SAN FRANCISCO ESTUARY INSTITUTE

REGIONAL MONITORING PROGRAM

Mercury in biosentinel fish in San Francisco Bay: First-year project report

A Report of the Regional Monitoring Program

Exposure and Effects Pilot Study

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Abstract

Significant management actions are underway that have the potential to change mercury (Hg) concentrations in fish from the San Francisco Estuary. The Hg TMDL is a major effort to reduce Hg accumulation in Estuary fish, and there is concern that extensive tidal marsh restoration could increase Hg in the food web. The TMDL implementation plan includes monitoring of sport fish to protect humans and small fish to protect piscivorous wildlife. Small fish are a useful tool for monitoring inter-annual changes in methylmercury (MeHg) in aquatic ecosystems. They integrate fine-scale spatial and temporal patterns of MeHg uptake into the food web, while providing field data on risk to wildlife. From November through December of 2005, eight nearshore locations in San Francisco Bay were sampled with beach seines. Multiple composite samples of five to ten individuals each were collected at each sampling location, weighed, measured, and analyzed for whole-body total Hg concentration. Seven small fish species representing a range of vagility and salinity tolerance were captured. Of 97 composite samples analyzed, 39 (40%) had Hg concentrations higher than a proposed 0.03 $\mu g\ g^{-1}$ (wet-weight) TMDL target threshold. The average wet-weight mercury concentration of the samples was 0.049 $\mu g\ g^{-1}$ and the average total length was 52 mm. Mississippi silverside (*Menidia audens*) had higher Hg concentration than other species tested, and bay goby (*Lepidogobius lepidus*) had lower concentrations. For cheekspot goby (*Ilypnus gilberti*), concentrations were significantly higher at Alviso Slough than stations farther north. For Mississippi silverside, concentrations were significantly higher at four South Bay sites than at China Camp or Benicia State Park.

Introduction

Mercury (Hg) contamination is one of the highest-priority water quality issues for the San Francisco Estuary (Wiener *et al.* 2003, SFBRWQCB 2006), and the Hg strategy adopted by CALFED stated that "the primary problem with Hg in aquatic ecosystems can be defined as biotic exposure to methylmercury" (Wiener *et al.* 2003, p. iv Exec. Summ.). In the Total Maximum Daily Load (TMDL) plan for Hg, management actions are being initiated to reduce Hg loads to the Estuary (SFBRWQCB 2006). Nevertheless, proposed large-scale wetland restoration around the margins of the open-water habitat (Goals Project 1999) may exacerbate Hg exposure by causing greater Hg accumulation in the food web. This is because wetlands are sites of methylmercury (MeHg) production, and landscapes with higher percentages of wetlands are associated with higher MeHg export (St. Louis *et al.* 1994, Davis *et al.* 2003b, Marvin-DiPasquale *et al.* 2003). Plans are in place to restore 49,000 acres of wetlands throughout the San Francisco Estuary (SFEI 2006). Adaptive implementation of the Hg TMDL and adaptive management of habitat restoration will depend heavily on appropriate monitoring of impacts on water quality (Mumley and Looker 2004).

The California Bay-Delta Authority, recognizing the potential impacts of habitat restoration on Hg exposure in the Bay-Delta watershed, assembled a team of international Hg experts to develop a *Mercury Strategy for the Bay-Delta Ecosystem* (Wiener *et al.* 2003). A centerpiece of this Strategy was monitoring mercury in small fish.
Small fish are useful because they:

- accumulate the form of Hg (MeHg) that causes a health risk to biota,
- indicate the net amount of MeHg production in their home-range area,
- integrate exposure over a defined period of time (e.g., one year), making them a cost-effective and informative monitoring tool,
- indicate spatial patterns over relatively small scales (including near-shore areas) compared to larger sport fish, and
- indicate the exposure risks for piscivorous wildlife and other predators higher in the food chain, which may include sport fish and eventually humans.

In San Francisco Bay, the endangered least tern (*Sterna antillarum browni*) forages extensively on small fish, with prey total length averaging 50 mm (Elliott 2005). Because small fish accumulate MeHg and are important wildlife prey, they have recently been added as a target indicator in the Hg TMDL (SFBRWQCB 2006).

Mercury studies from other parts of the country use small fish to indicate inter-annual and spatial variation in net MeHg production in aquatic ecosystems (e.g., Wiener *et al.* 1990, Snodgrass *et al.* 2000, Greenfield *et al.* 2001, Essington and Houser 2003). Fish size correlates with many factors that influence Hg accumulation, including age, growth rate, and trophic position. Young-of-year fish within small, specified size ranges are useful bioindicators of Hg bioavailability. Slotton *et al.* (2002, 2004) demonstrate the successful use of Mississippi silverside (*Menidia audens*) for this purpose in the Sacramento-San Joaquin Rivers Delta.

The Regional Monitoring Program for Water Quality in San Francisco Bay (RMP) funded a three-year pilot study to develop baseline data on mercury concentrations in small fish in San Francisco Bay. The study includes annual monitoring of fixed monitoring stations in 2005 through 2008. The ultimate objective is to develop a monitoring program to evaluate long-term change in Hg bioavailability in the Estuary, including response to wetland modifications and other management actions. This report summarizes findings from the first year of monitoring in this study, and develops preliminary hypotheses based on these findings. In the report, whole body mercury concentrations are presented for seven fish species, captured from seven sites throughout San Francisco Bay.

Methods

Study design and target species

The food webs in different habitats may have different Hg uptake due to variation in environmental conditions at the base of the food web. To account for some of this potential variation, small fish from two habitat types, demersal (benthic) and pelagic, were targeted. Additionally, because salinity varies among locations in San Francisco Bay, both polyhaline and euhaline species were targeted. Species successfully captured and analyzed for Hg are summarized in Table 1.

The sampling design involves fixed stations, to allow analysis of trends in bioaccumulation of Hg over time. Fish were sampled at nearshore locations by beach

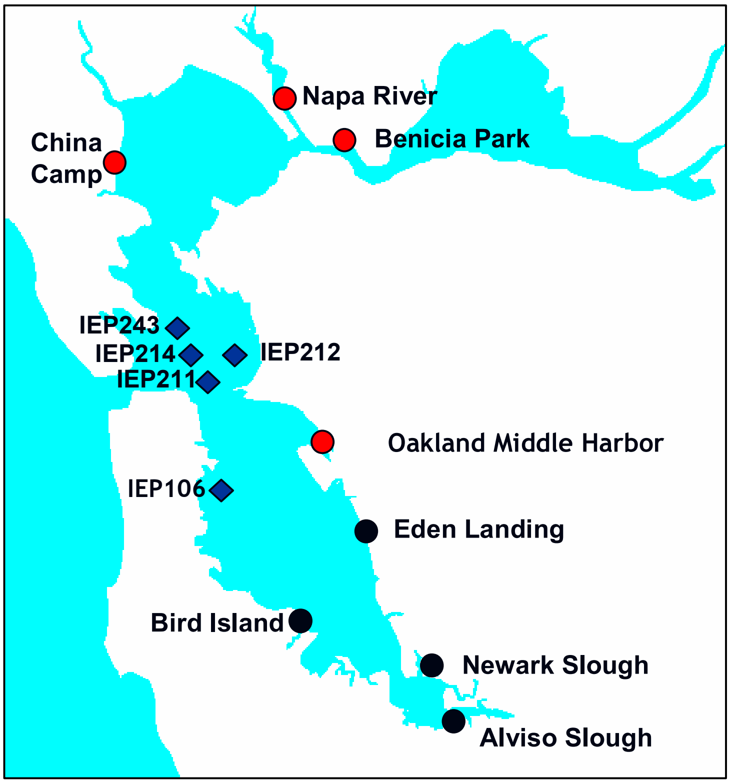

Figure 1. Map of sampling stations. Circles were sampled by beach seining; blue rectangles (♦) were bay goby samples obtained from IEP benthic trawl surveys. For beach seining sites, colors refer to location, with South Bay sites as black circles (●) and Central and North Bay sites as red circles (●).

seine at eight sites (Figure 1). The sites were selected to include sites currently adjacent to natural wetlands, and sites where future wetland restoration activity is planned. The goal of the design is to enable annual monitoring and comparison of long term Hg trends in natural vs. restored wetlands. Natural wetland sites include Newark Slough, China Camp, and Benicia State Park. Sites with planned wetland restoration include Bird Island, Napa River, Eden Landing, and Alviso Slough, and Oakland Middle Harbor. Additional fish were captured by the IEP Bay Study, which conducts otter trawling in deep water locations.

Four composites of whole fish from each species from each location were targeted for total Hg analysis. Five to ten individual fish were targeted for inclusion in each composite. In many fish species, Hg concentration increases with fish size, making it necessary to account for size variation in tissue Hg (Huckabee *et al.* 1979, Slotton *et al.* 2002). This may be accomplished by trying to minimize size variation among sites or developing statistical size vs. Hg relationships for each site (Tremblay *et al.* 1998). Due to budgetary limitations, it was not possible to analyze large numbers of samples from each station/species combination in the present study. Therefore, we attempted to limit size variation within species by targeting a limited size range (Table 1). To further reduce analytical costs, total Hg was analyzed rather than MeHg, because the vast majority of Hg assimilated by fish is MeHg (Grieb *et al.* 1990, Slotton *et al.* 2002, Wiener *et al.* 2002).

