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Fish communities of the Sacramento River Basin: implications for conservation of native fishes in the Central Valley, California

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Synopsis

The associations of resident fish communities with environmental variables and stream condition were evaluated at representative sites within the Sacramento River Basin, California between 1996 and 1998 using multivariate ordination techniques and by calculating six fish community metrics. In addition, the results of the current study were compared with recent studies in the San Joaquin River drainage to provide a wider perspective of the condition of resident fish communities in the Central Valley of California as a whole. Within the Sacramento drainage, species distributions were correlated with elevational and substrate size gradients; however, the elevation of a sampling site was correlated with a suite of water-quality and habitat variables that are indicative of land use effects on physio-chemical stream parameters. Four fish community metrics – percentage of native fish, percentage of intolerant fish, number of tolerant species, and percentage of fish with external anomalies – were responsive to environmental quality. Comparisons between the current study and recent studies in the San Joaquin River drainage suggested that differences in water-management practices may have significant effects on native species fish community structure. Additionally, the results of the current study suggest that index of biotic integrity-type indices can be developed for the Sacramento River Basin and possibly the entire Central Valley, California. The protection of native fish communities in the Central Valley and other arid environments continues to be a conflict between human needs for water resources and the requirements of aquatic ecosystems; preservation of these ecosystems will require innovative management strategies.

Introduction

The rivers of the western United States and many other arid environments have been extensively altered, primarily to provide water for agricultural and urban development (Reisner 1986). The Sacramento River drainage of California illustrates many of the problems resulting from such human activities. The Sacramento River Basin (Figure 1) is a relatively large, diverse watershed approximately 70 000 km^2 in area and includes portions of 10 ecological regions (Omernik 1987, Domagalski et al.[1]). The water resources of the basin have been developed to support agricultural and urban activities in the Central Valley and in southern California. This water is supplied by large storage reservoirs located in the foothills of the Sierra Nevada. The natural flow regime and

[1] Domagalski, J.L., D.L. Knifong, P.D. Dileanis, L.R. Brown, J.T. May, V. Connor & C.N. Alpers. 2000. Water quality in the Sacramento River Basin, California, 1994–1998. U.S. Geological Survey Circular 1215, U.S. Geological Survey, Reston. 36 pp.

geomorphic processes of the rivers have been substantially changed below dams. Within-basin diversions via canals are relatively small compared to the quantities delivered through natural river channels to pumping plants in the Sacramento-San Joaquin Delta for export to the San Joaquin Valley or southern California (Kahrl et al. 1978, Mount 1995). Changes in water and habitat quality in higher elevation ecological regions have been less dramatic. Streams in the regions have been affected by logging, grazing, urbanization, and smaller-scale dams and diversions operated for municipal water supply and production of hydroelectricity (Moyle & Randall 1998).

Declines and extinctions of native fish species and the introduction of new fish species in the Central Valley, California have occurred concurrently with these environmental changes (Moyle 1976a, Brown & Moyle 1993, Brown 2000). Results of these previous studies suggest that introduced species are better adapted for the altered environments and may affect native species through both competition and predation. Brown (2000) suggested that there is a potential for developing a metric-based assessment of environmental perturbation for the Central Valley as has been done for other areas of the country (Fausch et al.1984, Hughes & Gammon 1987).

The purposes of this paper are: (1) determine the associations of the resident fish communities with environmental variables in the Sacramento Basin streams; and (2) evaluate the responses of six fish community metrics to environmental conditions. The metrics we calculated were: percentage of native fish, number of native species, percentage of fish intolerant of environmental degradation, number of species tolerant of environmental degradation, percentage of omnivorous species, and percentage of fish with external anomalies, including lesions, tumors, deformities, and parasites. Also, we compare these results to those of a recent study of San Joaquin River drainage fish communities (Brown 2000) to provide a perspective on environmental conditions and water management practices and their potential effects on fish communities in the Central Valley of California, as a whole.

Methods

Study design

A total of twenty-two sites were sampled from 1996 to 1998 (Table 1, Figure 1). The multiple-year sampling performed between 1996 and 1998 was intended

Table 1. Site name, site code, site elevation, land use, and year(s) sampled for study sites.

Site name	Site code	Elevation (m)	Land use[b]	Year(s) sampled
McCloud River at the Nature Conservancy Preserve[a]	MC	683	MD	1996–1998
Deer Creek below Hwy 99 Bridge	DC1	61	MD	1997–1998
Deer Creek near Vina[a]	DC2	146	MD	1996–1998
Deer Creek near Ishi Wilderness Area	DC3	524	MD	1997
Deer Creek at Potato Patch Campground	DC4	1049	MD	1997–1998
Big Chico Creek at Chico	BC1	50	UR	1996–1998
Big Chico Creek above Chico	BC2	82	MD	1996–1998
Big Chico Creek near Forest Ranch	BC3	317	MD	1997
Big Chico Creek at Soda Springs Campground	BC4	1134	MD	1997–1998
Butte Creek near Meridian	BU1	15	AG	1997
Butte Creek near Afton	BU2	21	AG	1997
Butte Creek near Nelson	BU3	37	AG	1997
Butte Creek near Paradise	BU4	104	MD	1997–1998
Butte Creek near Butte Meadows	BU5	585	MD	1997
Butte Creek at Cherry Hill Campground	BU6	1427	MD	1997–1998
Sacramento River near Colusa	SACR	12	MD	1996, 1998
Cache Creek near Guinda	CC	107	MD	1996–1997
Yuba River near Marysville	YR	22	MD	1996, 1998
Feather River near Nicholas	FR	6	MD	1996, 1998
Colusa Basin Drain near Knights Landing	CBD	8	AG	1996, 1998
Sacramento Slough near Karnak	SACS	6	AG	1996
American River at Sacramento	AMR	9	MD	1996

[a]Sites where three stream reaches were sampled for spatial variability of fish community structure.
[b]Major land use categories: MD = minimally developed; AG = agricultural land use; and UR = urban land use.

