (m^3/sec)	Salinity Conditions in the Southern Reach[a]
≤ 140[b]	oceanic salinities present (31-32°/oo)
140-280	measurable change of 1-2°/oo in northern part; weak vertical differences of 1-2°/oo
280-390	central and southern parts (south of San Bruno Shoal) affected only if outflow maintained for a long period
390-840	surface salinities throughout reach noticeably depressed
840-1120	salinity near San Bruno Shoal reduced to about 26°/oo
1120-2800	salinity structure throughout the southern reach is profoundly affected
2800-3360	stratifies entire reach with surface salinities about 15°/oo and bottom about 25°/oo
3360-9350	lowered salinity in the central part by > 4°/oo for 8 days
≥9350	lowered salinity in the central part of below 10°/oo

a/ Taken in part from Imberger *et al*. 1977.

b/ 140 $m^3 \cdot sec^{-1}$ = 5000 $ft^3 \cdot sec^{-1}$ = 10,000 acre-ft$\cdot$day^{-1}

The above statements are oversimplified to illustrate concepts. There are many confounding factors, but the main point is that the relative *in situ* change in salinity, stratification, temperature, nutrients, and solids depends not only on the level of outflow or previous flow condition, but also on the location in the Bay. This concept is important because it implies that flow regimes necessary to affect South Bay are more than adequate to change conditions in the rest of the Bay. South Bay has approximately half of the surface area, yet it requires more than twice the flow to affect its condition.

CHAPTER TWO

BIOLOGICAL RESOURCES OF THE BAY

The San Francisco Bay complex has essentially four different habitat areas, differing in the degree of marine and freshwater influence. Suisun Bay, located only a few miles downstream of the junction of the Sacramento and San Joaquin rivers, is the embayment most highly influenced by freshwater inflow. Salinities are highly variable in this basin, responding quickly to changes in Delta outflow and typically ranging from fresh water to about one-third that of sea water during an average year.

San Pablo Bay also undergoes wide salinity fluctuations in response to variations in Delta outflow, but is much more influenced by water from the Pacific Ocean than Suisun Bay. Salinities in San Pablo Bay can vary seasonally from near that of sea water during very low outflow periods to less than one-fourth that of sea water during periods of intense outflow.

South San Francisco Bay, without any major source of freshwater inflow, generally displays much lower salinity variations than the northern bays. Fresh water flowing from the Sacramento and San Joaquin rivers does have a major effect on average salinities, and outflows must reach quite high levels before average salinities decrease to less than about two-thirds that of sea water.

The Central San Francisco Bay (the area bordered by the Golden Gate, Richmond-San Rafael, and Bay bridges) is the most highly marine area in the Bay. Although surface salinities do reach very low levels during extremely high outflow periods, gravitational or estuarine circulation transports high salinity ocean water into the Bay, increasing the "average" salinities and moderating salinity extremes.

Just as the four areas of the San Francisco Bay complex are generally characterized by different salinity regimes, they also are characterized by different biota. The estuarine species are most concentrated in the northern bays and the more marine species are more abundant in the South and Central Bay.

Following is a general description of the more abundant fish and invertebrate species that inhabit San Francisco Bay. A brief description of their importance, both to man and as part of the Bay ecosystem, also is included. More comprehensive fish and invertebrate species lists are in other sections of this report.

FISHERY RESOURCES

Estuarine Fishes

Striped Bass (Morone saxatilis)

Striped bass are the most sought after gamefish in the San Francisco Bay area. Adult bass, after spawning in the Sacramento and San Joaquin rivers and Delta, move into the more marine areas of the Bay where they are the object of an intense commercial passenger fishing boat and skiff fishery, particularly during the summer and fall. Many bass move from the Central Bay region to San Pablo Bay, Suisun Bay, and the Delta during the fall and remain in those regions until moving upstream into fresh water for spawning in April or May.

Sub-adult bass (less than 3 years old) are most numerous in the lower salinity portions of the estuary and lower Delta. Striped bass, during the first year of life, are primarily consumers of zooplankton and crustaceans, with Neomysis mercedis being a particularly important part of their diet. Older bass rely more on forage fish, including smelt, anchovies, and younger striped bass as well as larger pelagic invertebrates.

White Sturgeon (Acipenser transmontanus) and Green Sturgeon (A. medirostris)

White sturgeon, also the object of an intense sport fishery, are the largest species of fish occurring in San Francisco Bay, occasionally reaching weights of more than 300 pounds, but more typically weighing up to 70 or 100 pounds at the time of capture. Green sturgeon average somewhat smaller, are less abundant than white sturgeon, and thus are a small part of the fishery. Sturgeon are taken by anglers in all parts of the Bay, but are most abundant in San Pablo and Suisun bays.

Adult sturgeon migrate up the Sacramento River during the late winter and early spring, spawning above the river's confluence with the Feather River. Some young sturgeon migrate downstream when an inch or so long, but most move downstream slowly reaching the Delta at a length of 5 to 6 inches. Larger juveniles (18 to 30 inches) inhabit the same areas as the adults, and are common in Suisun and San Pablo bays.

Sturgeon are primarily benthic feeders, consuming crabs, clams, and shrimp, but are known to eat large amounts of forage fish such as longfin smelt.

Chinook Salmon (Oncorhynchus tshawytscha)

Although a minor element in the San Francisco Bay sport fishery, this species is significant in the nearby ocean sport and commercial fishery. It is dependant on San Francisco Bay as a migration route for smolts from upriver spawning areas to the ocean and as a return pathway for maturing adults. Salmon smolts are believed to remain in upper areas of the estuary for a short period of time while becoming acclimated to salt water, and they eat larger zooplankton, aquatic insects, and mysid shrimp at this time. An occasional sport fishery occurs within the Bay, usually localized between Angel Island and Point San Quentin. These adults, beginning their spawning migration, may still be consuming forage fish such as anchovies or smelt before they stop feeding until spawning and death.

Longfin Smelt (Spirinchus thaleichthys)

Longfin smelt, while considered anadromous because of its movement into freshwater portions of the Delta for spawning, is one of the true estuarine species present in San Francisco Bay. Adults of the species appear to be almost wholly restricted to the less saline areas of Suisun and San Pablo bays where they may constitute an important portion of the forage base of striped bass and other large piscivorous fish.

Marine Fishes

Sharks - Brown Smoothhound (Mustelus henlei), Spiny Dogfish (Squalus acanthias), and Leopard Shark (Triakis semifasciata)

Sharks were formerly an important element of the Bay commercial fishery. However, recently they are caught more often in the sport fishery. At least one commercial passenger fishing boat routinely completes successful shark fishing trips in the Bay. The species common in San Francisco Bay are bottom feeders and are most abundant in the shallower areas of the Central and South Bay. The presence of near term pups in pregnant female brown smoothhounds and the abundance of juveniles in catches indicates that San Francisco Bay is also the nursery area for this abundant species.

Pacific Herring (Clupea harengus)

Central San Francisco Bay is one of the prime spawning areas of this species in California with the spawning population estimated at near 25,000 tons during the 1976-77 winter. The 1980-83 spawning biomass has been estimated to be between 60 and 100,000 tons (Tasto, pers. comm.). This species currently supports a lucrative specialized commercial fishery and is also an important forage fish. Spawning is usually in the intertidal and shallow subtidal regions, particularly concentrated on shorelines in Marin and San Francisco counties. Larvae and young fish do remain in the Bay before moving into the ocean and are a part of the forage base of larger fishes.

Northern Anchovy (Engraulis mordax)

In absolute numbers, anchovies are the most abundant fish in San Francisco Bay. They support a minor commercial bait fishery and are a major forage base for piscivorous fish in the more marine areas of the Bay. Though primarily a coastal species, some spawning and rearing does occur in the Central Bay, and eggs and larvae are at times found in South San Francisco Bay and San Pablo Bay areas.

Topsmelt (Atherinops affinis) and Jacksmelt (Atherinopsis californiensis)

Top and jacksmelt, members of the silverside family, are popular targets of the pier and jetty fishery in San Francisco Bay. These species are typically marine and are most abundant in the Central and South bays, but they are able to tolerate the reduced salinities in San Pablo Bay. Spawning does occur in the Bay and juveniles are extremely abundant along beaches and backwaters. Adults become too large (12+ inches) to be a major component of the forage base, but juveniles are probably consumed by many larger piscivorous fish species. No significant commercial fishery currently exists for these species in the Bay area.

White Croaker (Genyonemus lineatus)

White croaker, typically found in shallow bays and coastal regions along the Pacific Coast, are present in the marine areas of San Francisco Bay. Although it is small in size, it is considered a desirable food fish and is a minor part of the Bay sport harvest.

Starry Flounder (Platichthys stellatus)

The starry flounder is the most abundant flatfish occurring in San Francisco Bay. Although classified as a marine species, it is apparently much more tolerant of reduced salinities than other species of flatfish. The center of the adult population in the San Francisco Bay complex is San Pablo and Suisun bays, but juveniles have been found in fresh water as far upstream as Rio Vista and Mossdale and were found in San Luis Reservoir shortly after it was filled indicating they were sucked from the Delta by project pumping. A sizable sport fishery is supported by this species in the northern bays, but the northern California commercial fishery is based on an offshore (ocean) population.

Surfperch (Family Embiotocidae)

More than a half dozen species of surfperch are common in San Francisco Bay and they are an important family of fishes in the Bay ecosystem. Surfperch, which generally feed on benthic invertebrates, are very abundant near piers, seawalls, and jetties where they are accessible to shore anglers and constitute a large portion of the sport harvest. They are not presently commercially harvested.

Freshwater Fishes

Although numerous native and introduced freshwater fish species are abundant in drainages flowing into San Francisco Bay, they are not considered a major part of the Bay ecosystem and are only incidently harvested by sport anglers fishing in Bay waters.

Invertebrates

Bay Shrimp (Crangon franciscorum)

The Bay shrimp is the most abundant shrimp in the San Francisco Bay complex. It is the object of a commercial fishery and is an important element in the forage base of Bay fishes. It is tolerant of lower than ocean salinities and highest populations are found in Suisun and San Pablo bays. Spawning and early larval development is in deeper, more saline areas of the Bay but juveniles migrate to shallower, lower salinity regions after larval settling. C. franciscorum is joined by a similar species, Crangon nigricauda in the more marine areas of the Bay.

Dungeness Crab (Cancer magister)

Dungeness crab, commercially the most valuable crustacean in northern California, is present in the Bay only as larvae and juveniles. Larvae move into the Bay, carried by gravitational circulation, during April and May. Young-of-the-year are present in the Central and San Pablo Bay areas and spend about 1 year growing in the Bay before returning to the ocean. Growth rates of juvenile crabs living in San Francisco Bay are reported to be about twice that of juvenile crabs living in ocean waters.

Benthic Invertebrates

In the latter half of the 19th century and the first decades of the 20th century, San Francisco Bay supported large scale commercial shellfish operations in South San Francisco Bay and areas along the Marin shores of San Pablo Bay. These culture operations, based on exotic Atlantic oysters and soft shell clams, yielded over 15,000,000 and 3,000,000 pounds, respectively, of oysters and clams annually during the peak years at the close of the 19th century. Declining water quality associated with increased coliforms brought a halt to these operations and virtually all operations within San Francisco Bay had ceased by 1930. Since 1956, public health considerations have eliminated all potential commercial operations and have severely restricted or discouraged sport harvest.

Clams, while currently harvested from only a few intertidal beds by man, are still an important segment of the San Francisco Bay ecological community. They function as an important link in the food chain, converting energy from detritus, phytoplankton, and zooplankton into organisms utilized by desirable benthic feeding species such as flounder and sturgeon, and assuming further improvement in water quality, have the potential of supporting extensive sport and/or commercial fisheries.

Benthic organisms, because of their limited ability to change locations, face a different set of problems in dealing with salinity fluctuations. Highest species diversities and standing crops are found in areas of the Central and South Bay where salinity variations are minimal, while areas in Suisun Bay and San Pablo Bay contain lower standing crops and are typified by a community composed of recently established young of the few species tolerant of salinity changes.

Another environmental factor controlling the distribution and abundance of benthic resources is the stability of subtidal sediments. Sedimentation, either from storm generated waves and wind suspended or river based materials, have a deleterious effect on existing populations. Regions in the Bay which are routinely impacted by suspended sediment generally are typified by species considered to be opportunistic. These organisms are able to occupy vacant habitats quickly which have not yet been populated by species found in more "mature" communities.

LIFE CYCLE DESCRIPTIONS OF FRESHWATER OUTFLOW-RELATED SPECIES

Certain fish in the San Francisco Bay biota have life cycles that are related to, dependent upon, or associated with freshwater outflows into the Bay. Some fish use currents which are affected by outflows, while others spawn during times of high flows and low salinity. Still others depend on the Bay as a nursery area to enhance the survival of larvae and/or juveniles. Life cycles of four of these types of fish will be described below.

English Sole (*Parophrys vetulus*)

The English sole is a commercially important marine species that spawns offshore, but the juveniles occupy shallow bay and estuarine nursery areas during early life before migrating to deeper offshore water as adults. San Francisco Bay serves as an important nursery area for juvenile English sole.

Mature adults spawn offshore over the continental shelf during the winter months in California, with a peak in January and February (Misitano 1976, Boehlert 1982). Eggs and larvae are pelagic and thus float with the currents for 6 to 10 weeks (Hart 1973). During this period the young are transported by water currents from the spawning grounds shoreward towards nursery grounds in the intertidal zone, bays, and estuaries (Misitano 1976).

Entry into the nursery area coincides closely with the completion of metamorphosis and the start of bottom dwelling habits, at an average size of 23 mm (Misitano 1976). Metamorphosing individuals are active swimmers, apparently tending to stay on the bottom during the day, but moving up into the water column at night (Pearcy and Myers 1974). Larvae and juveniles enter the bay using the upper water levels during night flood tides (Boehlert 1982), but during the day they are transported in the lower levels of more saline waters, where net transport is upstream via gravitational circulation patterns. Retention in the estuary requires active behavioral responses by the larvae, such as change in depth distribution, to enhance transport into and reduce movement out of estuaries (Pearcy and Myers 1974). Thus larvae are able to utilize the two-layered transport system that exists during the winter, when net transport on the bottom is up the estuary (Pearcy and Myers 1974), such as that occurring in San Francisco Bay.

Nursery grounds are typically shallow areas with fine sandy substrate and relatively quiet water (Olson and Pratt 1973). Sediments in these protected waters provide an ideal feeding habitat for the juvenile fish (Pearcy and Myers 1974).

In addition, there is generally a lack of large predators and there is reduced competition among age groups of the same species (Rosenberg 1982). Sexually mature English sole have never been observed in these nursery areas (Misitano 1976).

Survival of the young is related to the development time, as well as to transport by water movements (Hart 1973) from the spawning grounds outside the Bay to nursery grounds inside the Bay. In a study on the effect of salinity and temperature on the early development and survival of the English sole (Alderdice and Forrester 1968), the optimum conditions for survival were determined to be 25 to 28°/oo salinity and 8-9° C. Some studies show that English sole survival, not growth, is enhanced in the estuarine nursery ground, as compared with the open coast (Rosenberg 1982). Other studies suggest that English sole larval density is positively correlated with the ocean-bay salinity difference and freshwater input (Boehlert 1982).

Thus, it appears that San Francisco Bay provides the ideal conditions for an English sole nursery area, including reduced salinities, appropriate temperatures, two-layered circulation patterns with net upstream transport during winter, relatively calm and shallow water, and sandy substrate.

In a trawl survey conducted in San Pablo and Suisun bays during 1964 (Ganssle 1966), small English sole were common. They averaged between 4-10 cm in length during May through July and 7-18 cm during August through December. In 1963, however, only one individual was caught.

English sole gradually leave the shallow shoal areas and move into deeper channels with growth. During September and November of their first year, most immature English sole leave the estuarine nursery area and move into deep oceanic water (Misitano 1976).

Longfin Smelt (Spirinchus thaleichthys)

The longfin smelt is an abundant and truly-euryhaline species that occupies nearly pure sea water to completely fresh water in the San Francisco Bay-Delta system (Moyle 1976).

Their life cycle is considered to be anadromous, and although little is known about their saltwater life history, they have been taken in the ocean down to 75 fathoms in shrimp trawls (Hart 1973). They are most abundant, however, in San Pablo and Suisun bays, where salinities are normally greater than 10°/oo (Moyle 1976).

Radtke (1966) and Ganssle (1966) found that longfins move upstream from the Bay into the Delta in the winter and spring in order to spawn. From December to May, during this spawning migration, a single size group is apparent. Ganssle (1966) found a mass movement of young smelt downstream into Suisun and San Pablo bays during April and May. Messersmith (1966) substantiates this movement and found that longfin smelt were common in Carquinez Strait from January to July, but were rare in other months. Radtke (1966) found that this smaller size group comprised 87% of the catch during June, July, and August. He found no smelt present in the Delta during the fall and that the highest catches during the rest of the year occurred in the western Delta.

The majority of spawning takes place in the freshwater sections of the lower Delta, particularly in the lower Sacramento River (Moyle 1976). Longfin smelt reach sexual maturity at the end of their second year. Most adults die after spawning, but a few females may survive to spawn a second time (Moyle 1976, Hart 1973). The adhesive eggs are deposited on rocks or aquatic plants (Hart 1973), or may adhere to the river bottom (Stevens and Miller 1980). They hatch in 40 days at 7° C, and the pelagic larvae are 7 mm in length (Hart 1973, Stevens and Miller 1980). The young fish then move downstream during the spring (Moyle 1976).

Annual abundance indices were determined for young longfin smelt in the Sacramento-San Joaquin River system (Stevens and Miller 1980). The abundance of young longfin smelt increased directly with river flow rates occurring during the spawning and nursery periods, in particular their survival was most affected by spring and early summer flows. Apparently when the young fish are moving downstream, high flows result in increased dispersal, which in turn decreases density dependent mortality factors, such as competition.

Pacific Herring (Clupea harengus pallasi)

The Pacific herring is a marine species that does not spawn in the open ocean or outer coast in California, but instead migrates into protected bays and estuaries to spawn. In addition, the young remain for a time, using the area as a nursery before returning to the sea. San Francisco Bay is the largest and most important spawning and nursery area for central California's Pacific herring population.

Annual inshore spawning migrations are variable with time, sometimes being recognizable in October and September, and other times only occurring immediately preceding spawning (Hart 1973). Pacific herring have a homing instinct and return to their birthplace in order to breed as adults (Miller and Schmidtke 1956, Spratt 1981). In San Francisco Bay, pre-spawning herring concentrate in schools and mass spawnings occur at roughly 2 week intervals from December to March (Miller and Schmidtke 1956). The spawning cycle in the Bay seems to be related to the tidal cycle since 88% of all spawnings occur when the daily high tide is at night (Spratt 1981). However, spawning can occur at any hour and during any tide.

Females arrange the eggs in rows directly on the substrate (Hart 1973). The spawn generally covers all available surfaces in layers that are one or two eggs thick, but it can be as thick as 1¼ to 2 inches (Miller and Schmidtke 1956). There is no pairing, but the whole spawning area is usually white with milt, so the fertilization rate is high (Hart 1973).

Immediately after spawning the adult herring apparently return to the sea, since no spent individuals have ever been caught on the fishing grounds (Miller and Schmidtke 1956). Their movements in the ocean are generally unknown, but during the summer it is believed that some of the San Francisco Bay herring can be found in Monterey Bay (Spratt 1981).

The major spawning areas in San Francisco Bay are in the intertidal zone and in the immediately adjacent subtital areas to a depth of 15 feet (Spratt 1981). The most frequently used intertidal areas are just inside the Golden Gate Bridge along the Marin Peninsula, the Tiburon Peninsula, Angel Island, between Richmond and Oakland, and the shoreline between China Basin and the airport, comprising about 40 miles of shoreline. But the largest spawning areas are in the subtidal zone, particularly in Richardson Bay and in the large shallow area between Richmond and Oakland.

During extremely low outflow years, herring have been known to spawn as far north as Rodeo and Carquinez Strait, but more commonly they only spawn as far north as Point San Pablo, whereas the southernmost extension of spawning appears to be Point San Mateo in the South Bay during years of relatively high outflow (Miller and Schmidtke 1956).

Alderdice and Velsen (1971) conducted a laboratory study on the effects of salinity and temperature on Pacific herring eggs and larvae. They found that maximum spawning success occurred at or near 16.98°/oo salinity and 8.7° C. Overall, they found that both eggs and larvae are tolerant of a wide range of salinities (12-26°/oo) and temperatures. Herring are known to spawn in salinities that optimize viability (8-28°/oo), but maximum egg and larval survival occurs within 13-19°/oo, with the optimum at 16.98°/oo. Alderdice and Velsen point out that in California herring spawn only in bays and estuaries, not on the open coast, and that there is limited availability of large areas of reduced salinity. This restricted availability of spawning salinities could serve to restrict overall abundance. They feel that populations on the North American coast are confined to regions providing protected spawning waters of reduced salinity (8-28°/oo) and temperatures between 5 and 10° C. San Francisco Bay is the largest spawning region south of British Columbia and Puget Sound providing the requirement of a reasonably large protected body of water of reduced salinities just within the upper temperature limit. Thus, minor annual water temperature fluctuations, and differences in freshwater runoff and its influence on salinity, could determine both the extent and occurrence of spawning as well as the survival of eggs, larvae, and juveniles.

Juvenile herring typically remain in the protected inshore areas through the summer congregating, feeding, and growing to a length of 3 to 4 inches before they disappear into the deeper water of the open ocean in fall (Hart 1973).

In a trawl survey conducted in Carquinez Strait during 1961-1962, the Pacific herring was the second most abundant species, comprising 27% of the overall total numbers with the principal catch occurring in March and July (Messersmith 1966). In a midwater trawl survey conducted in San Pablo and Suisun bays in 1963, newly hatched herring were found in San Pablo Bay beginning in February and March, with a peak of juvenile abundance in May and June, but few occurred in August and they were absent from September on (Ganssle 1966). It thus appears that San Francisco Bay serves as a nursery area for the young-of-the-year until they disappear out to sea in the fall.

Northern Anchovy (*Engraulis mordax*)

The northern anchovy is a marine species that spawns within San Francisco Bay as well as in the adjacent areas of open ocean. Although found in the Bay throughout the year, a large influx usually occurs in May and this elevated abundance persists through September (Smith and Kato 1979).

Spawning takes place at night in the upper layers of water. Fertilization is external, nearly all eggs are fertilized, and they are pelagic. Eggs hatch in 2 to 4 days, depending on the temperature, larvae are 2.5 to 3.0 mm long, and at about 1 inch the juvenile resembles the adult. A few reach sexual maturity at the end of 1 year, at 90 to 100 mm in length; about half reach maturity between 2 and 3 years, at 130 mm; and all are mature by 4 years of age, at 150 mm. Several spawnings occur each year. In winter anchovies generally move offshore, but they return to inshore areas in the spring. They usually remain at or near the bottom during the day and come to the surface at night (Hart 1973).

Little is known about the amount of anchovy spawning actually occurring in San Francisco Bay, but worldwide they are known to spawn over a broad range of conditions, from oceanic to estuarine (Ganssle 1966). During their period of elevated abundance, in late spring and early summer periods of higher outflow, all ages of anchovies were caught in San Pablo Bay, including many ripe and ripening adults, but as summer progressed the proportion of large fish decreased until, during the fall and winter, only recently born and a few 1 and 2 year old fish were caught (Ganssle 1966). The presence of ripe and ripening fish, along with many small, young individuals, indicates that the species probably spawns in San Pablo Bay (Smith and Kato 1979).

Pelagic anchovy eggs have been found in the California Current during every month of the year, with a peak of abundance in late winter and early spring and another minor peak in early fall. Adult anchovies are normally found in San Francisco Bay in greatest abundance from midsummer through early fall, but anchovy larvae were present in Richardson Bay, a small bay off of Central San Francisco Bay, between August and March, with the highest density occurring in December (Eldridge 1977).

Although generally classed as a marine species (Ganssle 1966), the northern anchovy is probably the most abundant fish species in San Francisco Bay and thus is most likely an important forage fish for larger species (Smith and Kato 1979).

VALUES OF BIOLOGICAL RESOURCES IN SAN FRANCISCO BAY

In order to characterize the importance of the San Francisco Bay-Delta estuarine system, it is helpful to place some value on the biological resources that make up the system. Besides the more obvious values of sport and commercial fisheries, there are also general recreational and aesthetic values. In order to maintain the recreational, commercial, and aesthetic value of the Bay, the estuary itself must be ecologically healthy, thus, the innate ecological value of the system must be maintained.

Sport Fishery

Sport fishing is the most popular recreational activity in the San Francisco Bay and Delta area. The 1980 user estimate at present facility capacity was 4.4 million recreational days, but the potential demand was estimated to be

19.0 million recreational days (The California Water Policy Center 1979). Facilities include piers, public beaches, skiff rentals, launching facilities, and more than 100 commercial passenger fishing boat operations.

The three most important species sought after on commercial passenger fishing boats are chinook salmon, striped bass, and halibut, but most salmon fishing takes place in the ocean. In Carquinez Strait, commercial passenger fishing boat effort concentrates on striped bass and sturgeon, but in other parts of the Bay additional species are sought after including brown rockfish, surfperch (seven species), lingcod, jacksmelt, topsmelt, white croaker, sharks, and rays. Sharks and rays are especially sought after in South Bay, in particular soupfin shark, six and seven-gill sharks, and leopard sharks, but brown smoothhounds, spiny dogfish, and skates are also taken. None of these species are taken in significant numbers when compared to bass, sturgeon, and halibut catches.

Shore fishermen fishing from beaches and piers attempt to catch lingcod, cabezon, surfperch, starry flounders, and speckled sanddabs. Striped bass and salmon are caught from shore less often.

The primary people that benefit from the sportfishery resources of San Francisco Bay are, of course, the anglers. However, anglers in turn also help support the Bay and Delta area economics because they spend money in the vicinity for the bait, equipment, food, and gas necessary in order to pursue their hobby. Thus, sport fishing benefits the general economy as well as the anglers.

Commercial Fishery

Several commercial fishery operations presently exist in San Francisco Bay which harvest herring, shrimp, and anchovies. Other species have supported important commercial fisheries in the past, including striped bass, sturgeon, surfperch, sharks, shad, salmon, and shellfish (Smith and Kato 1979). These resources are no longer commercially exploited for various reasons, such as changes in abundance, overexploitation, and economic considerations. Thus, their harvest has been restricted to the recreational sport fishery.

The commercial herring fishery is by far the most lucrative in San Francisco Bay at the present time. The fishery concentrates on herring roe, the ripe ovaries of females, and eggs-on-kelp which is gathered by divers in spawning areas. All of these are exported to Japan where they are sold as expensive gourmet items (Smith and Kato 1979).

A recent study of the herring resource in San Francisco Bay (Spratt 1981) has concluded, based on the age composition of the harvest, that it appears recruitment has remained good after several fishing seasons, since age groups 2 and 3 constantly dominant the catch, and age 6 through 9 continue to be well represented. The most recent and most accurate estimate of the spawning biomass of herring in the Bay, for the 1979-80 season, was 52,869 tons. Since the fishery was so profitable, there was fear that overexploitation and population reductions would occur, so a commercial harvest quota was established. The 1977-78 quota for adult herring was 4,558 tons and the quota for eggs-on-kelp was 4.5 tons, including plant material (Smith and Kato 1979). Fishing at current levels should thus be sustainable, assuming that recruitment continues to be successful each year (Spratt 1981).

The northern anchovy is probably the most abundant species of fish in San Francisco Bay, and as such it presently supports a moderate commercial fishery (Smith and Kato 1979). The majority of the catch is packed and frozen as bait for recreational fisheries, but an additional amount is taken for use as live bait, which is primarily used in the sport fishery for striped bass and halibut. Both live and dead anchovies also are sometimes used for bait in the commercial albacore tuna fishery. There is no estimate of anchovy biomass for San Francisco Bay. The present commercial fishery has stabilized at around 385 tons.

There are three species of native shrimp (Crangon spp.) and one species of introduced shrimp (Palaemon macrodactylus) present in San Francisco Bay (Smith and Kato 1979). The commercial shrimp fishery presently supplies bait for striped bass and sturgeon sport fishing. The shrimp are sold both frozen and live, but live bait is the most popular. The fishery is small, but lucrative, since sport fishermen will pay approximately $12.00 per pound for bait shrimp. Most fishing for shrimp occurs in San Pablo Bay, with some limited fishing in South Bay. Since the Bay shrimp are so small, there is limited demand for them as food, and it appears that they cannot be economically processed on a large scale.

The Dungeness crab, Cancer magister, has undergone a population decline in recent years, but it still supports one of the more important commercial fisheries in the San Francisco Bay area. The boats operate out of Bay fishing ports but all of the actual fishing takes place outside of the Golden Gate on sandy bottom in shallow water (Skinner 1962). However the Bay is a very important nursery ground for young crabs (Tasto, pers. comm.). It is only permissible to take males that are at least 6¼ inches in size. Males can reach this size in 3 to 4 years. The commercial take in the 1977-78 season for the San Francisco area and Bodega Bay was 587,283 pounds (Orcutt 1978).

Ecological Values

Estuaries are productive ecosystems. Nutrients are carried into the estuary by river outflows and provide the necessary chemicals to support phytoplankton growth, especially in the large shallow areas where light can easily penetrate. The phytoplankton in turn supports zooplankton. Generally, this food base provides ample energy to allow the estuary to be used as a nursery area for many species of fish and invertebrates. The small fish and larval invertebrates feed on zooplankton, phytoplankton, and each other. Small and numerous adult fish, such as smelt, anchovies, and herring, feed on the lower levels of the food chain, and in turn provide forage for larger fish such as salmon, flatfish, and striped bass, as well as for other wildlife such as birds and aquatic mammals. There is also a benthic community with animals that filter planktonic organisms from the water column and macrophytic algae, both of which provide food for larger organisms.

This is a rather simple view of the complex food web that exists in the Bay-Delta system. This web is actually based upon an interaction of physical, chemical, and biological factors, and this balance is affected by fluctuating environmental phenomena, both natural and manmade. Maintaining such a balance in the entire system is necessary in order to retain its ecological value (or health) and its ability to provide the biological resources necessary to support commercial and recreational uses. Additionally, maintaining San Francisco Bay as a healthy estuary provides ecological value not only to the system itself and its inhabitants, but even more importantly it is of value to the surrounding human community, as well as the ocean and upriver biological systems. A healthy bay is aesthetically pleasing and encourages much recreational use. User estimates for recreational activities in the San Francisco Bay and Delta area for 1980 have been determined (The California Water Policy Center 1979). Including fishing, hunting, nature walking, boating, picnicking, camping, and hiking, the actual use at present facility capacity was estimated to be 10.1 million recreational days, but the potential demand was estimated to be 69.0 million recreational days. Thus, there is a significant amount of unsatisfied recreational demand presently existing in the Bay-Delta area. There is no general agreed upon procedure for estimating the value of the aesthetic and therapeutic benefits of these consumptive and non-consumptive uses, but it certainly contributes significantly to the health and well-being of the State's populace.

CONDITION OF SELECTED SAN FRANCISCO BAY RESOURCES

The San Francisco Bay-Delta system has undergone some dramatic changes during the past century. The region was once the foremost fishing center on the West Coast, but it has long since relinquished the position (Smith and Kato 1979). Manmade changes, including extensive land reclamation, dredging, water pollution, water development projects, and overfishing, have resulted in declining resources, with many of the commercial fisheries beginning their decline even before the turn of the century (Skinner 1962). Other organisms have been on the increase, such as accidentally introduced invertebrates and some fishes. Finally, other factors have affected water quality and therefore the health of organisms or their use by man.

Declining Resources

Dungeness Crab (Cancer magister)

The crab fishery is one of the more important in the San Francisco Bay region. Landings typically fluctuated between 1 and 8 million pounds, with an average of about 3 million pounds (Skinner 1962), until there was a drastic population decline in the early 1960's. The population has continued at a very low level to the present, thus being a long-term trend rather than a short-term fluctuation. A special study was conducted in order to determine the reasons for this decline and recommend procedures to improve the situation (Dungeness Crab Research Program 1981). The Department of Fish and Game conducted research on aspects of life history, pollution, and oceanography. The crab decline was found to be most closely correlated with persistent changes in ocean conditions that began 3 years prior to the start of the decline. These changes included increases in water temperature and in the frequency of intensified northward-flowing currents. The ovaries of female crabs were smaller in the warmer water, while hatching success was maximized in colder water. Thus, the long-term effects of warmer water lowered production. Additionally, strong northward-flowing currents have transported early crab larval stages, which are found progressively further offshore as they develop, farther north than usual, making their subsequent inshore movement into the Bay at later stages more difficult.