Fish collection and sample preparation

Fish were collected by beach seine from intertidal and subtidal sites around margins of the San Francisco Estuary between October 18 and December 20, 2005. Beach seine sites were sampled in the following order: Oakland Middle Harbor, China Camp State Park, Eden Landing, mouth of Steinberger Slough (Bird Island), mouth of Newark Slough, mouth of Alviso Slough, Napa River and Benicia State Park (Figure 1). Bay goby were received from the IEP Bay Study. This study captures fish by benthic trawling in the main channel and shoal areas from sites throughout the San Francisco Estuary (Orsi 1999). In 2005, bay goby were analyzed for Hg from IEP sites 106, 211, 212, 214, and 243 (Figure 1).

We identified all captured *Menidia spp.* as Mississippi silverside (*Menidia audens*; see Table 1). We base this determination on recent taxonomic work indicating a separate species from inland silverside (*Menidia audens*) (Suttkus *et al.* 2005), and our taxonomic identification of the samples. Other reports evaluating *Menidia spp.* in the Bay-Delta region refer to them as inland silverside (*Menidia beryllina*) (e.g., Moyle 2002, Slotton *et al.* 2004, Froese and Pauly 2006).

Table 1. Species captured in 2005 for Hg analysis. Habitat affinity, salinity affinity, and movement are approximate, and based on published reviews and personal observations (Orsi 1999, Goals Project 2000, Moyle 2002, Froese and Pauly 2006, Kathy Hieb, pers. comm., and Andy Jahn, pers. obs.). Euhaline = inhabits waters of marine salinity (approximately 30 ppt). Polyhaline = inhabits waters of brackish salinity (approximately 18 to 30 ppt). Number of sites indicates number of sites at which the species was captured.

Common name	Scientific name	Habitat affinity	Salinity affinity	Number of sites	Movement	Target size(mm)[a]
Bay goby	*Lepidogobius lepidus*	Deep channel benthic	Euhaline	5	Disperses from shoals to channel, and moves from South and San Pablo Bay to Central Bay	20 – 40
Cheekspot goby	*Ilypnus gilberti*	Shallow water benthic	Euhaline	4	Small home range (burrow dweller)	20 – 40
Arrow goby	*Clevelandia ios*	Shallow water benthic	Euhaline	2	Small home range (burrow dweller)	20 – 50
Shimofuri goby	*Tridentiger bifasciatus*	Shallow water benthic	Polyhaline	2	Small home range	40 – 70
Yellowfin goby	*Acanthogobius flavimanus*	Shallow water benthic	Polyhaline	1	Seasonal upstream or downstream movement for reproduction	NA
Topsmelt	*Atherinops affinis*	Shallow water pelagic	Euhaline	5	Large home range	55 – 100
Mississippi silverside	*Menidia audens*	Shallow water pelagic	Polyhaline	6	Large home range. Exhibits daily onshore-offshore dispersal and lateral movements in freshwaters	50 – 80

a. total length

Mercury in Biosentinel Fish

Upon arrival at field sites, ancillary measurements including salinity (PSU), conductivity (mS), and water temperature (ºC) were taken with a WTW 340i multimeter (Weilheim, Germany). GIS coordinates were collected with a Garmin GPS III Plus (Olathe, Kansas). Fish were collected via beach seine, then stored in a plastic or galvanized metal bucket filled with site water. Total length was measured for each individual fish, and fish were rinsed with deionized water if necessary to remove dirt and sediment. Each composite was placed in a separate freezer weight Ziploc ® bag. Each composite sample was weighed to the nearest 0.1 g. Deionized water was added to bags to avoid freezer burning the samples. Bags were on ice until returning to the lab and then transferred to conventional (- 20º C) freezers.

Mercury analysis

Samples were shipped overnight on ice to the Department of Biology/River Studies Center at the University of Wisconsin – La Crosse. Upon receipt at the laboratory, whole fish carcasses were thawed, weighed (nearest 0.001 g), re-frozen and stored in a conventional freezer. Frozen carcasses were lyophilized to a constant dry-weight in a Virtis DBT Benchtop 7.0 Freeze Dryer for a minimum of seven days at ≤ - 85º C and ≤ 100 mtorr. To assess constant dry-weight, 10% of the samples were weighed after a minimum of seven days, dried overnight, and re-weighed.

In preparation for analysis of total mercury, dried carcasses from each composite sample were digested whole or homogenized prior to digestion in a stainless-steel blender. Digestion was conducted on all carcasses in the composite sample (samples with few, very small fish) or on approximately 0.1 g subsamples of homogenized composite samples following a modification of EPA Method 1631. Samples and subsamples were digested for 3 h at 90 - 95º C in a solution of H_2SO_4 and HNO_3 followed by digestion with BrCl for 8 h at 40º C. Each digestate was analyzed by flow injection cold-vapor atomic fluorescence spectroscopy with a Leeman Labs Hydra AF Gold Plus Mercury Analyzer. Total mercury concentrations in composite samples are not corrected for recovery or blanks and were reported on a dry-weight basis. Wet-weight total Hg concentrations were calculated based on dry weights and tissue percent moisture.

Samples were analyzed in two batches (08-Feb-06, 16-Feb-06). The accuracy of mercury determinations for each batch of fish samples was verified by the concomitant analyses of (1) certified reference materials from the National Research Council of Canada (NRCC) and the U.S. National Institute of Standards and Technology (NIST), (2) triplicate subsamples of homogenized fish, (3) spiked (before digestion) subsamples of homogenized fish, and (4) blanks and standards taken through the digestion procedures. Quality control criteria and quality assurance results for determinations of total mercury in composite samples conformed to requirements in Table 4b of the 1999 Quality Assurance Plan of the RMP (Lowe *et al.* 1999) and are summarized in Appendix I. Concentrations in all fish samples analyzed exceeded the estimated limit of quantification (Clesceri *et al.* 1998) of 0.0097 $\mu g\ g^{-1}$ Hg dry-weight.

Statistical analysis and comparison to thresholds

Hg data were log-transformed prior to parametric testing. Evaluations of variation among species and variation among sites by species were conducted by analysis of variance (ANOVA). Bartlett's and Levene's tests were performed to establish homogeneity of variances. In cases where significant ANOVA results were observed, the Student-Newman-Keuls multiple range (SNK) test was conducted to identify significant differences among individual species or sites (Underwood 1997). Linear regression analysis was performed to the evaluate relationship between length and Hg for individual species (Draper and Smith 1998). Statistical analyses were performed using SYSTAT (version 11) and SAS 9.1.

To aid in interpretation, results are compared to two thresholds. The first threshold is the wildlife objective for small (30 - 50 mm) fish proposed in the revised Hg TMDL for San Francisco Bay. This threshold of 0.03 $\mu g\ g^{-1}$ wet-weight in whole fish was selected to be protective of California least tern and other piscivorous wildlife that forage in the Bay

(SFBRWQCB 2006). The second threshold is a tissue threshold for biological effects to fish, including growth, reproduction, development, and behavior. This threshold of 0.2 μg g^{-1} wet-weight in whole fish was developed by Beckvar *et al.* (2006) based on tissue threshold-effects levels from paired no-effect and low-effect concentrations obtained in a thorough review of all available literature. Beckvar *et al.* (2006) indicate that this threshold is protective of juvenile and adult fish.

Results

Target species were collected at seven of the eight beach seine collection locations. Collection efforts were not successful at the Napa River collection location.

Multiple composites of six fish species were collected and analyzed. The average wet-weight mercury concentration of the 97 samples analyzed was 0.049 μg g^{-1} (Table 2), and the average total length was 52 mm. Only three of the samples exceeded the 0.2 μg g^{-1} tissue effects threshold presented by Beckvar *et al.* (2006). However, 39 of the samples (40%) exceeded the wildlife effects threshold of 0.03 μg g^{-1} proposed for the TMDL by the San Francisco Bay Regional Water Quality Control Board (SFBRWQCB 2006). When only samples from 30 to 50 mm were examined, following the proposed TMDL wildlife objective, 5 of 21 samples (24%) were at or above the 0.03 μg g^{-1} threshold. All sample results are presented in Appendix II, with sampling locations identified in Appendix III.

A statistically significant difference in Hg was observed among species (ANOVA R^2 = 0.69; $p < 0.0001$). Based on results of the SNK multiple comparison test, concentrations were highest in Mississippi silverside, intermediate in topsmelt, shimofuri goby, cheekspot goby, and arrow goby, and lowest in bay goby (Figure 2).