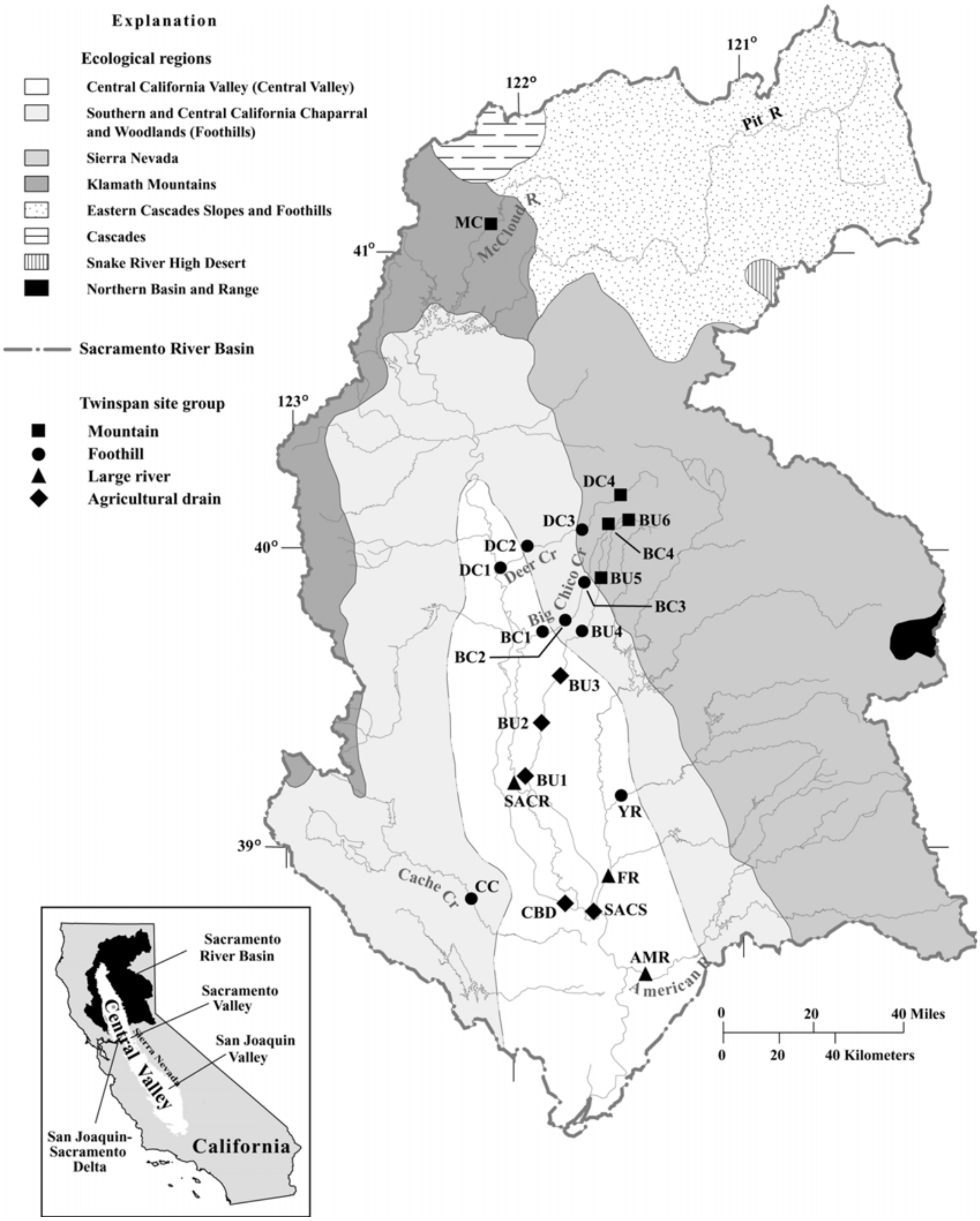

Figure 1. Locations of study sites, ecological regions and TWINPSAN site groups.

to assess annual variability of fish communities. Three reaches were sampled at two sites to assess spatial variability within sites. Fish sampling was performed during the low-flow period of the year, which is typically late July through late September.

Data collection

Sampling reach length was determined in one of two ways. When distinct habitat types (pools, riffles, runs) were present, the reach location and length were selected to include two or more repetitions of the habitat types present (Meador et al.[2]). Otherwise, reach length was defined as 20 times the wetted channel width with a minimum and maximum reach length of 150 and 300 m for wadeable streams, and 500 and 1000 m for larger, non-wadeable streams.

Fish were sampled by a combination of electrofishing (boat or backpack), seining (9 m length with 6 mm mesh), or snorkeling, as determined by the environmental conditions at each site (Meador et al.[3]). In general, electrofishing was the primary collection method. Electrofishing consisted of one pass along each stream bank. Seining effort was variable because of the rarity of appropriate seining beaches at many of the sampling sites. Seining effort consisted of one or more seine hauls at all appropriate seining beaches within the sampling reach. At sites where federally and state protected anadromous salmonids were expected, snorkeling was the primary method. Snorkeling consisted of one pass through the stream reach by one snorkeler. At six sites (BC2, BC4, BU4, BU6, SACR, and YR), different sampling methods were used in 1998 compared to previous years because of endangered species restrictions, equipment availability, or site conditions. Snorkeling was on the only sampling technique used in 1998 at sites BC2, BC4, BU4, BU6, and YR, compared to a combination of backpack electrofishing and snorkeling in previous years. At the SACR site there was a greater emphasis on beach seining and only 1 boat electrofishing pass in 1998 compared to previous years when boat electrofishing was the only method used.

Captured fish were identified (Moyle 1976b) and counted. Fishes that could not be identified in the field were vouchered for laboratory identification. All fish captured were examined for external anomalies. Fish observed during snorkeling surveys were identified and counted.

Collection of physiochemical parameters was conducted on the same day or within several days of fish collections. Water samples for measurements of specific conductance and pH were collected using width- and depth-integrated sampling or by grab sampling. Field measurements of specific conductance, pH, water temperature, and dissolved oxygen were made with electronic meters. Instantaneous discharge was determined at ungaged sites.

Habitat variables were measured at six transects within each sampling reach[2]. At sites with repeating habitat types, transects were placed to reflect the relative availability of each habitat type; otherwise, transects were placed at equally spaced intervals. Reach length and wetted channel width were measured with a graduated tape or an electronic rangefinder. The extent of riparian canopy closure was measured from midstream at each transect with a clinometer as the number of degrees of open sky above the transect. Depth, velocity, and substrate were measured at three or more points within each transect. Measurement points generally were at about one-quarter, one-half, and three-quarters of the stream width. Depth was measured with a wading rod. Velocity was measured with an electronic flow meter (Marsh-McBirney). Substrate was visually estimated as the dominant substrate at each transect point and was classified as (1) organic detritus, (2) silt, (3) mud, (4) sand (0.02–2 mm), (5) gravel (2–64 mm), (6) cobble (64–256 mm), (7) boulder (>256 mm), or (8) bedrock or hardpan (solid rock or clay forming a continuous surface. Variables with multiple measurements at a site were analyzed as mean or geometric mean values.

Stream gradient, stream sinuosity, and elevation were determined from U.S. Geological Survey 1 : 24 000 topographic maps. Stream sinuosity was measured as river distance divided by the straight-line distance between the upstream and downstream ends of a segment of stream (minimum of 2 km). Basin areas and the percentages of agricultural and urban land use within each area were determined using

[2] Meador, M.R., C.R. Hupp, T.E. Cuffney & M.E. Gurtz. 1993a. Methods for characterizing stream habitat as part of the National Water-Quality Assessment Program. U.S. Geological Survey, Open-File Report 93–408. 48 pp.

[3] Meador, M.R., C.R. Hupp, T.E. Cuffney & M.E. Gurtz. 1993b. Methods for sampling fish communities as part of the National Water-Quality Assessment Program. U.S. Geological Survey, Open-File Report 93–104. 40 pp.

geographic information system databases (U.S. Geological Survey[4]).