Although the reason remains unknown, it was found that juvenile crabs grow faster in San Francisco Bay than in nearshore areas outside the Bay (Dungeness Crab Research Program 1981). Studies showed that 80% of the 1975 year class entered the Bay complex (Tasto 1979), thus San Francisco Bay appears to be a major nursery area for the Dungeness crab.

Striped Bass (Morone saxatilis)

The striped bass population has undergone a serious decline, leaving the adult population at one-quarter of what it was 20 years ago and the production of young over the last 5 years at one-third to one-half the expected values. Studies conducted from 1959 to 1976 have shown that young bass survival was directly correlated with outflow and diversions from the Delta, and that variations in young bass survival appears to be important in determining subsequent recruitment to the fishery. Recently, however, from 1977 to present, young bass survival has been consistently poorer than expected for the amount of outflow and diversions (Stevens 1979). A State Water Resources Control Board organized study conducted by the Striped Bass Working Group (1982) revealed several factors that in combination could help explain the reason for the decline and why the population is not recovering.

First, phytoplankton production in Suisun Bay and the western Delta has fallen to extremely low levels. Phytoplankton probably is necessary to support the zooplankton that the young bass feed on when they are carried into the nursery area. The first major phytoplankton decline occurred during a drought in 1977, and since then the spring phytoplankton blooms have only partially returned to pre-drought levels. Also, blooms have been delayed in most years until after the young bass need the zooplankton. Adequate blooms in the western Delta have only occurred twice since 1976, in both cases when the export pumps (CVP/SWP) have been shutdown, but the exact reason for this phenomenon is unknown.

A second factor that the committee thought may be affecting young bass production may relate to wastewater treatment plants. These plants have been converted from primary to secondary treatment, thus eliminating a large source of organic nutrients that could feed young zooplankton and thus bass.

A third element affecting the decline indirectly is water diversion projects. Over the last 20 years they have resulted in high losses of young fish which lowered the number of adults, which lowered the young, etc. Such a cyclic process caused the population to spiral downward resulting in lower populations than expected.

Fourthly, there is evidence that undesirable levels of toxicants occurr in striped bass, but because long-term data were not available to the committee they could not evaluate the consequences of this on the population.

The adult striped bass population has been reduced to a point where total egg production is only about 10% of what it was 20 years ago. Even though billions of eggs are still produced, the reduced egg production results in reduced numbers of young bass, which in turn results in lower recruitment, and an even smaller spawning stock.

It is likely that all of the above factors are affecting the striped bass populations and contributing to their decline. Striped bass were originally introduced, and for many years they were abundant enough to support an important commercial fishery. Since 1935, the harvest has been restricted to sport fishing, with the striped bass becoming one of the most popular species of all. At the present time, this valuable recreational fishery is imperiled due to a combination of changing environmental factors in the Bay-Delta system.

White Sturgeon (Acipenser transmontanus)

Towards the end of the last century, sturgeon suddenly became popular and the fishery was heavily exploited (Skinner 1962). This, in combination with heavy silting from hydraulic mining operations, caused a drastic decline in the population, and by 1917 they were fully protected. Sport fishing was allowed in 1954 when the population had sufficiently recovered, and commercial passenger fishing boat catches peaked in the mid-1960's (Smith and Kato 1979).

Sturgeon abundance declined between 1967 and 1974, and then increased from 1974 to 1977, but the total catch has continued to decline (Kohlhorst 1980). The mean size of sturgeon increased from 1964 to 1974 and then decreased through 1978, but survival rate changed little. Since sturgeon take 12 to 15 years to become sexually mature, the population decline was probably due to poor recruitment during the mid-1950's. It was not due to overexploitation since mean size increased as abundance decreased.

Three potential causes of poor recruitment of white sturgeon have been identified (Kohlhorst 1980). Degradation of habitat for juveniles may occur due to high diversion rates and low freshwater flows. Low freshwater flows may restrict available habitat or reduce food supplies, while high diversion rates either directly remove fish or disrupt migration patterns. Environmental contaminants, in particular PCB's, which have been found in high levels in adults, may reduce the survival of larval sturgeon and subsequent recruitment. Declines in spawning stock size also may be an important factor in the decline.

Increasing Resources

Almost 100 species of exotic marine invertebrates have been introduced into San Francisco Bay by man during the past 130 years, and about 96 of these have become established members of the Bay fauna (Carlton 1979).

Palaemon macrodactylus, the Korean shrimp, was accidentally introduced in the early 1950's and has become established in brackish waters of the Bay system (Smith and Kato 1979). Palaemon is a potential competitor with the native shrimps (Crangon spp.), but they have become most abundant in the more brackish areas of the Bay, while the native species are most common in more saline areas. Palaemon has become a common member of the Bay fauna, and thus has become important as a forage species and has been included in the shrimp bait fishery (Smith and Kato 1979).

The Japanese littleneck clam, Tapes japonica, was first collected in the Bay in 1946, but its abundance has now made it important in the diet of some sport fishes, such as sturgeon (Carlton 1979). Since the Japanese littleneck became established, it has taken over much of the habitat formerly occupied by the native littleneck (Protothaca stamina) (Smith and Kato 1979). Japanese littlenecks are presently abundant in the Bay, and although subject to intensive sport clamming in some areas, despite public health warnings, the resource remains essentially unused. They are tolerant of a wide range of salinities, adapting well to extremely saline conditions, and also are found where salinities are as low as $16^{0}/oo$. They prefer gravel bottoms, and will not develop on substrates where no attachment is possible or where young are subject to gill clogging.

The yellowfin goby, Acanthogobius flavimanus, a native of Japan, was first collected in the San Joaquin River Delta in 1963 near Stockton, and since then it has spread throughout the Bay as well as north into the rivers and up and down the coast, becoming one of the most common species in the Bay-Delta system (Brittan, Hopkirk, Conners, and Martin 1970). They are unusually tough and resilient, able to withstand drastic changes of salinity in captivity, and thus have been able to spread widely and rapidly. In Palo Alto harbor they outnumber the staghorn sculpin, Leptocottus armatus, which was formerly the most common species. Their effect on the native freshwater and estuarine species is unknown, but freshwater populations of the small tidewater goby may be in danger of elimination through competition. However, yellowfin gobies do have some resource potential as sport, commercial, or bait fish, and in Japan they are considered to be a delicacy (Moyle 1976).

Contaminated Resources

San Francisco Bay has large numbers of shellfish species, including some with potential commercial and recreational value, such as the soft-shell clam, Japanese littleneck, mussels, and the native oyster. The State Public Health Department, however, will not allow any Bay shellfish to be harvested for human consumption, due to contamination of shoreline waters by sewage and other inputs, despite the fact that there has been considerable improvement of water quality in the Bay in recent years (Smith and Kato 1979).

Harmful chemicals, such as heavy metals and chlorinated hydrocarbons, are accumulated in tissue and can be biomagnified as they pass up the food chain. Fish, which are usually at a rather high trophic level, will accumulate these chemicals in their flesh, and thus can sometimes become contaminated and harmful to consumers. Examples of rather high chemical levels have been found in striped bass, sturgeon, and starry flounders, among others. Although not yet to the point of being high enough to prompt governmental closure of fisheries, warnings about excessive bass consumption have been posted. This problem must be considered a real and potential danger in the future.

CHAPTER THREE

BIOLOGICAL RESPONSES TO FLOW CHANGES

In general, an individual organism will respond in some predictable way when stressed by an environmental factor. Sometimes, similar species will respond similarly and sometimes similar responses to particular types of environmental stress are seen at the population level. There are four types of general responses that fish and wildlife populations display when stressed. These responses are briefly discussed below:

Populations Can Remain Stable. Some groups of organisms are particularly tolerant and will not be affected when stressful situations occur. Such species can tolerate wide ranges of salinity and temperature or can feed on a wide range of foods. An example of such a group in San Francisco Bay is the goby community. There are several species of this group and they are able to live under most Bay conditions. Flow-related stresses may not significantly affect such species and their populations may remain stable as flow changes occur.

Populations Can Increase. Some groups of organisms can benefit from stressful circumstances. Usually, they are particularly tolerant to a particular stress that eliminates or reduces its competitors and it can respond by becoming a community dominant or at least increasing in number. For example, if freshwater flows were reduced in the Bay, salinities would increase. Such increases would stress estuarine fish but favor marine species. Thus, marine species could become more numerous.

Populations Can Be Reduced. If a group of organisms cannot tolerate the stress of unfavorable conditions, it is likely that the numbers of that group will be reduced. The stress acts on individuals in the group and may acutely impact them, or cause chronic problems. The cumulative impact of all these individual responses is that the overall success of that group is reduced. If outflow reductions are considered as a stress, estuarine fish may exemplify a group that may be reduced. Reduced fresh water would mean that marine conditions would be more prevalent, and thus the amount of available habitat for brackish or estuarine fish would be affected or at least the location of that habitat would be changed.

Populations Could be Eliminated. If a particular stress is severe enough or if the tolerance of an organism is sufficiently low, a population could be completely eliminated. When this happens on a local basis, the occurrence of that organism is then restricted to other areas where conditions are better.

If it happens on a scale which covers the entire range of an organism, that organism could become extinct. Worldwide there are numerous examples of extinction, and currently many more organisms are nearing extinction (mostly due to severe stress related to habitat loss or alteration). In the context of the Bay, while it is conceivable that flow changes could eliminate some species, no species is known to be threatened with elimination at this time, despite the fact that flows have been reduced to about half of historical levels.

When looking at an entire system such as the Bay, it is important to recognize that the same stress could result in all four of the above responses being displayed by different groups of organisms at the same time. The consequences of such a shift in natural circumstances cannot be easily predicted. Many times such consequences resulting from over stressing a system result in ecological imbalances. For example, stressed systems sometimes display algal blooms, scums, or significant changes in species composition. A particular species that was insignificant before the stressful factor was present could become very numerous, to the point of being a nuisance. When such things happen, people who are affected by these changes become involved and bring pressure to bear on regulatory agencies or political entities. Sports groups or clubs, homeowner groups, or environmental organizations are particularly adept at applying such pressure. A recent example in the Bay is the political furor and subsequent legislative hearing that occurred when the macro-algae bloom occurred in San Pablo Bay during 1980.

There is one final consideration regarding general biological responses to stress. In most cases, organisms do not respond at the first sign of stress. A certain level of stress must be applied before a response is initiated or observed through measurement techniques. In other words, there is some threshold level that must be reached before a response is started. Such threshold levels may also apply to an entire system.

Theoretically and conceptually there is support for the existence of a threshold effect in biological and ecological systems. A threshold effect is produced when the intensity of some causative agent (stress) rises above a certain threshold (Watt 1973). Watt provides the example that some animals do not begin looking for food until after their hunger level has surpassed a threshold. Physiological or ecological thresholds have been shown to be characteristic of distinctive growth patterns in the life of fish (Parker and Larkin 1959). Warren (1971) has applied the threshold concept in toxicological considerations. He defines a "threshold reaction time" as the minimum length of exposure the animal can tolerate before reacting by dying or collapsing, no matter what the level of the lethal agent may be. Belyea (1952) expanded the concept to include multi-species complexes. He showed that the response of perennials to being eaten is characterized by thresholds, lags, and cumulative effects. His work on balsam fir trees and spruce budworms showed that no tree mortality occurred unless pest density rose above a certain minimum (threshold) level. Finally, Watt (1973) has expanded the concept to a systems level. In a discussion on the effects of perturbations of weather on biological systems he states that "the effects of a single perturbation can be much larger than expected if it is applied to a system repeatedly, either because of cumulative effects or because some threshold is finally exceeded." In the present context of estuarine dynamics, diversions might occur increasingly without significant, noticeable impacts only until some system-specific threshold is exceeded. After that, effects could increase disproportionally. To date, however, most identified biological effects of flow in the San Francisco Bay estuary have all been continuous functions of flow rather than threshold effects.

BIOLOGICAL RESOURCE RESPONSES TO OUTFLOW-RELATED CHANGES IN ENVIRONMENTAL CONDITIONS

In previous sections of this report it was shown that Delta outflow can be characterized by various descriptive components (Volume, Velocity, Quality, and Pulses with Duration, Timing, and Frequency). Further, it was shown that certain changes in outflow have or will come about which will alter these components. The projected ways in which components will be altered and how those alterations will affect environmental conditions of the Bay have been discussed. The next objective is to determine how biological resources will respond to these changed conditions. It is important to recognize that there is a cause-effect relationship involved when flow alterations occur. For example, flows are reduced and the response is altered outflow characteristics. These characteristics cause physical/chemical environmental changes which, in turn, cause certain biological responses. The remainder of this section will present a categorization of particular biological responses.

In this discussion, the physical/chemical factor or condition which causes a biological response will be called an <u>effector</u>. Each effector has at least two important characteristics: a <u>response time</u>, or a time period necessary for the effector to bring about biological change; and a <u>duration</u>, or period of time during which the biological response remains observable. Generally, response times are either <u>immediate</u> or <u>delayed</u>, while durations can be <u>short-term</u>, <u>long-term</u>, or <u>permanent</u>.

Outflow-related effectors will cause fish and wildlife resources to respond in only one or two ways. First, the <u>distribution</u> or spatial occurrence patterns can be altered, and/or second, <u>overall abundances</u> will be changed. All other population responses will ultimately be reflected in one of these two results (including growth rate, death rate, fecundity, predation, etc.).

The following section will discuss how various outflow regulated effectors can cause distributional and abundance changes. The response time and duration of each effector will be listed and a discussion will explain how the effector alters resources, and then examples from San Francisco Bay (if available) and from existing literature sources will be provided.

Distributions

The most obvious effect of flow changes on biological resources is altered distributions. Fish and wildlife can respond by changing location when they are stressed by outflow-related conditions. Distributional changes can be brought about by two effectors.

Effector - Salinity

Response Time: Immediate

Duration: Usually short-term, but can be permanent.

Discussion. When salinity levels are changed by flow changes, adult fish and shrimp often times respond by moving to another part of their range where salinity is more favorable. It can take a period of time before salinities increase above the tolerance limit of the organisms, but as soon as limits are exceeded the fish will begin to respond by moving to another location. Thus, they will actively avoid unfavorable conditions. Usually, such responses to salinity changes are short-term as they are responses to short-term salinity fluctuations. Organisms disperse when conditions change and then return after conditions are again favorable. However, response to a salinity change can be permanent if the salinity change is permanent or part of a long-term trend.

Changes in fish distributions due to flow-caused salinity changes have been documented in the Western Delta and San Pablo Bay. Ganssle (1966) showed that the salinity gradient was very influential in determining the distributions of 61 species of fish which he collected in the system. He found that when ocean salt moved upstream, the number of marine species increased there. Herrgesell et al. (1981) reported that during a prolonged drought, salinity increases caused freshwater fish to move out of Suisun Marsh and allowed marine species to move in. Turner and Chadwick (1972) have also suggested that the annual distribution of young striped bass in the estuary is related to river flow and salinity with bass being farther upstream in years of low runoff and high salinity.

Painter (1966a) found that chlorinity (salinity) was the major factor that determined the longitudinal distribution of zooplankton in the San Francisco Bay estuary. His work, which was carried out in San Pablo, Grizzly, and Honker bays, found that the common zooplankton genera could be divided into three groups based on chlorinities. Each of these three groups was distributed in a different part of the system. Painter (1966b) also found that of the many environmental and biological factors in combination that determined the distribution of zoobenthic animals in the estuary, chlorinity was the easiest to identify.

Salinity also has been shown to be an important factor regulating organism distributions in other estuaries. Distributions of white catfish in the tidal portions of York River were affected by drought-induced salinity changes (Wojcik 1982). These fish shifted their distributions downriver during high flow (low salinity) and upriver when flows decreased and salinities increased. Wenner, Shealy, and Sandifer (1982) found that salinities, as affected by flow changes, also influenced distributions of fish and decapods in the North and South Santee estuarine system in South Carolina. During a 1981 drought in Virginia, Austin (1981) found that spawning and nursery areas for American shad, river herring, and striped bass were pushed upstream in the Chesapeake Bay system by salinity intrusion. Additionally, Austin found that shipworms, barnacles, and other boring and fouling organisms also changed their distributions in response to salinity changes. Keup and Bayless (1964) studied fish distributions in the Neuse River Basin, North Carolina, and concluded that in most natural brackish water environments, the fish are able to escape intolerable salinity conditions by emigrating to more tolerable parts of the estuary. There are many other examples of salinity-induced distributional patterns in estuaries that will not be reviewed here. For a further treatment of this topic, see Gunter (1938, 1945, 1961), Kilby (1955), Kinne (1966), Copeland and Bechtel (1974).

The duration of salinity effects can sometimes be permanent. Most estuarine animals are adapted to salinity changes, but if changes are greater than normal, last longer, or if individual organisms can't escape to other areas, widespread mortality of individuals can occur. Some examples due to both decreases and increases in salinity are presented in Table 3-1.

TABLE 3-1. Some Examples of Mass Mortality Associated with Salinity Changes (Data From Brongersma-Saunders 1957, Kjerfve and Greer 1978, Burrell 1977, and Breithaupt and Dugas 1979).

Location	Organism	Cause	Result
Knysna River, Africa	Fish, octopus, invertebrates	Salinity decrease	Mass mortality
Chesapeake Bay	Oysters	Salinity decrease	Mass mortality
Texas estuaries	Oysters, other invertebrates	Salinity decrease	Mass mortality
Lagoa dos Patos	Fish	Salinity decrease	Mass mortality
Laguna Madre	Fish	Salinity increase	Mass mortality
Gulf of Kara Bugaz (Caspian Sea)	Fish	Salinity increase	Mass mortality
Santee River	Oysters and clams	Salinity decrease	32-66% mortality
Louisiana Coast	Oyster drill	Salinity decrease ($15^{o}/oo$)	Eliminated drill

In most estuaries, such individual mortalities do not mean that the entire population is eliminated. Often these individual mortalities only reduce the whole population until individuals are replaced in a more favorable area.

Effector - Flow-Related Currents and Circulation Patterns

Response Time: Immediate

Duration: Usually short-term, but can be permanent.

<u>Discussion</u>. Organism distributions can be affected by flow-altered currents and circulation patterns. Generally, it is the young or larval stages that are directly affected. Flow changes can increase or decrease velocities and small organisms that usually drift with currents can be displaced to other parts of the system. This dispersal can be behaviorally passive or active, in a landward or seaward direction, in an estuary or in the open sea, or in any combination of the above pairs (Shaw 1981). Since movement is dependent on currents, the organisms' response occurs immediately as soon as flows change. The duration of the effects of current changes is usually short-term. Larvae grow and can return to other areas more favorable to their existence. In other cases, organisms can be carried to areas where conditions result in their death; therefore, such effects are permanent for those individuals.

The relationships between water movement (flow) and the distribution of fish and fish food organisms has been documented in the San Francisco Bay estuary. The proportion of young striped bass in downstream nursery areas increases as flow increases (Turner and Chadwick 1972; Chadwick, Stevens, and Miller 1977) (Figure 3-1).

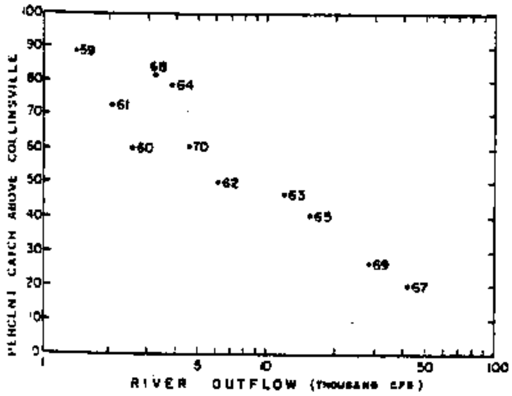


FIGURE 3-1. Relationship Between River Outflow During June and July and the Percent of Young Striped Bass Above Collinsville (From Turner and Chadwick 1972).

Outflow also controls the distribution of young salmon, shad, and longfin smelt in the Bay-Delta system. Higher flows transport the pelagic eggs of American shad and striped bass, and also young fish which tend to be passive, such as larvae of shad and smelt, to downstream areas; likewise high flows carry some salmon fry into Suisun, San Pablo, and Central San Francisco bays, where some unknown portion successfully rear to smolt size (Stevens 1977; Stevens and Miller 1980; Kjelson, Fisher, and Raquel 1981). The extent of such transportation varies from year to year with flows. Herrgesell <u>et al</u>. (1981) have reported that freshwater flow-related Bay circulation affects the distribution of English sole. Stronger and more consistent bottom flows in the northern reach of the estuary generally cause more ocean spawned young sole to be swept into North Bay than to the South Bay where gravitational circulation is less.

Invertebrate distributions are likewise affected by flow-related transport. The opossum shrimp (Neomysis mercedis) is hydraulically and behaviorally concentrated just upstream of the "entrapment zone." Since the zone's location moves in relation to flow, changes in shrimp distributions also occur (Orsi and Knutson 1979).

Transport of estuarine organisms by flow-related, estuarine circulation has been documented elsewhere. Shaw (1973) provides a good review. He reports the following: (1) Sagitta elegans and barnacle nauplii are carried by bottom countercurrents toward the upper end of the Saint John River, New Brunswick; (2) distributions of oyster larvae in St. Mary's River, Maryland are affected by longitudinal circulation; (3) bivalve larvae are transported by tidal transport in the James River, Virginia; (4) Atlantic croaker larvae are transported up the Chesapeake Bay channel by saline landward moving currents; and (5) larval and juvenile hogchoker distributions in the Patuxent River, Maryland move upstream using salt wedge transport. After reviewing existing data, Shaw (1981) concludes:

> It is no coincidence that the two intervals of maximum larval fish abundance, which occur during the spring and fall, are times of high vertical stratification and river runoff which are conducive to two-layered circulation and potentially to larval retention and transport.

This statement points to the importance of flow-related processes in determining the location of larval fish.

Barraclough and Phillips (1978) also have documented the role of flows in affecting juvenile salmon occurrence patterns. They found that pink, chinook, and coho salmon juvenile distributions in the Strait of Georgia (Vancouver, B.C.) appeared to be influenced considerably by tide and wind generated surface currents and by the volume of freshwater discharge from the Fraser River.

Abundances

The second significant way that flow changes impact biological resources is by affecting conditions which ultimately alter the abundance of those resources. Such biological responses to flow are much more difficult to document. Generally, the cause and effect relationship between flows and organism abundances operates through a chain of events rather than through direct effects of flow on abundance. Usually, other mechanisms that are stimulated or regulated by flows affect short or long-term survival. Some of these mechanisms increase abundance while others lower abundance.

Effector - Salinity

Response Time: Delayed

Duration: Short-term, but can have long-term impacts.

Discussion. Usually changes in salinity cause immediate responses by organisms. As discussed above, distributions are altered. However, other salinity related, cause-effect mechanisms can act on a delayed basis and result in increases or decreases in organism abundance. Responses are delayed because other mechanisms or processes must first be activated by salinity changes and then those processes must, through time, impact organism survival. Usually, the duration of salinity-induced altered abundance is short-term, but the results of short-term abundance changes can have long-term effects.

The best example of such a complicated process is the phytoplankton population in South Bay. During periods of high outflow and neap tides, freshwater flows into South Bay cause salinity stratification. During these periods in early spring, surface chlorophyll a increases from <5 to >40 mg/m^3, indicating phytoplankton abundance increases. Cloern (1982) suggests that high grazing pressure by infauna (benthos) may partly explain the spring bloom during periods of stratification. He notes that algal cells retained in the surface layer are not subjected to benthic grazing, and therefore surface populations can grow rapidly. Irrespective of the mechanism, the point is that salinity acts as an effector which stimulates stratification which reduces settling and therefore reduces benthic grazing. The result is a delayed increase in phytoplankton abundance. The actual duration of such a response by phytoplankton is short-term because it lasts only as long as the bay is stratified. However, the impacts of such increased abundance could be reflected in better survival of other food chain members who depend on energy derived from this phytoplankton.

Effector - Salinity

Response Time: Delayed

Duration: Long-term

Discussion. Long-term reductions in freshwater input into estuaries results in an increase in the average or net salinity of the system. As salinities increase, those organisms that cannot tolerate such increases move upstream or disappear from the system. Numbers of marine species, those species most tolerant of higher salinities, will increase in the estuary. Such changes in species composition due to increased salinities usually occur over delayed time periods, and, if freshwater inputs are not again increased, will become permanent. Such composition changes have been documented in estuarine systems. Austin (1981) reports that drought-caused increases in salinity in Chesapeake Bay have pushed brackish water fish species (American shad, river herring, and striped bass) upstream. At the same time he noted that fish normally limited to ocean or near ocean salinities became more common in the bay. For example, coastal-ocean spadefish were collected in York River headwaters. Juveniles of tropical ocean grouper and butterfly fish also were collected off the river mouth, and significant catches of summer flounder were reported for the first time north of the Chesapeake Bay Bridge at Annapolis.

Similar conditions have been observed in the Santee estuary in South Carolina. During 1942 most of the Santee River was diverted from the estuary into the Cooper River and composition changes reflected those diversions. Wenner et al. (1982) recently developed a profile of the fish and decapod crustacean community in the system in order to study the effects of a rediversion project which was begun in 1975. Wenner et al. concluded that areas with less freshwater input had higher biomass and density of sciaenid fish and panaeid shrimp. She concluded that after rediversion:

> Species diversity will undoubtedly decrease due to decreased utilization of the lower portion of the Santee River by marine stenohaline species. Lower salinity conditions at and near the mouth should deter penetration of the estuary by these species.

Such evidence shows that flow reductions allow marine species to become more abundant in estuarine conditions and disperse brackish species, but also show that the changes are not permanent if flows are returned to normal.

Effector - Flow-Related Currents and Circulation Patterns

Response Time: Delayed

Duration: Long-term

Discussion. Currents and velocities associated with freshwater outflows can affect the abundance of selected estuarine species. Generally, the mechanisms involved affect young or larval stages, as opposed to adults. Young fish, for example, can be carried to areas where their survival can be decreased or enhanced. Such a biological response is a delayed response because abundance is not immediately increased by flows. Time is necessary for the young fish to survive and grow in the new area. The duration of such responses is long-term because increased survival of juveniles is likely to be reflected in increased numbers of adults some years later.

The role of current transportation in abundance alteration has been documented in the Bay system. Turner and Chadwick (1972) analyzed 11 years (1959-1970) of striped bass data and concluded that their relative abundance, when the mean length in the population was 1.5 inches, was positively correlated with the amount of outflow from the Delta, water temperature, the proportion of Delta outflow diverted from the Delta, and salinity. They suggested that all of these correlations reflected the same basic cause because these independent variables are all related to flow. Young bass abundance typically peaks in the zone where fresh and salt water mix initially. Turner and Chadwick found that at flows associated with better survival, this zone is located in the Suisun Bay area. They concluded the high proportion of shallow embayments there probably enhanced food chain productivity. When flows were lower, the zone moved upstream and survival and abundance was lower. Stevens (1977) analyzed commercial passenger fishing boat catch statistics for the estuary for the periods 1938-1954 and 1958-1972 and found that recruitment to the fishery was determined by flows in the first summer of life. Thus, he showed that the duration of abundance response to flow transport is a long-term response that is reflected in later life stages.

Abundances of young fall run chinook salmon, American shad, and longfin smelt also have been shown to increase directly with river flow rates (Stevens and Miller 1980). Using catches at the fish screens of the CVP and SWP water diversions, and abundance indices from midwater trawl surveys, they concluded that survival of these species was enhanced by river flow increases during and/or shortly after spawning seasons. They noted that several factors may be responsible for the enhancement, with their relative importance varying between the species, but the one factor common to all is that high flows disperse the young, probably resulting in decreased density-dependent mortality.

Finally, Kjelson, Raquel, and Fisher (1982), using mark-recapture studies, have shown that survival of chinook salmon smolts in the Delta appears to be influenced by water temperature and/or river flow rates. However, these two factors are so closely related that they were unable to separate their individual impacts on smolt survival.

Studies in the Hudson Bay estuary have shown that phytoplankton populations are affected by flow transportation. In that system the phytoplankton biomass that is carried into the estuary by freshwater flows is large relative to other inputs of organic carbon (Malone, Neale, and Boardman 1980). This study also concluded that net fluxes of phytoplankton-carbon into the estuary from adjacent coastal waters can be significant relative to other in-Bay phytoplankton production rates. Since net upstream flows are related to outflows and downstream flows carry phytoplankton also, the increased chlorophyll levels (abundance) in some estuaries could be due to flow-related factors alone.

Wenner _et al_. (1982) have documented a decrease in abundance of fishes and decapods in their North Carolina, Santee River study area. During a 1975 high flow period (freshet), the total number of species that they collected was lower than during any other sampling period. They observed this particularly in the upriver stations. They attributed these reductions to the tendency of fishes and decapods to escape from areas where salinity is drastically lowered by floodwaters, or _in the case of juveniles and small-bodied species, to their being flushed downstream and out of the system_. Wenner _et al_. did not speculate on the fate of these organisms after being transported from the estuary.

Effector - Nutrients (Fertility)

Response Time: Delayed

Duration: Usually long-term

Discussion. The abundance of primary producers (e.g. phytoplankton, macrophytes, etc.) and consumers (e.g. zooplankton, shrimp, fish, etc.) in most aquatic systems, including estuaries, is related to the amount of nutrients available to "drive" the food web. Inorganic nutrients (e.g. dissolved silica, nitrogen, phosphorus, etc.) are important because they stimulate primary producers, while nutrients from organic sources (detritus) are important because they provide a food source for consumers. All things being equal, systems with increased levels of nutrients will be more fertile and will maintain higher abundances of biological resources. Systems that have small nutrient inputs may be nutrient "limited" and therefore may maintain lower abundances of various organisms.

Many elements (and biochemical mechanisms) collectively determining estuarine fertility may have their origin outside the estuary (Kutkuhn 1966). In other words, estuaries are not closed, self-contained ecological systems, and their production of organic matter, or their fertility, is dependent upon nutrients from the sea, and more importantly from the land. Kutkuhn (1966) states that there is no tangible evidence that appreciable reduction in freshwater discharge and its "nutrient" load would not, in time, seriously impair estuarine fertility. All this means that flow-regulated nutrient levels can cause significant changes in organism abundance in estuaries.

Generally, when flow-related changes in nutrients occur, biological responses are delayed. Time is needed for the system to "adjust" to altered food levels. Such responses are long-term, or occur at least as long as nutrient levels remain constant. Sometimes responses are observed in in-situ processes such as recycling, settling, or resuspension.

Recently, research has been directed toward the role of freshwater flow as a nutrient source and the effects of such sources on estuarine production. Several conclusions have come from studies on seven major estuarine systems in Texas. Armstrong (1982) found that the nutrients derived from freshwater inflows dominated the nutrient budget of these seven systems. In all cases, freshwater inflows accounted for over 80% of the nutrients reaching the system. Armstrong also found that these nutrients acted as an effector to stimulate biological production (or organism abundances). He found an increase in shellfish yield with an increase in freshwater input. He suggests this pattern demonstrates again that "salinity is a major environmental controlling variable and that nutrient loading stimulates directly or indirectly the detrital food chain through which the shellfish feed."

Boynton, Kemp, and Keefe (1982) also have compared estuarine responses to nutrient inputs from freshwater flows and found that a relationship existed between nitrogen loading from inflows and phytoplankton production in 14 estuaries that they studied (Figure 3-2). A similar relationship did not exist for phosphorus loading. They further found evidence suggesting the response time of nutrient effects in outflow is delayed. Plankton production in Chesapeake Bay was plotted for a 6-year period (1972-1977). During 1972, tropical storm Agnes occurred and inflow from the storm brought 2 to 3 times higher levels of nitrogen and phosphorus into the system. Boynton *et al.* found that although phytoplankton production was high, 603 g C m^{-2} yr^{-1}, the maximum annual production did not occur until the next year, 1973. Production in 1973 was 782 g C m^{-2} yr^{-1}, a year in which N and P loadings were more typical of average conditions. Boynton *et al.* concluded that much of the organic matter which was decomposed in the bay during the summer of 1973 appears to have been derived from inputs and phytoplankton production of the previous year (1972). They cite evidence of similar mechanisms in other systems.

McComb *et al.* (1981) found that phytoplankton and water nutrient levels are low in summer, but high during and after an input of river nutrients from winter flows in the Peel-Harvey estuarine system in Western Australia. Similar observations have been made in Charlotte Harbor, Florida. Phytoplankton populations respond positively to seasonal pulses of nutrients with higher productivity occurring during or just after high river flow (Fraser and Wilcox 1981).

The relationship between phytoplankton abundance and nutrient sources in the San Francisco Bay-Delta entrapment zone is not so certain. Most evidence indicates that populations are lowest in Suisun Bay at very low flows, highest at intermediate flows, and in between at high flows. Evidence tends to indicate that populations respond to nutrient (nitrogen) concentrations rather than total input and to residence time.

