Spatial trends and impairment assessment of mercury in sport fish in the Sacramento-San Joaquin Delta Watershed

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ABSTRACT

A three-year study was conducted to examine mercury in sport fish from the Sacramento-San Joaquin Delta. More than 4000 fish from 31 species were collected and analyzed for total mercury in individual muscle filets. Largemouth bass and striped bass were the most contaminated, while redear sunfish, bluegill and rainbow trout exhibited the lowest concentrations. Spatial variation in mercury was evaluated with an analysis of covariance model, which accounted for variability due to fish size and regional hydrology. Significant regional differences in mercury were apparent in size-standardized largemouth bass, with concentrations on the Cosumnes and Mokelumne rivers significantly higher than the central and western Delta. Significant prey-predator mercury correlations were also apparent, which may explain a significant proportion of the spatial variation in the watershed.

Keywords: Mercury | Fish | Sacramento-San Joaquin Delta | Spatial trends | Human health

CAPSULE

Regional differences in sport fish mercury were found in the Sacramento-San Joaquin Delta.

INTRODUCTION

Mercury, a heavy metal that is highly toxic in the organic form methylmercury, is known to accumulate to concentrations of concern in food webs of the Sacramento-San Joaquin Delta (henceforth "Delta") and its watershed. The mercury problem in California dates back to the 19th century when mercury was mined from the Coast Range and transported to the Sierra Nevada for use in gold extraction. Historical releases of mercury from gold mining areas were substantial (1.4 – 3.6 million kg; USGS 2000), and in many watersheds mercury continues to wash downstream from these areas today.

Methylmercury can pose a problem when it bioaccumulates through the food web at concentrations of concern for humans or wildlife. The primary route of exposure for humans is through the consumption of contaminated fish. Studies conducted during 1998 – 2000 in the Delta, found mercury at concentrations of concern for human health in striped bass, largemouth bass, white catfish, and other popular sport fish species (Davis et al. 2000, Wood et al. 2006, Davis et al. 2008a). This is of particular concern because almost all mercury in fish is in the form of methylmercury, which has a high affinity for proteins in edible fish muscle (Bloom 1992). Methylmercury is one of the most toxic forms of mercury, which has been linked with irreversible damage to the developing human central nervous system (Choi 1990, Mergler et al. 2007).

In the Delta, one of the most popular areas for sport and subsistence fishing in California, exposure to methylmercury is of particular concern for human health and water quality managers (Silver et al. 2007). In the past few years, numerous consumption advisories have been issued by the California Office of Environmental Health Hazard Assessment (OEHHA) for the Delta and its watershed (e.g., Gassel et al. 2006, Klasing et al. 2006). These include advisories for Bear Creek, Cache Creek, Lake Natoma, the lower American River, lower Cosumnes River, lower Feather River, lower Mokelumne River, Putah Creek, San Joaquin River, and the northern and southern Delta, which are all primarily due to potentially harmful levels of mercury. Additional advisories will be developed from information gathered through this study when separate consumption advice is required. The large number of advisories is a clear indication of the concern for human health exposure to methylmercury in sport fish from this region.

The Fish Mercury Project ('FMP' or 'Project') was a three-year study to examine mercury in sport fish from the Delta watershed and to increase public awareness of fish contamination issues. An overall goal of the Project was to help reduce short-term methylmercury exposure to humans and wildlife. The Project closely followed recommendations of the California Bay Delta Authority (CBDA) "Mercury Strategy" (Wiener et al. 2003) to monitor fish in support of adaptive management of the mercury problem. During 2005-2007, more than 4000 fish from 31 species were collected from 146 popular sport fishing locations in the Delta watershed (Figure 1, Tables 1 and 2). This monitoring included coordinated studies by the Sacramento River Watershed Program and the Central Valley Regional Water Quality Control Board. Collaboration with these agencies allowed for a greater geographic scope in sampling, and coordination ensured no duplication of effort. The most frequently sampled species were largemouth bass, redear sunfish, bluegill, common carp, Sacramento sucker, rainbow trout, white catfish, channel catfish, striped bass, and Sacramento pikeminnow. Sample sizes for the main target species (largemouth bass) often met our sampling objective of 12 individuals per site. For other species, the target of five individuals was met at many sites, depending on the species' geographic range. The other major components of the FMP were an equally significant effort investigating mercury in biosentinel (short lived, small fish) species (Slotton et al. 2009, in prep), a largemouth bass food web model (Greenfield et al. 2009, submitted), and coordination with monitoring of methylmercury in water by the Central Valley Regional Water Quality Control Board (Foe et al. 2009, in prep) . This paper integrates all of these aspects of the study to address the two main objectives:

1) To characterize mercury concentrations in sport fish to assess the health risks of consuming contaminated fish, and

2) To characterize spatial and inter-annual trends in mercury in the food web to determine mercury accumulation

METHODS

Sampling and Design

Fish sampling focused on species commonly caught by sport and subsistence fishers. Primary targets were dependent on the region of the watershed being sampled, with largemouth bass, Sacramento sucker, common carp, redear sunfish, and bluegill being the most frequently caught species in this study. Largemouth bass were sampled at a wide range of total length to model regional and site-specific differences in length:mercury relationships (Tremblay et al. 1995, Tremblay et al. 1998). Secondary target species were collected when primary targets were unavailable, with channel catfish, Sacramento pikeminnow, rainbow trout, and white catfish being the most common. A detailed analysis of striped bass data will be presented separately in a companion article in conjunction with the Regional Monitoring Program for Water Quality in the San Francisco Estuary, but the data for striped bass have been included here when relevant. In total, 31 species, representing more than 4000 individual fish, were collected.

Sport fish were collected from locations in the Sacramento-San Joaquin Delta watershed during May 2005 through December 2007 (Figure 1, Table 1). One hundred and twenty-four FMP sampling locations were designated for sampling; these included popular fishing areas and provided broad geographic coverage across the watershed. In addition to the FMP sites, the Sacramento River Watershed Program sampled fish at three sites in 2005, and the Central Valley Regional Water Quality Control Board also collected fish from 19 sites in 2005 and 2006. Fish were collected by Moss Landing Marine Laboratories staff with an electrofisher boat and fyke nets. The crew remained on location until the desired number of primary target species was caught. The secondary target species caught during this time were also kept. Total length (longest length from tip of tail fin to tip of nose/mouth), fork length (longest length from tail fork to tip of nose/mouth), and weight (for larger fish) were measured in the field. Information on bycatch, including species and approximate numbers of non-target species, was recorded. Fish were wrapped in chemically cleaned Teflon sheeting and frozen on dry ice for transportation to the laboratory.

Analytical and QA/QC

Fish were kept frozen wrapped in Teflon in their original bags until the time of dissection. Dissection and compositing of muscle tissue samples were performed following USEPA guidance (U. S. EPA 2000). At the time of dissection, fish were placed in a clean lab in their original bags to thaw. After thawing, fish were cleaned by rinsing with de-ionized (DI) and ASTM Type II water, and were handled only by personnel wearing polyethylene or powder-free latex gloves (glove type is analyte dependent). Weights for individual fish, when not measured previously, were taken prior to dissection. All dissection materials were cleaned by scrubbing with Micro® detergent, rinsing with tap water, DI water, and finally ASTM Type II water. All fish were dissected skin-off, and only the fillet muscle tissue was used for analysis.

Total mercury in muscle tissue was measured at Moss Landing Marine Laboratories. The lab analyzed all fish as individuals. Tissue samples were analyzed according to EPA 7473, "Mercury in Solids and Solutions by Thermal Decomposition, Amalgamation, and Atomic Absorption Spectrophotometry" with a Milestone Direct Mercury Analyzer (Model DMA-80). Clean techniques were followed during preparation of samples, blanks, and standards, using ASTM Type II water and analytical grade chemicals. A continuing calibration verification (CCV) was performed after every 10 samples, and samples run between CCVs that drifted greater than 10% were rerun. Three blanks, a standard reference material (DORM-2), a duplicate sample, and a pair of spiked samples were analyzed with each set of samples.

The mercury samples were digested and analyzed in multiple batches. Batches consisted of 20 samples per batch. Standard Reference Material (NRC-DORM-2: dogfish muscle) recoveries were within the acceptable range of 75% – 125% recovery (range for all species 88% – 112%) established by the CalFed QAPP (Puckett and van Buuren 2000). The mercury matrix spike recoveries were all within the acceptable range of 75% – 125% recovery (range for all species 76% – 125%). Relative Percent Differences (RPDs) for spiked samples were within the acceptable range of less than 25% (range for all species 0% – 17%). All of the mercury lab duplicate RPDs were also in the acceptable range below 25% (range for all species 0% – 10%), and all method blanks were below the detection limit.

Moss Landing Marine Labs participated in an inter-comparison study implemented for all California Bay Delta Authority mercury projects (van Buuren 2006) in 2005 and 2006. Three percent (3%) of MLML's tissue samples (40 samples) were sent to an independent laboratory (Frontier GeoSciences in Washington State) in each year to assess the reliability of results. Analysis shows that the RPDs between labs for the field samples were within the acceptable range of 0 – 25%.

Data Analysis

Concentration Categories

Mercury concentrations are presented in four categories loosely based on Advisory Tissue Levels by the California Office of Environmental Health Hazard Assessment (OEHHA) (Klasing and Brodberg 2008). OEHHA is the agency responsible for managing health risks due to consumption of contaminated sport fish in California. The assessment provided in this paper should <u>not</u> be considered consumption advice. ATLs are just one component of a complex process of data evaluation and interpretation used by OEHHA in the assessment and communication of fish consumption risks. The nature of the contaminant data or omega-3 fatty acid concentrations in a given species in a water body, as well as risk communication needs, may alter strict application of ATLs when developing site-specific advisories. OEHHA uses ATLs as a framework, along with best professional judgment, to provide fish consumption guidance on an ad hoc basis that best combines the needs for health protection and ease of communication for each site (Klasing and Brodberg 2008).

The lowest concentration category used in this paper (less than 0.1 µg/g) is a range where OEHHA generally encourages consumption. The highest concentrations (above 0.4 µg/g) are in a range where OEHHA generally discourages consumption for women of childbearing age and for children 17 and younger. Intermediate categories were developed to bridge the gap between these endpoints, thus 0.1 – 0.25 µg/g and 0.25 – 0.4 µg/g were used.

Controlling for Length:Mercury Relationships

Two methods were used to control for the relationship of fish length to mercury concentration within species. A general linear modeling approach (analysis of covariance) was used when data were sufficient (see below). Size limits (Table 2) were applied, when comparing regions, for all other species. USEPA guidance (U. S. EPA 2000) specifies that the smallest fish in a composite should be no less than 75% the length of the largest. This compositing guidance was used to control for length by establishing size limit categories in each species.

Predicting Spatial and Temporal Differences in Mercury Concentrations

A general linear mixed model (PROC MIXED in SAS v. 9.1; Littell et al. 1996) was used to examine spatial variation in mercury concentrations and the length:mercury relationship in largemouth bass. In the description given below, the model procedure and model effects are capitalized for emphasis. PROC MIXED estimates model parameters (i.e., slope and intercept) with numerical maximum likelihood techniques and allows for the rigorous modeling of random effects. This approach has two main advantages. First, the maximum likelihood model selection procedure allows non-nested models to be compared to each other. Second, treating sampling site as a random effect (see below) provides a basis for drawing inferences regarding similar habitats throughout the study area. Thus, the findings can be more confidently extrapolated to the full region rather than just to the particular sampling locations.

To analyze large-scale differences in mercury, spatial variation was examined by treating REGION as a fixed effect in the model, which represented the major river or water source for the area. Ten different regions were identified in the Project sample space, which encompassed the major rivers and tributaries of the Sacramento-San Joaquin Delta watershed (see below on data included). SITE was treated as a random effect (nested within REGION) under the assumption that the sampled sites were representative of the universe of possible sites within the Project space. Fish length (LENGTH) and a squared length term (LENGTH^2) were included as covariates to evaluate support for linear and quadratic relationships between LENGTH and MERCURY in the model. Finally, we included first-order interaction terms between both length terms and the SITE and REGION to model spatial variation in length:mercury relationships. The full model containing all effects can be expressed as:

$$\begin{aligned} MERCURY_{(ijk)} = {} & \beta_0 + (\beta_{REGION(i)} * REGION_{(i)} + \varepsilon_{SITE_{(j)}(REGION_{(i)})}) + \beta_{LENGTH} * LENGTH_{(k)} + \\ & \beta_{LENGTH^2} * LENGTH_{(k)}{}^2 + \beta_{REGION_{(i)}*LENGTH}(REGION_{(i)} * LENGTH_{(k)}) + \\ & \varepsilon_{SITE_{(j)}(REGION_{(i)})*LENGTH}(SITE_{(j)} * LENGTH_{(k)}) + \beta_{REGION_{(i)}*LENGTH^2}(REGION_{(i)} * LENGTH^2_{(k)}) + \\ & \varepsilon_{SITE_{(j)}(REGION_{(i)})*LENGTH^2}(SITE_{(j)} * LENGTH^2_{(k)}) + \varepsilon_{ijk} \end{aligned}$$

where $MERCURY_{(ijk)}$ is the mercury concentration (µg/g, wet wt) for fish k caught at site j of region i, β_0 is the model intercept, $\beta_{REGION(i)}$ is the effect of region i on mercury concentration, $REGION_{(i)}$ is the dummy variable associated with region i, β_{LENGTH} is the slope term for fish length, $LENGTH_{(k)}$ was the length (mm) of fish k, $\beta_{LENGTH}{}^2$ is the slope term for the square of fish length, $LENGTH_{(k)}{}^2$ was squared length of fish k, $\varepsilon_{SITE(j)(REGION(i))}$ is the random error in mercury concentration associated with site j nested within region i, $\varepsilon_{SITE(j)(REGION(i))*LENGTH}$ is the random error associated with the interaction between site j and fish length, $\varepsilon_{SITE(j)(REGION(i))*LENGTH}{}^2$ is the random error associated with the interaction between site j and the square of fish length, and ε_{ijk} is the random error associated fish k caught at site j of region i. The random errors are normally and independently distributed with a mean of zero.