Data analysis

Multivariate analyses were utilized to explore fish community structure and the relation of community structure to environmental characteristics. Multivariate analyses were done using both percentage abundance and presence–absence data. The two analyses resulted in only minor differences in results. Only the percentage abundance results are presented. To minimize the effect of rare species in analyses, only species that were found at three or more sites and constituted at least 5% of the fish captured at one site were incorporated into the analyses (Gauch 1982). Additionally, Western mosquitofish, *Gambusia affinis*, and lampreys, *Lampetra* spp., were not included in multivariate analyses due to low capture efficiency with the 6.4 mm mesh size of nets used in this study.

Species and site groups were defined using two multivariate methods, two-way indicator species analysis (TWINSPAN) (Hill 1979) and canonical correspondence analysis (CCA) using the statistical package CANOCO (ter Braak 1986, 1987, Jongman et al. 1987). Data from only one sample (1996 or 1997) were used for these analyses in order to eliminate possible bias due to multiple samples from a site.

TWINSPAN is a divisive numerical classification technique developed for hierarchical classification of community data. The analysis was limited to three divisions (level-1, level-2, and level-3) potentially yielding eight groups. Level-3 groups were used for more detailed examination of site and species groups. CCA is a direct gradient ordination technique for relating species and sites to physiochemical parameters. Sites and species groups were defined by visual examination of ordination plots and were then compared with TWINSPAN groupings.

The four groups defined by the TWINSPAN level-2 division were used for comparisons of environmental and fish community metric data among site groups using analysis of variance (ANOVA). Level-2 division groups were used because several level-3 division groups included only one or two sites. When the ANOVA was significant, pair-wise comparisons were conducted to assess differences between the TWINSPAN site groups.

Principal component analysis (PCA) was used as an exploratory technique to describe the primary environmental gradients in the basin. Variables were examined for normality by visual inspection of normality probability plots and were $\log_{10}(x + 1)$ transformed where appropriate and then standardized to a mean of 0 and standard deviation of 1. PCA was performed on 16 environmental variables representing various spatial scales ranging from watershed characteristics to instream habitat and water chemistry. Only principal components (PCs) with eigenvalues greater than 1 were retained for interpretation. Loadings were qualitatively designated as 'high' for absolute values greater than 0.60.

Associations of species and sites with environmental variables were investigated using CCA. CCA was conducted in the forward selection mode, and the significance of each variable was tested in a sequential fashion using a Monte-Carlo simulation algorithm before being added to the final model. All variables significant at $p < 0.05$ were included in the final model.

Spatial and annual variations of fish communities were evaluated using detrended correspondence analysis (DCA). DCA was performed using CANOCO (ter Braak 1987). Data for all years and reaches were included. Only species that were found at three or more sites and making up at least 5% of the fish captured at one site were included in the DCA. DCA is an improved eigenvector ordination technique based on reciprocal averaging, correcting its two main faults, arch distortion and violation of the orthogonality criterion (Gauch 1982). Reciprocal averaging or correspondence analysis is a multivariate technique that maximizes the correlation between species scores and sample scores along an assumed gradient (Hill & Gauch 1980).

Calculation of metric values was based on all individuals captured. Native species were determined from Moyle (1976b). Trophic and tolerance categories were derived from the works of Moyle (1976b), Moyle & Nichols (1973, 1974), and P.B. Moyle (University of California, Davis, 1996 written communication). Kruskal–Wallis ANOVA was used to test the significance of fish community metrics between TWINSPAN site groups.

[4] U.S. Geological Survey. 1986. Land use and land cover digital data from 1 : 250 000 and 1 : 1 000 000 scale maps. National Mapping Program, Technical Instructions, Data Users Guide 4, U.S. Geological Survey, Reston. 36 pp.

Results

A total of 36 fish taxa were captured during the study (Table 2). Thirteen taxa were native to California and 23 taxa were introduced. Twenty-one of the total 36 fish taxa were used for multivariate analyses. Of these 21, only 11 taxa are native to California.

TWINSPAN species groups

The initial TWINSPAN division generally separated native and introduced species with the exception that brown trout, *Salmo trutta*, and smallmouth bass, *Micropterus dolomieu*, were included with the native species, and tule perch, *Hysterocarpus traski*, prickly sculpin, *Cottus asper*, and Sacramento hitch, *Lavinia exilicauda*, were included with the introduced species. The second level of division resulted in four groups of species.

The first of the four species groups (I) defined by the second TWINSPAN division was composed entirely of native species, except for brown trout. The native species included rainbow trout, *Oncorhynchus mykiss*, juvenile chinook salmon, *Oncorhynchus tshawytscha*, hardhead, *Mylopharodon conocephalus*, California roach, *Hesperoleucus symmetricus*, speckled dace, *Rhinichthys osculus*, and riffle sculpin, *Cottus gulosus*. The level-3 division of this group separated the two trout species from the other species because of high percentage abundances at the highest elevation sites. The other species were characteristic of the Foothill ecoregion.

Sacramento sucker, *Catostomus occidentalis*, and Sacramento pikeminnow, *Ptychocheilus grandis*, comprised the second TWINSPAN species group (II). Both of these species were widely distributed over the study area. Sacramento sucker was captured at 14 of 22 sites, and Sacramento pikeminnow was found at 11 of 22 sites. Sacramento suckers were found in nearly all stream types sampled, except for the highest elevation sites, which were dominated by trout.

The third species group (III) consisted of smallmouth bass, which occurred at 9 of the 22 sampling sites. The distribution of smallmouth bass included large river sites and sites on the lower valley-floor portions of the tributary streams.

The fourth species group (IV) was composed primarily of introduced species but included three native species, tule perch, prickly sculpin, and Sacramento hitch. The introduced species (threadfin shad, *Dorosoma petenense*, common carp, *Cyprinus carpio*, largemouth bass, *Micropterus salmoides*, bluegill, *Lepomis macrochirus*, green sunfish, *Lepomis cyanellus*, white crappie, *Pomoxis annularis*, and channel catfish, *Ictalurus punctatus*) (Table 2) in this group were commonly found at the large river sites and agricultural drainage sites. Tule perch and prickly sculpin were found predominantly at the large river sites.

TWINSPAN site groups

The first TWINSPAN division of sites roughly separated the large river and agricultural drainage sites on the valley floor of the Central Valley ecoregion from the sites located in the Foothills and Sierra Nevada ecoregions. The second TWINSPAN division resulted in the four site groups (Figure 1).

The mountain group (MT) consisted of five high-elevation tributary sites where the fish community was dominated by rainbow trout, juvenile chinook salmon, and brown trout (Table 2). The level-3 division of this group separated three sites (BC4, BU6, and MC) from the others on the basis of high percentage abundances of brown trout.

The foothill group (FH) consisted of nine sites within the Foothills and Central Valley ecoregions. These sites were dominated by native minnow and sucker species, including Sacramento pikeminnow, hardhead, speckled dace, California roach, and Sacramento sucker (Table 2). The level-3 division of this group separated sites in the mid-elevation foothills (DC2, DC3, BC3, and BU4) from those on the valley floor (DC1, BC1, and YR).

The large river group (LR) included three large river sites that had similar relative abundances of the native tule perch and prickly sculpin, as well as the introduced black crappie, *Pomoxis nigromaculatus*. Tule perch was found at foothill group sites, but at relatively low abundances. The other species captured at large river sites were a mixture of native species characteristic of the foothill group and the introduced species found in the fourth group, the agricultural drain group (Table 2).