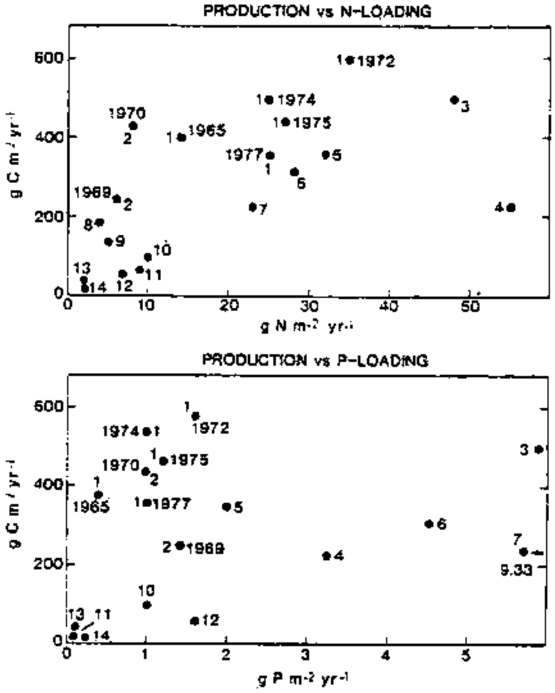


FIGURE 3-2. Regression Plots Relating Nitrogen and Phosphorus Loadings to Annual Phytoplankton Production in a Variety of Estuarine Ecosystems: (1) Chesapeake Bay, (2) Patuxent River, (3) Pamlico River, (4) Byfjord, (5) Apalachicola Bay, (6) Narragansett Bay, (7) San Francisco Bay, (8) St. Margarets Bay, (9) Long Island Sound, (10) Kungsbacka Fjord, (11) Loch Etive, (12) St. Lawrence River, (13) Baltic Sea, and (14) Kaneohe Bay (From Boynton et al. 1982).

Evidence from another estuary documents the fact that flow-related nutrient levels affect the abundance of certain invertebrates and fishes. Sutcliffe (1972) studied such relationships in St. Margarets Bay (Nova Scotia) and concluded that "the nutrient flux stimulated by freshwater runoff may be an important factor in the bay either for recirculating regenerated materials vertically or bringing in and distributing nutrients from the outside." He found that the catch of four commercially important species (lobster, halibut, haddock, and soft shell clams) was positively correlated with runoff levels which were correlated with nutrient levels. Finally, Viosca (1938) documents the fertilizing effects of freshwater flows from the Bonnet Carre spillway on the entire biota in Lake Pontchartrain (Mississippi estuary) thusly:

> The effect of the spillway was on the whole, very beneficial because of its fertilizing effect on the waters of Lakes Pontchartrain and Borgne, and Mississippi Sound. A biological cycle of

organism was started which was destined to materially increase the food supply in this area for some time. The plant growths were greatly stimulated, and associated animal life, such as scuds and grass shrimp was found in great concentration. Plankton feeders, such as mullet, anchovies, menhadden, and shad were seen in great abundance everywhere and in addition to the large crop of crawfish and river shrimp which served as an accessory food supply for a time, both species of saltwater shrimp thrived. The commercial shrimp crop taken in Lake Borgne and Mississippi Sound was the greatest since the shrimp trawl was introduced in 1917.

Effector - Pollutants (Toxicants)

Response Time: Immediate (acute) or delayed (chronic)

Duration: Usually long-term or permanent

Discussion. Water quality constituents transported in outflow, particularly toxicants, can affect the abundance of organisms in estuaries; however, outflow probably affects toxicants more significantly by influencing dilution rates.

Organisms can respond to toxicants in one of two ways. If toxicant levels are high enough, organisms will respond immediately by dying. Such an immediate response is called an acute response. If toxicant levels are low, but still more concentrated than the organism is normally exposed to, the organism will respond in various ways after a delayed time period. Such delayed responses are called "chronic" responses. Chronic responses do not always kill individual organisms, but usually affect some biological or physiological process which affects its health. Usually, when individuals are affected, the abundance of the overall population of that organism also is affected. Recently, chronic impacts have been documented using a physiological stress test called "Scope for Growth" (SFG) (Martin *et al.* DFG preliminary MS). SFG tests measure the energy that an organism captures for body growth and gamete production (reproduction). Generally, decreases in SFG indicate that an organism is being stressed in a chronic way by some constituent in its environment.

The duration of an organism's response to pollutants can be permanent or long-term. If the organism is acutely affected, obviously that organism responds permanently by dying. If the organism responds chronically to a pollutant, the duration of such responses is long-term. Responses can last a lifetime on an individual level or can last indefinitely on a population level. Some organisms respond to pollutants as long as pollutants are present in their environment, while others store pollutants up and respond when they metabolize body fat.

Estuarine pollution is a complex topic and the role of outflows in impacting pollutants is not completely understood. Therefore, this topic will only be discussed superficially. Some information specific to South San Francisco Bay will be considered. Luoma and Cain (1979) have found that the rate of freshwater-discharge is a primary factor that mitigates the contamination of a clam, *Macoma balthica*, in South Bay. They documented that copper and silver concentrations in the tissue of this clam declined rapidly during winter and spring when significant quantities of fresh water and sediments from the Delta entered South Bay even though the source of these metals was from local runoff. Whatever the mechanisms involved, the implications of this work suggest that reductions in outflow would result in increased levels of copper and silver in clam tissue and therefore possibly cause acute or chronic toxicity responses in these organisms. Recently, Martin et al. (DFG preliminary MS) have documented that the decline in scope for growth of *Mytilus edulis* (mussel) in South Bay was significantly correlated with increased body concentrations of chromium, copper, mercury, silver, aluminum, zinc, total chlordanes, and dieldrin. This information suggests that pollutant uptake by mussels is chronically affecting their health.

More work must be done to document the role of outflows and pollutant dynamics in estuaries.

The Importance of Previous Flow Conditions

The *timing* of previous flow conditions can affect the type and magnitude of all of the above biological responses to the various outflow-related effectors. For example, the first large flow pulse of the year will have a greater relative effect on salinity regimes in the Bay than the second or third. When the second pulse occurs, organisms will already have responded by actively or passively changing their distribution or abundances. Likewise, the first outflow pulse of the year will probably carry the greatest concentrations of nutrients due to flushing of accumulated nutrient materials from the watershed. By the time second or third pulses occur, organisms will have already begun to respond to increased nutrient levels. Unless there are threshold or seasonal effects, actual responses for the second pulse will be relatively lower than for the first pulse.

Finally, the type and magnitude of biological responses to various flow-related effectors can be altered by the *magnitude* of previous flow conditions. If the previous flow pulses were small, the levels of various effectors may not have elicited a response. If previous flow pulses were large, then the level of effectors may have been significant enough to cause a biological response, therefore the relative importance of the previous flow would be increased.

CHAPTER FOUR

COMPREHENSIVE FLOW STUDIES FROM OTHER SYSTEMS

Few comprehensive evaluations of the effects of freshwater inflow into estuaries have been reported, but relevant studies have been conducted in three widely separated geographic areas: the Texas Gulf Coast, the Gulf of St. Lawrence (Canada) and the Azov and Black sea regions (USSR).

The most comprehensive of these studies, specifically directed to determine the effects of freshwater inflow upon the bays and estuaries of Texas, was conducted by the Texas Department of Water Resources between 1975 and 1980. This multidisciplinary study included an evaluation of long term historical records of surface water hydrology, meterology, water quality and commercial fishery harvests, as well as project-collected data defining nutrient dynamics, biological community structure and sport fishing effort. This information was used to provide quantitative estimates of seasonal inflow needed to maintain estuarine viability in each of six major Texas estuaries. In the Gulf of St. Lawrence, biologists and oceanographers of the Department of Environment (Canada) investigated the relationships between area outflow and regional commercial fisheries harvest in the Gulf and surrounding waters, and found that the harvest levels of many species correlated with freshwater inflow (some positively, some negatively). Physical mechanisms possibly causing these changes were proposed in this study. In the Soviet Union, changes in the harvests of estuarine-dependent fish species have occurred following flow alterations caused by major water development in the drainages emptying into the Black, Azov and Caspian seas. Although most information available on the causes of these changes is rather descriptive and non-quantitative, it does describe biological changes following freshwater inflow reductions in these Russian estuarine systems.

TEXAS GULF COAST INVESTIGATIONS

The Texas Gulf investigations were authorized and funded by amendments to the Texas Water Code, which directed the Texas Water Board to investigate the effects of freshwater inflows upon the bays and estuaries of Texas. This legislation also declared it to be public policy that the maintenance of a proper ecological environment of bays and estuaries and the health of related living marine resources be considered in the issuance of permits for the storage or diversion of state waters (Texas DWR 1979-81). Although direction and coordination responsibility for this study was assigned to the Texas Department of Water Resources, much of the data collection and analysis was conducted by other agencies including USGS, USCE, USFWS, NMFS, Texas Department of Parks and Wildlife, and institutions of the Texas University system. Methods and findings from ecological studies of similar estuaries in other locations also were utilized in the development of study design, analysis of data, and reporting of findings.

Methods

In order to meet the expressed purpose of this study (to describe and measure the freshwater inflow/salinity/biological relationships of Texas estuarine environment), data sets and analytical methods were developed to examine the quantitative relationships between freshwater inflow and the following:

1. the cycling and exchange of nutrients within each estuary,
2. the flooding and draining of deltaic marshes in contributing rivers,
3. the water movements and salinity levels and distributions in each open bay system, and
4. the production of estuarine dependent fish.

Following is a summary of the rationale for data bases used and analytical techniques employed to determine each of these four inflow relationships and the use of these relationships in the final inflow analysis.

The Cycling and Exchange of Nutrients

Monthly water quality records for phosphate, total nitrogen and total organic carbon in each estuary were examined to describe the seasonal nutrient fluctuations. This evaluation was purely descriptive as nutrient levels found directly within the estuaries were from all sources, including inflow, recycling within the estuary, and marine water exchange.

Monthly water quality records from contributing rivers of the watersheds were used to calculate monthly mass inputs of phosphorus, nitrogen and total dissolved carbon resulting from river inflow to each estuary. The study found that in these systems _nutrient concentrations_ decreased during periods of high flow, but that the _total mass_ input of nutrients was greater due to the greater volumes of incoming water. The period of record of adequate water quality data was presumably too short (generally 1-3 years) to mathematically define the river flow vs. nutrient loading relationship and nutrient input from contributing drainages (excluding marsh innundation by flooding) and so this data was not used as a constraint in outflow determination in the final analysis.

Incoming nutrients from tidal and lower river flood plain sources were also determined from applied studies of specific marshes. In general, both tidally inundated (not outflow-related) and flood inundated marshes were found to be significant exporters of total organic carbon and phosphorus. Studies also indicated that peak export of these nutrients from flood inundated deltaic marshes occurred during the initial 48 hours of flooding. These findings, supported by evidence from a large number of similar investigations in other Atlantic and Gulf Coast estuaries, led to the requirement that water for seasonal flooding of deltaic marshes be included in the final inflow analysis.

The Flooding and Exchange of Nutrients Within Each Estuary

To determine the quantity of water needed for periodic flooding of deltaic marshes, a computer simulation model was developed. This general model, when given the topography of any of the riverine marsh systems, could predict water levels in these marshes under different inflow levels and different monthly tidal conditions (spring and neap tides). The resulting simulated water elevations, mapped against deltaic marsh elevations, were used to determine the relationship between inflow and marsh inundation. This was used to determine the amount of inflow necessary to flood deltaic marshes for the minimal required period of time (48 hours) necessary for nutrient transfer into estuarine waters.

Sufficient water for this flooding on a seasonal basis (usually spring and fall, simulating historical conditions) was included in the final monthly inflow requirement analysis.

Water Movements and Salinity Distributions in Each Open Bay System

The prediction of the effects of varying freshwater inflow on currents and salinity distribution required the development and application of computer simulations to assess a wide variety of geomorphic, meteorological, chemical and physical data bases. The computer model was essentially bipartite. The tidal-hydrodynamic portion of the model used topographic descriptions of each estuary including inflow sources, tidal conditions, water inflows and withdrawls, bottom friction, rainfall and evaporation, and wind vector data to predict water circulation plots and net velocities. This output, when combined with salinity source concentrations and locations and used as input in a salinity-mass transport computer simulation, was able to predict salinity levels at locations throughout each estuary under varying inflow, tidal and meteorological conditions.

The results of this analysis, per se, did not put any restrictions on the finally developed inflow levels but was the means by which it was determined if a particular inflow proposal would meet the salinity-circulation requirement set by biological and other criteria.

Production of Estuarine Dependent Fish

The Texas commercial fishery harvest from estuarine and Gulf waters was valued by the study at over 135 million dollars annually. A similar additional economic value was attributed to the sport fishery. Since over 97 percent of the fish harvested by the commercial fleet are classed as estuarine dependent species, living all or a portion of their life within the geographic boundaries of estuaries, the environmental requirement and tolerances of these species was a primary consideration in the final determination of outflow requirements.

Commercially important species classified as estuarine-dependent, and included in this analysis, included finfish (seatrout, red and black drum) and shellfish (oysters and blue crab) which are normally harvested directly from Texas estuaries. Also included were Gulf shrimp (red, black and pink) which are harvested both from estuaries and adjacent offshore waters but which require estuarine environments during early life stages.

Salinity tolerances and optima for the appropriate life stage (stages) of each commercially important estuarine dependent species were compiled from all available sources. Using this data, monthly upper and lower viability limits for salinity were imposed on regions within each estuary. Recognizing the short-term tolerances of extreme salinity changes by estuarine species, these regional viability limits were not imposed on a short term basis (i.e. one portion of an extreme tidal event or flood event lasting hours or a few days), but did form an overall restriction on longer term (monthly) average salinities in the final analysis.

Additional short-term biological investigations (1 to 2 years) identified important species at lower levels in the food chain. These species of phytoplankton, zooplankton and benthic organisms were classified by regional abundance in each estuary. These regional distributions, controlled largely by the salinity requirement of each species, were not directly used in the development of regional salinity requirements, but the importance of the preservation of the lower trophic level food organisms was used as additional justification of the requirement that no long-term changes in regional salinity levels occur in each estuary.

The quantitative relationship between outflow and production of estuarine dependent species was determined by regression analysis of historic inflow vs. subsequent commercial harvest of individual and combined species. Inflow was divided into winter, spring, summer, autumn and late fall seasonal components (these were slightly modified in some analyses). In some cases the size of the adult population exploited by the fishery was not necessarily dependent on estuarine conditions during the year of harvest. Sometimes they were dependent upon survival of estuary-dwelling larval or juvenile populations in earlier years. In those cases, regressions against harvest were also calculated with inflows during years antecedent to the commercial harvest.

In the case of the finfish which are primarily resident in the estuary from birth to commercial harvest, a three year running average of seasonal inflow was used rather than a single year.

A qualitative examination of the responses of the fishery harvest to increasing outflow was carried out. This showed both the variability between different species within a single estuary, and the variability in response between two populations of the same species in different estuaries. The study found that within an individual estuary, different components of the fishery respond differently to seasonal inflow patterns (Table 4-1). In the combined Nuence and Mission-Aransas estuary, the harvest of most species responded favorably (e.g. increased) with increasing outflows during spring, summer and late fall, while responses to increased outflow during winter were mixed.

All finfish (seatrout, black and red drum) exhibited a universally negative response to increasing winter inflow, while two components of the shellfish harvest (white shrimp and oysters) responded favorably to increased winter inflow. The responses of taxonomically similar penaeid shrimp were also mixed, with white shrimp harvest increasing in response to increased outflow, while the harvests of other shrimp species responded negatively to increased winter inflows.

A comparison of the freshwater inflow responses of the same species in different estuaries indicated the uniqueness of individual estuaries even when they are in close geographical proximity and harbor similar animal populations (Table 4-2). The Lavaca-Tres Palacios estuary is located approximately 60 km (40 miles) north of the Nuence and Mission-Aransas estuary and drains a considerably larger hydrological basin (Table 4-2). These estuaries have somewhat different seasonal distributions of inflow, and the fishery harvest also responds differently to increasing inflow. Increased spring inflows stimulate the white shrimp harvest in both estuaries, but increased late fall inflows elicit a positive response in the Nuence and Mission-Aransas estuary, and a negative response in the Lavaca-Tres Palacios Estuary. Similar contradictions between these two estuarine systems are also observed in the summer inflow response of bay oysters and winter and summer responses of total finfish harvests.

These qualitative relationships between fishery harvests and inflow not only indicate the uniqueness of individual species in their response to inflow, but also indicate the inadequacy of applying a general set of outflow requirements to different estuaries. Since each estuarine biological community responds differently to inflow alterations, each estuary requires special analysis in order to determine the unique relationship existing between inflow and the particular community components.

The least squares estimates of the significant regression relationsips were used in a final total analysis of inflow impacts to predict harvest levels under different inflow alternatives.

Results of Texas Studies - Analysis of Inflow Impacts

The data bases compiled as described above were used to develop three different sets of estuarine inflow requirement alternatives. These inflow needs (Table 4-3) were predicted to meet the following objectives:

Alternative I <u>Subsistence</u> - To minimize annual inflow while meeting salinity standards required to maintain endemic biological community structure in estuaries and to provide

TABLE 4-1. Summary[1/] of Qualitative Responses of Estuarine Dependent Species to Increases in Seasonal Inflow as Determined by Commercial Harvest in the Nuence and Mission-Aransas Estuaries, Texas. (+ = Increased Harvest; – = Decreased Harvest; and NS = No Significant (α= .05) Relationship Between the Inflow and Subsequent Harvest.)

Species	Inflow Period				
	Winter (Jan-Mar)	Spring (Apr-Jun)	Summer (Jul-Aug)	Autumn (Sep-Oct)	Late Fall (Nov-Dec)
White Shrimp	+	+	NS	NS	+
Brown and Pink Shrimp	–	+	NS	NS	NS
Blue Crab	NS	+	+	NS	NS
Bay Oyster	+	NS	+	NS	+
Combined Shellfish[2/]	+	+	NS	NS	NS
Spotted Seatrout	–	NS	+	NS	+
Red Drum	–	+	+	NS	+
Black Drum	–	NS	+	–	+
Combined Finfish[3/]	–	NS	+	–	+

1/ Adapted from TDWR LP-108. Jan 1981.

2/ All shrimp, Blue Crab and Oyster.

3/ Seatrout and all Drum

TABLE 4-2. Seasonal Inflow and Selected Commercial Harvest Response to Increased Inflow Comparisons in the Nuence and Mission-Aransas Estuaries and the Lavaca-Tres Palacios Estuary, Texas.[1] (Mean Flows and Standard Errors are in Thousands of Acre Feet. + = Increased Harvest; - = Decreased Harvest; and NS = No Significant Relationship (α = .05) Between Seasonal Inflow and Subsequent Harvest.)

	Inflow Period				
	Winter (Jan-Mar)	Spring (Apr-Jun)	Summer (Jul-Aug)	Autumn (Sep-Oct)	Late Fall (Nov-Dec)
Flows:					
Nuence & Mission-Aransas					
$\bar{X}$	77.7	272.0	136.8	572.8	164.0
Std. Er.	± 22.8	± 67.9	± 50.9	±233.7	± 40.5
Lavaca-Tres Palacios					
$\bar{X}$	621	1183.1	303.1	730.3	454.9
Std. Er.	± 98.2	±208.3	± 50.4	±147.1	97.5
Harvest Response:					
White Shrimp					
Nuence & Mission-Aransas	+	+	NS	NS	+
Lavaca-Tres Palacios	NS	+	NS	NS	-
Bay Oyster					
Nuence & Mission-Aransas	+	NS	+	NS	+
Lavaca-Tres Palacios	+	NS	-	NS	+
Finfish					
Nuence & Mission-Aransas	-	NS	+	-	+
Lavaca-Tres Palacios	+	NS	-	NS	NS

---

[1] Adapted from TDWR LP-108, Jan. 1981 and TDWR LP-106, June 1980.

TABLE 4-3. Inflow Requirements of Texas Gulf Coast Estuaries Required to Meet Subsistance, Harvest Maintenance and Shrimp Harvest Enhancement Alternatives. All Flows in maf. Water Surplus to the Need is Also Summarized.

Estuary	Sabine-Neches	Trinity-San Jacinto	Lavaca-Tres Palacios	Guadalupe	Mission-Aransas & Nueces	Statewide Total
Average Gauged Inflow 1941-1976	10,677	6,820	1,893	1,808	679	21,927
Subsistance Inflow Requirement (Alt. I)	5,686	4,605	1,229	1,241	372	13,133
Percent of Average Inflow	53	67	65	69	55	60
Fishery Maintenance Requirement (Alt. II)	1/	4,888	1,886	1,620	416	14,496
Percent of Average Inflow	-	71	100	90	61	66
Shrimp Enhancement Requirement (Alt. III)	1/	4,749	1,889	1,826	593	14,743
Percent of Average Inflow	-	69	100	100+2/	87	67
Surplus						
Alt. I	4,991	2,265	664	576	307	8,794
Alt. II	4,991	1,982	7	188	263	7,431
Alt. III	4,991	2,120	4	-18	86	7,184

1/ No statistically significant estimate - Maintenance and enhancement requirements assumed equal to subsistance requirements.

2/ Requires slight interbasin transfer.

minimal marsh inundation needs (no restrictions were imposed by inflow-fishery harvest relationships).

Alternative II <u>Maintenance of Fishery Harvest</u> - To minimize inflow required to meet above requirements and to maintain commercial fishery harvest at average 1962 through 1976 historical levels.

Alternative III <u>Shrimp Harvest Enhancement</u> - To meet all requirements in Objective I and to maximize the annual shrimp harvest (this option assumes water from storage would be available for release during certain periods and that minor interbasin transfers would be used to meet these requirements).

Two significant principles regarding inflow needs of Texas estuaries are apparent from these analyses. First, only 31 to 47 percent of the inflowing surface water was found to be surplus if estuarine preservation is to be a requirement in water development policy. If maintenance of fisheries is to be part of that policy, up to 100 percent of the gauged inflow in some estuaries is required to meet this goal. (On a statewide basis 60 and 66 percent of the total inflow is required to meet estuarine preservation and fishery preservation requirements, respectively.)

Second, most surplus water is present in the two northernmost estuaries, the Sabine-Neches and Trinity-San Jacinto systems. These drainages are located in the subtropical climate zone in Texas where water supplies are generally considered adequate.

Although this study is the most comprehensive attempt to quantitatively evaluate the impacts of varying freshwater inflow into an estuarine system, there are definite weaknesses in this approach which limit its applicability to San Francisco Bay. Furthermore, the Texas results have not been used there as yet to implement estuarine management plans.

The biological investigations conducted in the Texas study were not of sufficient duration to relate populations and outflow (not enough data points). Only temporal and distributional data were used in the final analysis, reducing management options only to salinity control by regulation of freshwater inflow as a solution to maintaining biological communities. Investigations in San Francisco Bay at this level have thus far not provided the desired understanding of flow impacts, particularly for effects on abundance. More intensive, longer duration biological data collection, evaluated in conjunction with the physical and chemical inflow models developed, could provide a much better understanding of the biological mechanisms that control productivity in the Texas estuaries. This, in turn, could lead to the development of new management options and strategies for preserving estuarine productivity in the face of continued reduction of freshwater inflow.

The reliance on recent commercial fisheries harvest data in Texas also may not be directly applicable to San Francisco Bay. In Texas previous research has demonstrated that 97 percent of the Texas harvest consists of species that are directly dependent on conditions in Texas estuaries during some phase of their life cycle, regardless of location at time of capture.

Conversely, in California, while many commercial species such as Dungeness crag, English sole, anchovy and herring are present in San Francisco Bay at some life stage, the importance of the Bay to the total sport and commercial harvest is not yet known.

Another problem common to both Texas and California is possible biases and errors in commercial catch statistics. Harvest statistics are usually compiled from the records of fish wholesalers and processors. During the recent past these records have been considered quite accurate, but the fishing effort required to harvest the catch is not generally available. When populations of a particular desirable species are low, prices tend to be higher, inducing increased fishing effort which results in a higher catch than would be made if effort were constant. Conversely, in time of great abundance, effort may be reduced due to low prices or demand and a lesser portion of the population harvested. These factors tend to reduce the accuracy of catch statistics as an indicator of fishery abundance. (It should be noted that the Texas investigators did modify reported harvests of Gulf shrimp when effort data was available.)

Also, regression analysis, as used in the Texas study, is a useful tool in quantitating the response of a dependent variable (harvest) to an independent variable (inflow) and determining the degree of association between them, but it does not provide information on the nature of the cause and effect relationship. In Texas and other states of the Gulf Coast, most species of commercial interest have been the subject of many biological investigations which have provided information on their specific biological and physiological requirements. This knowledge, when combined with the chemical and hydraulic changes accompanying inflow alterations provides species specific theories relating outflow to abundance and adds considerable credibility to the Texas evaluations. Unfortunately, at present much less is known of the biology and physiology of most species occuring in San Francisco Bay.

The applicability of the marsh inundation requirements is also uncertain. In San Francisco Bay, most of the historical marshes contiguous with the Bay and Delta were filled or isolated by levees before major inflow alterations were imposed on the estuary. During the last 60 years, periodic flooding has been confined to designated floodways and overflow bypass systems. These areas would include the Butte basin, Sutter and Yolo bypasses and the leveed floodway areas of Sacramento-San Joaquin basin rivers. No quantitative estimate of organic material contributed during inundation periods is available but it is logical to assume that these areas are the source of a significant amount of organic nutrients in the San Francisco Bay system.

ST. LAWRENCE INVESTIGATIONS

Inflow/productivity relationships in the Gulf of St. Lawrence were developed by researchers of the Fisheries Research Board of Canada following investigations on primary productivity and nutrient dynamics of St. Margarets Bay, Nova Scotia. This investigation noted significant relationships between chlorophyll a concentrations and monthly inflows. Supporting information, developed within the estuary, indicated that nitrogen stimulation, induced by freshwater inflow, caused phytoplankton growth. Incoming fresh water was responsible, by direct input and induced offshore upwelling, for 56% of the total nitrogen in the euphotic upper layers of the bay waters (Sutcliffe 1972).

This finding led to evaluations of other available historical inflow data to determine if this freshwater inflow-primary productivity link could be followed up the food chain to higher level consumer organisms. Additional highly significant inflow-abundance relationships were found between local inflow and abundance of lobster larvae, Homarus americanus, in the Northumberland Strait region of the Gulf of St. Lawrence (Sutcliffe 1973). This positive correlation between runoff and larval abundance was hypothesized to be the result of a progression of events. High runoff (freshwater inflow) induces offshore upwelling and subsequent transport of nutrients into the euphotic zone. This in time induces high phytoplankton productivity, which positively impacts lobster larval populations.

Highly significant correlations between spring inflow from the St. Lawrence and subsequent commercial landings of adult lobster and halibut also were noted (Sutcliffe 1973). Fluctuations of freshwater inflow during the projected year of birth of the target species accounted for up to 73% of the fluctuation in Quebec fishery harvests.

Subsequent analysis of commercial harvests from the Gulf of Maine and various environmental parameters, including Gulf of St. Lawrence inflow, yielded significant correlations (both positive and negative) between certain monthly outflows and subsequent fishery harvests for every species examined (Sutcliffe et al. 1977). However, in nearly all cases, similar correlations between harvest and seawater temperatures at the time of birth also were found, indicating that a much more complex mechanism than the simple earlier primary productivity hypothesis may be present.

Examinations of the relationship between St. Lawrence outflow and subsequent ocean temperatures (Sutcliffe et al. 1976) indicated that outflows did explain a portion of the variability of ocean temperatures on the Scotian shelf and the Gulf of Maine. However, difficulties in relating salinities to freshwater inflow in these far removed regions indicated that numerous other environmental factors played a major role in temperature regulation. These were hypothesized to include atmospheric weather fluctuations, direct local inflow into the Gulf of Maine from rivers in northern New England and the southern Atlantic Canadian Provinces, and fluctuations of the south flowing Labrador Current.

Rather than of immediate practical relevance in present San Francisco Bay investigations, the St. Lawrence body of research serves as an example of how complex and poorly understood the total physical, chemical, and biological impacts of freshwater outflow are. The correlations present between outflow quantities and indicators of productivity are significant, but the mechanisms of these relationships are not obvious. The search for these linking mechanisms may point the direction for ongoing and future investigation in San Francisco Bay.

USSR ESTUARINE INVESTIGATIONS

In the Soviet Union, extensive water development on rivers tributary to the Black and Azov seas has been accompanied by ecological changes such as reductions in fishery harvests in the estuaries. While only a portion of the total literature documenting these changes has been translated, enough is available to outline the changes that have occurred and to give the hypothesized casual agents.

The Azov Sea

The Azov Sea is a relatively small embayment connected to the Black Sea by the narrow Kerchensky Strait. The total volume of this shallow sea is 320 Km^3 (260 maf) and historical (pre-development) salinities were maintained at approximately 10 $^o/oo$, balanced by inflow of 42 Km^3 (34 maf) annually from the Kuban and Don rivers and restricted water exchange through the Kerchensky Strait with the more saline Black Sea (AzNIIRKh 1972). The large Tzimlayansky Dam and water project on the Don River and smaller irrigation projects on the Kuban River, between 1952 and 1973, reduced the annual inflow by 8 Km^3 (6.6 maf) annually and was responsible for an increase of salinity to 12.6 $^o/oo$. (Meleshkin, et al. 1973).

During a similar time period (1952-1968), standing biomass of phytoplankton, zooplankton and benthic organisms in the Azov Sea declined 46, 31 and 20 percent respectively (AzNIIRKh) and the decade 1960 to 1969 was marked by a 25 percent reduction in the harvest of important commercial fish species (Boyko and Makarov 1971).

Numerous causative agents have been identified for these declines. The primary causes listed in the literature are:

1. Blocking sturgeon access to spawning grounds by dam construction (Dubinina 1973).
2. Reductions in fish spawning in temporarily flooded lowlands in the lower reaches of the Don River. These areas were severely impacted by water project induced reductions in flood frequency and severity (Dubinina 1973)
3. Reductions in nutrient and sediment input important to lower level food chain organisms, caused by both reductions in total inflow and reduced input from intermittently flooded lowlands (Bronfman and Makarova 1973).

4. Overall salinity shifts, which have caused replacement of desirable estuarine species by less desirable, more marine species (Meleshkin, *et al*. 1973).

Four types of solutions have been considered to rectify declines in Azov Sea fisheries. The first has been a major commitment toward artificial propagation of endemic species. This has been helpful in restoring sturgeon stocks but has only reduced the rate of decline in other fish species (Rosengurt 1983).

Another method has been to release water for fish spawning and to flood during years when excess water is available. This has historically met very limited success with flooding occurring only 37 percent of the time (Dubinina 1973). However, additional water storage behind large hydropower dams and land reclamation schemes, which include 80,000 hectares (197,680 acres) of lowland committed to seasonal flooding, should provide for more reliable seasonal flood and subsequent fish spawning (Rosengurt 1983).

Additional water needs within the Azov Sea drainage basins are expected to be met with water imports from the Volga River basin. Interbasin water transfers from the Volga basin will reduce future inflow losses to the Azov basins but may only transfer problems from the estuaries in the Azov Sea to the Volga estuary in the Caspian Sea (Rosengurt 1983).

The method proposed to restore historical salinity levels in the Azov Sea involves a reduction in the water exchange between the Azov and Black seas by means of dam and lock structures or a narrow canal constructed in the Kerchevsky Strait (Meleshkin, *et al*. 1973).

The Northwest Black Sea

The Black Sea, which is connected to the Agean and Mediterranean seas by the Straits of Bosphoros, is a true inland ocean, with both continental shelf areas and depths exceeding 1,000 m (3,300 ft). The northwest lobe of this sea covers a large area (70,000 Km^2 - 27,000 mi^2) of continental shelf with an average depth of about 20 m (66 ft). Three major rivers flow into this shelf area. The Danube River empties directly into the western reach from a typical delta and the Dniester and Dnieper rivers empty into well defined bays situated on the north and east coasts of this gulf.

Before water development, the shallow continental shelf of the Northwest Black Sea annually received 198, 54 and 10 Km^3 (245, 67 and 12 maf) of inflow from the Danube, Dniester and Dnieper rivers, respectively. Water development has reduced these inflows to about 165, 32 and 6 Km^3 (203, 39 and 7.5 maf), resulting in both an average increase in the salinity of the entire region of the Black Sea from 16.5 ^{o}/oo to 18.5 ^{o}/oo and much greater salinity increases locally in the Dnieper and Dniester river bays.

Historically, the northwest region supplied 15 to 20 percent of the total fishery harvest from the Black Sea. However, post flow division changes have occurred. Major biological changes in this region include a three-fold reduction in the harvest of desirable fish (herring, anchovies, horse mackerel and sturgeon) and a four-fold decrease in the regional harvest of mussels during the 10 year period between 1963 and 1972 (Rozengurt 1983). The shellfish population was further reduced during 1974 due to anoxic conditions in the deeper layers of water.