A combined dataset of all three years of data was used in the linear model analysis of spatial effects. However, in general, different sites were sampled in different years. Thus, spatial and temporal effects were to a certain extent confounded. Our approach was to treat site as a random factor and acknowledge that any temporal variation was included in the random site term. Note that differences in mercury due to inter-annual variation were also modeled separately (see below). Only sites with at least nine samples and a 130 mm or greater range in lengths were included in the analysis.

An information-theoretic approach (Burnham and Anderson 2002) was used to evaluate support for a suite of *a priori* models, where each model contained a different combination of the parameters described above. Specifically, Akaike's Information Criteria (AIC) corrected for small samples sizes (AIC$_\text{c}$) was used to rank each of the competing models based on the level of support from the data. AIC$_\text{c}$ is a statistic used to estimate the relative distance between competing models and the unknown true model that generated the data. Therefore, the model with the smallest AIC$_\text{c}$ value indicates the "closest" to unknown reality. Furthermore, in the calculation of AIC$_\text{c,}$ models are penalized for the number of parameters. Thus, AIC$_\text{c}$ selects the model that fits the data best and also has the smallest number of parameters (i.e., simplicity and parsimony). In addition, AIC$_\text{c}$ weights were computed to determine the strength of evidence for each competing model to supplement inferences made simply from AIC$_\text{c}$ values. AIC$_\text{c}$ weights represent the probability that a model being evaluated is the "best" among the suite of candidate models. AIC$_\text{c}$ values and AIC$_c$ model weights were calculated using the formulas given in Burnham and Anderson (2002).

The modeling procedure first estimated the level of support for different combinations of random effects, using restricted maximum likelihood methods. All fixed effects were included in this stage of the model. Once the appropriate random effects structure was identified, the procedure evaluated the level of support for models with different combinations of fixed effects. The model with the greatest AIC$_\text{c}$ weight and lowest AIC$_\text{c}$ value was selected for the final model, but models within 1-2 AIC$_\text{c}$ values were considered to be competing models (Burnham and Anderson 2002).

The next step was to test whether the relationship between fish length and mercury concentrations differed among regions. First, the method employs dummy variables to determine differences in means, slopes, and curve shapes among locations. The resulting regression equations were used to calculate predicted mercury concentrations (mean and 95% confidence interval) for each location at a standardized total length of 350 mm. The 350-mm standard size was selected based on the peak in the length-frequency distribution of largemouth bass sampled in the Project. Finally, the model tested for differences among regions using linear contrasts of mean mercury concentration. This procedure consisted of a t-test comparing average mercury concentrations based on a 350-mm standardized length fish. The t-test assessed the probability that the difference in estimated mean mercury concentrations between regions was significantly different from zero.

As mentioned previously, some level of inter-annual variation was included in our results of the spatial analysis. Therefore, to address this question, a dataset of eight sampling locations was used to examine temporal differences in mercury across the watershed (2005 vs. 2007). Additionally, five of those eight sites overlapped with the dataset from 2000 summarized in Davis et al. (2008), and thus were also included in this analysis. As described for analysis of spatial effects, restricted maximum likelihood methods (REML) were used to estimate parameters and competing models were ranked with AICc model selection criteria. Using the selected model from PROC MIXED, the relationship between fish length and mercury concentrations was tested between years for each location at 350-mm standardized length. The same procedure using linear contrasts described above was used to examine variation among years.

Mapping and GIS Methods

The map figures were designed with ESRI ArcInfo 9.1 software and are in a California Teale Albers NAD 83 Projection. A connection to the GIS from the SWAMP Tissue 2.5 database (Microsoft Access 2003) was established to display the locations and results of queries.

RESULTS AND DISCUSSION

Variation in Mercury Among Species

Mercury concentrations in all target species (presented in µg/g or parts-per-million, wet weight) exceeded the 0.10 µg/g threshold to some degree (Table 2). Of the target species, represented by 50 fish or more, only redear sunfish and rainbow trout had the majority of samples (50% or more) below 0.1 µg/g. Conversely, nine species had the majority above this level. Largemouth bass was the most intensively sampled of the primary species (n = 466), and exhibited an average concentration of 0.40 µg/g. Forty percent (40%) of the fish exceeded 0.40 µg/g and only four largemouth bass were below 0.10 µg/g. These results suggest that largemouth bass could be a significant dietary source of methylmercury. In contrast, redear sunfish and bluegill, the next most abundant species in our sampling (n = 234 and n = 220, respectively), were relatively low in mercury. These species averaged 0.12 µg/g and 0.14 µg/g, respectively. Approximately half of the redear and bluegill samples (57% and 49%, respectively) were below 0.10 µg/g, suggesting that consumption of these species may contribute to low levels of dietary mercury exposure.

Common carp and Sacramento sucker were the next most frequently sampled primary target species. Both species are known to grow relatively large, and are omnivorous, primarily feeding on benthic-dwelling organisms (Moyle 2002). The vast majority of common carp samples exceeded 0.10 µg/g, with approximately one-third in each of the 0.10 – 0.25 µg/g (34%) and 0.25 – 0.40 µg/g (37%) categories. Most of the remaining samples were even higher in concentrations, with 21% exceeding 0.40 µg/g. In all likelihood, the high concentrations found in common carp can be attributed to its large size (434 – 659 mm) and variable diet (Moyle 2002). Sacramento sucker, like largemouth bass and common carp, exhibited some higher concentrations, with most of the samples (42%) from 0.10 – 0.25 µg/g. However, likely due to its moderate size (329 – 489 mm) and primarily feeding at a lower trophic level, few suckers (7%) exceeded 0.40 µg/g and more than one-quarter (28%) were below 0.10 µg/g.

Rainbow trout exhibited the lowest mercury concentrations of all the target species. Mercury concentrations averaged 0.04 µg/g across all sites. Nearly all samples (93%) corresponded to the < 0.1 µg/g category, with the remaining 7% from 0.10 to 0.40 µg/g. White catfish and channel catfish were also relatively well sampled (n > 100), but suggested moderate mercury levels. In both species, the largest proportion of samples (51% and 43%, respectively) corresponded to 0.1 – 0.25 µg/g. Striped bass was the only target species for which all samples exceeded 0.10 µg/g. This species averaged 0.40 µg/g with 50% of the samples exceeding 0.40 µg/g, and an additional 33% from 0.25 – 0.40 µg/g. Not surprisingly, mercury exposure from consuming striped bass is of high concern in the Delta (OEHHA 1994, Gassel et al. 2006). Finally, although Sacramento pikeminnow was sampled the least frequently of the target species (n = 77), this species was among the most contaminated. Twenty-two percent (22%) of the samples exceeded 0.40 µg/g, which ranked third highest after striped bass and largemouth bass.

The relative degree of mercury contamination among species sampled in the Project was expected, based on their feeding ecology and trophic positions. Largemouth bass and striped bass are large sport fish (up to 579 mm and 1149 mm, respectively, in this study) and are top piscivores inhabiting the Delta watershed. Adults are known to consume all varieties of fish and large invertebrates that are found in their habitat (Moyle 2002). A high exposure to methylmercury was therefore anticipated in these species, given their size and position in the food web. Common carp, Sacramento sucker, and channel catfish also grow rather large (commonly > 400 mm in this study), but their diets do not primarily consist of fish. Rather, detritus and benthic invertebrates are primary food items. Similarly, rainbow trout are insectivores, consuming surface-dwelling invertebrates (Moyle 2002). These species were the least contaminated of the large fish sampled in the Project. Redear sunfish and bluegill are relatively small in size and occupy a lower position in the food web (Moyle 2002), feeding primarily on shelled invertebrates (particularly clams and crustaceans). Therefore, the lower concentrations in bluegill, redear sunfish, and rainbow trout were predictable due to different diets compared to other species sampled in the Project.

The results of this study suggest that redear sunfish and bluegill are species lower in mercury, and thus may be good alternatives to species such as striped bass, largemouth bass, and other piscivores for limiting human dietary mercury exposure. Rainbow trout were consistently low in mercury as well, with the highest concentration found in the Project being 0.36 µg/g. However, the trout were generally distributed over a different range than the other species sampled in the Project, as they were primarily found in high-elevation lakes.

Spatial Differences in Mercury Concentrations

The second main purpose of sport fish sampling was to characterize spatial trends in mercury accumulation in the food web. The model selection procedure indicated that the effects of total length, site, and region represented the 'best' model to examine spatial variation in largemouth bass mercury concentrations (model results not presented). A component of this model not implemented in previous analysis of covariance models of fish mercury concentrations in the Delta (e.g., Davis et al. 2008a), is the inclusion of a random spatial variable to represent the sampling site, which allows our results to be inferred across the full study area. The authors acknowledge that site selection was not strictly random, however, due to the wide geographic coverage of sites (n = 146 locations), we consider these data to be representative of the entire Project space. With this approach, we can make inferences regarding locations not sampled from similar habitats within the study area. However, the patterns that can be assessed with the data in hand are spatial trends across all sites and regions, without reference to specific habitat types.

Since largemouth bass exhibited some of the highest concentrations in the Project, comparison of standardized length bass (350-mm fish) to the concentration categories (Figure 2) provides a worst-case picture of the mercury problem across the watershed. Mercury concentrations were above 0.10 µg/g at all sites evaluated, with the highest proportion of sites (29 of 67, 43%) corresponding to the > 0.4 µg/g category. The majority of these sites were located on the Sacramento River and in the north Delta region. In contrast, moderate (0.10 – 0.25 µg/g) mercury concentrations were evident in the central Delta and lower San Joaquin River region. A few sites in the southern portion of the San Joaquin watershed also had concentrations above 0.40µg/g. However, most of these were not located on the major rivers, but in lakes and reservoirs at higher elevation. Unfortunately, statistical evaluation of mercury by habitat type was not feasible with these data. However, a statewide sampling of largemouth bass from lakes and reservoirs is currently being conducted by the Surface Water Ambient Monitoring Program, with results due in 2009 (Davis et al. 2008b). Alternatively, it was possible to statistically evaluate spatial patterns by separating the watershed into distinct regions based on hydrology and water source (Figure 1), as described below. Site-specific estimates for 350-mm largemouth bass are presented in Supplemental Table 1.

Mercury concentrations in 350-mm largemouth bass were higher in the northern portion of the watershed than in the central Delta and further south. The Sacramento River, Feather River, eastern drainages, and north Delta exhibited relatively similar average concentrations that ranged from 0.33 to 0.48 µg/g (Figure 3). The highest concentrations were found on the Cosumnes and Mokelumne Rivers, which averaged 0.83 ± 0.40 µg/g. The large confidence intervals in this region were due to one site (Mokelumne River at Lodi Lake) where concentrations in fish were much lower than at the other sites. In contrast, mercury was much lower at regions in the southern portion of the watershed. Largemouth bass had the lowest concentrations in the western and central Delta (both averaged 0.23 µg/g) and higher concentrations on the San Joaquin River (0.43 µg/g). Statistical comparison of means indicated that locations along the Cosumnes and Mokelumne Rivers had significantly higher concentrations ($p < 0.001$) than locations in all other regions of the watershed. The central Delta was significantly lower than the Sacramento River ($t = -3.29$, $p = 0.001$) and the San Joaquin River ($t = -3.38$, $p = 0.008$). This spatial pattern corroborates the most recent study in the region (Davis et al. 2008a), but with nearly three times as many locations included in the analysis.

