Environmental Biology of Fishes **66:** 123–132, 2003.

Fish community structure and environmental correlates in the highly altered southern Sacramento-San Joaquin Delta

Frederick Feyrer[a] & Michael P. Healey[b]
[a]*Aquatic Ecology Section, California Department of Water Resources, 3251 S Street, Sacramento, CA 95816, U.S.A. (e-mail: ffeyrer@water.ca.gov)*
[b]*Central Valley Bay-Delta Branch, California Department of Fish and Game, 4001 North Wilson Way, Stockton, CA 95205, U.S.A.*

Received 29 April 2002 Accepted 10 June 2002

Key words: non-native species, native species, environmental degradation, seasonality, freshwater flow

Synopsis

We sampled 11 sites in the southern Sacramento-San Joaquin Delta from 1992–1999, to characterize fish communities and their associations with environmental variables. Riparian habitats were dominated by rock-reinforced levees, and large water diversion facilities greatly influenced local hydrodynamics and water quality. We captured 33 different taxa, only eight of which were native. None of the native species represented more than 0.5% of the total number of individuals collected. The abundance of native species was consistently low but typically peaked during high outflow periods. Fish communities were predominantly structured along environmental gradients of water temperature and river flow. Native species (tule perch, *Hysterocarpus traski*, & Sacramento sucker, *Catostomus occidentalis*) were associated with conditions of high river flow and turbidity, while the majority of the non-native species were associated with either warm water temperature or low river flow conditions. The exceptions were the non-native striped bass, *Morone saxatilis*, and white catfish, *Ameiurus catus*, which were positively associated with relatively high river flow. Variation in fish community structure was greater among river locations within years than within river locations among years, thus fish communities at each river location were consistently different each year. Differences in fish communities among river locations were correlated with river flow and turbidity. We predict that the fish communities of this region will remain numerically dominated by non-native species if the environmental conditions we observed persist in the future.

Introduction

Fish communities are often used as indicators of environmental quality (Karr 1991, Moyle 1994, Brown 2000, Waite & Carpenter 2000). Physical habitat degradation and altered hydrodynamics are often associated with fish communities dominated by non-native taxa (Aparicio et al. 2000, Waite & Carpenter 2000). In many systems, especially in California's Central Valley, natural flow regimes are critically important to maintaining native fish communities (Meng et al. 1994, Brown 2000, Marchetti & Moyle 2001). However, maintaining natural flow regimes is increasingly difficult because of water development projects that acquire and redistribute water for agricultural and municipal demands.

The point of drainage for California's Central Valley watershed is the Sacramento-San Joaquin Delta (Delta), a large complex system that has been highly modified by human activity (Nichols et al. 1986). The State Water Project (SWP) and the Central Valley Project (CVP) export pumping facilities are located in the south Delta and greatly influence hydrodynamics and water quality of the system (Nichols et al. 1986, Arthur et al. 1996). The projects together form the largest man-made water system in the world and supply agricultural irrigation water for California's Central Valley plus municipal water for two thirds of California's populous (∼22 million people). Additionally, dams associated with the water projects highly regulate river inflow to the region and compromise the natural hydrograph. The south Delta is arguably the most altered region of the system considering the influence of the water export facilities and associated river flow control structures (Nichols et al. 1986, Arthur et al. 1996), as well as degraded habitat quality in the lower San Joaquin River (SJR) drainage (Saiki 1984, Brown 2000).

The fish faunas of the central Delta (Grimaldo et al. 2002), and downstream in Suisun Marsh (Moyle et al. 1986, Meng et al. 1994), are dominated by non-native taxa. It has been hypothesized that the numerically dominant non-native species are better adapted for the altered water quality, habitat, and hydrologic conditions than the native species (Bennett & Moyle 1996). In support of this hypothesis, Grimaldo et al. (2002) found that native species were most abundant during the spring when water quality and hydrology are most similar to historic natural conditions. Furthermore, several species exhibit a significant positive abundance-river flow relationship (Jassby et al. 1995, Meng et al. 1994, Sommer et al. 1997).

In this paper, we report on an 8 year study of fishes in the south Delta. Our goals for this paper were to (1) describe faunal composition, including the status of native species, (2) determine the relative importance of environmental variables structuring fish communities, and (3) examine spatial (river location) and temporal (year-to-year) variation in fish community structure within the south Delta.