The agricultural drain group (AG) included sites in areas in which agricultural land use was predominant. These sites were dominated by introduced species including threadfin shad, common carp, largemouth bass, and bluegill (Table 2). The native species – Sacramento hitch, Sacramento pikeminnow, and Sacramento sucker – were found in low numbers

(Table 2). The level-3 division of this group separated out two sites in the lower Butte Creek watershed (BU2 and BU3) that had relatively low abundances of fish.

Environmental data

PCA yielded three PCs with eigenvalues greater than 1, which explained 75% of the variance in the data. Variable loadings for the first two PCs are given in Table 3. The first two PCs accounted for 47% and 20% of the variance, respectively. The remaining PC had no variables that loaded highly.

Variables that loaded highly on PC1 included elevation, mean dominant substrate size, specific conductance, water temperature, basin area, and agricultural and urban land use (Table 3). PC1 describes a gradient from high-elevation Sierra Nevada sites to lower elevation valley-floor sites (Figure 2).

PC2 separates sites on the basis of specific conductance, water temperature, and mean velocity. Generally, this axis separates the agricultural drains (BU1, BU2, BU3, SACS, and CDB) from the rest of the sites.

The four TWINSPAN site groups had distinctly different physical characteristics (Table 4). Thirteen of 16 ANOVA comparisons were statistically significant. The pairwise comparisons were generally consistent with the gradient described by PC1. Agriculture drain group sites generally had the highest water temperatures and specific conductance values. The foothill and mountain site groups generally had low specific conductance values, high canopy cover and larger mean dominant substrate size.

Canonical correspondence analysis

The forward selection procedure of CCA resulted in the retention of 2 of 18 environmental variables in the final model (Table 5). Substrate size and elevation of the site were the most important factors in the analysis and were important on both CCA axes. It is important to note that elevation and substrate size act as surrogates for the group of variables associated with PC1 (Table 3).

CCA axis 1 described a gradient in species percentage abundances from the species dominating the valley floor sites to the species dominating the Sierra Nevada, particularly trout (Figure 3a). The central position of Sacramento pikeminnow and Sacramento sucker (TWINSPAN species group II) is consistent with the broad distribution of these species and the resulting co-occurrence with a variety of native and introduced species associated with the foothill and large river site groups. Similarly, smallmouth bass was broadly distributed but tended to be most abundant in the presence of species characteristic of the large river and agricultural drain groups.

The TWINSPAN agricultural drain and large river site groups are separated from the other groups on CCA axis 1 (Figure 3b). The TWINSPAN agricultural drain site group and the mountain site group form the extremes of the ordination. The foothill site group and large river site group are intermediate on CCA axis 1 in the ordination space. CCA axis 2 separated mountain sites from the foothill sites and agricultural drain sites from large river sites.

Spatial and annual variation

The first four DCA axes explained 35% of the variance within the species data. The first two axes explained 17% and 8% of the variance, respectively. Visual inspection of the DCA site plot (Figure 4) and site scores indicate that there was little spatial or annual variation in fish community composition at individual sites, relative to differences among sites. The largest annual differences appeared to occur for BU4, SACR, FR, and CBD. Inspection of the raw data for each sampling site indicated that the annual variation was generally associated with differences in percentage abundances rather than presence or absence of any particular species. The variation in sampling methodology for sites BU4 and SACR may have contributed to annual variability in percentage abundance of fish observed; however, other sites where survey methods varied (BC2, BC4, BU6, and YR) showed low annual variability.

Fish community metrics

All metrics tested were statistically different among TWINSPAN site groups (Table 6). The percentage of native fishes was lowest in the agricultural drain group. The number of native species and the percentage of intolerant fishes were lowest in the agricultural drain group, but the number of native species was not statistically different from that of the mountain group. The number of tolerant species and the percentage of omnivorous fishes were not statistically different between the agricultural drain group and the large river group. The percentage of fishes with external anomalies was highest in the agricultural drain group and was

Table 2. Common and scientific names, origin, trophic group, tolerance, species code, and percentage of fish caught in each TWINSPAN species and site groups for all species captured.

Common name and species code	Scientific name	Origin	Trophic group	Tolerance	TWINSPAN species group	TWINSPAN site group AG (N = 5)	LR (N = 3)	FH (N = 9)	MT (N = 5)
Petromyzontidae (lampreys)									
Unknown lampreys (—)	*Lampetra* sp.	—	Det.	I	—	0	4.1 (1)	0.3 (4)	0
Clupeidae (shad and herring)									
American shad (—)	*Alosa sapidissma*	I	Plank.	M	—	0	0	2.9 (1)	0
Threadfin shad (TFS)	*Dorosoma petenense*	I	Plank.	M	IV	27.8 (2)	0.9 (1)	0	0
Salmonidae (salmon and trout)									
Brown trout (BT)	*Salmo trutta*	I	Invert.	I	I	0	0	0.0 (1)	15.8 (3)
Rainbow trout (RT)	*Oncorhynchus mykiss*	N	Invert.	I	I	0	3.3 (1)	5.3 (6)	73.9 (5)
Chinook salmon (CS)	*Oncorhynchus tshawytscha*	N	Invert.	I	I	0	0.7 (2)	2.9 (3)	0.6 (1)
Cyprinidae (minnows)									
Common carp (CP)	*Cyprinus carpio*	I	Omn.	T	IV	6.7 (4)	0.7 (2)	0	0
Goldfish (—)	*Carassius auratus*	I	Omn.	T	—	0.2 (1)	0	0.0 (1)	0
Golden shiner (—)	*Notemigonus crysoleucas*	I	I	T	—	0	1.2 (2)	0	0
Red shiner (—)	*Cyprinella lutrensis*	I	Omn.	T	—	0.3 (1)	0	0	0
Hardhead (HH)	*Mylopharodon conocephalus*	N	Omn.	I		0	0	14.5 (8)	0
Sacramento hitch (HCH)	*Lavinia exilicauda*	N	Plank.	M	IV	7.5 (2)	0	0.4 (2)	0
Sacramento pikeminnow (PKM)	*Ptychocheilus grandis*	N	Inv/Pis.	M	II	0.2 (1)	13.0 (3)	15.7 (7)	0
Speckled dace (SD)	*Rhinichthys osculus*	N	Inv.	I	I	0	0	7.7 (4)	0
California roach (RCH)	*Hesperoleucus symmetricus*	N	Omn.	M	I	0	0.2 (1)	6.6 (5)	0
Sacramento splittail (—)	*Pogonichthys macrolepidotus*	N	Omn.	M	—	0	0.7 (2)	0	0
Catostomidae (suckers)									
Sacramento sucker (SKR)	*Catostomus occidentalis*	N	Omn.	M	II	0.9 (3)	15.1 (3)	19.8 (8)	0
Embiotocidae (surfperch)									
Tule perch (TP)	*Hysterocarpus traski*	N	Inv.	I	IV	0	20.3 (3)	3.1 (2)	0
Ictaluridae (catfish)									
Black bullhead (—)	*Ameiurus melas*	I	Inv.	T	—	0	0.2 (1)	0.1 (1)	0

