GOLD MINING IMPACTS ON FOOD CHAIN MERCURY IN NORTHWESTERN SIERRA NEVADA STREAMS

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TECHNICAL COMPLETION REPORT

Project Number: W-816

August 1995

University of California Water Resources Center

The research leading to this report was supported by the University of California, Water Resources Center, as part of Water Resources Center Project UCAL-WRC-W-816

ABSTRACT

More than three million kilograms of mercury are estimated to have been lost into northwestern Sierra Nevada rivers during the course of gold mining in the Gold Rush period of the last century (1840s - 1880s). Mercury was used extensively in the gold recovery process to amalgamate fine gold particles. Gold mining has continued at a less intensive scale through the present, with a relative resurgence of dredging operations during the past decade. In this study, we investigated mercury levels in aquatic invertebrates and trout in the rivers of this region of the Sierra Nevada to determine the localized impacts of mining-derived mercury. These organisms were used as indicators of the bioavailable fraction of mercury, specifically that portion which can enter, transfer through, and be concentrated by the food web. The biota samples were used to determine relative "hot spots" of mercury contamination and to rank the various streams and rivers as to relative bioavailable mercury levels. Trout mercury was also investigated from a health perspective, to determine whether historic or current mining represented a human health concern.

Thirty-five sites were sampled throughout the region during a two year period. A clear signature of mining-derived mercury was found, with notably elevated levels in the aquatic food webs of the upper forks of the Yuba River, the Middle Fork of the Feather River, the Bear River, and the North Fork of the Cosumnes River. Mercury was low throughout most of the American River watershed and in many tributaries away from the most intensively mined stretches of the various rivers. Areas appropriate for potential mitigation work are being further defined in ongoing work. Mercury concentrations in trout, while variable, were found to be uniformly below existing health standards, indicating the lack of direct health concerns within the region itself. Foothill reservoirs were found to operate as interceptors of mercury, with significantly lower levels found in biota below many reservoirs, as compared to upstream. Mercury concentrations in aquatic organisms increased in a predictable pattern with increasing trophic feeding level. Mercury in aquatic invertebrates can be used to determine relative mercury presence and bioavailability, to predict mercury levels in trout, and to integrate localized mercury conditions over the lifetime of the respective organisms. Because of the strong relationship with trophic feeding level, relative mercury concentrations may also be used to indicate the ecological feeding niche of individual organisms.

KEYWORDS : mercury, gold, mining, trout, invertebrates, uptake, food chain, contamination, streams, California

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ACKNOWLEDGEMENTS

We are grateful to the many agency personnel who were generous with their time and conversation and who helped direct our site selection process in the early part of the project. We also appreciate being provided access to several otherwise difficult to reach sites. In particular, we thank staff of: the Foresthill Ranger District in the American River Watershed, the North Yuba Ranger Station in the Yuba River Watershed, various stations in the Feather River Area, the Yuba Water Agency, the University of California Agricultural Field Station at the lower Yuba River, the Central Valley Region Regional Water Quality Control Board, and the California Department of Fish and Game. The State Toxic Substances Monitoring Program provided much parallel and related data and, in large part, forms the basis for this work. Special thanks go to our colleague, Dr. Michael Brett, who played an important role in the development of this project and who provided helpful suggestions throughout the data reduction and interpretation process.

INTRODUCTION: PROBLEM AND RESEARCH OBJECTIVES

Mercury pollution of aquatic systems is a major concern of researchers and regulatory agencies on both a regional and global scale. In its methylated form, mercury is readily concentrated and transferred through aquatic food chains, where it can become a significant neurological toxicant to higher trophic level consumers, including man. The primary pathway into humans is fish consumption. Much of the current mercury research is focused on the pervasive problem associated with low level atmospheric deposition of industrially-derived mercury across wide areas which have low pH and poorly buffered surface waters. In these regions, mercury can accumulate to dangerous levels in fish with even trace level inputs (e.g. the Northeast United States, Southeast Canada, Scandinavia and much of Western Europe). While the high alkalinity waters of the western U.S. render atmospheric sources of mercury relatively insignificant, California has historically been impacted by large-scale bulk contamination of mercury. This has been the result of extensive mercury mining in the Coast Range of Central California, the use of very large amounts of mercury in Sierra Nevada streams and rivers for gold mining, and the subsequent movement of mercury from both of these areas into downstream rivers and lakes, foothill reservoirs, and ultimately the Delta/Bay ecosystem. In this work, we investigated regional patterns of mercury accumulation in aquatic biota collected in the historic and current gold mining region of the northwestern Sierra Nevada. While some attention has been devoted to mercury accumulation in downstream sinks, little or no research has focused on probable upstream source regions associated with current and, primarily, historic use of mercury for gold mining. It has been estimated that over 3 million kilograms of mercury were lost into Sierra Nevada streams in the course of the California Gold Rush (CVRWQCB 1987).

Previous sampling efforts in these streams, as part of the State's Toxic Substances Monitoring Program (TSMP), have been limited and most of this was done prior to the 1986 floods and the resurgence of small scale mining. Indeed, much of the routine sampling for the TSMP program is conducted on the lower reaches of the stem rivers and in foothill reservoirs. Mining, on the other hand, is concentrated along mid-elevation stretches of northern Sierra Nevada rivers, namely the forks of the upper Feather, Yuba, and American Rivers, the Bear River, Rubicon River, Cosumnes River, and the Mokelumne River. These rivers have been sampled sporadically by the Toxic Substances Monitoring Program (TSMP 1990, 1991, 1992). However, site selection and the species composition of the fish collected indicates that this work was generally carried out in regions well downstream of the reaches where gold mining is prevalent. We feel our data constitutes a valuable contribution to the Program's data base and its objective of identifying human health risks and major sources of toxic substances.

Small scale mining, suction dredging and panning for gold in the northwest region of the Sierra Nevada mountains has increased markedly during the last ten years. This is in part attributable to the recent series of flood runoff years in 1986, 1993, and 1995, which impacted the channel of many rivers in this region and, in the process, exposed new gold. These high flows also exposed and mobilized old mercury. Additionally, current mining activity could potentially introduce additional mercury to the streams as well as disrupt formerly buried historic mercury. This project addresses the status of mercury contamination in Sierra Nevada gold mining streams, both in terms of on-site biotic mercury accumulation and as potentially ongoing sources of mercury contamination to downstream regions. The primary objectives of the project have been to:

- Determine levels of mercury in stream biota within the region most impacted by historic and current gold mining and demonstrate whether there is significant localized uptake of mercury into the stream food web in the vicinity of major historic and current mining operations.
- Produce data which will help to assess the importance of this region as an ongoing source of mercury to downstream rivers and reservoirs, and rank upstream tributaries in terms of mercury bioavailability.
- Determine whether a human or environmental health hazard exists in relation to trout mercury concentrations in the project area.
- Supplement mercury information collected from other areas of the state.

We believe that all of these objectives were achieved in this work, together with a number of other important scientific findings.

We chose mid-elevation sampling sites from among the main Sierra Nevada gold-mining rivers (figure 1, table 1). During the two years of this project (July 1993 - June 1995), we focused on the region between the Feather River watershed and the American River watershed, including the forks of the upper Feather, Yuba, Bear, and American Rivers. Special attention was given to those areas with high densities of active mining claims. These locations were determined by communication with agency and other personnel familiar with given stretches of river, and through our own reconnaissance. We quickly determined that mercury distribution was very widespread throughout this region and the most effective sampling approach was to, as extensively as possible, sample throughout these rivers and their major tributaries. Where possible, samples were collected at or just below actively mined stretches of river, as well as at control sites upstream and/or along unmined stretches.

In this research, we utilized exclusively biotic samples. In-stream aquatic insect species were sampled as bioindicators of relative mercury bioavailability at each of the sites and as surrogates for fish, which were not available at many of the sites. The invertebrate mercury data also provided information on the transfer of mercury through the stream food web. Fish were of interest for their specific mercury concentrations, from a health perspective, as well as also being indicators of relative mercury availability. We chose rainbow trout as one focus of the survey because this species is the dominant vertebrate in many of these rivers, and because mercury bioaccumulation in this species represents perhaps the main vector of human exposure to mercury in this region. Other fish were sampled when appropriate and possible.

Sampled trout were generally representative of individuals taken by fishermen. While a range of sizes and ages were taken, the focus was on three year olds, typically 9-12 inches in length. Trout of this size class dominate angling catches, are the major contributors to in-stream reproductive success of this species, and are the group most heavily relied upon by the Department of Fish and Game in both research and policy making (Harry Rectenwald, Calif. Dept. of Fish and Game, personal communication). Stream aquatic insects were taken from a variety of trophic levels whenever possible, as described below in the methodology section.

This research, supported by the Water Resources Center, has functioned as an effective seed project, and has helped us to expand our ongoing investigations of aquatic mercury in California to include studies which (1) focus on mercury "hot spots" located by this study and investigate the extent of their downstream influences, (2) investigate additional sites within the region and ultimately to the south of Sacramento and in the Coast Range, (3) investigate the mode of mercury uptake into the food chain, (4) link biotic mercury accumulation to aqueous mercury speciation, and (5) investigate potential mitigation strategies to reduce mercury loading to Sierra Nevada rivers and ultimately the Sacramento River, the Sacramento/San Joaquin Delta, and San Francisco Bay .

TABLE 1.

U.C. Davis Sierra Nevada Gold Region Biotic Mercury Sites

FEATHER RIVER DRAINAGE

1. North Fork Feather River at Belden. (10/26/94)
2. Yellow Creek (tributary to N Fk Feather R), 2 miles above confluence. (6/11/94)
3. Caribou Branch of North Fork Feather River, 4 miles above confluence. (10/27/94)
4. East Branch of North Fork Feather River, 10 miles above confluence with Caribou Branch. (10/26/94)
5. Indian Creek, tributary to E Branch N Fk Feather River, 7 miles above confluence. (9/27/94)
6. Spanish Creek, tributary to E Branch N Fk Feather River, 2 miles above confluence. (8/26/94)
7. Middle Fork Feather River, 1 mile below Nelson Creek. (9/22/94)
8. Nelson Creek, tributary to Middle Fork Feather River, 1 mile above confluence. (9/21/94)
9. Upper Middle Fork Feather River, 3 miles upstream of Clio. (9/23/94)

YUBA RIVER DRAINAGE

10. Lower Yuba River below Englebright Reservoir, at University of California field station. (12/16/93)
11. North Fork Yuba River constrained (low) flow below New Bullard's Bar Reservoir. (3/15/94)
12. North Fork Yuba River, 2 miles downstream of westmost Highway 49 crossing. (11/5/93)
13. Canyon Creek, tributary to N Fk Yuba, just above confluence. (11/6/93)
14. Downie River, tributary to N Fk Yuba, at Downieville. (11/2/93)
15. Middle Fork Yuba River, just upstream of Oregon Creek and Highway 49 crossing. (10/21/93)
16. Middle Fork Yuba River, 1 mile upstream of Tyler Foote crossing and Kanaka Ck. 10/19/93)
17. Middle Fork Yuba River, 1 mile upstream of Plumbago Road. (3/24/94)
18. South Fork Yuba River 1 mile downstream of Washington. (11/12/93)
19. Deer Creek below Lake Wildwood, at Mooney Flat Road. (12/9/94)
20. Deer Creek at Bittney Spring Road. (12/9/94)

(continued)

TABLE 1. *(continued)*

BEAR RIVER DRAINAGE

21. Bear River below Camp Far West Reservoir. (12/9/94)
22. Bear River at Highway 49 crossing. (12/9/94)
23. Wolf Creek, tributary to Bear River, 2 miles above confluence. (12/9/94)

AMERICAN RIVER DRAINAGE

24. Lower American River at Howe Avenue. (12/16/94)
25. Lower American River 1 mile below Lake Natoma. (12/16/94)
26. North Fork American River in vicinity of Humbug Bar. (11/19/93)
27. Middle Fork American River below Oxbow Reservoir. (2/25/94)
28. North Fork of the Middle Fork American River, 1 mile above confluence. (3/2/94)
29. Rubicon River, tributary to Middle Fork American River, just above confluence. (2/1/94)
30. Middle Fork American River at "End of the World". (2/1/94)
31. Duncan Creek, tributary to Middle Fork American River, 3 miles above confluence. (11/16/93)
32. South Fork American River above Folsom Lake. (12/16/94)
33. South Fork American River below Slab Creek Reservoir. (12/20/93)
34. South Fork American River 1 mile upstream of Pacific. (4/11/94)