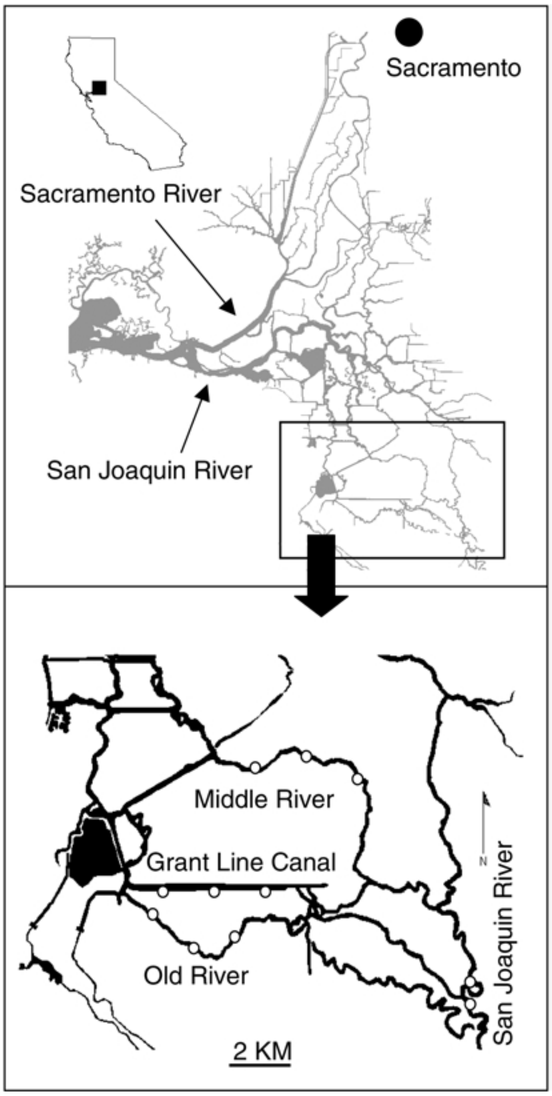

Figure 1. Location of sampling sites (open circles) in the Sacramento-San Joaquin Delta.

Study area

The Delta (Figure 1), located upstream of the confluence of the Sacramento and SJRs, consists of over 1000 km of waterways with a drainage area encompassing approximately 40% of California's surface area (Nichols et al. 1986). Annual discharge averages about 34 000 m^{-3} per year. Approximately 60% of natural discharge is diverted either upstream of the Delta, within the Delta, or at the CVP and SWP diversion facilities for agricultural and municipal consumption (Nichols et al. 1986).

We sampled fishes within three tidally influenced south Delta sloughs, Old River (OR), Middle River (MR), Grant Line Canal (GLC), and also within the SJR (Figure 1). As throughout most of the channels in the Delta, these waterways are constricted within flood control levees. Rock-reinforced banks dominated riparian habitats at these locations and only remnants of natural wetland vegetation were present. Non-native submerged aquatic vegetation, primarily the Brazilian waterweed, *Egeria densa*, dominated the aquatic littoral zone. Channel bottom substrates consisted primarily of mud, sand, or peat. Agriculture was the dominant land use activity beyond the channel levees and many local agricultural diversion facilities were located within the study area.

Methods

Data collection

We sampled fishes in the south Delta over an 8 year period, 1992–1999. Initially, we conducted monthly sampling year-round from April 1992–November 1995. Thereafter, we conducted monthly sampling April–November 1996, March–November 1997, March–October 1998, and March–September 1999. We sampled fishes at 11 permanent stations – three stations each within OR, MR, GLC, and two stations within SJR (Figure 1). The SJR stations were sampled 1992–1995 while all other stations were sampled each year. The SJR sites were terminated after 1995 due to resource constraints. Each station was sampled by boat-employed pulsed DC electroshocking starting just after dusk along transects approximately 500 m in length on one bank. Each station was sampled usually once per month except in rare instances when equipment breakdown or logistical problems arose; 909 samples were obtained over the study period. All fishes captured were identified to species, measured for fork length (millimeters), and released alive after sampling was completed. Fish catch data from this study are available in raw form from the Interagency Ecological Program website at http://iep.water.ca.gov/.

Four environmental variables were recorded with each sampling event, water temperature ($^{\circ}$C), specific conductance (μS), turbidity (NTU), and dissolved oxygen (mg l^{-1}), while tidally averaged daily flow ($m^3\ s^{-1}$) for each site was obtained from the California Department of Water Resources' CALSIM Hydrology Model.

Data analysis

Environmental variables were compared among river locations with a generalized linear model procedure with month as a covariate. Differences were considered significant at $p < 0.05$. To determine the relationship between the abundance of native species and river flow, we examined the concordance of average monthly catch per shock hour (CPUE) of all native species and average river flow. We conducted this analysis for each year and considered the rank correlations significant at $p < 0.05$.

We used canonical correspondence analysis (CCA) to investigate associations of fish communities with environmental variables (ter Braak & Verdonschot 1995, Legendre & Legendre 2000). CCA is a multivariate direct ordination technique that extracts synthetic environmental gradients that maximize niche separation within communities, thereby facilitating the interpretation of how species abundances relate to environmental variables. Analyses were conducted with the CANOCO software program (ter Braak & Smilauer 1998). To reduce the influence of rare taxa, we limited the CCA to species that occurred in at least 10% of all samples. Non-transformed species proportional abundance data and all five environmental variables (centered and standardized) for each sample were initially included in the analysis. We used the forward selection procedure with Monte Carlo simulations (199 permutations) to constrain the final model to only included environmental variables significant at $p < 0.05$ (ter Braak & Smilauer 1998).

