The Future of the Delta Ecosystem and Its Fish

Technical Appendix D

Peter B. Moyle
William A. Bennett

August 2008

Description

This document is an appendix to the Public Policy Institute of California report, *Comparing Futures for the Sacramento-San Joaquin Delta*, prepared by a team of researchers from the Center for Watershed Sciences (University of California, Davis) and the Public Policy Institute of California.

Supported with funding from Stephen D. Bechtel Jr. and the David and Lucile Packard Foundation

PPIC | PUBLIC POLICY INSTITUTE OF CALIFORNIA

The Public Policy Institute of California is dedicated to informing and improving public policy in California through independent, objective, nonpartisan research on major economic, social, and political issues. The institute's goal is to raise public awareness and to give elected representatives and other decisionmakers a more informed basis for developing policies and programs.

The institute's research focuses on the underlying forces shaping California's future, cutting across a wide range of public policy concerns, including economic development, education, environment and resources, governance, population, public finance, and social and health policy.

PPIC is a private, nonprofit organization. It does not take or support positions on any ballot measures or on any local, state, or federal legislation, nor does it endorse, support, or oppose any political parties or candidates for public office. PPIC was established in 1994 with an endowment from William R. Hewlett.

Mark Baldassare is President and Chief Executive Officer of PPIC.
Thomas C. Sutton is Chair of the Board of Directors.

Contents

Summary iv

Acknowledgments v

Acronyms vi

Introduction 1

1. DESIRABLE FISH SPECIES 4
   Fish Groupings 6

2. ECOSYSTEM CHANGE AND FUTURE DELTA ATTRIBUTES 11
   Recent Shifts in the Estuarine Environment 11
   Ecosystem Response to Future Island Flooding 15

3. EXPORT ALTERNATIVES AND FISH 18

4. ACTIONS TO IMPROVE CONDITIONS FOR FISH 21
   Adaptive Management 21
   Flow Regime 21
   Alien Species 22
   Toxicants 22
   San Joaquin River Contamination 23
   Entrainment 24
   New Tidal Habitats 24
      Cache Slough 24
      Suisun Marsh 25
   Improved Floodplain Habitats 26
   Island Manipulations 26
   Anticipating Climate Warming 27

Conclusions 28

References 30

Addendum D1 - Species Characteristics Used in Principal Components Analysis 36

About the Authors 38

Summary

Recent legal rulings indicate that management of the Delta must benefit both water supply and the Delta ecosystem. Here we focus on fish as indicators of the condition of the Delta ecosystem because they are major drivers of ecosystem-related policy. We address four basic questions. (1) What species of fish are important (desirable) for making decisions that affect ecosystem function? (2) What are likely to be attributes of the Delta ecosystem in the future? (3) What are the likely effects on fish of the four strategic water export alternatives: (i) continued through-Delta pumping; (ii) diverting water around the Delta through a peripheral canal; (iii) employing a "dual facility" that combines both of these alternatives; and (iv) ending exports altogether? (4) What actions could improve the Delta for desirable fish?

An analysis of the life history and environmental characteristics of the most abundant fish species in the Delta indicates that they fall into five distinct groups (assemblages) that respond differently to environmental change, indicating that changing conditions in the Delta will affect each group differently. The present configuration and management of the Delta has created environmental conditions that consistently favor less desirable non-native species and are unfavorable for desirable species. The condition of the Delta will most likely change to a system with much more open water, with poorly understood effects on fishes (although most likely better than the present system for most desirable fishes). Of the four water management options, halting exports completely from the Delta is most likely to significantly improve conditions for desirable fishes, although new invasions of harmful species can even reduce the positive effects of this option. Continuing the present policy that includes exporting large amounts of water through the southern Delta pumps will continue to promote the decline of many desirable fish species. No matter what option is adopted, numerous additional actions will have to be taken to improve conditions in the Delta and Suisun Marsh for desirable fishes. All will require innovative management and some will require major land and channel manipulations.

Acknowledgments

Numerous people have contributed to this appendix, directly or indirectly, through numerous discussions. Some of these people are Jeffrey Mount, Jay Lund, Ellen Hanak, Bill Fleenor, Richard Howitt, Wim Kimmerer, Robert Schroeter, Chris Enright, and John Durand. We thank Bruce Herbold, Fred Nichols, and Ted Sommers for helpful comments on an earlier draft.

This appendix reflects the views of the authors and does not necessarily reflect the views of the staff, officers, or Board of Directors of the Public Policy Institute of California.

Acronyms

CVP	Central Valley Project
DWR	Department of Water Resources
EC	Electro-conductivity (salinity indicator)
ENSO	El Nino Southern Oscillation
ESA	Endangered Species Act
IEP	Interagency Ecological Program
PC	Peripheral Canal
PCA	Principal Components Analysis
PDO	Pacific Decadal Oscillation
POD	Pelagic organism decline
SWP	State Water Project
SWRCB	State Water Resources Control Board
USBR	US Bureau of Reclamation
USFWS	US Fish and Wildlife Service

Introduction

Terminal floodplain systems of the world, such as the Sacramento-San Joaquin Delta, the Okavango Delta in Africa, the Mekong Delta in Southeast Asia, and the Ganges River Delta in Bangladesh are undergoing or are threatened with massive reconstruction as the result of climate change (including sea level rise), diversion of freshwater inflows, and intense human use of the floodplain landscape (Lund et al. 2007, Mosepele et al. in press, Hogan et al. 2004, Black 2008). One of the most conspicuous results of this change has been a shift in fish faunas and a decline in fisheries. Some of the most extreme change has taken place in California, not only in the Delta, but also in the Tulare Lake Basin, where the historic terminal floodplain system has been almost completely turned into farmland, eliminating the native fish fauna and once-productive fisheries (Moyle 2002). The problems facing the Sacramento-San Joaquin Delta (henceforth, the Delta) are thus found worldwide, although the Delta is one of the most highly altered of the world's terminal floodplain systems, as reflected in its declining fish and fisheries.

Fish, therefore, because of their economic and iconic value, increasingly drive major decisions for managing the Delta as an ecosystem. This shift in policy followed decades of letting the fish fend for themselves, or in the case of Chinook salmon, steelhead, and striped bass, raising them in hatcheries which served as short-sighted attempts to mitigate for fragmentation of their natural habitats and for direct entrainment in water export facilities. In some of the first regulatory actions that recognized the importance of the Delta to fish, the State Water Resources Control Board (SWRCB) determined in the 1970s (Decisions 1379 and 1485), that outflow standards had to protect fish and wildlife, especially striped bass. Eventually, the importance of fish rose dramatically with the listing of the winter-run Chinook salmon as threatened under the federal Endangered Species Act (ESA) in 1989 (the listing changed to endangered in 1994) and the listing as threatened of delta smelt in 1993, followed by listings of spring-run Chinook salmon, Central Valley steelhead, and southern green sturgeon. Other species, such as longfin smelt, are most likely to be listed under the ESA in the near future.

Despite the listings, policymakers, with the implicit approval of water and fisheries managers, have generally assumed that with careful monitoring and management of dams, diversions, and other water facilities, including the federal and state pumping plants in the southern Delta, water exports could steadily increase without harming fish populations. Yet after decades of monitoring entrainment losses of fish at the pumping plants, the consequences of direct and indirect pumping effects on populations of desirable fishes generally remains uncertain, although recent efforts are beginning to estimate the likelihood of its importance (Kimmerer 2008, Grimaldo et al. submitted). Nevertheless, as pumping from the southern Delta has increased, key fish populations have clearly decreased, demonstrating a general failure to manage the system adequately for fish. The failure in managing the ecosystem, including water exports, for fish in the Delta has been evident in the steady declines of pelagic (open water) fishes, most conspicuously the threatened delta smelt. It is also evident in the declining populations of all four runs of Chinook salmon, recently leading to the complete closure of one of California's most valuable fisheries. One result of these fish declines was the ruling by U.S. District Court Judge Oliver Wanger, in September 2007 which, in effect, restricted pumping from the southern Delta to improve conditions for delta smelt.[1] A similar ruling for the two listed runs of Chinook salmon was issued by Judge Wanger in April 2008.[2]

The response to this fish-water crisis has been to establish diverse efforts to find solutions, including Governor Schwarzenegger's Blue Ribbon Task Force (Isenberg et al., 2008), the revision of the Delta Native Fishes Recovery Plan by the U.S. Fish and Wildlife Service (USFWS), the Department of Water Resources' (DWR) Delta Risk Management Strategy (DRMS) study, and the development of a Bay-Delta Conservation Plan. However, an independent study (Lund et al. 2007) pointed out that successful solutions to the fish-water crisis must recognize that physical, biological, and economic solutions need to accept that the Delta is changing rapidly and is likely to be very different in the near future (within the next 50 years) than it is today. This conclusion is reinforced in the present report (Chapter 2 and Appendix B). The Delta is extremely likely to change from a system of tidal freshwater channels flowing between levees enclosing islands used for farmland, to a more diverse system with many flooded islands and large amounts of open water.

Continuation of a geographically static Delta and Suisun Marsh with armored and frequently repaired levees around all islands is unlikely. In any case, maintaining the Delta in its same configuration would likely make it increasingly inhospitable for desirable (including listed) fish species without huge and risky investments in: (1) gates, flood bypasses, and other means to manipulate flow patterns, (2) leveed islands flooded specifically for fish conservation purposes with gates and pumps to control salinity and biotic invaders, (3) conservation sites, such as Cache Slough and Yolo Bypass, on the edges of the main Delta, (4) extra releases of water from reservoirs, and (5) invasive species control and other management continuous actions. To some extent, the actions requiring intensive engineering for ecosystem purposes would artificially (and probably expensively) create attributes similar to those of the Delta we consider likely to develop more naturally under other management alternatives. Thus, we do not consider further the maintainance of the current configuration of Delta levees.

Regardless of eventual configuration, the future Delta requires changes in water management. The four broad water export alternatives for the Delta considered in this study are: (1) continued through-Delta export pumping, (2) water conveyance around the Delta (a peripheral canal), (3) a dual conveyance system, combining the first two alternatives, and (4) eliminating the Delta as a source of water for export users. In this appendix, we first consider how these different alternatives might perform over time from the perspective of desirable Delta fish species. We then recognize that solving the fish/ecosystem problem will require large investments and innovative management regardless of which alternative is implemented. We thus describe some of these likely solutions that will need to transcend merely minimizing water exports as they apply to fish. Although they are only a few of many ecosystem

---

[1] The final order was issued in December 2007. See Natural Resources Defense Council, et al. v. Kempthorne, Findings of Fact and Conclusions of Law Re Interim Remedies Re: Delta Smelt ESA Remand and Reconsultation, United States District Court, Eastern District of California, 1:05-cv-1207 OWW GSA (2007) .

[2] The April 2008 ruling holds that the 2004 biological opinion issued by the National Marine Fisheries Service regarding the ability of federal and state water export projects to protect winter and spring-run Chinook salmon and steelhead was invalid. Subsequent proceedings will determine remedies and may involve pumping cutbacks.

components that will be affected by the various proposed solutions, we focus on fish because they are currently major drivers of ecosystem-related policy due to their traditional high iconic status and economic value in fisheries.

The basic questions we attempt to answer are:

1. What species of fish are important (desirable) for making decisions about factors that affect ecosystem function?

2. What are the likely attributes of the Delta ecosystem in the future?

3. How are the four water export alternatives likely to affect fish?

4. What actions can be taken to improve the Delta for desirable fish?

1. Desirable Fish Species

Over 50 species of fish have been found in the Delta (Moyle 2002, 2008), but only about 32 are common enough to be encountered on a regular basis, in numbers (Table D.1). Of these species, we classify 16 as "desirable" from a management perspective (with a score of 2 through 4 in Table D.1) because they have at least two of the following attributes: (a) listed as threatened or endangered, or proposed for listing, under state or federal endangered species acts; (b) support a sport, subsistence, or commercial fishery, or serving an important function as forage for fishery species; (c) endemic or native; and (d) dependent on the estuary, especially the Delta, to complete their life cycle, either by living there or migrating through it.

Under this classification, anadromous fishes (fish that live in ocean water and move inland to spawn, such as salmon) are estuarine-dependent because conditions must be suitable for survival of both juveniles and adults migrating through the system. Striped bass and American shad are regarded as desirable despite being non-native species, because they are estuarine-dependent, have been naturalized in the system for well-over a century, and have long supported important sport fisheries. In contrast, largemouth bass are not regarded as desirable even though they have recently become a major sport fish in the Delta. Largemouth bass are not native, are not estuarine-dependent; they are actually increasing in abundance in habitats that once favored the endangered species.