Channel catfish (CCF)	*Ictalurus punctatus*	I	Inv/Pis.	M	IV	3.1 (3)	0.2 (1)	0.1 (1)	0
White catfish (—)	*Ameiurus catus*	I	Inv/Pis.	T	—	2.9 (2)	0	0	0
Poeciliidae (livebearers)									
Western mosquitofish (—)	*Gambusia affinis*	I	Inv.	T	—	1.4 (3)	0	0	0
Atherinidae (silversides)									
Inland silverside (—)	*Menidia beryllina*	I	Plank.	M	—	1.4 (2)	0.9 (2)	0	0
Percichthyidae (temperate basses)									
Striped bass (—)	*Morone saxatilis*	I	Pisc.	M	—	0	0	1.1 (1)	0
Centrarchidae (sunfish)									
Largemouth bass (LMB)	*Micropterus salmoides*	I	Pisc.	T	IV	7.8 (5)	3.8 (3)	0.1 (1)	0
Smallmouth bass (SMB)	*Micropterus dolomieu*	I	Pisc.	M	III	0.5 (1)	6.8 (3)	1.2 (5)	0
Spotted bass (—)	*Microterus punctulatus*	I	Pisc.	M	—	0	0.2 (1)	0	0
Bluegill (BG)	*Lepomis macrochirus*	I	Inv.	T	IV	16.9 (3)	6.6 (2)	0	0
Redear sunfish (—)	*Lepomis microlophus*	I	Inv.	M	—	12.4 (1)	2.4 (1)	0	0
Green sunfish (GSF)	*Lepomis cyanellus*	I	Inv.	T	IV	2.7 (3)	1.4 (1)	0.1 (2)	0
Warmouth (—)	*Lepomis gulosus*	I	Inv.	T	—	4.0 (2)	0	0	0
White crappie (WC)	*Pomoxis annularis*	I	Inv/Pis.	T	IV	2.1 (2)	0.7 (1)	0	0
Black crappie (BC)	*Pomoxis nigromaculatus*	I	Inv/Pis.	M	IV	0.8 (1)	1.6 (2)	0	0
Percidae (perch)									
Bigscale logperch (—)	*Percina macrolepida*	I	Inv.	T	—	0.5 (1)	0.4 (1)	0	0
Cottidae (sculpin)									
Prickly sculpin (PSCP)	*Cottus asper*	N	Inv.	M	IV	0	14.8 (3)	0	0
Riffle sculpin (RSCP)	*Cottus gulosus*	N	Inv.	I	I	0	0	18.3 (6)	9.7 (1)

Species codes were assigned only for species included in multivariate analyses. Origin: N = native to California; I = introduced to California. Trophic group: Det. = detritivore; Inv. = invertivore; Inv/Pis. = Combination invertivore and piscivore; Omn. = omnivore; Pisc. = piscivore; and Plank. = planktivore. Tolerance to environmental degradation: I = intolerant; M = moderately tolerant; and T = tolerant. TWINSPAN species group: corresponds to groups shown in Figure 3a. TWINSPAN site groups: AG = agricultural drain group; LR = large river group; FH = foothill group; MT = mountain group; N = number of sites in a TWINSPAN site group. Value represent the percentage of individuals of each species captured and, in parentheses, the total number of sites where species were captured.

Table 3. Principal component loadings for habitat and water quality variables from PCA of physical data from sites sampled during this study. **Bold** values were considered high (>|0.60|).

Environmental variable	PC1	PC2
Basin area (km^2)[a]	**0.942**	(b)
Open canopy (degrees)	**0.914**	(b)
Mean width (m)[a]	**0.869**	(b)
Agricultural + urban land (%)[a]	**0.759**	−0.517
Discharge ($m^3\ s^{-1}$)[a]	**0.749**	0.385
Mean depth (m)	**0.676**	(b)
Water temperature (°C)	0.549	**−0.737**
Mean velocity ($m\ s^{-1}$)	0.38	**0.638**
Stream sinuosity[a]	0.347	0.396
Specific conductance ($\mu S\ cm^{-1}$)[a]	(b)	**−0.827**
Dissolved oxygen ($mg\ l^{-1}$)	−0.347	0.386
pH	**−0.606**	−0.478
Mean dominant substrate	**−0.657**	0.548
Canopy cover (%)	**−0.752**	(b)
Gradient	**−0.765**	(b)
Elevation (m)[a]	**−0.897**	(b)
Proportion of variance explained	0.47	0.20

[a]Variables were log transformed for analysis.
[b]Loading less than |0.30|.

significantly different from the rest of site types sampled. The large river group was intermediate between the agricultural drain group and the foothill group.

Discussion

In general, stream fishes in the Sacramento River Basin during 1996–1998 appeared to respond to a longitudinal gradient in physical environmental conditions; this result is consistent with that of previous but less geographically extensive studies of Central Valley fishes (Moyle & Nichols 1973, Moyle et al. 1982, Brown 2000). The CCA ordination stressed elevation and mean dominant substrate size; these variables, particularly elevation, were largely acting as surrogates for an environmental gradient summarized by PC1 (Figure 3, Table 3).

Although introduced species were found at many of the Sacramento River Basin sites, they were only abundant at agriculture drainage sites (Table 2). The agricultural drains appeared to be highly stressful environments given the predominance of tolerant fish species and the high percentage of fish with anomalies (Table 6). In contrast, introduced species dominated Central Valley streams in the San Joaquin River Basin from 1993 to 1995 (Brown 2000). It is important to note that the study by Brown (2000) was conducted at the end of a 6-year drought and may represent extremely stressful conditions for native species (Brown & Ford 2002).

Differences in water-management practices between the Sacramento River Basin and San Joaquin River Basin may account for differences in dominance of introduced species. In the San Joaquin River drainage, water captured in foothill reservoirs is generally diverted into canal systems, leaving little water in the streams. Additional diversions occur as streams flow through the San Joaquin Valley. Inputs of poor quality agricultural return water also occur. In contrast, in the Sacramento River drainage, water is generally released into stream channels for downstream delivery rather than diverted, although the timing and magnitude of flows is altered from the natural flow regime. Furthermore, the Sacramento River system is much larger, having approximately 10 times the annual discharge of the San Joaquin River. There are also temperature criteria in place in the lower Sacramento River to maintain cold water conditions for native anadromous salmonids. As a result of these differing water management practices, the lower San Joaquin River system is characterized by lower water velocities, warmer temperatures, finer substrates and poorer water quality relative to the Sacramento River. Native fishes have presumably evolved to deal with seasonal fluctuations in water temperature and stream discharge. In contrast, the introduced species in the drainage, with the exception of smallmouth bass and brown trout, tend to be warm-water species poorly adapted for sustaining substantial populations under current conditions of fluctuating high discharges of cold water in the lower Sacramento River system (Baltz & Moyle 1993, Brown & Moyle 1993, Moyle & Light 1996 a,b). Studies in California (Baltz & Moyle 1993, Moyle & Light 1996a,b, Brown & Ford 2002), in other Mediterranean-climate streams in general (Moyle 1995, Elvira 1995, Godinho et al. 1997), and elsewhere (Minkely & Meffe 1987, Meffe 1991) indicate that native species communities are resistant to invasion when natural flow conditions are maintained. Physiological and behavioral responses of species to temperature and flow conditions are strong factors in structuring native California stream fish communities (Baltz et al. 1982, Cech et al. 1990).