COSUMNES RIVER DRAINAGE

35. North Fork Cosumnes River at Mt Aukum Rd. (12/20/93)

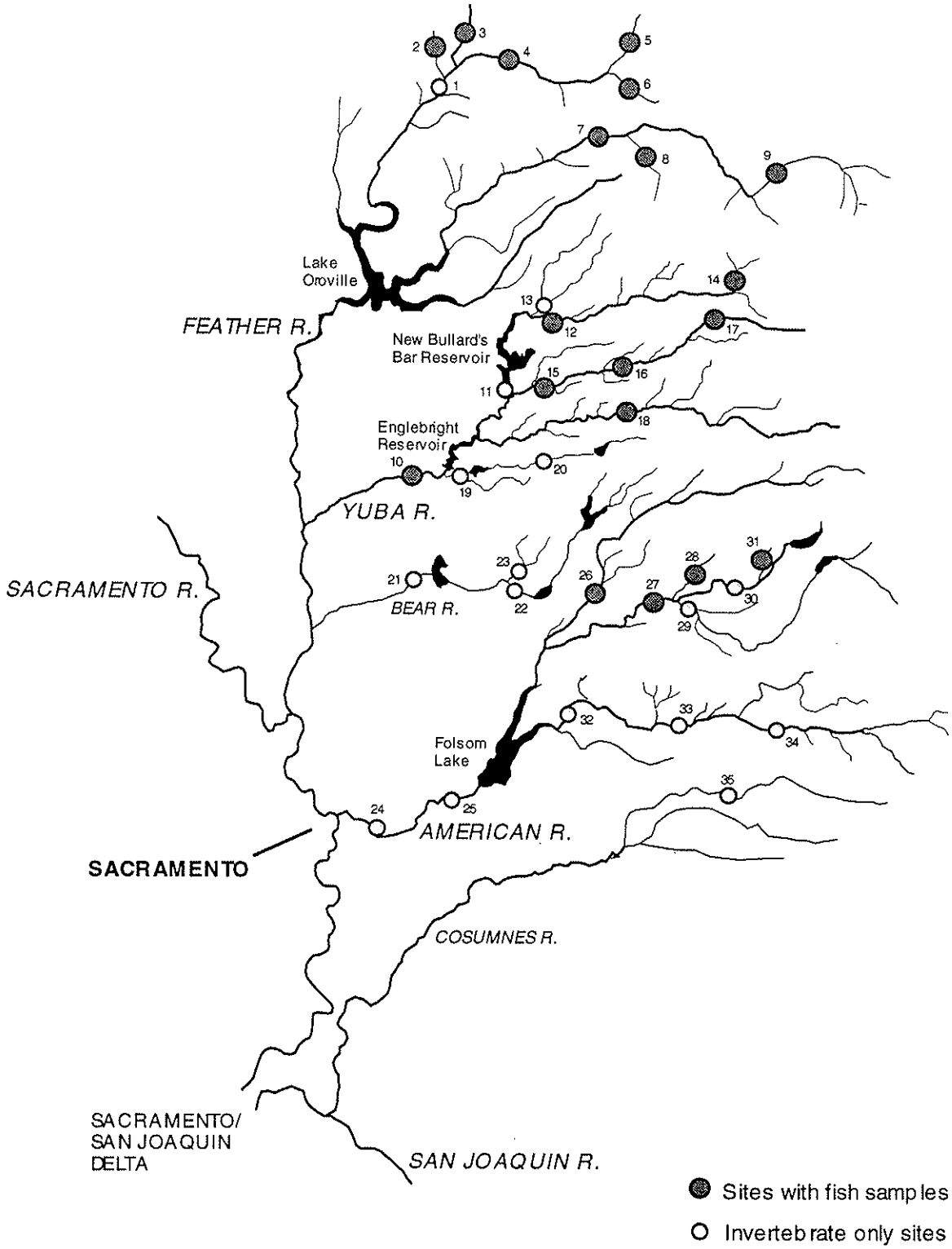


Fig. 1. Sampling Sites Used in Water Resources Center Mercury Project

METHODOLOGY

Site Selection

Sampling sites were chosen by a variety of methods. Likely high mercury regions were determined through conversations with employees of the Forest Service, California Department of Fish and Game, regional Water Quality Control Boards, and other agencies, as well as through our own reconnaissance and conversations with miners. Additional sites were chosen upstream and downstream of intensively mined stretches. Additional major tributaries were sampled as possible. Tributaries were sampled for trout ≥ 1 mile upstream of their confluences with main rivers, in order to guard against migration from downstream. Stream invertebrates could be effectively sampled closer to the confluence and remain representative of the given tributary.

Collection Techniques

Stream invertebrates were taken from riffle habitat at each of the sites, i.e. from rapids or cobble bottomed stretches with maximal flow, where aquatic insects tend to be most concentrated among the rock interstices. Felt-soled boots were used to permit effective movement in this habitat. Neoprene waders were used when water temperatures were below ~12 °C. Stream invertebrates were collected primarily with the use of a kick screen. Screens were constructed with a 1 m x 1.6 m section of heavy duty stainless steel screening which was fastened securely to 4 cm x 1.2 m wooden dowels at both sides with brass wire. A 1.5 mm mesh size was used, trapping invertebrates thicker than this in cross section. One researcher spread and positioned the screen perpendicular to the flow, bracing the side dowels against the bottom, while the other researcher overturned boulders and cobble directly upstream of the screen. These rocks were hand scrubbed into the flow, dislodging any clinging biota. Following the removal of the larger rocks to the side of the stretch, the underlying cobble/pebble/gravel substrate was disrupted by shuffling the boots repeatedly. Invertebrates were washed into the screen by the current. The screen was then lifted out of the current and taken to the shore, where teflon coated forceps were used to pick macro-invertebrates from the screen into jars with teflon-lined caps. This process was repeated until a sufficient sample size of each taxon of interest was accumulated to permit future analysis for mercury. Whenever possible, we attempted to collect consistent samples from the following four invertebrate trophic levels: herbivores, net collectors, small-item predators, and top insect predators. When present, we took Pteronarcyid stonefly nymphs or a variety of mayfly nymphs for the herbivore trophic level and Hydropsychid caddisfly nymphs for the net collector group. Medium to large Perlid stoneflies (either *Callineuria* or *Hesperoperla*) were taken wherever

possible to represent the small-item predator insects, while hellgrammites (*Corydalus*) were the preferred top predator stream insect.

Several fish collection techniques were investigated initially, including gill netting, electroshocking, and angling. We quickly determined that angling was the most effective method for taking a cross section of trout sizes from clear, fast moving Sierra foothill rivers and streams. To guard against potentially taking seasonal migrant fish from downstream reservoirs, fish sampling was largely confined to the months of August through December. Stocked individuals were rarely taken and were easily differentiated from native fish by their characteristic fused and bent fin rays. We sampled exclusively native fish for mercury content, with the emphasis on rainbow trout. The attempt was made to collect trout across a range of sizes and ages at each site, permitting the construction of site-specific fish size vs mercury regressions. These relationships were used to normalize trout mercury content at each site to a standard, inter-comparable size of trout. We chose a standard size of 250 g for normalization. This size was typical of 2-3 year old, 9-12 inch long trout which represent the majority of "keeper" fish taken by the angling public. Fish were weighed and measured in the field. At sites where stomach contents were assessed, this was also done in the field. Stomach contents were obtained with a stainless steel scalpel and were removed to an acid-cleaned jar with teflon-lined cap. Items were identified and assessed percent volumes, following standard fisheries sampling protocol.

Sample Preparatory Techniques

Stream insects were analyzed for mercury in homogenized composite samples of multiple whole individuals. Typically, ≥ 10 individuals were composited for each of the trophic levels through small-item predators (stoneflies), and 2-5 individuals of the top predator insect group such as hellgrammites, based on availability. Samples were pooled by taxa into separate jars. The insects were maintained live on ice. Within 24 hours of collection, the contents of each jar were carefully cleaned and sorted. This was accomplished by resuspending the jar contents in a tray of clean water and, with teflon-coated forceps, individually rinsing and shaking each individual insect in the clean water to remove any extraneous material. Insects were keyed to at least the family level, using a variety of aquatic insect texts and manuals. Trophic feeding category of organisms was determined based on the recommendations of Merrit and Cummins (1984). In uncertain cases, the magnified examination of mouthparts was used to help make this determination. Cleaned insects were placed in well rinsed jars and frozen. At the onset of sample analysis, the jar contents were dried at 50-60 °C for 24 hours and then ground with teflon coated instruments or glass mortar and pestle to a homogeneous powder. The resulting powder was dried a second time to constant weight before analytical sub-samples were taken for digestion. All aquatic insect

mercury analytical work was performed with dry powdered sample, both to ensure homogeneity of sample and to enhance mercury detection capacity. Percent moisture was determined on homogenized wet samples from several replicates of each major group, to permit the conversion between wet and dry concentrations.

In contrast to the dry, composite sample insect work, fish mercury was analyzed primarily in muscle tissue on a fresh (wet) weight basis, in accordance with standard practices which focus on the potential health risks of consuming mercury in fillet meat (TSMP 1990). Muscle samples were taken from fresh fish at streamside. Fish muscle was sampled from the dorso-lateral (shoulder) region utilized by the California Department of Fish and Game. For each individual fish, the skin over the region was pulled back before the sample was taken with a stainless steel scalpel. Samples of approximately 0.20 g were rolled lightly over a laboratory tissue paper to remove extraneous surface moisture and then carefully placed into pre-weighed, acid-washed digestion tubes with teflon-lined caps. The precise weight of each muscle sample was later determined by re-weighing the digestion tubes with samples, together with empty "blank" tubes, on a balance accurate to 0.001 g. This direct sub-sampling technique reflects fresh weight muscle (fillet) mercury concentrations, without introducing potential sources of error associated with homogenization techniques. We have found mercury concentration to be extremely uniform throughout the dorso-lateral region of muscle (Slotton 1991). Thus, direct sub-sampling accurately reflects overall muscle mercury concentration. For cases where liver mercury was also measured, identical procedures were followed. Wet/dry conversions were calculated for trout fillet tissue by determining percent moisture from 10 fillet samples from different fish. These were very similar and the mean value (78.2% ± 1.9%) was used to convert analyzed fresh weight parts per million mercury to a dry weight basis, for direct comparison with the invertebrate dry weight values.

Analytical Methodology

Mercury analytical methodology followed the protocols developed at U.C. Davis (Slotton 1991) and summarized in Slotton et al. (1995). The method combines features of a number of previous techniques, and is notable for allowing excellent reproducibility, low detection levels, high numbers of samples per batch and thus room for high numbers of QA/QC samples, and the ability to re-analyze digests.

The method can be summarized as follows: digestion is performed in teflon-capped pyrex test tubes in a two stage process. Environmental samples are broken down in a 2:1 mixture of concentrated sulfuric acid to concentrated nitric acid, the digest mixture found to be most effective in a comparative study (Sadiq and Zaidi 1983). This first stage utilizes a temperature of 90-100 °C

and pressure (sealed tubes) for 1.5 hrs, resulting in clear solutions. In the second stage, also 1.5 hrs, potassium permanganate is added for additional oxidation and digest stabilization. This portion of the digest procedure is performed at 80-95 °C with the tubes refluxing, uncapped. The resulting digests can be diluted or not, depending on the mercury concentrations and required level of detection, and are stable indefinitely, both before and following detection. Detection utilizes typical cold vapor atomic absorption techniques with a mercury lamp of 253.7 nm wavelength. The method differs from standard flow-through systems which reduce the entire digest in a one-time detection. A long path length, minimum volume gas cuvette and holder have been manufactured for positioning in the beam path and a specialized injection port allows direct introduction of reduced mercury in vapor. Reduction of digest mercury is performed inside a 12 cc calibrated syringe on a 2.0 cc aliquot of digest together with 2.0 cc of stannous chloride/hydroxylamine sulfate/sodium chloride reductant. A 6.00 cc airspace is utilized for partitioning of the volatile reduced mercury within the syringe and, after partitioning is complete, this airspace is injected directly into the low volume cuvette mounted in the beam path for detection. The amount of digest and, thus, proportion of sample detected is accurately determined through difference, with the digest tubes weighed to ± 0.001 g both before and immediately after removal of the analytical aliquot. Weight of total digest is initially determined by weighing the empty tube and then the full tube of digest. Level of detection was approximately 0.01 mg kg^{-1} (ppm).

QA/QC was quite extensive, with approximately 16 of the 40 tubes in each run dedicated to this purpose. QA/QC samples in each run included an extensive set of aqueous mercury standards, a minimum of 3 certified reference material samples in an appropriate matrix, duplicates, and spike recovery samples. QA/QC samples passed through all phases of the digest and were treated identically to analytical samples. Replication was typically ≤ 5% difference between duplicates, recoveries of certified reference materials were uniformly within 20% of certified values, spike recoveries were within 15% of predicted concentrations, and standard curves generally had R^2 values in excess of 0.98.

Fish Data Reduction

In order to reduce the fish muscle mercury concentration data to a single, inter-comparable number for each site, we developed trout size vs mercury concentration curves for the fish taken at each location. Data for fish weights and corresponding mercury concentrations were plotted for each sample set. Based on a visual line of best fit, a graphic relationship between trout size and mercury concentration was estimated for each site. This approach was taken for the following reasons: (1) obvious outlier individuals could be omitted when they were clearly of different origin

than the rest of the fish in a set, typically due to recent migration from an adjoining stream with different mercury bioavailability, (2) fish size vs mercury concentration relations often follow a curvilinear rather than straight line function, and (3) standard polynomial function curve fitting routines tend to wrap the upper portion of these mercury curves, unnaturally, back down toward zero, rather than following the asymptotic, steadily increasing function typical in actual fish vs mercury relations. However, a straight line could generally be fitted to the trout data of most sample sets, within the range of sizes utilized. Examples of this normalization approach are presented in Appendix A.

RESULTS

In the two years of this study, we were able to sample aquatic biota at a total of 35 different stream and river sites throughout the Sierra Nevada foothill gold region (figure 1, table 1). Sampling was generally constrained to the months of September through February for a variety of reasons, including (1) prohibitively high flow in late winter through early summer and (2) frequently low invertebrate biomass at other times of year. In 1993, we focused our sampling efforts on tributaries of the Yuba and American River watersheds, while in the second year of the project we worked mainly in the Feather River, Bear River, and Deer Creek drainages. In table 2, biota mercury data for all sites are displayed both numerically and graphically, on a dry weight basis. The mercury data are also displayed on a regional map, with all main trophic levels superimposed in figure 2 and individual trophic categories displayed together with associated mercury data in figures 3-7.

Trout

Trout were sampled in sufficient numbers for statistical analysis at nineteen locations, with a total of 124 fish collected and analyzed for fillet muscle mercury. This included 116 native rainbow trout, 5 small brown trout, 1 large brown trout, and 2 mid-sized squawfish. Data for individual fish are presented in table 3 and are displayed on a regional basis in figure 7. On a wet weight (fresh) basis, normalized fillet muscle mercury concentrations in 250 g trout varied between 0.03 mg kg^{-1} (ppm) and 0.21 mg kg^{-1}. The normalized values represent the synthesis of data from 4-13 fish from each site. Trout from all sites demonstrated a generally positive size vs mercury concentration relationship, with largest fish typically having the highest concentrations. Highest trout mercury was found at sites along the Middle and South Forks of the Yuba River, and the Middle Fork of the Feather River. These sites were among those noted in the course of the study as having the greatest current mining activity. They also include some of the historically most

intensively mined regions. Low mercury concentrations ($\leq$ 0.06 mg kg^{-1}, normalized) were found in trout from many tributaries of the Feather and American rivers, as well as upstream of the major mining activity along the Middle Fork of the Yuba River. Fish from the North Fork of the Middle Fork of the American River (Station # 28) and Spanish Creek (Station # 6), a tributary to the North Fork Feather River, were relatively higher in mercury as compared to other sites in their watersheds. When converted to units of dry weight parts per million, the 250 g normalized trout mercury concentrations of this study range from a low of 0.14 mg kg^{-1} to a high of 0.94 mg kg^{-1}. These data are used in table 2 for comparison with the invertebrate data, which are on a dry weight basis.

Several collections of piscivorous squawfish and adult brown trout were made during the course of the study. Being largely fish eaters, these species feed at a higher trophic level, as compared to mid-sized rainbow trout which feed primarily on a mix of aquatic and terrestrial insects. The piscivorous fish contained significantly higher concentrations of mercury than rainbow trout from the same locations (table 3). At the Middle Fork Yuba River site near Oregon Creek, squawfish contained 0.41 mg kg^{-1} muscle mercury in same sized fish, as compared to rainbow trout which had 0.19 mg kg^{-1} (both on a wet weight basis). At the Middle Fork American River Site below Oxbow Reservoir, a large (965 g) brown trout was taken which had muscle mercury at 0.37 mg kg^{-1}, while a comprehensive sample of rainbow trout from the same river stretch had muscle mercury at only 0.05 mg kg^{-1}. The correlation between trophic feeding level and mercury concentration is also apparent in the data from Duncan Creek and the South Fork American River at Slab Creek Reservoir (table 3). At these sites, samples of small (< 250 g) rainbow and brown trout were taken together. At these sizes, the species are both insectivorous. Mercury concentrations were found to be identical at these sites between the two species.