We used detrended correspondence analysis (DCA) to investigate spatial (location: slough/river) and temporal (year-to-year) variation in fish community structure. DCA is an indirect eigenvector ordination technique based upon reciprocal averaging that corrects for the 'arch effect' observed in correspondence analysis (Gausch 1982, Legendre & Legendre 2000). Primary gradients within communities are effectively displayed by DCA, and species turnover rates can be inferred by scaling the axes to standard deviation units of sample scores, 50% turnover in species composition occurs over approximately one standard deviation (Gausch 1982). We limited the DCA to data collected from April–September, the only months sampled in all years. Species proportional abundance data were summarized by location and year for this analysis because we were interested in knowing if the fish communities at each location were annually persistent. Only species that occurred in at least 10% of the total samples were included in the analysis. We utilized detrending by segments with the CANOCO software program (ter Braak & Smilauer 1998) and therefore only visually interpreted scores along axis one of the DCA plot as ecologically meaningful (Legendre & Legendre 2000). As we will demonstrate later, DCA site scores clustered in the same order each year. We used Pearson product-moment correlations to determine if DCA axis one scores were correlated with any of the five environmental variable average values for the corresponding site and year.

Results

Physical conditions

There were notable differences in average physical conditions among the sampling locations (Table 1). SJR possessed the greatest mean river flow, specific conductance, turbidity, dissolved oxygen concentration, and the lowest water temperature. MR possessed the lowest river flow, dissolved oxygen concentration, and highest water temperature. OR and GLC possessed conditions intermediate of MR and the SJR.

Physical conditions also exhibited strong seasonality from April through September (Figure 2). For all locations, river flow was highest early in the season and lowest late in the season. SJR and GLC exhibited significantly higher river flow than OR and MR ($p < 0.05$). Water temperature was lowest early in the season and highest late in the season with no significant differences among locations ($p > 0.05$). Specific conductance generally increased over the season, except in OR where it decreased slightly. Specific conductance at SJR was significantly higher than at OR ($p < 0.05$). Turbidity generally increased across the season until September, when it decreased slightly. Turbidity at SJR and GLC was significantly higher than at MR and OR ($p < 0.05$). Dissolved oxygen concentration generally decreased across the season until September, when it increased. SJR exhibited the highest concentration of dissolved oxygen ($p < 0.05$).

Fish species composition

Over the study period, 70 939 fishes representing 33 species were collected (Table 2). Only eight native species were captured, none of which represented more than 0.5% of the total catch. The most common species were bluegill, *Lepomis macrochirus*, redear sunfish, *Lepomis microlophus*, white catfish, *Ameiurus catus*, and largemouth bass, *Micropterus salmoides*. These species comprised over 65% of the total catch and each occurred in at least 79% of the total samples. Over the study period, CPUE of non-native species peaked in spring and fall, while the CPUE of native species was consistently very low across all months with a small peak in April (Figure 3). The CPUE of native fishes was significantly rank correlated with river flow across months in all years ($p < 0.05$). With the exception of 1995, all rank correlations exhibited a positive slope.

Associations among fish communities and environmental variables

The forward selection procedure resulted in the retention of all five environmental variables in the final CCA model. The first two CCA axes explained a total of 10% of the variation in species distribution (8% & 2%, respectively; Table 3). Inter-set correlations indicated that river flow and water temperature were important gradients for the first two CCA axes (Table 3).

The influence of all five environmental variables on community structure was depicted in a CCA ordination plot (Figure 4). We found that native species (tule perch, *Hysterocarpus traski*, and Sacramento sucker, *Catostomus occidentalis*) were associated with high river flow and turbidity. High river flow is characteristic of early season conditions in the south Delta, while the highest turbidity was observed in SJR and GLC, the locations with the highest river flow (Figure 2). The majority of the non-native species were associated with either high water temperature or low river flow. High water temperature and low river flow were conditions characteristic of MR and OR (Figure 2). Two non-native species, striped bass, *Morone saxatilis*, and white catfish, *Ameiurus catus*, were associated with relatively high river flow.

Table 1. Environmental variable mean values and standard deviations (in parentheses) for the four sampling regions in the south Delta, 1992–1999.