Table D.1 - Common fishes of the Delta and their desirability rating

a) Desirable fishes

Species	Status	Fisheries	Native	Key attributes	Dependence on Delta	Delta Desirability rating
Delta smelt	T	none	Y	1 yr life cycle Delta endemic	Spawning and rearing	4
Longfin smelt	T*	none	Y	2 yr life cycle	Spawning and rearing	4
Green sturgeon	T	minor	Y	Mainly river & ocean species	Anadromous	4
Steelhead rainbow trout	T	important	Y	Passes through as adult, juveniles	Anadromous	4
Spring chinook	T	Formerly important	Y	Same	Anadromous	4
Winter Chinook	T	Formerly important	Y	Same	Anadromous	4
Fall Chinook	D	important	Y	Same	Anadromous	3
Late-fall chinook	SC	important	Y	Same	Anadromous	3
White sturgeon	D	important	Y	Much of life cycle in estuary	Anadromous	3
Pacific lamprey	D	minor	Y	Same	Anadromous	3
Splittail	SC	minor	Y	Floodplain spawner	Migratory, rearing	3
Striped bass	D	important	N	Piscivore, estuary dependent	Semi-anadromous	2
American shad	D	important	N	Plankton feeder	Anadromous	2

Sacramento blackfish	D	minor	Y	Omnivore, fresh water	No	2
Sacramento hitch	D	minor	Y	Insectivore, fresh water	No	2
Prickly sculpin	A	none	Y	Forage for predatory fishes	No	2

b) Other fishes

Species	Status	Fisheries	Native	Key attributes	Dependence on Delta	Delta Desirability rating
Tule perch	D	none	Y	Livebearer	No	1
Sacramento sucker	A	none	Y	Bottom feeder, spawns in streams	No	1
White catfish	A	Important	N	Bottom predator	No	1
Black bullhead	A	minor	N	Bottom scavenger	No	1
Largemouth bass	A	important	N	Top carnivore *Egeria* beds	No	1
Bluegill	A	minor	N	Insectivore *Egeria* beds	No	1
Redear sunfish	A	minor	N	Insectivore *Egeria* beds	No	1
Common carp	A	minor	N	Disturbs bottom	No	1
Threadfin shad	A	none	N	Forage for predatory fishes esp. striped bass	No	1
Golden shiner	A	none	N	Bait fish	No	0
Wakasagi	?	none	N	Invasive	No	0
Bigscale logperch	A	none	N	Cryptic bottom fish	No	0
Inland silverside	A	none	N	Egg and larval predator	No	0
Shimofuri goby	A	none	N	Small, pelagic larvae	No	0
Yellowfin goby	A	none	N	Benthic predator	No	0
Western mosquitofish	A	none	N	Small, planted for mosquito control	No	0

Notes: Abbreviations are as follows: Status (T = listed as threatened or endangered, SC = state special concern species, D =declining, A= abundant or common); Native (Y = yes, N = no); Dependence on estuary (No = not dependent, anadromous = important for passage and/or rearing). The Delta desirability rating is based on the number of desirable attributes, out of four (see text), although any listed (threatened or endangered) species automatically was assigned a score of "4." Overall ranks can be interpreted as follows: 0 = low, non-native, nuisance etc., 1= native species that does not require Delta for persistence or non-native with some value to fisheries, 2 = non-native estuarine dependent species with important fishery or native species with fishery or other desirable attributes, 3 = estuarine-dependent native species, with fishery, 4 = listed. Many other species also are found in the Delta but these species are less abundant and/or less widely distributed than species presented here. Scientific names appear in Moyle (2002) or Matern et al. (2002).

* The longfin smelt has been proposed for state and federal listing, and is treated as a listed species here.

Fish Groupings

To examine if fishes of the Delta could be grouped into assemblages that would likely respond to habitat changes in a similar fashion, we scored 26 of the 32 common species for ten metrics that define their life history strategies and environmental tolerances (Table D.2). Following previous studies with North American fishes (Winemiller and Rose 1992), fishes worldwide (Vila-Gispert et al. 2002), and Delta fishes (Nobriga et al. 2005), we examined their similarities using a principal components analysis (PCA) (Manly 2005). The first three principal components (components) explain 78 percent of the variance in life history and habitat metrics (Figure D.1). The loadings of each metric and score of each species on the three components, especially components 2 and 3, resulted in five fairly consistent groups of fishes (Figure D.2):

1. Short-lived native pelagic species (delta smelt, longfin smelt), desirable in our classification (denoted in red in Figure D.2);

2. Delta freshwater planktivores (threadfin shad, inland silverside, hitch), mostly not desirable (magenta in Figure D.2)

3. Anadromous species (striped bass, American shad, Chinook salmon) plus brackish water benthic species (those that live on or near the bottom, including staghorn sculpin, starry flounder) – a group composed of mostly native, salinity-tolerant fishes (blue in Figure D.2)

4. Slough-resident fishes (mostly non-native species associated with beds of aquatic vegetation, including largemouth bass, bluegill, bigscale logperch, common carp, white catfish), not desirable (green in Figure D.2)

5. Freshwater benthic fishes (mostly native species: splittail, Sacramento sucker, prickly sculpin, tule perch, plus the non-native mosquitofish and shimofuri goby) – a group including some desirable fishes (black in Figure D.2).

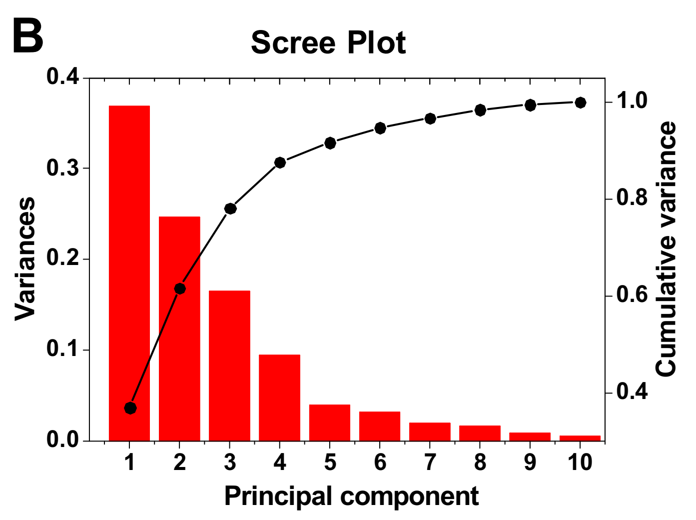
.Table D.2 - Characteristics of 26 common Delta fish species used in the principal components analysis

Species	Code	Spawning	Life Span	Size Mat.	Fecundity	Migration	Gen. time	Parent care	Temperature	Salinity	Habitat
Delta smelt*	DS	2	2	2	3	3	2	2	3	3	2
Longfin smelt*	LFS	2	3	3	4	4	3	2	3	3	2
Chinook salmon*	KS	2	4	6	4	5	4	3	2	4	3
Splittail*	SPT	4	5	3	5	3	4	2	3	3	5
Striped bass*	SB	2	6	6	6	4	5	2	3	4	2
Sacramento hitch*	HIT	2	5	3	5	2	4	2	4	2	2
Sacramento sucker	SUK	2	6	4	4	3	5	2	3	2	5
Tule perch	TP	2	5	3	2	2	3	5	3	3	3
Prickly sculpin*	PSCP	2	5	2	4	2	3	4	3	3	5
American shad*	AmS	2	5	5	6	5	5	2	3	4	2
White catfish	WCF	2	6	4	3	2	4	4	4	2	5
Largemouth bass	LB	3	6	4	4	2	4	4	4	2	4
Bluegill	BG	3	5	3	5	2	4	4	4	2	4
Redear sunfish	RSN	3	5	3	5	2	4	2	4	2	4
Golden shiner	GSN	3	5	3	4	2	2	2	4	2	4
Bigscale logperch	BLP	3	4	2	3	2	3	4	4	2	4
Inland silverside	ISS	4	3	2	5	2	2	2	4	4	3
Common carp	CP	4	6	4	6	2	5	2	4	2	5
Threadfin shad	TFS	2	4	2	5	2	2	2	4	2	2
West. mosquitofish	MoQ	3	2	2	3	2	2	5	4	2	4
Shimofuri goby	SG	3	2	2	3	2	2	4	4	3	5
Yellowfin goby	YFG	2	4	3	5	3	3	4	3	4	5
Three-spine stickleback	STBK	3	2	2	3	3	2	4	2	4	4
Staghorn sculpin	STAG	2	3	3	4	3	2	4	2	4	5
Starry flounder	SF	2	5	4	5	5	3	2	2	4	5
Sac. pikeminnow	SASQ	2	6	4	5	2	4	2	4	2	3

Notes: Explanation of each metric appears in Addendum D1. * indicates desirable species following classification in Table D.1.

A Data labels

Species	Code
delta smelt	DS
longfin smelt	LFS
chinook salmon	KS
splittail	SPT
striped bass	SB
hitch	HIT
sucker	SKR
tule perch	TP
prickly sculpin	PSCP
American shad	AMS
white catfish	WCF
largemouth bass	LMB
bluegill	BG
redear sunfish	RSN
golden shiner	GSN
bigscale logperch	BLP
inland silverside	ISS
common carp	CP
threadfin shad	TFS
west mosquitofish	MSQ
shimofuri goby	SG
yellowfin goby	YFG
3-spine stickleback	STBK
staghorn sculpin	STAG
starry flounder	SF
pikeminnow	PKM



C Component Loadings

Life History Metric	PC 1	PC 2	PC 3
Spawn frequency	0.12290	-0.20717	0.04870
Life Span	-0.46604	-0.38186	-0.16339
Size at Maturity	-0.48997	0.04263	-0.25761
Fecundity	-0.30002	-0.01987	0.17554
Anadromous	-0.26211	0.52748	-0.15117
Generation time	-0.46539	-0.20798	-0.18254
Parental care	0.35633	-0.07910	-0.56904
Temperature	0.04276	-0.38309	0.27890
Salinity	-0.02242	0.51485	-0.18810
Habitat	0.15177	-0.26359	-0.61694

Figure D.1 Overview of principal components analysis of Delta fish species

Notes: (A): List of Delta fish species with abbreviations; (B) Scree Plot showing relative importance (percent variation explained) of each principal component; (C) Metrics of life history characteristics and environmental tolerances as ranked (loadings) on the first three axes from the principal components analysis. These three components together explained 78% of the variation in the metrics among 26 Delta fish species. High negative (red highlight) and positive (blue highlight) loadings were used to interpret each component.

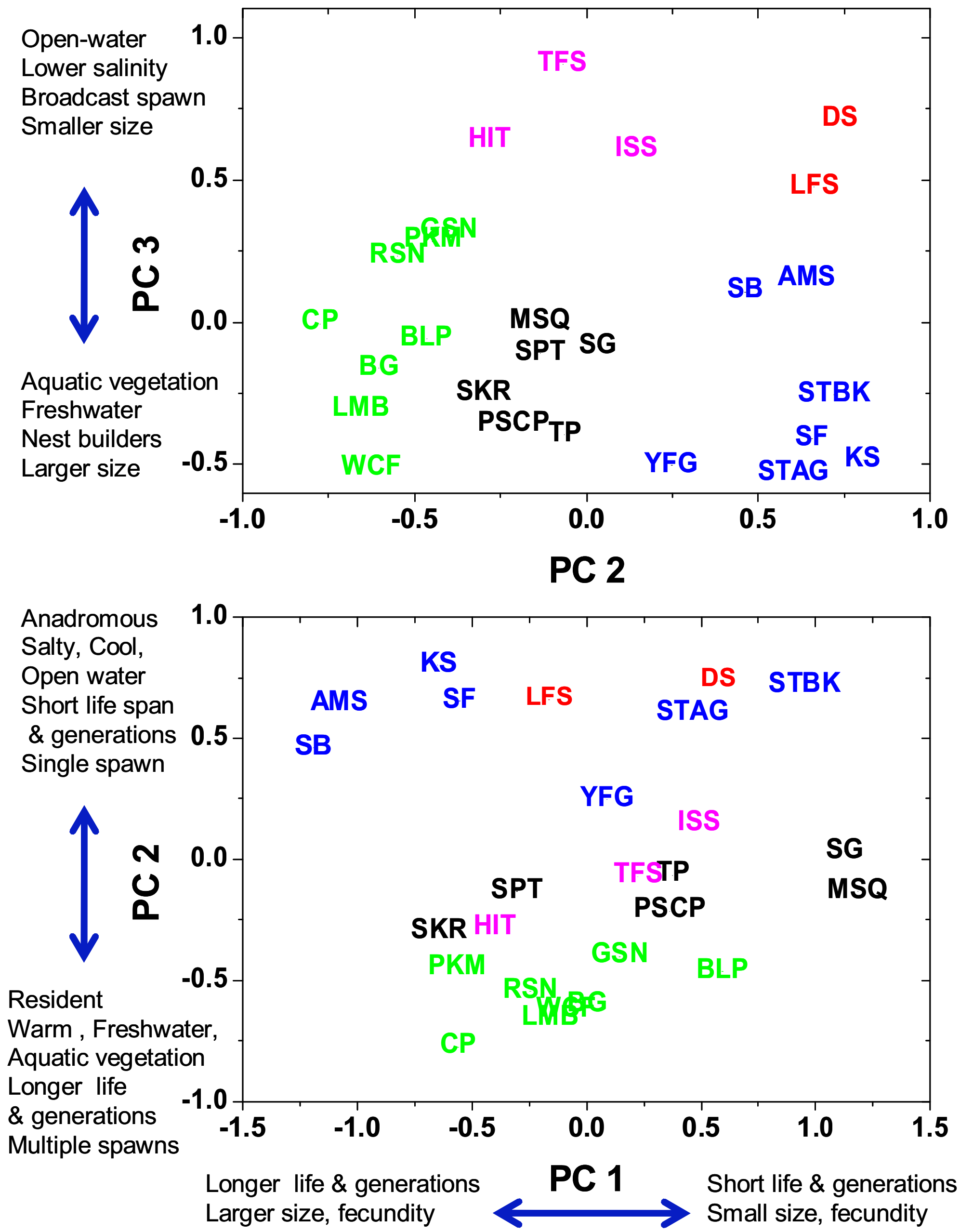


Figure D.2 Assemblages of fishes that respond to changes in Delta conditions in a similar fashion