The relationship between muscle mercury and liver mercury was investigated in the first year of the study. The data are presented together with muscle mercury data in table 3. Generally, the liver mercury concentrations in these fish were very similar to corresponding muscle mercury levels. Mean liver mercury from 77 rainbow and small brown trout was 97.9% of corresponding muscle mercury concentrations, with a standard deviation of 23.5%. We have found, in other research, that liver mercury is frequently 150-200% of muscle mercury in extremely polluted sites, such as Coast Range lakes and reservoirs in the historic mercury mining district of California (Slotton 1991). These liver data, together with the lower absolute tissue mercury concentrations, indicate a relatively more moderate level of mercury bioavailability in the Sierra gold district.

Trout stomach contents were analyzed for mercury at a subset of the sampling sites. This data is displayed in table 2 together with other trophic mercury data for each site. The food item mercury data was generally reflective of corresponding stream invertebrate mercury levels. In the

several cases where food item mercury was considerably lower than corresponding stream invertebrate mercury, it was noted that terrestrial insects dominated the stomach contents.

Stream Invertebrates

Aquatic invertebrates were taken at each of the 35 sites. Approximately 150 separate invertebrate composite samples were collected, identified, processed, and analyzed for mercury in the research reported here. The sites varied considerably in invertebrate diversity and types present. The most consistently available groups were net collector caddisfly nymphs of the family Hydropsychidae (omnivores), stonefly nymphs of the family Perlidae (small-item predators), and hellgrammites of the family Corydalidae (large-item predators). The lowest trophic feeding level of stream invertebrates taken, herbivorous species, were represented by a variety of families, with Pteronarcyid stoneflies being the most frequently taken. A variety of mayfly species represented this trophic level at a number of sites. Additional herbivores included large beetle nymphs of the family Ptilodactylidae. The omnivore/collector feeding level was represented exclusively by Hydropsychid caddis nymphs, which were widespread throughout much of the region. The invertebrate small-item predator trophic level included Rhyacophyllid caddis nymphs, Perlodid stoneflies, and damselfly nymphs in addition to the Perlid stoneflies which were most generally available. In addition to hellgrammite nymphs, the larger-item invertebrate predator trophic level also included large predaceous dipteran larvae of the family Tipulidae and Gomphid dragonfly nymphs.

The invertebrate mercury data are presented in table 2 and figures 2-7. Mercury was detected at ≥ 0.02 mg kg^{-1} (dry weight) in all invertebrate samples taken throughout the Sierra Nevada gold country. Inter-site mercury differences were generally consistent among all invertebrate (and trout) trophic levels, with low mercury sites demonstrating low biotic Hg levels throughout the food web and sites with high biotic Hg in one group typically having elevated Hg levels in all co-occurring organisms.

Similar to the trout results, notably elevated mercury in stream invertebrates was found at sites along the Middle and South Forks of the Yuba River, and the Middle Fork of the Feather River. Also as found for trout, invertebrates from the North Fork of the Middle Fork of the American River (Station # 28) and Spanish Creek (Station # 6), a tributary to the North Fork Feather River, were relatively higher in mercury as compared to other sites in their watersheds. Low mercury concentrations (≤ 0.15 mg kg^{-1}, dry weight) were found in all trophic levels of invertebrates from many tributaries of the Feather and American rivers, as well as upstream of the major mining activity along the Middle Fork of the Yuba River, similar to co-occurring trout.

Invertebrates were also sampled at 16 sites where trout were not present in sufficient quantities for adequate collections. These invertebrate-only collections identified several additional elevated mercury streams, including the Bear River and Wolf Creek (stations 22 and 23), which were very high, the North Fork of the Cosumnes River (station 35), and Deer Creek (station 19). Other invertebrate-only collections indicated relatively low mercury bioavailability at sites including: the lower American River below Folsom Lake (stations 24 and 25), the South Fork of the American River (stations 32-34), the Rubicon River (station 29), and the Bear River below Camp Far West Reservoir (station 21).

Notably lower invertebrate mercury concentrations were found below many of the foothill reservoirs, as compared to concentrations in similar biota upstream. Specifically, the invertebrates below New Bullard's Bar Reservoir (station 11) were considerably lower in mercury than those collected upstream of the reservoir on the North Fork of the Yuba River (station 12). Hydropsychid net caddis nymphs were 0.08 ppm in their dry weight mercury concentration below the dam, as compared to 0.24 ppm upstream of the reservoir. Perlid stoneflies were 0.11 ppm below, 0.25 ppm above, and Corydalid hellgrammites were 0.33 below vs 0.50 above. Similarly, the invertebrates collected below Englebright Reservoir (station 10) were far lower in mercury than samples collected upstream of the reservoir on the Middle and South Forks of the Yuba River (stations 15, 16, and 18). On the Bear River, Hydropsychid net caddis nymphs were 0.29 and 0.46 ppm Hg at sites above Camp Far West Reservoir (stations 22 and 23), as compared to 0.17 ppm in extensive, replicate collections from below the dam.

Trophic level relationships to mercury accumulation

A pattern of increasing mercury concentrations in progressively higher trophic levels was found at the majority of sites (figure 2, table 2). In figures 8 and 9 we summarize the food-chain mercury data from sites where trout were sampled, normalized to 250 g rainbow trout muscle concentrations at each of the sites. In figure 8, the normalized invertebrate data are plotted for trophic guilds vs trout, and in figure 9 the dominant single family or genus of each guild is used. The means and confidence intervals are similar with either analysis.

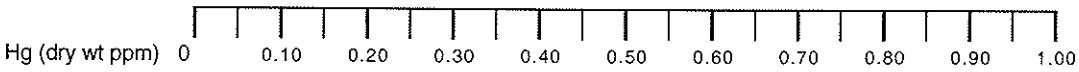
A relatively predictable pattern results, with the highest trophic level stream invertebrates having mercury concentrations approximately half those seen in normalized 250 g trout from the same sites. Among the invertebrates, herbivorous species as a group consistently had the lowest mercury concentrations (averaging 14% of those found in co-existing trout). Low mercury levels in herbivore species was not a function of age and, thus, time of exposure. Similar low concentrations were found in Pteronarcyid stonelfies up to three years old, as well as in annual mayflies. Predaceous invertebrates accumulated considerably higher concentrations. Relatively

small predators such as nymphs of Perlid stoneflies, Rhyacophyllid caddisflies, and damselflies had mercury concentrations averaging 38% of the concentrations in corresponding normalized trout muscle, while the largest invertebrate predators, characterized by the large-jawed hellgrammites, averaged 47% of trout concentrations. Hydropsychid caddis larvae, which were an important component of the invertebrate biomass at many of the sites, averaged 31% of corresponding trout in their mercury levels. This was lower than that of the larger invertebrate predators but considerably higher than the mercury concentrations seen in herbivores, suggesting that these larvae, which feed by capturing drift in their nets, consume primarily other invertebrates rather than algal material. We believe that relative mercury concentrations in aquatic species may offer a useful tool for determining relative, time-integrated trophic feeding level.

In figures 10-16, mercury concentrations in different trophic categories and types of invertebrates are plotted against corresponding trout mercury to determine relative correlations. Interestingly, the R^2 correlation coefficients between invertebrates and trout taken from the same sites increased steadily with increasing invertebrate trophic feeding level. Herbivores, as a group, demonstrated the weakest correlation with corresponding trout ($R^2 = 0.31$). Hydropsychid caddis larvae had a stronger correlation ($R^2 = 0.44$). Small predaceous invertebrates such as Perlid stoneflies had considerably tighter correlations with trout ($R^2 = 0.69$), while the highest trophic level invertebrates, characterized by hellgrammites, demonstrated the strongest correlations with corresponding trout ($R^2 = 0.78$). Correlations between individual invertebrate family or genus and trout (figures 11, 14, and 16) were generally not significantly stronger than those using grouped trophic guild members, though this may be partially a function of lower sample size for particular invertebrates.

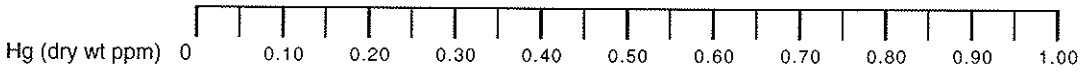
In figures 17-28, correlations in mercury concentration between invertebrates are plotted, first between adjacent trophic feeding levels (figures 17-22) and finally between more distantly separated groups (figures 23-28). As a set, these inter-invertebrate correlations were all quite high. R^2 correlation coefficients of 0.72-0.89 were found between adjacent trophic levels (figures 17, 19, and 21) and coefficients of 0.50-0.80 were found between non-adjacent but co-occurring trophic levels (figures 23, 25, and 27).

Table 2. Biota Mercury Data (dry wt ppm) For All Water Resources Center Sierra Nevada Sites



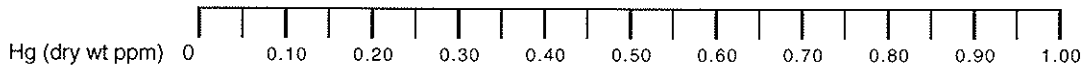
identification	trophic level	Hg
1. North Fork Feather River at Belden. (10/26/94)		
Hydropsychidae (net caddis)	net collector	0.05
Perlidae-Gold sp (Callineuria)	small predator	0.04
2. Yellow Creek (trib. of North Fk Feather R.), 2 miles above confluence. (6/11/94)		
(Large Mayflies)	herbivores	0.03
Hydropsychidae (net caddis)	net collector	0.04
Rhyacophyllidae (pred. caddis)	small predator	0.04
Perlidae (golden stonefly)	small predator	0.03
Corydalidae (hellgrammite)	large predator	0.05
Tipulidae (cranefly)	large predator	0.06
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.12***
	(trout diet)	0.05
3. Caribou Branch North Fork Feather River, 4 miles above confluence. (10/27/94)		
Pteronarcyidae	leaf shredder	0.02
Hydropsychidae (net caddis)	net collector	0.05
Perlidae-Dark sp (Hesperoperla)	small predator	0.06
Gomphidae (dragonfly)	large predator	0.08
Corydalidae (hellgrammite)	large predator	0.07
Tipulidae (cranefly)	large predator	0.09
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.20***
	(trout diet)	0.06

Table 2. Biota Mercury Data (continued)



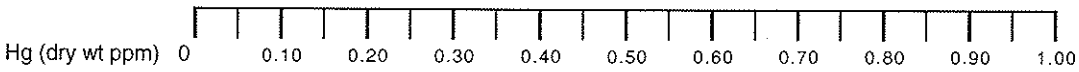
identification	trophic level	Hg
4. East Branch of North Fork Feather River,10 miles above confluence with Caribou Branch. (10/26/94)		
Hydropsychidae (net caddis)	net collector	**0.07**
Rhyacophyllidae (pred. caddis)	small predator	**0.15**
Perlidae-Dark sp (Hesperoperla)	small predator	**0.15**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.24***
	(trout diet)	**0.05**
5. Indian Creek, tributary to E Branch N Fk Feather River, 7 miles above confluence. (9/27/94)		
Oligoneuriidae (mayfly)	herbivore	**0.05**
Hydropsychidae (net caddis)	net collector	**0.07**
Damsefly nymphs	small predator	**0.08**
Perlidae (golden stonefly)	small predator	**0.15**
Rhyacophyllidae (pred. caddis)	small predator	**0.18**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.14***
	(trout diet)	**0.04**
6. Spanish Creek, tributary to E Branch N Fk Feather River, 2 miles above confluence. (8/26/94)		
Ptilodactyllidae (lg aq beetle nymph)	herbivore	**0.08**
Rhyacophyllidae (pred. caddis)	small predator	**0.20**
Damsefly nymphs	small predator	**0.28**
Perlidae (golden stonefly)	small predator	**0.35**
Gomphidae (dragonfly)	large predator	**0.24**
Corydalidae (hellgrammite)	large predator	**0.30**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.51***
	(trout diet)	**0.10**

Table 2. Biota Mercury Data (continued)



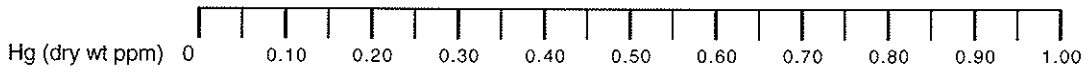
identification	trophic level	Hg
7. Middle Fork Feather River, 1 mile below below Nelson Ck. (9/22/94)		
Pteronarcyidae	leaf shredder	**0.10**
Hydropsychidae (net caddis)	net collector	**0.28**
Rhyacophyllidae (pred. caddis)	small predator	**0.25**
Perlidae (golden stonefly)	small predator	**0.40**
Gomphidae (dragonfly)	large predator	**0.24**
Corydalidae (hellgrammite)	large predator	**0.47**
Tipulidae (cranefly)	large predator	**0.69**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.56***
	(trout diet)	**0.08**
8. Nelson Creek, tributary to Middle Fork Feather River, 1 mile above confluence. (9/21/94)		
Limnephilidae (stone case caddis)	herbivore	**0.05**
Perlidae (golden stonefly)	small predator	**0.13**
Corydalidae (hellgrammite)	large predator	**0.15**
Tipulidae (cranefly)	large predator	**0.16**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.40***
	(trout diet)	**0.05**
9. Upper Middle Fork Feather River, 3 miles upstream of Clio. (9/23/94)		
Oligoneuriidae (mayfly)	herbivore	**0.03**
Hydropsychidae (net caddis)	net collector	**0.08**
Damselfly Nymphs	small predator	**0.13**
Rhyacophyllidae (pred. caddis)	small predator	**0.16**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.68***
	(trout diet)	**0.07**

Table 2. Biota Mercury Data (continued)