Species composition of the plankton and benthic communities in the lower reaches of the Dnieper and Dniester rivers and adjoining bays have also changed. During the last 30 years, marine species have become more predominant. The nutrient value of these altered zooplankton communities in the Dniester River is valued at only 1/6 of its historical level. Before diversions, unprecedented blooms of the dinoflagellate Exuviella cordata have replaced the historical diatom phytoplankton populations in some areas.

In addition to flow related salinity increases and reductions of nutrient inputs, additional factors are partially responsible for these changes in biological conditions. The dredging of navigation channels in both the Dnieper and Dniester bays has greatly increased the penetration of salt water by gravitational circulation. Hence salinity in the upper bays and deltas has increased more than expected due only to reductions in river outflow. (Salinity increases in the Dniester River deltas has reduced crayfish harvest in the Dniester Delta by 85% and has necessitated the upstream relocation of municipal and agricultural water diversion points.) Increasing municipal, industrial and agricultural waste discharges, concurrent with outflow reductions have also caused changes in planktonic, benthic and fisheries communities in the deltas and bays of the Dniester and Dnieper rivers.

The Caspian Sea

The Caspian Sea receives water from a 3.6 million square Km (1.4 million mi^2) closed drainage basin covering most of central Russia between Moscow, the Ural Mountains and the northern portion of Iran. The large inland sea (335,000 Km^3 - 80,000 mi^2) has no outlet and is composed of 3 basins oriented in a general north-south alignment. The southern and central basins are true seas, with depths to 1,000 meters (3,300 ft). The northern basin contains only 1 percent of the sea's water and is a shallow continental shelf region, similar to the northwest area of the Black Sea. Also similar to the Black Sea, most of the fishery harvest is taken from this continental shelf area.

Most of the freshwater inflow to this closed sea originates from the Volga River which emptys into the northwest area of the sea creating estuarine salinity conditions. Additional small amounts of fresh water enter from the highly developed Rual, Kura, Samur and Sulak rivers but present discharges are minor. Productive estuaries are no longer associated with these river systems.

Since the Caspian Sea is closed with no connections to other seas or oceans, its surface level fluctuates in response to climatically induced inflows. Geological evidence indicates that during the present epoch (710,000 years B.P.) climatologically induced surface elevation changes have been within an 8 meter (25 ft) range. Level fluctuations of this magnitude have resulted in major water surface area changes in the north Caspian Sea and Volga River delta.

Significant reductions of surface elevation in the Caspian Sea began with a 9 year drought between 1932 and 1940 during which inflow was only about 75 percent of the historical average (the long term historical average is about 300 Km^3 - 245 maf). This drought, and a less severe dry period lasting throughout the mid nineteen sixties, has resulted in an overall reduced surface elevation of 2.5 meters (9 ft) and the dewatering of about 15,000 Km^2 (5,790 mi^2) of Volga delta and estuarine aquatic habitat. This has significantly reduced the available spawning and rearing habitat of the estuarine dependent fish which support the traditional fishery. With a return to more normal climatic conditions, the sea level has continued to decrease. Now, as a result of upstream diversions from the Volga River which totaled 29 Km^3 (23.5 maf) in 1973, these diversions are estimated to increase to 66 Km^3 (53.5 maf) annually, and will result in an additional 1.4 meter (4.6 ft) decrease in surface elevation with additional dewatering of delta fish habitat.

Additional impacts of water diversion and power development on the Volga has caused a major decrease in spring flood discharge which has reduced nutrient input into the north Caspian Sea at the start of the phytoplankton growing season and decreased the area over which favorable salinities for plankton production and juvenile fish development (less than 6 $^o/oo$ salinity) occur.

Increasing pollution from municipal, industrial and agricultrual waste discharges are also threatening the ecological communities in the Volga Delta region. Reductions in outflow retard the dilution of these pollutants, especially in a closed sea system where no tides or tidally induced currents are present to promote dispersal of waste discharges.

Applicability of the Russian Experience to San Francisco Bay

Although many of the suspected flow/biological mechanisms studied in the Soviet Union are similar to those proposed in San Francisco Bay, there are some differences in the hydrological conditions which make direct comparisons questionable. A major difference is the amount of circulation and water exchange induced by tidal currents. In San Francisco Bay, tidal fluctuations are considerable, ranging as much as 2.6 m (10 ft) during spring tides and total water exchange with the Pacific Ocean may be as much as 24% of the total volume of the Bay during a single tidal cycle. Conversely, in Soviet estuaries, tidal fluctuations in the small seas are nearly indistingushable and mixing between fresh and salt water by tidally induced currents is minor or nonexistant in these systems.

In the Soviet Union, many of the important fish species impacted by outflow reductions are those which spawn in spring flooded marshes. While similar species may once have been important in the San Francisco Bay ecosystem, similar lowlands in California were generally reclaimed long before there was any documentation of large populations of such dependent species. Also tidal and seasonally flooded lowlands (excepting the flood bypasses) were largely developed in California long before recent population declines of potentially impacted species, such as striped bass and Dungeness crab.

Another problem in directly using Soviet conclusions in evaluating the San Francisco Bay ecosystem is the difficulty in securing translations of much of the pertinent research. The available translated material is largely review in nature and does not describe the data or analytical techniques used in arriving at the stated conclusions. While some reported changes are caused directly by reduced flows (e.g. reductions in nutrient input and changes in salinity regimes), the available information is not of sufficient detail to estimate the proportion of overall fishery losses which are due to flow reductions. If more detailed accounts of the biological research by Soviet scientists were available, greater use of their findings could be made in an evaluation of outflow impacts on biological communities in San Francisco Bay.

CHAPTER FIVE

RESULTS OF 1980 - 1982 DELTA OUTFLOW STUDY

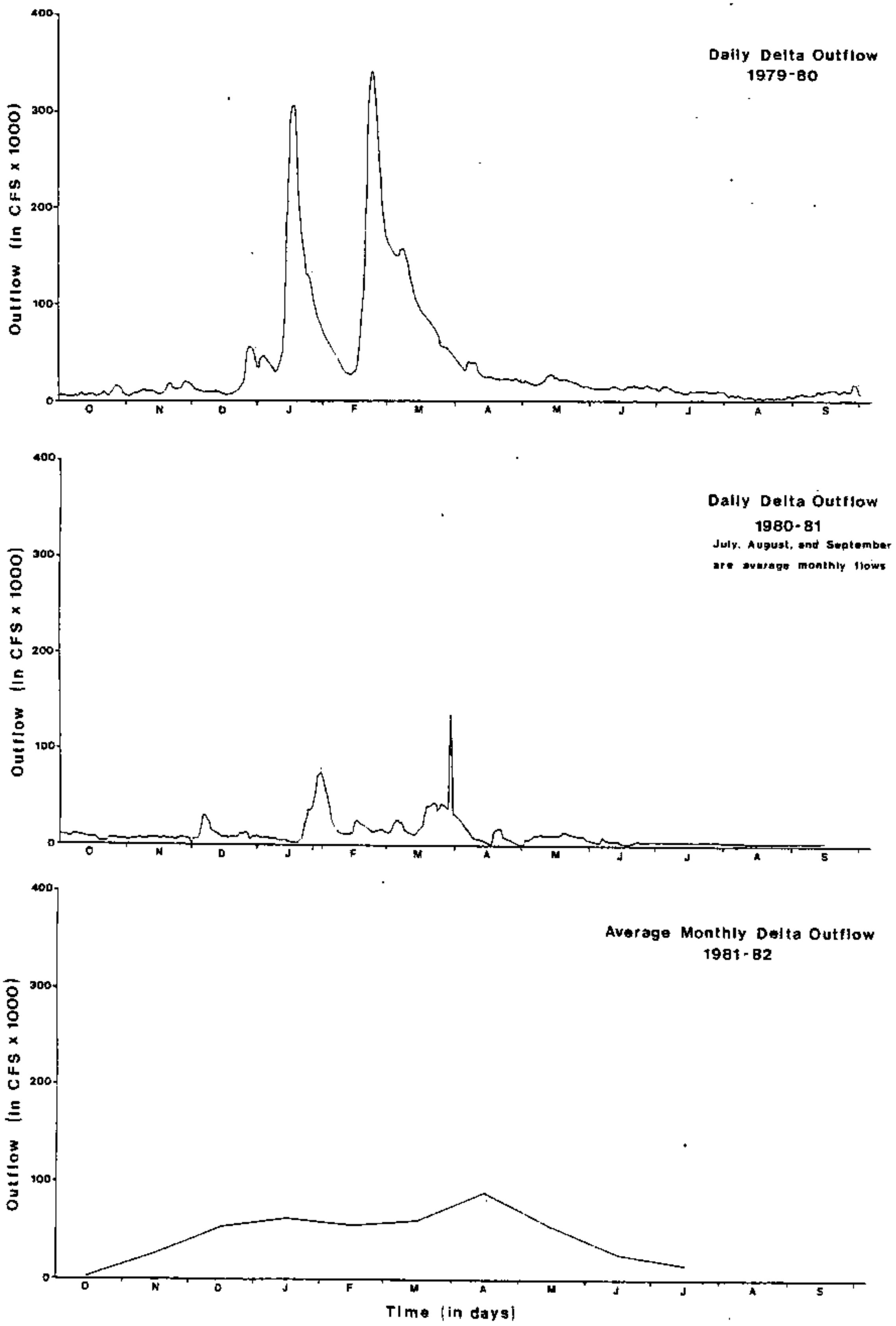
Previous sections of this report have provided supporting evidence showing the relationship between various fishery resources and freshwater outflows in other estuaries around the world. Some information developed in the San Francisco Bay system has been given, but most of this information has been developed from studies within or upstream of the entrapment zone. Few studies have addressed the importance of freshwater flows in San Francisco Bay proper. The Four-Agency Delta Outflow/San Francisco Bay study is one comprehensive effort that is currently being conducted with the singular objective of documenting the system's fishery flow needs downstream from the entrapment zone. This study began field activities in January, 1980, and most of the first 3 years of biological field data has been processed and entered into the data storage/handling system. The remainder of this section of the report will discuss some hydrologic and biological results, but summarizing this data began in January, 1983, so data analysis is very preliminary. Information presented in this section only shows certain trends, but cause and effect relationships cannot be definitively established at this time.

Delta outflows varied dramatically during the 3 years of study (Figure 5-1). SWRCB Decision 1485 has established a year classification system based upon forecasts of Sacramento Valley unimpaired runoff. DWR makes a preliminary determination of water year type during February, March, and April with the final determination made in May. Table 5-1 provides the May determinations and unimpaired runoffs for the 3 years of study.

TABLE 5-1. Unimpaired Runoff in Millions of Acre-Feet (maf) and Year Type Classification for the Years 1980-1982 (From DWR Bulletin 120).

Year	Unimpaired Runoff	Year Type
1980	22.9	Wet
1981	11.5	Dry
1982	32.9	Wet

FIGURE 5-1. Hydrographs for Water Years 1979-80, 1980-81, and 1981-82. Data For 1981-82 Based on Mean Monthly Estimates Only and Does Not Include Yolo Bypass Flows, Which Were Large in 1982.



FISHERY STUDY RESULTS

Method Descriptions and Definitions

Fish samples were collected as described in the Delta/Outflow Study Plan (see previous reference for full title). These fish usually represent one of 5 life stages which are identified, counted and measured. Egg, yolk-sac, post-larval and juvenile stages are collected with a 505-µ mesh egg and larval net. Juvenile and adult stages are caught using beach seines, otter trawls and mid-water trawls. Results of the beach seine survey will not be covered in this report.

Adult fish are defined as those fish with adult characteristics that are captured in the midwater and otter trawls; juveniles are fish less than 50 mm fork length which have completed fin ray development and have scales present; post-larval fish are those that have absorbed their yolk-sac but have not completed fin ray development and lack scales; and yolk-sac fish are those with a yolk-sac present.

Each life stage of each species has a different susceptibility to capture in the various nets used in this study, thus the catch data should be interpreted carefully. For example, the yolk-sac stage of species which have adhesive eggs are underrepresented in our study. Since most juvenile fish are able to avoid capture in the egg and larval net and are small enough to pass through the cod end mesh of the midwater and otter trawls, data on the juvenile life stage fishe has not been included. Most adults, however, are well represented in the trawl catches,except for individuals of some species that are longer than about 15 inches and can readily escape the nets.

We identified fish to the lowest taxonomic level possible. For most this was the species level, but in some cases (e.g. yolk-sac and post-larval fishes), it was as high as the family level. Those catches in this report listed as "Osmeridae, unidentified" are probably either delta or longfin smelt; "Stichaeidae" are either monkeyface eels or rock pricklebacks; "Gobidae type II" are yellowfin, arrow and/or cheekspot gobies; "Sebastes, unidentified" are most likely brown rockfish; "Pleuronectidae, unidentified" are probably starry flounders or English sole and "Cottidae, unidentified" can be one of a number of sculpins which inhabit the rocky intertidal habitat.

Yolk-sac and post-larval life stage data are reported as total number per cubic meter collected in a given area for a given time.

The various regions of the Bay are defined as follows: South San Francisco Bay, the Bay south of the Oakland-San Francisco Bridge; Central San Francisco Bay, that part of the Bay between the Oakland-San Francisco Bridge and the Richmond-San Rafael Bridge; San Pablo Bay, all water between the Richmond-San Rafael Bridge and the Carquinez Bridge; and the West Delta, all water from the Carquinez Bridge upstream to Sherman Island and the Antioch Bridge (see Figure 5-2).

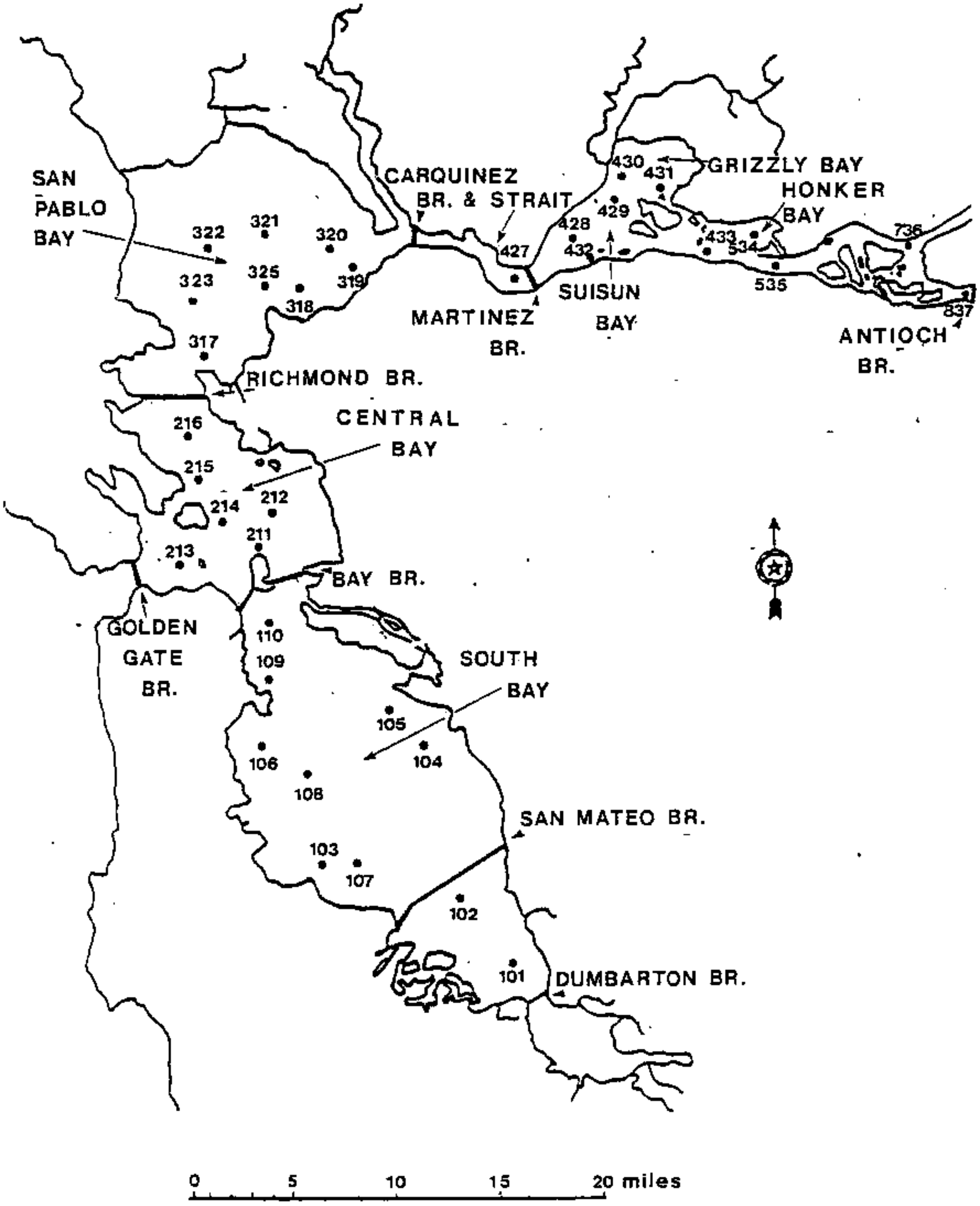


FIGURE 5-2. Map of San Francisco Bay Showing Various Bay Reaches and Study Sampling Stations.

The data has been summarized on a quarterly and annual basis. A quarter is considered to be a 3-month period (e.g. Jan-March, April-June, etc.).

Species Collected From 1980 to 1983

A list of the 100 identified and 9 unidentified species collected by this study between January 1980 and February 1983 is displayed in Table 5-2. This list includes fish collected in the seining segment of our study. Table 5-2 also indicates the life stages of the various fish.

Yolk-Sac and Larval Fish Results

Spatial and temporal yolk-sac and post-larval fish catch summaries for the most common species are presented in Tables 5-3 thru 5-5.

The most common species of yolk-sac and post-larval fish collected were Pacific herring, northern anchovies, longfin smelt, unidentified osmerids, striped bass, various groups of gobies, staghorn sculpins, and prickly sculpins. With the exception of striped bass and prickly sculpins, the juvenile and adults of these common species are the major forage fish for the commercially and recreationally valuable fish caught in and near the Bay.

Pacific herring come into the Bay during the winter and spring of each year and spawn in the intertidal and subtidal areas of the South and Central San Francisco Bay and San Pablo Bay. Large numbers of Pacific herring larval stages were caught in San Pablo Bay and the West Delta. This is particularly interesting because no sexually mature adults were collected in San Pablo Bay or the West Delta in 1980, 1981, or the first quarter of 1982. Since no spawning adults were found in San Pablo Bay and the West Delta and large numbers of larval stage Pacific herring were found there, it is reasonable to assume that upstream current transportation from the Central Bay is responsible.

Based on yolk-sac data it appears that northern anchovies spawn all year but the peak occurs during the second and third quarters. The larval stages are found throughout the Bay including the West Delta; however, no sexually mature adults were found in the West Delta. The currents again are the most plausible explanation for the West Delta distribution of northern anchovies.

Longfin smelt were found in all areas when there were sufficient outflows to disperse the larval stages. Catches were much higher in 1980 and 1982 than in 1981. Outflows were also much higher in 1980 and 1982 than 1981.

English sole distribution and abundance in the Bay may also be related to high outflows (Figure 5-3). Larval English sole are carried into the Bay on the currents and are dispersed onto the shoals of the South Bay and San Pablo Bay. This species was more abundant and more widely distributed in the Bay during the high flow years of 1980 and 1982 than in 1981.

TABLE 5-2. List of Species Collected From 1980-1983.

FAMILY NAME SCIENTIFIC NAME	COMMON NAME	LIFE STAGE COLLECTED				
Petromyzontidae						
Lampetra tridentata	Pacific Lamprey	A	J			
Carcharhinidae						
Mustelus henlei	Brown Smoothhound	A	J			
Triakis semifasciata	Leopard Shark	A	J			
Squalidae						
Squalus acanthias	Spiny Dogfish	A				
Rajidae						
Raja binoculata	Big Skate	A	J			
Myliobatidae						
Myliobatis californica	Bat Ray	A				
Acipenseridae						
Acipenser medirostris	Green Sturgeon	A				
Acipenser transmontanus	White Sturgeon	A	J		Y	
Clupeidae						
Alosa sapidissima	American Shad	A	J	P		
Clupea harengus	Pacific Herring	A	J	P	Y	E
Dorosoma petenense	Threadfin Shad	A	J	P	Y	
Engraulidae						
Engraulis mordax	Northern Anchovy	A	J	P	Y	E
Salmonidae						
Oncorhynchus kisutch	Silver Salmon	A				
Oncorhynchus tshawytscha	King Salmon	A	J			
Salmo gairdnerii	Steelhead	A	J			

TABLE 5-2 (Continued)

FAMILY NAME SCIENTIFIC NAME	COMMON NAME	LIFE STAGE COLLECTED
Osmeridae		
Osmeridae, unidentified		P Y E
Allosmerus elongatus	Whitebait Smelt	A
Hypomesus nipponensis	Japanese Pond Smelt	A
Hypomesus pretiosus	Surf Smelt	A J P
Hypomesus transpacificus	Delta Smelt	A J P Y
Spirinchus starksi	Night Smelt	A
Spirinchus thaleichthys	Longfin Smelt	A J P Y
Bathylagidae		
Bathylagus pacificus	Pacific Blacksmelt	P
Myctophidae		
Stenobrachius leucopsarus	Northern Lampfish	P
Tarletonbeania crenularis	Blue Lanternfish	P
Cyprinidae		
Cyprinidae, unidentified		P Y
Carassius auratus	Goldfish	A
Cyprinus carpio	Carp	A P Y
Pogonichthys macrolepidotus	Sacramento Splittail	A J P Y
Ptychocheilus grandis	Sacramento Squawfish	A J
Ictaluridae		
Ictalurus catus	White Catfish	A J
Ictalurus melas	Black Bullhead	A
Ictalurus nebulosus	Brown Bullhead	A
Ictalurus punctatus	Channel Catfish	A

TABLE 5-2 (Continued)

FAMILY NAME SCIENTIFIC NAME	COMMON NAME	LIFE STAGE COLLECTED
Batrachoididae		
Porichthys notatus	Plainfin Midshipman	A J
Gobiesocidae		
Gobiesox maeandricus	Northern Clingfish	P
Gadidae		
Gadidae, unidentified		P
Microgadus proximus	Pacific Tomcod	A J P
Bythitidae		
Brosmophycis marginata	Red Brotula	P
Cyprinodontidae		
Lucania parva	Rainwater Killifish	A
Poeciliidae		
Gambusia affinis	Mosquitofish	A J
Atherinidae		
Atherinops affinis	Topsmelt	A J P Y
Atherinopsis californiensis	Jacksmelt	A J P Y E
Menidia audens	Mississippi Silverside	A J P
Gasterosteidae		
Gasterosteus aculeatus	Threespine Stickleback	A J P Y
Syngnathidae		
Syngnathus leptorhynchus	Bay Pipefish	A J
Percichthyidae		
Morone saxatilis	Striped Bass	A J P Y

TABLE 5-2 (Continued)

FAMILY NAME SCIENTIFIC NAME	COMMON NAME	LIFE STAGE COLLECTED
Centrarchidae		
Centrarchidae, unidentified		J P Y
Lepomis macrochirus	Bluegill	A
Percidae		
Percina macrolepida	Bigscale Logperch	A J P Y
Sciaenidae		
Genyonemus lineatus	White Croaker	A J P Y E
Embiotocidae		
Amphistichus argenteus	Barred Surfperch	A J
Amphistichus koelzi	Calico Surfperch	A
Amphistichus rhodoterus	Redtail Surfperch	A
Cymatogaster aggregata	Shiner Perch	A J
Embiotoca jacksoni	Black Perch	A J
Hyperprosopon argenteum	Walleye Surfperch	A J
Hypsurus caryi	Rainbow Seaperch	A
Micrometrus minimus	Dwarf Perch	A J
Phanerodon furcatus	White Seaperch	A J
Rhacochilus toxotes	Rubberlip Seaperch	A J
Hysterocarpus traski	Tule Perch	A J
Rhacochilus vacca	Pile Perch	A J
Labridae		
Oxyjulis californica	Senorita	A

TABLE 5-2 (Continued)

FAMILY NAME SCIENTIFIC NAME	COMMON NAME	LIFE STAGE COLLECTED			
Clinidae					
Clinidae, unidentified				P	
Gibbonsia metzi	Striped Kelpfish			P	Y
Neoclinus uninotatus	Onespot Fringehead			P	
Stichaeidae					
Stichaeidae, unidentified				P	Y
Pholidae					
Apodichthys falvidus	Penpoint Gunnel	A			
Pholis ornata	Saddleback Gunnel	A			
Ammodytidae					
Ammodytes hexapterus	Pacific Sandlance		J		
Gobidae					
Gobidae, unidentified			J		
Gobidae, Type II				P	Y
Arrow & Cheekspot Gobies				P	Y
Lepidogobius lepidus	Bay Goby	A	J	P	Y
Acanthogobius flavimanus	Yellowfin Goby	A	J	P	Y
Ilypnus gilberti	Cheekspot Goby	A	J	P	Y
Clevelandia ios	Arrow Goby	A	J	P	Y
Tridentiger trigonocephalus	Chameleon Goby	A	J	P	Y
Coryphopterus nicholsii	Blackeye Goby			P	
Gillichthys mirabilis	Longjaw Mudsucker	A	J	P	Y
Stromateidae					
Peprilus simillimus	Pacific Butterfish	A			

TABLE 5-2 (Continued)

FAMILY NAME SCIENTIFIC NAME	COMMON NAME	LIFE STAGE COLLECTED
Scorpaenidae		
Sebastes, unidentified		J P Y
Sebastes auriculatus	Brown Rockfish	A J
Sebastes melanops	Black Rockfish	J
Hexagrammidae		
Hexagrammos decagrammus	Kelp Greenling	A J P
Ophiodon elongatus	Lingcod	A J P Y
Oxylebius pictus	Painted Greenling	P
Cottidae		
Cottidae, unidentified		P Y
Hemilepidotus spinosus	Brown Irish Lord	P
Leptocottus armatus	Staghorn Sculpin	A J P Y
Oligocottus snyderi	Fluffy Sculpin	A
Scorpaenichthys marmoratus	Cabezon	A J P Y
Artedius harringtoni	Scalyhead Sculpin	A
Artedius notospilotus	Bonyhead Sculpin	A J P Y
Oligocottus maculosus	Tidepool Sculpin	A P
Cottus asper	Prickly Sculpin	A J P Y
Agonidae		
Odontopyxis trispinosa	Pygmy Poacher	A
Cyclopteridae		
Liparis pulchellus	Showy Snailfish	A J

TABLE 5-2 (Continued)

FAMILY NAME SCIENTIFIC NAME	COMMON NAME	LIFE STAGE COLLECTED
Bothidae		
<u>Citharichthys sordidus</u>	Pacific Sanddab	A
<u>Citharichthys stigmaeus</u>	Speckled Sanddab	A J
<u>Paralichthys californicus</u>	California Halibut	A J P
Pleuronectidae		
Pleuronectidae, unidentified		P Y E
<u>Hypsopsetta guttulata</u>	Diamond Turbot	A J P Y
<u>Parophrys vetulus</u>	English Sole	A J P Y
<u>Platichthys stellatus</u>	Starry Flounder	A J P Y
<u>Pleuronichthys decurrens</u>	Curlfin Turbot	A J
<u>Pleuronichthys verticalis</u>	Hornyhead Turbot	A
<u>Psettichthys melanostictus</u>	Sand Sole	A J P
Cynoglossidae		
<u>Symphurus atricauda</u>	California Tonguefish	A J
Unidentified		P Y E

Life stage key:

Adult	A
Juvenile	J
Post Larval	P
Yolk-sac	Y
Egg	E

TABLE 5-3. Quarterly Yolk-sac and Post-Larval Total Catches (number/m^3) During 1980 to 1982.

Key for Table 5-3

number/m^3	code	number/m^3	code
0.001-0.100	1	10.001-25.000	6
0.101-0.500	2	25.001-50.000	7
0.501-1.000	3	50.001-100.000	8
1.001-5.000	4	100.001-1000.000	9
5.001-10.000	5		

Species of Yolk-sac Fish	1980				1981				1982
	Quarter				Quarter				Quarter
	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar
Pacific Herring	6			5	5			2	6
Northern Anchovy	4	4	5	3	1	4	5	3	5
Longfin Smelt	4	1		1					4
Osmeridae, unidentified	4	1		4	5	2			6
Jacksmelt	2	2	1	1	2	2	2		1
Striped Bass		6	2			5			
White Croaker	4	1		1	1			1	1
Bay Goby		2	2	1	1	2	3	2	1
Staghorn Sculpin	2		1	2	3	1		1	2
Prickly Sculpin	1	1			2				1
English Sole	1								

Species of Post-Larval Fish	1980				1981				1982
	Quarter				Quarter				Quarter
	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar
Pacific Herring	7	4	1	6	9	1		7	9
Northern Anchovy	4	4	6	5	4	5	6	5	2
Longfin Smelt	6	2				2			4
Osmeridae, unidentified	2	4			7	4	1	1	8
Jacksmelt	3	2	1	1	2	3	2	1	1
Striped Bass		4	2			5			
White Croaker	4	2	1	2	3	2	1	2	2
Gobiidae Type II	8	8	4	3	7	6	4		
Bay Goby	2	4	3	2	2	2	3	4	2
Yellowfin Goby	1	1			4	6	1	1	5
Arrow and Cheekspot Gobies					3	6	5	4	
Staghorn Sculpin	2	1	1	1	4	1		2	3
Prickly Sculpin	4	3	1		4	2			3
English Sole	1	1			1				3

TABLE 5-4. Quarterly Catches of Yolk-sac Fish in Each Major Section of the Study Area During 1980 to 1982.

Key for Table 5-4

Area	Code	Number/m^3	Code	Number/m^3	Code
Western Delta	WD	0.001-0.100	1	10.001-25.000	6
San Pablo Bay	SPB	0.101-0.500	2	25.001-50.000	7
South San Francisco Bay	SSFB	0.501-1.000	3	50.001-100.000	8
Central San Francisco Bay	CSFB	1.001-5.000	4	100.001-1000.000	9
		5.001-10.000	5		

	1980																1981																1982			
	Quarter																Quarter																Quarter			
	Jan-Mar				Apr-Jun				Jul-Sep				Oct-Nov				Jan-Mar				Apr-Jun				Jul-Sep				Oct-Dec				Jan-Mar			
	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD
Pacific Herring	3	4	4	5									1	1	5	2	2	1	5	1									1	2		1	2	6		
Northern Anchovy	4	2	2			4	1		1	4	4			2	2	1			1		1	1	4	1	2	4	3	4	1	3	1	1				
Longfin Smelt	2	1	4	4			1									1																	2	3	4	
Osmeridae, unidentified				4				1												5				2												6
Jacksmelt	1	1			1	2	1	1		1	1			1			1	1	1		1	1	2		1	2	1						1	1		
Striped Bass								6				2												5			1									
White Croaker	3	2	1			1			1		1		4	3	2		1	1											1	1	1		1			
Bay Goby					2				2	1	1		1	1				1			2	1			2	1	1		1	1	1		1			
Staghorn Sculpin	1	2	1										1		1	1	2		2	1	1	1			1				1		1		1	1	1	
Prickly Sculpin	1			1				1									1			2															1	1
English Sole	1																																			

TABLE 5-5. Quarterly Catches of Post-Larval Fish in Each Major Section of the Study Area During 1980 to 1982.