Variable	Middle River	Old River	Grant Line Canal	San Joaquin River
Flow ($m^3\ sec^{-1}$)	5.8 (9.0)	10.2 (14.8)	57.5 (66.2)	104.5 (146.1)
Water temperature (°C)	19.3 (5.1)	18.8 (4.7)	19.1 (4.5)	18.1 (5.3)
Specific cond. (μS)	406 (181)	609 (271)	543 (248)	676 (305)
Turbidity (NTU)	13.8 (11.8)	14.4 (10.4)	17.6 (11.3)	19.5 (17.7)
Dissolved oxygen ($mg\ l^{-1}$)	7.9 (1.5)	7.6 (1.5)	7.9 (1.4)	8.9 (1.6)

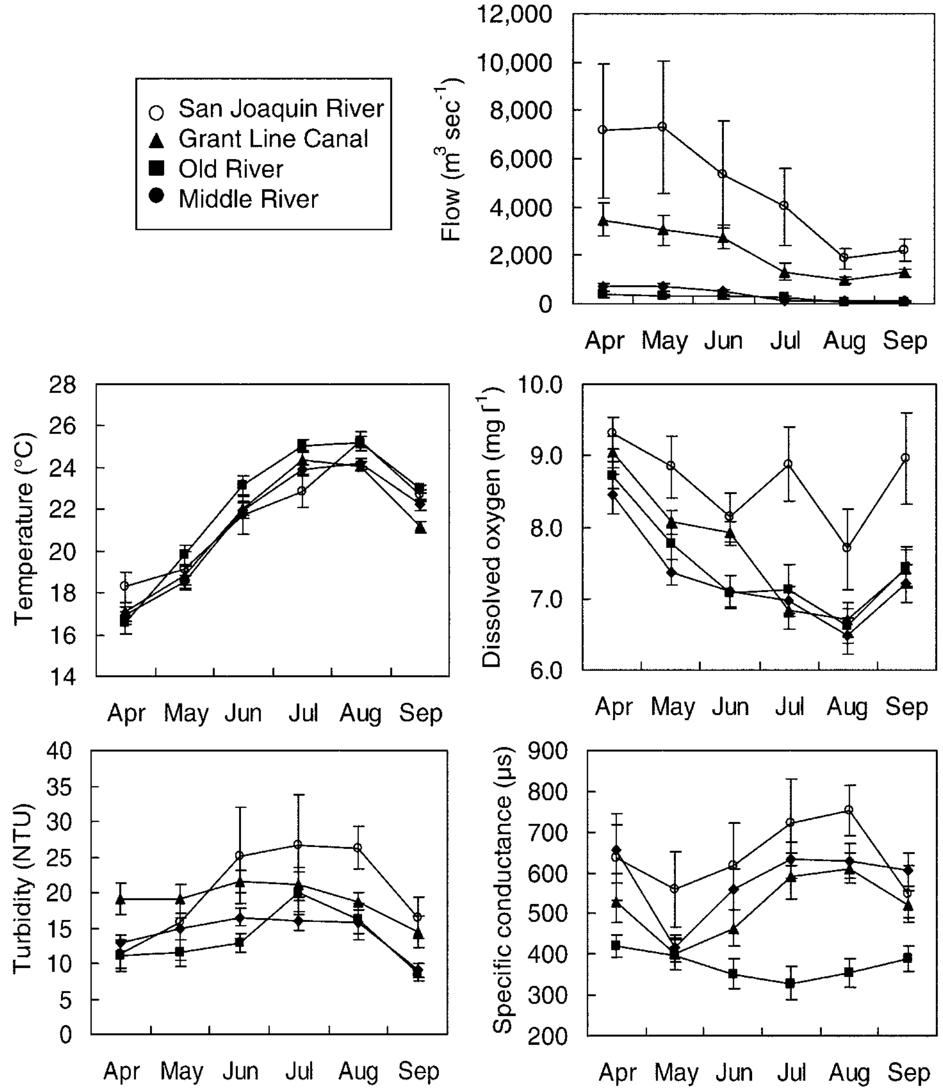

Figure 2. Mean monthly values for environmental variables at each location over the study period. Error bars represent one standard error.

Fish community structure

The first axis of the DCA ordination accounted for 45.2% of the variance of the annual fish community data (eigenvalue = 0.23) with a gradient length of 1.6 standard deviation units. Site scores along axis one of the DCA ordination diagram (Figure 5) showed that variation in fish community structure was greater among locations within years than within locations among years. For each year separately, site scores clustered along a MR–OR–GLC–SJR gradient. This suggested that the fish communities at each location were persistent in that they were consistently different each year each. DCA axis one scores were most correlated with river flow (Table 4). This suggested that the year-to-year consistency in fish communities across locations was influenced primarily by an environmental gradient of river flow. The location with the highest river flow, SJR, possessed the most unique fish community. The DCA species scores also suggested that locations clustered along an environmental gradient of river flow (Figure 5). Species shown to be associated

Table 2. Taxa, code, status (A = non-native, N = native), total number, and percent number (if greater than 1%) of fishes captured in the south Delta, 1992–1999.

