Assessing Evidence on the Importance of Various Limiting Factors on Selected Ecological Features of the San Francisco Estuary

Report to CALFED

By Members of the IEP Estuarine Ecology Project Work Team

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INTRODUCTION

In response to anticipated needs of the CALFED[1] Bay-Delta Program, the Estuarine Ecology Project Work Team (EET) of the Interagency Ecological Program (IEP) has summarized the evidence regarding the likely impacts of various factors on diverse ecological features of the San Francisco Estuary, including the Sacramento-San Joaquin Delta. Two tasks were completed with general agreement among the participants. First, evidence was assessed for impacts on each selected taxon due to food limitation, toxic concentrations of contaminants, entrainment, and habitat limitation. Second, a priority was assigned to each factor based on its probable role in limiting recovery.

The taxa selected for consideration were: American shad, threadfin shad, delta smelt, longfin smelt, striped bass, splittail, white catfish, starry flounder, chinook salmon, the mysid or opossum shrimp *Neomysis mercedis*, copepods, cladocerans, phytoplankton, clams, amphipods, rotifers, and the bay shrimp *Crangon franciscorum*. These species and functional groups represent a broad cross-section of the ecosystem.

Membership on the EET includes scientists from CDFG, CDWR, USBR, USEPA, SFEI, MWD[1], University of California Bodega Marine Laboratory, San Francisco State University Tiburon Center, and private consultants, and represents a broad spectrum of knowledge, expertise, and backgrounds. EET members who have contributed to this report include: Chuck Armor, Doug Ball, Bill Bennett, Kathy Hieb, Bruce Herbold, Tim Hollibaugh, Wim Kimmerer, Sharon Kramer, Liz Howard, Peggy Lehman, Lee Mecum, Dave Mayer, Lee Miller, Jim Orsi, Tara Smith, Ted Sommer, and Bruce Thompson. Phyllis Fox and Chris Foe provided valuable information on toxic contaminants and several helpful reviews of earlier drafts. Additional suggestions were made by Jim Arthur, Marty Kjelson, Dave Kohlhorst, Don Stevens, and Frank Wernette based on earlier drafts.

This document represents the knowledge and opinions of the EET, but does not necessarily reflect policies or positions of the team members' respective agencies and organizations. It also identifies some of the large gaps in knowledge that will need to be addressed as restoration plans are developed. This document has been presented to several other IEP project work teams to solicit their review and ideas, and has been reviewed by various IEP scientists. The team is gratified that early drafts of this report have already stimulated substantive discussions, and hopes that this document will serve as a focus for further discussion of the technical basis for restoration and research priorities.

This report is a summary of the Team's views on known effects and actions that are most likely to improve the Estuary's fish populations. Little or no information exists to enable us to predict actual responses of the Estuary's aquatic organisms to changes in toxic substances or physical habitat. As restoration actions proceed, unique opportunities will be created to assess the response of individuals and populations to different types and scales of restoration actions. Staged implementation, coupled with intensive, well-crafted evaluations, will permit a continual assessment of the likelihood of success of each action. This will provide the optimum path to efficient and effective restoration of the Estuary's aquatic populations and resources.

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1 See Glossary for acronyms and terminology

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The EET, and others in IEP, caution that changes to the Estuary do not constitute a scientific experiment in that there are neither controls nor replicates. The San Francisco Estuary is a large, complex system with many sources of variation, many of which are unknown. Therefore, monitoring alone is insufficient to assess management actions unambiguously. To evaluate the effectiveness of management actions requires a conceptual model of the presumed effect, numerical predictions of how much change is expected, and a variety of response variables whose changes can be readily observed and unequivocally ascribed to the management action taken.

Some of the conclusions in this report about restoration priorities use information derived from responses of the ecosystem to changes caused by introduced species. These exotic species have altered the lower trophic levels by reducing phytoplankton concentrations and the abundance of native benthic and pelagic species. To a large extent the introduced species have replaced the natives. The effects of these changes in lower trophic levels has not been obvious on higher trophic levels. Introduced species, however, have the potential to limit the success of management and restoration activities and as more exotic species are established in the Estuary they may have observable but unpredictable effects on fish.