Key for Table 5-6

Area	Code	Number/m^3	Code	Number/m^3	Code
Western Delta	WD	0.001-0.100	1	10.001-25.000	6
San Pablo Bay	SPB	0.101-0.500	2	25.001-50.000	7
South San Francisco Bay	SSFB	0.501-1.000	3	50.001-100.000	8
Central San Francisco Bay	CSFB	1.001-5.000	4	100.001-1000.000	9
		5.001-10.000	5		

	1980																1981																1982			
	Quarter																Quarter																Quarter			
	Jan-Mar				Apr-Jun				Jul-Sep				Oct-Nov				Jan-Mar				Apr-Jun				Jul-Sep				Oct-Dec				Jan-Mar			
	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD
Pacific Herring	5	6	5	4			4	3		1			1	1	6	5	4	6	8	8			1	1					4	2	6	4	7	8	9	8
Northern Anchovy	3	4	2		1	4	2	1	2	4	6	3	1	4	2	3	3	2	2	2	1	4	4	4	1	4	4	5	1	4	2	4	1	2	2	
Longfin Smelt	2	2	5	5			2	1																2									1	1	4	
Osmeridae, unidentified				2			1	4											1	7				4							1	1				8
Jacksmelt	3	2	1		1	2	2	1		1	1	1	1				1	2	1	2	1	2	2	2	1	2	2		1	1			1	1	1	
Striped Bass							1	4				2												5												
White Croaker	3	2	2	1	1	1	2	1			1		2	1	1	1	2	2	2	1	1	1	1	1		1			2	1	1		2	1	1	
Gobiidae Type II	5	5	6	6	3	7	7	4	1	4	4	2	1	2	2	2	5	6	6	4	1	6	4			4										
Bay Goby	2	1	1		3	2	1		2	2	1		1	1	1	1	1	2			2	1	1	1	2	1	1	1	3	2	1		2	1	2	1
Yellowfin Goby				1		1		1									4		4	3	4		5	4	1			1	1	1	1		4	5	4	2
Arrow and Cheekspot Gobies																	1		2	2	2		6	4	2	4	4	3	1	4	2	2				
Staghorn Sculpin	2	2	1		1	1	1				1		1	1	1	1	1	2	3			1	1						1	1	1		1	2	1	
Prickly Sculpin	1	1	3	4			2	3			1						1		1	4			1	3									1	1	2	2
English Sole	1	1	1				1										1																2	1	2	1

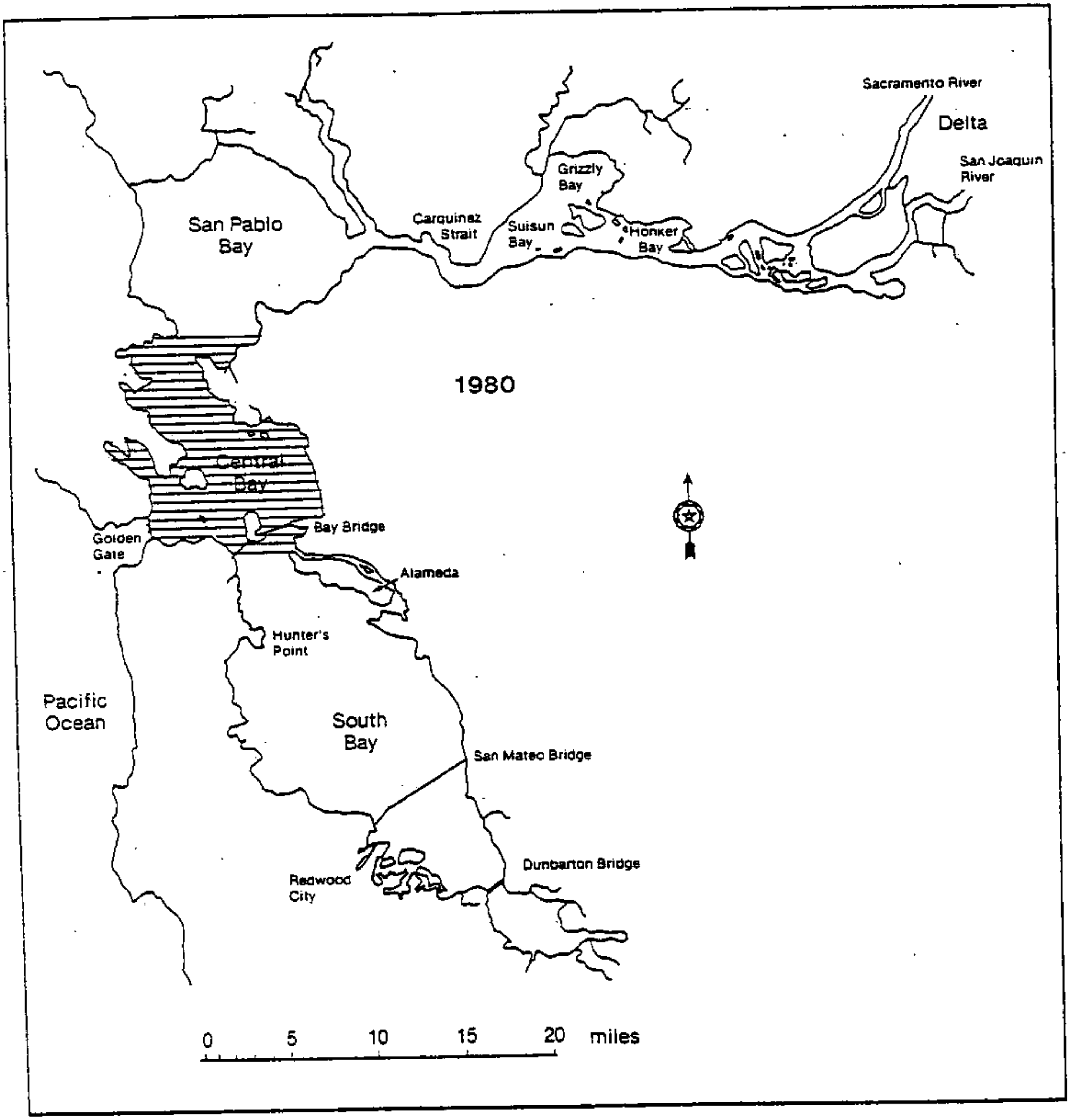


FIGURE 5-3. Distribution of Larval Stage English Sole During 1980, 1981, and 1982.

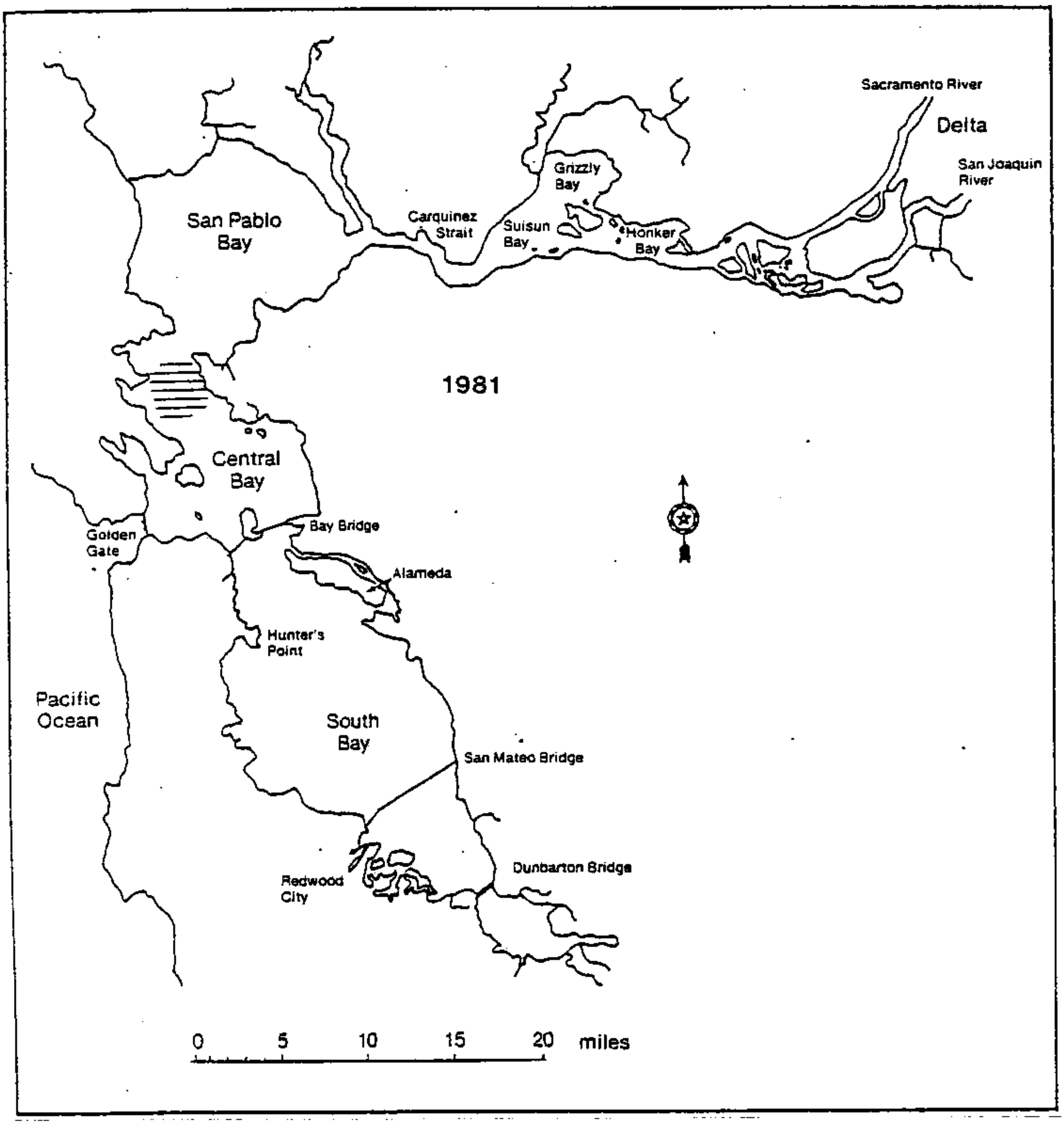


FIGURE 5-3. (Cont'd.)

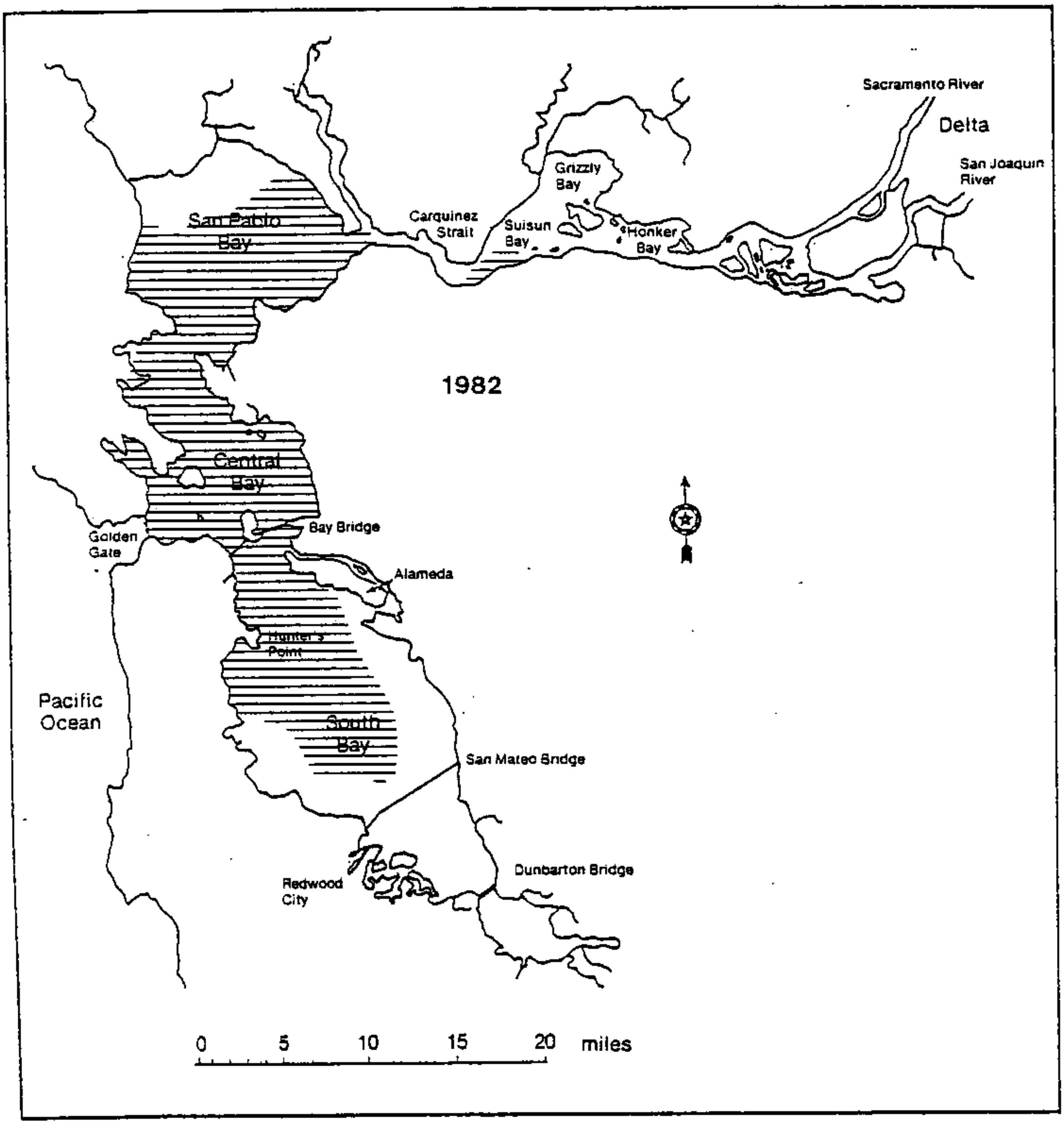


FIGURE 5-3. (Cont'd.)

The appearance of larval stages and not the adults of rare marine species in 1980 and 1982 (e.g. northern lampfish and northern clingfish) also supports the hypothesis that high flows increase bottom currents from the ocean and carry in more marine species in high flow years. Parenthetically, the list of these odd or rare larval marine species has increased greatly in the winter and spring of 1982-83, an extremely high flow year.

Adult Fish Results

Tables 5-6 and 5-7 present the catches of the more common and selected adult fish on a quarterly and annual basis and the relative catches in each major area on a temporal basis.

The sharks, skates, and rays were found in the South and Central Bay with no seasonal trends evident (Table 5-6 and 5-7). Several species of the larger sharks known to exist in the Central Bay have yet to be collected.

The catches of adult Pacific herring were greater in 1980 and 1982 than 1981. The majority of these fish were young-of-the-year. This trend does not follow the larval Pacific herring trend where 1981 and 1982 catches were greater than the 1980 catch (Tables 5-3, 5-5 and 5-6). The adult northern anchovy catches do not parallel the larval catches either; however, in this case the adult northern anchovy catches consist mostly of a broad mixture of young-of-the-year, 1, and 2 year old fish (Table 5-6). The higher salinities in 1981 allowed the adult northern anchovies to increase their range into the Western Delta (Table 5-7). The effect of this increased range on the catches in 1981 is under investigation.

One of the major factors affecting adult fish distribution in the San Francisco Bay system is salinity. As stated earlier, a reasonable hypothesis would be that in wet years estuarine or euryhaline species should extend their distributions and increase their abundance; while in dry years marine species should increase their ranges and abundances in the Bay. These trends can be seen in the data; however, it is too early to establish cause and effect. Marine species, such as the Embiotocids (surfperches), jacksmelts, and plainfin midshipman, were caught in increased numbers in 1981 when compared to 1980 and 1982 (Table 5-6), while the catches of estuarine species (e.g. longfin smelt, yellowfin gobies, staghorn sculpins, and starry flounders) were higher in 1980 and 1982 (Table 5-6).

Marine species (e.g. English sole and speckled sanddabs) which require the strong bottom currents to transport and disperse their larval and juvenile stages into and around the Bay, had increased catches in 1980 and 1982 when compared to 1981. Since these bottom currents are related to outflow, the catches of these marine species may also be related to Delta outflow.

In order to test the hypothesis that distribution of groups of adult fish are related to salinity and hence Delta outflow, the fish were categorized with respect to electrical conductivity where they were caught (Table 5-8). Generally the fish fall into four groups: freshwater, estuarine, marine, and anadromous. As more data becomes available, this table will be refined so that all species of adult fish can be separated into definite salinity preference groups. The

TABLE 5-6. Quarterly Total Catches of Adult Fish During 1980 to 1982.

Key for Table 5-7

Total Catch	Code	Total Catch	Code
0-10	1	1001-5000	6
11-50	2	5001-10000	7
51-100	3	10001-15000	8
101-500	4	15001-50000	9
501-1000	5	50001-100000	10

Species of Adult Fish	1980				1981				1982		
	Quarter				Quarter				Quarter		
	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep
Brown Smoothhound	2	2	1	1	1	1	2	2	1	2	2
Leopard Shark	2	2	1	1	2	1	1	1	2	2	1
Spiny Dogfish		1			1		1	1		1	1
Big Scate	1	1	1	1	2	1	1	1	1	2	1
Bat Ray	1	2	1	1	2	1	2	1	1	2	1
American Shad	2	1	3	3	3	2	3	3	2	2	5
Pacific Herring	4	6	7	4	4	5	5	4	4	8	7
Northern Anchovy	5	9	9	8	5	9	10	8	7	9	10
Delta Smelt	1	1	4	3	4	3	4	3	3	2	3
Longfin Smelt	3	7	7	6	6	6	4	4	4	8	7
Plainfin Midshipman	1	3	3	2	1	2	4	4	2	3	3
Pacific Tomcod	2	2	2	2	2	1	1	3	2	2	2
Jacksmelt	2	3	3	2	2	4	5	4	2	4	3
Striped Bass	4	4	5	4	4	6	6	4	5	4	6
White Croaker	3	6	6	4	2	4	4	3	2	4	2
Barred Surfperch		1	1	1	1	2	1	1	1	1	1
Shiner Perch	5	4	5	4	4	5	6	4	5	6	5
Black Perch					1		1	1	1	1	
Walleye Surfperch	2	2	2	1	1	4	3	2	1	4	2
Dwarf Perch			2	1	2		1	1	2	1	1
White Seaperch		1	2		1	1	2	1	1	1	1
Rubberlip Seaperch	1			1			1			1	
Pile Perch	1	1	2		1	1	2	2	1	1	2
Bay Goby		1	4	2	1	4	4	2	4	5	4
Yellowfin Goby	4	6	4	4	3	2	3	2	3	4	4
Staghorn Sculpin	4	4	4	4	3	4	3	3	3	5	4
Speckled Sanddab	6	5	4	2	3	2	3	2	4	4	2
English Sole	4	6	5	3	5	5	4	3	4	5	4
Starry Flounder	3	4	5	4	4	3	3	3	2	4	4

TABLE 5-7. Quarterly Total Catches of Adult Fish in Each Major Section of the Study Area During 1980 to 1982.

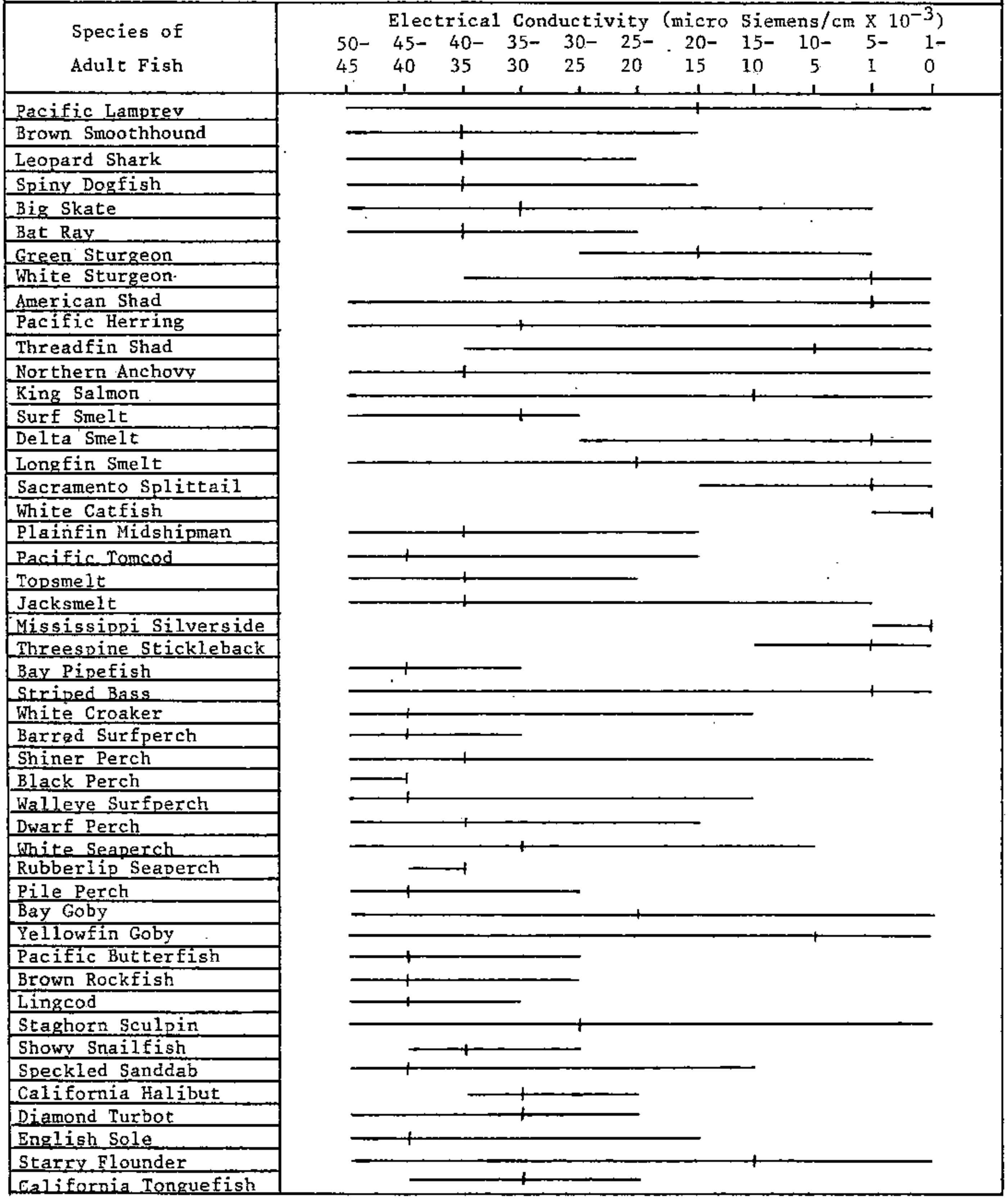
Key for Table 5-8

Area	Code
Western Delta	WD
San Pablo Bay	SPB
South San Francisco Bay	SSFB
Central San Francisco Bay	CSFB

Total Catch	Code	Total Catch	Code
0-10	1	1001-5000	6
11-50	2	5001-10000	7
51-100	3	10001-15000	8
101-500	4	15001-50000	9
501-1000	5		

Species of Adult Fish	1980																1981																1982											
	Quarter																Quarter																Quarter											
	Jan-Mar				Apr-Jun				Jul-Sep				Oct-Dec				Jan-Mar				Apr-Jun				Jul-Sep				Oct-Dec				Jan-Mar				Apr-Jun				Jul-Sep			
	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD	CSFB	SSFB	SPB	WD
Brown Smoothhound	1	1			1	2	1		1	1	1			1			1	1				1			1	2			1	2			1	1			2	2			1	1	1	
Leopard Shark	2	2				2	1			1				1				2				1				1				1				2			1	2	1		1	1	1	
Spiny Dogfish					1	1	1										1								1					1								1			1			
Big Skate	1				1		1		1				1		1			1	2				1		1		1		1				1	1			1	1	1				1	
Bat Ray	1	1			1	2			1	1	1		1	1				1				1			1	2			1	1			1	1			1	2			1	1	1	
American Shad	1	2	2	1				1				3			2	3	2	1	2	2		1	1	2				3			1	3	1	1	1		1		1	1	1			5
Pacific Herring	2	4	1		6	6	6	2	6	6	4	2	2	4	3	2	1	2	4	1	4	4	4	1	4	4	2	1	2	3	2	1	2	4	1		6	6	5	2	6	5	6	4
Northern Anchovy	4	4	3	1	9	6	8	4	6	6	9	6	7	5	6	4	2	4	2	1	7	6	7	6	9	9	9	7	6	7	4	6	6	6	3	1	9	9	6	1	7	8	9	4
Delta Smelt				1				2				4				3				4				3	1			4	1			3			1	3				2				3
Longfin Smelt	1	1	2	3	6	2	6	6	4	2	7	6	4	2	6	6	3	2	4	6	2		4	5	4	2	1	4	2	1	2	4	3	2	4	4	5	1	8	6	6	3	6	6
Plainfin Midshipman	1	1			2	1	2	1	1	1	3	2	1	1	1	1		1	1		1	1	1		2	3	2	2	1	4			1	1	1		2	1	3			3	2	
Pacific Tomcod	2	2	1		2	1	1	1	2				1		1	1	1	1	1		1		1		1				3	1	1		2	2	1		2	2	1		2	2		
Jacksmelt	1	2	1		1	2	2	1	1	3	2		2	1	1		1	2	1		1	2	4		4	4	4	1	2	3	4		2	2	1	1	2	4	3		3	2	2	
Striped Bass	1	1	4	4			2	4		1	2	5				4		1	2	4			2	6			3	6			2	4	1	1	4	4	1	1	4	3	1		1	6
White Croaker	2	2	1	1	2	4	5	2	3	2	6		2	3	2	1	1	1	1	1	2	3	3	1	2	3			3	2			2	2	1	2	2	2	4	1	2	2	2	
Barred Surfperch						1			1		1		1	1				1			1	2				1				1				1				1				1		
Shiner Perch	5	4	2	1	4	4	3	1	4	4	4		3	3	2		4	3	2		4	4	3		4	6	4	1	3	4	1		4	5	2		4	5	4		4	4	4	
Black Perch																	1	1							1	1			1						1				1					
Walleye Surfperch	1	2	1		1	1	1		2	2	1		1								2	4	1		2	2	2		1	1	1		1	1			2	4	1		1	2	1	
Dwarf Perch										2				1			1	2								1				1	1			2	1			1				1		
White Seaperch					1	1	1		2	1	1						1	1			1	1			2	2			1	1				1	1		1	1			1	1		
Rubberlip Seaperch			1							1															1												1							
Pile Perch	1		1		1	1	1		2	1	1							1				1			1	2	1		1	1				1	1		1	1	1		1	1	1	
Bay Goby					1		1		1	1	3	3	1	1	1		1	1	1		1	2	4	2	3	4	1		1	2	1		1	4	3	1	4	4	4	1	1	2	4	
Yellowfin Goby	2	3	3	3	2	4	4	4	2		2	4		1	2	3	1	1	2	2			2	2	1	1	1	3	1		1	2			3	2		1	2	3	1		2	4
Staghorn Sculpin	4	2	2	2	2	2	4	2	2	1	4	2	2	1	2	3	1	2	2	1	2	1	3	1	2	1	2	2	2	1	1	2	2	2	2	1	2	2	4	3	2	1	4	2
Speckled Sanddab	6	4	1		5	3	3		4	1	2		2	2	1		2	2	2		1	1	2		3	2	1		2	2	1		3	2	1		4	2	1	1	2	1	1	
English Sole	4	3	2		5	4	4	1	4	1	4		3	1	1		4	3	4	1	2	4	4	1	4	2	2		3	1	1		4	2	3		4	4	3		3	1	3	
Starry Flounder	1	2	2	2	2	1	3	3	2	1	5	4	1	1	4	3	1	1	2	3	1	1	2	2	2	1	2	2	1	1	1	2	1	1	2	2	2	1	3	4	2	1	3	3

TABLE 5-8. Electrical Conductivities Associated With the 1980 and 1981 Catches of Adult Fish. The Horizontal Line Indicates the Range of Electrical Conductivities in Which Fish Were Collected and the Vertical Mark Denotes the Mean Electrical Conductivity of the Catch Frequency Distribution.



changes in distributions and abundances of these groups will then be analyzed in relation to outflow.

Summary of Fish Results

Pacific herring, northern anchovies, longfin smelt, and gobies were the most numerous larval fish collected. Catches of larval longfin smelt were greater in 1980 and 1982 than in 1981. Larval Pacific herring and northern anchovies were found in the Western Delta despite the lack of evidence of any spawning activity there. Catches of larval English sole and rare marine species were higher in 1980 and 1982.

Catches of adult longfin smelt paralleled the larval catches. Adult northern anchovy catches were higher in 1981 than in 1980. This is the opposite of the larval northern anchovy catches. Estuarine species (e.g. longfin smelt, staghorn sculpins, yellowfin gobies, and starry flounders) had higher catches in 1980 and 1982 while marine species (e.g. surfperch, jacksmelt, and plainfin midshipman) were more common in the catches in 1981. Catches of English sole and speckled sanddabs were greater in 1980 and 1982 than 1981. Many of these trends parallel Delta outflows for those years.

SHRIMP STUDY RESULTS

The three major shrimp species in San Francisco Bay are the two native crangonids, _Crangon franciscorum_ and _Crangon nigricauda_, and the introduced _Palaemon macrodactylus_. _C. nigricauda_ inhabits the higher salinity areas of the Bay, and probably also the nearshore area outside the Golden Gate. _C. franciscorum_ is more truly estuarine, with only the larvae and possibly a few adults found outside the Golden Gate. _P. macrodactylus_ prefers fresher conditions than either crangonid, and is found mainly in Suisun Bay. These shrimp are a large component of the bottom-dwelling community of the Bay, and with their short life cycle of 12 to 18 months, populations would be expected to respond quickly to changes in local conditions. Preliminary results of 3 years of otter trawl monthly surveys throughout the Bay are discussed here. Comparative catches and distributional abundances between years are reported for each species. Preliminary evidence of population response to changes in salinity and Delta outflow is presented.

C. franciscorum

C. franciscorum is the major shrimp species in San Francisco Bay. Our numerical catch of this species totaled over the 3 years was 12 times higher than _C. nigricauda_, and 32 times higher than _P. macrodactylus_. We are sampling most of the range of this species in the northern reaches of San Francisco Bay, but are missing the major portion of the South Bay population which is in the sloughs. Another research effort is investigating shrimp in this area and has shown that, while catch abundance is similar there, the actual area inhabited is very small (M. Stevenson, pers. commun.). Therefore, the South Bay slough population is, in most years, a minor part of the total _C. franciscorum_ population.

Abundance

C. franciscorum catch abundance changed markedly from year to year during the first 3 years of our study (Table 5-9). The highest catches were in 1982, when large numbers of juveniles moved into both San Pablo and Suisun Bay in the spring. Abundances remained high through the summer (Figure 5-4) probably due to both high survival and continuing recruitment. The total catch of gravid females for the months May through August was also high in comparison with the other 2 years, with a survey average of 535 gravid females for those 4 months.

In 1981 initial recruitment in the spring was high, but there was a sharp drop in catch as the summer progressed. The total catch for the year was 3.5 times less than in 1982. In addition, after relatively good catches of gravid females in the winter and spring (a mean of 395/survey for January through May), the next 7 months averaged 23/survey with a range from 0 to 60. Both these results indicate poor conditions for the C. franciscorum population in the latter part of 1981.

The catch in 1980 was in between the other two years at 1.9 times less than the 1982 catch (Table 5-9). The spring recruitment appeared to be weaker, with lower mean catches in the late spring (Figure 5-4). A peak in catch of gravid females was evident in 1980 from May to August with a mean of 274.5/survey. As with total catch, the pattern is similar to 1982, but the numbers are less.

Distribution

Abundances remained high in both San Pablo Bay and Suisun Bay through the summer of 1982. Only a few C. franciscorum moved above Suisun during August, when salinity rose from near 0 to 1.6 ^{o}/oo in Honker Bay. San Pablo Bay salinies remained at or below about 20^{o}/oo through the summer and fall, and only the southernmost areas were above this level in the late fall and early winter. In contrast, in 1981 San Pablo Bay means for the monthly surveys were as high as 23^{o}/oo in May and rose to 27^{o}/oo in September. These salinities appear to be prohibitively high for the majority of the smaller shrimp. Temperature probably interacts with salinity to influence distribution, but close analysis of which variables are most important still needs to be done.

Both 1980 and 1981 show evidence of migration of shrimp into upstream areas in late summer. In 1980 the migration was from San Pablo to Suisun, and in 1981 it was from Suisun to Honker Bay and upstream. This coincides with a salinity rise to 20^{o}/oo and above in both downbay areas, a similar finding to 1982.