Linear regression analysis of all samples combined indicated a statistically significant positive relationship between total length and tissue mercury concentration. This

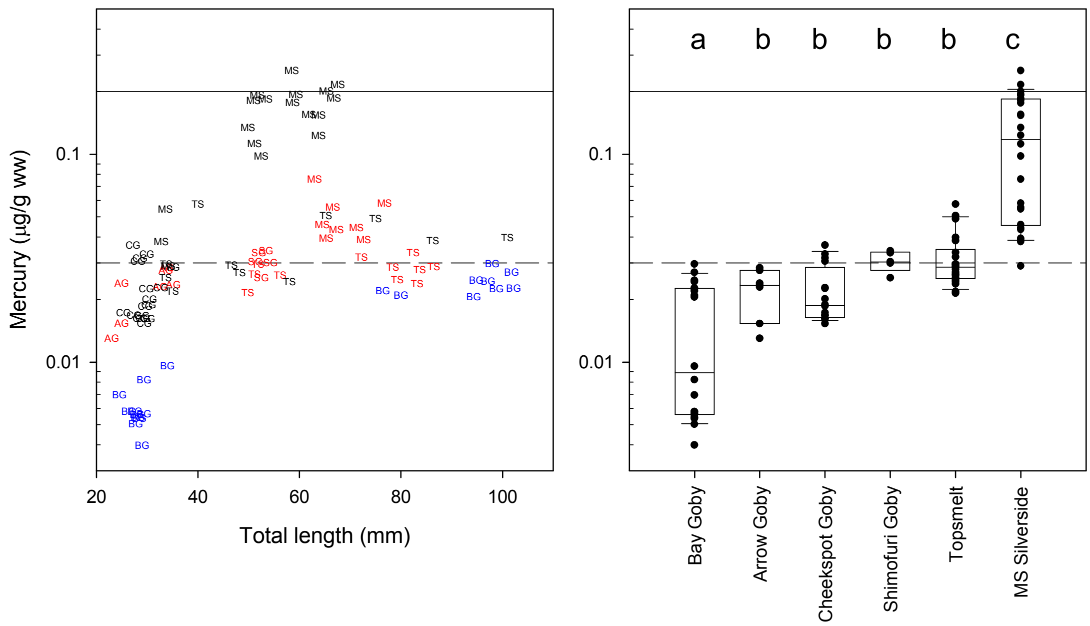

Figure 2. Mercury results for all samples collected in 2005. Left panel: length versus Hg indicating species and general sampling location. MS = Mississippi silverside; TS = topsmelt; AG = arrow goby; BG = bay goby; CG = cheekspot goby; SG = shimofuri goby. Symbol color follows Figure 1, with black symbols indicating South Bay sites (Eden Landing and south), red symbols indicating Central and North Bay sites (Oakland Harbor and north), and blue symbols indicating IEP bay goby collections. Right panel: species versus Hg. Letters indicate results of Student-Newman-Keuls test; species with different letters have significantly different Hg concentrations. In both panels, the dashed line at 0.03 µg g^{-1} indicates the proposed Hg TMDL target for protection of avian wildlife (SFBRWQCB 2006) and the solid line at 0.2 µg g^{-1} indicates a threshold above which effects to fish may occur (Beckvar *et al.* 2006). Note log scale y-axis.

relationship explained about a quarter of the total variation in mercury content among samples ($R^2 = 0.23$; Table 2), suggesting that some of the variation among species may be explained by differences in fish size. Evaluating individual species, statistically significant positive relationships between length and mercury were observed for bay goby and arrow goby (Table 2, Figures 3 and 4 left panels). No significant relationship between length and mercury was observed for cheekspot goby or topsmelt (Table 2, Figures 5 and 6 left panels). In Mississippi silverside, site differences in both fish length and mercury content prevented a valid test of a trend with length (Table 2, Figure 7). For shimofuri goby and yellowfin goby, the size range and sample size were insufficient to evaluate length vs. Hg (Table 2, Figure 8).

Table 2. Summary statistics and model results for Hg concentrations in fish captured in San Francisco Bay, October through December, 2005. N = Number of composite fish samples analyzed. Site effect = results of ANOVA for differences among site. Length effect = results of linear regression analysis for length versus Hg relationship. Bold values are statistically significant ($p < 0.05$).

Species	N	Length (mm) range (mean)	Hg mean ± SD ($\mu g\ g^{-1}$ wet)	Above TMDL target [a]	Above Beckvar threshold [b]	Site effect		Length effect	
						R^2	p	R^2	p
Bay goby	20	25 – 102 (58)	0.014 ± 0.0093	0	0	**0.93**	**< 0.0001**	**0.93**	< **0.0001**
Cheekspot goby	16	25 – 33 (29)	0.022 ± 0.0070	4/16	0	**0.85**	**< 0.0001**	0.00	0.89
Arrow goby	7	23 – 35 (30)	0.022 ± 0.0059	0	0	0.55	0.057	**0.62**	**0.035**
Shimofuri goby	5	51 – 54 (53)	0.031 ± 0.0035	3/5	0	c	c	c	c
Yellowfin goby	1	35	0.028	0	0	c	c	c	c
Topsmelt	22	34 – 101 (62)	0.032 ± 0.0097	7/22	0	0.39	0.13	0.05	0.34
Mississippi silverside	26	33 – 77 (56)	0.119 ± 0.070	25/26	3/26	**0.69**	**0.0001**	0.01	0.64
All samples	97	23 – 102 (52)	0.049 ± 0.056	39/97	3/97	-	-	**0.23** [d]	< **0.0001** [d]

a. 0.03 $\mu g\ g^{-1}$ wet-weight on average for 30 – 50 mm fish (SFBRWQCB 2006). b. 0.20 $\mu g\ g^{-1}$ wet-weight (Beckvar *et al.* 2006). c. insufficient data for analysis. d. Linear regression is based on log-transformed length and Hg data.

Mercury in Biosentinel Fish

Examining all species, mercury concentrations at a given length tended to be higher at more southern sites (Eden Landing and farther south) than at more northern sites (Oakland Middle Harbor and farther north; Figure 1, Figure 2 left panel). When individual species were examined, significant differences among sites were observed for bay goby, cheekspot goby, and Mississippi silverside (Table 2). For bay goby, spatial variation was confounded with variation in fish size (Figure 3). Stations IEP106 and IEP212 had relatively small fish (averaging 29 and 27 mm, respectively) and low mercury concentrations (0.005 and 0.006 µg g^{-1} wet-weight). Fish sizes and mercury concentrations were higher at station IEP211 (average size = 78 mm; average Hg = 0.022 µg g^{-1}), station IEP214 (101 mm and 0.026 µg g^{-1}), and station IEP243 (96 mm and 0.023 µg g^{-1}; Figure 3). Because of this association, it was not possible to assess whether mercury exposure was significantly different at the different bay goby stations. For cheekspot goby, concentrations were significantly higher at Alviso Slough (mean = 0.033 µg g^{-1} ww) than at three other capture locations (mean = 0.018 µg g^{-1} wet-weight), while the sizes of fish analyzed at Alviso Slough were similar to the other capture locations (Figure 5).

For Mississippi silverside, all samples conformed to the target size range of 50 – 80 mm, with the exception of three composites between 33 and 34 mm collected at Steinberger Slough. Only at Steinberger Slough, with these three small-fish composites included, was a positive relationship between size and Hg observed ($p < 0.005$, $R^2 = 0.89$, N = 6; Figure 7); similarly strong positive length vs. Hg relationships have been observed for silversides in the Delta and elsewhere by Slotton *et al.* (2002, 2004). To avoid confounding size difference with spatial variation, the three samples below the target size range were removed from the spatial ANOVA. Results indicated two groups (Figure 7, right panel), with the two sites in North Bay (average Hg = 0.05 µg g^{-1}) significantly lower than the four sites in South Bay (average Hg = 0.15 µg g^{-1}). In contrast to Mississippi silverside, the other pelagic fish species (topsmelt) exhibited statistically

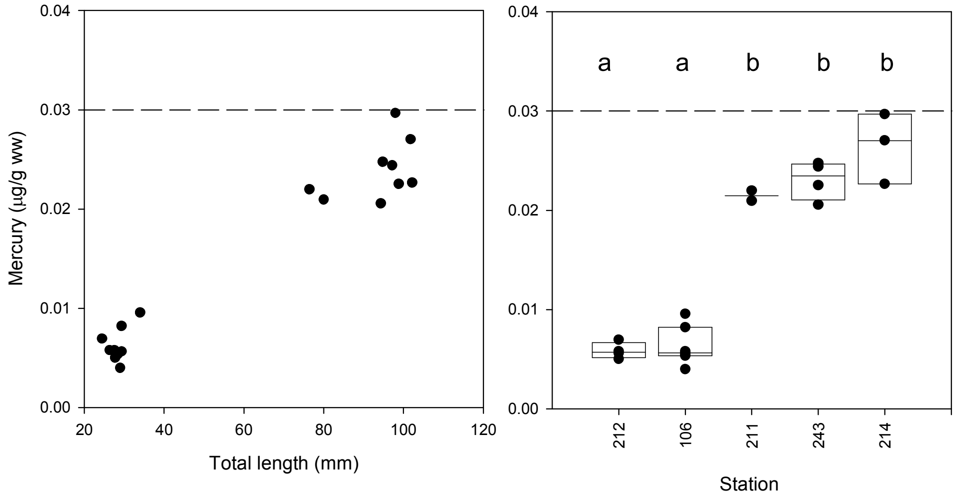

Figure 3. Mercury results for bay goby samples collected in 2005. Left panel: length versus Hg. Right panel: collection location versus Hg. Letters indicate results of Student-Newman-Keuls test; stations with different letters have significantly different Hg concentrations. In both panels, the dashed line indicates the Hg TMDL target for protection of avian wildlife (SFBRWQCB 2006).