ASSESSMENT OF EVIDENCE

Each factor was graded A, B, AB, BC, C, or 0

A Evidence of possible population-level effect; sufficient x-y relationship between some aspect of the factor and population abundance or survival, with a reasonable biological mechanism postulated. Note that such an x-y relationship is insufficient to infer an equivalent cause-effect relationship.

B Evidence of an individual-level effect from lab or field data or evidence of individual cause-effect relationship without an x-y relationship to support a population-level effect; Synergistic or compound effects are likely to appear here since x-y relationships between one factor and its affected population are obscured.

AB Probable population-level effect of an observed individual-level effect but no x-y relationship to support it.

BC Evidence of individual-level effect of local conditions on related species.

C No evidence, or incomplete understanding.

0 Evidence for no effect.

A brief review of evidence for each factor is provided below with species grouped by grade from the above list. A summary of grades is included in Table 1.

Finally, the relative importance of each factor was addressed with a numerical scoring system (1-4) where "1" represents the most important factor and "4" represents the least important. The scores are provided in Table 1 (along with the grades from above) and the rationale for the rankings is discussed is a final summary section.

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EVIDENCE FOR EACH FACTOR

FOOD LIMITATION

A (population-level effect)

Neomysis : Abundance declined with lowered phytoplankton abundance following invasion by *Potamocorbula* (Orsi and Mecum, In press). *Neomysis* is too big to be eaten by *Potamocorbula* so competition for their common food is the most likely mechanism.

Striped bass: Growth rates of young striped bass are low relative to those measured in some other estuaries (Lee Miller, unpublished). The significant correlation of survival from egg to young-of-year (YOY) with X2 and copepod biomass (Kimmerer, unpublished manuscript) suggests that egg-to-YOY survival is partly explained by food abundance or availability. Modeling studies by Cowan (1993) suggest that small variations in survival from food limitation could limit striped bass abundance. Bennett et al. (1995) failed to find any evidence of starved larvae in limited field sampling, but in later experiments found that small larvae were more susceptible to predation than large larvae; thus reduction in growth through food limitation could result in lower survival and recruitment even if larvae were not starving.

Copepods (A or 0; species-, location-, and time-specific): Lehman (1992) found a significant correlation between chlorophyll and copepod biomass, which could suggest food limitation. However, this effect is specific to species, location and time, and documenting food limitation can be quite difficult. For example, food limitation was not observed in experiments with *Eurytemora* in the Delta (Kimmerer, unpublished data). However, *Eurytemora* abundance peaks in spring in the San Joaquin River at Stockton, then declines in June when *Pseudodiaptomus forbesi* becomes abundant, suggesting competition and food limitation (J. Orsi, CDFG, personal observation). Higher egg production was observed in *Acartia* in the South Bay in response to a spring bloom in 1993 (Kimmerer, unpublished data).

Cladocerans: There is a significant correlation between chlorophyll *a* and cladoceran biomass in the Sacramento and San Joaquin rivers, suggesting food limitation Lehman (1992). As with copepods, this effect may be sensitive to location and species.

Phytoplankton: Nutrients are considered the "food" supply for phytoplankton in this report. Phytoplankton are rarely limited by nutrients. Correlations between chlorophyll a and nutrient concentrations are positive (Lehman 1992), but concentrations can reach limiting levels during blooms (Cloern 1987; Jassby and Powell 1994). Light limitation through turbidity and depth has a dominant effect on phytoplankton growth rates in the Estuary, and grazing is a significant limit on biomass.

AB (Probable population-level effect)

White catfish: Delta growth rates and survival are inversely proportional to density, suggesting that either food or habitat is limiting (Kohlhorst, CDFG, unpublished data).

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B (Individual-level effect)

Splittail: In Suisun Marsh, splittail are the only resident native fish with emptier guts when *Neomysis* abundance is low than at other times (Herbold 1987), suggesting that a reduction in this food source could affect the population. Flooding of terrestrial habitat results in splittail guts filled with earthworms (Caywood 1974), indicating that higher fecundity of splittail in wet years may result from better feeding conditions; the x-y relationship of adult abundance with flow is an ambiguous support of population-level effects (Daniels and Moyle 1983).

Crangon (bay shrimp): The species has shown low abundance relative to its historical X2 response since early 1990's (Kimmerer pers. obs.). *Neomysis* has been low during that period, suggesting that food limitation could be a factor (Orsi and Mecum in press). However, a depleted spawning stock provides an alternative explanation for the failure of this species to rebound (IEP 1993 and 1994-95 annual reports).