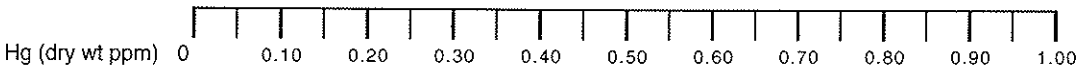
identification	trophic level	Hg
10. Lower Yuba River below Englebright Reservoir, at University of California field station. (12/16/93)		
Ephemerellidae (mayfly)	herbivore	**0.07**
Hydropsychidae (net caddis)	net collector	**0.12**
Perlodidae (stonefly)	small predator	**0.07**
Tipulidae (cranefly)	large predator	**0.18**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.42***
11. North Fork Yuba River constrained (low) flow below New Bullard's Bar Reservoir. (3/15/94)		
Hydropsychidae (net caddis)	net collector	**0.08**
Perlidae (golden stonefly)	small predator	**0.11**
Corydalidae (hellgrammite)	large predator	**0.33**
12. North Fork Yuba River, 2 miles downstream of westmost Highway 49 crossing. (11/5/93)		
Pteronarcyidae (giant stonefly)	leaf shredder	**0.05**
Hydropsychidae (net caddis)	net collector	**0.24**
Perlidae (golden stonefly)	small predator	**0.25**
Tipulidae	large predator	**0.38**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.50***
13. Canyon Creek, tributary to N Fk Yuba, just above confluence. (11/6/93)		
Hydropsychidae (net caddis)	net collector	**0.10**
Perlidae (golden stonefly)	small predator	**0.16**
Corydalidae (hellgrammite)	large predator	**0.27**

Table 2. Biota Mercury Data (continued)



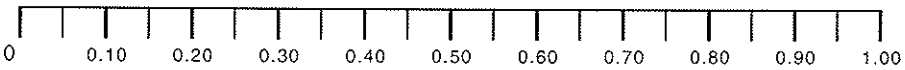
identification	trophic level	Hg
14. Downie River, tributary to N FK Yuba, at Downieville. (11/2/93)		
Hydropsychidae (net caddis)	net collector	**0.10**
Perlodidae (stonefly)	small predator	**0.11**
Perlidae (golden stonefly)	small predator	**0.11**
Tipulidae (cranefly)	large predator	**0.19**
Corydalidae (hellgrammite)	large predator	**0.22**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.45***
15. Middle Fork Yuba River, just upstream of Oregon Creek and Highway 49 crossing. (10/21/93)		
Pteronarcyidae (giant stonefly)	leaf shredder	**0.10**
Perlidae (golden stonefly)	small predator	**0.45**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.87***
Mean 250 g Squawfish	*(fish predator)*	***1.87***
16. Middle Fork Yuba River, 1 mile upstream of Tyler Foote crossing and Kanaka Creek. (10/19/93)		
Pteronarcyidae (giant stonefly),1 yr	leaf shredder	**0.05**
Pteronarcyidae; large (2 yr)	leaf shredder	**0.06**
Hydropsychidae (net caddis)	net collector	**0.33**
Perlidae (golden stonefly)	small predator	**0.38**
Gomphidae (dragonfly)	large predator	**0.39**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.66***
17. Middle Fork Yuba River, 1 mile upstream of Plumbago Road. (3/24/94)		
Peltoperlidae (stonefly)	herbivore/detrit.	**0.03**
Perlidae (golden stonefly)	small predator	**0.11**
Corydalidae (hellgrammite)	large predator	**0.14**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.20***

Table 2. Biota Mercury Data (continued)



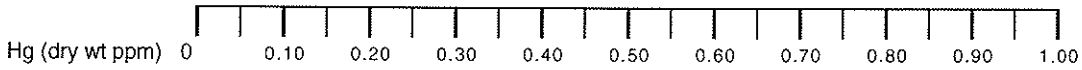
identification	trophic level	Hg
18. South Fork Yuba River, 1 mile downstream of Washington. (11/12/93)		
Pteronarcyidae (giant stonefly)	leaf shredder	**0.08**
Hydropsychidae (net caddis)	net collector	**0.18**
Perlidae (golden stonefly)	small predator	**0.30**
Corydalidae (hellgrammite)	large predator	**0.44**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.94***
19. Deer Creek below Lake Wildwood, at Mooney Flat Road. (12/9/94)		
Hydropsychidae (net caddis)	net collector	**0.30**
Corydalidae (hellgrammite)	large predator	**0.55**
20. Deer Creek at Bitney Spring Road. (12/9/94)		
Hydropsychidae (net caddis)	net collector	**0.23**
Perlidae (golden stonefly)	small predator	**0.22**
Tipulidae (cranefly)	large predator	**0.16**
21. Bear River below Camp Far West Reservoir. (12/9/94)		
Hydropsychidae (net caddis)	net collector	**0.17**
22. Bear River at Highway 49 crossing. (12/9/94)		
Hydropsychidae (net caddis)	net collector	**0.29**
Rhyacophyllidae (pred. caddis)	small predator	**0.34**
Perlidae-Dark sp (Hesperoperla)	smallpredator	**0.69**
Corydalidae (hellgrammite)	large predator	**0.77**
23. Wolf Creek, tributary to Bear River, 2 miles above confluence. (12/9/94)		
Hydropsychidae (net caddis)	net collector	**0.46**
Perlodidae (stonefly)	small predator	**0.44**
Tipulidae (cranefly)	large predator	**0.35**

Table 2. Biota Mercury Data (continued)



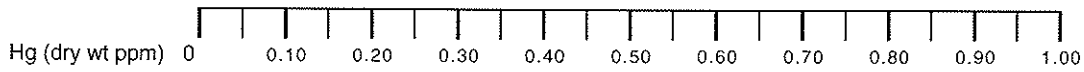
identification	trophic level	Hg
24. Lower American River at Howe Avenue. (12/16/94)		
Hydropsychidae (net caddis)	net collector	**0.11**
25. Lower American River, 1 mile below Lake Natoma. (12/16/94)		
Hydropsychidae (net caddis)	net collector	**0.11**
26. North Fork American River in vicinity of Humbug Bar. (11/19/93)		
Pteronarcyidae (giant stonefly)	leaf shredder	**0.02**
Hydropsychidae (net caddis)	net collector	**0.04**
Perlidae-Gold sp (Calineuria)	small predator	**0.05**
Perlidae-Dark sp (Hesperoperla)	small predator	**0.06**
Gomphidae (dragonfly)	large predator	**0.07**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.27***
27. Middle Fork American River below Oxbow Reservoir. (2/25/94)		
Pteronarcyidae (giant stonefly)	leaf shredder	**0.02**
Perlodidae (stonefly)	herbivore	**0.05**
Perlidae (golden stonefly)	small predator	**0.09**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.20***
950 g Brown Trout (dry ppm)	*(fish predator)*	***1.68***
28. North Fork of the Middle Fk American River, 1 mile above confluence. (3/2/94)		
Pteronarcyidae (giant stonefly)	leaf shredder	**0.05**
Perlidae (golden stonefly)	small predator	**0.18**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.55***

Table 2. Biota Mercury Data (continued)



identification	trophic level	Hg
29. Rubicon River, tributary ro Middle Fork American River, just above confluence. (2/1/94)		
Pteronarcyidae (giant stonefly)	leaf shredder	**0.02**
Hydropsychidae (net caddis)	net collector	**0.05**
Perlidae (golden stonefly)	small predator	**0.07**
30. Middle Fork American River at "End of World". (2/1/94)		
Perlidae (golden stonefly)	small predator	**0.16**
Corydalidae (hellgrammite)	large predator	**0.14**
31. Duncan Creek, tributary to Middle Fork American River, 3 miles above confluence. (11/16/93)		
Peltoperlidae (stonefly)	herbivore	**0.02**
Hydropsychidae (net caddis)	net collector	**0.05**
Perlidae (golden stonefly)	small predator	**0.07**
Corydalidae (hellgrammite)	large predator	**0.11**
Mean 250 g Trout (dry ppm)	*(insect predator)*	***0.24***
32. South Fork American River above Folsom Lake. (12/16/94)		
Pteronarcyidae	leaf shredder	**0.03**
Hydropsychidae (net caddis)	net collector	**0.08**
Perlodidae- Osobenus	small predator	**0.07**
Perlidae-Gold sp (Callineuria)	small predator	**0.10**
Perlidae-Dark sp (Hesperoperla)	small predator	**0.14**
33. South Fork American River below Slab Creek Reservoir. (12/20/93)		
Perlidae (golden stonefly)	small predator	**0.04**

Table 2. Biota Mercury Data (continued)



identification	trophic level	Hg
34. South Fork American River, 1 mile upstream of Pacific. (4/11/94)		
Heptageneidae (mayfly)	herbivore	**0.03**
Ephemerellidae (mayfly)	herbivore	**0.05**
Ptilodactylidae (lg aq beetle nymph)	herbivore	**0.07**
Hydropsychidae (net caddis)	net collector	**0.07**
Perlidae-Gold sp (Callineuria)	small predator	**0.08**
Perlidae-Dark sp (Hesperoperla)	small predator	**0.09**
35. North Fork Cosumnes River at Mt. Aukum Rd. (12/20/93)		
Pteronarcyidae (giant stonefly)	leaf shredder	**0.05**
Ptilodactylidae (lg aq beetle nymph)	herbivore	**0.20**
Perlidae-Dark sp (Hesperoperla)	small predator	**0.38**
Perlidae-Gold sp (Callineuria)	small predator	**0.52**
Gomphidae (dragonfly)	large predator	**0.60**

TABLE 3. Mercury Data From Individual Fish

wt (g)	Length (mm)	Sex	Muscle ppm Hg	Liver ppm Hg
2. Yellow Ck (off N Fk Feather River), 6/11/94				
107 g	197	f	0.02	
150 g	230	m	0.02	
210 g	257	f	0.02	
245 g	270	f	0.03	
280 g	285	f	0.03	
280 g	288	m	0.03	
315 g	297	f	0.03	
normalized 250 g trout muscle (wet wt ppm Hg):			***0.03***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.12***	
3. Caribou N Fk Feather River, 10/27/94				
75 g	190	m	0.03	
115 g	223	f	0.03	
120 g	223	m	0.02	
210 g	266	m	0.04	
240 g	274	m	0.04	
normalized 250 g trout muscle (wet wt ppm Hg):			***0.04***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.20***	
4. E Branch N Fk Feather River, 10/26/94				
75 g	193	m	0.04	
160 g	248	m	0.03	
207 g	266	f	0.04	
423 g	348	m	0.05	
515 g	370	f	0.07	
627 g	385	f	0.12	
normalized 250 g trout muscle (wet wt ppm Hg):			***0.05***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.24***	
5. Indian Ck (Trib, E Branch N Fk Feather River), 9/27/94				
151 g	242	f	0.03	
153 g	243	f	0.02	
335 g	304	m	0.03	
normalized 250 g trout muscle (wet wt ppm Hg):			***0.03***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.14***	
6. Spanish Ck (Trib, E Branch N Fk Feather River), 9/26/94				
139 g	241	f	0.10	
133 g	238	m	0.13	
164 g	250	f	0.06	
185 g	258	f	0.09	
285 g	298	f	0.06	
normalized 250 g trout muscle (wet wt ppm Hg):			***0.11***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.51***	

TABLE 3. Mercury Data From Individual Fish

wt (g)	Length (mm)	Sex	Muscle ppm Hg	Liver ppm Hg
7. Middle Fk Feather River (Below Nelson Ck), 9/22/94				
74 g	195	m	**0.12**	
109 g	223	?	**0.09**	
137 g	238	m	**0.10**	
170 g	245	m	**0.17**	
273 g	294	m	**0.09**	
normalized 250 g trout muscle (wet wt ppm Hg):			***0.12***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.56***	
8. Nelson Ck (Tributary to M Fk Feather River), 9/21/94				
60 g	185	?	**0.07**	
160 g	245	m	**0.07**	
230 g	292	f	**0.09**	
305 g	304	f	**0.10**	
340 g	325	m	**0.23**	
430 g	338	f	**0.06**	
normalized 250 g trout muscle (wet wt ppm Hg):			***0.09***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.40***	
9. Upper Middle Fk Feather River, Above Clio, 9/23/94				
70 g	176	m	**0.09**	
112 g	210	m	**0.08**	
144 g	222	f	**0.10**	
137 g	224	f	**0.14**	
174 g	245	f	**0.17**	
normalized 250 g trout muscle (wet wt ppm Hg):			***0.15***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.68***	
10. Lower Yuba below Engelbright Reservoir,12/16/93				
170 g	235	f	**0.09**	0.11
235 g	274	m	**0.13**	0.09
255 g	272	f	**0.07**	0.08
400 g	314	f	**0.10**	0.09
440 g	329	m	**0.07**	0.08
565 g	370	m	**0.11**	0.06
860 g	408	f	**0.13**	0.09
910 g	417	m	**0.12**	0.08
1040 g	434	m	**0.12**	0.07
normalized 250 g trout muscle (wet wt ppm Hg):			***0.09***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.42***	

TABLE 3. Mercury Data From Individual Fish

wt (g)	Length (mm)	Sex	Muscle ppm Hg	Liver ppm Hg
12. North Fork Yuba River Near Canyon Creek, 11/5/93				
145 g	236	f	**0.14**	0.16
200 g	270	f	**0.09**	0.08
300 g	306	f	**0.10**	0.10
320 g	314	f	**0.11**	0.13
340 g	311	m	**0.10**	0.07
normalized 250 g trout muscle (wet wt ppm Hg):			***0.11***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.50***	
13. Canyon Creek at N Fk Yuba,11/6/93				
305 g	294	m	**0.11**	0.10
14. Downie River (tributary of N Fk Yuba), 11/2/93				
55 g	176	m	**0.04**	0.04
85 g	195	m	**0.06**	0.04
150 g	239	f	**0.08**	0.06
155 g	243	m	**0.06**	0.05
410 g	356	f	**0.15**	0.13
465 g	348	m	**0.07**	0.06
normalized 250 g trout muscle (wet wt ppm Hg):			***0.10***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.45***	
15. Middle Fork Yuba above Oregon Creek, 10/21/93				
Rainbow Trout				
100 g	204	f	**0.15**	0.12
260 g	260	m	**0.21**	0.19
250 g	278	f	**0.17**	0.20
normalized 250 g trout muscle (wet wt ppm Hg):			***0.19***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.87***	
Squawfish				
370 g	321	m	**0.56**	0.33
480 g	339	f	**0.81**	0.42
16. Middle Fork Yuba above Kanaka Creek, 10/93				
94 g	210	m	**0.10**	0.09
130 g	235	f	**0.12**	0.10
135 g	237	m	**0.12**	0.09
150 g	240	m	**0.13**	0.12
320 g	298	m	**0.13**	0.19
375 g	320	f	**0.20**	0.17
505 g	368	m	**0.21**	(Lost Liver)
515 g	363	m	**0.24**	0.30
615 g	387	m	**0.21**	0.19
normalized 250 g trout muscle (wet wt ppm Hg):			***0.15***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.66***	