Spatial and annual variation

Visual inspection of DCA scores and raw data indicate that spatial and annual variability in fish community

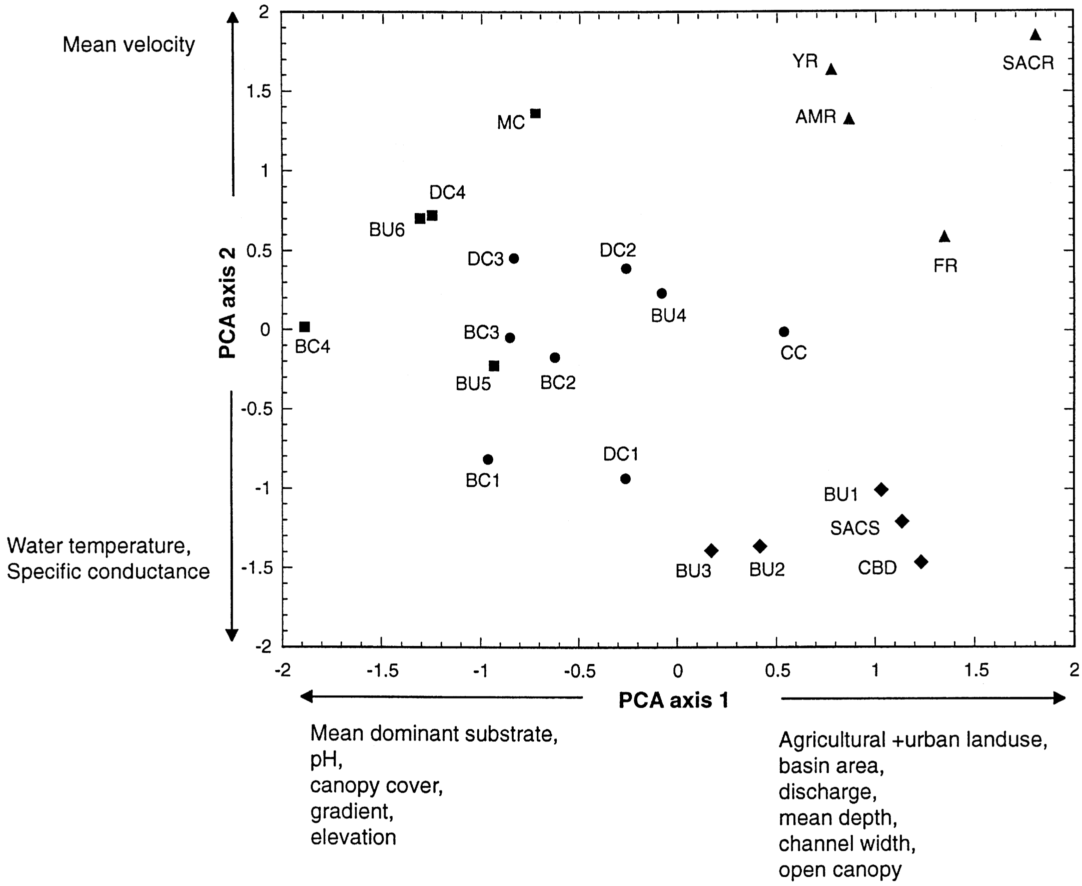

Figure 2. PCA plot of site scores on the first two PCs derived from the environmental variables. Locations of sites are shown in Figure 1. TWINSPAN site groups are represented by different symbols; squares indicate sites within the Mountain site group, circles indicate sites within the Foothill site group, triangles indicate sites within the Large River site group, and diamonds indicate sites within the Agriculture Drain site group.

structure were minimal within the context of the large geographic scale of the study area (Figure 4). Relative abundance of species varied rather than the presence or absence of species as has been observed in other systems (Rahel 1990). Sites MR and DC2, for which three adjacent reaches were sampled, showed little spatial variation in species composition and relative abundance.

Similar results for fish community structure were obtained at most of the sites where sampling methodology varied for 1998 sampling efforts (BC2, BC4, BU4, BU6, SACR, and YR) (Figure 4). Inspection of the raw data indicated little or no variation in species composition. Most annual variation was in the relative abundance of each species at the site. For sites with less-diverse species communities (BC4 and BU6), the variation resulting from different sampling methods was minimal. For sites with intermediate species richness (BC2, BU4, and YR), the variation in community structure appeared to be greatest in riffle-oriented species, such as sculpins and dace. For SACR, a site with relatively high species richness, the variation in community structure related to 1996 and 1998 sampling methods appeared to be similar to annual variation observed at a similar site, Feather River (FR) at Nicholas where methodology did not change. Clearly, it is highly desirable to use the same sampling methodology throughout a study, but in this case the changes do not seem to have affected the results to a significant degree.

Fish community metrics

Differences among site groups for the fish community metrics tested (Table 6) indicate that an index of biotic

Table 4. Mean (geometric mean for log-transformed variables) and range (in parentheses) for selected water-quality and habitat variables for site groups resulting from TWINSPAN analysis of fish species percentage abundance (see Figure 3b for sites in each group).

Variable	TWINSPAN site group			
	AG (N = 5)	LR (N = 3)	FH (N = 9)	MT (N = 5)
Water-quality variables				
pH	8^{AB} (7.4–8.4)	6.9^{A} (6.7–7.2)	7.9^{B} (6.3–8.4)	8.1^{B} (7.9–8.3)
Specific conductance ($\mu S\,cm^{-1}$)[a]	370^{A} (246–741)	78^{B} (43–121)	144^{B} (72–311)	119^{B} (95–162)
Dissolved oxygen ($mg\,l^{-1}$)	7.9 (6.2–9.6)	9.2 (8.4–10)	8.8 (7.8–10)	9.9 (7.6–11.2)
Habitat variables				
Discharge ($m^3\,s^{-1}$)[a]	9.8^{AB} (1.5–26.7)	64^{A} (29.6–146.9)	3.2^{B} (1.1–14.7)	3.3^{B} (1.6–5.7)
Water temperature(°C)	26.5^{A} (24.6–29.0)	17.8^{BC} (16.8–19.4)	19.7^{B} (14.4–30.7)	12^{C} (7.2–20.1)
Mean depth (m)	1.6^{AB} (0.45–2.76)	2.5^{A} (1.11–4.58)	0.89^{B} (0.30–1.23)	0.91^{AB} (0.55–1.19)
Mean velocity ($m\,s^{-1}$)	0.16 (0–0.24)	0.49 (0.11–0.92)	0.38 (0.08–0.91)	0.25 (0.10–0.47)
Mean dominant substrate[b]	1.6^{A} (1–2)	3.5^{B} (3–4.4)	5.0^{C} (4–5.8)	5.3^{C} (5–5.5)
Mean width (m)[a]	33.0^{ABC} (14.5–48.4)	79.4^{C} (52.5–123.3)	18.9^{AB} (6.4–44.3)	15.2^{B} (8.5–29.0)
Open canopy angle (degrees)	124^{AB} (105–155)	174^{A} (162–180)	100^{B} (26–171)	40^{C} (20–67)
Canopy cover (%)	20^{AB} (4–32)	1^{A} (0–3)	25^{AB} (0–87)	46^{B} (23–72)
Stream gradient (%)	0.05^{A} (0–0.13)	0.05^{A} (0.02–0.09)	0.71^{A} (0.17–2.53)	2.95^{B} (1.51–5.19)
Stream sinuosity[a]	2.17 (2.0–2.4)	2.4 (2.1–2.9)	2.2 (2.1–2.3)	2.1 (2.0–2.2)
Elevation (m)[a]	15^{A} (7–38)	10^{A} (7–13)	106^{B} (23.3–525)	927^{C} (586–1429)
Agricultural + urban land (%)[a]	38^{A} (8–68)	8^{AB} (7–9)	2^{BC} (0–11)	1^{C} (0–1.7)
Basin area (km^2)[a]	1758^{AB} (407–4256)	13459^{A} (5046–31695)	519^{BC} (152–3475)	179^{C} (39–1130)