Notes: Figures plot distribution of 26 fish species along the three axes, or principal components, noted in Figure D.1. The lower graph mainly separates the fish by life history traits (temporal scale) with some separation by broad habitat, while the upper graph separates fish by habitats (spatial scale). Data symbols are species codes (see Figure D.1) which are color-coded to group species into roughly distinct assemblages with similar life history and habitat requirements: red = group one: short-lived estuarine pelagic species; magenta = group two: Delta freshwater planktivores; blue = group three: anadromous and brackish-water benthic species; green = group four: slough-resident, aquatic vegetation species; black = group five: freshwater benthic species.

The first principal component loads most heavily on life history characteristics (life span, fecundity, etc.), the second component loads heavily on a combination of life history and habitat characteristics and the third component loads most heavily on habitat characteristics. Thus, plotting the scores for each species for components one (PC1) and two (PC2) against one another aligns the fish from large long-lived species to smaller and short-lived species, with some tilt towards more estuarine-dependent species on top and less estuarine-dependent species on bottom. The plot of species scores for PC 2 vs PC 3 divides the fishes more clearly into the five habitat groupings: noted above. The life history strategies implied by these species groups are consistent with the findings of previous analyses (Winemiller and Rose 1992, Vila-Gispert et al. 2002, Nobriga et al. 2005) as well as other community-level studies (Matern et al. 2002, Brown and May 2006).

This analysis indicates that shifting Delta conditions and habitats will affect species assemblages disproportionately and over different time scales. It also suggests that the Delta can be managed to favor one or more groups (e.g., groups one and three – red and blue in Figure D.2). Thus, management actions favoring delta smelt and longfin smelt (red), such as increasing open water habitat, might also reduce abundance of centrarchid fishes (green); however, it may be several years before the effectiveness of such a management action could be judged due to the longer generation times of these undesirable fishes. Although this analysis further supports the concept that ecosystem-based management can be conducted to favor multiple desirable species, rather than having to focus on single-species management, it also indicates that most alien species will persist regardless of management strategy employed. While there could be some conflicts in managing the Delta for different species groups, the analysis suggests that desirable species in general will benefit from creation of habitats that tend to have cool water and to fluctuate in salinity, regardless of preference for open water or benthic habitats.

2. Ecosystem Change and Future Delta Attributes

The large scale-changes likely to take place in the Delta are discussed in Lund et al. (2007), Moyle (2008), Chapters 2 and 4 of the main report, and Appendices B and C. From a fish perspective, the most important changes will be: (1) increase in open-water habitat, (2) greater spatial and temporal habitat heterogeneity, (3) greater heterogeneity in water quality, and (4) increases in areas occupied by alien species that have major effects on ecosystem structure and function. The PCA results presented above suggest that species assemblages will respond to these changes differently. It follows that reassessing how the ecosystem has responded to management over previous decades can help in assessing what may happen in the future.

Recent Shifts in the Estuarine Environment

Here we first examine how the ecosystem shifted from a highly variable estuarine environment with desirable fish species to the current environment dominated by alien species with many endangered native species. For this analysis, we employed phase-space plots (Puccia and Levins 1985), which chart the relative position of key ecosystem physical drivers and fish assemblages over time, using data from long-term monitoring.

Data on physical variables include total volume of water exported from the state and federal facilities during the summer (July through September, from DAYFLOW), and water surface salinity (measured as electrical conductivity (EC)) and water clarity (measured as Secchi depth in centimeters (cm)) for Delta stations in the Inter-agency Ecological Program (IEP) summer tow-net fish survey.

Data for most fishes comprising the assemblages identified above were compiled for 20 Delta stations regularly sampled since 1976 by the IEP juvenile beach-seine survey for salmon smolts. Overall, this survey contains probably the best long-term record of any single survey for the Delta for documenting the expansion of alien fish species and the decline of natives, because of its broad geographic distribution and the inclusion of both benthic and pelagic fishes. Estimates of fish biomass by species (e.g., delta smelt) and assemblage (e.g., centrarchids, including largemouth bass and bluegill sunfish and pelagic species, including juvenile striped bass and delta smelt) were derived from catch and length frequency records and then transformed into biomass using length-weight relationships from Kimmerer et al. (2005). Time series of each physical variable and fish biomass estimate were first examined (Figure D.3). Then all physical variables and species or assemblage biomass estimates were standardized to zero mean and unit variance and plotted to examine relative changes over time (Figure D.4).

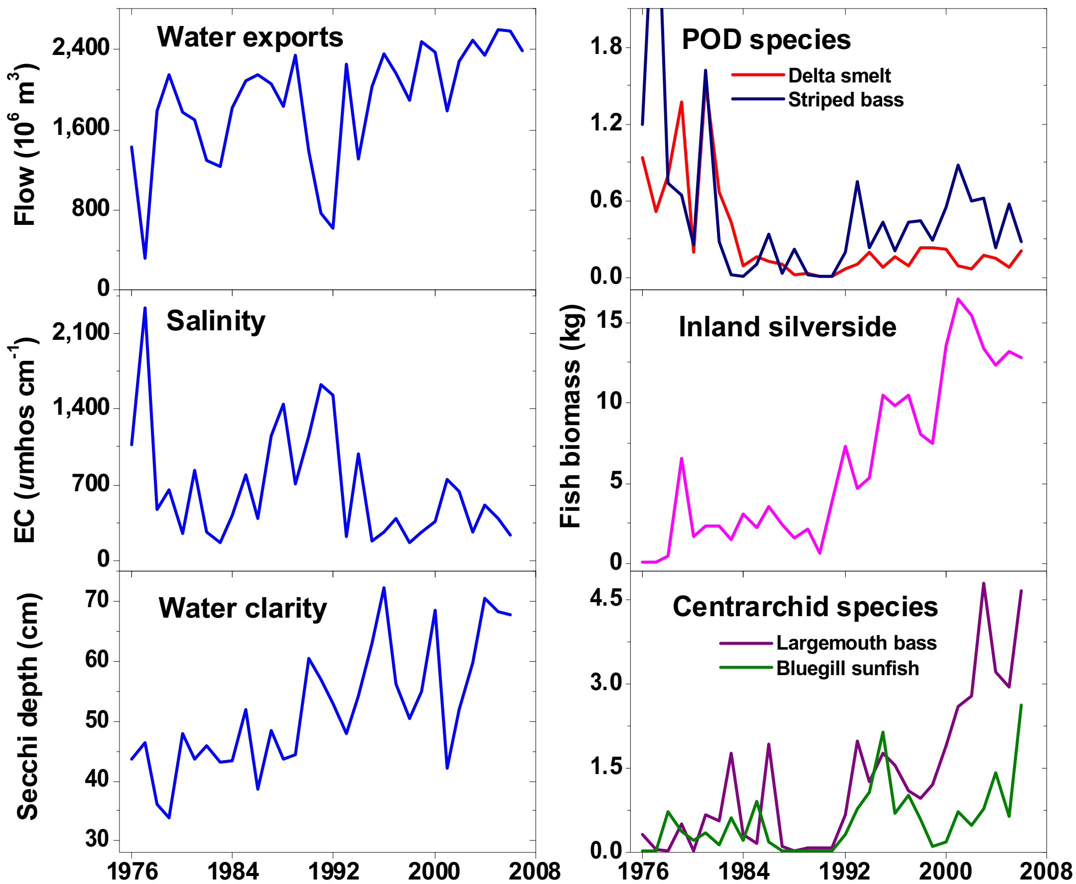


Figure D.3 Summer trends in key physical variables and fish biomass estimates for the Delta, 1976 – 2006

Sources and Notes: Water exports are the total flow rates for the State Water Project and Central Valley Project facilities during July-September (from DAYFLOW). Delta averaged surface salinity, as specific electrical conductance (EC), and water clarity, as Secchi depth, over 17 continuously sampled stations in the IEP summer tow-net survey. Estimates of fish biomass for delta smelt and juvenile striped bass (<150mm) (species targeted in the study of "pelagic organism decline" (POD)), inland silverside, as well as largemouth bass and bluegill sunfish (centrarchid species) are from 20 continuously sampled locations throughout the Delta in the IEP juvenile fish beach seine survey since 1976. Details and data for DAYFLOW are at www.iep.ca.gov/dayflow/index.html; data and sampling methods for each fish survey are at http://baydelta.ca.gov/.

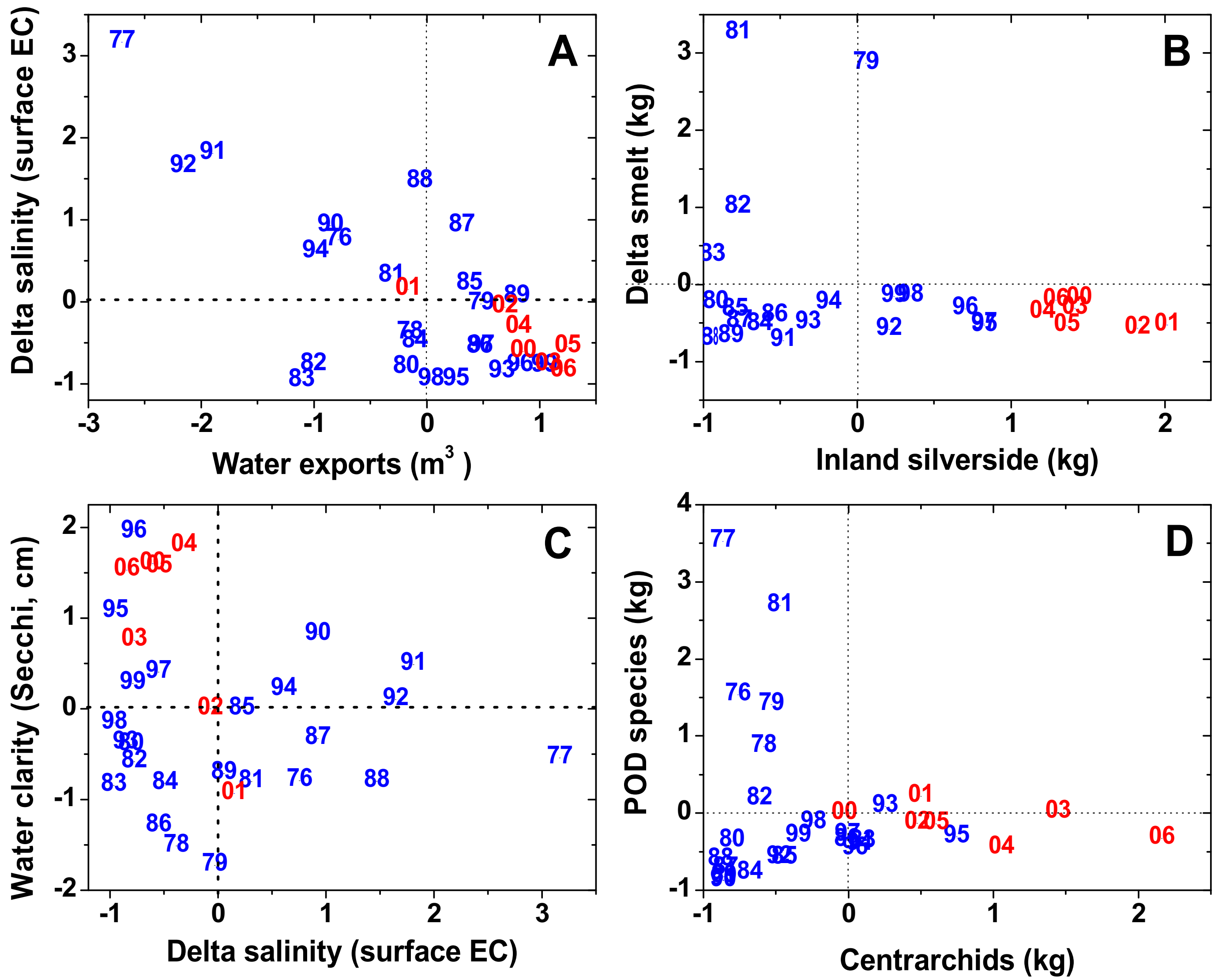


Figure D.4 Phase-space plots of physical variables and fish species or assemblages in the Delta, 1976 - 2006

Notes: Plots shows data plotted in Figure D.3 standardized with zero mean and unit standard deviation. Data symbols depict years, with those since 2000 in red.