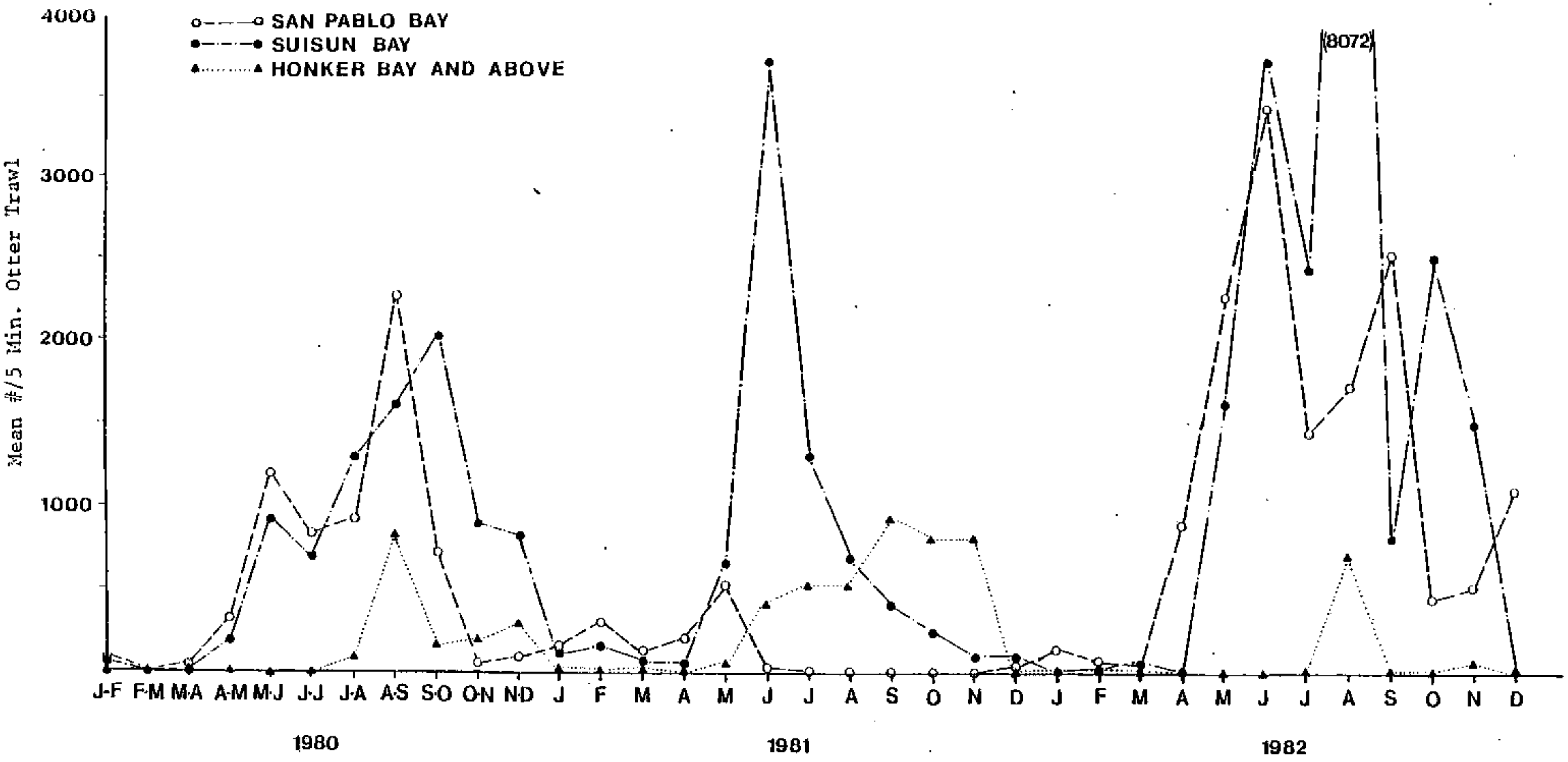
C. nigricauda

C. nigricauda was found almost exclusively in the areas below the Carquinez Strait in all 3 years of our study, confirming its preference for more marine conditions. Differences in distributional abundance do emerge when the years are compared (Table 5-9), and these can be generally correlated with salinity.

TABLE 5-9. Comparisons of Catch/5 Minute Otter Trawl. Catch Between Years Are Directly Comparable, While Catch Between Sections of San Francisco Bay Are Not Because of Differences in Bottom Area.

	South Bay	Central Bay	San Pablo Bay	Suisun Bay	Honker Bay and Above	Mean Catch/ Survey	%
C. franciscorum							
1980 Mean catch/trawl	77.9	31.5	588.2	780.3	163.1	11788.1	29.0%
Percent	(4.7%)	(1.9%)	(35.8%)	(47.6%)	(10.0%)		
1981 Mean catch/trawl	125.8	12.2	122.5	569.5	12.1	6346.1	15.6%
Percent	(15.0%)	(1.4%)	(14.5%)	(67.7%)	(1.4%)		
1982 Mean catch/trawl	43.1	20.4	1216.9	1723.3	57.6	22582.1	55.4%
Percent	(1.4%)	(0.7%)	(39.8%)	(56.2%)	(1.9%)		
C. nigricauda							
1980 Mean catch/trawl	60.0	45.9	129.1	0.3	<0.1	1910.2	53.2%
Percent	(25.5%)	(19.5%)	(55.0%)	(<0.1%)	(<0.1%)		
1981 Mean catch/trawl	49.5	5.9	58.3	0.2	-	1029.2	28.7%
Percent	(27.7%)	(6.7%)	(65.6%)	(<0.1%)			
1982 Mean catch/trawl	28.3	32.0	21.8	0.1	-	649.8	18.1%
Percent	(34.5%)	(39.0%)	(26.5%)	(<0.1%)			
P. macrodactylus							
1980 Mean catch/trawl	1.0	0.2	4.4	60.5	10.1	514.3	40.2%
Percent	(1.4%)	(<0.1%)	(5.8%)	(79.5%)	(13.3%)		
1981 Mean catch/trawl	0.5	-	0.3	47.5	37.6	491.3	38.4%
Percent	(0.6%)		(0.3%)	(55.3%)	(43.8%)		
1982 Mean catch/trawl	0.6	-	5.9	31.4	0.4	274.6	21.4%
Percent	(1.6%)		(15.4%)	(82.0%)	(1.0%)		

FIGURE 5-4. Mean Catch of *Crangon franciscorum* Per 5 Minute Otter Trawl for Three Different Areas of San Francisco Bay During 1980-1982.



Abundance

Fifty-five percent of the mean catch for the year 1980 was from San Pablo Bay. This is primarily a result of a large influx of small shrimp of this species in May (see Figure 5-5). Correlation with any hydrodynamic event is not obvious at this stage of analysis. A similar peak in catch appears in April and May of 1981 and 1982, but the numbers are not nearly as high.

Distribution

In 1982, C. nigricauda remained in Central Bay and did not enter San Pablo Bay in any numbers until June when the bottom salinities had risen to 8-15°/oo from a low of 0-2°/oo in April and 5-11°/oo in May. In contrast, higher salinities throughout the spring of 1981 appear to be responsible for the movement of C. nigricauda directly into San Pablo Bay.

How these changes in distribution relate to total catch is still unclear. Total catch appears to have dropped over the 3 years of the study, but we have yet to confirm this statistically. Timing of life history events such as spawning, hatching, and juvenile migration are not as synchronized as with the other two species. Consequently correlations with environmental variables will be harder to make. Analysis of length frequency, egg stage, and larval catch data is planned and may help clarify relationships between Delta outflow and C. nigricauda abundance.

Palaemon macrodactylus

The major population of P. macrodactylus is centered in Suisun Bay, while there is a smaller population in the sloughs of South Bay which we only occasionally sample at our southern-most station. We catch this species in much greater abundance at the deeper stations than at those 10 feet or less. The summer peaks in abundance (Figure 5-6) comprise adults, not juveniles, and appear to be the result of a reproductive migration into the areas we are sampling. This is further supported by preliminary analysis of data on gravid females. In May through October, 67% of the females were gravid in 1980 and 1982, and 64% were gravid in 1981. In 1 month of each year over 90% of the females caught were gravid.

Distributional abundance changed between years and generally followed changes in salinity. In 1981, 55.3% of the catch was from Suisun and 43.8% was from Honker Bay and upstream. In this year the bottom salinity in the channel near Chipps Island (Stations 534 and 535, Figure 5-2) was 5°/oo and above during most of the surveys, June through October; and at the Sacramento River sampling site (Station 736), it was as high as 2.8°/oo in July and 3.5°/oo in October. In contrast, in 1982 salinity was close to 0 in and above Honker Bay in all months except August, when it reached 1.6°/oo in Honker Bay. In this year 83.4% of the catch of Palaemon was in Suisun Bay and only 1% was in the upper reaches. While we only have surface salinities for 1980, they are in between the 2 years cited above, as is the distributional abundance (see Table 5-9).

The adults of this species overlap with juveniles of C. franciscorum, at least in salinity preference. If they have similar diets, competition for food may

FIGURE 5-5. Mean Catch of <u>Crangon nigricauda</u> Per 5 Minute Otter Trawl for Three Different Areas of San Francisco Bay During 1980-1982.

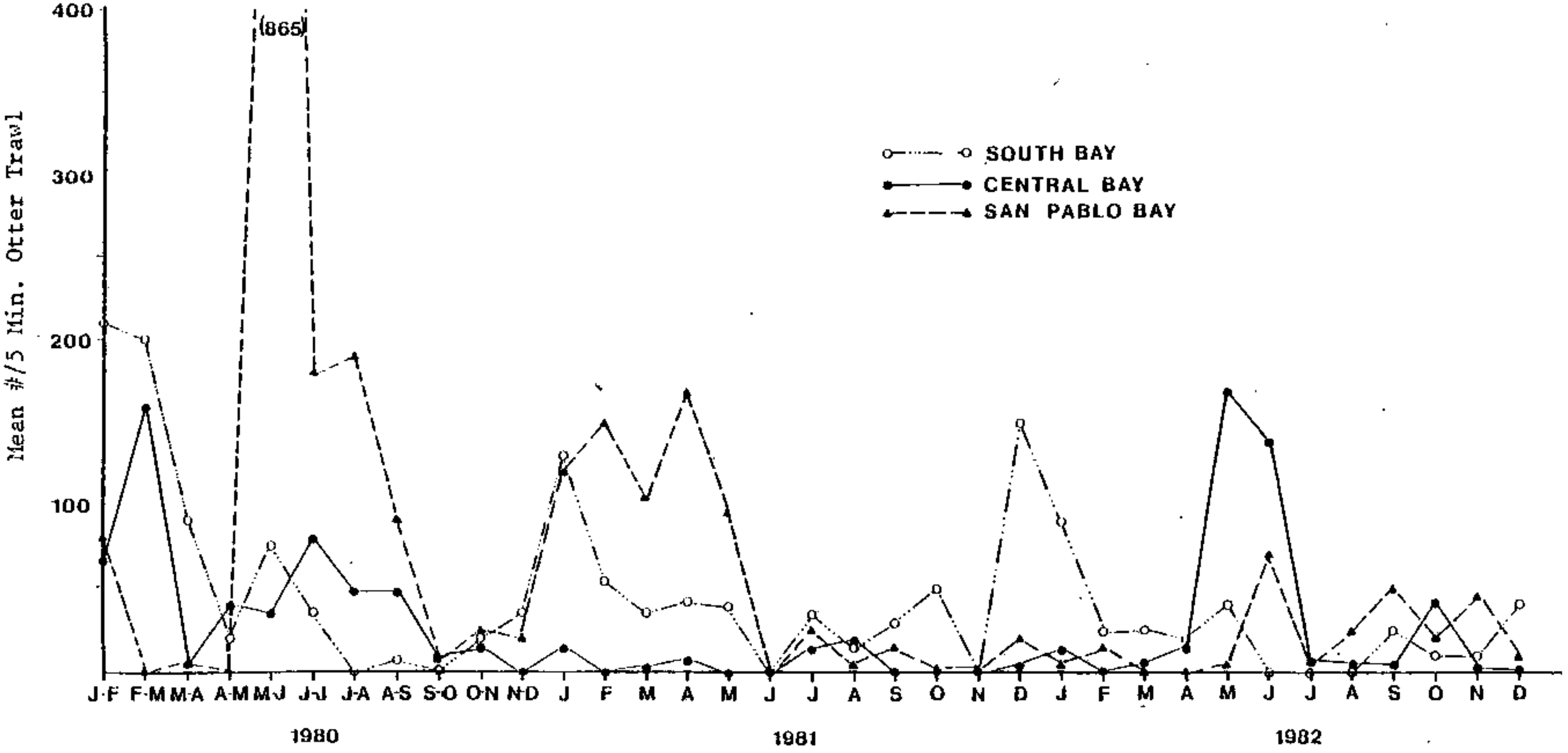
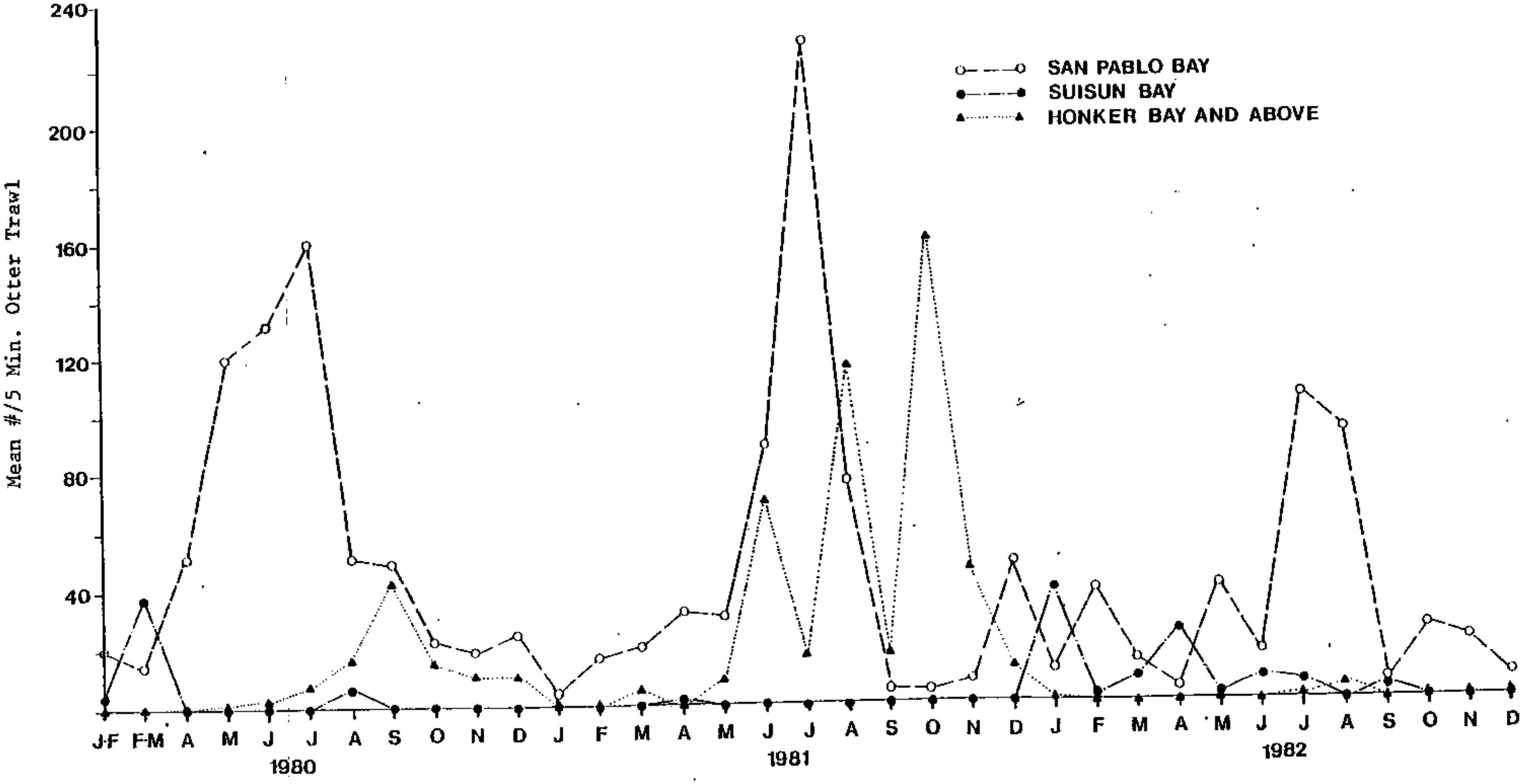


FIGURE 5-6. Mean Catch of <u>Palaemon macrodactylus</u> Per 5 Minute Otter Trawl for Three Different Areas of San Francisco Bay During 1980-1982.



be important in regulating the population. The tow catch in 1982 may reflect low population levels for that year as a result of the large numbers of juvenile *C. franciscorum* in Suisun Bay.

Summary

1. *C. franciscorum* catches were highest in 1982 when salinities were lowest and Delta outflows highest.
2. *C. franciscorum* catches were 3.5 times lower in 1981 when salinities were above 20 °/oo in much of the Bay and Western Delta and Delta outflows were lowest.
3. *C. franciscorum* catches were intermediate in 1980 when salinities and Delta outflow were intermediate.
4. *P. macrodactylus* catches are mainly adults, while *C. nigricauda* and *C. franciscorum* catches are predominantly juveniles.
5. Preliminary analysis indicates that the distribution and migrations of all three species can be correlated with salinity, but other variables have not been included and may modify these findings.

CHAPTER SIX

CONCLUSIONS

This report has discussed freshwater outflows and estuarine systems. Specifically, it has described the physical characteristics of outflow from the Sacramento-San Joaquin Delta, reviewed historical and present outflows, projected levels of future outflows, and described how projected changes in outflow levels will affect the physical/chemical environmental conditions of the Bay. It has described the biological resources of the Bay, the values of those resources and the present condition of some of them. Chapter 3 outlined the general responses of biological resources to stressful conditions and described more specifically how outflow changes can affect biological resources. Additionally, information from estuarine studies in Texas, Canada, and Russia and from the current San Francisco Bay System Study was presented.

Several implications can be drawn from all of the information presented in this report. These implications should be considered when flow management in estuarine systems is contemplated. The remainder of this report will briefly discuss these implications.

1. FLOW REDUCTIONS DEFINITELY CAUSE SIGNIFICANT BIOLOGICAL CHANGES

A considerable body of estuarine research has documented that freshwater flow reductions cause significant biological changes in estuaries of all types. In most cases, changes result from specific responses by organisms to physical conditions such as increased salinities, altered circulation patterns (including reduced flood plain inundation) and reduced nutrient input. Evidence documenting flow-related biological changes has been developed in several Russian estuaries, the St. Lawrence system, seven Texas estuaries, and the San Francisco Bay-Delta system, as well as several other systems. The ecological and/or economic significance of flow-related biological changes has not been completely defined in most systems. In some cases, the same flow change favors some organisms, while negatively impacting others.

2. SOME BIOLOGICAL CHANGES ARE SYSTEM SPECIFIC, WHILE OTHERS ARE COMMON TO ALL ESTUARIES

Some types of biological changes occur only in certain types of systems. For example, flow-related changes in survival of marine larval forms can only occur in systems that support significant numbers of marine forms that depend upon certain circulation patterns to carry young into estuarine nursery areas. The flow related changes in fish production in Texas estuaries are such an example. Another example of a system specific biological response is the decrease in production of walleye, bream and carp in the Don River flood plain in Russia. Such a response can only occur in a system that has broad shallow flood plain areas which support significant fish populations. Generally, system specific responses relate to physical or biological factors which are unique or occur infrequently in estuaries.

On the other hand, some biological responses are more general and occur in most estuaries. One such response is salinity dependent distributional change. Estuarine organisms in all systems have definite salinity tolerances and when those are exeeded by flow induced changes, the organisms must move to areas more favorable to their physiology.

3. DISTRIBUTIONAL CHANGES OCCUR UNIVERSALLY, ALTHOUGH THEY CAN BE SPECIES AND SYSTEM SPECIFIC

Distributional change due to flow alteration is a general response in estuaries. However, individual species and life stages respond differently. Distributional patterns of some species with pelagic eggs or larval forms, such as striped bass, American shad, longfin smelt or chinook salmon, typically are affected by flow changes, but each responds in relation to its own salinity tolerance. Other species with attached eggs, sessile life styles or those with adult forms absent from the system do not respond by changing distributions. For example, Pacific herring eggs are attached to the substrate and will not be carried to other locations by flow change. Oysters and other benthic invertebrates cannot immediately respond by changing location when environmental conditions occur and sometimes are killed by influxes of fresh or marine water.

Distributional changes can also be specific to certain systems. For example, distributional change is more pronounced in shallow estuaries with highly variable amounts of inflow such as San Francisco Bay. In these systems large salinity changes often occur suddenly. The estuarine volume is not sufficient to buffer highly variable flows. Distributional change is less pronounced in estuaries with deep channels, few shoal areas, and relatively constant outflows (e.g. Columbia River Estuary or fjord type systems). Systems that tend to be classified as mixed show more distributional responses than stratified systems.

4. ABUNDANCE CHANGES ARE NOT WELL UNDERSTOOD, THEREFORE IT IS UNCERTAIN AS TO HOW GENERAL THEY ARE - HOWEVER, THEY TEND TO BE SPECIES AND SYSTEM SPECIFIC

Freshwater flow changes can impact biological resources by altering the overall abundance of those resources. Such biological responses to flow are much more difficult to document because generally, the cause and effect relationship between flows and organism abundances operates through a chain of events rather that direct effects of flow on abundance. Several physical and/or biological mechanisms may be involved in the final biological response and such mechanisms are not always obvious, well understood, or easy to document.

Another problem with analysis of abundance changes stems from difficulties associated with biological sampling. Sampling variability often prevents identification of small but significant changes in abundance.

In light of the above problems, it is difficult to ascertain how general flow-related abundance changes are, but available information indicates they are common and often species and system specific.

All species do not respond to flow changes by a change of abundance in the same way. This fact has been documented in the Nuence-Mission-Aransas estuary where white shrimp production is positively related to winter inflows, while brown and pink shrimp production is negatively correlated to winter flows. Likewise, bay oyster production benefited from winter flows while blue crabs did not. Production of the three sciaenid fishes, sea trout, red drum and black drum, is negatively correlated with winter flow, but positively correlated with summer flow. This set of correlations amoung these organisms was unique to this estuary; different estuaries with the same species exhibited different responses.

Abundance changes also are system specific. For example, the south San Francisco Bay phytoplankton response (increase in production during periods of neap tide and high freshwater inflow) is specific to San Francisco Bay or at least other systems with similar, seldom stratified bay reaches. Another system specific example is the influx of phytoplankton into the Hudson Bay estuary from adjacent productive coastal waters. Similar mechanisms operate in the Gulf of St. Lawrence. Such increases in estuarine phytoplankton could not occur in estuaries adjacent to relatively non-productive oceans. In contrast, in Texas esturies over 80% of the nutrients used in biological production reach the system directly by freshwater inflow, not ocean water upwelling.

5. SOME CHANGES ARE CONTINUOUS FUNCTIONS OF FLOW REDUCTION, BUT OTHERS INVOLVE THRESHOLD EFFECTS - THRESHOLD EFFECTS ARE MORE THREATENING IN THAT SMALL CHANGES CAUSE LARGE BIOLOGICAL EFFECTS, WHICH ARE OFTEN DISASTROUS AND CAN OCCUR WITH LITTLE WARNING

The abundance responses of striped bass, salmon, American shad and longfin smelt in the San Francisco Bay-Delta system appear to be continuous functions of flow. Survival of these species increase or decrease incrementally with flow variation. However, response in other systems involve threshold effects. Fish production of some important commercial species in the Don River system is dependent upon flooding of shallow flood plains. As long as outflows are high enough to flood these areas, production is high and incremental decreases do not appreciably decrease production. However, when flows decrease below some point where flooding does not occur (a threshold level) disasterous reductions in fish production result. A similar process is operative in the Texas systems where much production is dependent upon marsh flooding and detritus input. It is possible that the flooding of the Yolo and Sutter Bypasses in the Bay-Delta watershed represents a threshold process. As yet, the effects of such flooding on the Bay system has not been documented.

The most significant aspect of threshold effects is that small changes in flow can have major biological effects and therefore disasters can occur with little warning.

6. THE WIDESPREAD NATURE OF REPORTED EFFECTS AND THE EFFECTS OBSERVED IN THE SAN FRANCISCO BAY SYSTEM WARRENT CONCERN

The effect of the freshwater flow on biological resources has been documented in estuaries around the world including Raritan Bay, Chesapeake Bay, St. Margaret Bay, southern Florida estuaries, the Gulf of Mexico systems, the Columbia River estuary, Strait of Georgia (Vancouver, B.C.), the northwestern part of the Black Sea, the Azov Sea, the Caspian Sea, the Nile River estuary and the Murray River in Australia. In addition, flow related effects on abundance and distribution have been observed in the San Francisco Bay-Delta system. This evidence demonstrates that freshwater flows are an important component of estuarine dynamics and that significant concern is warranted when substantial flow alterations are contemplated.

7. THERE IS NO SOUND BASIS FOR MAKING GENERAL CONCLUSIONS ON ABUNDANCE/FLOW IMPACTS.

Notwithstanding the widespread nature of the reported effects of flow variation on biological resources, it is prudent not to generalize regarding abundance/flow impacts. Some researchers (e.g. Rozengurt 1983) have suggested that:

> The universality of deterioration of estuaries in response to massive reductions in freshwater inflow leads to state that... 2) decreased fresh-water runoff, reductions exceeding 30% of the original flow, leads to increased effects of ocean processes (winds, tides, currents) on the estuary through demonstrating increases in salt intrusion and salinification of the underground basins, flood plain....,

Rozengurt mentions other flow-related problems such as eutrophication and pollutants and concludes that "all of these factors result in marked reduction in biological productivity and massive decreases in landings of fish and shellfish" (Rozengurt 1983, p 157).

Due to the wide variation in biological response, both on a species and system-specific basis reported in the literature and in San

Francisco Bay, it appears that generalizations such as these should not be made. There may be some level of reduction that causes serious impacts in each system but certainly that level varies among systems and among species.

8. IN LIGHT OF THE ABOVE CONCLUSIONS, MANAGEMENT AGENCIES MUST AWAIT STUDY RESULTS FROM SAN FRANCISCO BAY BEFORE WATERSHED MANAGEMENT RECOMMENDATIONS CAN BE DEVELOPED

From evidence reviewed in this report, variation in species and system responses to flow alteration seems to be the rule. Therefore, it is necessary to develop flow/resource information <u>specific</u> to San Francisco Bay. Proposed watershed projects will further reduce freshwater inflow levels that reach the Bay. Before recommendations can be developed regarding the impacts of such projects on the Bay, more study of flow/resource relationships specific to this system is necessary.

LITERATURE CITED

Alderdice, D. F. and C. R. Forrester. 1968. Some effects of salinity and temperature on early development and survival of the English sole (Parophrys vetulus). J. Fish. Res. Bd. Canada 25(3):495-521.

Alderdice, D. F. and F. P. J. Velsen. 1971. Some effects of salinity and temperature on early development of Pacific herring (Clupea pallasi). J. Fish. Res. Bd. Canada 28:1545-1562.

Armstrong, N. E. 1982. Responses of Texas estuaries to freshwater inflows. pp. 103-120. In: V. S. Kennedy, ed. Estuarine Comparisons. Academic Press, New York, New York.

Austin, H. M. 1981. Drought and marine fisheries. Sport Fishing Institute Bulletin 326:8.

Azniirkh. 1972. Processing of the AZNIRKH (Fishery Research Institute of the Sea of Azov). V. 10, pp. 54-55. (Trans)

Barraclough, W. E. and A. C. Phillips. 1978. Distribution of Juvenile Salmon in the Southern Strait of Georgia During the Period April to July, 1966-1969. Canadian Fisheries and Marine Service Technical Report No. 826. Nanaimo, British Columbia.

Belyea, R. M. 1952. Death and deterioration of Balsam Fir weakened by Spruce Budworm defoliation in Ontario. J. For., 50:729-738.

Boehlert, George W. 1982. Effects of physical factors on the temporal recruitment patterns of larval English sole, Parophrys vetulus, to estuarine nursery areas. EOS Transactions, Am. Geophysical Union 63(45):942.

Boyko, E. G. and E. V. Makarov. 1971. Fish production in the Sea of Azove under conditions of changing water regime. Geoyrafichskie Problemy Izuchew I Osuoeniya Pripodnykh Persursov Nizhneso Dona I Severiogo Kauaza. pp. 188-190 (Trans)

Boynton, W. R., W. M. Kemp, and C. W. Keefe. 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production. pp. 69-90. In: V. S. Kennedy, ed. Estuarine Comparisons. Academic Press, New York, New York.

Breithaupt, R. L. and R. J. Dugas. 1979. A study of the southern oyster drill (Thais haemastoma) distribution and density on the oyster seed grounds. Technical Bulletin No. 30. Louisiana Wildlife and Fisheries Commission.

Brittan, M. R., J. D. Hopkirk, J. D. Connors, and M. Martin. 1970. Explosive spread of the Oriental goby, Acanthogobius flavimanus, in the San Francisco Bay-Delta region of California. Proc. Calif. Acad. Sci. 38(11):207-214.

Bronfman, A. M. and G. d. Makaroua. 1973. The chemical base of the productivity in the sea of Azov under the condition of expected transformation of its water balance. Izvesnya Severo - Kaukazskogo Nauchnogo Tsentza Uysshej Shkoly. N. 1, pp. 31-34 (Trans)

Brongersma-Sanders, M. 1957. Mass mortality in the sea. pp. 941-947. In: J. W. Hedgpeth, ed. Treatise on Marine Ecology and Paleoecology, Volume I, Ecology. The Geological Society of America Memoir 67, Washington, D.C.

Burrell, V. G., Jr. 1977. Mortalities of oysters and hard clams associated with heavy runoff in the Santee River system, South Carolina in the spring of 1975. Proc. Natl. Shellfish. Assoc. 67:35-43.

California Water Policy Center. 1979. The value of fish and wildlife of San Francisco Bay, a preliminary survey. U. S. Fish and Wildlife Service Special Report, Sacramento, CA. 21 p.

Carlton, J. T. 1979. Introduced invertebrates of San Francisco Bay. pp. 427-444. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division/AAAS, Calif. Acad. Sci., San Francisco.

Chadwick, H. K. 1964. Annual abundance of young striped bass, Roccus saxatilis, in the Sacramento-San Joaquin Delta, California. Calif. Fish Game 50(2): 69-99.

Chadwick, H. K., D. E. Stevens, and L. W. Miller. 1977. Some factors regulating the striped bass population in the Sacramento-San Joaquin Estuary, California. pp. 18-35. In: W. Van Winkle, ed. Proc. of the Conference on Assessing the Effects of Power-Plant-Induced Mortality in Fish Populations. Pergamon Press.

Cheng, R. T. and V. Casulii. 1982. On Lagrangian residual currents with applications in south San Francisco Bay, California. Water Resources Research 18:1652-1662.

Cheng, R. T. and T. J. Conomos. 1980. Studies of San Francisco Bay by the U. S. Geological Survey. Proceedings of the Institute of Environmental Sciences. 1980:299-303.

Cheng, R. T. and R. A. Walters. 1982. Modeling of estuarine hydrodynamics and field data requirements. pp. 89-108. In: R. H. Gallagher, D. H. Norrie, J. T. Oden, and O. C. Zienkiewicz, eds. Finite Elements in Fluids. Volume 4.

Cloern, J. E. 1982. Does the benthos control phytoplankton biomass in south San Francisco Bay? Marine Ecology Progress Series 9:191-202.

Copeland, B. J. and T. J. Bechtel. 1974. Some environmental limits of six Gulf coast estuarine organisms. Contrib. Mar. Sci. 18:169-204.

Correll, D. L. 1981. Eutrophication trends in the water quality of the Rhode River (1971-1978). pp. 425-435. In: B. J. Neilson and L. E. Cronin, eds. Estuaries and Nutrients. Humana Press, Clifton, New Jersey.

Conomos, T. J. 1979. Properties and circulation of San Francisco Bay waters. pp. 47-84. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Conomos, T. J., R. E. Smith, D. H. Peterson, S. W. Hager, and L. E. Schemel. 1979. Processes affecting seasonal distributions of water properties in the San Francisco Bay estuarine system. pp. 115-142. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Davis, C. O. 1982. The San Francisco Bay ecosystem: A retrospective overview. pp. 17-37. In: W. J. Kockelman, T. J. Conomos, and A. E. Leviton, eds. San Francisco Bay: Use and Protection. Pacific Division, AAAS, San Francisco, Calif.

Department of Water Resources. 1982. Draft Environmental Impact Report: Proposed Additional Pumping Units, Harvey O. Banks Delta Pumping Plant. California Resources Agency, Sacramento, Calif.

Department of Water Resources and Department of Fish and Game. 1982. Draft Environmental Impact Report on the Proposed Agreement to Manage the Fish and Wildlife Resources of the Sacramento-San Joaquin Estuary. California State Resources Agency, Sacramento, Calif.

Dubnina, V. G. 1973. Hydrology of the flood plain fish spawning grounds in the lower reaches of the Don River and some prospects of their utilization for fishery in Tzvestia Severo-Kavkazaskogo nauchnogo tzentra vyschey schkoly N. 1. pp. 84-88 (Trans)

Dungeness Crab Research Program. 1981. A summary of the Dungeness Crab Research Program 1974-1980. Calif. Dept. Fish and Game, Marine Res. Br. Admin. Rept. No. 81-3.

Eldridge, M. B. 1977. Factors influencing distribution of fish and eggs and larvae over eight 24-hour samplings in Richardson Bay, California. Calif. Fish Game 63(2):101-106.

Fisher, H. B. and W. B. Kirkland, Jr. 1978. Flushing of South San Francisco Bay: Results of Dye Concentration Measurements in the Bay-Delta Physical Model. Waterfront Design Associates, Alameda, California.