For all other species not analyzed by the modeling approach, length and sample size limits were applied to compare average mercury concentrations among the different regions of the watershed. Striped bass and common carp, the two largest fish species, followed the same general pattern in mercury as largemouth bass (Table 3). Striped bass were sampled at three sites in each of the Sacramento River, north Delta, and San Joaquin River regions. Each region averaged over 0.40 μg/g, with bass on the San Joaquin River having the highest concentrations (0.52 ± 0.20 μg/g). Mercury concentrations are often highly variable in striped bass due to their relatively large size, variable diet, and large movement patterns of individuals (Moyle 2002). Common carp were lower than the two bass species. Average mercury concentrations in carp were greater than 0.25 μg/g, except for in the central Delta, where mercury in carp was 0.16 ± 0.03 μg/g, more than half that of the north Delta and San Joaquin River. This spatial pattern was evident with many of the other species as well. Bluegill, channel catfish, redear sunfish, rainbow trout, and white catfish all had relatively low concentrations in the central Delta, but higher concentrations elsewhere. Bluegill and redear sunfish also had distinct spatial patterns in the Delta watershed, despite the smaller size of these species. Bluegill ranged from 0.08 μg/g in the central Delta to 0.17 μg/g in the northern Delta. The only region that appeared to have moderately high concentrations in bluegill was the Cosumnes-Mokelumne region, where mercury averaged 0.29 μg/g. Redear sunfish followed the same spatial pattern as the larger target species, although the differences were more subtle, consistent with redear sunfish being generally lower in mercury relative to the other species. As with bluegill, redear sunfish were generally lower in mercury (0.08 – 0.12 μg/g), except on the Cosumnes and Mokelumne Rivers. In this region, concentrations were nearly twice as high (0.21 μg/g).

Factors Controlling Spatial Differences in Fish Mercury Concentrations

Examining regional patterns of mercury in sport fish across the watershed has highlighted relatively low concentrations in the central Delta and relatively high concentrations in the Cosumnes and Mokelumne Rivers (Davis et al. 2008a). The Cosumnes floodplain has been indicated as a hot spot for mercury in sport fish, as numerous species of varying size and trophic level (particularly, largemouth bass, bluegill, and redear sunfish) have exhibited higher concentrations in this region. As a result, consumption advisories have recently been issued for consuming fish from the lower Cosumnes and Mokelumne rivers due to elevated methylmercury concentrations in largemouth bass and other commonly caught species (Klasing et al. 2006). Moreover, the highest mercury concentration observed in the study was in an individual black crappie collected from Cosumnes River in 2006 that measured 2.34 μg/g. With such high concentrations on the Cosumnes River, we suspect that some facet of its environment could explain the spatial difference compared to adjacent waters.

Due to the extensive mercury contamination in the Delta watershed, substantial effort has been recently devoted to better understand the cycling of methylmercury in sediments, water, and biota (e.g., Heim et al. 2007, Marvin-DiPasquale et al. 2007). To address the unexplained pattern of higher mercury concentrations in fish from the Cosumnes River and other tributaries relative to the central Delta, recent studies have aimed to identify the processes governing mercury transformation and trophic transfer in these systems. Cosumnes River is the last major, non-dammed river that flows directly into the Delta, with substantial densities of submerged aquatic vegetation and seasonally inundated floodplains. Franks Tract, on the other hand, is a permanently flooded island in the central Delta, with mostly non-vegetated open water habitat (California Department of Fish and Game 1998). Heim et al. (2007) presented sediment methylmercury concentrations sampled from both systems during 1999-2000. Interestingly, these data suggest surface sediment methylmercury concentrations were higher in the central Delta (0.72 ± 0.68 ng/g dry weight) than in the Cosumnes River (0.10 ± 0.10 ng/g). Ecosystem type (i.e., vegetated marsh vs. open water) was found to explain a large degree of the variability (Heim et al. 2007), but did not completely account for the contrasting pattern in average concentrations. Relationships between mercury in fish to wetland types and other landscape features has been of interest to water quality managers, particular in areas of the Delta where wetland restorations are currently planned (Melwani et al. 2007). A recent suite of studies conducted for the California Bay-Delta Authority Ecosystem Restoration Program, aimed to identify the factors that may dictate habitat differences in mercury cycling (Marvin-DiPasquale et al. 2007). These studies indicated that unlike some other areas of the U.S., such as the Chesapeake Bay (Mason and Lawrence 1999) and the Florida Everglades (Gilmour et al. 1998), sediment methylmercury concentrations did not readily explain mercury concentrations higher in the food web. Instead, factors such as bacterial activity, availability of reactive mercury species, and suspended sediment loads, determined regional differences in water column mercury and subsequent transfer up the food web (Marvin-DiPasquale et al. 2007). These factors likely play an important role in other systems highly influenced by mercury contamination as well, but perhaps not to the degree of the Sacramento-San Joaquin Delta. Consequently, sediment methylmercury concentrations observed in the Delta have not necessarily paralleled concentrations in higher trophic level fish (Heim et al. 2007, Davis et al. 2008a). These implications were recently summarized by Pickhardt et al. (2006) who showed higher methylmercury uptake and accumulation rates in redear sunfish from the Cosumnes River relative to Franks Tract. Pickhardt et al. (2006) suggested that higher mercury in fish from Cosumnes River could be explained not only by the differing biogeochemistry, but also consistently lower pH and dissolved organic carbon relative to Franks Tract. In freshwater systems, mercury bioavailability to fish has been shown to increase when pH and DOC are lower than surrounding waters (Watras et al. 1998, Pickhardt et al. 2006). These studies have contributed significantly in identifying the processes that may help to identify areas of concern for future management decisions with respect to mercury clean-up actions, and methods to predict aquatic habitats having higher mercury accumulation in sport fish.

As with sediments, direct water-born exposure to methylmercury by fish may also differ significantly among habitats and relate to accumulation higher in the food-web. The relationship between total (unfiltered) methylmercury concentrations in water with that in sport fish is one hypothesis currently being investigated by scientists in the region. In contrast to Delta sediments, in a few cases, methylmercury concentrations in the water column have been shown to correlate well with mercury concentrations in fish (e.g., Sveinsdottir and Mason 2005). Such correlations are probably due to higher aqueous concentrations entering the base of the food web, which leads to higher methylmercury uptake at each ascending level of the food web. However, current evidence is limited by the few studies that have measured mercury in both water and fish from the same locations. The Central Valley Regional Water Quality Control Board has been investigating this scenario by collecting monthly methylmercury water samples over the last few years from more than 10 sites around the Delta, many of which overlap with FMP sampling locations by design. Significant positive correlations between annually-averaged methylmercury concentrations in water to that in 350-mm largemouth bass have been shown for some of these sites (Wood et al. 2006, Foe et al. 2009, in prep).

Mercury accumulation in predator species is thought to be largely derived from consumption of contaminated invertebrates and fish prey (Hall et al. 1997). Therefore, correlations between sport fish and biosentinel mercury were expected to explain a significant portion of the spatial variation observed in the watershed. Preliminary results from a food web model for largemouth bass using data collected by this study as well as other sources (Greenfield et al. 2009, submitted) suggests that growth rate, consumption rate, and prey concentrations significantly affect spatial differences in mercury for adult largemouth bass. However, by varying various input parameters to the model, prey mercury in particular, was shown to have the most significant influence. Mercury in adult largemouth bass was correlated to pulses of mercury in prey over a 9-month to 2-year time interval. Largemouth bass are opportunistic predators, consuming any abundant invertebrate and fish prey of appreciable size (Moyle 2002). Gut content analysis of more than 100 largemouth bass from two sites in the Delta showed that crayfish, gobies, juvenile sunfish, and silversides were the most common prey items for largemouth bass (M. Norbriga, Department of Water Resources, Davis, California, unpublished data). In this study, linear regression was employed to examine whether correlations could be determined between mercury in whole prey fish and coexisting, size-standardized adult largemouth bass across eight sites. Two biosentinel species were selected for the evaluation; Mississippi silverside (*Menidia beryllina*, the most widespread small fish species) and juvenile largemouth bass, for comparison to adults of the same species. Statistical analysis indicated significant, positive relationships ($r^2 \sim 0.9$, $p < 0.05$) to adult largemouth bass concentrations for both biosentinel species (Figure 4). Previously, few studies have demonstrated such a relationship, likely due to the complex interactions between direct and indirect accumulation of mercury in predatory fish (e.g., Sveinsdottir and Mason 2005). However, prior studies have not measured mercury in small fish species as intensively as was performed for this study (Slotton et al. 2009, in prep). These results suggest that adult bass in the Delta watershed are reasonably good indicators of mercury entering the base of the food web, as their concentrations are highly correlated to that in primary consumers. The significant correlation of prey concentrations averaged over a three-year sampling period may also indicate that this time interval has provided a reasonable approximation of the dietary exposure history for largemouth bass. Finally, the prey-predator mercury relationships in mercury illustrated here are the first the authors are aware of for the Delta watershed.

To examine whether consistent relationships existed among species, in order for our results in largemouth bass to be extrapolated, mercury concentrations averaged by site were compared to other sport fish. The data used for this evaluation included species that were sampled at 10 or more of the same sites. Largemouth bass concentrations were statistically significant ($p \ll 0.05$) and positively correlated with concentrations in six other fish species examined, except Sacramento sucker (Table 4). This suggests that mercury concentration in many of the species sampled can be estimated using concentrations in largemouth bass, which may have implications for future studies of mercury in sport fish.

Based on the detailed information on mercury contamination and spatial trends obtained through this study, the FMP has provided the basis upon which future sport fish sampling designs may be developed. This study has revealed the importance of characterizing different trophic levels of the food web, rather than for the need to sample all abundant fish species from a watershed to characterize patterns in contamination. The regional approach to evaluating fish mercury concentrations also proved successful, with generally consistent mercury concentrations apparent across similar habitats. As a result, future studies of sport fish mercury concentrations may seek to optimize the efficiency of their sampling by selecting representative species for different trophic levels and by considering existing information on expected high and low areas for exposure in a watershed. In addition, the statistical analysis indicated that wide ranges (> 130 mm) in total length of largemouth bass, and sample sizes of more than eight largemouth bass per site are necessary to build robust length: mercury relationships to evaluate spatial patterns. Future efforts can use the extensive dataset generated in this study in power analysis to determine the necessary sample sizes required to detect spatial and temporal trends of fish mercury concentrations.

Temporal Comparison of Mercury Concentrations

The third main purpose of sport fish sampling was to characterize inter-annual variation in sport fish mercury. Statistical analysis of mercury concentrations in 350-mm largemouth bass from 2000, 2005, and 2007 did not show a discernible trend, but a consistent pattern of inter-annual fluctuation was evident. Mercury in largemouth bass was not significantly different between 2000 and 2007, but 2005 was on average 0.13 µg/g lower than each of the other years (Figure 5). Note that the confidence intervals of each mean value may appear to span the same range, but in-fact do differ by a small proportion among sites. The lower concentrations observed across sites in 2005 may be due to factors such as water chemistry or largemouth bass life history. For example, the largemouth bass modeling effort has been evaluating the role that seasonal variation and life-history of largemouth bass play in explaining the concentrations observed in the region. Preliminary results suggest that up to 75% of the bass concentrations could be explained by pulses in prey mercury occurring 9-months to 2-years prior (Greenfield et al. 2009, submitted). However, differences in age-weight ratios were also apparent, with fish in 2005 being heavier at a given age than fish from 2000 and 2007 (Davis et al. 2008a). Therefore, growth dilution may also have contributed to the lower mercury concentrations predicted for largemouth bass in 2005. Negative association of growth rate with tissue mercury concentrations has been suggested in the literature (Simoneau et al. 2005), but remains an area of on-going research.

Mercury concentrations in striped bass in San Francisco Bay have shown similar temporal patterns to largemouth bass. Striped bass sampled over a period of 33 years (1970 - 2003) have shown some inter-annual fluctuations, but no overall trend (Davis et al. 2006). These findings are consistent with the long residence time of mercury in the Bay and Delta (Conaway et al. 2007). Thus, the available information suggests that mercury concentrations in sport fish in some regions of the Delta watershed may remain elevated for decades, in the absence of significant management actions to reduce accumulation in the food web. Clearly, continued monitoring of mercury in sport fish of the watershed will be essential to efforts to address this widespread water quality problem.

CONCLUSIONS

During the three years of study in the CALFED Fish Mercury Project, the main objective of characterizing mercury concentrations to assess health risks from consuming contaminated fish was achieved using data from frequently caught species in the watershed. After three years of intensive sampling in the Sacramento-San Joaquin Delta, largemouth bass was consistently the most contaminated of the target species, followed by striped bass, common carp and catfish.

Of all species sampled, redear sunfish, bluegill, and rainbow trout were identified as having generally low concentrations and potentially being good alternatives for human consumption. It is important to remember, however, that these conclusions only pertain to methylmercury, given that organics analyses were not conducted on these samples. To this end, information on organic contaminants and mercury from more than 100 lakes and reservoirs popular for fishing across the State will soon be available through the Surface Water Ambient Monitoring Program (Davis et al. 2008b). Preliminary results indicate that in addition to mercury, PCBs may be of greatest concern for human health.