Figure D.4 illustrates an ecosystem shift from a dynamic regime favoring delta smelt and other pelagic species to the current regime dominated by alien fishes and Brazilian waterweed. As water exports during summer increase, the variability in summer salinity decreases (panel A) presumably because of the need to keep Delta water fresh for export through releases from dams. As biomass of inland silverside (potential alien predator and competitor with delta smelt) increases, biomass of delta smelt becomes consistently small (panel B). As summer salinity becomes less variable, water clarity increases (the result of retention of sediment by reservoirs and increasing pond weed abundance) (panel C). As alien centrarchid fishes (largemouth bass, bluegill sunfish) become more abundant, biomass of native smelt and striped bass (POD species) becomes smaller and less variable in the sampling (panel D). For most plots, the points become closer together and in some cases appear to cycle in recent years (after 2000-01), suggesting a new ecological regime that will be difficult to shift back to a more desirable state.[3]

This shift presumably occurred as a result of the long-term (slow) process of steadily increasing pumping rates over time which requires the maintenance of freshwater conditions in the Delta during summer (Figure D.3), as well as the relatively rapid invasion by Brazilian waterweed and other factors that favored slough-resident (e.g., centrarchid species) and freshwater alien planktivore (e.g., inland silverside) fish assemblages. Species in these assemblages may suppress populations of desirable species through competition and predation (Bennett and Moyle 1996), and/or their expansion may reflect an overall shrinkage in brackish pelagic habitat required by native smelt and juvenile striped bass (Feyrer et al. 2007; Nobriga et al. 2008).

This scenario is similar to those reported for temperate freshwater lakes where interactions between multiple processes operating at different temporal scales work together to shift a "desirable" clear-water regime with abundant aquatic vegetation and centrarchid fishes to an "undesirable" turbid-water regime with less vegetation and abundant planktivorous fishes (Carpenter 2003, Scheffer and Carpenter 2003, Folke et al. 2004, Rogers and Allen 2008). Once the shift to turbid water has occurred, it is very hard for the lakes to switch back to a clear-water state. (The obvious difference here is that the desirable regime for the Delta is the opposite of the one for temperate lakes.) The lake examples imply considerable ability for ecosystem states to persist even when the cause of the shift to a different state is removed. Likewise, even with a shift of the current water management strategy, it will be very difficult for the Delta ecosystem to shift back to the desirable regime (i.e., one with abundant pelagic native fishes) due to the habitat-stabilizing properties of the Brazilian waterweed and life history strategies (e.g. longer life spans) of the centrarchid fishes.

Overall, the present state of the system will most likely continue as long as the Delta maintains its present configuration and water management practices. However, the current ecological regime is only as stable as the levees it depends upon, which means the Delta is bound to change again, to a different dynamic regime, as levees fail.

---

[3] The dynamic relationship among different ecosystem states is referred to as *hysteresis.* Hysteresis in this case refers to the potential of the Delta to shift among multiple stable states, each with a different but fairly predictable, persistent fish assemblage. The shift from one state to another is not necessarily readily reversible even if the conditions that caused the shift are removed. Instead, the ecosystem may shift to yet another state, perhaps one not seen before, or fail to shift at all (see Beisner et al. 2003 for a fuller explanation).

Ecosystem Response to Future Island Flooding

This future change in ecological regime will result from the combination of sea level rise, island subsidence, and fragile levees that make it extremely likely that many of the islands in the western and central Delta will breach and fill with water. The flooding is likely to occur on multiple islands simultaneously, with little opportunity to repair levees in an economically viable way (Appendix B and Chapter 2 of the main report). However, islands in the western Delta that are essential for keeping the water fresh at the intakes of the pumps may be repaired if Delta export diversions remain in use (Appendix C and Chapter 4 of main report).

It is often assumed that large-scale Delta island flooding will harm desirable fish (e.g., Delta Risk Management Strategy Program, 2007), especially given the experience with existing flooded islands, most notably Franks Tract in the Central Delta, which has become a home to numerous invasive species. However, our analysis suggests that Franks Tract is a poor model for the future Delta because it is much shallower than most future flooded islands will be. Moyle (2008) concluded that this drastically altered Delta will be a better place for many fish species, simply because of the much larger extent and volume of aquatic habitat. Whether desirable fish species will benefit substantially from this new condition is uncertain and will depend in part on the structure and management of the new system, especially in relation to salinity, temperature, and other aspects of water quality in the flooded area. If the flooding simultaneously involves several of the most subsided islands and no levee repair is attempted, then flooding is most likely to produce conditions that will ultimately favor desirable pelagic species such as delta smelt and striped bass.

For unplanned island failures, a "worst case" scenario would involve simultaneous levee failures on multiple islands during a period when river flows are not high. In this case, much of the volume of Suisun Bay would be sucked into the Delta ("the big gulp"), while Suisun Bay water would be replaced by salt water from San Pablo Bay. In the short run, this rapid change in conditions could cause extensive fish mortality. However, even in this situation, the ultimate consequence of permanent island flooding would be the creation of large areas of open water with depths of ten to 20 feet (three to six meters (m)), strongly mixed by winds, tides, and freshwater inflows. Of course, the configuration and location of flooded islands will affect their ability to support desirable fish species.

Presumably, flooded islands in the western and northwestern Delta (e.g., Sherman and Twitchell Islands) will provide the best habitat for desirable fishes because they will likely be more saline, at least seasonally, or fluctuate more in salinity across seasons. They are also adjacent to Sacramento River and northern Delta habitats traditionally favored by desirable fishes. However, key unknowns about the nature of the new open water habitat are: (1) the exact characteristics of the physical and chemical habitat created, such as depth, turbidity, flow, and salinity; (2) how productive this new habitat is likely to be in terms of algae, copepods, and other organisms that support food webs leading to fish; and (3) how susceptible it will be to invasions by harmful alien species such as overbite clam, Brazilian waterweed, and Asian clam.

Under any circumstances, island flooding *will* increase habitat heterogeneity in the Delta and Suisun Marsh by increasing the amount and diversity of aquatic habitats. Habitat diversity is a key ecosystem feature, potentially providing refuges in space and time that disproportionately favor desirable species and promote their persistence through adverse times. While there will be extensive open water habitat (of variable depths), many upstream areas will remain as tidal fresh water, flowing between leveed islands as it does today, and many peripheral areas will change, with or without human assistance. For example, Suisun Marsh is likely to become a largely subtidal and intertidal brackish water marsh (Figure D.5). Greater aquatic habitat heterogeneity also will increase water quality heterogeneity in the Delta, with more brackish water areas that seasonally will become fresh. Salinity and temperature also are likely to vary in complex ways with depth, area, and inflow patterns. In addition, climate change will increase water temperatures overall, but especially in spring and summer[4].

As islands flood and open water habitat increases, the first response is likely to be an increase in planktivorous fishes, as happened in Lake Okeechobee, Florida, following elimination of aquatic vegetation by the action of hurricanes (Rogers and Allen 2008). The beneficiary species would presumably be the open water fish groups (1 and 2), which contain species currently in decline, including delta smelt, longfin smelt, and juvenile striped bass. Jassby and Cloern (2000) indicate that flooded islands are likely to have somewhat increased phytoplankton production above that in the channels, favoring food webs leading to fish (Sobczak et al. 2002). Transport of nutrients and primary productivity from such areas to those of lower quality can further raise overall ecosystem productivity (Cloern 2007), and thereby promote species diversity and abundance of desirable fishes.

The existing dominant alien species (clams, plants) unfortunately will also likely take advantage of increased open water habitat. The big question is how much area these species will occupy and what effects they will have on ecosystem processes. Presumably the dominant aliens will be least abundant in areas that fluctuate the most in salinity. Their ability to colonize new areas also may be restricted by greater depths of islands (e.g., Brazilian waterweed seems to be restricted to depths above 11.5 to 13 feet (3.5 to 4.0 m) and other factors, such as wind-produced turbidity[5] and abundance of predators.

Thus, just creating more overall habitat space for desirable fishes is no guarantee that their populations will increase. The quality of the evolving waterscape also has to be complex in space and time, with some habitat patches producing high densities of food organisms that can be dispersed to neighboring areas with other desirable qualities. Still other patches may be effective as sinks, trapping toxic materials from pesticides to ammonium so that they do not affect the entire region. For example, low water clarity on flooded islands might inhibit phytoplankton growth, resulting in relatively unproductive open water habitat, but water on such islands may still be effective at providing refuges from predation for desirable fishes.

---

[4] We recognize that there is a high degree of uncertainty regarding the exact nature of the changes that are likely to take place in this flooded Delta; many scenarios are possible. Hydrodynamic modeling could provide a better idea of the changes in water quality and flow that are likely to result from island flooding, but we think there is already enough evidence to support the general supposition of increased aquatic habitat heterogeneity in space and time. .

[5] Jassby and Cloern (2000) indicate that flooded islands may actually be clearer than surrounding channels are today because particulate matter would settle out. We assume, however, that the winds that blow for much of the time (with fairly long periods of calm) will keep the water stirred up, decreasing clarity much of the time. This is one of the many aspects of flooded islands that would benefit from a modeling study or experimental flooding of an island.

Likewise, low nutrient concentrations or high densities of alien clams could limit pelagic productivity of some new areas. However, habitats with high productivity that are connected to low productivity areas can subsidize such local deficiencies and provide higher quality habitat overall. All of these attributes will vary depending on human manipulation of the ecosystem, as discussed in the final sections of this appendix.

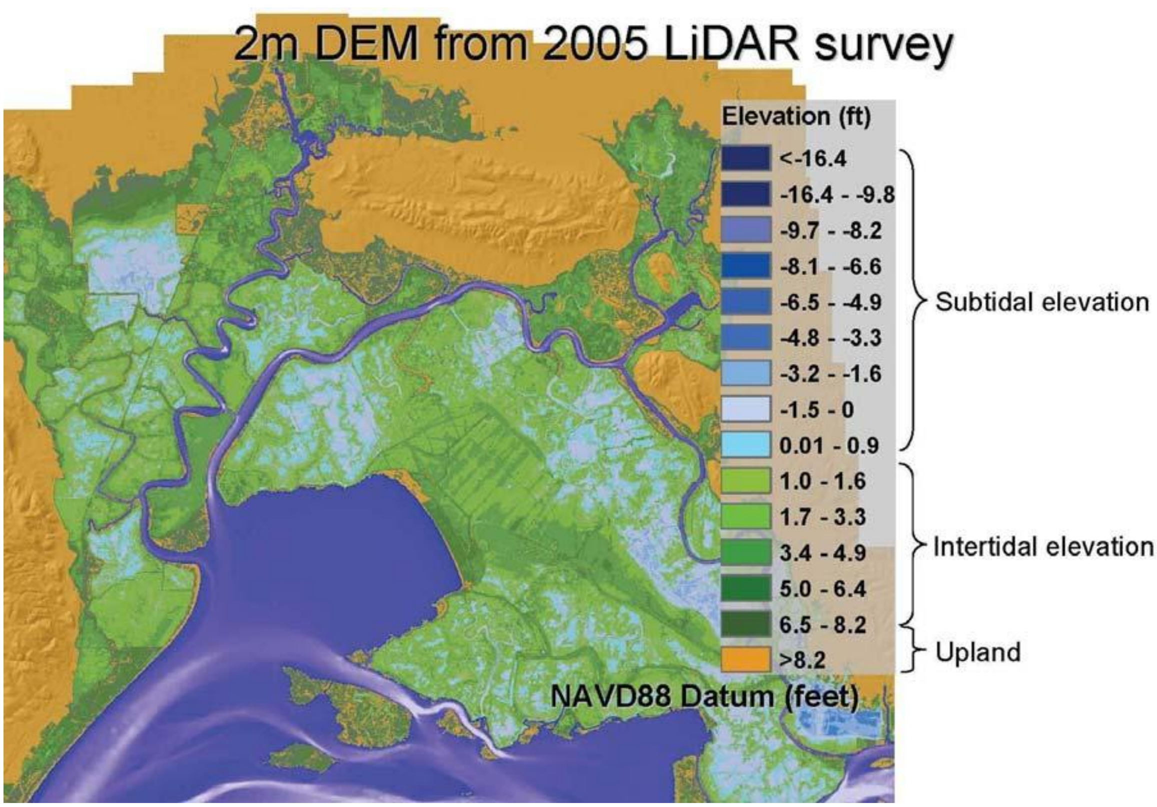


Figure D.5. Digital elevation model of Suisun Marsh

Source: Based on 2m grid from September 2005 LIDAR survey. Figure provided by Chris Enright, DWR.