TABLE 3. Mercury Data From Individual Fish

wt (g)	Length (mm)	Sex	Muscle ppm Hg	Liver ppm Hg
17. Middle Fork Yuba above Plumbago Rd, 3/24/94				
270 g	292	f	**0.05**	0.04
380 g	346	f	**0.06**	0.06
580 g	385	m	**0.12**	0.08
710 g	391	f	**0.12**	0.09
730 g	415	f	**0.19**	0.20
normalized 250 g trout muscle (wet wt ppm Hg):			***0.05***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.20***	
18. South Fork Yuba at Washington, 11/12/93				
20 g	112	?	**0.14**	(not analyzed)
70 g	183	f	**0.13**	0.11
70 g	186	?	**0.12**	0.14
85 g	195	?	**0.12**	0.15
90 g	200	m	**0.11**	0.13
90 g	201	?	**0.11**	0.13
90 g	207	f	**0.12**	0.16
100 g	205	?	**0.11**	0.12
135 g	234	m	**0.10**	0.12
140 g	230	m	**0.13**	0.15
150 g	237	f	**0.11**	0.13
230 g	274	f	**0.22**	0.22
310 g	305	f	**0.26**	0.35
450 g	345	f	**0.30**	0.48
normalized 250 g trout muscle (wet wt ppm Hg):			***0.21***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.94***	
26. North Fork American River Near Humbug Bar 11/19/93				
110 g	216	f	**0.03**	0.02
140 g	237	f	**0.05**	0.03
150 g	245	m	**0.03**	0.03
595 g	384	m	**0.15**	0.14
normalized 250 g trout muscle (wet wt ppm Hg):			***0.06***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.27***	

TABLE 3. Mercury Data From Individual Fish

wt (g)	Length (mm)	Sex	Muscle ppm Hg	Liver ppm Hg
27. Middle Fk American River Below Oxbow Reservoir, 2/25/94				
Rainbow Trout				
295 g	297	f	**0.05**	0.04
330 g	308	f	**0.06**	0.05
335 g	313	f	**0.06**	0.05
385 g	327	f	**0.06**	0.05
385 g	332	f	**0.04**	0.05
400 g	334	m	**0.07**	0.05
normalized 250 g trout muscle (wet wt ppm Hg):			***0.04***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.20***	
Brown Trout				
965 g	452	f	**0.37**	0.67
28. N Fk Middle Fk American River--Middle Fk up to Skunk Ck, 3/2/94				
90 g	211	f	**0.11**	0.08
120 g	227	f	**0.10**	0.08
160 g	247	f	**0.11**	0.07
normalized 250 g trout muscle (wet wt ppm Hg):			***0.12***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.55***	
31. Duncan Creek (tributary of Middle Fk American R.), 11/16/93				
Rainbow Trout				
35 g	149	m	**0.02**	0.02
55 g	170	f	**0.02**	0.02
80 g	186	f	**0.03**	0.04
85 g	195	f	**0.03**	0.03
100 g	205	m	**0.03**	0.03
100 g	215	m	**0.04**	0.05
120 g	223	m	**0.03**	0.03
170 g	246	m	**0.04**	0.05
normalized 250 g trout muscle (wet wt ppm Hg):			***0.05***	
normalized 250 g trout muscle (dry wt ppm Hg):			***0.24***	
Brown Trout				
55 g	173	m	**0.03**	0.04
110 g	214	f	**0.04**	0.04
135 g	230	m	**0.05**	0.04
150 g	237	m	**0.04**	0.05
33. South Fk American River Below Slab Creek Reservoir, 12/20/93				
Rainbow Trout				
86 g	197	m	**0.07**	0.06
Brown Trout				
83 g	207	m	**0.06**	0.06

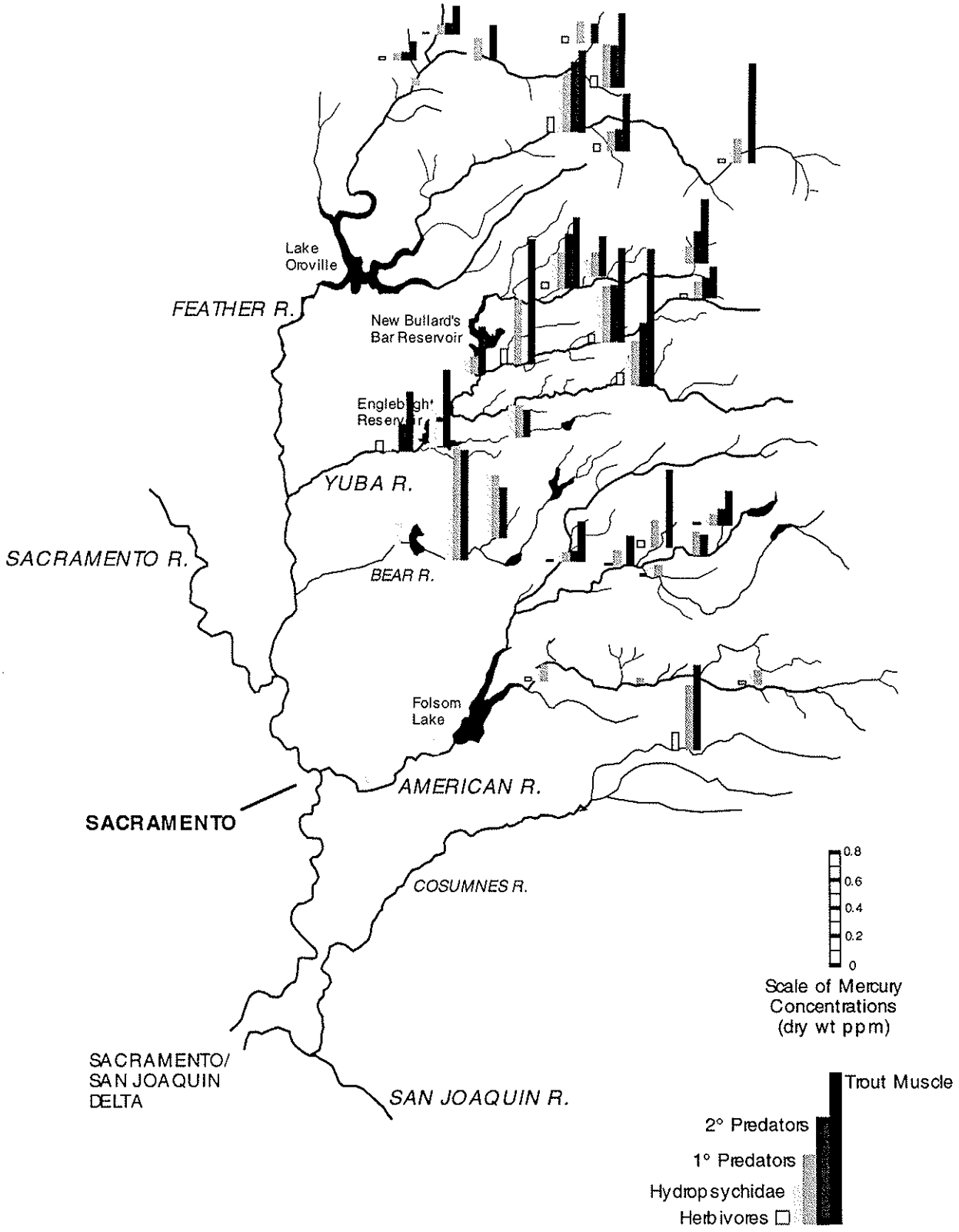


Fig. 2. Superimposed Regional Mercury Data for All Main Trophic Levels
(all as dry weight parts per million mercury)

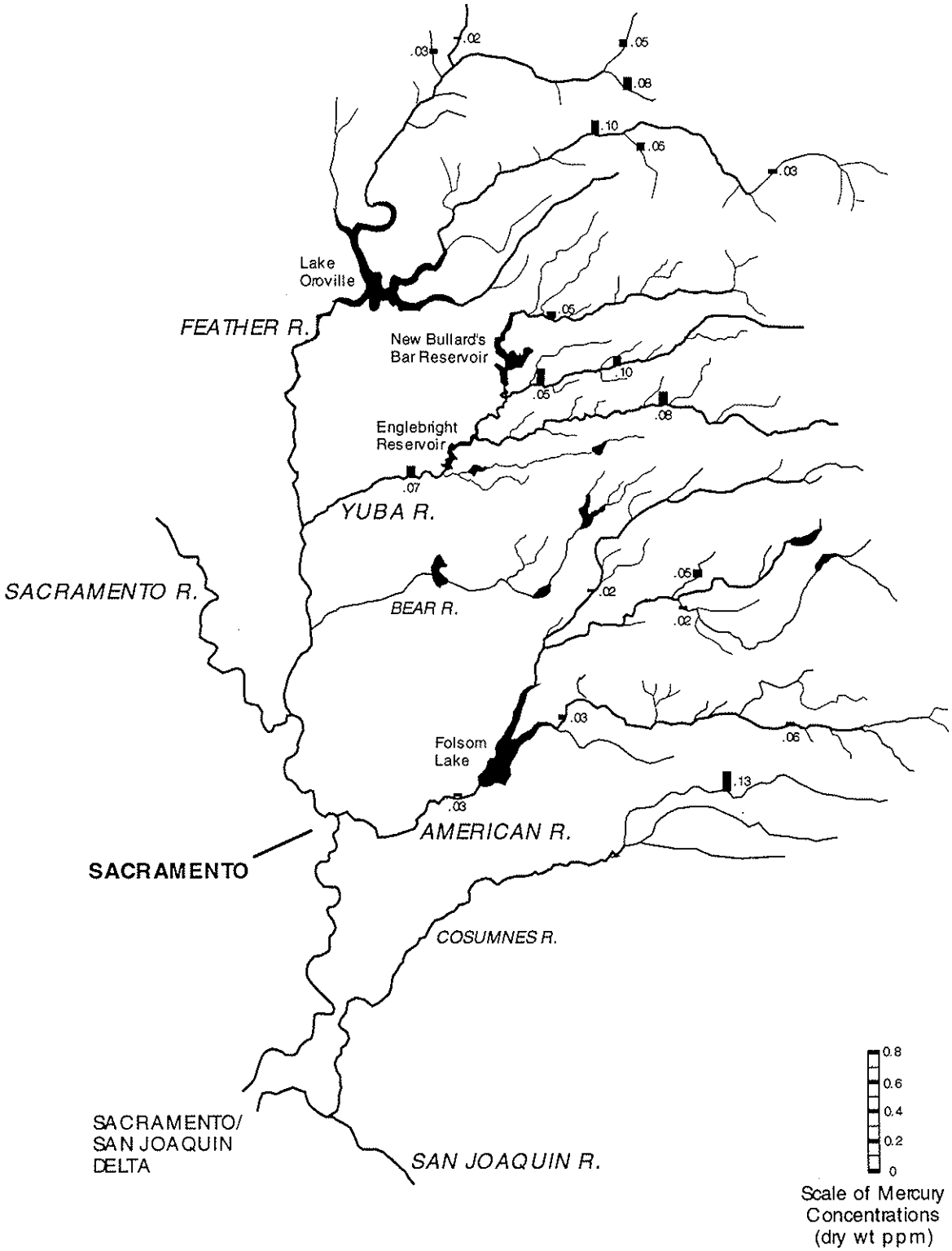


Fig. 3. Regional Mercury Data for Herbivorous Aquatic Invertebrates
(in units of dry weight parts per million mercury)

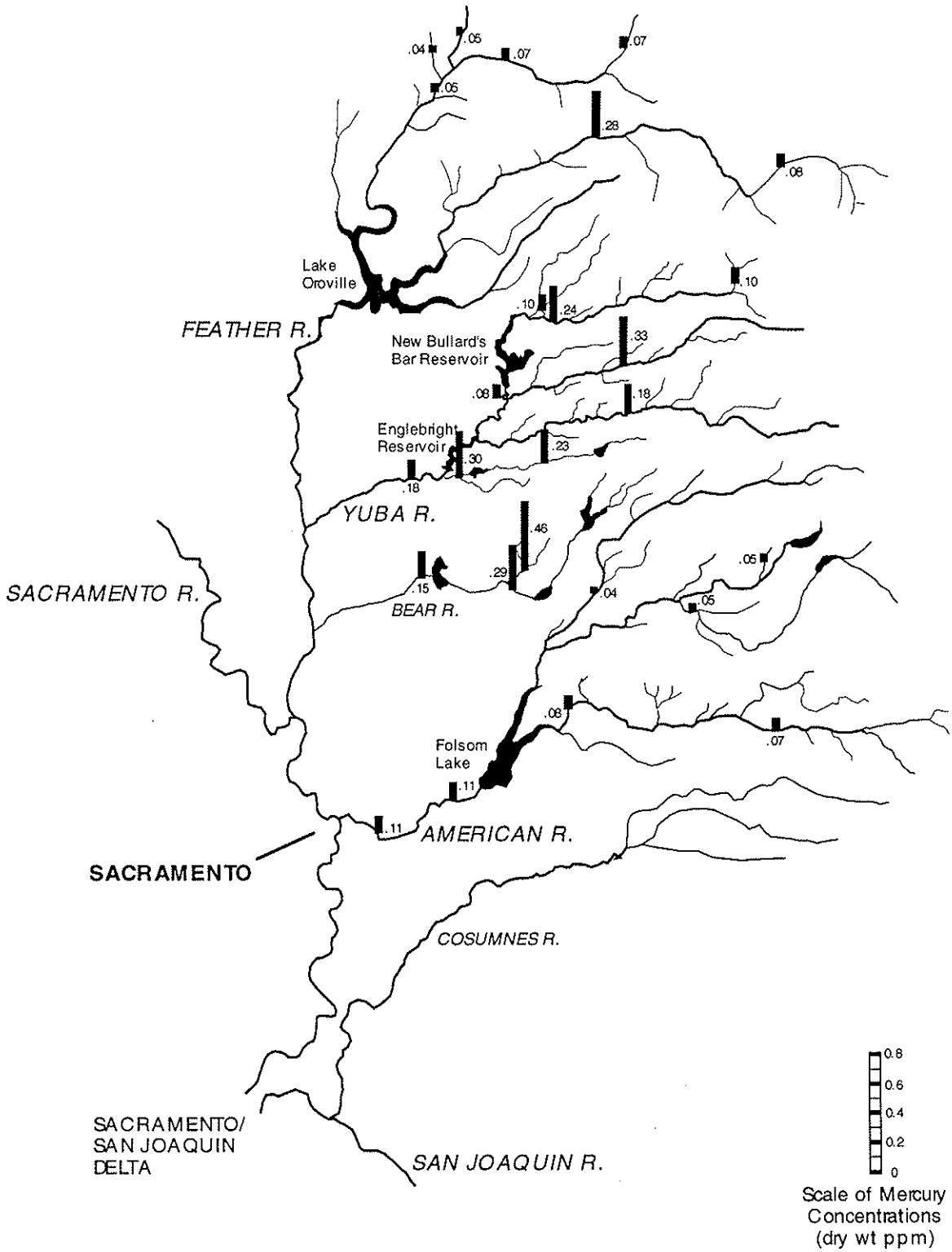


Fig. 4. Regional Mercury Data for Hydropsychid Caddisfly Nymphs

(in units of dry weight parts per million mercury)