The second main objective of the Project was to characterize spatial trends in the food-web to determine mercury accumulation. Overall, the spatial patterns in mercury observed during 2005-2007 were consistent with patterns documented by previous studies in the Delta. Davis et al. (2008) reported relatively high concentrations in largemouth bass from both the Cosumnes and Mokelumne Rivers in 1999 and 2000. Locations on the Feather, Sacramento, and San Joaquin rivers were also noted in that study to be elevated over concentrations in the central Delta. In the present study, large, piscivorous species exhibited the greatest spatial variation, with mercury concentrations highest at locations on the lower portions of the Sacramento and San Joaquin Rivers, the north Delta, Cosumnes and Mokelumne rivers. Lower concentrations were found in numerous species on the higher reaches of the San Joaquin River and the central Delta. The largest spatial difference in mercury was found for largemouth bass, which differed by 0.6 μg/g between the Cosumnes River and the central Delta. This variation in mercury may be explained by a number of factors, including exposure to methylmercury concentrations in water and prey. Furthermore, integration of the biosentinel data with that of largemouth bass indicated relatively strong prey-predator mercury relationships across habitats. As a result, largemouth bass have shown to be good indicators of mercury entering the Delta food web, although may not be as sensitive to inter-annual trends as small prey fish. Furthermore, largemouth bass mercury was shown to correlate with mercury concentration in other sport fish species. This suggests that selection of species for characterizing mercury concentration could be optimized in future studies using information on trophic level, size, and distribution in the watershed.

ACKNOWLEDGMENTS

The authors gratefully thank Zach Peery (Moss Landing Marine Laboratories) for his expert guidance in implementing the statistical modeling. Thanks to Matt Nobriga (Department of Water Resources) for providing unpublished gut content data for largemouth bass. We are eternally grateful to the efforts of the Fish Mercury Project Peer Review Panel, Drs. James Wiener, Barbara Knuth, Drew Bodaly, and Tom Grieb, and Ms. Patricia McCann. We also thank our contract managers at GCAP, particularly, Leann Adrovich and Mary Menconi. The Fish Mercury Project was funded by the CALFED Bay-Delta Program.

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Table 1. Fish Mercury Project sampling locations 2005 – 2007.

Station Code	Station Name	Site Type	Year(s) Sampled	Region	Waterbody Type
AMHY	American Hatchery	Advisory	2005	Hatchery	Hatchery
ARDP	American River at Discovery Park	SRWP	2005	American River	River
ARGP	American River at Goethe Park	CVRWQCB	2005	American River	River
ARNIM	American River at Hazel Ave and Nimbus Dam	Advisory/CVRWQCB	2005, 2006	American River	River
BBRC	Bullards Bar Reservoir at Central	Advisory	2006	Feather River	Lake/Reservoir
BBRE	Bullards Bar Reservoir at East Arm	Advisory	2006	Feather River	Lake/Reservoir
BCHWY	Butte Creek at Colusa Highway	Advisory	2006	Sacramento River	River
BIGB	Big Break	Index	2005, 2007	Western Delta	River
BKLAK	Bucks Lake	Advisory	2006	Feather River	Lake/Reservoir
BMLAK	Baum Lake	Advisory	2006	Sacramento River	Lake/Reservoir
BRES	Bethany Reservoir	Advisory	2007	San Joaquin River	Lake/Reservoir
BRRO	Bear River at Rio Oso	CVRWQCB	2005	Feather River	River
BVSL	Beaver Slough	Advisory	2005	Northern Delta	River
CARV	Calaveras River	Advisory	2005	Central Delta	River
CBD99	Colusa Basin Drain at Road 99E	CVRWQCB	2005	Sacramento River	River
CCMOU	Clear Creek	Restoration	2005	Sacramento River	River
CCMOU06	Clear Creek Near Mouth	Advisory	2006	Sacramento River	River
CMRES	Camanche Reservoir	Advisory	2005	Eastern Drainages	Lake/Reservoir
COLHY	Coleman Hatchery	Advisory	2005	Hatchery	Hatchery
COS	Cosumnes River	Intensive/Advisory	2005, 2007	Cos/Mok Rivers	River
COSRM1	Cosumnes River at River Mile 1	Restoration	2006	Cos/Mok Rivers	River
CRSCNL	Cross Canal	Advisory	2006	Sacramento River	River
DAHY	Darrah Springs Hatchery	Advisory	2005	Hatchery	Hatchery
DBAY	Discovery Bay	Advisory	2005	Central Delta	River
DHSL	Dead Horse Slough	Advisory	2007	Cos/Mok Rivers	River
EPRSE	East Park Reservoir Southeast	Advisory	2006	Western Drainages	Lake/Reservoir
EPRSW	East Park Reservoir West	Advisory	2006	Western Drainages	Lake/Reservoir
FREWR	Fremont Weir	Advisory	2006	Sacramento River	River
FRGR	Feather River at Gridley	CVRWQCB	2005, 2006	Feather River	River
FRHY	Feather River Hatchery	Advisory	2005	Hatchery	Hatchery
FRNI	Feather River at Nicolaus	SRWP	2005	Feather River	River
FRORO	Feather River at Oroville Outlet	Advisory	2006	Feather River	River
FRTR	Frank's Tract	Intensive	2005, 2007	Central Delta	River
GEOSL	Georgiana Slough	Advisory	2006	Northern Delta	River

Station Code	Station Name	Site Type	Year(s) Sampled	Region	Waterbody Type
HBMFD	Honker Bay (McAvoy Fish Derby)	Advisory	2006	Western Delta	River
HCUT	Honker Cut	Advisory	2005	Central Delta	River
HNLK	Hensly Lake	Advisory	2007	San Joaquin River	Lake/Reservoir
HTCRK	Hat Creek	Advisory	2006	Sacramento River	River
INVRN	Indian Valley Reservoir North	Advisory	2006	Western Drainages	Lake/Reservoir
INVRS	Indian Valley Reservoir South	Advisory	2006	Western Drainages	Lake/Reservoir
ITSL	Italian Slough	Advisory	2005	Central Delta	River
JKLK	Jenkinson Lake	Advisory	2005	Eastern Drainages	Lake/Reservoir
LIBIS	Liberty Island	Advisory	2006	Northern Delta	River
LKALN	Lake Almanor North	Advisory	2006	Feather River	Lake/Reservoir
LKALS	Lake Almanor South	Advisory	2006	Feather River	Lake/Reservoir
LKBRI	Lake Britton	Advisory	2006	Sacramento River	Lake/Reservoir
LKDP	Lake Don Pedro	Advisory	2007	San Joaquin River	Lake/Reservoir
LKMS	Lake McSwain	Advisory	2007	San Joaquin River	Lake/Reservoir
LKTU	Lake Tulloch	Advisory	2007	San Joaquin River	Lake/Reservoir
LMBA	Lake McClure at Bagby	Advisory	2007	San Joaquin River	Lake/Reservoir
LMBC	Lake McClure at Barrett Cos	Advisory	2007	San Joaquin River	Lake/Reservoir
LMR1	Lower Mokelumne River 1	Advisory	2007	Cos/Mok Rivers	River
LMR2	Lower Mokelumne River 2	Advisory	2007	Cos/Mok Rivers	River
LMR3	Lower Mokelumne River 3	Advisory	2007	Cos/Mok Rivers	River
LMR5	Lower Mokelumne River 5	Advisory	2007	Cos/Mok Rivers	River
LMR6	Lower Mokelumne River 6	Advisory	2007	Cos/Mok Rivers	River
LMR7	Lower Mokelumne River 7	Advisory	2007	Cos/Mok Rivers	River
LOSL	Lost Slough	Advisory	2005	Cos/Mok Rivers	River
MCHY	Moccasin Hatchery	Advisory	2005	Hatchery	Hatchery
MCVFD	Ryer Island (McAvoy Fish Derby)	Advisory	2006	Western Delta	River
MERHP	Merced River at Hatfield State Park	Restoration/CVRWQCB	2005, 2006	San Joaquin River	River
MERR	Merced River	Advisory	2007	San Joaquin River	River
MILK	Millerton Lake	Advisory	2005	Eastern Drainages	Lake/Reservoir
MKHY	Mokelumne Hatchery	Advisory	2005	Hatchery	Hatchery
MMSL	Mendota Pool/Mendota Slough	Advisory	2005, 2007	Central Delta	River
MORES	Modesto Reservoir	Advisory	2007	San Joaquin River	Lake/Reservoir
MPLS	Mammoth Pools	Advisory	2007	Eastern Drainages	Lake/Reservoir
MRHW4	Middle River at HWY 4	Advisory	2005	Central Delta	River
MRHY	Merced Hatchery	Advisory	2005	Hatchery	Hatchery

Station Code	Station Name	Site Type	Year(s) Sampled	Region	Waterbody Type
MRIND	Middle River at Bullfrog	Index	2005, 2007	Central Delta	River
MRLL	Mokelumne River at Lodi Lake	Advisory	2005	Cos/Mok Rivers	River
MRMIS	Middle River at Mildred Island	Advisory	2005	Central Delta	River
MS140	Mud Slough at HWY 140	Advisory	2007	San Joaquin River	River
MSHY	Mount Shasta Hatchery	Advisory	2005	Hatchery	Hatchery
NDPRSL	Prospect Slough	Intensive	2005, 2007	Northern Delta	River
NHRES	New Hogan Reservoir	Advisory	2005	Eastern Drainages	Lake/Reservoir
NIMHY	Nimbus Hatchery	Advisory	2005	Hatchery	Hatchery
ONF	O'Neal Forebay	Advisory	2007	San Joaquin River	Lake/Reservoir
ORCCF	Old River at Cliffton Court Forebay	Advisory	2006	San Joaquin River	River
ORTB	Old River at Tracy Blvd.	Advisory	2005	San Joaquin River	River
PARES	Pardee Reservoir	Advisory	2005	Eastern Drainages	Lake/Reservoir
PCUT	Paradise Cut	Advisory	2005	San Joaquin River	River
POTSL	Potato Slough	Index	2005, 2007	Central Delta	River
RFAD	Rice fields/Agricultural Ditches	Advisory	2006	Sacramento River	Other
RIOVFD1	Rio Vista Fish Derby1	Advisory	2006	Northern Delta	River
RIOVFD2	Rio Vista Fish Derby2	Advisory	2006	Northern Delta	River
SACCM33	Sacramento River at Channel Marker 33	Advisory	2006	Western Delta	River
SACCSL	Sacramento River at Cache Slough	Advisory	2006	Northern Delta	River
SACDES	Sacramento River Near Deschutes Rd	Advisory	2006	Sacramento River	River
SACHC	Sacramento River at Hamilton City	Restoration	2005	Sacramento River	River
SACKL	Sacramento River at Knights Landing	Advisory	2006	Sacramento River	River
SACMS	Sacramento River at Miner Slough	Advisory	2006	Northern Delta	River
SACRIO	Sacramento River at Rio Vista	Index	2005, 2007	Northern Delta	River
SACRM59	Sacramento River - West Sacramento at Rivermile 59 - Between Discovery Park and Miller Park	Advisory	2006	Northern Delta	River
SACSCOT	Sacramento River Near Hamilton (Scotty's Boat Landing)	Advisory	2006	Sacramento River	River
SACTIS	Sacramento River at Tisdale Boat Ramp AKA River Bend Marina	Advisory	2006	Sacramento River	River
SACVER	Sacramento River Near Verona Marina, Village Resort AKA Joe's Place	Advisory	2006	Sacramento River	River
SALTSL	Salt Slough at Hwy 165	CVRWQCB	2005	Central Delta	River
SGORDM	Stony Gorge Reservoir at Dam	Advisory	2006	Western Drainages	Lake/Reservoir
SGORS	Stony Gorge Reservoir South	Advisory	2006	Western Drainages	Lake/Reservoir

Station Code	Station Name	Site Type	Year(s) Sampled	Region	Waterbody Type
SHLK	Shasta Lake	Advisory	2006	Sacramento River	Lake/Reservoir
SHMAIN	Shasta Lake Main Stem	Advisory	2006	Sacramento River	Lake/Reservoir
SHMCR	Shasta Lake at McCloud River	Advisory	2006	Sacramento River	Lake/Reservoir
SHSAC	Shasta Lake at Sacramento River	Advisory	2006	Sacramento River	Lake/Reservoir
SJCL	San Joaquin River at Crows Landing	CVRWQCB	2005	San Joaquin River	River
SJFF	San Joaquin River at Fremont Ford	CVRWQCB	2005	San Joaquin River	River
SJH99	San Joaquin River at HWY 99	Advisory	2005	San Joaquin River	River
SJHY	San Joaquin Hatchery	Advisory	2005	Hatchery	Hatchery
SJLPK	San Joaquin River at Laird Park	Advisory	2005	San Joaquin River	River
SJMO	San Joaquin River at Mossdale	Advisory	2005	San Joaquin River	River
SJPAT	San Joaquin River at Patterson	CVRWQCB	2005	San Joaquin River	River
SJR140	San Joaquin River at HWY 140	Advisory	2007	San Joaquin River	River
SJRMR	San Joaquin River at Merced River	Advisory	2007	San Joaquin River	River
SJRSI	San Joaquin River at Sycamore Island	Advisory	2007	San Joaquin River	River
SJVER	San Joaquin River at Vernalis	Index	2005, 2007	San Joaquin River	River
SLR152	San Luis Reservoir at HWY 152	Advisory	2007	San Joaquin River	Lake/Reservoir
SLRSLC	San Luis Reservoir at San Luis Creek	Advisory	2007	San Joaquin River	Lake/Reservoir
SMCNL	Smith Canal	Advisory	2005	Central Delta	River
SMSL	Sand Mound Slough	Advisory	2005	Central Delta	River
SNSL	Snodgrass Slough Near Delta Meadows	Advisory	2006	Northern Delta	River
SRBND	Sacramento River at Bend Bridge	CVRWQCB	2005	Sacramento River	River
SRBND06	Sacramento River at Bend Bridge Near Red Bluff	Advisory	2006	Sacramento River	River
SRBUT	Sacramento River at Butte City	CVRWQCB	2005	Sacramento River	River
SRCOL	Sacramento River at Colusa	Advisory/CVRWQCB	2005, 2006	Sacramento River	River
SRCSP	Stanislaus River at Caswell State Park	CVRWQCB	2005	San Joaquin River	River
SRGR	Sacramento River at Grimes	CVRWQCB	2005	Sacramento River	River
SRM44	Sacramento River at RM44	Index	2005, 2007	Northern Delta	River
SRORD	Sacramento River at Ord Bend	CVRWQCB	2005	Sacramento River	River
SRVB	Sacramento River at Veterans Bridge	SRWP	2005	Sacramento River	River
SRWB	Sacramento River at Woodson Bridge	CVRWQCB	2005	Sacramento River	River
SSLK	Sacramento Slough at Karnak	CVRWQCB	2005	Sacramento River	River
SSMFD	Suisun Slough (McAvoy Fish Derby)	Advisory	2006	Western Delta	River
STRV	Stanislaus River	Advisory	2007	San Joaquin River	River
STSL	Steamboat Slough	Advisory	2006	Northern Delta	River
SUBY	Sutter Bypass Below Kirkville Road	Advisory	2006	Sacramento River	River