Salmon: Condition of smolts changes during migration through the Estuary. Food effects could be important in allowing successful smolt passage (MacFarlane, NMFS pers. comm.).

Clams: *Potamocorbula* growth rates are positively correlated with phytoplankton concentrations (J. Thompson, USGS, pers. comm.).

Rotifers: Several species of rotifers in the upper Estuary declined beginning in the late 1970s, roughly coincident with a decline in chlorophyll. This could have been a response to reduced food supply resulting from reduced discharge of phytoplankton and organic matter from wastewater treatment plants (Obrebski et al. 1992).

C (Incomplete or no evidence)

All others: Reasonable to suppose that individuals of any species are at least occasionally food limited.

TOXIC CONCENTRATIONS OF CONTAMINANTS

Discussion centered principally on organic chemicals in the water and sediments and the toxicity of metals and organic compounds in the sediments. Numerous bioassays of sediment and water have demonstrated toxic concentrations of some pollutants at various places and times. Clearly this is cause for concern. However, effects of pollutants on populations have proven difficult to assess in any ecosystem and are especially intractable here, because complex interactions among pollutants and other environmental factors are likely. Changes in abundance of a species with distance from a toxic source would satisfy the A criteria. Bioassay results do not necessarily apply to species of concern in this ecosystem. Possible ecosystem-level effects of aquatic toxicity have only begun to be analyzed.

A (population-level effect)

Delta smelt: Preliminary analyses from Bruce Herbold (unpublished data) demonstrate an inverse relationship between copper applications to rice fields and delta smelt midwater trawl abundance. There is a similar statistical relationship for the delta smelt summer townet index. There is no information available on the sensitivity of delta smelt to copper.

Striped bass: Bailey et al (1994) published inverse relationships between rice pesticides (particularly bufencarb) and abundance of young striped bass. These data were reanalyzed by Phyllis Fox (unpublished data), who also found significant relationships, although not for bufencarb and with lower r^2 values. Supporting evidence for toxicity includes results from Bennett et al. (1995), who found liver alterations in young striped bass in the Delta. In contrast, longer holding times for rice field water has reduced the input of several pesticides, resulting in an improvement of condition of young bass, yet abundance of young bass has not increased. The counter-example to the above analyses is that the simplest explanation for the decline in young bass abundance (which drives most of the variability explained by the above analyses) is a reduction in egg production due to the decline in the abundance of adults (CDFG 1992a).

Several studies of adult striped bass have noted effects of toxic contaminants on reproductive success (Crosby et al. 1984), and the annual summer die-off of bass in Carquinez Strait is associated with high liver concentrations of organic toxicants (Cashman et al. 1992).

AB (Probable population-level effect)

Starry flounder: Widespread impairment of growth and reproductive abilities strongly implicated toxic substances (Spies and Rice 1988; Spies et al. 1988), but there is no direct evidence for a population-level effect.

Amphipods: Amphipods showed some evidence of covariation with concentrations of toxic substances in sediments, but confounding factors cannot be ruled out (Thompson et al. 1995; SFEI 1995; SFEI 1996). Semiannual sediment bioassays with amphipods have consistently shown toxicity at the confluence of the Sacramento and San Joaquin rivers.

Clams: On a transect from the confluence of the Sacramento and San Joaquin rivers to San Pablo Bay, metal concentrations decreased, while the degree of asynchronous reproduction in clams decreased and their condition factor increased (C. Brown and J. Thompson, USGS, unpublished data). This may be confounded with effects of salinity.

B (Individual-level effect)

Neomysis: Ambient toxicity testing by CDFG revealed occasionally significant toxicity of water from Rio Vista to *Neomysis* (Finlayson et al. 1991). The historical range of this species included tidal freshwater portions of the Estuary but it has never been abundant there.

BC (Effect on related species)

Cladocerans: Water column bioassays on *Ceriodaphnia* show that samples from the Sacramento Basin, San Joaquin Basin and the Delta are frequently toxic, suggesting a probable effect on resident species (Adams et al. 1996; Foe 1991; Bailey et al. 1995).