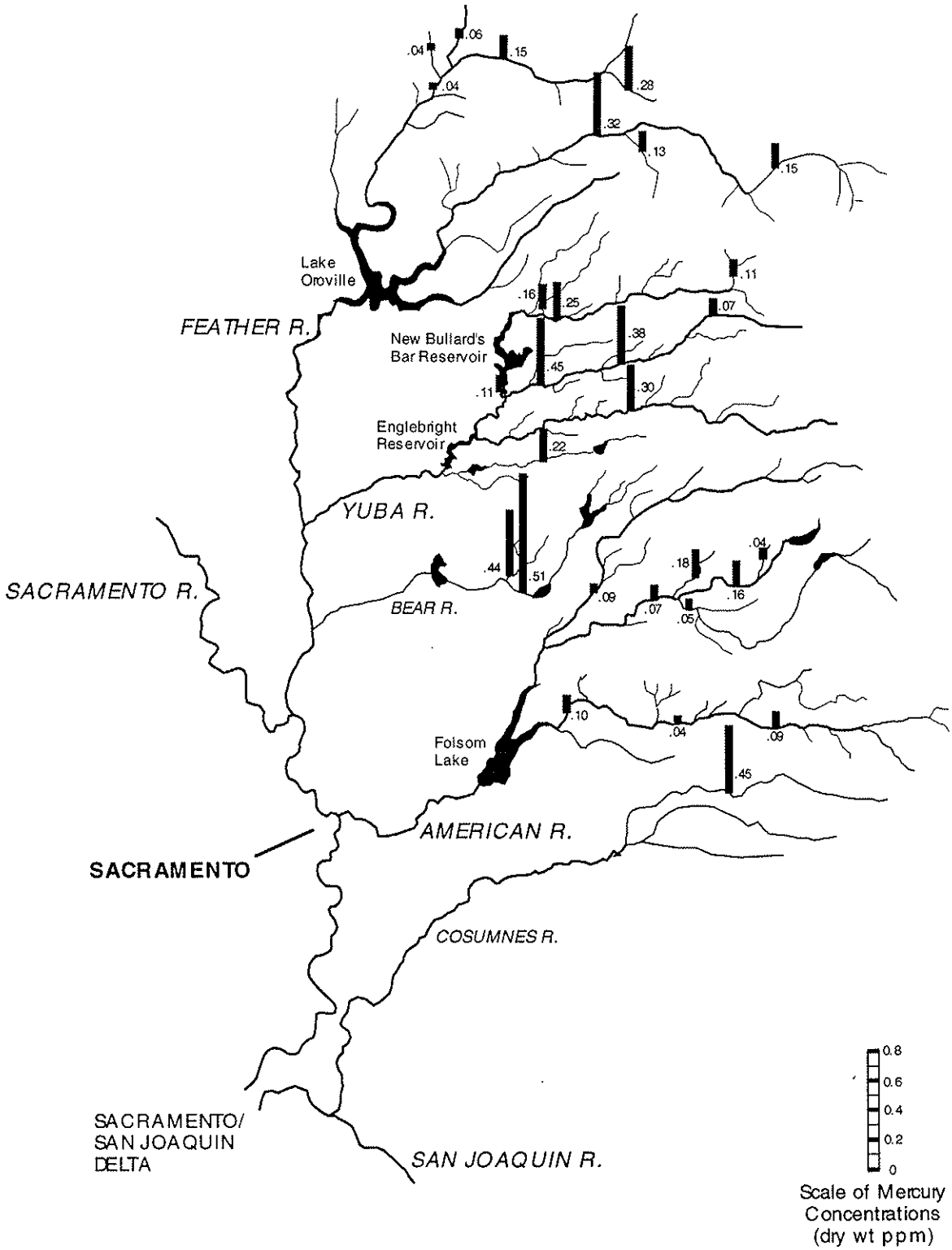


Fig. 5. Regional Mercury Data for Small-Item Invertebrate Predators

(in units of dry weight parts per million mercury)

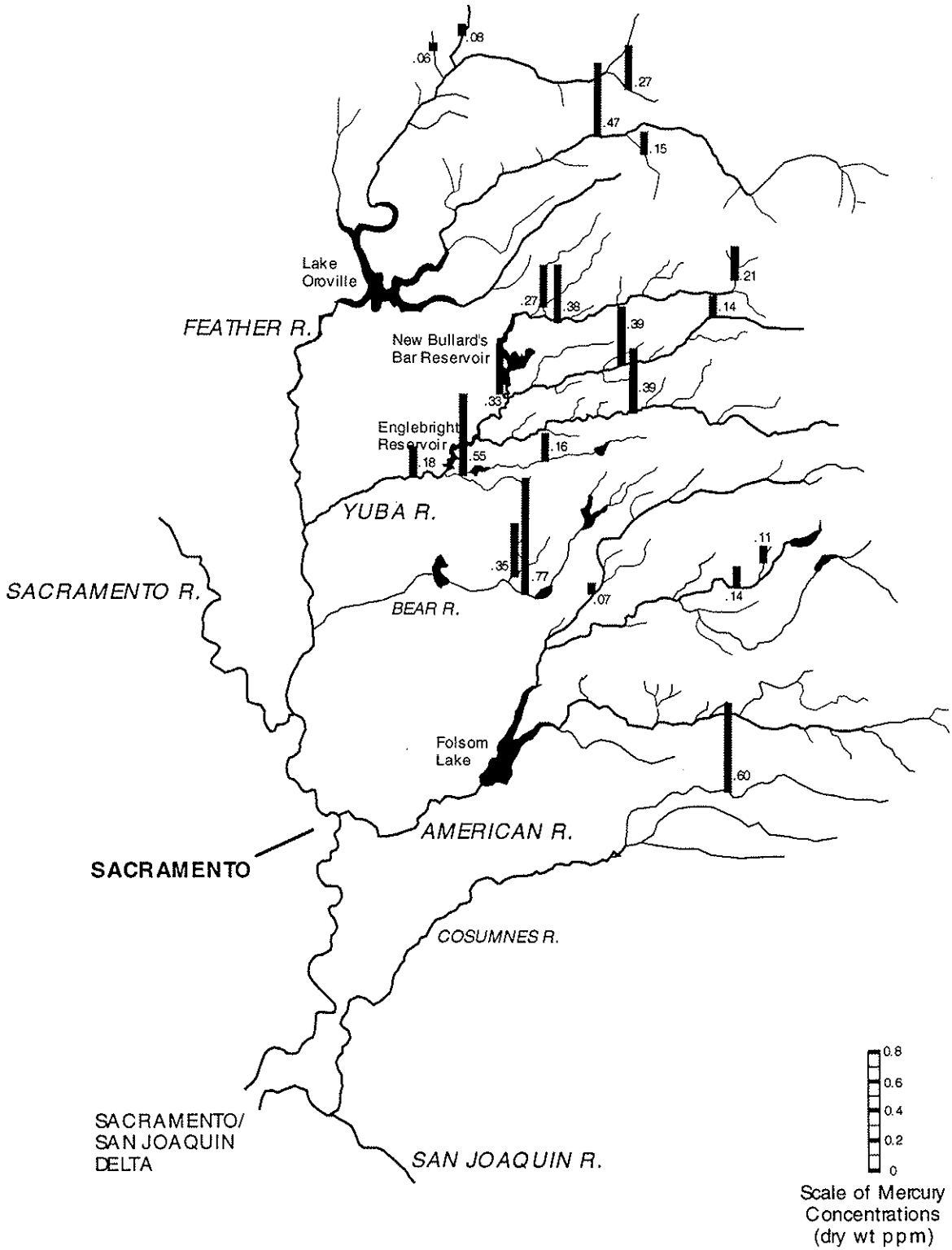


Fig. 6. Regional Mercury Data for Large-Item Invertebrate Predators

(in units of dry weight parts per million mercury)

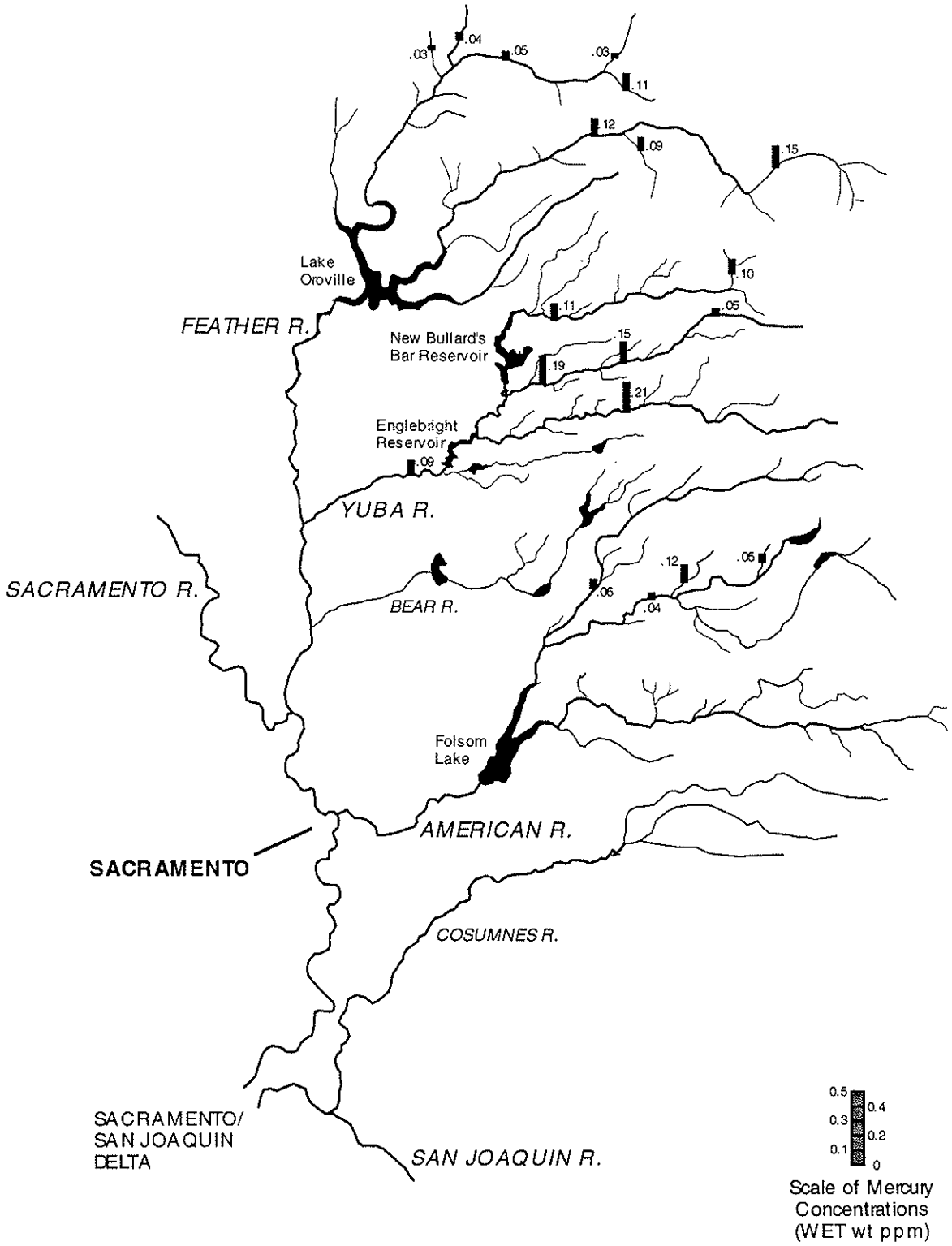


Fig. 7. Regional Mercury Data for Rainbow Trout

(in units of wet weight parts per million mercury, fillet muscle, normalized to 250 g trout)

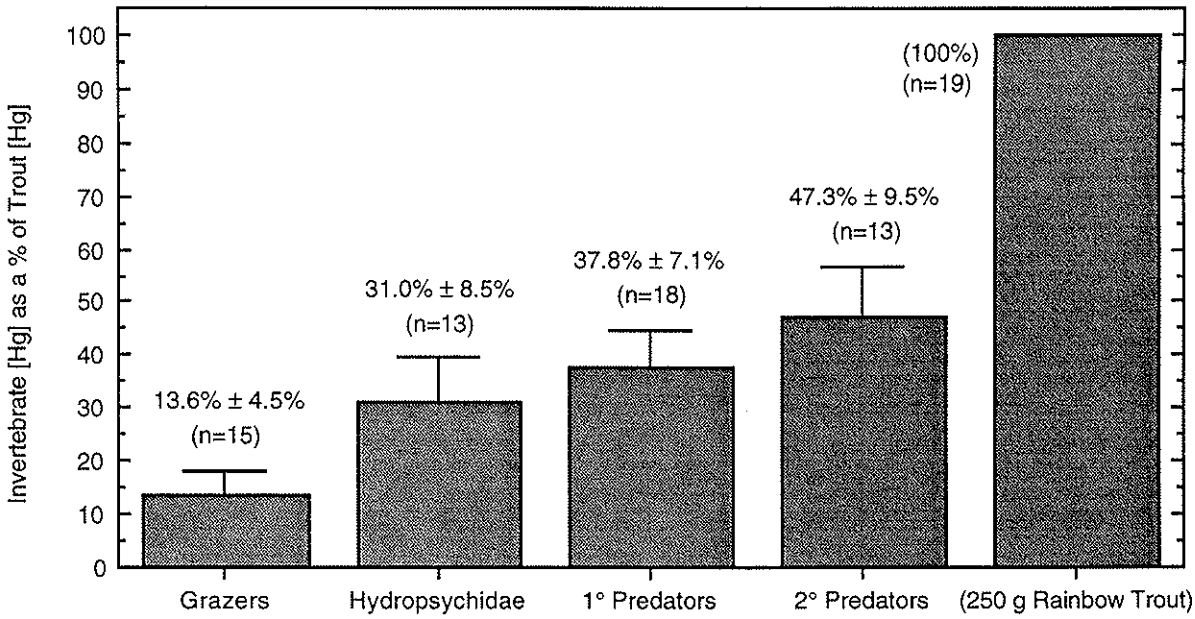


Fig. 8. Invertebrate mercury as a proportion of corresponding fish mercury, among sites with sampled fish