Station Code	Station Name	Site Type	Year(s) Sampled	Region	Waterbody Type
TLAK	Turlock Lake	Advisory	2007	San Joaquin River	Lake/Reservoir
TOED	Toe Drain	Restoration	2006, 2007	Northern Delta	River
TUO3SHI	Tuolumne River at Shiloh Rd.	Restoration	2005	San Joaquin River	River
TURV	Tuolumne River	Advisory	2007	San Joaquin River	River
TYSL	Taylor Slough	Advisory	2005	Western Delta	River
UCSMFD	Upper Cache Slough (McAvoy Fish Derby)	Advisory	2006	Northern Delta	River
WDCUT	Werner Dredger Cut	Advisory	2005	Central Delta	River
WHSL	Whiskey Slough	Advisory	2005	Central Delta	River
WLKB	Whiskeytown Lake at Brandy Creek	Advisory	2006	Sacramento River	Lake/Reservoir
WLKCC	Whiskeytown Lake at Clear Creek	Advisory	2006	Sacramento River	Lake/Reservoir
WRES	Woodward Reservoir	Advisory	2007	San Joaquin River	Lake/Reservoir
YRVMY	Yuba River at Marysville	CVRWQCB	2005	Feather River	River

Table 2. Size limits, sample sizes, and percent of samples in each of four mercury concentration categories, by species.

Common Name	Genus	Species	Length Limits (mm)	Number Of Samples	< 0.1 µg/g %	0.1 – 0.25 µg/g %	> 0.25 – 0.4 µg/g %	> 0.4 µg/g %
Largemouth Bass	*Micropterus*	*salmoides*	307 – 435	466	1	26	33	40
Redear Sunfish	*Lepomis*	*microlophus*	152 – 228	234	57	37	3	3
Bluegill	*Lepomis*	*macrochirus*	116 – 176	220	49	42	5	4
Common Carp	*Cyprinus*	*carpio*	434 – 659	201	8	34	37	21
Sacramento Sucker	*Catostomus*	*occidentalis*	329 – 489	195	28	42	23	7
Rainbow Trout	*Oncorhynchus*	*mykiss*	262 – 381	143	93	6	1	0
White Catfish	*Ameiurus*	*catus*	243 – 378	124	21	51	14	14
Channel Catfish	*Ictalurus*	*punctatus*	367 – 518	117	11	43	24	22
Striped Bass	*Morone*	*saxatilis*	479 – 702	78	0	17	33	50
Sacramento Pikeminnow	*Ptychocheilus*	*grandis*	257 – 472	77	12	31	34	23
Brown Bullhead	*Ameiurus*	*nebulosus*	248 – 347	53	87	11	2	0
Spotted Bass	*Micropterus*	*punctulatus*	289 – 408	47	0	26	17	57
Black Crappie	*Pomoxis*	*nigromaculatus*	191 – 272	45	24	27	36	13
Chinook Salmon	*Oncorhynchus*	*tshawytscha*	284 – 926	44	48	27	23	2
American Shad	*Alosa*	*sapidissima*	363 – 522	41	76	17	5	2
Goldfish	*Carassius*	*auratus*	281 – 415	37	51	35	11	3
Smallmouth Bass	*Micropterus*	*dolomieu*	283 – 423	36	8	14	17	61
Tule Perch	*Archoplites*	*interruptus*	126 – 195	25	52	40	8	0
Steelhead Rainbow Trout	*Oncorhynchus*	*mykiss*	395 – 690	25	56	44	0	0
Pumpkinseed	*Lepomis*	*gibbosus*	102 – 176	18	89	11	0	0
Hardhead	*Mylopharodon*	*conocephalus*	339 – 467	17	0	24	29	47
Brook Trout	*Salvelinus*	*fontinalis*	222 – 296	14	100	0	0	0
Kokanee	*Oncorhynchus*	*nerka*	173 – 231	13	23	77	0	0
White Sturgeon	*Acipenser*	*transmontanus*	1266 – 1688	9	0	78	22	0
Hitch	*Lavinia*	*exilicauda*	200 – 269	7	86	14	0	0
Warmouth	*Lepomis*	*gulosus*	179 – 238	6	33	67	0	0
Lake Trout	*Salvelinus*	*namaycush*	244 – 325	5	100	0	0	0
Sacramento Perch	*Archoplites*	*interruptus*	118 – 157	5	0	100	0	0
Brown Trout	*Salmo*	*trutta*	323 – 430	5	80	20	0	0
Flathead Catfish	*Pylodictis*	*olivaris*	193 – 257	2	100	0	0	0
Shiner Surfperch	*Cymatogaster*	*aggregata*	468 – 624	1	100	0	0	0

Table 3. The mean, upper & lower confidence intervals, and standard deviation for mercury, by region. Fish size was constrained using length limits in Table 2.

Region	Common Name	Number of Fish	Number of Sites	Hg Lower Bound CI (95%)	Average Hg (µg/g)	Hg Upper Bound CI (95%)	Standard Deviation
Central Delta	Bluegill	56	13	0.060	0.082	0.104	0.04
Cos-Mok Rivers	Bluegill	11	3	0.071	0.289	0.506	0.19
Eastern Drainages	Bluegill	15	3	0.077	0.153	0.229	0.07
Feather River	Bluegill	14	3	0.070	0.161	0.253	0.08
Northern Delta	Bluegill	22	5	0.081	0.167	0.252	0.10
Sacramento River	Bluegill	33	7	0.091	0.144	0.197	0.07
San Joaquin River	Bluegill	46	11	0.102	0.132	0.162	0.05
Central Delta	Channel Catfish	10	3	0.050	0.094	0.138	0.04
Sacramento River	Channel Catfish	18	4	0.385	0.421	0.456	0.04
San Joaquin River	Channel Catfish	17	4	0.116	0.169	0.222	0.05
Western Drainages	Channel Catfish	26	3	0.144	0.211	0.278	0.06
Central Delta	Common Carp	18	5	0.127	0.155	0.184	0.03
Northern Delta	Common Carp	29	5	0.290	0.365	0.440	0.09
Sacramento River	Common Carp	17	5	0.158	0.256	0.353	0.11
San Joaquin River	Common Carp	61	13	0.239	0.304	0.370	0.12
Sacramento River	Rainbow Trout	36	5	0.023	0.032	0.042	0.01
San Joaquin River	Rainbow Trout	32	6	0.021	0.059	0.096	0.05
Central Delta	Redear Sunfish	58	11	0.061	0.076	0.092	0.03
Cos-Mok Rivers	Redear Sunfish	20	3	0.152	0.208	0.264	0.05
Northern Delta	Redear Sunfish	36	6	0.086	0.113	0.139	0.03
Sacramento River	Redear Sunfish	30	7	0.087	0.119	0.152	0.04
San Joaquin River	Redear Sunfish	25	6	0.061	0.082	0.102	0.03
Feather River	Sacramento Sucker	14	3	0.051	0.190	0.328	0.12
Northern Delta	Sacramento Sucker	37	7	0.182	0.237	0.292	0.07
Sacramento River	Sacramento Sucker	58	12	0.129	0.176	0.223	0.08
San Joaquin River	Sacramento Sucker	45	10	0.142	0.204	0.267	0.10
Northern Delta	Striped Bass	17	3	0.210	0.409	0.609	0.18
Sacramento River	Striped Bass	22	3	0.369	0.422	0.475	0.05
San Joaquin River	Striped Bass	21	3	0.272	0.524	0.777	0.22
Central Delta	White Catfish	33	7	0.097	0.119	0.141	0.03
Northern Delta	White Catfish	38	5	0.163	0.304	0.445	0.16
San Joaquin River	White Catfish	30	5	0.117	0.183	0.250	0.08

Table 4. Relationship in mercury concentrations between largemouth bass and other frequently sampled sport fish species. All relationships were positive.

Species Compared to Largemouth bass	N	r^2	F-ratio	p-value
Sacramento sucker	20	0.01	0.13	0.72
White catfish	19	0.57	22.1	0.0002
Bluegill	38	0.46	30.5	< 0.0001
Channel catfish	16	0.52	15.1	0.002
Common carp	26	0.46	20.1	0.0002
Redear sunfish	29	0.46	22.9	0.0001

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Figure 1. Sport fish sampling locations (2005 – 2007). See Table 1 for site names corresponding to site codes.

Figure 2. Mercury concentrations in 350-mm largemouth bass. No sites corresponded to < 0.1 µg/g.

Figure 3. Predicted mercury concentrations (mean ± 95% confidence intervals) for 350-mm largemouth bass in each region. Regions represented by three or more sites were included.

Figure 4. Relationship between average mercury concentration in Mississippi silverside (left) and juvenile largemouth bass (right) to 350-mm adult largemouth bass at co-located sites sampled in the Project.

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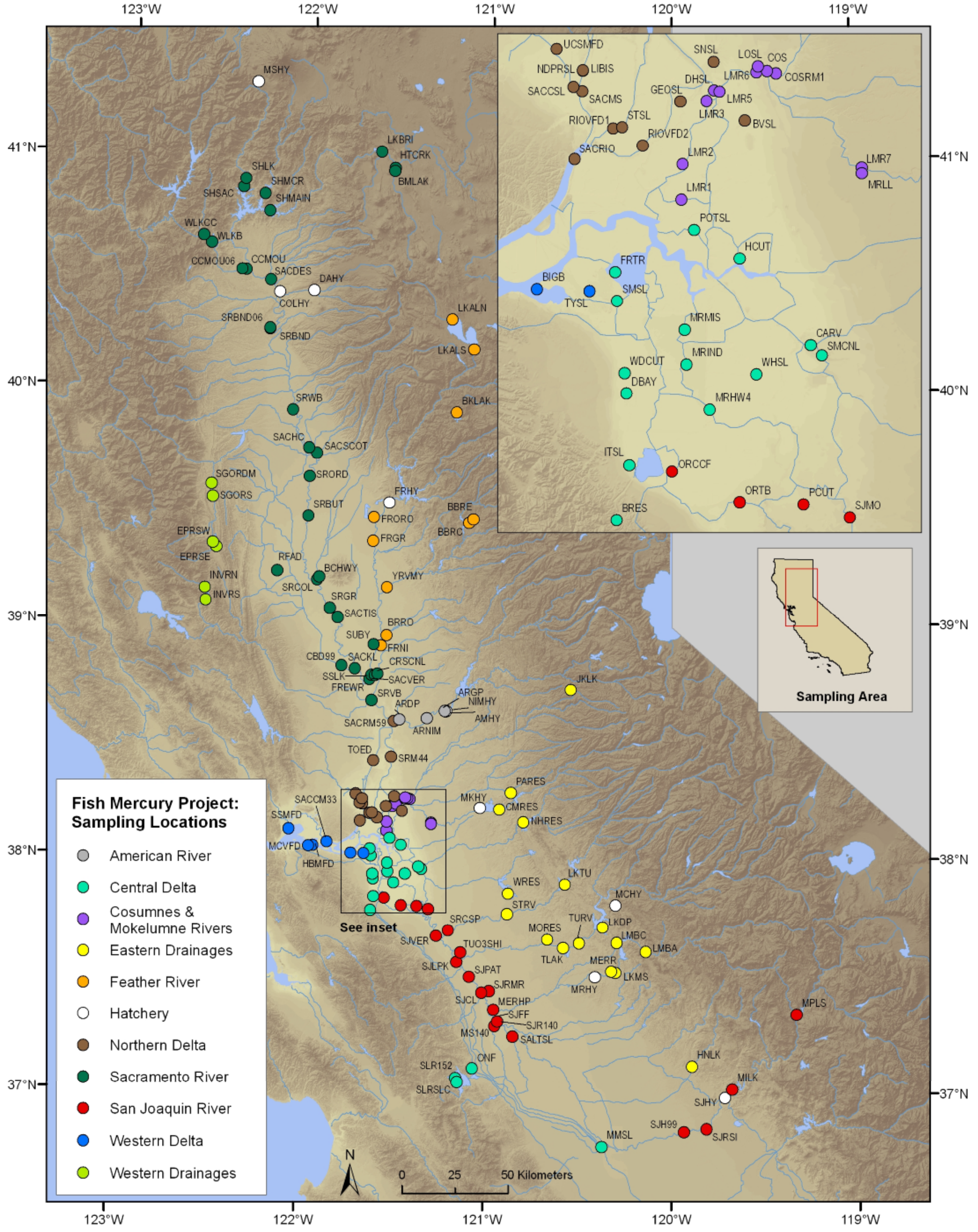