Taxa	Code	Status	Number (%)
Bluegill, *Lepomis macrochirus*	BG	A	19 820 (28)
Redear sunfish, *Lepomis microlophus*	RS	A	9 521 (13)
White catfish, *Ameiurus catus*	WC	A	9 088 (13)
Largemouth bass, *Micropterus salmoides*	LB	A	7 950 (11)
Golden shiner, *Notemigonus crysoleucas*	GS	A	5 393 (8)
Striped bass, *Morone saxatilis*	SB	A	5 043 (7)
Inland silverside, *Menidia beryllina*	IS	A	4 262 (6)
Threadfin shad, *Dorosoma petenense*	TS	A	3 589 (5)
Common carp, *Cyprinus carpio*	CP	A	1 726 (2)
Channel catfish, *Ictalurus punctatus*	CC	A	712 (1)
Yellowfin goby, *Acanthogobius flavimanus*	YG	A	497 (1)
Chinook salmon, *Oncorhynchus tshawytscha*	CS	N	390
Tule perch, *Hysterocarpus traski*	TP	N	384
Warmouth, *Lepomis gulosus*	WM	A	313
Sacramento sucker, *Catostomus occidentalis*	SS	N	278
Goldfish, *Carassius auratus*	GF	A	256
Sacramento blackfish, *Orthodon microlepidotus*	SB	N	238
Black crappie, *Pomoxis nigromaculatus*	BC	A	226
Shimofuri goby, *Tridentiger bifasciatus*	SG	A	192
Brown bullhead, *Ameiurus nebulosus*	BB	A	186
Bigscale logperch, *Percina macrolepida*	LP	A	180
Green sunfish, *Lepomis cyanellus*	GS	A	138
Smallmouth bass, *Micropterus dolomieui*	SB	A	138
Splittail, *Pogonichthys macrolepidotus*	SPT	N	94
Mosquitofish, *Gambusia affinis*	GAM	A	67
American shad, *Alosa sapidissima*	AS	A	63
Prickly sculpin, *Cottus asper*	PS	N	60
Sacramento pikeminnow, *Ptychocheleius grandis*	SP	N	55
Black bullhead, *Ameiurus melas*	BLB	A	43
Fathead minnow, *Pimephales promelas*	FM	A	18
Red shiner, *Cyprinella lutrensis*	RSH	A	13
White crappie, *Pomoxis annularis*	WC	A	4
Steelhead, *O. mykiss*	STH	N	2

with river flow by CCA were clustered in the same region of the DCA plot as the locations with the highest river flow.

Discussion

Faunal composition

The fish communities we observed in the south Delta were similar to those observed in other regions of the Delta (Moyle et al. 1986, Meng et al. 1994, Grimaldo et al. 2002) and its watershed (Saiki 1984, Brown 2000, Marchetti & Moyle 2001) in that non-native species were dominate; native species represented less than 5% of all individuals captured. Although our study may be somewhat biased for selecting fishes with certain morphologies or behavioral traits because sampling was only conducted by boat electroshocking after dusk, other sampling gears used over the same time period have not collected additional resident native species in the south Delta (our unpublished data).

Reasons for the limited number of native species in the Delta include a combination of influences such as degraded physical habitat such as channelization, altered hydrodynamics (Nichols et al. 1986), and negative interactions with non-native species such as competition (Marchetti 1999) or predation (Turner & Kelley 1966, Bennett & Moyle 1996). These characteristics exemplify the south Delta and reflect our results. The non-native species we found abundant in the south Delta generally have broad environmental tolerances and can withstand the altered habitats better than the natives. Our findings of abundant non-native species in altered habitats are consistent with other recent studies. Waite & Carpenter (2000) found non-native species to be prevalent in streams that they classified as heavily altered within Oregon's Willamette Basin. Aparicio et al. (2000) found that the decline of native species in a Mediterranean watershed on the Iberian Peninsula of Spain was associated with physical habitat and environmental degradation.

The relative importance of environmental variables structuring fish communities

The abundance of native species (tule perch and Sacramento sucker) was associated with conditions and locations of high river flow and turbidity. These results are consistent with other studies in the Delta and its watershed (Brown 2000, Marchetti & Moyle 2001,

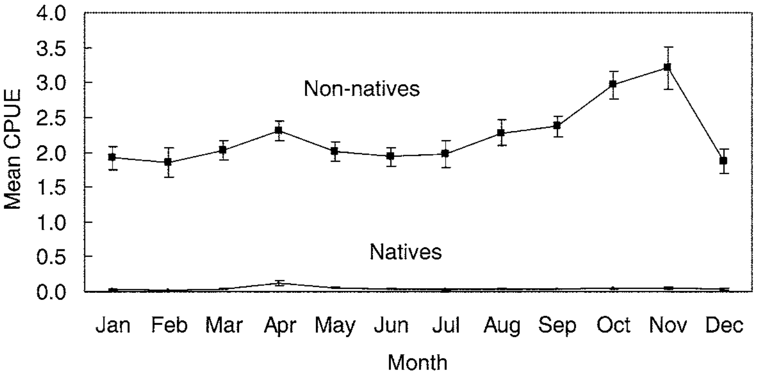

Figure 3. Mean monthly catch per shock hour (CPUE) of native and non-native species over the study period. Error bars represent one standard error.