Phytoplankton: Bioassays found that waters in the Sacramento Basin and Delta reduced growth of *Selenastrum capricornutum*, a green alga, 11-22% of the time (Connor and Foe 1993). Algal toxicity in the system has been noted from zinc and copper (Connor et al. 1994), diuron and simazine (Connor 1995).

C (Incomplete or no evidence)

Chinook salmon: Concentrations of hepatic PCBs were higher in juvenile salmon from San Francisco Bay than from hatcheries or the Delta, but overall contaminant levels were lower than in fish from Puget Sound (Varanasi et al. 1993).

American shad: Exposure to toxic pulses or chronic conditions is possible due to their extended rearing period (4-6 months) in the Delta and upstream tributaries.

All others have been studied little if at all. It is reasonable to suppose that individuals of any species are at least occasionally stressed by toxic substances. Species or life stages resident in the Delta are more likely to suffer chronic effects than migrants. Demersal organisms, including white catfish, splittail and sturgeon are more likely to be exposed to sediment-bound toxic substances than pelagic species.

ENTRAINMENT

Entrainment is broadly defined to include all diversions of water that take in or damage aquatic organisms (i.e. water projects, power plants, and agricultural diversions). Effects of entrainment discussed here include indirect impacts such as impingement on screens, raised predation rates due to diversion structures, and effects of changes in hydraulic patterns in the zone of influence of large water diversions.

A (population-level effect)

Striped bass: CDFG's striped bass model (Kohlhorst et al. 1992), UC Davis' update of the CDFG model (Botsford and Brittnacher 1994) and Alan Jassby's model of X2 effects combined with entrainment effects (Jassby et al. 1995) all show relationships between striped bass recruitment and rates of diversion at the projects.

Phytoplankton: Export pumping was negatively correlated with phytoplankton community composition (Lehman and Smith 1991) and chlorophyll a concentration (Lehman 1992). Jassby and Powell (1994) found that diversions and Delta outflow together account for 86% of the variability in chlorophyll *a* concentrations in the entrapment zone. They also reported that San Joaquin river flow and exports accounted for 62% of the variability in annual chlorophyll *a* concentrations at a station in the lower San Joaquin River.

Chinook salmon (San Joaquin): Releases of coded-wire-tagged (CWT) salmon in the San Joaquin River strongly suggest that diversion through Old River, which requires salmon to pass by the state and federal pumping intakes, results in decreased survival, although the proximate cause of mortality is not well understood (USFWS 1992). The effect of the export pumps on San Joaquin salmon is supported by analyses of escapement by Mesick (1994).

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AB (Probable population-level effect)

Delta smelt, longfin smelt - Entrainment rates are generally highest when the weakest year classes are present (i.e. dry years), suggesting that a greater proportion of smelt are entrained when the population is most sensitive. The primary mechanism for increased entrainment is low outflow, which shifts the population closer to the diversions (CDWR and USBR 1994).

White catfish: As with the smelts, there is an inverse relationship of abundance of young with entrainment rates (CDFG 1992b). Again, the concern is that entrainment effects are proportionally higher when year class strength is lowest.

Rotifers (AB for one species in the south Delta; otherwise C): *Trichocerca* was more abundant in the south Delta before, and less abundant after higher pumping rates (percent inflow diverted increased) became common (Arthur et al., in press). Note that this pattern could also be explained on the basis of changes in organic matter input (see Food above).

B (Individual-level effect)

Chinook salmon (Sacramento): CWT studies in the Sacramento River show that mortality is related to diversion of fish into the central Delta--these effects may be direct (entrainment loss) or indirect (less suitable habitat or increased predation). (USFWS 1992)

Crangon franciscorum and starry flounder should perhaps be considered as "A/B" following the rationale used for smelt, although data are much more limited. During years with low outflow when populations are reduced, the distribution of *C. franciscorum* and starry flounder shifts into the vicinity of PG&E Delta power plants. Data are available only for a wet year, when large numbers of *Crangon* and starry flounder were entrained or impinged (as estimated by Ecological Analysts 1981a, b, c), although these reports concluded that population-level effects were unlikely. Entrainment rates may be substantially higher in dry years (K. Hieb, personal observation).