In units of dry wt parts per million Hg, together with 95% confidence intervals

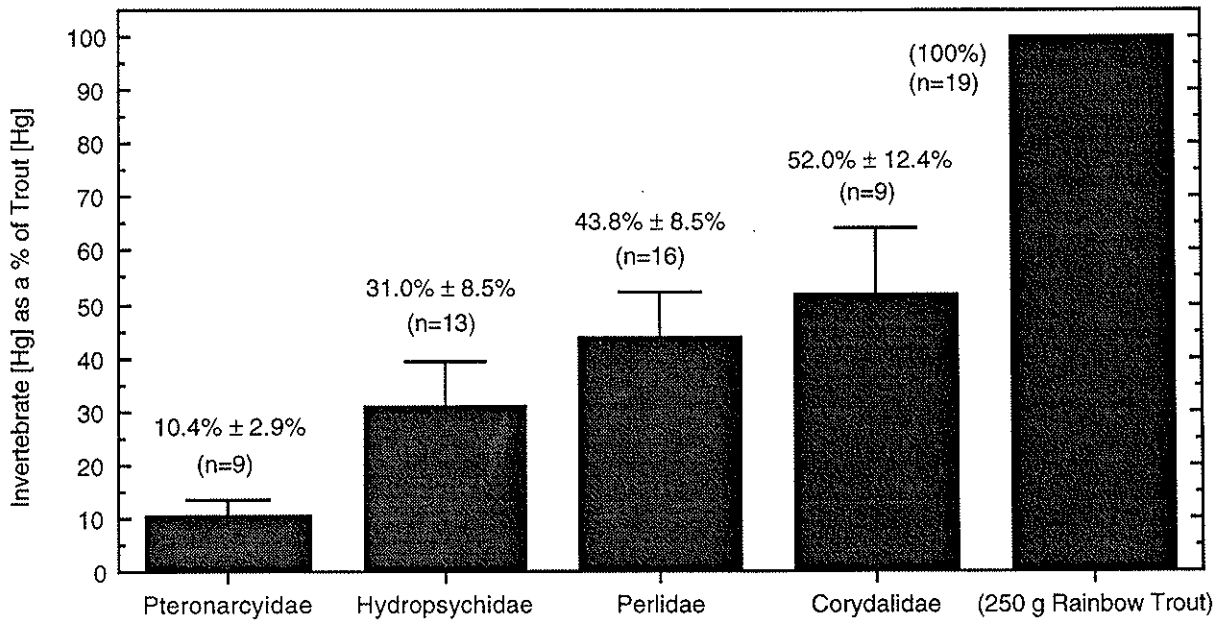


Fig. 9. Invertebrate mercury in individual families as a proportion of corresponding fish mercury, among sites with sampled fish

In units of dry wt parts per million Hg, together with 95% confidence intervals

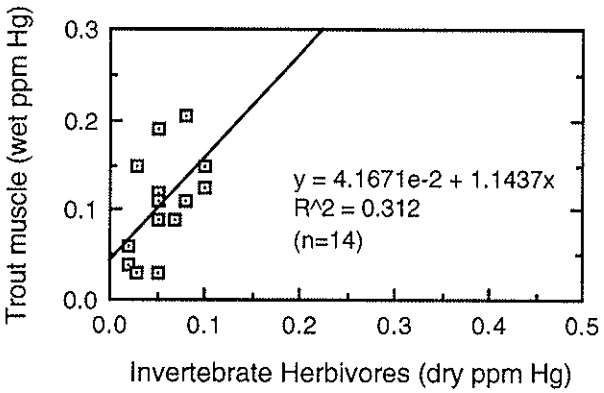


Fig. 10. Invertebrate Herbivores vs Trout

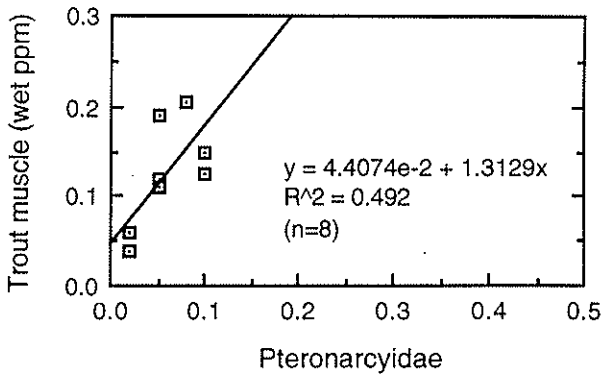


Fig. 11. Pteronarcyidae (Giant Herbivorous Stoneflies) vs Trout

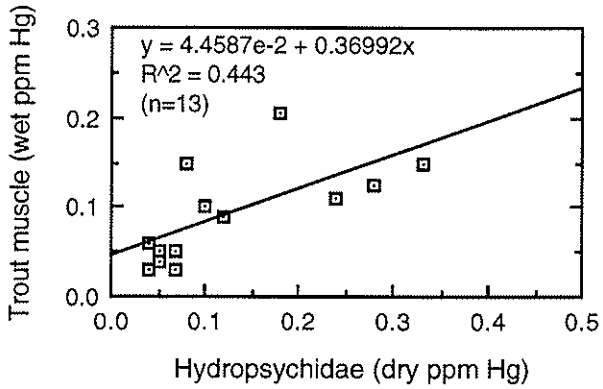


Fig. 12. Hydropsychidae (Net Collector Caddis) vs Trout

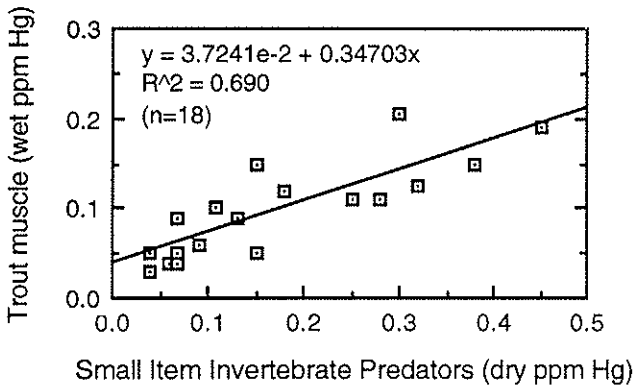


Fig. 13. Small Item Invertebrate Predators (Perlid Stoneflies, etc.) vs Trout

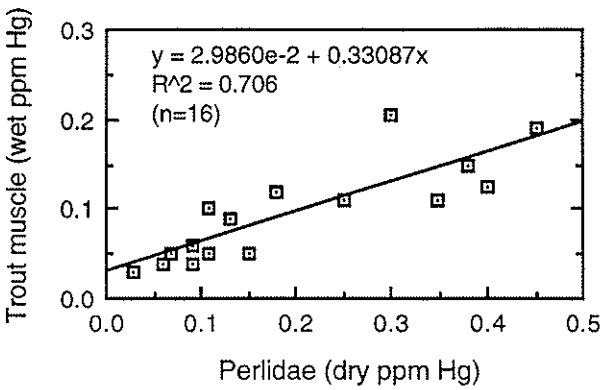


Fig. 14. Perlid Stoneflies vs Trout

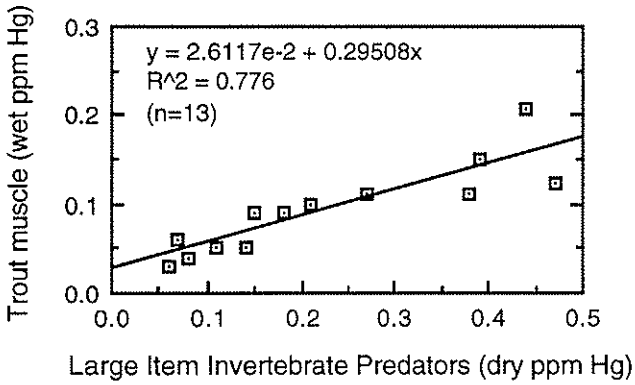


Fig. 15. Large Item Invertebrate Predators (Hellgrammites, etc.) vs Trout

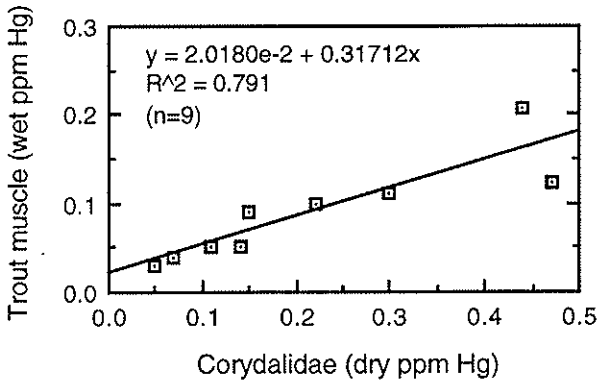


Fig. 16. Corydalid Hellgrammites vs Trout

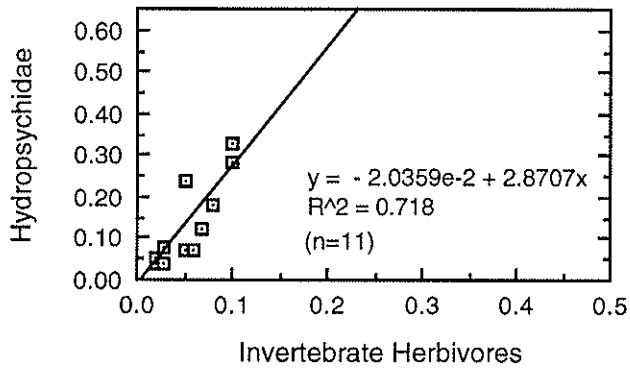


Fig. 17. Invertebrate Herbivores vs Hydropsychidae (Net Collector Caddis)

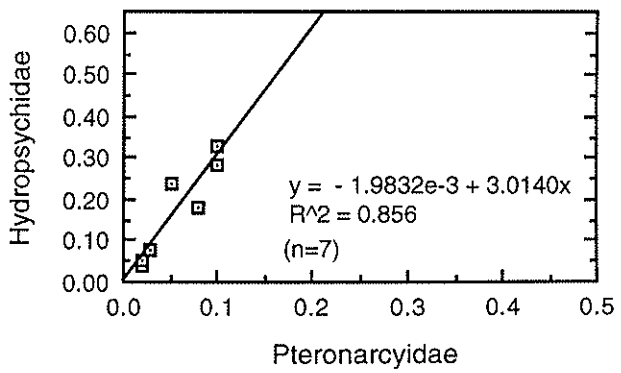


Fig. 18. Pteronarcyidae (Giant Herbivorous Stoneflies) vs Hydropsychidae (Net Collector Caddis)

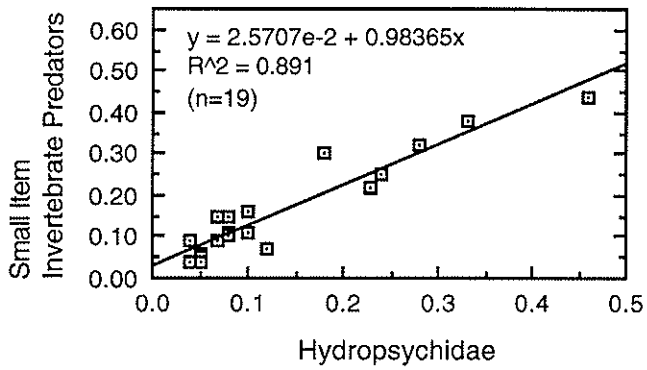


Fig. 19. Hydropsychidae (Net Collector Caddis) vs Small Item Predators (Perlid Stoneflies, etc.)

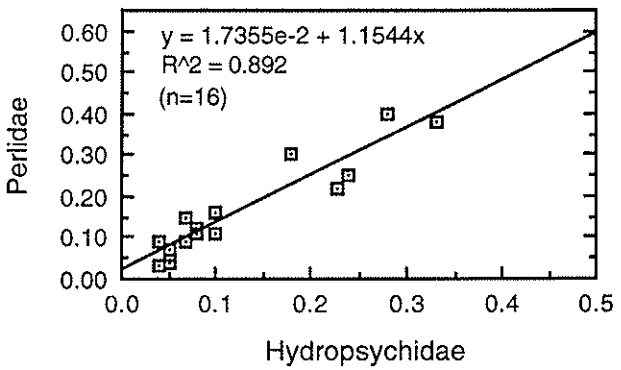


Fig. 20. Hydropsychidae (Net Collector Caddis) vs Perlidae (Predaceous Golden Stoneflies)

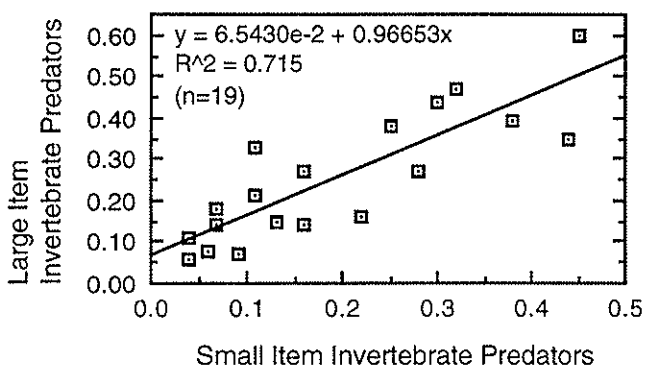


Fig. 21. Invertebrate Small Item Predators (Perlid Stoneflies, etc.) vs Large Item Predators (Hellgrammites, etc.)

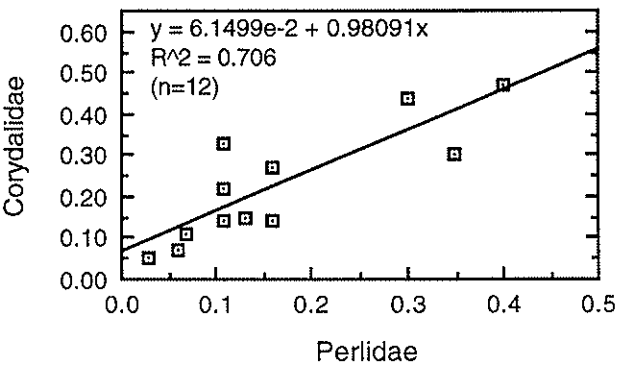


Fig. 22. Perlid Stoneflies vs Corydalid Hellgrammites

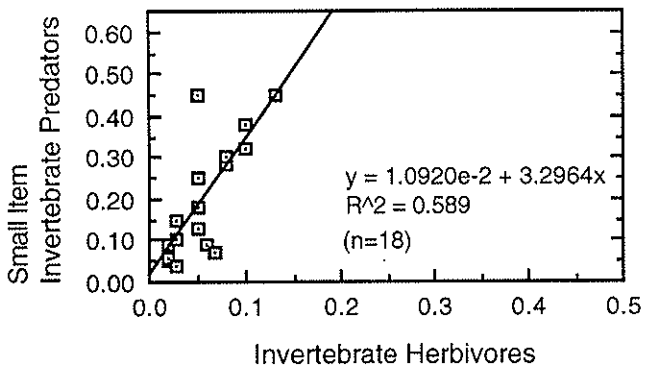


Fig. 23. Invertebrate Herbivores vs Small Item Predators (Perlid Stoneflies, etc.)