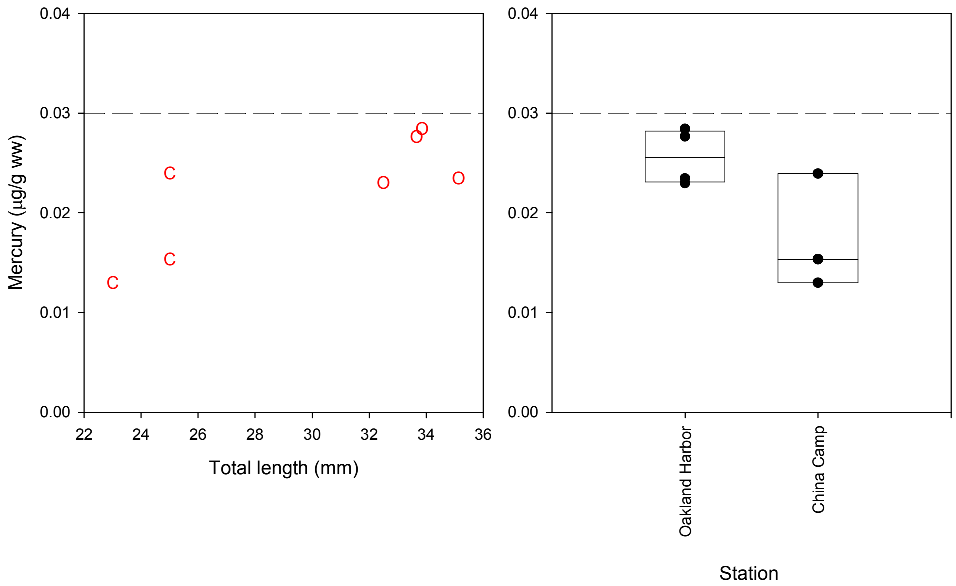

Figure 4. Mercury results for arrow goby collected in 2005. Left panel: length versus Hg organized by station and general sampling location. C = China Camp; O = Oakland Middle Harbor. Symbol color indicates collection location, with red symbols indicating that all samples were collected in Central and North Bays (i.e., Oakland Harbor and China Camp). Right panel: location versus Hg. In both panels, the dashed line indicates the Hg TMDL target for protection of avian wildlife (SFBRWQCB 2006).

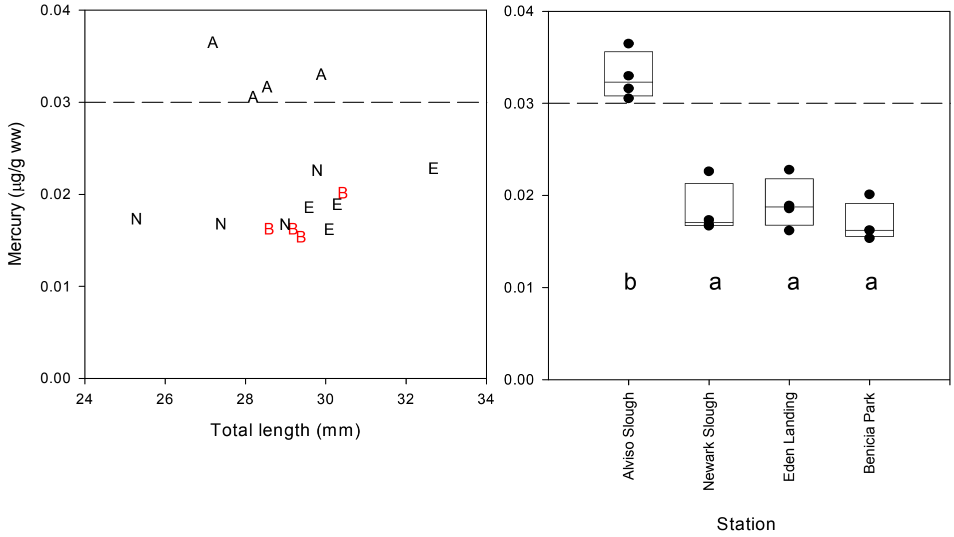

Figure 5. Mercury results for cheekspot goby collected in 2005. Left panel: length versus Hg organized by station and general sampling location. A = Alviso Slough; N = Newark Slough; E = Eden Landing; B = Benicia Park. Symbol color follows Figure 1, with black symbols indicating South Bay sites (Eden Landing and south), and red symbols indicating North Bay (Benicia Park). Right panel: location versus Hg. Letters indicate results of Student-Newman-Keuls test; stations with different letters have significantly different Hg concentrations. In both panels, the dashed line indicates the Hg TMDL target for protection of avian wildlife (SFBRWQCB 2006).

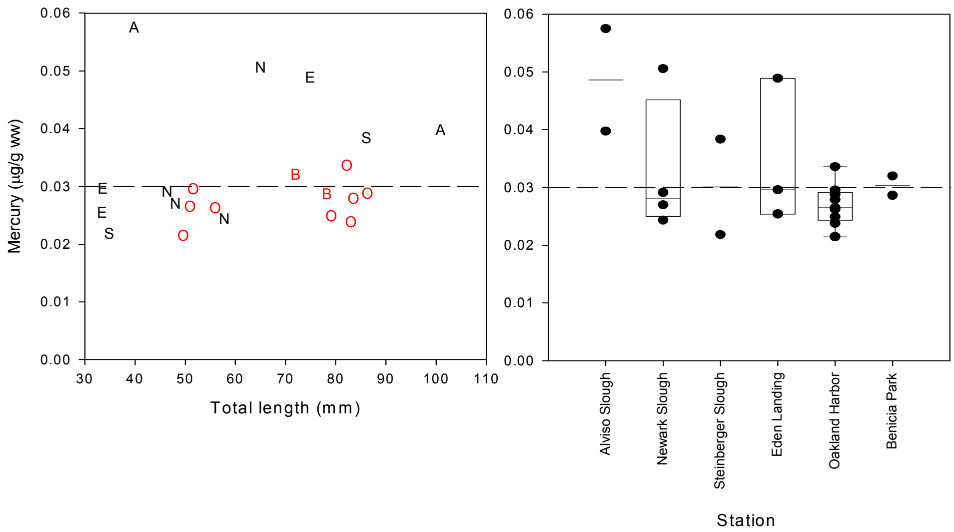

Figure 6. Mercury results for topsmelt collected in 2005. Left panel: length versus Hg organized by station and general sampling location. A = Alviso Slough; N = Newark Slough; E = Eden Landing; B = Benicia Park; S = Steinberger Slough; O = Oakland Middle Harbor. Symbol color indicates collection location (following Figure 1), with black symbols indicating South Bay sites, and red symbols indicating Central and North Bay sites. Right panel: location versus Hg. In both panels, the dashed line indicates the Hg TMDL target for protection of avian wildlife (SFBRWQCB 2006).

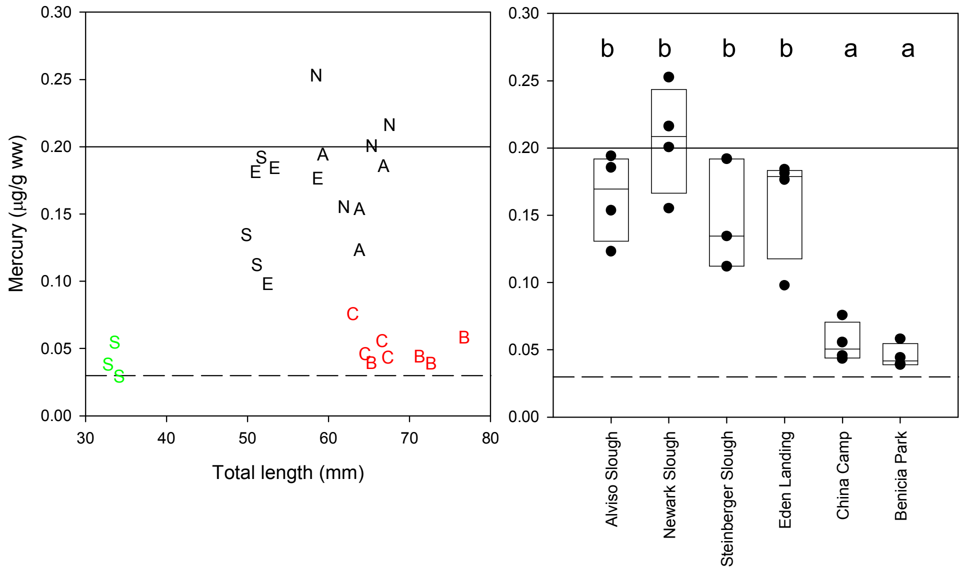

Figure 7. Mercury results for Mississippi silverside collected in 2005. Left panel: length versus Hg organized by station and general sampling location. A = Alviso Slough; N = Newark Slough; E = Eden Landing; B = Benicia Park; S = Steinberger Slough; C = China Camp. Symbol color: black symbols indicate South Bay sites (Eden Landing and south); red symbols indicate North Bay sites (China Camp and Benicia); green symbols indicate Steinberger Slough undersized fish excluded from Anova (3 of 6 composites; see text). Right panel: location versus Hg. Letters indicate results of Student-Newman-Keuls test; stations with different letters have significantly different Hg concentrations. In both panels, the dashed line indicates the Hg TMDL target for protection of avian wildlife (SFBRWQCB 2006) and the solid line indicates a threshold above which adverse effects to fish may occur (Beckvar *et al.* 2006).