Notes: Negative elevations indicate depths of areas that would be flooded under current conditions if all levees disappeared. Regions in blue are subsided below local mean low water. Regions in green have intertidal elevations between about 1.0 and 6.7 feet. Upland regions are shown in brown. Generally, elevations shown here are biased upwards because LIDAR reflects elevation at plant height; Actual elevations are roughly one to three feet lower. Land areas lower than about 6.7 feet have undergone soil oxidation and subsidence due to land use practices. Bay and slough depths are measured using the ten meter bathymetry grid developed by USGS.

3. Export Alternatives and Fish

The four broad water export alternatives available to California are (1) continued through-Delta exports, (2) a peripheral canal, (3) a dual conveyance system (combining through-Delta pumping and a canal), and (4) ending Delta exports. These four alternatives represent classes of solutions with an array of potential configurations. Each alternative will have to be implemented in a dramatically altered Delta, with an unknown geographic and biotic configuration. Thus, predicting each alternative's effects on fish is highly speculative and likely to be wrong, at least in the details. Nevertheless, a discussion of likely effects is useful for helping to make strategic decisions about which alternative to implement.

As a first cut in this analysis, we surveyed a group of estuarine experts familiar with the Delta regarding the likely outcomes for four desirable fishes (delta smelt, longfin smelt, young-of-year striped bass, and Sacramento River salmon) (Appendix E). Most participants felt that, under present circumstances, ending exports would probably provide the greatest benefits for desirable fishes, while continuing through-Delta exports would be least likely to benefit the three pelagic fishes. Under future conditions, several decades hence, through-Delta exports were also viewed as the worst option for salmon. The group also indicated that there was considerable potential for significantly improving fish outcomes by "doing everything right" including carefully managing water exports. There was also a general consensus that it might become harder to manage the Delta for favorable fish outcomes in the future, when considering the added effects of climate change, including island flooding. The results of this exercise, which relied on a rapid expert assessment based on individuals' informed judgments, helped us to evaluate in more detail the likely effects of the four alternatives in the future Delta, especially in terms of their likely impacts on fish populations.

Delta Exports. The characteristics of this alternative could range from the present system of drawing water through Delta channels to the pumps in the southern Delta to some version of the armored aqueduct described in Lund et al. (2007) - a through-Delta solution that relies on reinforcing the main passageway from the Sacramento River to the pumps to protect export waters from increasing salinity as sea level rises (for an illustration, see Figure 3.1 of the main report).

Continuing the present through-Delta pumping strategy implies maintaining the ecosystem in its current state, which is detrimental to desirable species, and prolonging the current saga of fish entrainment and related habitat problems. Modifying the system towards something like an armored aqueduct would likely create new problems, including how to move migratory fish through, around, or underneath the armored channel. It is, however, possible that some aspects of the new habitats (e.g., more open water) could partially compensate for the effects of pumping. This would be worth exploring in modeling scenarios.

Peripheral canal. With this export strategy, a peripheral canal (PC) would take Sacramento River water around the Delta to the existing pumps in the southern Delta. The intake(s) would have to be far enough upstream to avoid salt water and entrainment of native fish (e.g., delta smelt), and would have to be screened and operated to avoid entraining juvenile salmon and the eggs and larvae of striped bass, American shad, and other fish migrating down the river. However, the proposed size, location, and configuration of the canal could vary greatly (Appendix G). A fundamental biological advantage of a PC is that it could separate water supply from ecosystem functions, which currently are intertwined (Lund et al. 2007). A PC could better meet both water supply and ecosystem objectives, allowing the Delta to be reconfigured and managed for desirable organisms, within the constraints provided by the amount of freshwater inflow, alien species, toxicants, and other factors. Nevertheless, the principal problems for fish that any configuration of the PC would create include:

1. The intake(s) would have to be covered with large fish screens and even the best screens are prone to failure or are less effective than advertised (Moyle and Israel 2005). Intakes provide places for predatory fishes to lie in wait for prey. Out-migrating juvenile salmon would be vulnerable to the intake in most months, as would fishes such as striped bass and splittail seasonally. Striped bass eggs and larvae moving past the intake would be too small to be screened and would be entrained when present, unless the intake were shut down during their passage. A large intake operated during low flows or flood tides might even reverse flows and entrain delta smelt and other desirable native fishes.

2. Water entering the Delta from the San Joaquin River would no longer be as diluted with Sacramento River water or be as likely to be diverted into the Central Valley Project pumps (Appendix C). Overall, a higher percentage of San Joaquin River water, with its load of salts, toxicants, and other pollutants from agricultural and urban discharges, would spread more widely into the Delta. Jassby et al. (2002) also found that the San Joaquin River was a major source of carbon for the Delta, a benefit which may partially offset its negative effects. Eventually, higher quality water exports from a PC should alter water quality in the San Joaquin River by improving the quality of agricultural runoff, but the delay and magnitude of this effect are unknown.

3. Less water entering the Delta from the Sacramento River in some periods may reduce connectivity to Suisun Marsh and Bay for species that migrate seasonally, including delta smelt, splittail, and Chinook salmon. This could presumably be mitigated in part by managing outflows to benefit migratory species.

These potential disadvantages would have to be weighed against the overall advantage of having a Delta with a more "natural" tidal hydrology (less cross-Delta movement of water), especially in the context of a future, greatly altered ecosystem, as envisioned above. In our estimates of fish viability under a peripheral canal (Appendix J and chapter 8 of the main report), we assume that minimizing the potential environmental problems associated with a canal will be a precondition for a PC solution.

Dual facility. Under a dual facility arrangement, the PC might be smaller (or take a smaller total volume of exports), while the through-Delta export system would likely remain less armored and the southern Delta pumps would be used mainly for opportunistic pumping of water directly from the Delta (during high outflows). A dual facility might have fewer Sacramento River entrainment problems than a pure peripheral canal, through either smaller intake size for the canal portion or the ability to switch pumping between the two intake locations when large numbers of salmon or striped bass are moving down the river. However, through-Delta exports would still be able to entrain delta smelt and other desirable fish at virtually any time of year, so the main advantage of the dual facility would seem to be more flexibility in pumping between the two sources to reduce fish impacts and increase water supply reliability. The potential for opportunistic pumping from within the Delta is likely to diminish as sea level rises and western islands flood, because periods of high flow (winter and early spring) when water will be freshest (Appendix C and Chapter 4 of main report) tend to correspond to periods when pumping may have to be limited to avoid entrainment of smelt and other fishes.

Ending Delta exports. Ending exports would likely aid populations of desirable fishes, especially in low-flow years. The benefits would come from ending the effects of fish entrainment in the pumping plants and in ending the complex cross-Delta water movement patterns that now exist. This would return the Delta to a more natural pattern of hydrology, especially because the net annual outflows would presumably be higher as well. Of course, this optimistic result (different than reported in Lund et al. 2007) would happen mainly if considerable investment were made in improving habitat conditions for fish (next section), if large-scale flooding happened in ways beneficial to fish, and if upstream diversions did not increase significantly or change in timing. The end of exports would also presumably increase the influence of polluted San Joaquin River water on the Delta, perhaps negating some of the positive flow effects.

4. Actions to Improve Conditions for Fish

In the Delta, we are confronted with rebuilding an ecosystem, starting from existing base conditions that include constituents and characteristics unlike anything that existed previously. Obviously, the new Delta will be very different from the present system. Regardless of their location, water diversions will continue to have major ecosystem effects on the Sacramento-San Joaquin river system and Delta, as will upstream diversions, landscape alterations, habitat fragmentation from dams, levees, and by-pass systems, and other factors. These effects must be compensated by diverse actions if the new ecosystem is to support desirable fish and other creatures. Here are some of the rebuilding strategies that may lead to an ecosystem that favors desirable fish species. Other actions are described in the California Resources Agency's 2007 *Pelagic Fish Action Plan.* Given the many factors effecting fish declines, most of these actions would be required even if water exports were ended altogether.

Adaptive Management

The importance of adaptive management is discussed in Lund et al. (2007). Basically this means developing a coordinated, system-wide vision and plan for ecosystem rebuilding (i.e., conducting landscape design with population ecology objectives), with management decisions guided by large-scale experimentation and modeling. Because we are building a new ecosystem, experimentation is needed to improve scientific understanding and predict the effectiveness of management actions. The following recommendations are assumed to operate within such an adaptive management framework.

Flow Regime

The concept of a "Natural Flow Regime" is increasingly being applied to regulated rivers (Poff et al. 1997, 2007; Moyle and Mount 2007) allowing the development of flow regimes that favor native species adapted to a seasonal pattern of stream flow. Maintaining the natural pattern, even if total flow is diminished, has been shown to be surprisingly effective (e.g., Marchetti and Moyle 2001). Thus migratory fishes in the San Francisco Estuary (Table D.1) tend to move upstream to spawn in winter and spring, usually in response to increased outflows, and then use spring flows, combined with tidal currents, to move their young to suitable rearing areas downstream.

For example, splittail move upstream in winter to spawn on floodplains. As spring river flows decline and flooded areas drain, juvenile splittail enter the river and the Delta, moving downstream to rearing areas in Suisun Marsh and elsewhere (Moyle et al. 2004). Pumping in the southern Delta regularly reverses the natural seaward flow of rivers and sloughs in that region, disrupting the movement of delta smelt to low salinity habitat. The large number of young fish lost with the exported water is at least partially responsible for the smelt decline, especially in recent years (Bennett 2005; unpublished data).

Present flows in the Delta are created by the interaction of inflowing fresh water, tidal currents, and Delta pumping, with inflows determined by uncontrolled natural runoff, releases from dams, and upstream diversions. A fish-friendly Delta inflow regime will have to be flexible enough to adjust to changes in ecosystem physical structure (e.g., island flooding) while providing flows needed for desirable species to successfully complete their life histories (e.g., for spawning of Delta smelt or for maximizing survival of juvenile Chinook salmon). The four water export strategies should be evaluated to assess how each changes the hydrologic regime and how each can be altered to provide conditions for desirable fishes. Even in the case of ending exports, upstream diversions and reservoir operations significantly affect the flow regime, so changes in water management would have to be part of the evaluation.

Alien Species

Aggressive alien species (especially the "ecosystem engineers" - species that significantly alter habitat to facilitate their colonization) continually hinder conservation efforts in the San Francisco Estuary. As long as new species invade, their effects are going to be surprising and stochastic factors that frustrate good management of the estuary, underscoring the need for adaptive management. Lund et al. (2007, Table 3.1) provide a list of species poised to invade the Delta ecosystem with likely negative consequences.

Zebra and quagga mussels have invaded reservoirs in California recently and are likely to arrive in the Delta soon, probably carried by careless boat owners. These mussels could do major damage to the water supply systems in the Delta and cause further damage to the ecosystem by removing phytoplankton and zooplankton (Cohen 2005, 2007). To prevent such invasions, California needs to develop an aggressive regulatory and enforcement system to prevent new invasions of alien species statewide, along with tools to react quickly to eradicate newly established aliens, to prevent unpleasant surprises created by invaders that change ecosystem attributes (as Brazilian waterweed and overbite clam have done in recent years). A mandatory boat inspection system is needed to prevent spread of aquatic organisms carried on boat hulls (e.g., zebra and quagga mussels) and live wells (e.g., northern pike, bait minnows). More aggressive programs also are needed to deal with invaders that enter through ballast water, the pet industry, and the bait industry.