Fraser, T. H. and W. H. Wilcox. 1981. Enrichment of a subtropical estuary with nitrogen, phosphorus, and silica. pp. 481-498. In: B. J. Neilson and L. E. Cronin, eds. Estuaries and Nutrients. Humana Press, Clifton, New Jersey.

Ganssle, David. 1966. Fishes and decapods of San Pablo and Suisun bays. pp. 64-94. In: D. W. Kelley, ed. Ecological studies of the Sacramento-San Joaquin Estuary, Part 1. Calif. Dept. Fish and Game Fish. Bull. No. 133.

Goldman, C. R. 1970. Reduced flows and the future ecology of the San Francisco Bay-Delta system. pp. 174-190. In: W. G. Weist Jr. and P. E. Greeson, eds. Hydrobiology: "Bioresources of Shallow Water Environments." Proceedings of the Symposium on Hydrobiology, Miami Beach, Florida. The American Water Resources Association, Urbana, Illinois.

Gunter, G. 1938. Seasonal variations in abundance of certain estuarine and marine fishes in Louisiana, with particular reference to life histories. Ecol. Monogr. 8:313-346.

———— 1945. Studies on marine fishes of Texas. Publ. Inst. Mar. Sci. Univ. Tex. 1:1-190.

———— 1961. Some relationships of estuarine organisms to salinity. Limnology and Oceanography 6(2):182-190.

Hart, J. L. 1973. Pacific fishes of Canada. Fish. Res. Bd. Canada. Bull. No. 180.

Hedgpeth, J. W. 1982. A classification of San Francisco Bay. pp. 36-38. In: W. Davoren, J. W. Hedgpeth, L. Q. Barzin, and D. R. Storm, eds. The Bay Prospectus 1982: The Delta Construct 1982. The Bay Institute of San Francisco, Tiburon, California.

Herrgesell, P. L., D. W. Kohlhorst, L. W. Miller, and D. E. Stevens. 1981. Effects of freshwater flow on fishery resources in the Sacramento-San Joaquin Estuary. pp. 71-87. In: R. D. Cross and P. L. Williams, eds. Proceedings of the National Symposium on Freshwater Inflow to Estuaries. U. S. Fish and Wildlife Service, Washington, D.C.

Kelley, D. W. and W. E. Tippets. 1977. Delta Outflow and San Francisco Bay. A Report Prepared for the Delta Environmental Advisory Committee of the California Department of Water Resources. 32 p.

Keup, L. and J. Bayless. 1964. Fish distribution at varying salinities in Neuse River Basin, North Carolina. Chesapeake Science 5(3):119-123.

Kilby, J. D. 1955. The fishes of two Gulf coastal marsh areas of Florida. Tulane Stud. Zool. 2(8):175-247.

Kinne, O. 1966. Physiological aspects of animal life in estuaries with special reference to salinity. Neth. J. Sea Res. 3:222-244.

Kjelson, M. A., P. F. Raquel, and F. W. Fisher. 1980. Influences of freshwater inflow on chinook salmon (Oncorhynchus tshawytscha) in the Sacramento-San Joaquin Estuary. pp. 88-108. In: R. D. Cross and D. L. Williams, eds. Proceedings of the National Symposium on Freshwater Inflow to Estuaries. U. S. Fish and Wildlife Service, Washington, D.C.

Kjelson, M. A., P. F. Raquel, and F. W. Fisher. 1982. Life history of fall-run juvenile chinook salmon, Oncorhynchus tshawytscha, in the Sacramento-San Joaquin Estuary, California. pp. 393-411. In: V. S. Kennedy, ed. Estuarine Comparisons. Academic Press, New York, New York.

Kjerfue, B. and J. E. Greer. 1978. Hydrography of the Santee River during moderate discharge conditions. Estuaries 1(2):111-119.

Kohlhorst, D. W. 1980. Recent trends in the white sturgeon population in California's Sacramento-San Joaquin Estuary. Calif. Fish Game 66(4): 210-219.

Krone, R. B. 1966. Predicted suspended sediment inflows to the San Francisco Bay system. Report to Central Pacific River Basins Comprehensive Water Pollution Control Proj., Federal Water Pollution Control Proj., Federal Water Pollution Control Admin. (Southwest Region). 33 p.

——————— 1979. Sedimentation in the San Francisco Bay system. pp. 85-96. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Kutkuhn, J. H. 1966. The role of estuaries in the development and perpetuation of commercial shrimp resources. In: R. F. Smith, A. H. Swartz, and W. H. Massmann, eds. A Symposium on Estuarine Fisheries. Amer. Fish. Soc. Special Pub. No. 3. Presented at 94th Annual Meeting. Atlantic City, New Jersey, 1964.

Luoma, S. N. and D. J. Cain. 1979. Fluctuations of copper, zinc, and silver in tellenid clams as related to freshwater discharge - south San Francisco Bay. pp. 231-246. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division AAAS, San Francisco, Calif.

Malone, T. C., P. J. Neale, and D. Boardman. 1980. Influences of estuarine circulation on the distribution and biomass of phytoplankton size fractions. pp. 249-262. In: V. S. Kennedy, ed. Estuarine Perspectives. Academic Press. New York, New York.

Martin, M., G. Ichikawa, J. Goetzl, M. Reyes, and M. D. Stephenson. 1982. Relationships Between Physiological Stress and Trace Toxic Substances in the Bay Mussel, Mytilus edulis, From San Francisco Bay, California. Calif. Dept. Fish and Game, Marine Pollution Studies Laboratory Manuscript, Monterey, Calif.

McComb, A. J., R. P. Atkins, P. B. Birch, D. M. Gordon, and R. J. Lukatelich. 1981. Eutrophication in the Peel-Harvey estuarine system, western Australia. pp. 323-342. In: B. J. Neilson and L. E. Cronin, eds. Estuaries and Nutrients. Humana Press, Clifton, New Jersey.

Meleshkin, M. T., M. and M. Sh. Rosengurt. 1973. About ecological balance of the River - Estuary - Sea System and raising its economic efficiency. Vodnye Resursy N. 4, pp. 68-83 (Odessa) (Trans)

Meleshkin, M. T., M. Sh. Rosengurt, and D. M. Tulmazin. 1973. The problems of more efficient utilization of the resources of the Azov Sea. Problemy Economiki Morya I Mirovoco Okeana. Akademy Nauk Yccp (Odessa). N. 2, pp. 3-14 (Trans)

Messersmith, J. 1966. Fishes collected in Carquinez Strait in 1961-1962. pp. 57-63. In: D. W. Kelley, ed. Ecological studies of the Sacramento-San Joaquin Estuary, Part 1. Calif. Dept. Fish and Game Fish. Bull. No. 133.

Miller, D. J. and J. Schmidtke. 1956. Report on the distribution and abundance of Pacific herring (Clupea pallasi) along the coast of central and southern California. Calif. Fish Game 42(3):163-187.

Miller, W. J. 1982. Delta Outflow, San Francisco Bay, The Peripheral Canal and Proposition 9. Association of State Water Project Agencies, Sacramento, Calif.

Misitano, D. A. 1976. Size and stage of development of larval English sole, Parophrys vetulus, at time of entry into Humboldt Bay. Calif. Fish Game 62(1):93-98.

Monbet, Y., F. Manaud, P. Gentien, M. Pommepuy, G. P. Allen, J. C. Salomon, and J. L'Yavanc. 1981. The use of nutrients, salinity, and water circulation data as a tool for coastal zone planning. pp. 343-372. In: B. J. Neilson and L. E. Cronin, eds. Estuaries and Nutrients. Humana Press, Clifton, New Jersey.

Moyle, P. B. 1976. Inland Fishes of California. Univ. of Calif. Press, Berkeley. 405 p.

Olson, R. E. and I. Pratt. 1973. Parasites as indicators of English sole (Parophrys vetulus) nursery grounds. Trans. Am. Fish. Soc. 102(2): 405-411.

Orcutt, H. G. (compiler). 1978. Dungeness crab research program report for the year 1978. Calif. Dept. Fish and Game Mar. Res. Admin. Rept. No. 78-16.

Orsi, J. J. and A. C. Knutson, Jr. 1979. The role of mysid shrimp in the Sacramento-San Joaquin Estuary and factors affecting their abundance and distribution. pp. 401-408. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Painter, R. E. 1966a. Zooplankton of San Pablo and Suisun Bays. In: D. W. Kelley, ed. Ecological studies of the Sacramento-San Joaquin Estuary, Part I. Calif. Dept. Fish and Game Fish. Bull. No. 133. pp. 18-39.

——————— 1966b. Zoobenthos of San Pablo and Suisun Bays. pp. 40-56. In: D. W. Kelley, ed. Ecological studies of the Sacramento-San Joaquin Estuary, Part I. Calif. Dept. Fish and Game Fish Bull. No. 133.

Parker, R. R. and P. A. Larkin. 1959. A concept of growth in fishes. J. Fish. Res. Bd. Can. 23:1209-1248.

Pearcy, W. G. and S. S. Myers. 1974. Larval fishes of Yaguina Bay, Oregon: A nursery ground for marine fishes? NOAA Fish. Bull. 72(1):201-213.

Peterson, D. H., T. J. Conomos, W. W. Broakow, and P. C. Doherty. 1975. Location of the nontidal current null zone in Northern San Francisco Bay. Estuarine and Coastal Marine Science 3:1-11.

Radtke, L. D. 1966. Distribution of smelt, juvenile sturgeon, and starry flounder in the Sacramento-San Joaquin Delta with observations on food of sturgeon. pp. 115-129. In: J. L. Turner and D. W. Kelley, eds. Ecological studies of the Sacramento-San Joaquin Delta, Part II. Calif. Dept. Fish and Game Fish. Bull. No. 136.

Rosenberg, A. A. 1982. Growth of juvenile English sole, Parophrys vetulus, in estuarine nursery grounds. NOAA Fish. Bull. 80(2):245-252.

Rumboltz, M. C. 1979. Impact of Delta outflow upon salinity and waterfowl in the Suisun Marsh. U. S. Dept. of Interior, Bur. of Recl., Sacramento, Calif.

Russell, P. P., T. A. Bursztynsky, L. A. Jackson, and E. Y. Leong. 1982. Water and waste inputs to San Francisco estuary - An historical perspective. pp. 127-136. In: W. J. Kockelman, T. J. Conomos, and A. E. Leviton, eds. San Francisco Bay: Use and Protection. Pacific Division, AAAS, San Francisco, Calif.

Rozengurt, M. 1983. The Environmental Effect of Extensive Water Withdrawals on the River-Estuary - Sea Ecosystem Ecology. A report prepared for the Calif. Dept. of Water Res.

Shaw, R. F. 1981. Seasonal species composition, diversity, spatial distributions, and tidal retention and transport of ichthyoplankton in the Sheepscot River-Back River-Montsweag Bay estuarine system, Maine. Doctoral Dissertation, Univ. of Maine at Orono, Orono, Maine.

Skinner, J. E. 1962. An historical review of the fish and wildlife resources of the San Francisco Bay area. Calif. Dept. Fish and Game, Water Proj. Br. Rept. No. 1.

Smith, R. E., R. E. Herndon, and D. D. Harmon, eds. 1979. Physical and chemical properties of San Francisco Bay waters, 1969-1976. U. S. Geological Survey, Open File Report 79-511, San Francisco, Calif.

Smith, S. E. and S. Kato. 1979. The Fisheries of San Francisco Bay: Past, Present, and Future. pp. 445-468. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Spratt, Jerome D. 1981. Status of the Pacific herring, Clupea harengus pallasii, resource in California 1972 to 1980. Calif. Dept. Fish and Game Fish. Bull. No. 171.

State Water Resources Control Board. 1978. Final Environmental Impact Report for the Water Quality Control Plan and Water Right Decision: Sacramento, San Joaquin Delta, and Suisun Marsh. Calif. State Water Resources Control Board, Sacramento, Calif.

Stevens, D. E. 1977. Striped bass (Morone saxatilis) year class strength in relation to river flow in the Sacramento-San Joaquin Estuary, California. Trans. Amer. Fish. Soc. 106:34-42.

——————— 1979. Environmental factors affecting striped bass (Morone saxatilis) in the Sacramento-San Joaquin Estuary. pp. 469-478. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

——————— and L. W. Miller. 1980. Effects of flow on abundance of young chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento-San Joaquin River system. MS. Calif. Dept. Fish and Game, Bay-Delta Fishery Project.

Striped Bass Working Group. 1982. The striped bass decline in the San Francisco Bay-Delta Estuary. Calif. State Water Resources Control Board. 58 p.

Sutcliffe, W. H., Jr. 1972. Some relations of land drainage, nutrients, particulate material, and fish catch in two eastern Canadian bays. J. Fish. Res. Bd. Can. 29:357-362.

——————— 1973. Correlations between seasonal river discharge and local landings of American lobster (Homarus americanus) and Atlantic halibut (Hippoglossus hippoglossus) in the Gulf of St. Lawrence. J. Fish. Res. Bd. Can 30:856-859.

———————, K. Drinkwater, and B. S. Muir. 1977. Correlations of fish catch and environmental factors in the Gulf of Maine. J. Fish. Res. Bd. Can 34:19-30.

Sutcliffe, W. H., Jr., R. H. Loucks, and K. F. Drinkwater. 1976. Coastal circulation and physical oceanography of the Scotian Shelf and the Gulf of Maine. J. Fish. Res. Bd. Canada 33:98-115.

Tasto, R. N. 1979. San Francisco Bay: critical to the Dungeness crab? pp. 479-490. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

——————— 1983. Juvenile Dungeness crab, Cancer magister, studies in San Francisco Bay Area. In: P. W. Wild and R. N. Tasto, eds. Life history, environment, and mariculture studies of the Dungeness crab, Cancer magister, with emphasis on the central California fishery resource. Calif. Fish and Game Fish. Bull. 173 (in press).

Texas Department of Water Resources. 1979. The influence of freshwater inflows upon the major bays and estuaries of the Texas Gulf Coast - Executive Summary. LP-115, Austin, Texas.

——————— 1980. Lauaca-Tres Paliacios Estuary. A study of the influence of freshwater inflows. LP-106, Austin, Texas.

——————— 1980. Guadalupe Estuary: A study of freshwater inflows. LP-107, Austin, Texas.

Texas Department of Water Resources. 1981. Nueces and Mission Arkansas Estuaries. A study of freshwater inflows. LP-108, Austin, Texas.

———————— 1981. Trinity-San Jacinto Estuaries. A study of freshwater inflows. LP-113, Austin, Texas.

———————— 1981. Sabin Niches Estuary. A study of freshwater inflow. LP-116, Austin, Texas.

Turner, J. L. and H. K. Chadwick. 1972. Distribution and abundance of young-of-the-year striped bass (Morone saxatilis) in relation to river flow in the Sacramento-San Joaquin Estuary. Trans. Am. Fish. Soc. 101(3):442-452.

Viosca, P., Jr. 1938. Effect of the Bonnet Carre Spillway on Fisheries. La. Conserv. Rev. 6(4):51-53.

Warren, C. E. 1971. Biology and Water Pollution Control. W. B. Saunders Co. Philadelphia. 434 p.

Watt, K. E. F. 1973. Principles of Environmental Science. McGraw-Hill, New York. 319 p.

Wenner, E. L., M. H. Shealy, Jr., and P. A. Sandifer. 1982. A profile of the fish and decapod crustacean community in a South Carolina estuarine system prior to flow alteration. NOAA Tech. Rept. NMFS SSRF-757, Charleston, South Carolina.

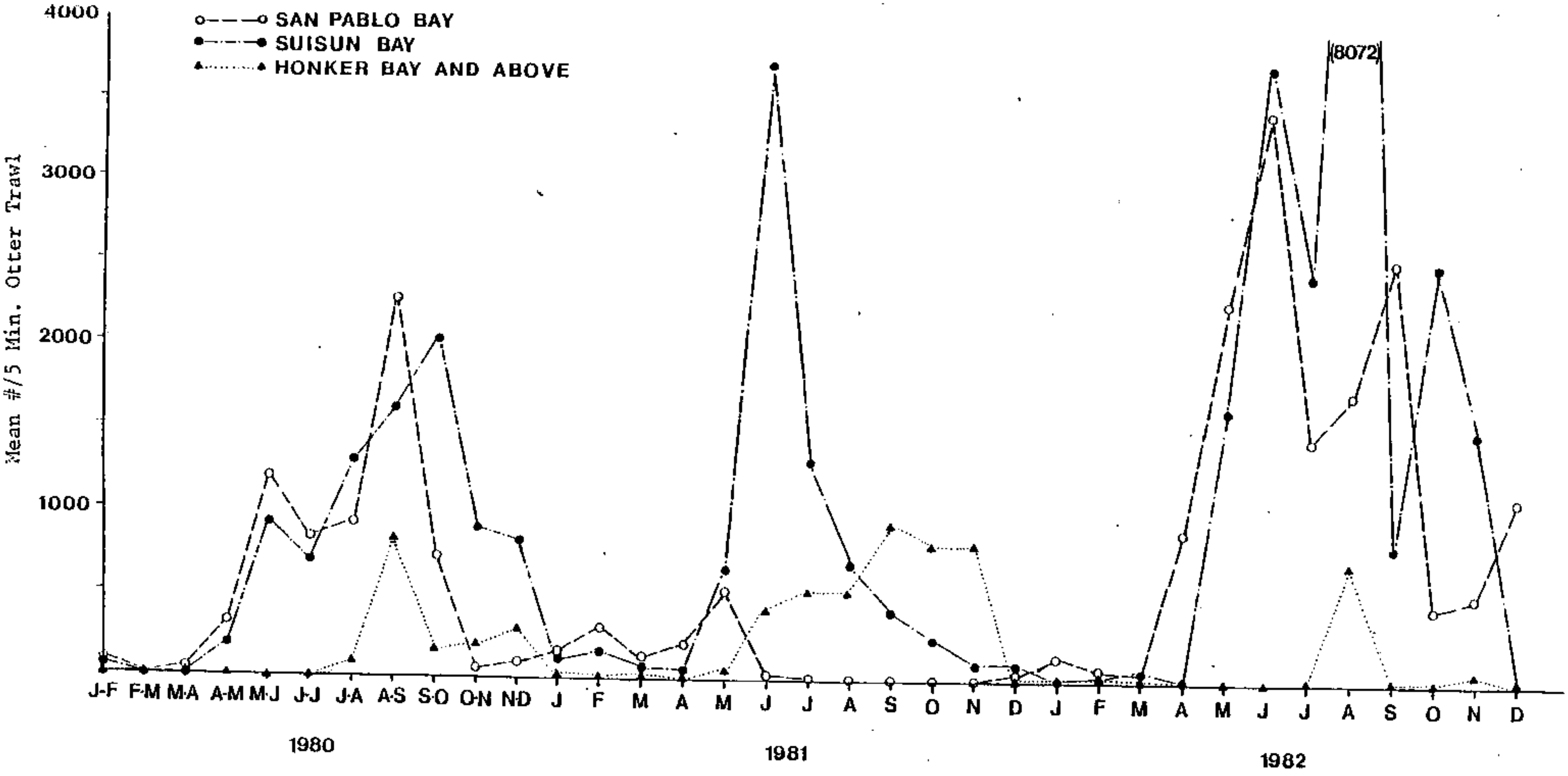
Wojcik, F. J. 1982. Catch data for white catfish indicate responses to change in salinity. Coastal Oceanography and Climatology News: Recent Events in United States Coastal Waters 4:28-29.

Zemlyansky, F. T. and U. N. Andreev. 1975. Utilization of biological resources in the Northwestern Port of the Black Sea. Problemy Economica Mozya, 1975. pp. 57-65 (Trans)

TABLE 5-9. Comparisons of Catch/5 Minute Otter Trawl. Catch Between Years Are Directly Comparable, While Catch Between Sections of San Francisco Bay Are Not Because of Differences in Bottom Area.

	South Bay	Central Bay	San Pablo Bay	Suisun Bay	Honker Bay and Above	Mean Catch/ Survey	%
C. franciscorum							
1980 Mean catch/trawl	77.9	31.5	588.2	780.3	163.1	11788.1	29.0%
Percent	(4.7%)	(1.9%)	(35.8%)	(47.6%)	(10.0%)		
1981 Mean catch/trawl	125.8	12.2	122.5	569.5	12.1	6346.1	15.6%
Percent	(15.0%)	(1.4%)	(14.5%)	(67.7%)	(1.4%)		
1982 Mean catch/trawl	43.1	20.4	1216.9	1723.3	57.6	22582.1	55.4%
Percent	(1.4%)	(0.7%)	(39.8%)	(56.2%)	(1.9%)		
C. nigricauda							
1980 Mean catch/trawl	60.0	45.9	129.1	0.3	<0.1	1910.2	53.2%
Percent	(25.5%)	(19.5%)	(55.0%)	(<0.1%)	(<0.1%)		
1981 Mean catch/trawl	49.5	5.9	58.3	0.2	-	1029.2	28.7%
Percent	(27.7%)	(6.7%)	(65.6%)	(<0.1%)			
1982 Mean catch/trawl	28.3	32.0	21.8	0.1	-	649.8	18.1%
Percent	(34.5%)	(39.0%)	(26.5%)	(<0.1%)			
P. macrodactylus							
1980 Mean catch/trawl	1.0	0.2	4.4	60.5	10.1	514.3	40.2%
Percent	(1.4%)	(<0.1%)	(5.8%)	(79.5%)	(13.3%)		
1981 Mean catch/trawl	0.5	-	0.3	47.5	37.6	491.3	38.4%
Percent	(0.6%)		(0.3%)	(55.3%)	(43.8%)		
1982 Mean catch/trawl	0.6	-	5.9	31.4	0.4	274.6	21.4%
Percent	(1.6%)		(15.4%)	(82.0%)	(1.0%)		

FIGURE 5-4. Mean Catch of *Crangon franciscorum* Per 5 Minute Otter Trawl for Three Different Areas of San Francisco Bay During 1980-1982.



Abundance

Fifty-five percent of the mean catch for the year 1980 was from San Pablo Bay. This is primarily a result of a large influx of small shrimp of this species in May (see Figure 5-5). Correlation with any hydrodynamic event is not obvious at this stage of analysis. A similar peak in catch appears in April and May of 1981 and 1982, but the numbers are not nearly as high.

Distribution

In 1982, C. nigricauda remained in Central Bay and did not enter San Pablo Bay in any numbers until June when the bottom salinities had risen to 8-15^{o}/oo from a low of 0-2^{o}/oo in April and 5-11^{o}/oo in May. In contrast, higher salinities throughout the spring of 1981 appear to be responsible for the movement of C. nigricauda directly into San Pablo Bay.

How these changes in distribution relate to total catch is still unclear. Total catch appears to have dropped over the 3 years of the study, but we have yet to confirm this statistically. Timing of life history events such as spawning, hatching, and juvenile migration are not as synchronized as with the other two species. Consequently correlations with environmental variables will be harder to make. Analysis of length frequency, egg stage, and larval catch data is planned and may help clarify relationships between Delta outflow and C. nigricauda abundance.

Palaemon macrodactylus

The major population of P. macrodactylus is centered in Suisun Bay, while there is a smaller population in the sloughs of South Bay which we only occasionally sample at our southern-most station. We catch this species in much greater abundance at the deeper stations than at those 10 feet or less. The summer peaks in abundance (Figure 5-6) comprise adults, not juveniles, and appear to be the result of a reproductive migration into the areas we are sampling. This is further supported by preliminary analysis of data on gravid females. In May through October, 67% of the females were gravid in 1980 and 1982, and 64% were gravid in 1981. In 1 month of each year over 90% of the females caught were gravid.

Distributional abundance changed between years and generally followed changes in salinity. In 1981, 55.3% of the catch was from Suisun and 43.8% was from Honker Bay and upstream. In this year the bottom salinity in the channel near Chipps Island (Stations 534 and 535, Figure 5-2) was 5^{o}/oo and above during most of the surveys, June through October; and at the Sacramento River sampling site (Station 736), it was as high as 2.8^{o}/oo in July and 3.5^{o}/oo in October. In contrast, in 1982 salinity was close to 0 in and above Honker Bay in all months except August, when it reached 1.6^{o}/oo in Honker Bay. In this year 83.4% of the catch of Palaemon was in Suisun Bay and only 1% was in the upper reaches. While we only have surface salinities for 1980, they are in between the 2 years cited above, as is the distributional abundance (see Table 5-9).

The adults of this species overlap with juveniles of C. franciscorum, at least in salinity preference. If they have similar diets, competition for food may

FIGURE 5-5. Mean Catch of Crangon nigricauda Per 5 Minute Otter Trawl for Three Different Areas of San Francisco Bay During 1980-1982.

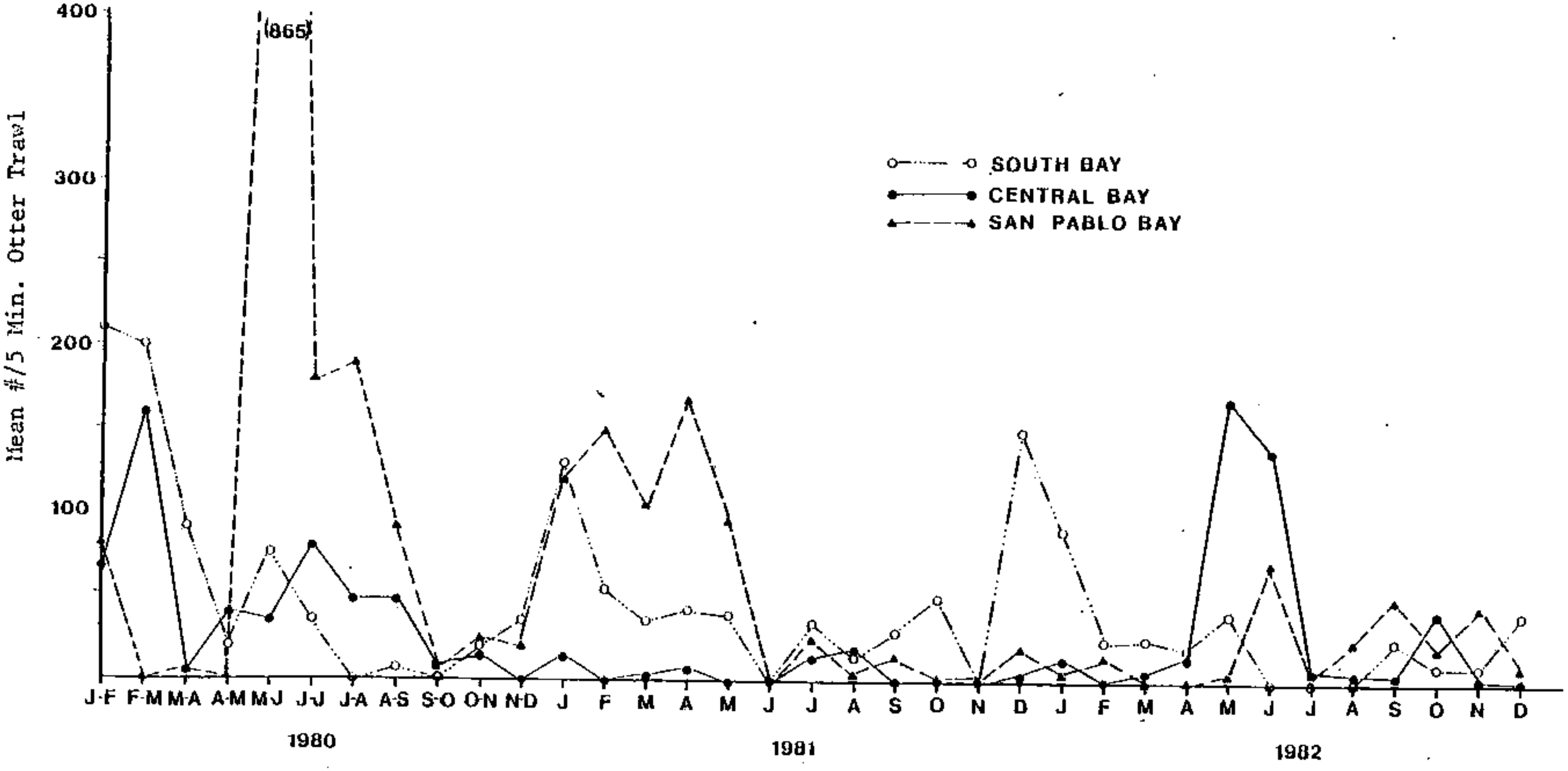
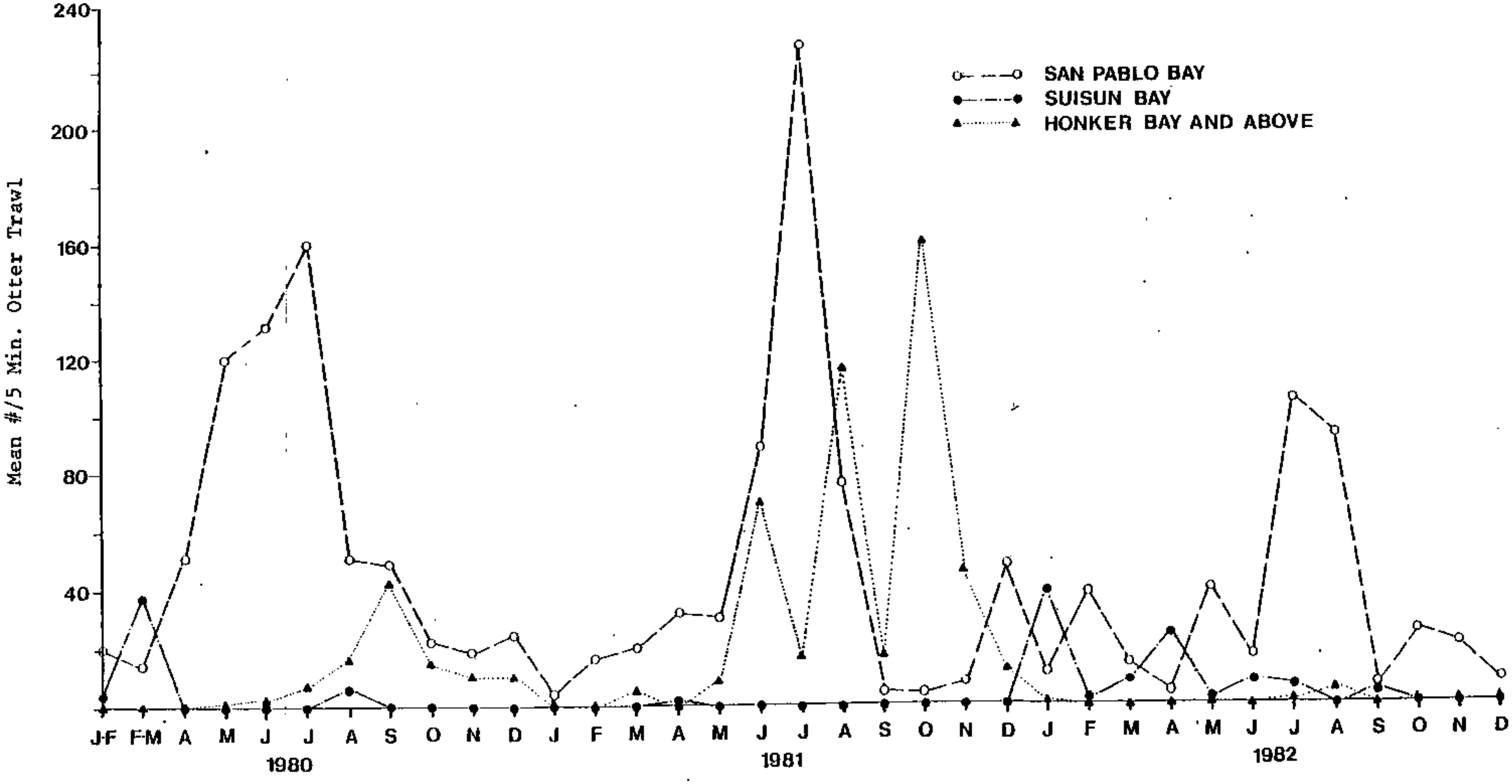


FIGURE 5-6. Mean Catch of Palaemon macrodactylus Per 5 Minute Otter Trawl for Three Different Areas of San Francisco Bay During 1980-1982.



be important in regulating the population. The tow catch in 1982 may reflect low population levels for that year as a result of the large numbers of juvenile C. franciscorum in Suisun Bay.

Summary

1. C. franciscorum catches were highest in 1982 when salinities were lowest and Delta outflows highest.
2. C. franciscorum catches were 3.5 times lower in 1981 when salinities were above 20 ‰ in much of the Bay and Western Delta and Delta outflows were lowest.
3. C. franciscorum catches were intermediate in 1980 when salinities and Delta outflow were intermediate.
4. P. macrodactylus catches are mainly adults, while C. nigricauda and C. franciscorum catches are predominantly juveniles.
5. Preliminary analysis indicates that the distribution and migrations of all three species can be correlated with salinity, but other variables have not been included and may modify these findings.