Other species: All species are entrained to some degree, constituting evidence of an entrainment effect, but there is no agreement on an appropriate measure to assess significance from entrainment data alone. Comparison of smelt and splittail results illustrates this problem: splittail individuals are entrained in large numbers in the summer in years when their fall abundance is high, whereas smelt are entrained in inverse proportion to their abundance. Simple calculations of percent of population entrained are of little value because many population sizes are unknown, the effects of entrainment vary with life stage and age, and density-dependent effects may distort the relationship between abundance at one life stage and another. Furthermore, little is known of entrainment rates of larvae.

B or 0 (Probable population effect, or evidence of no effect)

Neomysis: Although once entrained in substantial numbers, there is probably no population effect of entrainment on *Neomysis* because the proportion of the whole population entrained in the south Delta pumps is less than 0.1% (Kimmerer analysis cited by Orsi and Mecum in press). This level is unlikely to have a substantial effect because the population is capable of rapid reproduction. However, this analysis did not apply to the in-Delta agricultural diversions and other non-project pumps. Arthur and Ball argue for a significant effect but no analysis has been presented to counter Kimmerer's.

Copepods: Freshwater species must be entrained but results for *Eurytemora* (formerly the dominant copepod of the entrapment zone) are similar to *Neomysis.* Downstream species like *Acartia* are clearly not affected, whereas Delta resident species would be subject to much greater impacts (Kimmerer, personal observation).

Clams (Species specific): Large numbers of *Corbicula* occur in distribution canals south of the Delta (Hymanson et al. 1994), suggesting that substantial numbers of larvae could be entrained (Arthur, personal observation). By contrast *Potamocorbula* has year-round centers of distribution too far downstream (Hymanson 1991) to support a conclusion of significant impact for agricultural or water project entrainment.

C (Incomplete or no evidence)

Amphipods have been little studied in this Estuary.

HABITAT

Habitat includes the physical-chemical structure of the aquatic environment including aquatic vegetation as structure. Many aspects of habitat included here are strongly influenced by flow through inundation and inter-connection of different areas, effects on salinity, gravitational circulation, residence time, and other physio-chemical variables. Thus, relationships of abundance or survival to flow unattributable to other causes were assigned to this category (see Jassby et al. 1995, EET, in press, for discussions of the "fish-X2" relationships). Dilution of toxic substances and hydrodynamic effects of pumping are considered above. Efforts were made to identify those aspects of habitat that could be expected to yield improved conditions for aquatic resources with current flow conditions.

Note that, as defined, "habitat" comprises a wide variety of characteristics, not all of which are amenable to manipulation. Thus, the finding reported below that habitat is the most important environmental influence does not imply that construction of physical habitat would improve every species (see discussion under "Comparison of Factors" below).

A (population-level effect)

American shad: A positive x-y relationship of abundance index with river flow (Stevens and Miller 1983) is probably due to: 1) greater attraction flows (in that the number of adults spawning in a tributary is proportional to the amount of flow from that tributary) (CDFG 1981; Sommer unpublished data); 2) increased spawning area in upstream areas; and 3) improved rearing habitat (Miller and Sommer, personal observations).

Delta smelt: Abundance varies positively with the number of days when their preferred salinity zone is located within Suisun Bay, rather than upstream or downstream; this suggests a direct impact of habitat on successful rearing (Herbold 1994). Unger (1994) showed a significant relationship between abundance and the area of optimal salinity habitat. Predation by inland silversides may have reduced the value of in-Delta habitat in supporting delta smelt (Bennett 1995).

Longfin smelt: The species shows a strong relationship of abundance with X2 (Jassby et al. 1995), and young longfin smelt are most abundant in the entrapment zone. Likewise, CDFG (1992c) and Unger (1994) found a relationship between the area of optimal salinity habitat and abundance.

Striped bass: Survival of young striped bass varies with flow and X2 similarly to abundance of longfin smelt (Jassby et al. 1995; Kohlhorst et al. 1992), and habitat size also varies in a similar way with X2 for both species (Unger 1994). Successful transport of eggs from upstream spawning grounds depends on adequate velocities in river channels. Spawning activity in the lower San Joaquin River is a function of local salinity which is controlled by San Joaquin and local runoff and total Delta inflow (CDFG 1992a).