Another option for dealing with existing ecosystem engineers among the alien species is to try large-scale removal experiments to see how the ecosystem changes in response to removal. Fairly large-scale herbicide treatments of Brazilian waterweed have been tried on Frank's Tract, although the ecological effects have not been monitored (L. Anderson, UC Davis, personal communication). Another large-scale experiment that could be tried is removing overbite clams by targeted clam dredging in the ship channel through Suisun Bay. During the winter months, most clams outside the deep water of the channel are apparently consumed by diving ducks (Poulton et al. 2004; Richman and Lovvoern 2004).

Toxicants

A major accomplishment of the Clean Water Act of 1972 was to greatly reduce the sewage and toxic materials discharged into the San Francisco Estuary, significantly improving water quality. However, toxicants continue to be a problem, mainly through (1) bio-accumulation of materials, especially mercury and selenium (Stewart et al. 2004), which are particularly a problem in long-lived fish (striped bass, sturgeon) because they can accumulate in the fat reserves of eggs and become mobilized as the embryo develops; (2) micropollutants (pharmaceuticals), such as human hormones, and new pesticides, such as pyrethroids, known to disrupt endrocrine pathways of fish at low levels of exposure, resulting in various deleterious effects, most notably sex-change of fish (Kidd et al. 2007); (3) episodic toxic events such as the flushing of materials from storm drains or large-scale agricultural pesticide applications (Kuivilla and Foe 1995) and (4) releases of nutrients, especially ammonia, from sewage treatment plants and agricultural drainage (Dugdale et al. 2007). Ammonia can be directly toxic to some aquatic organisms and promote blooms of undesirable bluegreen cyanobacteria. An additional problem is the great diversity of pesticides applied in the region and the potential for synergistic effects on aquatic organisms.

These toxicity problems rarely result in dramatic kills of large fish; rather, their effects are likely to be through increased stress or changed behavior of individual fish, killing of food organisms (zooplankton), or killing of larval fish. Because it is extremely difficult to document how such effects contribute to changes in fish populations, toxicity remains a major source of uncertainty (Bennett 2005). For example, Bennett et al. (1995) found that herbicides from rice paddies were causing significant mortality to striped bass larvae in the Sacramento River, yet when the herbicide ceased being a problem, there was no obvious positive response in the bass population. Nevertheless, under the right circumstances such toxicant effects could be significant in population declines. To reduce this uncertainty (and to reduce potential human health problems) there is a strong need to reduce inputs of toxicants from regional agriculture and urban areas and adopt integrated programs of monitoring and investigation as part of any Delta re-building strategy (Anderson et al. 2006).

San Joaquin River Contamination

The lower San Joaquin River is largely an agricultural drain, laced with salts, pesticides, and nutrients. As a consequence, the river upstream of the Merced confluence supports mainly a low-diversity fish community made up of highly tolerant alien species (Brown 2000). This polluted water is then mixed with high quality water from the Merced, Tuolumne, and Stanislaus rivers and finally with Delta tidal water containing its own mixture of pollutants from local agriculture and cities. Some of this water is recycled to farms via Central Valley Project exports. Curiously, Jassby et al. (2002) and Sobczak et al. (2002) found that the San Joaquin River is also a major source of high quality (bioavailable) carbon, which can potentially increase phytoplankton production, important to fuel food webs that include fish.

The general effect of these polluted waters on the Delta ecosystem is reduced through mixing with Sacramento River water drawn across the Delta by the southern Delta pumps (Appendix C and chapter 2 of the main report). As a result, ecosystem improvements that involve reduced pumping from the Delta will, at least initially, increase the influence of San Joaquin River water through reduced dilution and wider spreading of the water in the Delta. The environment created by poor San Joaquin water quality likely already reduces juvenile salmon survival from San Joaquin tributaries, as indicated by findings that survival of juveniles entering the Delta is apparently extremely low and smolt survival depends heavily on high combined outflows of all three tributaries (Baker and Morhardt 2001). Thus long-term recovery of desirable fish populations in the Delta requires reduction of the lower San Joaquin River's contributions of salts and other pollutants to the southern Delta.

Entrainment

Loss of fish to diversions, from small pipes on small tributaries to the large pumps in the southern Delta, is an easy factor to blame for fish declines because there are thousands of diversions in the greater Delta watershed, they are conspicuous, and the fish they take can be enumerated, with high numbers often resulting. Thus a general policy of fisheries agencies has been to recommend that all diversions be screened to prevent loss of fish (Moyle and Israel 2005). Unfortunately, the problem is not that easy to resolve. Moyle and Israel (2005) point out that the effects of diversions on fish populations depend on the size of the diversion and the proportion of the water removed from the source, as well as timing, location, and operation. Generally, small diversions on large rivers or within the Delta are unlikely to affect fish populations (Nobriga et al. 2004). As Delta islands flood and agricultural tracts are lost, the present small impacts of these small Delta diversions will become even less important.

Even the largest diversions, such as the southern Delta pumps, have a complex relationship with fish populations (Bennett 2005; Kimmerer 2008). While capture of millions of small juvenile splittail or striped bass during a year of high abundance may have no detectable effect on their populations (Kimmerer et al. 2000; Moyle et al. 2004), prolonged entrainment of individuals from a key segment of the already-reduced delta smelt population can undermine natural selection and devastate their chances for persisting into the future (Bennett 2005, unpublished data).

Overall, diversions of all types should be carefully monitored and managed to reduce effects on fish populations; however, blanket prescriptions for operations have rarely worked as well as planned. If a large peripheral canal is built, for example, not only will huge fish screens have to be designed to minimize entrainment (and other effects) but the canal will have to have to be operated with the flexibility to avoid short-term fish effects. Doubt that both can or will be done apparently led many of the biologists surveyed in Appendix E to downgrade the PC as a reasonable alternative for salmon. As noted above, we take a somewhat more optimistic view and assume solving these problems will be part of the price of a PC solution.

New Tidal Habitats

Lund et al. (2007) indicate two major regions in the Delta with potential for creating large amounts of tidal habitat, the Cache Slough region (freshwater tidal habitat) and Suisun Marsh (brackish tidal habitat). In addition, many smaller peripheral areas can provide some of this function (e.g., Dutch Slough). A key consideration will be the degree to which corridors between such areas can be established and maintained in the future Delta.

Cache Slough

The Cache Slough region has the advantage of being a large area with strong tidal currents in natural channels, close to the Yolo Bypass, with a dendritic (branch-like) drainage pattern despite the presence of levees and cross channels. (The largest cross channel, Calhoun Cut, is being reconnected with some natural channels by the Solano Land Trust). Shallow areas in the region (e.g., Liberty Island) that have already been flooded have surprisingly little Brazilian waterweed, apparently because of high, wind-generated turbidity (T. Sommer, DWR, personal communication). The Cache Slough region is also a major spawning area for delta smelt, along with the nearby Sacramento Ship Channel, and is probably an important rearing area for Chinook salmon and splittail. Major problems include the presence of the pumps for the North Bay Aqueduct on Barker Slough, the apparent dominance of the channels by alien fish species (although the area is poorly surveyed), and the levees that separate much of the water from the land. Nevertheless, the region seems to have major potential as a restoration area where strong tidal currents and complex habitat could favor some desirable species.

Suisun Marsh

Suisun Marsh is a large area (89,000 acres) in which seasonally brackish tidal channels run between levees built by duck-hunting clubs and the State of California (Grizzly Island and Joice Island wildlife areas) to maintain freshwater marsh habitat for waterfowl, based on the salinity preferences of alkali bulrush (*Scirpus acutus*). The waterfowl areas are intensely managed and at times anoxic effluent from club fields causes fish kills (R. E. Schroeter and P.B. Moyle, unpublished data).

Managing salinity in the Marsh is a key to maintaining waterfowl habitat, and keeping salinities low is required by the SWRCB under D-1641. DWR and the U.S. Bureau of Reclamation (USBR) have contractual agreements to maintain the same standards under the Suisun Marsh Preservation Agreement. To keep these commitments, DWR has built and maintains tidal gates at the upper end of Montezuma Slough, where Sacramento River water flows into the marsh. The gates capture freshwater inflows into the Marsh by being open during ebb tide, letting the fresh water flow in as the channels drain seaward, and then close to prevent salt water intrusion with the rising tide.

Despite these manipulations, the Marsh maintains some 2,000 acres of unleveed tidal areas that are highly productive of fish and invertebrates and about 4,000 acres of marsh that fringes the outside edge of the levees. One of these areas, Nurse Slough, has blooms of zooplankton, abundant native fishes, and an absence of invasive clams, making it a good model for creating conditions in the Delta that favor pelagic fishes (R.E. Schroeter and P. B. Moyle, unpublished data). The fish and macroinvertebrates of the Marsh are well studied by UC Davis, with monthly samples taken since January 1979. The fish fauna is diverse but dominated by desirable species, including splittail and striped bass (Matern et al. 2002).

Because much of Suisun Marsh is at or just below sea level, a large proportion of it will flood from failures of its low, weak levees as sea level rises (Figure D.5). When the diked wetlands of Suisun Marsh rejoin the estuary, the tidal prism will significantly expand and the tidal gates will presumably no longer function to regulate salinity. The marsh fringes at higher elevations, or those sections protected by the levee that supports the Southern Pacific Railroad may continue, depending on sea level rise and how well the railroad can be maintained. Regardless, there will be large increases in low intertidal brackish-water tidal marsh and shallow subtidal open water habitat. The present semi-natural channels will presumably continue to dominate the hydrodynamics, but with more interaction with the surrounding marshlands.

There is much uncertainty regarding how fish will respond to such changes, but conditions most likely will improve for desirable species because of: (1) increased productivity from channel-marsh interactions (i.e., more food for fish); (2) more shallow water tidal areas for rearing by small fish such as splittail and juvenile Chinook salmon; and (3) extensive clam-and-waterweed free environments because of strong seasonal and interannual fluctuations in salinity.

Improved Floodplain Habitats

Studies on both the Yolo Bypass (Sommer et al. 2001 a,b) and the Cosumnes River floodplain (Moyle et al. 2007) demonstrate the value of seasonal floodplains to juvenile Chinook salmon, splittail and other native fishes. The Cosumnes River floodplain is flooded at least partially almost annually following the natural spring hydrograph, while the Yolo Bypass floods in about 70 percent of all years, although the timing is erratic and floods are often quite short in duration. A clear benefit to fish would be to have parts of the Bypass flood annually for significant periods of time and to have more floodplain area available where the Cosumnes-Mokelumne Rivers and San Joaquin River enter the Delta. Increases in the extent of floodplains and the creation of flood bypasses (e.g., along the San Joaquin River) can increase the flexibility of reservoir storage because reservoir levels would not have to be lowered as much to capture potential floodwaters.

Williams et al. (unpublished manuscript) have developed a tool to determine the smallest flood event capable of triggering significant ecological processes on these floodplains. To produce identifiable benefits, their "Floodplain Activation Flood" must occur with a suitable duration and timing (i.e., have a long enough residence time of the water), allow hydraulic connection between the river and the floodplain during flooding, and occur with sufficient frequency to make benefits meaningful interannually. They define this minimum flood fairly precisely for the Sacramento River and Yolo Bypass, suggesting a potential way to develop operational rules for regular flooding of parts of the Yolo Bypass. This would have to be done by installing a gate on the Fremont Weir to allow flooding at lower river stages along the edges of the Toe Drain (Tule Canal) that runs along the eastern side of the Bypass. A gate on the weir could also be constructed to allow for passage of the migratory fish that frequently ascend the drain along the edge of the bypass rather than the Sacramento River and become stranded when they reach the weir.

Island Manipulations

Adaptive management decisions for Delta islands require better knowledge of how fish populations will respond to large-scale island flooding. It is desirable, therefore, to conduct large-scale environmental manipulations to learn how to better manage these new habitats. Potential manipulations include experimentally flooding an island while monitoring closely the effects on biota and water quality and constructing a floodable island on the Delta Wetlands model to experiment with different flooding, salinity, and temperature regimes. An alternative strategy is to organize a rapid response team that could bring boats and sampling gear on short notice to a flooding island. Given that on average one to two islands have flooded in the Delta, on average, each year, the opportunities for such study would come often enough to make this worthwhile.