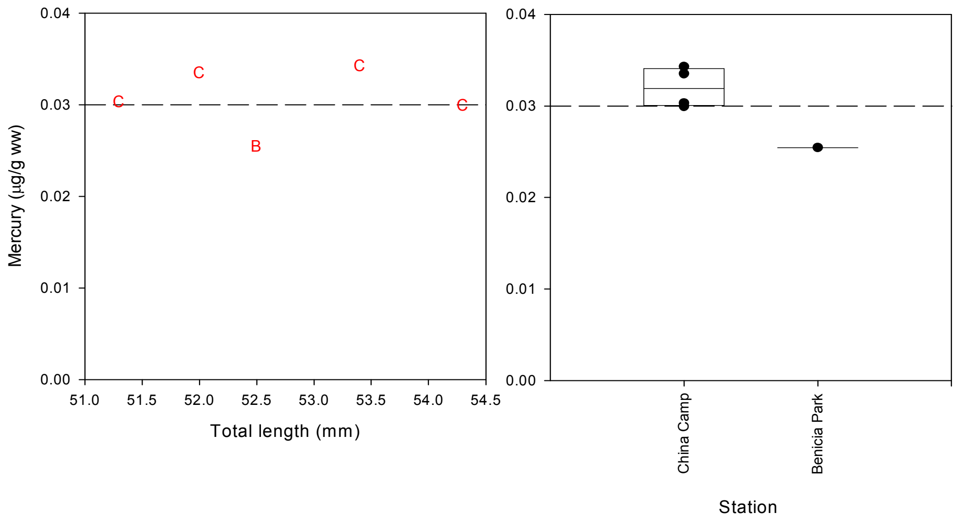

Figure 8. Mercury results for shimofuri goby collected in 2005. Left panel: length versus Hg organized by station and general sampling location. C = China Camp; B = Benicia Park. Symbol color indicates collection location, with red symbols indicating that all samples were collected in Central and North Bays. Right panel: location versus Hg. In both panels, the dashed line indicates the Hg TMDL target for protection of avian wildlife (SFBRWQCB 2006).

indistinguishable mercury concentrations among six sampling locations ($p = 0.13$, Table 2). For topsmelt, small sample size in some stations (N = 2 composites) may have reduced statistical power to detect spatial variation (Figure 6).

Discussion

This report presents the first-year sampling results from a multiple-year pilot study. Similar to other studies in the region (Slotton *et al.* 2002, Slotton *et al.* 2004), use of shoreline beach seining was successful for capturing several target fish species at multiple locations within the study area. Additionally, some significant spatial and taxonomic differences were observed, indicating that the overall sampling design had sufficient power to detect variation within the data set. Additional sampling is planned for 2006, 2007, and 2008. To help focus the sampling effort and interpretations in future years, a number of hypotheses may be made based on this first year of data. These preliminary hypotheses may require modification based on future findings from this and other studies.

A number of the tissue samples exceeded the TMDL threshold (SFBRWQCB 2006) for protection of California least tern (0.03 $\mu g\ g^{-1}$ wet-weight; Table 2), including several composites averaging < 50 mm total length (Figure 2). The mean concentration of all samples collected (0.049 $\mu g\ g^{-1}$) was also above the TMDL threshold. Least terns can consume fish up to about 9-15 mm in body depth, which roughly corresponds to topsmelt in the range of 60 - 97 mm total length (Atwood and Kelly 1984, Elliott *et al.* 2004, Elliott 2005, Zuria and Mellink 2005). Least terns are opportunistic piscivores (Elliott 2005), and are likely to include most of the species from this study in their diets. Data from this first sampling effort suggest a preliminary interpretation that the TMDL wildlife target may not be currently met at some of the sampling locations from this study. In order to better account for the influence of body size on this interpretation, it may be appropriate to composite samples according to body size, including a 30 – 50 mm size category corresponding with the TMDL targets (SFBRWQCB 2006).

Mercury in Biosentinel Fish

With this first year of data, two findings merit further discussion. First, Hg concentrations were higher in Mississippi silverside and lower in bay goby than other species monitored. Secondly, for one species (cheekspot goby), Alviso Slough had the highest Hg concentration, and for a second species (Mississippi silverside), Hg concentrations were higher at South Bay than at North Bay sites.

Differences among species

The differences in Hg among fish species likely resulted from a combination of body size and ecology. Body size explained about 25% of the overall variation in the data set, with the relatively small gobies (2-5 cm) significantly lower than the larger Mississippi silverside (4-8 cm). These smaller gobies likely consumed smaller prey, with lower trophic positions and lower MeHg. Nevertheless, body size did not explain all variation; topsmelt (6 – 10 cm), and bay goby from IEP sites 211, 214, and 243 (7.5 to 11 cm) were generally larger than silverside, but both species had significantly lower Hg than silverside (Figures 2, 3, 6, and 7).

The lower Hg concentrations in topsmelt and bay gobies than silverside may result from differences in habitat or diet. Adult topsmelt in estuarine environments have been found to consume a large proportion of macroalgae in their diets (Logothetis *et al.* 2001, Horn *et al.* 2006, Andy Jahn, unpublished data). It is possible that Bay topsmelt begin to exhibit herbivory by the end of their first summer. This would result in a lower trophic level and consequent reduction in mercury biomagnification. Regarding habitat, topsmelt move from shallows to Bay channels (Orsi 1999), and bay goby are generally restricted to higher salinity Bay channels (Orsi 1999, Goals Project 2000), where total Hg concentrations and methylation rates may be relatively low. Silversides are almost never encountered in offshore portions of San Francisco Bay or marine salinities; when encountered, they occur exclusively along Bay margins (Orsi 1999). In other regions, silversides have been shown to exhibit diel movement in freshwaters (Moyle 2002). Similarly, Mississippi silversides in San Francisco Bay margins may move upstream into the creeks and wetlands where they could be exposed to relatively high Hg and MeHg bioavailability.

The differences in spatial Hg variation among species may also be explained by known habits, distribution, and salinity preferences. Strong Hg variation among sites was not observed for topsmelt, which are expected to be a relatively mobile pelagic fish. In contrast, relatively sedentary cheekspot goby, and polyhaline (i.e., less saline habitat) Mississippi silverside exhibited significant variation among sites.

Figure 9 presents a preliminary conceptual model of how spatial variation and salinity tolerance may influence Hg concentration variability among species sampled. This conceptual model draws from similar models of habitat variation in southern California embayments (Allen 1982, Allen 1983), and life-history knowledge of the individual species (Moyle 2002). According to this conceptual model, Mississippi silverside and intertidal gobies (Table 1) reside in bay margins due to low salinity preference (silverside) or limited home range (arrow, cheekspot, and shimofuri goby). Sedentary

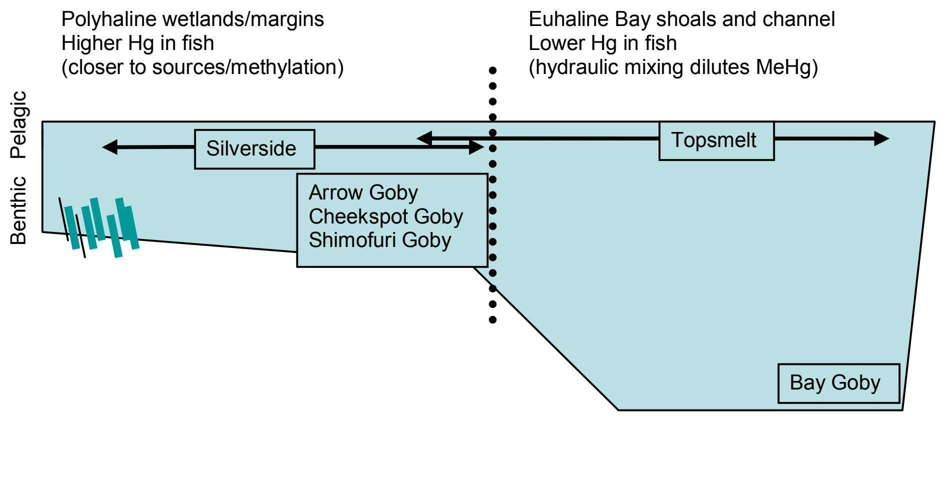

Figure 9. Conceptual model of spatial movement of fish, with respect to Hg sources and salinity. Higher total mercury loading and methylation occurs in the polyhaline wetlands, sloughs, and bay margins (left hand side) where Mississippi silverside may move upstream and forage. In the euhaline open waters of the bay (right-hand side), Hg is diluted by tidal mixing with marine waters, resulting in relatively low concentrations for bay goby and topsmelt (Figure 2).

behaviors among gobies include inhabiting burrows to avoid predation (arrow goby and cheekspot goby, Brothers 1975), and defending nests to protect offspring (shimofuri goby, Moyle 2002).

Spatial patterns

Our results suggest that silversides and some goby species may be useful indicators of site-specific information such as impact of proximity to anthropogenic mercury sources or higher methylation areas. This is consistent with Slotten *et al.* (2002, 2004), who focus on silversides as indicators of local Hg bioavailability in the Delta and its tributaries. Consideration of this site-specific information on bioavailable Hg is a potential improvement over the simplified one-box model currently used in the San Francisco Bay Mercury TMDL (SFBRWQCB 2006).

Findings in 2005 suggest that inclusion of multiple small fish species will provide both fine-scale and sub-embayment-level information on spatial variation in Hg bioavailability. Mississippi silverside and cheekspot goby are likely restricted to locations relatively close to the site of capture. In contrast, bay goby are believed to migrate from nursery areas and concentrate as adults in Central Bay (K. Hieb, pers. comm., Orsi 1999). Therefore, our trawl-captured samples are likely a mix of individuals coming from shoals in North, Central, and South Bays. Additional samples from the IEP trawling program should help identify spatial patterns in bay goby Hg.

A number of factors may drive the apparently higher Hg for Alviso slough cheekspot goby and South Bay Mississippi silverside. Alviso Slough carries water from the Guadalupe River, and some of the other South Bay sites (Newark Slough and Steinberger Slough) are relatively close to the Guadalupe River. Many studies indicate that the Guadalupe River is a source of total Hg to the Bay (Leatherbarrow *et al.* 2002, Thomas *et al.* 2002, McKee *et al.* 2005), with dissolved Hg concentrations in water generally elevated over other Bay locations (SFEI 2005). Largemouth bass (*Micropterus salmoides*) have higher tissue Hg concentrations in South Bay watershed reservoirs than other San Francisco Bay region reservoirs (SWAMP 2005), the Delta, Sacramento, or San Joaquin Rivers (Davis *et al.* 2003a).