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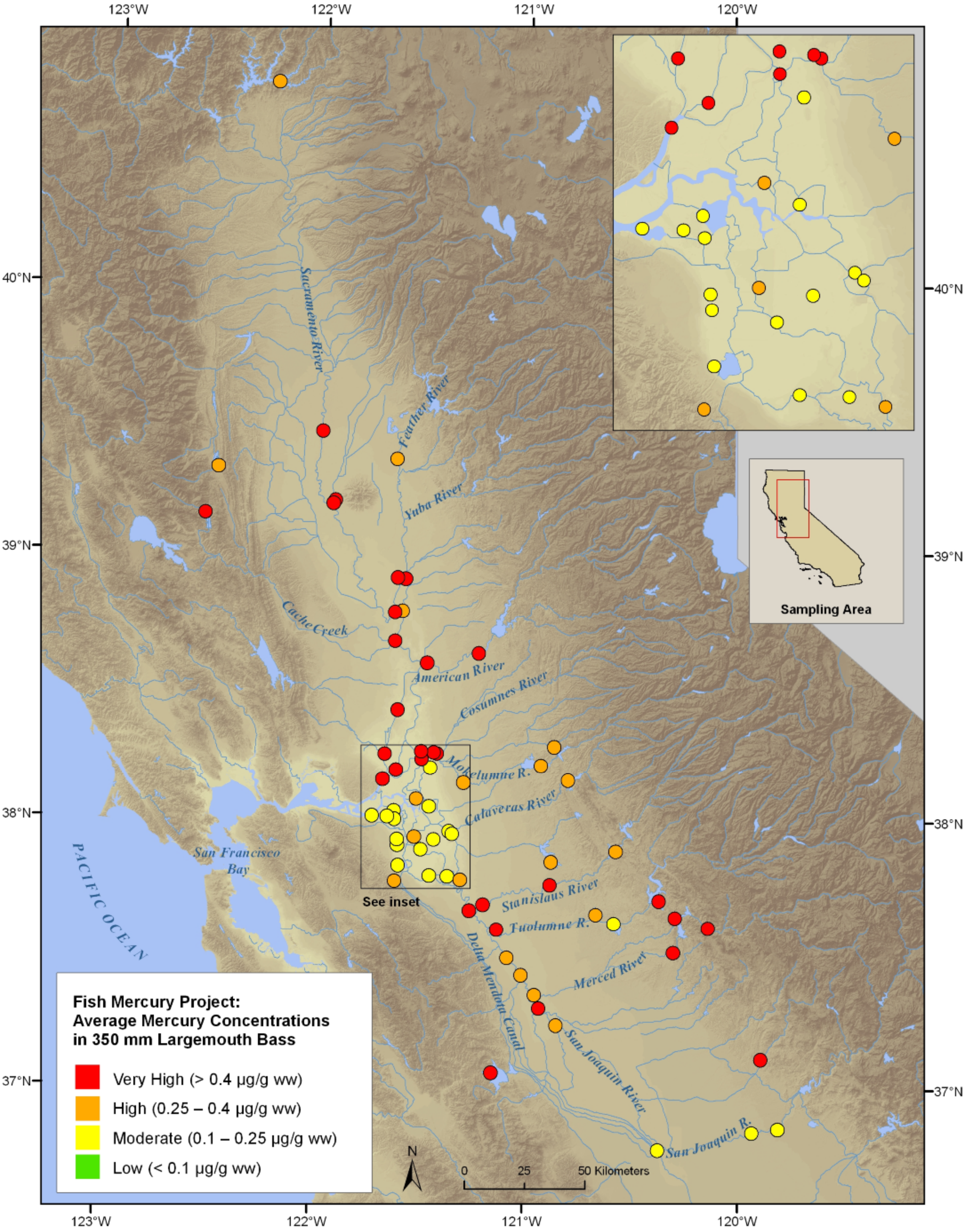

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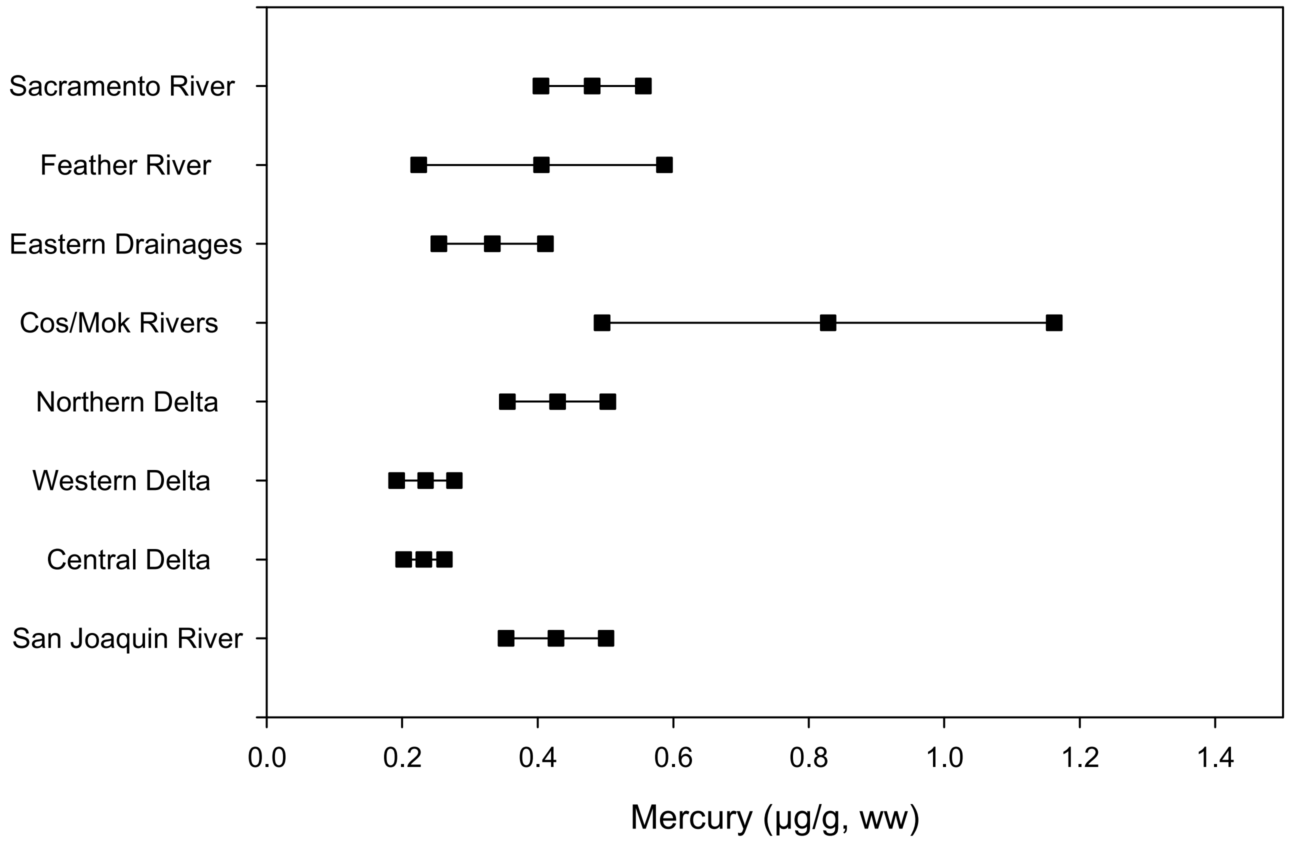

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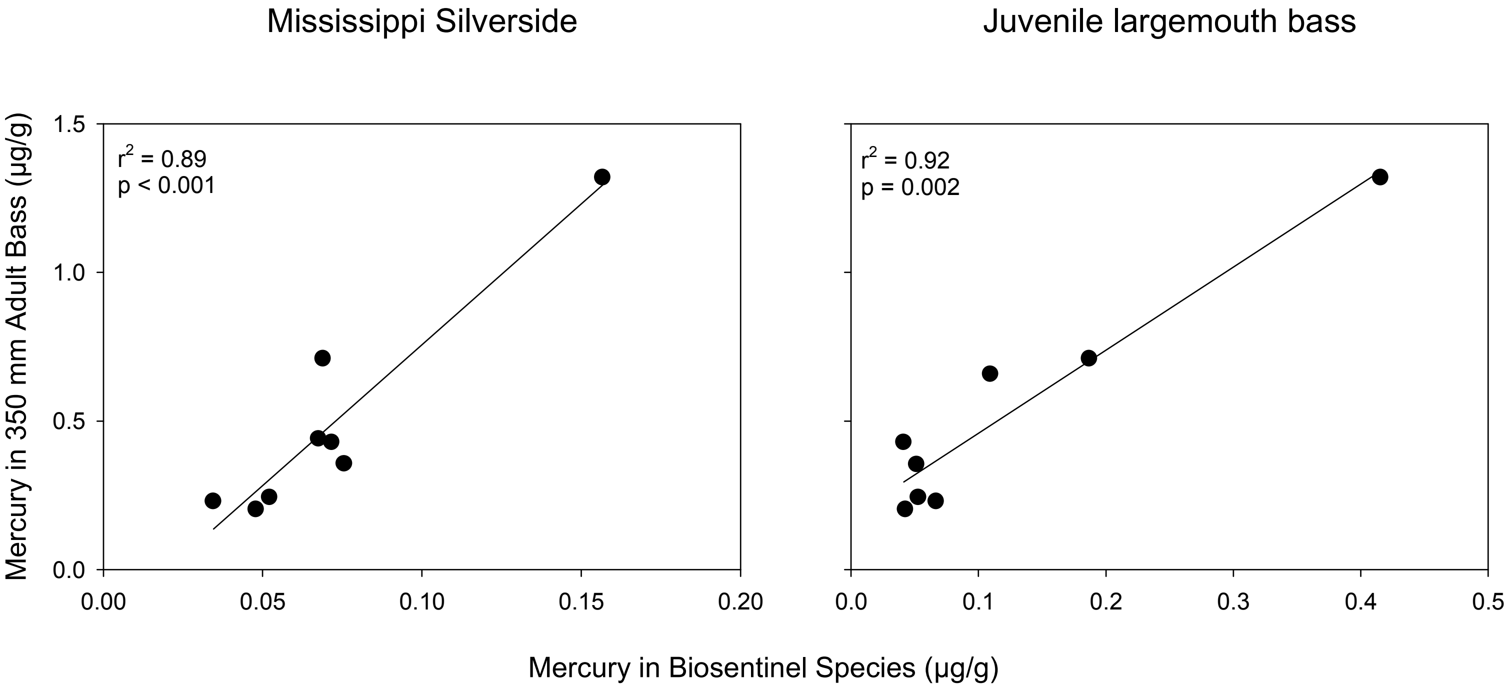