Table 3. Summary statistics for the CCA of fish abundance and environmental variables. Total Inertia = 1.63.

Variable	Axis 1	Axis 2
Eigenvalue	0.122	0.028
Species-environment correlation	0.601	0.448
Cumulative percentage of variation		
Explained by species only	7.5	9.2
Explained by species & env. var.	71.4	87.9
Inter-set correlations with axes		
River flow	0.361	0.230
Temperature	0.380	−0.331
Specific conductance	0.086	0.111
Turbidity	0.191	0.150
Dissolved oxygen	0.077	−0.054

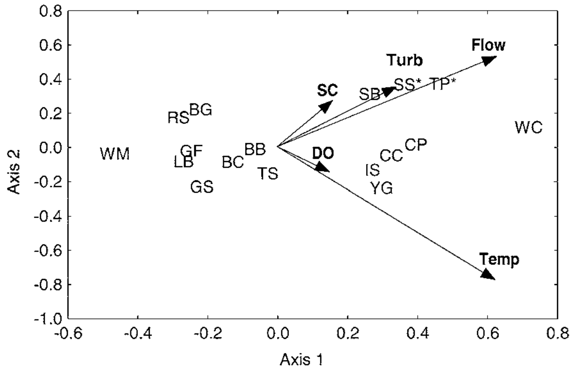

Figure 4. Plot of CCA showing species scores and the importance of environmental variables (vectors). Species codes are given in Table 2. Scores for LB and GF were shifted slightly to facilitate visual interpretation of the plot. Temp = water temperature, DO = dissolved oxygen, SC = specific conductance, Turb = turbidity, Flow = river flow. Native species are indicated by an asterisk.

Grimaldo et al. 2002). Hydrology in the Delta is highly altered and only resembles historic conditions during seasonal extreme flow events that typically occur during the spring. Grimaldo et al. (2002) found that the abundance of native species in the central Delta was highest during peak spring flows. Seasonal flow events may be beneficial for native species in the south Delta by providing optimal environmental conditions for spawning and rearing (Jassby et al. 1995, Sommer et al. 1997, Sommer et al. 2001), by displacing non-native species (Marchetti & Moyle 2001), and by providing suboptimal spawning and rearing conditions for some non-native species (Marchetti & Moyle 2001, Brown & Ford 2002). High flows also increase habitat area and turbidity, which could decrease the potential for predation induced mortality of native species and their progeny.

Environmental conditions in the south Delta were more favorable to non-native species than the natives. The majority of the non-native species were associated with either high water temperature or low river flow, conditions common in the south Delta due to the water diversion facilities and flow control structures. The environmental associations of striped bass, relatively high river flow and turbidity, were similar to those of the native species. This result was not surprising because striped bass is a pelagic anadromous species that requires moderate river flow for spawning and larval transport. White catfish was associated with high river flow and warm temperature, and the DCA indicated a location association with SJR. These results together suggest that white catfish were probably most susceptible to the electroshocking gear (i.e. present in shallow water) during the warm summer periods in the SJR (where river flow was highest).