Given current knowledge of Hg loading, the relatively low Hg concentrations in Mississippi silversides captured from China Camp and Benicia State Park was somewhat surprising. Mercury enters the North Bay via the Sacramento and San Joaquin Rivers (Leatherbarrow *et al.* 2005) and is present there as in-bay sediment deposits from historic mining operations (Hornberger *et al.* 1999). Possible explanations for the relatively low concentrations in Mississippi silverside at China Camp and Benicia Park include high exposure to open bay water, and consequent source dilution at the base of the food chain, or lower Hg methylation potential than at South Bay sites.

Sampling modifications and potential future studies

A purpose of this study is to provide standard protocols and initial data for developing a future small-fish monitoring program. Based on results from the first year, three sampling modifications are proposed:

A. **Replacement of Napa River Site.** Of the eight sites sampled, target species were not found at one site (Napa River). That site will therefore be dropped from the study. Napa River was originally selected as an indicator of potential changes resulting from the long-term wetland modifications in San Pablo Bay (Goals Project 1999). However, the CBDA Fish Mercury Project currently has an extensive monitoring network of biosentinel fish throughout San Pablo Bay-associated tributaries (Darell Slotton, pers. comm.). A suitable replacement site for Napa River could serve one of several possible functions: 1) further evaluate the hypothesis that tissue concentrations are higher in South Bay fish; 2) obtain additional data on prey Hg concentrations for California least tern; or 3) indicate impact of wetland restoration activity in a Suisun Bay location.
B. **Addition of size-stratified sampling.** The 2005 sampling design was intended to minimize size-Hg variation by restricting sizes of fish analyzed. Nevertheless,

results indicated significant effects of fish size on Hg for some species. To address this, while maintaining a relatively small number of analyses, an additional size category may be added for future analysis. In particular, for Mississippi silverside, shimofuri goby, bay goby, and topsmelt, fish could be specifically targeted from 30 to 50 mm, and from 50 to 80 mm. For other goby species, fish could be targeted from 20 to 35 and from 35 to 50 mm. Collection of a size category below 50 mm would also help to collect additional assessment data for the TMDL wildlife target (SFBRWQCB 2006). Given the difficulty fitting exact and overlapping size categories, sample collection will also focus on archiving composites from a range of sizes, with all samples selected for analysis after the field season is complete.

C. **Additional species.** The conceptual model presented in Figure 9 may be further evaluated by sampling additional species having known habitats and life histories. These could include diamond turbot (*Hypsopsetta guttulata*), a subtidal benthic species that was available at most sampling stations in 2005, and pelagic offshore species such as northern anchovy (*Engraulis mordax*) or Pacific herring (*Clupea harengus*).

Several potential additions to this study or new special studies may be proposed:

A. **Trace organics evaluation in small fish.** As with Hg, the Regional Water Board needs information on PCB and pesticide residues to fill a data gap on wildlife exposure for the TMDLs. The RMP Technical Review Committee has approved a budget augmentation to analyze 10 fish composites captured in 2007 for trace organic compounds.

B. **Expanded evaluation of spatial pattern.** The significant spatial variations observed suggest that the Mississippi silverside and cheekspot goby could be useful biomonitoring tools for identifying “hotspots” of Hg bioavailability in San Francisco Bay. This has been observed in other California waters by Slotton and colleagues (2002, 2004). In 2006, this study will have expanded spatial coverage, including 20 locations throughout South, Central, and San Pablo Bays.

C. **Evaluation of conceptual model.** The findings from this study combined with published and unpublished accounts about the biology of these species resulted in a hypothesized conceptual model for how local biology affects Hg bioaccumulation (Figure 9). This conceptual model could be tested with a special study that evaluates dietary variation (e.g., gut content and stable isotope analysis), vagility (mark recapture and stable isotope analysis), and gradients of contaminant vs. salinity for these forage fish species. Of particular interest are the life-history and dietary traits of silversides that may cause relatively elevated tissue Hg concentrations, compared to other small fish species.

The general success of 2005 sampling indicates that the study methodology was appropriate for using small fish as a long-term Hg monitoring tool. If this study were incorporated into RMP long-term status and trends monitoring, the biosentinel fish data would enable scientists to: 1) compare changes in Hg in time within and among sampling locations; 2) determine the success of the Hg TMDL in mitigating bioavailable Hg in the Estuary; and 3) evaluate the potential impact of regional wetland restoration activities.

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Appendix I. QA Results.

Table Ia. Summary results of quality-assurance analyses during determination of total mercury in samples of fish collected in 2005.

Material analyzed	Performance measure	Laboratory results	
		Batch 08-Feb-06	Batch 16-Feb-06
Aqueous standards to establish a standard curve by linear regression	Minimum of 5 non-blank standards and coefficient of determination ≥ 0.9990	7 non-blank standards; $R^2 = 0.9999$	9 non-blank standards; $R^2 = 1.0000$
Standard reference materials (triplicate subsamples of 2 standard reference materials)	Measured concentrations within the certified range	6 of 6 samples	6 of 6 samples
Fish tissue spiked before digestion (minimum of 10% of samples; subsamples spiked in triplicate with 35 to 80 ng Hg)	Percent recovery mean Range	 94.3% 89.7% - 99.6%	 93.7% 85.6% - 98.8%
Triplicate subsamples of fish (minimum of 10% of samples)	Method precision (coefficient of variation) mean Range	 5.0% 0.2% - 12.1%	 5.4% 4.0% - 10.2%
NIST mussel tissue	Limit of Quantification (μg g^{-1} dry-weight)		0.0097 μg g^{-1}

Table Ib. Results of analyses for total mercury of reference materials from the U.S. National Institute of Standards and Technology (NIST) and the National Research Council of Canada (NRCC). Reference materials were analyzed with samples of fish that were collected in 2005.

		Laboratory results	
		Mean concentration (95% confidence interval) ($ng\ g^{-1}$ dry-weight)	
Reference material	Certified concentration range ($ng\ g^{-1}$ dry-weight)	Batch 08-Feb-06	Batch 16-Feb-06
NIST mussel tissue	57.4-64.6	60.8 (60.2 – 61.3)	61.2 (59.4 – 62.3)

Appendix II. Raw data. NA = data not available. e = moisture data and subsequent wet-weight calculations estimated.