TWINSPAN site groups: AG = agricultural drain group; LR = large river group; FH = foothill group; MT = mountain group. Different letters indicate significant difference among site groups (Tukey's HSD-test following ANOVA). Values with the same letters were not significantly different.
[a]These variables were $\log_{10}(x + 1)$ transformed for analyses.
[b]Dominant substrate was classified as (1) organic detritus, (2) silt, (3) mud, (4) sand (0.02–2 mm), (5) gravel (2–64 mm), (6) cobble (64–256 mm), (7) boulder (>256 mm), or (8) bedrock or hardpan (solid rock or clay forming a continuous surface).

Table 5. Results of CCA relating fish percentage abundance data to environmental variables. Bolded canonical coefficients have T-values greater than 2.1 indicating that the variable makes an important contribution to the canonical axis (ter Braak 1987).

Environmental variable	Eigenvalue	CCA1	CCA 2
Mean dominant substrate	0.82	**−0.57**	**−1.31**
Elevation	0.55	**−0.49**	**1.34**
Cumulative percentage of species variance explained		16.5	26.3
Cumulative percentage of species-environment relationship explained		62.9	100.0

integrity (IBI) could be developed for streams of the Sacramento River Basin and potentially for the greater Central Valley, California. Metric values for the agricultural drainage sites were clearly different from those of the other sites. Moreover, the communities and corresponding metric values for the agricultural drainage sites are very similar to those observed in the lower San Joaquin River drainage (Brown 2000).

The metrics based on percentages of native fishes, percentage of intolerant fishes, number of tolerant species, and percentage of fishes with external anomalies showed similar responses associated with changes in environmental quality and TWINSPAN site groupings. The number of native species did not perform well as a metric because of the small number of species at mountain sites. This metric might be useful if restricted to more species-rich, lower elevation sites.

The percentage of omnivorous fishes was a poor metric in both the Sacramento and San Joaquin River Basins. A high value for the percentage of omnivorous fishes is usually viewed as an indicator of poor environmental quality (Karr 1981, Fausch et al. 1984, Hughes & Gammon 1987). In the San Joaquin River Basin, this metric inaccurately depicted sites as having poor environmental quality due to high abundances of the native omnivore Sacramento sucker (Brown 2000). A similar result was obtained in the Sacramento River Basin (Table 6) because the Sacramento sucker was the most widely distributed species observed in the study and was often abundant. This metric might be useful

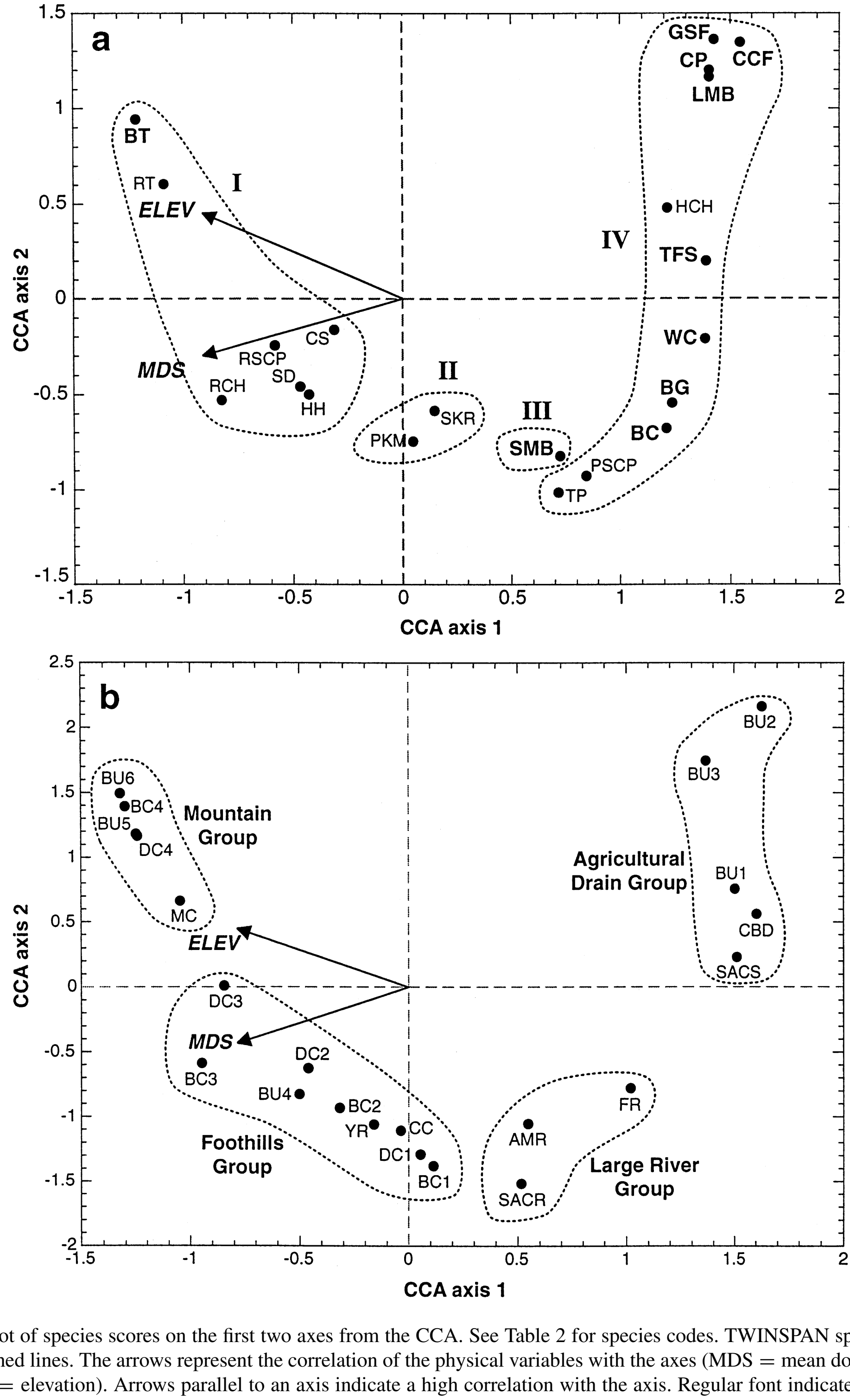

Figure 3. a – Plot of species scores on the first two axes from the CCA. See Table 2 for species codes. TWINSPAN species groups are enclosed by dashed lines. The arrows represent the correlation of the physical variables with the axes (MDS = mean dominant substrate size and ELEV = elevation). Arrows parallel to an axis indicate a high correlation with the axis. Regular font indicates native species, and bold font indicates introduced species. b – Plot of site scores on the first two axes from the CCA. See Table 1 for site names and codes. TWINSPAN sites groups are labeled and enclosed by dashed lines. The arrows represent the correlation of the physical variables with the axes (MDS and ELEV). Arrows parallel to an axis indicate a high correlation with the axis.