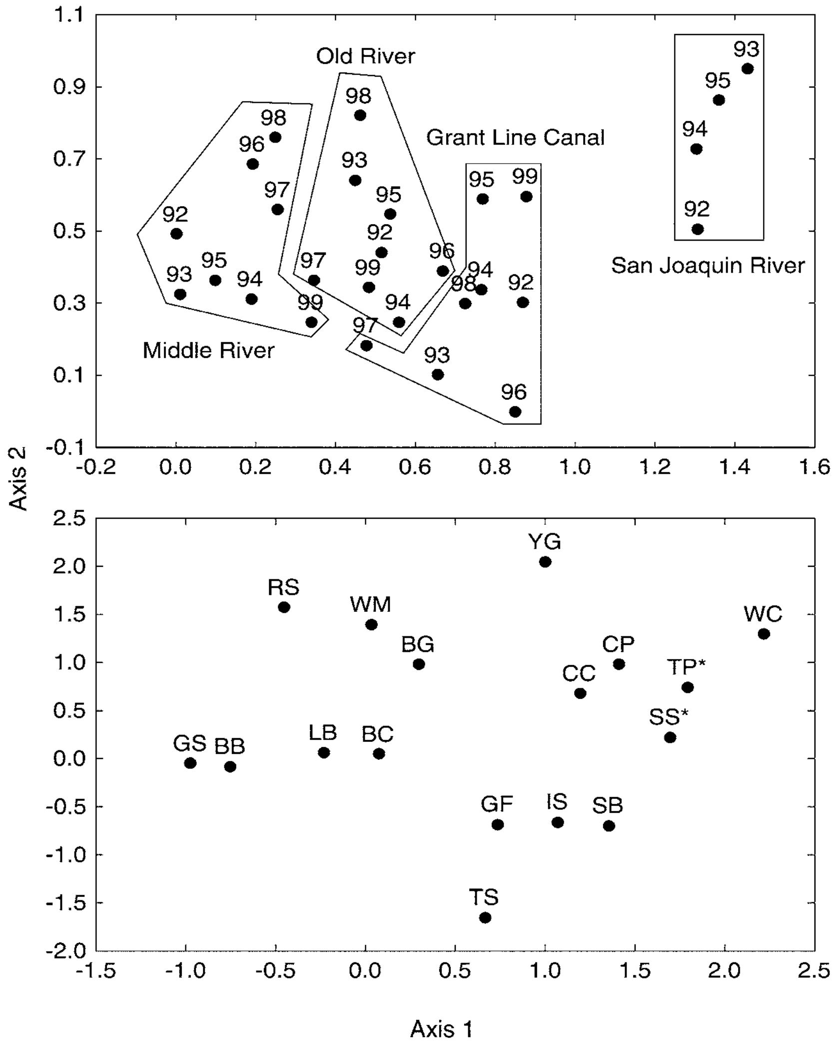

Figure 5. Plot of DCA showing site scores (top) and species scores (bottom). Site scores are coded by year and are enclosed by river location to facilitate interpretation. Species codes are given in Table 2. The scales are different in each diagram to facilitate interpretation. Native species are indicated by an asterisk.

Table 4. Pearson product-moment correlations between DCA axis one site scores and environmental variable mean values for the corresponding site and year. P-values are given in parentheses.

River flow ($m^3 sec^{-1}$)	Water temp. (˚C)	Specific cond. (μS)	Turbidity (NTU)	Dissolved oxygen ($mg l^{-1}$)
0.55 (0.002)	−0.26 (0.181)	0.42 (0.028)	0.45 (0.017)	0.43 (0.022)

Spatial and temporal variation in fish communities

Annual fish community structure in the south Delta appeared to be relatively stable under given flow regimes. The high correlation (0.55) between DCA axis one scores and mean river flow for the corresponding site and year suggested that fish communities varied spatially along an environmental gradient of river flow. Fish community structure in SJR was noticeably different from the slough locations according to the DCA. River flow was the primary factor differentiating our three slough locations, however the SJR differed from these sloughs substantially by river flow and several other physical characteristics. SJR was considerably deeper at center channel, and sampled sites were void of habitat features found at the slough sites such as wetland vegetation, structure such as downed trees, and extensive submerged aquatic vegetation. All of these features contributed to higher habitat complexity in the sloughs. Such habitat complexity and slow water at the slough locations appeared to contribute to the abundance of non-native centrarchids in the community, while species more tolerant of fast water were associated with the SJR.

Conservation implications

The results of this study suggest that fish communities in the south Delta could be influenced by habitat manipulations. Our results suggest that increasing river flow in structurally similar sloughs could promote the presence of native species, and that decreased habitat complexity with a substantial increase in river flow could potentially displace non-native centrarchids. However, it is not known what type of habitat complexity is needed to maintain native fish populations. Meffe (1991) attributed the failed invasion of non-native bluegill in a southeastern blackwater stream to natural stream flow. He also suggested that non-native species in southwestern streams were more easily displaced by major flow events than native species. Travnichek et al. (1995) documented the recovery of a fish assemblage after the initiation of minimum flows below an impoundment in the Tallapoosa River, Alabama. One limitation with this study is that tule perch and Sacramento sucker were the only native species used in the analyses and other natives may not respond in a similar fashion. Moreover, competition or predation from the prevalent non-native species may have influenced the environmental associations of these species. An additional concern is that upstream or downstream sources of recruitment for non-native species may preclude the persistence of a south Delta fish community dominated by native species. Therefore, it is imperative that the ecosystem function of habitat manipulations, and the competitive interactions and recruitment sources of species, be better understood before full-scale habitat restoration actions are implemented in the Sacramento-San Joaquin Delta.

Acknowledgements

This study would not have been possible without the field assistance of many seasonal technicians. The support of H. Rooks and Z. Hymanson is acknowledged. We are grateful to P. Nader who conducted the CALSIM hydrology modeling. We express our appreciation to members of the Interagency Ecological Program for the San Francisco Estuary, Resident Fishes Workteam, especially L. Brown, T. Sommer, L. Grimaldo, and M. Nobriga for critically evaluating earlier drafts of the manuscript. This project was funded by the California Department of Water Resources' South Delta Improvements Program and the California Department of Fish and Game.

References cited

Aparicio, E., M.J. Vargas, J.M. Olmo & A. de Sostoa. 2000. Decline of native freshwater fishes in a Mediterranean watershed on the Iberian Peninsula: A quantitative assessment. Env. Biol. Fish. 59: 11–19.