Date Collected	Sample ID	Station ID	Common Name	Scientific Name	Count	Mean Length (mm)	Composite Wet wt. (g) Field	Wet Wt Lab	Dry Wt Lab	Hg concn µg/g dw	%moisture	Hg concn µg/g ww
							g	g	g	µg/g dry	%	µg/g wet
10/18/2005	SF05-01-001	SF05-01-OMHEA	Arrow goby	*Clevelandia ios*	7	35.1	1.6	1.881	0.306	0.144	83.7%	0.023
10/18/2005	SF05-01-003	SF05-01-OMHEA	Arrow goby	*Clevelandia ios*	7	32.5	1.4	1.689	0.243	0.160	85.6%	0.023
10/18/2005	SF05-01-004	SF05-01-OMHEA	Arrow goby	*Clevelandia ios*	7	33.9	1.6	1.679	0.306	0.156	81.8%	0.028
10/18/2005	SF05-01-005	SF05-01-OMHEA	Arrow goby	*Clevelandia ios*	6	33.7	1.4	1.657	0.256	0.179	84.6%	0.028
10/27/2005	SF05-02-031	SF05-02-CHINA	Arrow goby	*Clevelandia ios*	2	25.0	NA	0.161	0.029	0.133	82.0%	0.024
10/27/2005	SF05-02-032	SF05-02-CHINA	Arrow goby	*Clevelandia ios*	2	25.0	NA	0.126	0.022	0.088	82.5%	0.015
10/27/2005	SF05-02-033	SF05-02-CHINA	Arrow goby	*Clevelandia ios*	2	23.0	NA	0.088	0.015	0.076	83.0%	0.013
11/7/2005	SF05-05-052	SF05-05-IEP212	Bay goby	*Lepidogobius lepidus*	8	27.8	1.3	0.801	0.098	0.041	87.8%	0.005
11/7/2005	SF05-05-053	SF05-05-IEP212	Bay goby	*Lepidogobius lepidus*	8	28.0	1.1	0.881	0.115	0.043	86.9%	0.006
11/7/2005	SF05-05-054	SF05-05-IEP212	Bay goby	*Lepidogobius lepidus*	8	26.4	1.4	0.720	0.086	0.048	88.1%	0.006
11/7/2005	SF05-05-055	SF05-05-IEP212	Bay goby	*Lepidogobius lepidus*	10	24.5	1.4	0.872	0.113	0.054	87.0%	0.007
11/8/2005	SF05-06-056	SF05-06-IEP106	Bay goby	*Lepidogobius lepidus*	10	27.6	1.2	1.080	0.106	0.059	90.2%	0.006
11/8/2005	SF05-06-057	SF05-06-IEP106	Bay goby	*Lepidogobius lepidus*	10	29.4	1.3	1.166	0.124	0.053	89.4%	0.006
11/8/2005	SF05-06-058	SF05-06-IEP106	Bay goby	*Lepidogobius lepidus*	9	29.0	1.2	1.073	0.100	0.043	90.7%	0.004
11/8/2005	SF05-06-059	SF05-06-IEP106	Bay goby	*Lepidogobius lepidus*	9	28.4	1.1	1.013	0.109	0.050	89.2%	0.005
12/14/2005	SF05-12-144	SF05-12-IEP211	Bay goby	*Lepidogobius lepidus*	7	76.4	12.1	13.026	2.022	0.142	84.5%	0.022
12/14/2005	SF05-12-145	SF05-12-IEP211	Bay goby	*Lepidogobius lepidus*	6	80.0	13.5	15.610	2.240	0.146	85.7%	0.021
12/14/2005	SF05-13-146	SF05-13-IEP243	Bay goby	*Lepidogobius lepidus*	6	94.3	21.5	24.621	3.477	0.146	85.9%	0.021
12/14/2005	SF05-13-147	SF05-13-IEP243	Bay goby	*Lepidogobius lepidus*	6	97.2	23.5	25.290	3.812	0.162	84.9%	0.024
12/14/2005	SF05-13-148	SF05-13-IEP243	Bay goby	*Lepidogobius lepidus*	6	94.8	21.8	25.020	3.509	0.176	86.0%	0.025
12/14/2005	SF05-13-149	SF05-13-IEP243	Bay goby	*Lepidogobius lepidus*	6	98.8	24.7	27.185	4.062	0.151	85.1%	0.023
12/14/2005	SF05-14-152	SF05-14-IEP214	Bay goby	*Lepidogobius lepidus*	5	98.0	19.3	20.588	3.073	0.199	85.1%	0.030
12/14/2005	SF05-14-153	SF05-14-IEP214	Bay goby	*Lepidogobius lepidus*	5	102.2	21.3	24.577	3.407	0.163	86.1%	0.023
12/14/2005	SF05-14-154	SF05-14-IEP214	Bay goby	*Lepidogobius lepidus*	5	101.8	21.1	23.330	3.492	0.181	85.0%	0.027
12/20/2005	SF05-15-156	SF05-15-IEP106	Bay goby	*Lepidogobius lepidus*	11	29.4	1.5	1.573	0.176	0.073	88.8%	0.008
12/20/2005	SF05-15-157	SF05-15-IEP106	Bay goby	*Lepidogobius lepidus*	10	28.2	1.4	1.157	0.121	0.052	89.5%	0.005
12/20/2005	SF05-16-158	SF05-15-IEP106	Bay goby	*Lepidogobius lepidus*	7	34.0	1.6	1.665	0.196	0.081	88.2%	0.010
11/2/2005	SF05-03-045	SF05-03-EDENL	Cheekspot goby	*Ilypnus gilberti*	10	32.7	0.8	1.699	0.274	0.141	83.9%	0.023
11/2/2005	SF05-03-046	SF05-03-EDENL	Cheekspot goby	*Ilypnus gilberti*	10	29.6	0.1	1.570	0.215	0.136	86.3%	0.019
11/2/2005	SF05-03-047	SF05-03-EDENL	Cheekspot goby	*Ilypnus gilberti*	10	30.3	0.5	1.848	0.262	0.133	85.8%	0.019
11/2/2005	SF05-03-048	SF05-03-EDENL	Cheekspot goby	*Ilypnus gilberti*	10	30.1	0.2	1.662	0.232	0.116	86.0%	0.016
11/10/2005	SF05-07-072	SF05-07-BIRDI	Cheekspot goby	*Ilypnus gilberti*	10	28.6	1.6	1.566	0.180	0.141	88.5%	0.016
11/10/2005	SF05-07-073	SF05-07-BIRDI	Cheekspot goby	*Ilypnus gilberti*	10	29.2	2.8	1.679	0.207	0.132	87.7%	0.016
11/10/2005	SF05-07-074	SF05-07-BIRDI	Cheekspot goby	*Ilypnus gilberti*	9	30.4	1.8	1.744	0.212	0.165	87.8%	0.020
11/10/2005	SF05-07-075	SF05-07-BIRDI	Cheekspot goby	*Ilypnus gilberti*	10	29.4	1.8	1.699	0.212	0.123	87.5%	0.015
11/14/2005	SF05-08-099	SF05-08-NEWSL	Cheekspot goby	*Ilypnus gilberti*	10	27.4	1.3	1.477	0.180	0.138	87.8%	0.017
11/14/2005	SF05-08-100	SF05-08-NEWSL	Cheekspot goby	*Ilypnus gilberti*	10	25.3	0.8	1.182	0.143	0.143	87.9%	0.017
11/14/2005	SF05-08-101	SF05-08-NEWSL	Cheekspot goby	*Ilypnus gilberti*	10	29.0	1.3	1.683	0.177	0.159	89.5%	0.017
11/14/2005	SF05-08-102	SF05-08-NEWSL	Cheekspot goby	*Ilypnus gilberti*	10	29.8	1.3	1.602	0.207	0.175	87.1%	0.023
11/15/2005	SF05-09-113	SF05-09-ALVSL	Cheekspot goby	*Ilypnus gilberti*	10	27.2	1.0	1.360	0.169	0.293	87.6%	0.036
11/15/2005	SF05-09-114	SF05-09-ALVSL	Cheekspot goby	*Ilypnus gilberti*	10	28.2	1.0	1.480	0.180	0.251	87.8%	0.031
11/15/2005	SF05-09-115	SF05-09-ALVSL	Cheekspot goby	*Ilypnus gilberti*	10	29.9	1.2	1.672	0.206	0.268	87.7%	0.033
11/15/2005	SF05-09-116	SF05-09-ALVSL	Cheekspot goby	*Ilypnus gilberti*	10	28.6	0.9	1.323	0.169	0.247	87.2%	0.032

Appendix II. Raw data (cont'd.). NA = data not available. e = moisture data and subsequent wet-weight calculations estimated.