Splittail: Access and areal extent of floodplain spawning habitat (measured as inundation of Yolo Bypass) is the best predictor of the abundance of young of year splittail. The importance of this habitat is supported by recent sampling of larvae and adults (Sommer et al. In prep; Baxter et al. In prep)

Starry flounder: Moderate to high outflow increases the amount of rearing habitat in San Pablo, Suisun and Honker bays (CDFG 1992c, Unger 1994). Greater extent of this habitat is correlated with starry flounder abundance in the Estuary later in the year. Gravitational circulation in the lower Estuary is strongly affected by freshwater flows and may aid immigration of young flounder into the estuarine nursery areas (CDFG 1992c).

Chinook salmon: Relationships between river flow and San Joaquin Basin adult escapement are based on simple regression models and more complex mechanistic models (Speed 1993). Attraction flows guide adults into and through the Estuary resulting in more widely-dispersed and successful spawning (USFWS 1995). High Delta temperatures may be stressful to returning adults or their developing eggs, and to resident and migrating juveniles. The Delta appears to be poor habitat for rearing of fry or migration of smolts, since physical characteristics of habitat known to be "good" based on stream and estuarine studies (e.g., low temperature, shallow vegetated areas, riparian vegetation) appear poor in the Delta (USFWS 1993). Scarcity of shallow-water and riparian habitats in the Delta is likely to decrease survival of young salmon, particularly fry, but no studies have specifically addressed this in the Delta.

Clams: Mollusk densities show a non-linear relationship to X2 (Jassby et al. 1995) that is due to differential responses of freshwater and euryhaline marine species (Nichols 1985). High spring Delta outflow shifts *Potamocorbula* recruitment further downstream and appears to increase mortality in the Sacramento and San Joaquin rivers (Peterson 1996), indicating that low salinity or physical disturbance are responsible.

Crangon: The amount of shallow, brackish water habitat in the San Pablo, Suisun and Honker bays appear to be a key factor for this species. Shallow water provides physical refuge frompredators and other shrimp, as *Crangon* is cannibalistic (K. Hieb, personal observation). A significant relationship between the area of optimal salinity habitat and abundance provides additional support for this hypothesis (CDFG 1992c, Unger 1994). Gravitational circulation may also aid the migration of young shrimp into nursery areas of the Estuary (CDFG 1992c)

Neomysis: *Neomysis* abundance is higher when X2 is in Suisun Bay than when it is in the Delta (Jassby et al. 1995; Orsi and Mecum in press).

Copepods: *Eurytemora* in the entrapment zone respond in a fashion similar to *Neomysis* if the long-term decline is taken into account (W. Kimmerer, unpublished data). Substantial changes in the composition and distribution of copepod species have occurred over the last 15 years, making assessment of habitat use difficult. Abundance of individual species of copepod in the Delta may depend on residence time or flow rates in much the same fashion as phytoplankton (Kimmerer, personal observation).

Phytoplankton: Habitat for phytoplankton in the Delta is greatly affected by exports (see Entrainment above) and also by residence time, which varies with flow conditions. However, the multiplicity of species and their various responses to conditions, and the dominant effects of grazing and light limitation in the turbid waters of the system, prevent clear patterns of population abundance with any single habitat feature in the Delta (P. Lehman, personal observation).

AB (Probable population-level effect)

White catfish: Delta growth rates and survival are inversely proportional to density, suggesting that either food or habitat is limiting (Kohlhorst, unpublished data).

B (Individual-level effect)

Rotifers and Cladocerans: Increased sewage treatment might have reduced the inputs of rotifers and cladocerans from these sources into the river (Lee Mecum, pers. obs.). Freshwater flow affects their abundance (Kimmerer unpublished), probably through residence time or flow velocities, but there is no evidence of other habitat effects.

C (Incomplete or no evidence)

Threadfin shad and amphipods have been little studied in this estuary (Lee Miller is writing a report on amphipods but has no conclusions yet).

COMPARISON OF FACTORS FOR EACH SPECIES

As biologists working with the various species of the Estuary, the members of the EET have attempted to assess the factors of toxic substances, food, entrainment and habitat in terms of their likelihood of serving as the primary control of resource abundance. In making this assessment the team has attempted to cite recent conditions that support their conclusions, but in many cases insufficient data exist to support unequivocally any conclusions. The following text and tabular summary (Table 1) represent the current status of ongoing arguments and the general consensus of opinion among members of the EET.