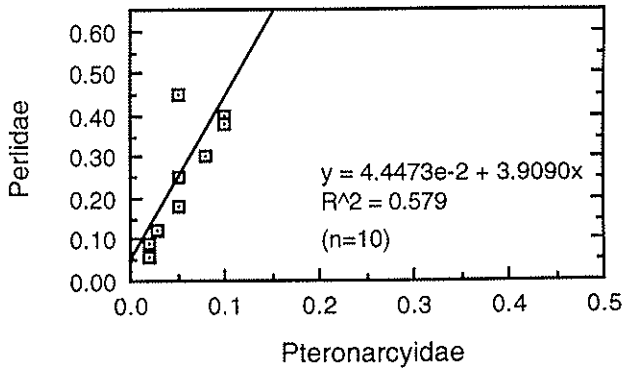


Fig. 24. Pteronarcyidae (Giant Herbivorous Stoneflies) vs Perlidae (Predaceous Golden Stoneflies)

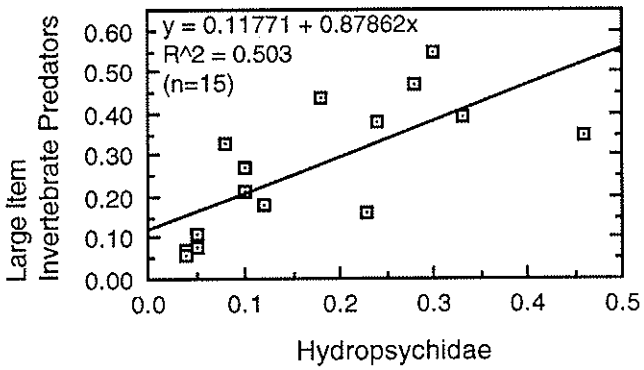


Fig. 25. Hydropsychidae (Net Collector Caddis) vs Large Item Invertebrate Predators (Hellgrammites, etc.)

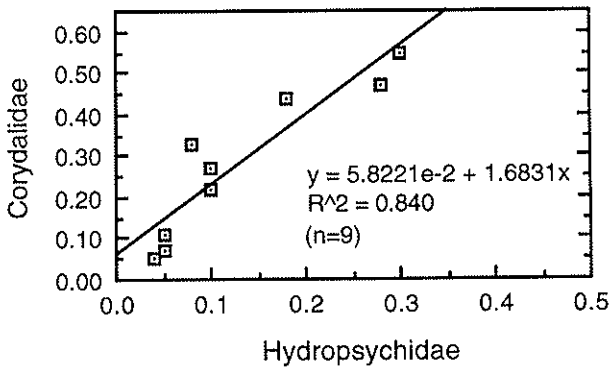


Fig. 26. Hydropsychidae (Net Collector Caddis) vs Corydalidae (Hellgrammites)

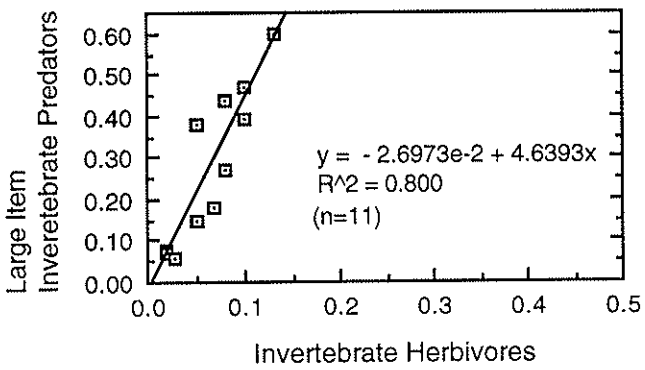


Fig. 27. Invertebrate Herbivores vs Large Item Predators (Hellgrammites, etc.)

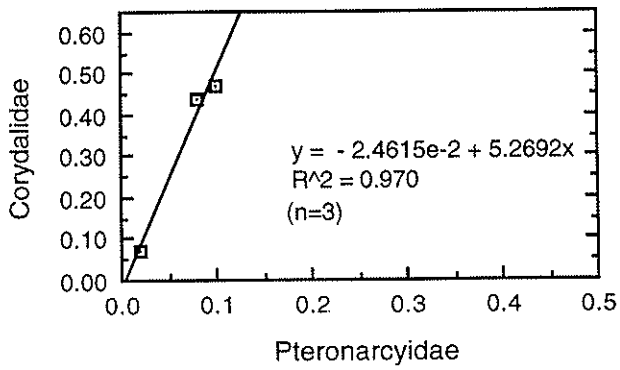


Fig. 28. Pteronarcyidae (Giant Herbivorous Stoneflies) vs Corydalidae (Hellgrammites)

DISCUSSION AND CONCLUSIONS

Biotic mercury presence and distribution in the Sierra gold region

A clear signature of anthropogenic mercury was present in the aquatic biota sampled throughout the historic Sierra Nevada gold region in this research. Concentrations ≥ 0.02 mg kg^{-1} (dry weight) were found in virtually all invertebrates sampled. On a wet weight basis, fish fillet muscle mercury was ≥ 0.03 mg kg^{-1} at all sites. Both invertebrates and fish demonstrated significantly higher mercury concentrations in regions that have sustained greatest intensities of gold mining pressure, both historically and at present.

Trout and invertebrate samples indicate relatively low levels of mercury bioavailability in the majority of the North Fork Feather River drainage and throughout most of the entire American River watershed. In contrast, significantly greater bioavailability was indicated by higher bioaccumulation of mercury in a number of areas. Notably higher mercury regions included the upper forks of the Yuba River, with the mid-reaches of the Middle and South Forks having the highest biotic mercury concentrations. Other relatively elevated mercury streams included the Bear River, the Middle Fork of the Feather River, Deer Creek, the North Fork of the Cosumnes River and, to a lesser extent, the North Fork of the Middle Fork of the American River, and Spanish Creek (tributary to the North Fork Feather River). These streams include the highest densities of active dredging operations, which also correspond generally to the greatest historical mining intensities. At sites located upstream of heavily mined stretches, e.g. the Plumbago site on the Middle Fork Yuba River, significantly lower mercury concentrations were found throughout the food web, as compared to levels within and downstream of intensively mined reaches. In ongoing work, we are attempting to more specifically define the spatial extent of mercury "hot spots", and are also trying to define a regional "background" minimum level of mercury concentrations in Sierra Nevada aquatic organisms. The biotic mercury concentrations found in this study can presumably be linked to relative concentrations of aqueous, bioavailable mercury moving down each of these streams.

Fish mercury concentrations in relation to environmental and health concerns

While these data clearly indicate the differences in relative mercury bioavailability among the various streams of the region, the absolute concentrations in rainbow trout were all well below existing health standards. Even at the highest mercury sites, the normalized 250 g rainbow trout, fresh weight, fillet muscle mercury levels were less than 50% of the 0.5 ppm guidelines suggested by the California Department of Health Services and the Academy of Sciences, and $\leq 21\%$ of the

existing U.S. FDA fish criterion of 1.0 ppm. The entire data set for 250 g normalized rainbow trout ranged between 0.03 and 0.21 mg kg^{-1} (ppm). Larger fish ranged higher but were still all within the 0.5 ppm guidelines. We conclude that there is relatively little direct health hazard associated with the consumption of rainbow trout from these waters.

Influence of reservoirs on downstream biotic mercury

It was expected that mercury bioavailability might be relatively low in the rivers and streams of this region, despite the presence of very large amounts of inorganic mercury from gold mining. This is because methyl mercury, the predominant form of mercury that enters and moves through the food web, requires a biological process, bacterial methylation, for the bulk of its production (Gilmour et al. 1992). The opportunity for bacterial mercury methylation or even the presence of significant bacterial populations is minimized in the fast moving, cold, clear water habitat typical of many of these Sierra Nevada foothill streams. However, once transported to calmer waters such as downstream reservoirs, turbid valley rivers, the Sacramento/San Joaquin Delta, and San Francisco Bay, the potential for bacterial methylation of mercury derived from the Sierra gold mining region increases dramatically. The foothill reservoirs, in particular, are likely sites of enhanced mercury methylation. Limited analyses of fish from some of these reservoirs have indeed found markedly higher mercury concentrations than those found in this study of the upstream rivers. Wet weight muscle mercury in smallmouth bass from New Bullard's Bar Reservoir averaged 0.63 ppm in a 1989 sampling of 5 fish averaging 287 g (TSMP 1991). Even carp taken from that reservoir (~800 g, n=6) averaged 0.61 ppm muscle mercury (TSMP 1992). This is in marked contrast to our upstream (North Fork Yuba River) rainbow trout data in this study (0.09-0.11 ppm in 200-340 g trout muscle).

We hypothesized that, as a result of enhanced mercury methylation within Sierra foothill reservoirs, there might be a detectable net export of bioavailable mercury from them to their downstream rivers. In contrast, the data collected in this study indicate the reverse. Not only do the reservoirs not appear to be net exporters of bioavailable mercury, but they seem to be acting as sinks for bioavailable as well as inorganic mercury. In most instances where we sampled upstream and downstream of Sierra foothill reservoirs, significantly *lower* mercury was found in the downstream biota, throughout the food web (e.g. upstream/downstream of Englebright, New Bullards Bar, and Camp Far West Reservoirs). We conclude that, despite the likely enhancement of mercury methylation within these reservoirs, the bioavailable mercury must be quickly taken up within the reservoir ecosystem itself, becoming largely unavailable for downstream transport. It was understood that these reservoirs must act as giant sinks for the inorganic mercury moving into them from upstream. The finding that they are also apparently not net exporters of bioavailable

mercury is a particularly interesting and relevant result of this study. Production and consumption of methyl mercury in the reservoir water column appears to be in equilibrium. This subject is one focus of ongoing research by our group.

Trophic feeding level relationship to mercury accumulation

Within each site, mercury concentrations in biota generally corresponded to trophic feeding level, with higher trophic levels of invertebrates containing greater concentrations of mercury. Corresponding rainbow trout, which prey on all of these invertebrates to varying extents, had still higher mercury accumulations, while piscivorous fish such as native squawfish and the larger brown trout had the highest mercury concentrations of all. Trophic bioconcentration of mercury is thus indicated to be a dominant mode of mercury accumulation by biota in this region. For basic ecological research, an interesting aspect of this work is the finding that relative mercury concentrations in aquatic species may offer a useful tool for determining the relative, time-integrated trophic feeding habits of specific aquatic invertebrates.

Correlations between the mercury contents of biota of different trophic levels were similar, whether identical types of organism were used for the comparison or a variety of representatives of each trophic guild. This suggests that when identical invertebrate species are not available between sites, a variety of species within the same trophic feeding guild may be utilized as comparative general indicators of relative mercury bioavailability.

Inter-trophic mercury correlations between various groups of co-existing invertebrates were found to be uniformly stronger than mercury concentration correlations between invertebrates and corresponding trout. This is likely due to the relative site fidelity of stream invertebrates, as compared to trout, which can wander extensively throughout their lifetime accumulation of mercury.

Correlations between mercury in stream invertebrates and mercury in co-occurring trout were stronger with increasing invertebrate trophic level. Predatory invertebrate species such as Perlid stoneflies and Corydalid hellgrammites were found to be the best indicators of corresponding trout mercury levels. The excellent correspondence between larger, predaceous invertebrates and co-occurring trout may be a function of similar diet and, particularly in the case of the large hellgrammites, similar ages and thus similar periods of mercury integration. Mercury in smaller, younger organisms such as most mayflies, Hydropsychid caddis larvae, and young predators may not correlate as well with trout mercury, but may instead be a better indicator of shorter term conditions of mercury bioavailability. Under potentially dramatic seasonally or annually changing conditions of mercury bioavailability, changes will be far less pronounced in older organisms as compared to more ephemeral species, for which the most recent time period represents a larger

proportion of the entire lifetime accumulation (Slotton et al. 1995). Thus, different organisms may be utilized for different types of information. Trout mercury is of direct interest for health reasons and provides a general indicator of regional, long-term mercury availability. Larger predaceous species may be utilized as surrogates for trout. The larger/older invertebrates of all types provide localized, long-term integration of relative mercury availability, when same types are compared. Finally, smaller/younger invertebrates can potentially be used as integrators of mercury conditions over shorter time scales. Ongoing research by our U.C. Davis Heavy Metals Limnology Group is investigating all of these areas.

Future Considerations

Stream invertebrates appear to be appropriate indicators for determining relative, integrated mercury bioavailability between sites throughout the Sierra Nevada gold region. However, the nature of the trophic structure of the invertebrate community must be considered. Invertebrates are more widely available than trout and, because they do not have the mobility of fish, their mercury accumulations can be linked with greater confidence to conditions directly at and upstream of a given locale. Certain invertebrate species can also function as surrogates for trout, with larger predatory types showing the strongest relationship. Other species may be useful in determining short-term mercury conditions. The great advantage of using native biota as indicators, as compared to standard water grab sampling protocol, is their natural and continuous integration of conditions over time and their accumulation of, by definition, the bioavailable fraction of mercury. One important focus of our ongoing environmental mercury research is in determining the relationship between aqueous mercury chemistry and corresponding integrated mercury accumulation by a range of native indicator species.

Biotic mercury data of the type presented in this study will be useful in isolating the highest mercury stream reaches. This will be instrumental both for regulatory considerations and for the development and focusing of future potential mitigation strategies.

We are currently completing mercury survey work in the region reported on here, i.e. the Feather River through American River watersheds, with the use of additional funding from the U.S. EPA through the Sacramento Sanitation District. This work is expected to be completed by early 1996. We will then present the results of this research at the upcoming International Conference on Mercury as a Global Pollutant (Hamburg, August 1996) and will also submit two or more formal articles for journal publication. Future projects include similar survey work in the Sierra Nevada gold region to the south, particularly the Cosumnes and Mokelumne Rivers, survey work throughout the California Coast Range mercury mining district, and simultaneous investigation of the research questions highlighted above.

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APPENDIX A. Examples of Fish Size vs Mercury Concentration Normalization