Date Collected	SampleID	StationID	Common Name	Scientific Name	Count	Mean Length (mm)	Composite Wet wt. (g) Field	Wet Wt Lab	Dry Wt Lab	Hg concn µg/g dw	%moisture	Hg concn µg/g ww
							g	g	g	µg/g dry	%	µg/g wet
10/27/2005	SF05-02-023	SF05-02-CHINA	Mississippi silverside	*Menidia audens*	10	67.3	12.0	13.672	2.267	0.262	83.4%	0.043
10/27/2005	SF05-02-024	SF05-02-CHINA	Mississippi silverside	*Menidia audens*	10	66.6	12.0	12.914	2.330	0.308	82.0%	0.056
10/27/2005	SF05-02-025	SF05-02-CHINA	Mississippi silverside	*Menidia audens*	10	64.5	11.5	12.814	2.249	0.261	82.4%	0.046
10/27/2005	SF05-02-026	SF05-02-CHINA	Mississippi silverside	*Menidia audens*	10	63.0	11.0	11.468	2.082	0.417	81.8%	0.076
11/2/2005	SF05-03-064	SF05-03-EDENL	Mississippi silverside	*Menidia audens*	6	58.7	6.3	5.334	0.889	1.059	83.3%	0.176
11/2/2005	SF05-03-065	SF05-03-EDENL	Mississippi silverside	*Menidia audens*	6	53.3	5.5	4.792	0.819	1.077	82.9%	0.184
11/2/2005	SF05-03-066	SF05-03-EDENL	Mississippi silverside	*Menidia audens*	6	51.0	5.0	4.034	0.647	1.130	84.0%	0.181
11/2/2005	SF05-03-067	SF05-03-EDENL	Mississippi silverside	*Menidia audens*	6	52.5	4.5	3.958	0.624	0.621	84.2%	0.098
11/10/2005	SF05-07-083	SF05-07-BIRDI	Mississippi silverside	*Menidia audens*	7	49.9	4.1	3.565	0.588	0.816	83.5%	0.135
11/10/2005	SF05-07-084	SF05-07-BIRDI	Mississippi silverside	*Menidia audens*	7	51.7	4.7	4.738	0.774	1.175	83.7%	0.192
11/10/2005	SF05-07-085	SF05-07-BIRDI	Mississippi silverside	*Menidia audens*	6	51.2	3.9	4.003	0.646	0.695	83.9%	0.112
11/10/2005	SF05-07-086	SF05-07-BIRDI	Mississippi silverside	*Menidia audens*	6	34.2	1.2	0.963	0.135	0.207	86.0%	0.029
11/10/2005	SF05-07-087	SF05-07-BIRDI	Mississippi silverside	*Menidia audens*	5	33.6	1.2	1.054	0.149	0.385	85.9%	0.054
11/10/2005	SF05-07-088	SF05-07-BIRDI	Mississippi silverside	*Menidia audens*	5	32.8	1.2	0.980	0.134	0.277	86.3%	0.038
11/14/2005	SF05-08-091	SF05-08-NEWSL	Mississippi silverside	*Menidia audens*	10	58.5	9.5	9.137	1.602	1.440	82.5%	0.253
11/14/2005	SF05-08-092	SF05-08-NEWSL	Mississippi silverside	*Menidia audens*	9	67.6	12.6	12.440	2.391	1.125	80.8%	0.216
11/14/2005	SF05-08-093	SF05-08-NEWSL	Mississippi silverside	*Menidia audens*	9	65.3	11.5	11.987	2.151	1.118	82.1%	0.201
11/14/2005	SF05-08-094	SF05-08-NEWSL	Mississippi silverside	*Menidia audens*	10	61.9	12.0	12.225	2.196	0.864	82.0%	0.155
11/15/2005	SF05-09-107	SF05-09-ALVSL	Mississippi silverside	*Menidia audens*	10	63.8	11.6	12.178	2.153	0.697	82.3%	0.123
11/15/2005	SF05-09-108	SF05-09-ALVSL	Mississippi silverside	*Menidia audens*	10	66.8	14.2	14.577	2.546	1.062	82.5%	0.186
11/15/2005	SF05-09-109	SF05-09-ALVSL	Mississippi silverside	*Menidia audens*	10	59.3	10.2	10.228	1.832	1.084	82.1%	0.194
11/15/2005	SF05-09-110	SF05-09-ALVSL	Mississippi silverside	*Menidia audens*	10	63.8	12.0	12.411	2.201	0.866	82.3%	0.154
12/9/2005	SF05-11-125	SF05-11-BENPK	Mississippi silverside	*Menidia audens*	10	65.3	15.0	16.398	2.503	0.258	84.7%	0.039
12/9/2005	SF05-11-128	SF05-11-BENPK	Mississippi silverside	*Menidia audens*	9	72.7	16.0	16.521	2.920	0.220	82.3%	0.039
12/9/2005	SF05-11-129	SF05-11-BENPK	Mississippi silverside	*Menidia audens*	9	76.8	19.0	18.990	3.441	0.321	81.9%	0.058
12/9/2005	SF05-11-135	SF05-11-BENPK	Mississippi silverside	*Menidia audens*	9	71.2	16.0	15.711	2.797	0.248	82.2%	0.044
10/27/2005	SF05-02-035	SF05-02-CHINA	Shimofuri goby	*Tridentiger bifasciatus*	10	54.3	18.0	19.483	3.185	0.183	83.7%	0.030
10/27/2005	SF05-02-036	SF05-02-CHINA	Shimofuri goby	*Tridentiger bifasciatus*	10	52.0	14.0	15.304	2.607	0.197	83.0%	0.033
10/27/2005	SF05-02-037	SF05-02-CHINA	Shimofuri goby	*Tridentiger bifasciatus*	10	51.3	14.0	13.707	2.538	0.164	81.5%	0.030
10/27/2005	SF05-02-038	SF05-02-CHINA	Shimofuri goby	*Tridentiger bifasciatus*	10	53.4	18.0	16.553	3.262	0.174	80.3%	0.034
12/9/2005	SF05-11-127	SF05-11-BENPK	Shimofuri goby	*Tridentiger bifasciatus*	2	52.5	3.0	2.941	0.554	0.135	81.2%	0.025
10/18/2005	SF05-01-017-A	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	6	86.5	NA	27.850	6.670	0.120	76.1%	0.029
10/18/2005	SF05-01-017-EPA1	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	5	49.8	NA	3.380	0.440	0.165	87.0%	0.021
10/18/2005	SF05-01-018	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	6	82.4	34.0	35.751	7.922	0.152	77.8%	0.034
10/18/2005	SF05-01-019	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	6	79.3	32.0	33.514	7.615	0.110	77.3%	0.025
10/18/2005	SF05-01-020	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	6	83.7	37.0	38.219	8.905	0.120	76.7%	0.028
10/18/2005	SF05-01-021	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	5	83.2	37.0	38.553	8.695	0.105	77.4%	0.024
10/18/2005	SF05-01-022-EPA2	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	5	56.2	NA	NA	1.002	0.163	83.9% e	0.026 e
10/18/2005	SF05-01-022-EPA3	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	5	51.8	NA	NA	0.691	0.182	83.8% e	0.030 e
10/18/2005	SF05-01-022-EPA4	SF05-01-OMHEA	Topsmelt	*Atherinops affinis*	6	51.2	NA	NA	1.059	0.158	83.3% e	0.026 e
11/2/2005	SF05-03-061	SF05-03-EDENL	Topsmelt	*Atherinops affinis*	5	75.0	11.0	13.689	2.534	0.264	81.5%	0.049
11/2/2005	SF05-03-062	SF05-03-EDENL	Topsmelt	*Atherinops affinis*	5	33.6	1.5	0.888	0.110	0.205	87.6%	0.025
11/2/2005	SF05-03-063	SF05-03-EDENL	Topsmelt	*Atherinops affinis*	4	33.8	1.2	0.658	0.083	0.235	87.4%	0.030
11/10/2005	SF05-07-089	SF05-07-BIRDI	Topsmelt	*Atherinops affinis*	4	86.3	16.3	16.832	3.411	0.189	79.7%	0.038
11/10/2005	SF05-07-090	SF05-07-BIRDI	Topsmelt	*Atherinops affinis*	8	35.0	3.0	2.126	0.277	0.167	87.0%	0.022

Appendix II. Raw data (cont'd.). NA = data not available. e = moisture data and subsequent wet-weight calculations estimated.

Date Collected	SampleID	StationID	Common Name	Scientific Name	Count	Mean Length (mm)	Composite Wet wt. (g) Field	Wet Wt Lab	Dry Wt Lab	Hg concn µg/g dw	%moisture	Hg concn µg/g ww
							g	g	g	µg/g dry	%	µg/g wet
11/14/2005	SF05-08-095	SF05-08-NEWSL	Topsmelt	*Atherinops affinis*	5	65.2	9.1	8.696	1.508	0.292	82.7%	0.051
11/14/2005	SF05-08-096	SF05-08-NEWSL	Topsmelt	*Atherinops affinis*	5	58.0	5.5	5.348	0.876	0.149	83.6%	0.024
11/14/2005	SF05-08-105	SF05-08-NEWSL	Topsmelt	*Atherinops affinis*	5	46.6	2.8	2.596	0.449	0.168	82.7%	0.029
11/14/2005	SF05-08-106	SF05-08-NEWSL	Topsmelt	*Atherinops affinis*	5	48.2	3.1	3.051	0.442	0.186	85.5%	0.027
11/15/2005	SF05-09-112-A	SF05-09-ALVSL	Topsmelt	*Atherinops affinis*	3	101.0	NA	12.563	2.009	0.248	84.0%	0.040
11/15/2005	SF05-09-112-B	SF05-09-ALVSL	Topsmelt	*Atherinops affinis*	2	40.0	NA	0.132	0.025	0.304	81.1%	0.057
12/9/2005	SF05-11-126	SF05-11-BENPK	Topsmelt	*Atherinops affinis*	5	72.2	10.0	10.901	1.744	0.200	84.0%	0.032
12/9/2005	SF05-11-131	SF05-11-BENPK	Topsmelt	*Atherinops affinis*	5	78.4	15.0	15.483	2.780	0.159	82.0%	0.029
11/10/2005	SF05-07-076	SF05-07-BIRDI	Yellowfin goby	*Acanthogobius flavimanus*	1	35.0	NA	0.325	0.043	0.215	86.8%	0.028

Appendix III. GIS coordinates and ancillary site information for all sites.

Station ID	Date	Time in	Time out	Location	Gear	Water Temperature (C)	Salinity (psu)	Latitude (°N)	Longitude (°W)
SF05-01-OMHEA	10/18/2005	8:32	13:00	Oakland Middle Harbor	25' beach seine	16.1	32	37.8021	122.3241
SF05-02-CHINA	10/27/2005	11:00	16:00	China Camp	25' beach seine	14.7	26	38.0143	122.4898
SF05-03-EDENL	11/2/2005	12:30	17:00	Eden Landing (Old Alameda Ck.)	25' beach seine	14.4	28.7	37.5936	122.1460
SF05-07-BIRDI	11/10/2005	10:50	15:10	Bird Island/Steinberger Slough	25' beach seine	17.4	28.5	37.5444	122.2263
SF05-08-NEWSL	11/14/2005	11:40	16:20	Newark Slough	25' beach seine	16.2	26.8	37.5083	122.0864
SF05-09-ALVSL	11/15/2005	12:48	17:30	Alviso Slough	25' beach seine	15.8	22.6	37.4595	122.0200
SF05-10-NANOR	12/8/2005	12:00	16:30	Napa River (Catalina Circle)	25' beach seine	Site 1: 11.3, Site 2: 13.1	Site 1: 15.7 Site 2: 26	38.1537	122.2849
SF05-11-BENPK	12/9/2005	10:45	16:35	Benicia State Park	25' beach seine	11.13	10.6 psu, 18.3 mS/cm	38.0639	122.1929
SF05-06-IEP106	11/8/2005	NA	13:00	IEP Study Site 106. South San Francisco Bay. Shoal SE of Candlestick Point.	Otter trawl	15.8	30.2	37.6952	122.3723
SF05-15-IEP106	12/20/2005	NA	13:00	IEP Study Site 106. South San Francisco Bay. Shoal SE of Candlestick Point.	Otter trawl	11.9	29.1	37.6913	122.3714
SF05-12-IEP211	12/14/2005	NA	12:00	IEP Study Site 211. San Francisco Bay, Shoal 1 km N of Treasure Island	Otter trawl	11.6	30.87	37.8357	122.3840
SF05-05-IEP212	11/7/2005	NA	12:30	IEP Study Site 212. San Francisco Bay, Shoal 3.5 km W of Berkeley Harbor	Otter trawl	14.8	29.98	37.8619	122.3461
SF05-14-IEP214	12/14/2005	NA	12:00	IEP Study Site 214. San Francisco Bay, Channel 1.5 km E of Angel Island	Otter trawl	11.6	31.43	37.8663	122.3999
SF05-13-IEP243	12/14/2005	NA	12:00	IEP Study Site 243. San Francisco Bay, Shoal E of Southhampton Shoal	Otter trawl	11.6	31.19	37.8864	122.4012