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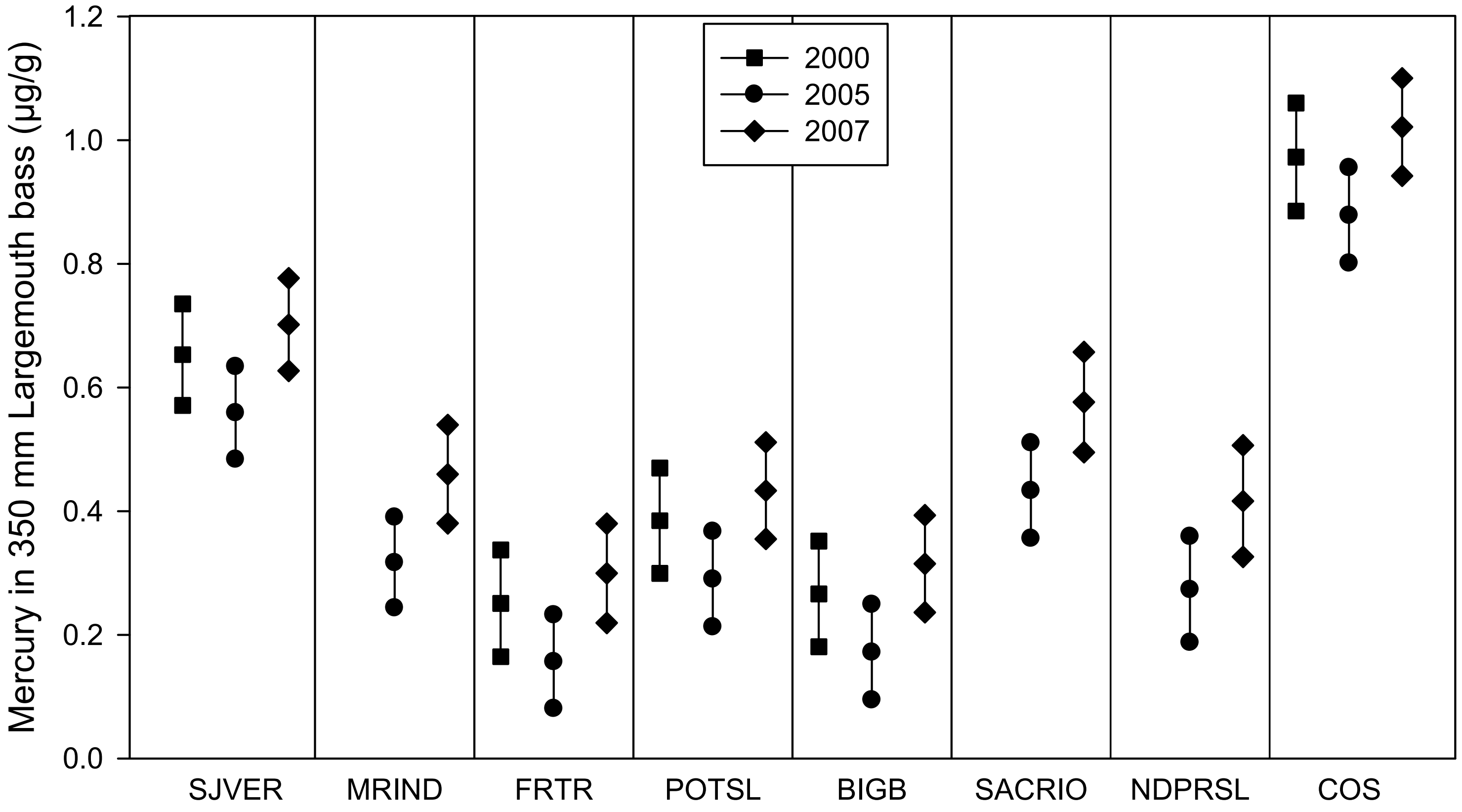

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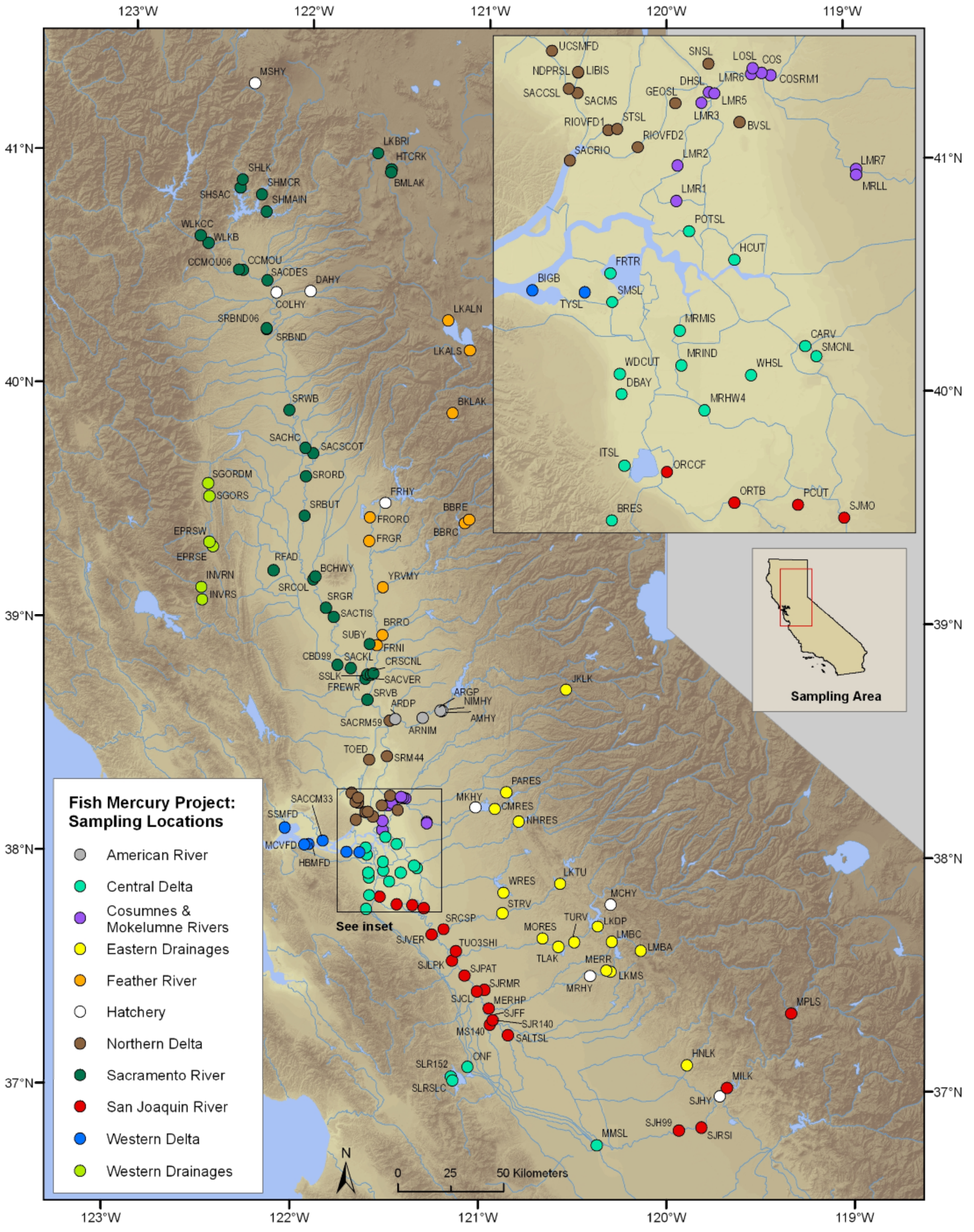

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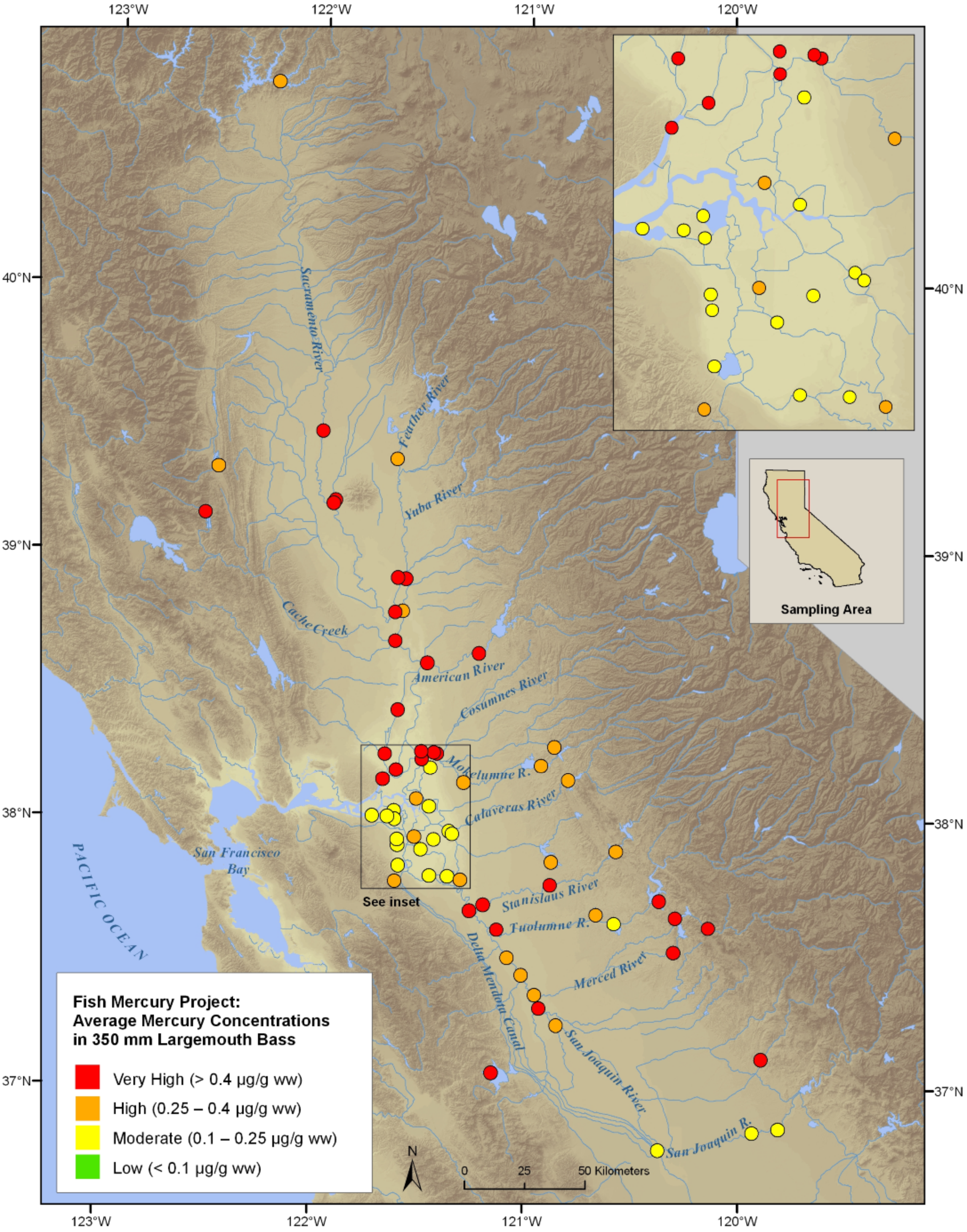

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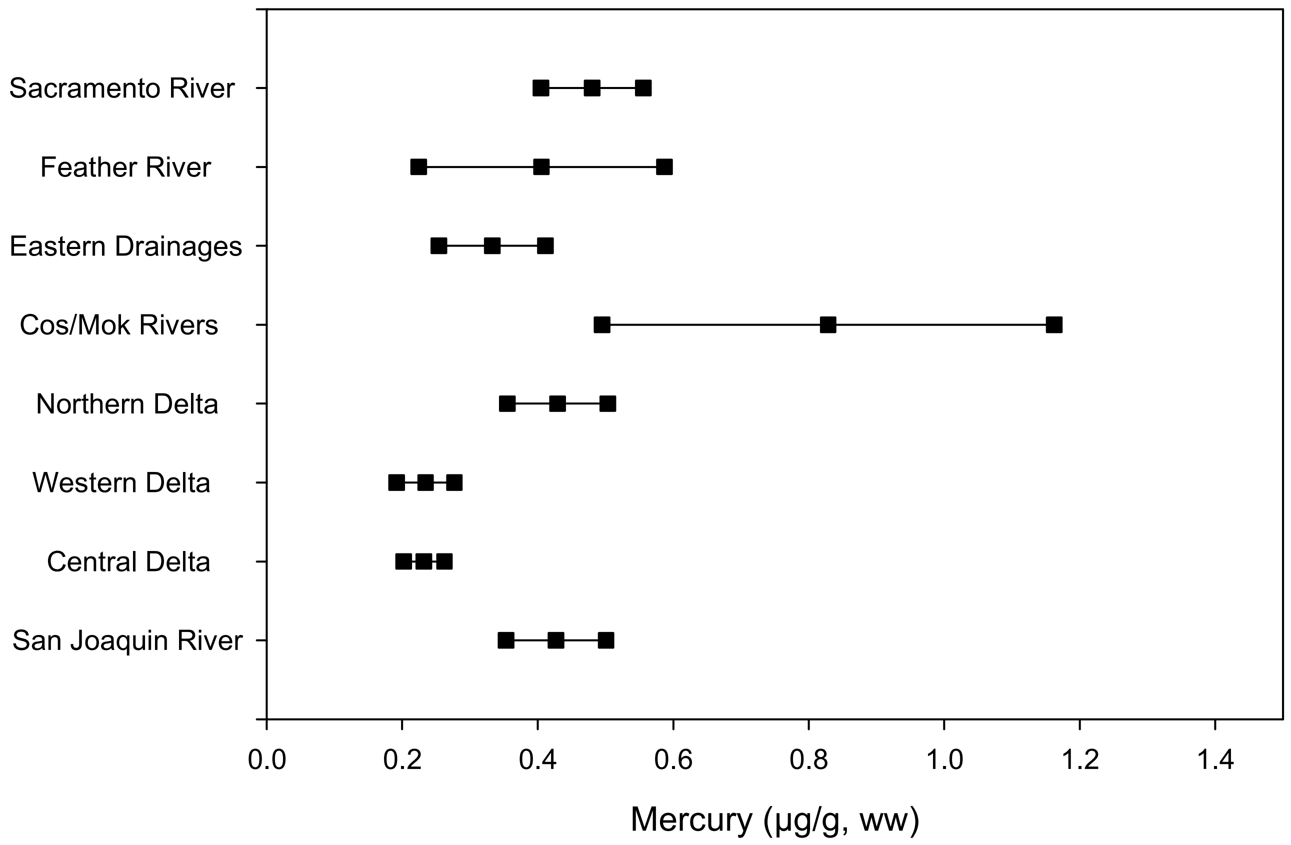