American shad — River flow is the only known correlate with abundance and probably acts through attraction of adults to suitable spawning areas and improved spawning and rearing habitat. American shad may benefit from restructuring stream channels to provide additional spawning and rearing habitat. The species is entrained regularly both in project and local diversions but there is no indication that the rate of entrainment controls abundance. The population moves out of the Estuary for much of the year and most growth of body mass and gonads occurs in the ocean; there is no evidence of food limitation for young fish in the Delta. Toxic effects are possible.

Delta smelt — The relationship between abundance index and the proportion of time in spring when X2 is located in Suisun Bay ("X2 days") suggests that habitat affects population size. This habitat may be advantageous through either improvements in food density or in improved escape from predation. However, most of the variability in delta smelt abundance is unaccounted for by their relationship with X2 days; this suggests either that other factors are important in limiting the abundance of delta smelt, or that abundance indices contain a large amount of measurement error, due in part to the low abundance of this species. Preliminary analyses suggest an inverse correlation between toxic substances and abundance, but insufficient information is available to establish a cause-and-effect relationship. Evidence suggests that food and entrainment could affect the species. Entrainment of POC or food organisms may provide an indirect link between entrainment and delta smelt survival. Spawning and rearing habitat may be less suitable now due to proliferation of inland silversides as a recently introduced predator on eggs and larvae.

Longfin smelt — The arguments for food and entrainment are similar to delta smelt, but the center of distribution is farther from the diversions, so entrainment is less likely to have an impact. The strong connection to X2/outflow suggests that variables unrelated to flow are unlikely to affect abundance.

Threadfin shad — Not much is known about what controls abundance of this species. Threadfin shad are found year-round in freshwater habitats of the Delta, and so they are highly susceptible in terms of location to entrainment and toxic substances. The seasonal temperature drop in fall is regularly associated with a die-off. The effects of any factor on populations are unknown.

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Striped bass	In reference only to young of year, there is clear evidence of entrainment effects at the population level and toxic effects at the individual level, and some evidence for food limitation at the population level. Most habitat effects are tied to flow for egg transport or through entrapment zone nursery habitat. Aspects of physical habitat (e.g. vegetation) may be less important than flow-related habitat for this open-water species. Since most young bass are resident in low-salinity regions of the Estuary, the population is subject to entrainment at Federal and State projects, power plants, and Delta pumps, especially when freshwater flow is low. Recent further declines in abundance of striped bass are as yet unexplained.
Splittail	Flooding of spawning habitat and heavy feeding on terrestrial organisms prior to spawning are two mechanisms by which habitat conditions influence successful reproduction. Entrainment is greatest in wet years when the species is abundant, which suggests that dry year abundance is driven more by spawning success. Splittail are benthic feeders so they are more apt to be exposed to sediment toxicity than many other estuarine fishes. There is a large potential to affect spawning and rearing habitat through physical changes.
White catfish	Spring-summer entrainment is probably more important than other factors. Entrainment also includes indirect effects on rearing habitat in the south Delta. Habitat or food abundance could also be a factor based on an inverse relationship between fish density and growth and survival. As a demersal feeder, white catfish are probably exposed to toxic contaminants.
Starry flounder	The abundance and quantity of habitat of this species are strongly dependent on outflow/X2. The sensitivity of starry flounder to flow is probably also partly due to covariation with the strength of gravitational flow at the Golden Gate, which assists migration of juveniles to estuarine nursery areas. Sediment toxicity effects have been noted. This species has declined substantially in abundance for reasons that are not now known.
Chinook salmon	Providing suitable habitat for migration and temperature control seem most important. Riparian and shallow-water habitat is scarce in the Delta. If the Delta is (or could become) important as rearing habitat, then improving conditions for rearing should be a goal of restoration. Smolt migration habitat is sensitive to flow and hydrodynamics because of cues for migration through the Delta, although the physical benefits of cover and shallow habitat probably become less flow-sensitive in tidal reaches of the Estuary. Entrainment also seems important, particularly for the San Joaquin run.
Neomysis	Food supply is probably the most important limitation since *Potamocorbula* became abundant.
Copepods	For most Delta species of copepod, entrainment could be important; for entrapment zone species, entrainment is unlikely to have a significant