Anticipating Climate Warming

Human-induced climate change is part of the new reality for ecosystem managers (Dettinger 2005, IPCC 2007, Barnett et al. 2008) and is yet another factor that will be pushing the Delta ecosystem into new states. Climate change at regional (Pacific), and either interdecadal (e.g., Pacific Decadal Oscillation (PDO)), or annual (e.g., El Niño Southern Oscillation (ENSO)) time scales historically have been important influences on the San Francisco Estuary and Delta ecosystem, including its fishes. These natural shifts in atmospheric and oceanic climate regularly contribute to extreme episodes in the Estuary and the Delta, such as droughts or floods, changes in water temperature, ecosystem productivity, and species composition through changes in immigration or emigration rates with the ocean (Peterson et al. 1995; Bennett and Howard 1999; Cloern et al. 2007). By and large, ecosystem managers have underappreciated the role of these natural climate shifts in fish declines (Bennett and Howard 1999; Bennett et al. 2004).

Whereas such effects on the ecosystem are of relatively short duration and magnitude, human-induced climate change is creating unprecedented and sustained changes. Some of these changes are already manifested in the Delta, such as the steady rise in sea level in the past century (a rise which appears to be accelerating), and the shift towards earlier timing of the snowmelt runoff from the Sierra Nevada (Cayan et al. 2001; Stewart, Cayan and Dettinger, 2004). Predictions of other climate change effects in California include a greatly reduced snowpack in the Sierras, resulting in more variability in annual and interannual flows in rivers (so both floods and drought become more frequent) and warming of water temperatures of 2 to 4° C (3.6 to 7.2° F) on average (Cayan et al. 2001). Sea level rise and increased flooding are likely to be major drivers of physical changes in the Delta and Suisun Marsh, by increasing the likelihood of major levee failure and extensive flooding (Appendix B and Chapter 2 of the main report).

The loss of snowpack and earlier timing of peak runoff will lead to decreased inflows in spring and summer, resulting in increasing salinity in the western Delta unless more releases are made from reservoirs. There is also likely to be less dilution of salts and other pollutants discharged into Central Valley rivers, especially the San Joaquin. Water temperature increase is a more subtle effect, which may be just large enough to push some species over the edge of survivability in critical months. For instance, delta smelt require temperatures below 20° C when spawning and rearing in the Delta, a temperature which may be exceeded much earlier in spring if atmospheric and river temperatures increase by more than 2°C overall. Likewise, adult spring-run Chinook salmon are already experiencing periods of near-lethal temperatures in Butte Creek, their most important spawning stream, resulting in mortality in some years. Reduced survival of adults may put additional pressure on improving Delta and other downstream habitats to increase survivorship of juvenile salmon.

Thermal problems with desirable species reflect the widespread latitudinal and altitudinal shifts in species ranges occurring worldwide (Barry et al. 1995; Parmesan 2006; Rogers-Bennett 2007). The sobering difference is that for species such as delta smelt, there is nowhere else to go. They will have to either adapt or face extinction. Therefore, human-induced climate change will be a significant factor increasing the likelihood of major changes in the environment and the fish fauna of the Delta.

Conclusions

The future Delta will be very different from the present Delta (Lund et al. 2007; Moyle 2008; Chapter 2, this volume; Appendix B). The projected large-scale changes to the Delta will be irreversible changes in the state of the system (Chapter 2). Key aspects of the new ecosystem will be large areas of open water habitat and greater heterogeneity in environmental conditions, especially salinity, than presently exist in summer. The decline of desirable fishes in the Delta in the past two to three decades has been associated with a general trend toward a less heterogeneous and more freshwater-dominated Delta environment. The low variability in summer water quality appears to be enhanced by the habitat-stabilizing properties of Brazilian waterweed, while fish assemblages reflect the long life spans of some alien fishes. These trends suggest that it will be hard to push the ecosystem back to a regime favoring desirable species without significantly altering the Delta environment. However, different groups of fishes are favored by different sets of environmental conditions, indicating that general management strategies can be established to benefit groups of desirable species (e.g. pelagic species, anadromous species), although the benefits of any management strategy can be greatly reduced by the invasions of new alien species.

Thus, any project designed to deliver Sacramento River water to the export aqueducts – whether through or around the Delta - must account for ecosystem change and future needs. The best water export strategy to favor desirable fishes is to end exports, assuming upstream diversions do not increase substantially. The worst strategy is to keep exporting large amounts of water from the southern Delta. Any export strategy (including ending exports) must include significant efforts to restore habitat diversity and function throughout the Delta and Suisun Marsh, if it is to be successful at bringing back large populations of desirable fish species. An effective restoration strategy would expand tidal marshes, increase annual floodplains, provide open water habitat with wide variation in salinity and temperature, reduce inputs of toxic materials, and prevent invasions of new alien species. Direct effects (entrainment) of diversions also have to be minimized. However, the vast size, complexity, and variability of environmental change in the Delta makes predictions of effects of any action on fish populations unreliable (Bennett and Moyle 1996). Because of these high uncertainties, large-scale *in situ* experiments are needed (e.g., flooding islands) to identify management strategies with the highest likelihood of success. Some large-scale restoration projects already can be conducted with a fairly high degree of certainty they will benefit many desirable species (e.g., in Cache Slough).

Despite the difficulty of making specific predictions, the existing track record clearly suggests that large-scale exports of water through the Delta are not compatible with conservation of desirable fish species. Delta environmental management (or lack thereof) over the last several decades has led the Delta ecosystem to shift to an undesirable dynamic regime with far less capacity to support desirable fish species. Regardless of the export (or no export) strategy chosen, a major effort is needed to create a more favorable environment for fishes by working *with* the inevitable large-scale changes (e.g., sea level rise and island flooding), rather than fighting them (only to lose) and to provide enough flexibility with inflows to allow for the variable environmental flows and water quality that are tied to fish life cycles.

The new Delta can have attributes that favor desirable fishes (and other organisms) provided that we recognize the importance of managing the system to strengthen its resilient properties (Scheffer et al. 2001; Folke et al. 2004; Walker and Salt 2006), rather than reacting to the fish body-count at the water export facilities. Clearly, humans will always be part of the system, and if we actively guide future change we can better ensure that we will benefit from a large array of potential ecosystem services built into the new system (reconciliation ecology, Rosenzweig 2002). Overall, the Delta ecosystem needs a clear and realistic vision of what it should look like in the future and how it should function. With management set in an adaptive management framework and leadership willing to accept failures as part of the natural process leading to improved conditions, the Delta can support large populations of desirable fishes, while also providing better services for humans.

References

Anderson, SL, GN Cherr, SG Morgan, CA Vines, RM Higashi, WA Bennett, WL Rose, A Brooks, & RM Nisbet 2006 Integrating contaminant responses in indicator saltmarsh species. *Marine Environmental Research* 62: S317-S321.

Baker, P. F. and J. E. Morhardt. 2001. Survival of Chinook salmon smolts in the Sacramento-San Joaquin Delta and Pacific Ocean. Pages 163-196 in R. L.Brown, ed. Contributions to the biology of Central Valley salmonids. Calif. Dept. of Fish and Game Fish Bulletin 179.

Barnett, T.P., D.W. Pierce, H.G. Hidalgo, and several others. 2008. Human-induced changes in the hydrology of the western United States. Science 319:1080-1083.

Barry, J.P., Baxter, C.H., Sagarin, R.D., and Gilman, S.E. 1995. Climate-related, long-term faunal changes in a California rocky intertidal community. Science (Wash., D.C.), 267: 672–675.

Bennett, W. A. 2005. Critical Assessment of the Delta Smelt Population in the San Francisco Estuary, California. *San Francisco Estuary Watershed Sci.* **3:** Art. 1.

Beisner, B.E., D. T. Haydon and K. Cuddington 2003. Alternative stable states in ecology *Frontiers in Ecology and the Environment* 7: 376-382

Bennett, W.A., and P. B. Moyle. 1996. Where have all the fishes gone: interactive factors producing fish declines in the Sacramento-San Joaquin estuary. Pages 519-542 *in* J. T. Hollibaugh, ed. *San Francisco Bay: the Ecosystem*. San Francisco: AAAS, Pacific Division.

Bennett, W.A. and E. Howard. 1999. Climate change and the decline of striped bass. *Interagency Ecological Program for the Sacramento San Joaquin Estuary Newsletter* 12:53-56.

Bennett, W. A., D. J. Ostrach, and D. E. Hinton. 1995. Larval striped bass condition in a drought-stricken estuary: evaluating pelagic food-web limitation. *Ecol. Appl.* **5:** 680-692.

Bennett, W.A., K. Roinestad, L. Rogers-Bennett, L.S. Kaufman and B. Henneman. 2004. Inverse regional responses to climate change and fishing intensity by the recreational rockfish (*Sebastes*, spp.) fishery in California. *Canadian Journal of Fisheries and Aquatic Sciences* 61:2499-2510.

Black, G. 2008. The gathering storm. OnEarth 30(2): 22-37

Brown, L. R. 2000. Fish communities and their associations with environmental variables, lower San Joaquin River drainage, California. *Environ. Biol. Fishes* **57:** 251-269.

Brown, Larry R. and Jason T. May. 2006. Variation in Spring Nearshore Resident Fish Species Composition and Life Histories in the Lower San Joaquin Watershed and Delta . *San Francisco Estuary and Watershed Science*. Vol. 4, Issue 2 (September), Article 1. http://repositories.cdlib.org/jmie/sfews/vol4/iss2/art1

Carpenter, S.R. 2003. Regime Shifts in Lake Ecosystems: Patterns and Variation. Excellence in Ecology Series 15. Oldendorf/Luhe, Germany: Ecology Institute.

Cayan DR, Kammerdiener SA, Dettinger MD, Caprio JM, Peterson DH. 2001. Changes in the onset of spring in the western United States. *Bull. Am. Meteorol. Soc*. 82:399–415

Cloern, J.E. 2007. Habitat connectivity and ecosystem productivity: implications from a simple model. American Naturalist 169:21-33.

Cloern, J.E., A.D. Jassby, J.K. Thompson, and K.A. Hieb. 2007. A cold phase of the East Pacific triggers new phytoplankton blooms in San Francisco Bay. Proceedings of the National Academy of Sciences 104:18561-18565.

Cohen, A.N. 2005. A Review of Zebra Mussels' Environmental Requirements. A report for the California Department of Water Resources, Sacramento CA. San Francisco Estuary Institute, Oakland, CA.

Cohen, A.N. 2007. Potential Distribution of Zebra Mussels (*Dreissena polymorpha*) and Quagga Mussels (*Dreissena bugensis*) in California. Phase 1 Report for the California Department of Fish and Game. San Francisco Estuary Institute, Oakland, CA.

Delta Risk Management Strategy Program of the Department of Water Resources, 2007. http://www.drms.water.ca.gov/

Dettinger, MD. 2005. From climate-change spaghetti to climate-change distributions for 21st Century California. *San Francisco Estuary and Watershed Science* 3, Article 4. http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4.

Dugdale, R.C., F.P. Wilkerson, V.E. Hogue, A. Marchi 2007. The role of ammonium and nitrate in spring bloom development in San Francisco Bay. Estuarine Coastal and Shelf Science 73:17-29.

Feyrer F, Nobriga, ML, Sommer, TR. 2007. Multi-decadal trends for three declining fish species: habitat patterns and mechanisms in the San Francisco Estuary, California, USA. *Canadian Journal of Fisheries and Aquatic Sciences* 64(4):723–734.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmquist, L. Gunderson, and C.S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Annual Reviews in Ecology and Systematics* 35:557-581.

Grimaldo, L.F., P.B. Moyle, P. Smith, and B. Herbold. *Submitted*. The effects of large-scale water diversions in a freshwater tidal estuary: can fish loses be managed? North American Journal of Fisheries Management.

Hogan, Z. S., P. B. Moyle, B. May, M. J. Vander Zander, and I. G. Baird. 2004. The imperiled giants of the Mekong. American Scientist 92: 228-237.

Isenberg, P., M. Florian, R.M. Frank, T. McKernan, S. Wright McPeak, W.K. Reilly, and R. Seed, "Blue Ribbon Task Force Delta Vision: Our Vision for the California Delta," State of California Resources Agency, Sacramento, California, January 2008.

IPCC (Intergovernmental Panel on Climate Change) 2007. Climate change 2007: climate change impacts, adaptation, and vulnerability. Summary for policymakers. 23pgs.

Jassby, A. D. and J. E. Cloern. 2000. Organic matter sources and rehabilitation of the Sacramento-San Joaquin Delta (California, USA). Aquatic Conservation: Marine and Freshwater Ecosystems 10: 323-352.

Jassby, A. D. ,J. E. Cloern and B. E. Cole. 2002. Annusal primary production: patterns and mechanisms of change in a nutrient rich tidal system.. Limnology and Oceanography 47: 698-712.

Kidd, K.A., P.J. Blanchard, K.H. Mills, V.P. Palace, R.E. Evans, J.M. Lazorchak, and R.W. Flick. 2007. Collapse of a fish population after exposure to a synthetic estrogen. *Proceedings of the National Academy of Sciences* 104:8897-8901.