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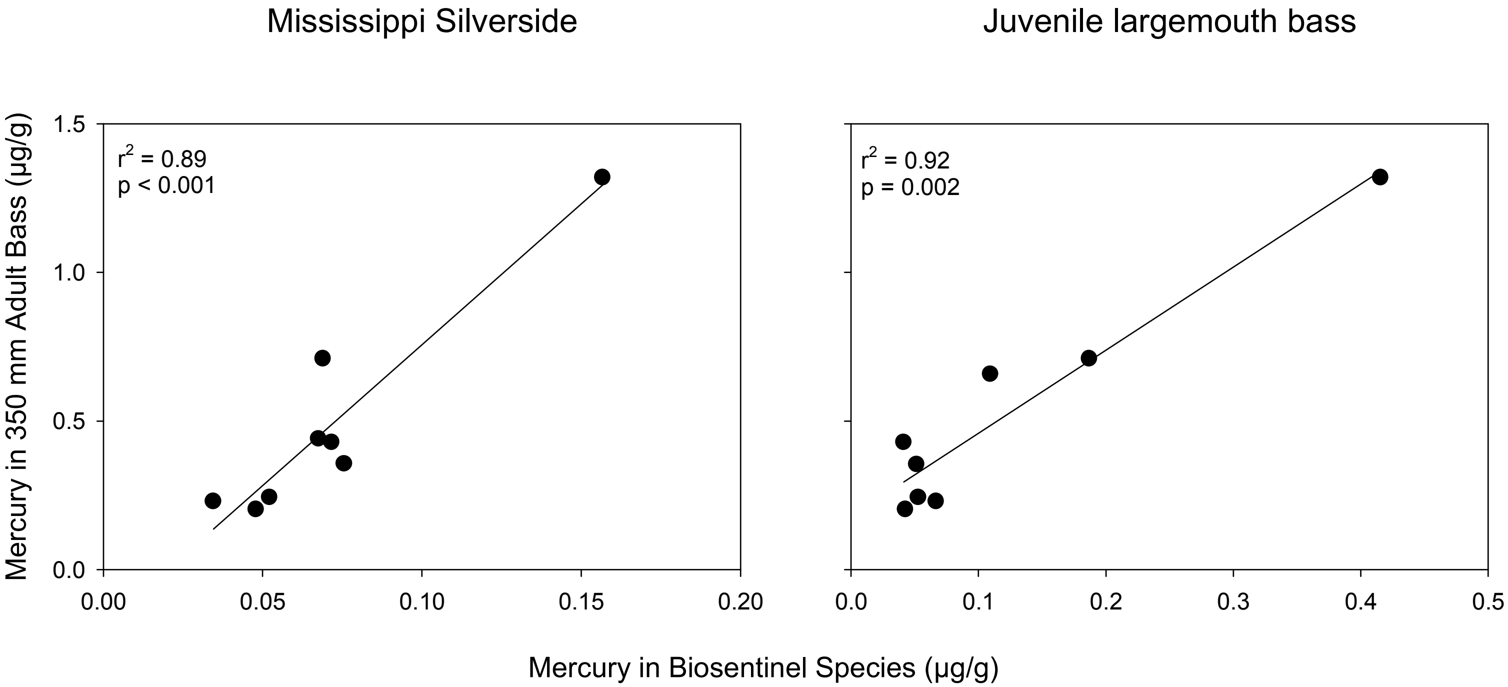

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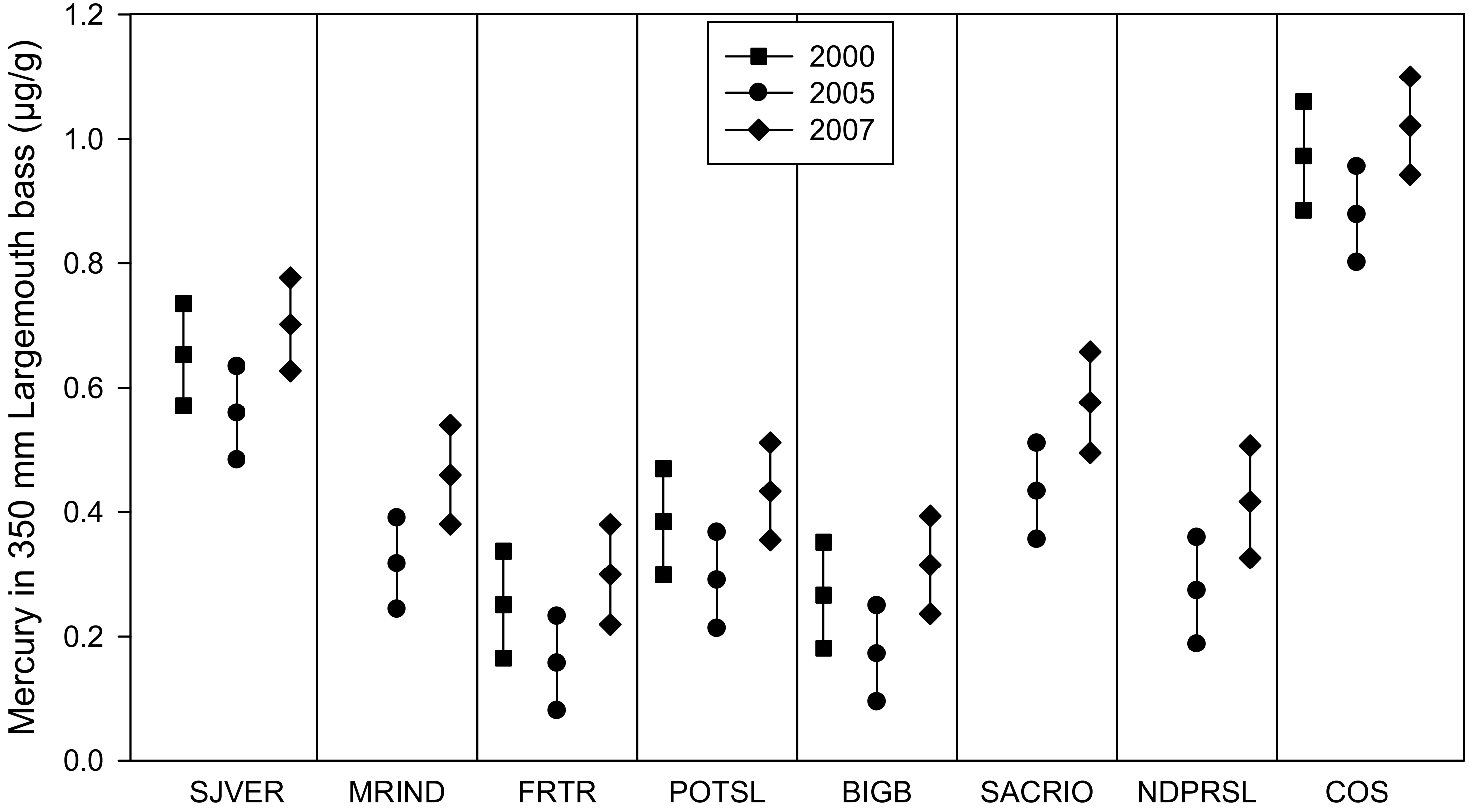

Figure 5. Predicted mercury concentrations (mean ± 95% confidence intervals) for 350-mm largemouth bass at eight sites sampled by the Project in 2005 and 2007, and by Davis et al. (2008). Refer to Table 1 for site abbreviations.

Supplemental Table 1. Predicted mercury concentrations for 350-mm largemouth bass at each site. Sites are arranged from north to south.

Years Sampled	Station Name	Hg Lower Bound CI (95%)	Average Hg (µg/g)	Hg Upper Bound CI (95%)	Standard Deviation
2006	Shasta Lake Main Stem	0.254	0.316	0.378	0.15
2005	Sacramento River at Butte City	0.462	0.562	0.661	0.16
2006	Butte Creek at Colusa Highway	0.384	0.466	0.548	0.14
2005, 2006	Sacramento River at Colusa	0.455	0.549	0.642	0.15
2006	Sutter Bypass Below Kirkville Road	0.313	0.408	0.503	0.15
2006	Cross Canal	0.278	0.362	0.446	0.15
2005	Sacramento Slough at Karnak	0.340	0.433	0.526	0.15
2005	Sacramento River at Veterans Bridge	0.578	0.676	0.774	0.16
2006	East Park Reservoir Southeast	0.266	0.370	0.475	0.17
2006	Indian Valley Reservoir North	0.824	0.925	1.027	0.18
2005, 2006	Feather River at Gridley	0.197	0.315	0.434	0.19
2005	Feather River at Nicolaus	0.482	0.580	0.679	0.18
2005	American River at Hazel Ave and Nimbus Dam	0.628	0.735	0.841	0.16
2005	American River at Discovery Park	0.495	0.594	0.693	0.24
2005	Pardee Reservoir	0.163	0.254	0.344	0.16
2005	Camanche Reservoir	0.282	0.382	0.483	0.18
2005	New Hogan Reservoir	0.262	0.362	0.463	0.18
2007	Woodward Reservoir	0.241	0.322	0.403	0.14
2007	Stanislaus River	0.425	0.515	0.604	0.15
2007	Lake Tulloch	0.282	0.375	0.468	0.14
2007	Modesto Reservoir	0.164	0.253	0.341	0.15
2007	Turlock Lake	0.155	0.241	0.327	0.15
2007	Lake Don Pedro	0.390	0.475	0.560	0.14
2007	Lake McClure at Barrett Cos	0.673	0.754	0.834	0.15
2007	Lake McSwain	0.471	0.562	0.654	0.14
2007	Hensly Lake	0.711	0.797	0.882	0.14
2007	Lake McClure at Bagby	0.775	0.867	0.958	0.15
2007	Dead Horse Slough	0.564	0.657	0.750	0.16
2005	Lost Slough	0.467	0.564	0.661	0.15
2005, 2006, 2007	Cosumnes River	1.117	1.208	1.299	0.16
2005	Mokelumne River at Lodi Lake	0.228	0.329	0.431	0.18
2006, 2007	Toe Drain	0.331	0.408	0.486	0.15
2006	Snodgrass Slough Near Delta Meadows	0.342	0.425	0.507	0.15
2005	Beaver Slough	0.133	0.227	0.322	0.14
2007	Prospect Slough	0.325	0.428	0.530	0.18
2006	Steamboat Slough	0.502	0.582	0.662	0.15
2005, 2007	Sacramento River at Rio Vista	0.414	0.494	0.574	0.16
2005, 2007	Big Break	0.152	0.250	0.348	0.17
2005	Taylor Slough	0.109	0.200	0.292	0.17
2005, 2007	Potato Slough	0.213	0.299	0.385	0.15
2005	Honker Cut	0.106	0.185	0.264	0.15
2007	Frank's Tract	0.114	0.202	0.290	0.16
2005	Sand Mound Slough	0.126	0.220	0.315	0.14
2005	Calaveras River	0.125	0.213	0.300	0.15
2005	Smith Canal	0.077	0.171	0.265	0.15
2005	Whiskey Slough	0.043	0.140	0.236	0.15
2005, 2007	Middle River at Bullfrog	0.248	0.321	0.395	0.18
2005	Werner Dredger Cut	0.096	0.196	0.295	0.15
2005	Discovery Bay	0.084	0.180	0.276	0.15
2005	Middle River at HWY 4	0.144	0.235	0.327	0.14
2005	Italian Slough	0.155	0.249	0.343	0.14
2007	Bethany Reservoir	0.302	0.389	0.477	0.15
2007	San Luis Reservoir at HWY 152	0.380	0.465	0.550	0.17
2005	Mendota Pool/Mendota Slough	0.111	0.206	0.301	0.15
2005	Old River at Tracy Blvd.	0.096	0.189	0.281	0.14
2005	Paradise Cut	0.127	0.206	0.285	0.15
2005	San Joaquin River at Mossdale	0.197	0.290	0.382	0.14
2005	Stanislaus River at Caswell State Park	0.414	0.504	0.594	0.14
2005, 2007	San Joaquin River at Vernalis	0.483	0.565	0.647	0.15
2005	Tuolumne River at Shiloh Rd.	0.449	0.533	0.616	0.15

Years Sampled	Station Name	Hg Lower Bound CI (95%)	Average Hg (µg/g)	Hg Upper Bound CI (95%)	Standard Deviation
2005	San Joaquin River at Patterson	0.283	0.372	0.461	0.14
2005	San Joaquin River at Crows Landing	0.326	0.397	0.469	0.15
2005, 2006	Merced River at Hatfield State Park	0.287	0.373	0.459	0.15
2005	San Joaquin River at Fremont Ford	0.311	0.404	0.497	0.14
2005	Salt Slough at Hwy 165	0.173	0.263	0.353	0.14
2005	San Joaquin River at HWY 99	0.024	0.116	0.209	0.14
2007	San Joaquin River at Sycamore Island	0.122	0.214	0.305	0.14