	impact on the population. Habitat, represented through residence time, is probably a significant control of population densities in the Delta. Changes in the physical structure of the Delta are likely to affect copepods if more areas with long residence times are constructed.
Cladocera	Reduced food abundance is the most likely limitation for this species, through reduced phytoplankton abundance and organic inputs from wastewater treatment facilities. Toxics could also play a role based on frequent mortality of bioassay species. Residence time is probably important in the same way as for copepods.
Phytoplankton	Residence time and entrainment are important to variability in phytoplankton in the Delta. Nutrients are important only infrequently because of the dominant effect of light limitation. There is frequent evidence of toxic effects in bioassay species, but no evidence of effects on biomass or production of resident species. Shallow-water habitat was once very important to the development of blooms in the entrapment zone, but grazing by *Potamocorbula* seems to have virtually eliminated these blooms.
Clams	Habitat of the overbite clam *Potamocorbula* is apparently the dominant control through flow effects on salinity, although there is some evidence that size structure of the population is affected by flow velocities. There are also possible food supply limitations at high abundances. Toxicity effects are not well known.
Amphipods	Little is known of any effects on amphipods, although pelagic amphipods in the entrapment zone behave similarly to mysids (Kimmerer, personal observation) and therefore presumably have similar responses to physical habitat. There is evidence for individual- and population-level effects of toxicity.
Crangon	The relative importance of different factors are similar to starry flounder, although the biological mechanisms are somewhat different. There is a strong effect of X2/outflow on abundance and habitat. Entrainment by PG&E could be a factor in dry years when the population moves up-estuary. Abundance of one food species (*Neomysis*) has declined since the *Potamocorbula* invasion, suggesting food limitation. *Crangon franciscorum* may benefit from additional shallow-water habitat in the western Delta.
Rotifers	The major factors are similar to cladocerans, although their populations may be less sensitive to toxic substances.

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Glossary

CALFED	A joint California and federal program tasked with developing a comprehensive solution to problems in the San Francisco Estuary
CDFG	California Department of Fish and Game
CDWR	California Department of Water Resources
EET	Estuarine Ecology Project Work Team, a part of the IEP
IEP	Interagency Ecological Program
MWD	Metropolitan Water District of Southern California
NMFS	National Marine Fisheries Service
SFEI	San Francisco Estuarine Institute
USBR	US Bureau of Reclamation
USEPA	US Environmental Protection Agency
USFWS	US Fish and Wildlife Service
USGS	US Geological Survey
X2	Distance in kilometers from the Golden Gate along the axis of the Estuary to the point where the near-bottom salinity is 2 practical salinity units (or parts per thousand); a measure of freshwater flow integrated over a biologically-relevant time scale

Table 1: Summary of factors and their relative importance for selected estuarine species. This table summarizes the foregoing discussion by listing, for each species and factor, the assessment of evidence (letter) and the EET's subjective evaluation of the relative importance of that factor in protecting or restoring the species or species group. Subjective ranking goes from 1 to 4 at most.

	FOOD Including nutrients	TOXIC CONTAMINATION	ENTRAINMENT Including flow alteration	HABITAT Including flow effects
American shad	C 3	C 3	B 2	A 1
Delta smelt	C 2	A 2	AB 2	A 1
Longfin smelt	C 2	C 4	AB 3	A 1
Threadfin shad	C 2	C 2	B 2	C 2
Striped bass	A 3	A 3	A 2	A 1
Splittail	B 2	C 4	B 3	A 1
White catfish	AB 2	C 3	AB 1	AB 2
Starry flounder	C 3	AB 2	B 4	A 1
Chinook salmon	B 3	C 3	A or B 2	A 1
Neomysis	A 1	B 3	B or 0 3	A 2
Copepods	A or 0 2	C 3	B or 0 3	A (EZ) or B 1
Cladocerans	A 1	BC 2	B 4	B 3
Phytoplankton	A (rarely) 3	BC 3	A 2	A 1
Clams	A 2	AB 2	B or O 3	A 1
Amphipods	C 2	AB 1	C 2	C 2
Rotifers	B 1	C 3	AB 3	B 2
Crangon	B 2	C 3	B 3	A 1

A: Evidence of population-level effect with x-y relationship; AB: Probable population-level effect based on individual-level effect; B: Evidence of individual-level effect but not population-level; BC: Evidence of individual-level effect on related species; C: No evidence or incomplete understanding; 0: Evidence for no effect.