CHAPTER SIX

CONCLUSIONS

This report has discussed freshwater outflows and estuarine systems. Specifically, it has described the physical characteristics of outflow from the Sacramento-San Joaquin Delta, reviewed historical and present outflows, projected levels of future outflows, and described how projected changes in outflow levels will affect the physical/chemical environmental conditions of the Bay. It has described the biological resources of the Bay, the values of those resources and the present condition of some of them. Chapter 3 outlined the general responses of biological resources to stressful conditions and described more specifically how outflow changes can affect biological resources. Additionally, information from estuarine studies in Texas, Canada, and Russia and from the current San Francisco Bay System Study was presented.

Several implications can be drawn from all of the information presented in this report. These implications should be considered when flow management in estuarine systems is contemplated. The remainder of this report will briefly discuss these implications.

1. FLOW REDUCTIONS DEFINITELY CAUSE SIGNIFICANT BIOLOGICAL CHANGES

A considerable body of estuarine research has documented that freshwater flow reductions cause significant biological changes in estuaries of all types. In most cases, changes result from specific responses by organisms to physical conditions such as increased salinities, altered circulation patterns (including reduced flood plain inundation) and reduced nutrient input. Evidence documenting flow-related biological changes has been developed in several Russian estuaries, the St. Lawrence system, seven Texas estuaries, and the San Francisco Bay-Delta system, as well as several other systems. The ecological and/or economic significance of flow-related biological changes has not been completely defined in most systems. In some cases, the same flow change favors some organisms, while negatively impacting others.

2. SOME BIOLOGICAL CHANGES ARE SYSTEM SPECIFIC, WHILE OTHERS ARE COMMON TO ALL ESTUARIES

Some types of biological changes occur only in certain types of systems. For example, flow-related changes in survival of marine larval forms can only occur in systems that support significant numbers of marine forms that depend upon certain circulation patterns to carry young into estuarine nursery areas. The flow related changes in fish production in Texas estuaries are such an example. Another example of a system specific biological response is the decrease in production of walleye, bream and carp in the Don River flood plain in Russia. Such a response can only occur in a system that has broad shallow flood plain areas which support significant fish populations. Generally, system specific responses relate to physical or biological factors which are unique or occur infrequently in estuaries.

On the other hand, some biological responses are more general and occur in most estuaries. One such response is salinity dependent distributional change. Estuarine organisms in all systems have definite salinity tolerances and when those are exeeded by flow induced changes, the organisms must move to areas more favorable to their physiology.

3. DISTRIBUTIONAL CHANGES OCCUR UNIVERSALLY, ALTHOUGH THEY CAN BE SPECIES AND SYSTEM SPECIFIC

Distributional change due to flow alteration is a general response in estuaries. However, individual species and life stages respond differently. Distributional patterns of some species with pelagic eggs or larval forms, such as striped bass, American shad, longfin smelt or chinook salmon, typically are affected by flow changes, but each responds in relation to its own salinity tolerance. Other species with attached eggs, sessile life styles or those with adult forms absent from the system do not respond by changing distributions. For example, Pacific herring eggs are attached to the substrate and will not be carried to other locations by flow change. Oysters and other benthic invertebrates cannot immediately respond by changing location when environmental conditions occur and sometimes are killed by influxes of fresh or marine water.

Distributional changes can also be specific to certain systems. For example, distributional change is more pronounced in shallow estuaries with highly variable amounts of inflow such as San Francisco Bay. In these systems large salinity changes often occur suddenly. The estuarine volume is not sufficient to buffer highly variable flows. Distributional change is less pronounced in estuaries with deep channels, few shoal areas, and relatively constant outflows (e.g. Columbia River Estuary or fjord type systems). Systems that tend to be classified as mixed show more distributional responses than stratified systems.

4. ABUNDANCE CHANGES ARE NOT WELL UNDERSTOOD, THEREFORE IT IS UNCERTAIN AS TO HOW GENERAL THEY ARE - HOWEVER, THEY TEND TO BE SPECIES AND SYSTEM SPECIFIC

Freshwater flow changes can impact biological resources by altering the overall abundance of those resources. Such biological responses to flow are much more difficult to document because generally, the cause and effect relationship between flows and organism abundances operates through a chain of events rather that direct effects of flow on abundance. Several physical and/or biological mechanisms may be involved in the final biological response and such mechanisms are not always obvious, well understood, or easy to document.

Another problem with analysis of abundance changes stems from difficulties associated with biological sampling. Sampling variability often prevents identification of small but significant changes in abundance.

In light of the above problems, it is difficult to ascertain how general flow-related abundance changes are, but available information indicates they are common and often species and system specific.

All species do not respond to flow changes by a change of abundance in the same way. This fact has been documented in the Nuence-Mission-Aransas estuary where white shrimp production is positively related to winter inflows, while brown and pink shrimp production is negatively correlated to winter flows. Likewise, bay oyster production benefited from winter flows while blue crabs did not. Production of the three sciaenid fishes, sea trout, red drum and black drum, is negatively correlated with winter flow, but positively correlated with summer flow. This set of correlations amoung these organisms was unique to this estuary; different estuaries with the same species exhibited different responses.

Abundance changes also are system specific. For example, the south San Francisco Bay phytoplankton response (increase in production during periods of neap tide and high freshwater inflow) is specific to San Francisco Bay or at least other systems with similar, seldom stratified bay reaches. Another system specific example is the influx of phytoplankton into the Hudson Bay estuary from adjacent productive coastal waters. Similar mechanisms operate in the Gulf of St. Lawrence. Such increases in estuarine phytoplankton could not occur in estuaries adjacent to relatively non-productive oceans. In contrast, in Texas esturies over 80% of the nutrients used in biological production reach the system directly by freshwater inflow, not ocean water upwelling.

5. SOME CHANGES ARE CONTINUOUS FUNCTIONS OF FLOW REDUCTION, BUT OTHERS INVOLVE THRESHOLD EFFECTS - THRESHOLD EFFECTS ARE MORE THREATENING IN THAT SMALL CHANGES CAUSE LARGE BIOLOGICAL EFFECTS, WHICH ARE OFTEN DISASTROUS AND CAN OCCUR WITH LITTLE WARNING

The abundance responses of striped bass, salmon, American shad and longfin smelt in the San Francisco Bay-Delta system appear to be continuous functions of flow. Survival of these species increase or decrease incrementally with flow variation. However, response in other systems involve threshold effects. Fish production of some important commercial species in the Don River system is dependent upon flooding of shallow flood plains. As long as outflows are high enough to flood these areas, production is high and incremental decreases do not appreciably decrease production. However, when flows decrease below some point where flooding does not occur (a threshold level) disasterous reductions in fish production result. A similar process is operative in the Texas systems where much production is dependent upon marsh flooding and detritus input. It is possible that the flooding of the Yolo and Sutter Bypasses in the Bay-Delta watershed represents a threshold process. As yet, the effects of such flooding on the Bay system has not been documented.

The most significant aspect of threshold effects is that small changes in flow can have major biological effects and therefore disasters can occur with little warning.

6. THE WIDESPREAD NATURE OF REPORTED EFFECTS AND THE EFFECTS OBSERVED IN THE SAN FRANCISCO BAY SYSTEM WARRENT CONCERN

The effect of the freshwater flow on biological resources has been documented in estuaries around the world including Raritan Bay, Chesapeake Bay, St. Margaret Bay, southern Florida estuaries, the Gulf of Mexico systems, the Columbia River estuary, Strait of Georgia (Vancouver, B.C.), the northwestern part of the Black Sea, the Azov Sea, the Caspian Sea, the Nile River estuary and the Murray River in Australia. In addition, flow related effects on abundance and distribution have been observed in the San Francisco Bay-Delta system. This evidence demonstrates that freshwater flows are an important component of estuarine dynamics and that significant concern is warranted when substantial flow alterations are contemplated.

7. THERE IS NO SOUND BASIS FOR MAKING GENERAL CONCLUSIONS ON ABUNDANCE/ FLOW IMPACTS.

Notwithstanding the widespread nature of the reported effects of flow variation on biological resources, it is prudent not to generalize regarding abundance/flow impacts. Some researchers (e.g. Rozengurt 1983) have suggested that:

> The universality of deterioration of estuaries in response to massive reductions in freshwater inflow leads to state that... 2) decreased fresh-water runoff, reductions exceeding 30% of the original flow, leads to increased effects of ocean processes (winds, tides, currents) on the estuary through demonstrating increases in salt intrusion and salinification of the underground basins, flood plain....

Rozengurt mentions other flow-related problems such as eutrophication and pollutants and concludes that "all of these factors result in marked reduction in biological productivity and massive decreases in landings of fish and shellfish" (Rozengurt 1983, p 157).

Due to the wide variation in biological response, both on a species and system-specific basis reported in the literature and in San

Francisco Bay, it appears that generalizations such as these should not be made. There may be some level of reduction that causes serious impacts in each system but certainly that level varies among systems and among species.

8. IN LIGHT OF THE ABOVE CONCLUSIONS, MANAGEMENT AGENCIES MUST AWAIT STUDY RESULTS FROM SAN FRANCISCO BAY BEFORE WATERSHED MANAGEMENT RECOMMENDATIONS CAN BE DEVELOPED

From evidence reviewed in this report, variation in species and system responses to flow alteration seems to be the rule. Therefore, it is necessary to develop flow/resource information <u>specific</u> to San Francisco Bay. Proposed watershed projects will further reduce freshwater inflow levels that reach the Bay. Before recommendations can be developed regarding the impacts of such projects on the Bay, more study of flow/resource relationships specific to this system is necessary.

LITERATURE CITED

Alderdice, D. F. and C. R. Forrester. 1968. Some effects of salinity and temperature on early development and survival of the English sole (Parophrys vetulus). J. Fish. Res. Bd. Canada 25(3):495-521.

Alderdice, D. F. and F. P. J. Velsen. 1971. Some effects of salinity and temperature on early development of Pacific herring (Clupea pallasi). J. Fish. Res. Bd. Canada 28:1545-1562.

Armstrong, N. E. 1982. Responses of Texas estuaries to freshwater inflows. pp. 103-120. In: V. S. Kennedy, ed. Estuarine Comparisons. Academic Press, New York, New York.

Austin, H. M. 1981. Drought and marine fisheries. Sport Fishing Institute Bulletin 326:8.

Azniirkh. 1972. Processing of the AZNIRKH (Fishery Research Institute of the Sea of Azov). V. 10, pp. 54-55. (Trans)

Barraclough, W. E. and A. C. Phillips. 1978. Distribution of Juvenile Salmon in the Southern Strait of Georgia During the Period April to July, 1966-1969. Canadian Fisheries and Marine Service Technical Report No. 826. Nanaimo, British Columbia.

Belyea, R. M. 1952. Death and deterioration of Balsam Fir weakened by Spruce Budworm defoliation in Ontario. J. For., 50:729-738.

Boehlert, George W. 1982. Effects of physical factors on the temporal recruitment patterns of larval English sole, Parophrys vetulus, to estuarine nursery areas. EOS Transactions, Am. Geophysical Union 63(45):942.

Boyko, E. G. and E. V. Makarov. 1971. Fish production in the Sea of Azove under conditions of changing water regime. Geoyrafichskie Problemy Izuchew I Osuoeniya Pripodnykh Persursov Nizhneso Dona I Severiogo Kauaza. pp. 188-190 (Trans)

Boynton, W. R., W. M. Kemp, and C. W. Keefe. 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production. pp. 69-90. In: V. S. Kennedy, ed. Estuarine Comparisons. Academic Press, New York, New York.

Breithaupt, R. L. and R. J. Dugas. 1979. A study of the southern oyster drill (Thais haemastoma) distribution and density on the oyster seed grounds. Technical Bulletin No. 30. Louisiana Wildlife and Fisheries Commission.

Brittan, M. R., J. D. Hopkirk, J. D. Connors, and M. Martin. 1970. Explosive spread of the Oriental goby, Acanthogobius flavimanus, in the San Francisco Bay-Delta region of California. Proc. Calif. Acad. Sci. 38(11):207-214.

Bronfman, A. M. and G. d. Makaroua. 1973. The chemical base of the productivity in the sea of Azov under the condition of expected transformation of its water balance. Izvesnya Severo - Kaukazskogo Nauchnogo Tsentza Uysshej Shkoly. N. 1, pp. 31-34 (Trans)

Brongersma-Sanders, M. 1957. Mass mortality in the sea. pp. 941-947. In: J. W. Hedgpeth, ed. Treatise on Marine Ecology and Paleoecology, Volume I, Ecology. The Geological Society of America Memoir 67, Washington, D.C.

Burrell, V. G., Jr. 1977. Mortalities of oysters and hard clams associated with heavy runoff in the Santee River system, South Carolina in the spring of 1975. Proc. Natl. Shellfish. Assoc. 67:35-43.

California Water Policy Center. 1979. The value of fish and wildlife of San Francisco Bay, a preliminary survey. U. S. Fish and Wildlife Service Special Report, Sacramento, CA. 21 p.

Carlton, J. T. 1979. Introduced invertebrates of San Francisco Bay. pp. 427-444. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division/AAAS, Calif. Acad. Sci., San Francisco.

Chadwick, H. K. 1964. Annual abundance of young striped bass, Roccus saxatilis, in the Sacramento-San Joaquin Delta, California. Calif. Fish Game 50(2): 69-99.

Chadwick, H. K., D. E. Stevens, and L. W. Miller. 1977. Some factors regulating the striped bass population in the Sacramento-San Joaquin Estuary, California. pp. 18-35. In: W. Van Winkle, ed. Proc. of the Conference on Assessing the Effects of Power-Plant-Induced Mortality in Fish Populations. Pergamon Press.

Cheng, R. T. and V. Casulii. 1982. On Lagrangian residual currents with applications in south San Francisco Bay, California. Water Resources Research 18:1652-1662.

Cheng, R. T. and T. J. Conomos. 1980. Studies of San Francisco Bay by the U. S. Geological Survey. Proceedings of the Institute of Environmental Sciences. 1980:299-303.

Cheng, R. T. and R. A. Walters. 1982. Modeling of estuarine hydrodynamics and field data requirements. pp. 89-108. In: R. H. Gallagher, D. H. Norrie, J. T. Oden, and O. C. Zienkiewicz, eds. Finite Elements in Fluids. Volume 4.

Cloern, J. E. 1982. Does the benthos control phytoplankton biomass in south San Francisco Bay? Marine Ecology Progress Series 9:191-202.

Copeland, B. J. and T. J. Bechtel. 1974. Some environmental limits of six Gulf coast estuarine organisms. Contrib. Mar. Sci. 18:169-204.

Correll, D. L. 1981. Eutrophication trends in the water quality of the Rhode River (1971-1978). pp. 425-435. In: B. J. Neilson and L. E. Cronin, eds. Estuaries and Nutrients. Humana Press, Clifton, New Jersey.

Conomos, T. J. 1979. Properties and circulation of San Francisco Bay waters. pp. 47-84. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Conomos, T. J., R. E. Smith, D. H. Peterson, S. W. Hager, and L. E. Schemel. 1979. Processes affecting seasonal distributions of water properties in the San Francisco Bay estuarine system. pp. 115-142. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Davis, C. O. 1982. The San Francisco Bay ecosystem: A retrospective overview. pp. 17-37. In: W. J. Kockelman, T. J. Conomos, and A. E. Leviton, eds. San Francisco Bay: Use and Protection. Pacific Division, AAAS, San Francisco, Calif.

Department of Water Resources. 1982. Draft Environmental Impact Report: Proposed Additional Pumping Units, Harvey O. Banks Delta Pumping Plant. California Resources Agency, Sacramento, Calif.

Department of Water Resources and Department of Fish and Game. 1982. Draft Environmental Impact Report on the Proposed Agreement to Manage the Fish and Wildlife Resources of the Sacramento-San Joaquin Estuary. California State Resources Agency, Sacramento, Calif.

Dubnina, V. G. 1973. Hydrology of the flood plain fish spawning grounds in the lower reaches of the Don River and some prospects of their utilization for fishery in Tzvestia Severo-Kavkazaskogo nauchnogo tzentra vyschey schkoly N. 1. pp. 84-88 (Trans)

Dungeness Crab Research Program. 1981. A summary of the Dungeness Crab Research Program 1974-1980. Calif. Dept. Fish and Game, Marine Res. Br. Admin. Rept. No. 81-3.

Eldridge, M. B. 1977. Factors influencing distribution of fish and eggs and larvae over eight 24-hour samplings in Richardson Bay, California. Calif. Fish Game 63(2):101-106.

Fisher, H. B. and W. B. Kirkland, Jr. 1978. Flushing of South San Francisco Bay: Results of Dye Concentration Measurements in the Bay-Delta Physical Model. Waterfront Design Associates, Alameda, California.

Fraser, T. H. and W. H. Wilcox. 1981. Enrichment of a subtropical estuary with nitrogen, phosphorus, and silica. pp. 481-498. In: B. J. Neilson and L. E. Cronin, eds. Estuaries and Nutrients. Humana Press, Clifton, New Jersey.

Ganssle, David. 1966. Fishes and decapods of San Pablo and Suisun bays. pp. 64-94. In: D. W. Kelley, ed. Ecological studies of the Sacramento-San Joaquin Estuary, Part 1. Calif. Dept. Fish and Game Fish. Bull. No. 133.

Goldman, C. R. 1970. Reduced flows and the future ecology of the San Francisco Bay-Delta system. pp. 174-190. In: W. G. Weist Jr. and P. E. Greeson, eds. Hydrobiology: "Bioresources of Shallow Water Environments." Proceedings of the Symposium on Hydrobiology, Miami Beach, Florida. The American Water Resources Association, Urbana, Illinois.

Gunter, G. 1938. Seasonal variations in abundance of certain estuarine and marine fishes in Louisiana, with particular reference to life histories. Ecol. Monogr. 8:313-346.

——————— 1945. Studies on marine fishes of Texas. Publ. Inst. Mar. Sci. Univ. Tex. 1:1-190.

——————— 1961. Some relationships of estuarine organisms to salinity. Limnology and Oceanography 6(2):182-190.

Hart, J. L. 1973. Pacific fishes of Canada. Fish. Res. Bd. Canada. Bull. No. 180.

Hedgpeth, J. W. 1982. A classification of San Francisco Bay. pp. 36-38. In: W. Davoren, J. W. Hedgpeth, L. Q. Barzin, and D. R. Storm, eds. The Bay Prospectus 1982: The Delta Construct 1982. The Bay Institute of San Francisco, Tiburon, California.

Herrgesell, P. L., D. W. Kohlhorst, L. W. Miller, and D. E. Stevens. 1981. Effects of freshwater flow on fishery resources in the Sacramento-San Joaquin Estuary. pp. 71-87. In: R. D. Cross and P. L. Williams, eds. Proceedings of the National Symposium on Freshwater Inflow to Estuaries. U. S. Fish and Wildlife Service, Washington, D.C.

Kelley, D. W. and W. E. Tippets. 1977. Delta Outflow and San Francisco Bay. A Report Prepared for the Delta Environmental Advisory Committee of the California Department of Water Resources. 32 p.

Keup, L. and J. Bayless. 1964. Fish distribution at varying salinities in Neuse River Basin, North Carolina. Chesapeake Science 5(3):119-123.

Kilby, J. D. 1955. The fishes of two Gulf coastal marsh areas of Florida. Tulane Stud. Zool. 2(8):175-247.

Kinne, O. 1966. Physiological aspects of animal life in estuaries with special reference to salinity. Neth. J. Sea Res. 3:222-244.

Kjelson, M. A., P. F. Raquel, and F. W. Fisher. 1980. Influences of freshwater inflow on chinook salmon (Oncorhynchus tshawytscha) in the Sacramento-San Joaquin Estuary. pp. 88-108. In: R. D. Cross and D. L. Williams, eds. Proceedings of the National Symposium on Freshwater Inflow to Estuaries. U. S. Fish and Wildlife Service, Washington, D.C.

Kjelson, M. A., P. F. Raquel, and F. W. Fisher. 1982. Life history of fall-run juvenile chinook salmon, Oncorhynchus tshawytscha, in the Sacramento-San Joaquin Estuary, California. pp. 393-411. In: V. S. Kennedy, ed. Estuarine Comparisons. Academic Press, New York, New York.

Kjerfue, B. and J. E. Greer. 1978. Hydrography of the Santee River during moderate discharge conditions. Estuaries 1(2):111-119.

Kohlhorst, D. W. 1980. Recent trends in the white sturgeon population in California's Sacramento-San Joaquin Estuary. Calif. Fish Game 66(4): 210-219.

Krone, R. B. 1966. Predicted suspended sediment inflows to the San Francisco Bay system. Report to Central Pacific River Basins Comprehensive Water Pollution Control Proj., Federal Water Pollution Control Proj., Federal Water Pollution Control Admin. (Southwest Region). 33 p.

―――――― 1979. Sedimentation in the San Francisco Bay system. pp. 85-96. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Kutkuhn, J. H. 1966. The role of estuaries in the development and perpetuation of commercial shrimp resources. In: R. F. Smith, A. H. Swartz, and W. H. Massmann, eds. A Symposium on Estuarine Fisheries. Amer. Fish. Soc. Special Pub. No. 3. Presented at 94th Annual Meeting. Atlantic City, New Jersey, 1964.

Luoma, S. N. and D. J. Cain. 1979. Fluctuations of copper, zinc, and silver in tellenid clams as related to freshwater discharge - south San Francisco Bay. pp. 231-246. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division AAAS, San Francisco, Calif.

Malone, T. C., P. J. Neale, and D. Boardman. 1980. Influences of estuarine circulation on the distribution and biomass of phytoplankton size fractions. pp. 249-262. In: V. S. Kennedy, ed. Estuarine Perspectives. Academic Press. New York, New York.

Martin, M., G. Ichikawa, J. Goetzl, M. Reyes, and M. D. Stephenson. 1982. Relationships Between Physiological Stress and Trace Toxic Substances in the Bay Mussel, Mytilus edulis, From San Francisco Bay, California. Calif. Dept. Fish and Game, Marine Pollution Studies Laboratory Manuscript, Monterey, Calif.

McComb, A. J., R. P. Atkins, P. B. Birch, D. M. Gordon, and R. J. Lukatelich. 1981. Eutrophication in the Peel-Harvey estuarine system, western Australia. pp. 323-342. In: B. J. Neilson and L. E. Cronin, eds. Estuaries and Nutrients. Humana Press, Clifton, New Jersey.

Meleshkin, M. T., M. and M. Sh. Rosengurt. 1973. About ecological balance of the River - Estuary - Sea System and raising its economic efficiency. Vodnye Resursy N. 4, pp. 68-83 (Odessa) (Trans)

Meleshkin, M. T., M. Sh. Rosengurt, and D. M. Tulmazin. 1973. The problems of more efficient utilization of the resources of the Azov Sea. Problemy Economiki Morya I Mirovoco Okeana. Akademy Nauk Yccp (Odessa). N. 2, pp. 3-14 (Trans)

Messersmith, J. 1966. Fishes collected in Carquinez Strait in 1961-1962. pp. 57-63. In: D. W. Kelley, ed. Ecological studies of the Sacramento-San Joaquin Estuary, Part 1. Calif. Dept. Fish and Game Fish. Bull. No. 133.

Miller, D. J. and J. Schmidtke. 1956. Report on the distribution and abundance of Pacific herring (Clupea pallasi) along the coast of central and southern California. Calif. Fish Game 42(3):163-187.

Miller, W. J. 1982. Delta Outflow, San Francisco Bay, The Peripheral Canal and Proposition 9. Association of State Water Project Agencies, Sacramento, Calif.

Misitano, D. A. 1976. Size and stage of development of larval English sole, Parophrys vetulus, at time of entry into Humboldt Bay. Calif. Fish Game 62(1):93-98.

Monbet, Y., F. Manaud, P. Gentien, M. Pommepuy, G. P. Allen, J. C. Salomon, and J. L'Yavanc. 1981. The use of nutrients, salinity, and water circulation data as a tool for coastal zone planning. pp. 343-372. In: B. J. Neilson and L. E. Cronin, eds. Estuaries and Nutrients. Humana Press, Clifton, New Jersey.

Moyle, P. B. 1976. Inland Fishes of California. Univ. of Calif. Press, Berkeley. 405 p.

Olson, R. E. and I. Pratt. 1973. Parasites as indicators of English sole (Parophrys vetulus) nursery grounds. Trans. Am. Fish. Soc. 102(2): 405-411.

Orcutt, H. G. (compiler). 1978. Dungeness crab research program report for the year 1978. Calif. Dept. Fish and Game Mar. Res. Admin. Rept. No. 78-16.

Orsi, J. J. and A. C. Knutson, Jr. 1979. The role of mysid shrimp in the Sacramento-San Joaquin Estuary and factors affecting their abundance and distribution. pp. 401-408. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Painter, R. E. 1966a. Zooplankton of San Pablo and Suisun Bays. In: D. W. Kelley, ed. Ecological studies of the Sacramento-San Joaquin Estuary, Part I. Calif. Dept. Fish and Game Fish. Bull. No. 133. pp. 18-39.

_______________ 1966b. Zoobenthos of San Pablo and Suisun Bays. pp. 40-56. In: D. W. Kelley, ed. Ecological studies of the Sacramento-San Joaquin Estuary, Part I. Calif. Dept. Fish and Game Fish Bull. No. 133.

Parker, R. R. and P. A. Larkin. 1959. A concept of growth in fishes. J. Fish. Res. Bd. Can. 23:1209-1248.

Pearcy, W. G. and S. S. Myers. 1974. Larval fishes of Yaguina Bay, Oregon: A nursery ground for marine fishes? NOAA Fish. Bull. 72(1):201-213.

Peterson, D. H., T. J. Conomos, W. W. Broakow, and P. C. Doherty. 1975. Location of the nontidal current null zone in Northern San Francisco Bay. Estuarine and Coastal Marine Science 3:1-11.

Radtke, L. D. 1966. Distribution of smelt, juvenile sturgeon, and starry flounder in the Sacramento-San Joaquin Delta with observations on food of sturgeon. pp. 115-129. In: J. L. Turner and D. W. Kelley, eds. Ecological studies of the Sacramento-San Joaquin Delta, Part II. Calif. Dept. Fish and Game Fish. Bull. No. 136.

Rosenberg, A. A. 1982. Growth of juvenile English sole, Parophrys vetulus, in estuarine nursery grounds. NOAA Fish. Bull. 80(2):245-252.

Rumboltz, M. C. 1979. Impact of Delta outflow upon salinity and waterfowl in the Suisun Marsh. U. S. Dept. of Interior, Bur. of Recl., Sacramento, Calif.

Russell, P. P., T. A. Bursztynsky, L. A. Jackson, and E. Y. Leong. 1982. Water and waste inputs to San Francisco estuary - An historical perspective. pp. 127-136. In: W. J. Kockelman, T. J. Conomos, and A. E. Leviton, eds. San Francisco Bay: Use and Protection. Pacific Division, AAAS, San Francisco, Calif.

Rozengurt, M. 1983. The Environmental Effect of Extensive Water Withdrawals on the River-Estuary - Sea Ecosystem Ecology. A report prepared for the Calif. Dept. of Water Res.

Shaw, R. F. 1981. Seasonal species composition, diversity, spatial distributions, and tidal retention and transport of ichthyoplankton in the Sheepscot River-Back River-Montsweag Bay estuarine system, Maine. Doctoral Dissertation, Univ. of Maine at Orono, Orono, Maine.

Skinner, J. E. 1962. An historical review of the fish and wildlife resources of the San Francisco Bay area. Calif. Dept. Fish and Game, Water Proj. Br. Rept. No. 1.

Smith, R. E., R. E. Herndon, and D. D. Harmon, eds. 1979. Physical and chemical properties of San Francisco Bay waters, 1969-1976. U. S. Geological Survey, Open File Report 79-511, San Francisco, Calif.

Smith, S. E. and S. Kato. 1979. The Fisheries of San Francisco Bay: Past, Present, and Future. pp. 445-468. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

Spratt, Jerome D. 1981. Status of the Pacific herring, Clupea harengus pallasii, resource in California 1972 to 1980. Calif. Dept. Fish and Game Fish. Bull. No. 171.

State Water Resources Control Board. 1978. Final Environmental Impact Report for the Water Quality Control Plan and Water Right Decision: Sacramento, San Joaquin Delta, and Suisun Marsh. Calif. State Water Resources Control Board, Sacramento, Calif.

Stevens, D. E. 1977. Striped bass (Morone saxatilis) year class strength in relation to river flow in the Sacramento-San Joaquin Estuary, California. Trans. Amer. Fish. Soc. 106:34-42.

——————— 1979. Environmental factors affecting striped bass (Morone saxatilis) in the Sacramento-San Joaquin Estuary. pp. 469-478. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

——————— and L. W. Miller. 1980. Effects of flow on abundance of young chinook salmon, American shad, longfin smelt, and delta smelt in the Sacramento-San Joaquin River system. MS. Calif. Dept. Fish and Game, Bay-Delta Fishery Project.

Striped Bass Working Group. 1982. The striped bass decline in the San Francisco Bay-Delta Estuary. Calif. State Water Resources Control Board. 58 p.

Sutcliffe, W. H., Jr. 1972. Some relations of land drainage, nutrients, particulate material, and fish catch in two eastern Canadian bays. J. Fish. Res. Bd. Can. 29:357-362.

——————— 1973. Correlations between seasonal river discharge and local landings of American lobster (Homarus americanus) and Atlantic halibut (Hippoglossus hippoglossus) in the Gulf of St. Lawrence. J. Fish. Res. Bd. Can 30:856-859.

———————, K. Drinkwater, and B. S. Muir. 1977. Correlations of fish catch and environmental factors in the Gulf of Maine. J. Fish. Res. Bd. Can 34:19-30.

Sutcliffe, W. H., Jr., R. H. Loucks, and K. F. Drinkwater. 1976. Coastal circulation and physical oceanography of the Scotian Shelf and the Gulf of Maine. J. Fish. Res. Bd. Canada 33:98-115.

Tasto, R. N. 1979. San Francisco Bay: critical to the Dungeness crab? pp. 479-490. In: T. J. Conomos, ed. San Francisco Bay: The Urbanized Estuary. Pacific Division, AAAS, San Francisco, Calif.

——————— 1983. Juvenile Dungeness crab, Cancer magister, studies in San Francisco Bay Area. In: P. W. Wild and R. N. Tasto, eds. Life history, environment, and mariculture studies of the Dungeness crab, Cancer magister, with emphasis on the central California fishery resource. Calif. Fish and Game Fish. Bull. 173 (in press).

Texas Department of Water Resources. 1979. The influence of freshwater inflows upon the major bays and estuaries of the Texas Gulf Coast - Executive Summary. LP-115, Austin, Texas.

——————— 1980. Lauaca-Tres Paliacios Estuary. A study of the influence of freshwater inflows. LP-106, Austin, Texas.

——————— 1980. Guadalupe Estuary: A study of freshwater inflows. LP-107, Austin, Texas.

Texas Department of Water Resources. 1981. Nueces and Mission Arkansas Estuaries. A study of freshwater inflows. LP-108, Austin, Texas.

———————— 1981. Trinity-San Jacinto Estuaries. A study of freshwater inflows. LP-113, Austin, Texas.

———————— 1981. Sabin Niches Estuary. A study of freshwater inflow. LP-116, Austin, Texas.

Turner, J. L. and H. K. Chadwick. 1972. Distribution and abundance of young-of-the-year striped bass (*Morone saxatilis*) in relation to river flow in the Sacramento-San Joaquin Estuary. Trans. Am. Fish. Soc. 101(3):442-452.

Viosca, P., Jr. 1938. Effect of the Bonnet Carre Spillway on Fisheries. La. Conserv. Rev. 6(4):51-53.

Warren, C. E. 1971. Biology and Water Pollution Control. W. B. Saunders Co. Philadelphia. 434 p.

Watt, K. E. F. 1973. Principles of Environmental Science. McGraw-Hill, New York. 319 p.

Wenner, E. L., M. H. Shealy, Jr., and P. A. Sandifer. 1982. A profile of the fish and decapod crustacean community in a South Carolina estuarine system prior to flow alteration. NOAA Tech. Rept. NMFS SSRF-757, Charleston, South Carolina.

Wojcik, F. J. 1982. Catch data for white catfish indicate responses to change in salinity. Coastal Oceanography and Climatology News: Recent Events in United States Coastal Waters 4:28-29.

Zemlyansky, F. T. and U. N. Andreev. 1975. Utilization of biological resources in the Northwestern Port of the Black Sea. Problemy Economica Mozya, 1975. pp. 57-65 (Trans)