Arthur, J.F., M.D. Ball & S.Y. Baughman. 1996. Summary of Federal and State Water Project environmental impacts in the San Francisco Bay-Delta Estuary, California. pp. 445–495. *In*: J.T. Hollibaugh (ed.). San Francisco Bay: The ecosystem. Pacific Division, American Association for the Advancement of Science, San Francisco, California.

Bennett, W.A. & P.B. Moyle. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin Estuary. pp. 519–542. *In*: J.T. Hollibaugh (ed.). San Francisco Bay: The ecosystem. Pacific Division, American Association for the Advancement of Science, San Francisco, California.

Brown, L.R. 2000. Fish communities and their association with environmental variables, lower San Joaquin River drainage, California. Env. Biol. Fish. 57: 251–269.

Brown, L.R. & T. Ford. 2002. Effects of flow on the fish communities of a regulated California river: Implications for managing native fishes. Regul. Riv. 18: 331–342.

Gauch, H.G. 1982. Multivariate analysis in community ecology. Cambridge University Press, Cambridge, U.K. 298 pp.

Grimaldo, L., R. Miller, C. Peregrin & Z. Hymanson. 2002. Improving native fish communities through the restoration of breached-leveed wetlands in the San Francisco Estuary: Can the opportunities meet expectations? unpubl. ms.

Jassby, A.D. & Seven Coauthors. 1995. Isohaline position as a habitat indicator for estuarine populations. Ecol. Appl. 5: 272–289.

Karr, J.R. 1991. Biological integrity: A long-neglected aspect of water resource management. Ecol. Appl. 1: 66–84.

Legendre, P. & L. Legendre. 2000. Numerical ecology. Developments in environmental modelling, 20. Elsevier Science. 853 pp.

Marchetti, M.P. 1999. An experimental study of competition between the native Sacramento perch (*Archopolites interruptus*) and introduced bluegill (*Lepomis macrochirus*). Biol. Invas. 1: 1–11.

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

Meffe, G.K. 1991. Failed invasion of a southeastern blackwater stream by bluegills: Implications for conservation of native communities. Trans. Amer. Fish. Soc. 120: 333–338.

Meng, L., P.B. Moyle & B. Herbold. 1994. Changes in abundance and distribution of native and introduced fishes of Suisun Marsh. Trans. Amer. Fish. Soc. 123: 498–507.

Moyle, P.B. 1994. Biodiversity, biomonitoring, and the structure of stream fish communities. pp. 171–186. *In*: S.L. Loeb & A. Spacie (ed.). Biological Monitoring of Aquatic Systems. Lewis Publishers, Boca Raton.

Moyle, P.B., R.A. Daniels, B. Herbold & D.M. Baltz. 1986. Patterns in the distribution and abundance of a noncoevolved assemblage of estuarine fishes in California. Fish. Bull. 84: 105–117.

Nichols, F.H., J.E. Cloern, S.N. Luoma & D.H. Peterson. 1986. The modification of an estuary. Science 231: 567–573.

Saiki, M.K. 1984. Environmental conditions and fish faunas in low elevation rivers on the irrigated San Joaquin Valley floor. Calif. Fish & Game 70: 145–157.

Sommer, T., R. Baxter & B. Herbold. 1997. Resilience of splittail in the Sacramento-San Joaquin Estuary. Trans. Amer. Fish. Soc. 126: 961–976.

Sommer, T., M.L. Nobriga, W.C. Harrell, W. Batham & W.J. Kimmerer. 2001. Floodplain rearing of juvenile chinook salmon: Evidence of enhanced growth and survival. Can. J. Fish. Aquat. Sci. 58: 325–333.

Travnichek, V.H., M.B. Bain & M.J. Maceina. 1995. Recovery of a warmwater fish assemblage after the inititation of a minimum-flow release downstream from a hydroelectric dam. Trans. Amer. Fish. Soc. 124: 836–844.

ter Braak, C.J.F. & P. Smilauer. 1998. CANOCO reference manual and user’s guide to CANOCO for Windows: Software for canonical community ordination (version 4). Microcomputer Power, Ithaca, New York, U.S.A. 474 pp.

ter Braak, C.J.F. & P.F.M. Verdonschot. 1995. Canonical correspondence analysis and related multivariate methods in aquatic ecology. Aquat. Sci. 57: 255–289.

Turner, J.L. & D.W. Kelley (ed.). 1966. Ecological studies of the Sacramento-San Joaquin Delta. Part II: Fishes of the Delta. Calif. Depart. Fish & Game Fish Bull. 136 pp.

Waite, I.R. & K.D. Carpenter. 2000. Associations among fish assemblage structure and environmental variables in Willamette Basin streams, Oregon. Trans. Amer. Fish. Soc. 129: 754–770.