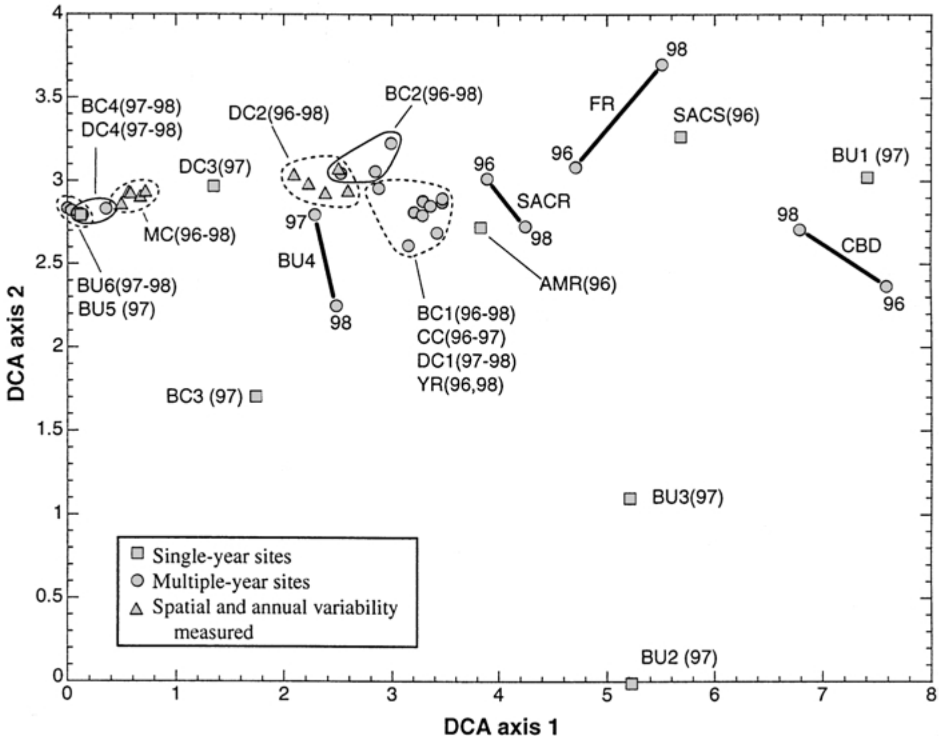

Figure 4. Plot of DCA site scores derived from fish species percentage-abundance data. Sites represented by squares were sampled only once during the study, circles were sampled during multiple years, and triangles were sampled for both spatial and annual variation. Lines connect or enclose sites values for particular sites. Years (1996–1998) are represented (in parentheses) by the last two digits of the year.

Table 6. Median and range for fish community metrics for TWINSPAN site groups (AG = agricultural drain group; LR = large river group; FH = foothill group; MT = mountain group; N = number of sites in a group). All metrics tested were significantly different among groups at $p < 0.05$ (Kruskal–Wallis one-way ANOVA). Values with the same letters were not significantly different in subsequent pairwise tests.

	TWINSPAN site group			
Fish community metrics	AG (N = 5)	LR (N = 3)	FH (N = 9)	MT (N = 5)
Native fishes (percent)	4^{A} (1.4–42)	81.7^{B} (30.7–95.6)	98^{B} (87–100)	72^{B} (53–100)
Native species (number)	1^{A} (1–3)	6^{B} (5–9)	5^{B} (4–11)	1^{A} (1–2)
Intolerant fishes (percent)	0^{A} (0)	25.4^{B} (9.2–35)	40.3^{B} (1.6–76.7)	100^{C} (100)
Tolerant species (number)	3^{A} (3–9)	4^{A} (2–4)	0^{B} (0–3)	0^{B} (0)
Omnivorous fishes (percent)	7.7^{A} (5–14)	15.5^{A} (3.4–25.6)	31.8^{B} (23.3–59.7)	0^{C} (0)
Fishes with anomalies (percent)	13.6^{A} (4–33)	3.8^{B} (2.7–11.2)	0^{C} (0–6.8)	0^{C} (0)

for Central Valley streams if only the percentage of non-native omnivores is assessed.

A fundamental problem for developing an IBI for the San Joaquin River drainage was the lack of adequate reference conditions in the lower San Joaquin River drainage (Brown 2000). Because the Sacramento and San Joaquin River systems had similar fish faunas prior to European settlement and development (Moyle 1976b), the Sacramento River Basin may serve the function of less-impacted conditions for the San Joaquin River Basin.

Conservation implications

Native fish species remain widely distributed and abundant in the Sacramento River Basin, especially in comparison with the San Joaquin River drainage in the southern Central Valley. The major exception is the agricultural drains where introduced species are dominant. On the basis of this study and other recent studies (Marchetti & Moyle 2001), most of the native species historically present (Schulz & Simmons 1973, Moyle 1976b) are still present in the Sacramento River drainage, with the exception of the locally extirpated Sacramento perch, *Archoplites interruptus*, and the extinct thicktail chub, *Gila crassicauda*. However, the presence of introduced species at low abundances throughout the basin is a concern. Changes in water management in response to climatic change or changes in agricultural or urban needs could result in environmental conditions favoring introduced species. The invasion of the Foothill ecoregion by introduced species, especially smallmouth bass, represents a serious challenge for conservation of native California stream fish communities (Moyle & Nichols 1974, Brown & Moyle 1993) and protection for some of the few relatively undisturbed spawning and rearing grounds for anadromous salmonids remaining in the Central Valley (Yoshiyama et al. 1998). The growing human population of California (projected to reach 42.4 million by the year 2010, California Institute[5]) combined with the natural water resource limitations of a Mediterranean-type climate will severely tax the water resources of the state. Accordingly, it is imperative to consider the potential effects of future management strategies on the native fish communities of the Central Valley. Successful conservation of native fish fauna of the Central Valley requires competent management of the rivers and upland streams, not merely as water source or water conveyance channels but also as living ecosystems (Nehlsen et al. 1992, Bottom 1995, Yoshiyama et al. 1998).

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[5] California Institute. 1999. California Institute population data: an online source for information on California and federal policy. URL: http://www.calinst.org/datapages/popproj.html

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