Kimmerer, W.L.. 2008. Losses of Sacramento River Chinook salmon and delta smelt to entrainment in water diversions in the Sacramento-San Joaquin Delta. *San Francisco Estuary and Watershed Science*.

Kimmerer, W. J., J.H. Cowan Jr., L.W. Miller, K.A. Rose. 2000. Analysis of an estuarine striped bass population: Influence of density-dependent mortality between metamorphosis and recruitment. *Canadian Journal of Fisheries and Aquatic Sciences* 57:478-486.

Kimmerer, W.J., S.R. Avent, S.M. Bollens, F. Feyrer, L.F. Grimaldo, P.B. Moyle, M. nobriga, T. Visintainer 2005. Variability in length-weight relationships used to estimate biomass of estuarine fish from survey data. *Transactions of the American Fisheries Society* 134:481-495.

Kuivila, K. M., and C. G. Foe. 1995. Concentrations, transport and biological effects of dormant spray pesticides in the San Francisco estuary, *California. Environmental Toxicology and Chemistry* 14:1141-1150.

Lund, J., E. Hanak., W. Fleenor, W., R. Howitt, J. Mount, and P. Moyle. 2007. *Envisioning futures for the Sacramento-San Joaquin Delta. San Francisco*: Public Policy Institute of California. 284 pp.

Manly, B.F.J. 2005. *Multivariate Statistical Methods: a Primer* – 3rd edition. Chapman and Hall, Boca Raton, Florida.

Marchetti, M. P., and P. B. Moyle. 2001. Effects of flow regime on fish assemblages in a regulated California stream. *Ecol. Appl*. **11:** 530-539.

Matern, S. A., P. B. Moyle, and L. C. Pierce. 2002. Native and alien fishes in a California estuarine marsh: Twenty-one years of changing assemblages. *Trans. Amer. Fish. Soc*. 131: 797-816.

Mosepele, K., P. B. Moyle, G. S. Merron, D. Purkey, and B. Mosepele. in press. Fish, floods, and ecosystem engineers: aquatic conservation in the Okavango Delta, Botswana. BioScience.

Moyle, P.B. 2002. *Inland Fishes of California*. University of California Press, Berkeley, California.

Moyle, P.B. 2008 (in press). The future of fish in response to large-scale change in the San Francisco Estuary, California. *In* K.D. McLaughlin, editor. Mitigating Impacts of Natural Hazards on Fishery Ecosystems. American Fishery Society, Symposium 64, Bethesda, Maryland.

Moyle PB, Baxter RD, Sommer TR, Foin TC, Matern SA. 2004. Biology and population dynamics of Sacramento splittail (*Pogonichthys macrolepidotus*) in the San Francisco Estuary: a review. *San Francisco Estuary and Watershed Science* 2: article 3.

Moyle, P.B., P.K. Crain, and K. Whitener. 2007. Patterns in the use of a restored California floodplain by native and alien fishes. *San Francisco Estuary and Watershed Science* 5(3): article 1.

Moyle, P. B., and J. A. Israel. 2005. Untested assumptions: effectiveness of screening diversions for conservation of fish populations. *Fisheries* **30:** 20-28.

Moyle, P. B. and J. F. Mount 2007. Homogenized rivers, homogenized faunas. *Proceedings, National Academy of Sciences* 104: 5711-5712.

Nobriga, M.L., Z. Matica, and Z.P. Hymanson 2004. Evaluating entrainment vulnerability to agricultural irrigation diversions: a comparison among open-water fishes. Pages 281-295 in F. Feyrer, L.R. Brown, R.L. Brown, and J.J. Orsi, editors. Early life history of fishes in the San Francisco Estuary and watershed. American Fisheries Society, Symposium 39, Bethesda, Maryland.

Nobriga, M.L., T.R. Sommer, F. Feyrer, and K. Fleming. 2008. Long-term trends in summertime habitat suitability for delta smelt (Hypomesus transpacificus). *San Francisco Estuary and Watershed Science*. Vol. 6, Issue 1, Art. 1.

Nobriga, ML, Feyrer, F, Baxter, RD, Chotkowski, M. 2005. Fish community ecology in an altered river delta: spatial patterns in species composition, life history strategies and biomass. *Estuaries* 28:776-785.

Parmesan, C. 2006. Ecological and evolutionary responses to recent climate change. Annual Review of Ecology, Evolution, and Systematics 37:637-669.

Peterson, D.H., Cayan, D.R., DiLeo, J., Noble, M. and Dettinger, M.D., 1995, The role of climate in estuarine variability: American Scientist 83, 58-67.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. *BioScience* 47: 769-784.

Poff, N.L., Olden, J.D., Merritt, D. M. and Pepin, D. M. 2007. Homogenization of regional river dynamics by dams and global diversity implications. Proceedings, National Academy of Sciences 104: 5704-5710.

Poulton, V. K., J. R. Lovvorn, and J. Y. Takekawa. 2004. Spatial and overwinter changes in clam populations of San Pablo Bay, a semiarid estuary with highly variable freshwater inflow. *Estuar. Coast. Shelf Sci*. **59:** 459-473.

Puccia, C.J. and R. Levins. 1985. *Qualitative Modeling of Complex Systems: an Introduction to Loop Analysis and Time Averaging*. Harvard University Press, Cambridge, MA, USA.

Richman, S. E., and J. R. Lovvorn. 2004. Relative foraging value to lesser scaup ducks of native and exotic clams from San Francisco Bay. *Ecol. Appl.* **14:** 1217-1231.

Rogers, M. W. and M. S. Allen 2008. Hurricane impacts to Lake Okeechobee: altered hydrology creates difficult management tradeoffs. *Fisheries* 33:11-17.

Rogers-Bennett, L. 2007. Is climate change contributing to range reductions and localized extinctions in northern (*Haliotis kamtschatkana*) and flat (*Haliotis walallensis*) abalones? *Bull Mar Sci* 81:283-296.

Rosenzweig, M. 2002. *Win-win Ecology*. Oxford University Press.

Scheffer, M., and S.R. Carpenter 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in Ecology and Evolution* 18:648-656.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in Ecosystems. *Nature* 413:591-596.

Sobczak, W. V., J. E. Cloern, A. D. Jassby, and A. B. Müller-Solger. 2002. Bioavailability of organic matter in a highly disturbed estuary: the role of detrital and algal resources. PNAS 99:8101-8105.

Sommer T, Harrell B, Nobriga M, Brown R, Moyle P, Kimmerer W, Schemel L. 2001a. California's Yolo Bypass: evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. *Fisheries* 26: 6-16.

Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. 2001b. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. Canadian *Journal of Fisheries and Aquatic Sciences* 58: 325-333.

Sommer TR, Harrell WC, Solger AM, Tom B, Kimmerer W. 2004. Effects of flow variation on channel and floodplain biota and habitats of the Sacramento River, California, USA. *Aquatic Conservation-Marine and Freshwater Ecosystems* 14: 247-261.

Stewart, I., Cayan DR, Dettinger MD. 2004. Changes in snowmelt runoff timing in western North America under a 'business as usual" climate change scenario. Climate Change 62:257-281.

Stewart, AR, Luoma, SN, Schlekat, CE, Doblin, MA and Hieb, KA. 2004. Food web pathway determines how selenium affects aquatic ecosystems: a San Francisco Bay case study. *Environ. Sci. Technol.* 38:4519-4526.

Vila-Gispert, A., R. Moreno-Amich, and E. Garcia-Berthou. 2002. Gradients of life history variation: An intercontinental comparison of fishes. *Reviews in Fish Biology and Fisheries* 12:417-427.

Walker B. and D. Salt. 2006. *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Island Press, Washington, D.C.

Williams, P., Andrews, B. Opperman, J., Bozkurt, S., and Moyle PB. (unpublished manscript) Quantifying activated floodplains on a lowland regulated river: its application to floodplain restoration in the Sacramento Valley

Winemiller, K.O. and K.A. Rose. 1992. Patterns of life-history diversification in North American fishes: implications for population regulation. *Canadian Journal of Fisheries and Aquatic Sciences* 49:2196-2218.

Addendum D1 - Species Characteristics Used in Principal Components Analysis

The following characteristics were used to determine groups of species (assemblages) that would react similarly to changes in Delta conditions.

1. Importance in making policy decision regarding Delta water
    - 5 = very important, includes all listed species plus splittail
    - 4 = estuarine species with important fisheries
    - 3 = declining native species, not listed
    - 2 = native species (not declining) or non-native species with fisheries
    - 1 = not important, includes non-native fishes without fisheries or with minor fisheries

2. Origin
    - 2 = native
    - 1 = non-native

3. Migration
    - 4 = anadromous
    - 3 = semi-anadromous
    - 2 = migrate within estuary or from estuary to freshwater for spawning
    - 1 = resident

4. Trophic position (position on food chain) in Delta (adults, unless only juveniles present)
    - 4 = Piscivore
    - 3 = Large invertivore
    - 2 = Invertivore (zooplankton, small invertebrates)
    - 1 = Omnivorous (including detritus etc.)

5. Estuarine dependence
    - 2 = require estuary to complete life cycle
    - 1 = do not require estuary

6. Usual age of first reproduction of females, years (generation time)

7. Parental care
    - 4 = live bearers
    - 3 = nest builders
    - 2 = brood hiders
    - 1 = broadcast spawners

8. Submerged vegetation association
    - 3 = most abundant around Egeria and other submerged aquatic vegetation
    - 2 = Uses submerged aquatic vegetation but not dependent on it
    - 1 = Does not use or avoids submerged aquatic vegetation

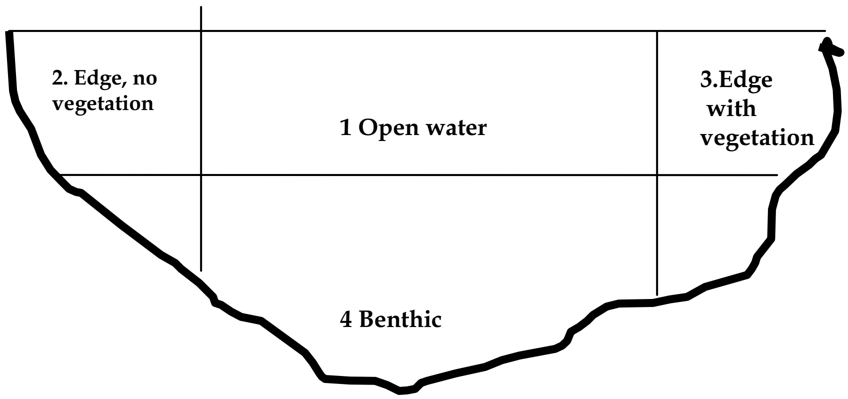
9. Temperature preference

3 = Optimal temperatures >18°C
2 = Optimal temperatures 16-20°C
1 = Optimal temperatures <18°C

10. Salinity preference (of life stage in estuary)

3 = 0-35 parts per thousand (widely distributed)
2 = 2-10 (estuarine)
1 = <5 (fresh water)

11. Principal habitat (>50% of 24 hour cycle May-Oct)



12. Pelagic larvae

2 = no
1 = yes

About the Authors

William A. Bennett is a professional researcher in fish ecology with the John Muir Institute of the Environment at the University of California, Davis. His research has focused primarily on understanding the population dynamics of fishes in the San Francisco Estuary and near-shore marine environments in California. He has worked extensively with the Interagency Ecological Program and the CALFED Bay-Delta program to investigate the delta smelt and striped bass populations in the San Francisco Estuary. His work with the Pacific Estuarine Ecosystem Indicator Research Consortium has focused on tidal-marsh goby populations. He has also studied the relative influences of fishing intensity and climate change on the near-shore rockfish fishery.

Peter B. Moyle has been studying the ecology and conservation of freshwater and estuarine fish in California since 1969 and has focused on the San Francisco Estuary since 1976. He was head of the Delta 145 Native Fishes Recovery Team and a member of the Science Board for the CALFED Ecosystem Restoration Program. He has authored or coauthored over 160 scientific papers and five books, including Inland Fishes of California (2002). He is a professor of fish biology in the Department of Wildlife, Fish, and Conservation Biology at the University of California, Davis and is associate director of the UC Davis Center for Watershed Sciences.

PUBLIC POLICY INSTITUTE OF CALIFORNIA
500 Washington Street, Suite 600
San Francisco, California 94111
phone: 415.291.4400
fax: 415.291.4401

PPIC SACRAMENTO CENTER
Senator Office Building
1121 L Street, Suite 801
Sacramento, California 95814
phone: 916.440.1120
fax: 916.440.1121

www.ppic.org