IMPACTS OF MERCURY ON BENTHIC INVERTEBRATE POPULATIONS AND COMMUNITIES WITHIN THE AQUATIC ECOSYSTEM OF CLEAR LAKE, CALIFORNIA

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Abstract. Benthic invertebrates from Clear Lake, site of an inactive mercury (Hg) mine, were analyzed for population and community level parameters in response to a significant point source of sediment-associated Hg. Using multiple regression, at least one taxon (*Placobdella* leeches) showed a significant decline and another taxon (*Procladius* midges) showed a significant increase in response to increasing sediment Hg. Responses of invertebrates to sediment Hg levels are complex, likely due to partial confounding between sediment Hg (especially methyl Hg), grain size and depth. Stepwise multiple regression analyses indicate that individual taxa often responded significantly to several environmental factors. *Chironomus* populations declined with increasing grain size, depth and total Hg; *Procladius* declined with increasing depth, but increased with increasing sediment grain size and Hg levels; *Chaoborus* declined with increasing depth; oligochaetes increased with increasing TOC; and *Placobdella* leeches declined with both increasing depth and sediment Hg levels. Additional multi-variate routines were used to demonstrate more complex relationships than are typically elucidated by standard multiple regression statistics. The complex results presented here may indicate that there are significant population effects above some threshold of sediment Hg concentrations. Community level parameters (diversity and evenness) declined with increasing sediment Hg levels, but with considerable variation at low Hg levels. Simple regression yielded a negative relationship between diversity and evenness versus sediment total Hg that was nearly significant, and one with sediment methyl Hg that was not close to significance. Multiple regression indicated that depth was more important than sediment Hg in describing the variation in diversity.

1. Introduction

Mercury (Hg) is one of the best known heavy metal pollutants. In marine or aquatic habitats it is most closely bound to sediments or particulate material in the water column (Luoma, 1989; Gill and Bruland, 1990; Suchanek *et al.*, 1993). Since Hg is highly insoluble, water does not hold a significant proportion of the Hg pool but it can act as an important transport medium for particulate-bound Hg. Therefore, most significant environmental impacts associated with Hg can be ultimately traced to the sediment-bound pool, especially for benthic invertebrates, which are food sources of higher trophic level taxa.

While considerable information exists on Hg (primarily as total Hg) levels and effects in many invertebrates, fishes, mammals and birds (see review by Eisler, 1987), very little work has been published on resulting population or community level effects. Many forms of pollution are known to induce population declines and community level changes, mostly as declines in numerical abundance, species richness or diversity parameters (Moore *et al.*, 1979; Winner *et al.*, 1980; Bazzanti and Seminara, 1987; Suchanek, 1993, 1994). Moore *et al.* (1979) showed decreased benthic invertebrate population and diversity levels with distance from a mine that was a point source for several heavy metals, although they point out that this decline may have been due to other environmental factors as well. Winner *et al.* (1980) found similar negative impacts on stream invertebrates in relation to heavy metal pollution.

Here we describe the results of a study on benthic invertebrate population and community responses to Hg at Clear Lake, California. Mining operations from ca. 1872-1957 at the Sulphur Bank Mercury Mine at Clear Lake deposited an estimated 100 metric tons of Hg into the aquatic ecosystem of the lake. Inorganic Hg contamination in surficial sediments at the mine face has been measured as high as 250 μg/g, although results from different studies show considerable scatter in highest values. In the vicinity of the mine Suchanek *et al.* (1993, in prep a, in prep b, unpublished data) found sediment total Hg of 183 μg/g, meHg (meHg) of 15.9 μg/kg, chironomid body burden up to 27.69 μg/g, and

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oligochaete body burden up to 41.67 μg/g. All of these values declined linearly or exponentially with distance from the mine, falling nearly below detection in sediment and to less than 0.5 μg/g in invertebrates at a distance of ca. 30 km from the mine. The present study assesses the potential influence of mercury contamination from the mine and other physical factors upon individual benthic invertebrate populations and the diversity of the benthic invertebrate community at Clear Lake.

2. Materials and Methods

Clear Lake (39°00'N; 122°45'W), located in the coast range, is the largest natural lake entirely within the borders of California. It is also shallow (mean depth *ca.* 10m), polymictic, highly eutrophic and experiences frequent noxious blue-green cyanobacteria blooms during late summer/fall and sometimes late spring (Richerson *et al.*, 1994).

Quantitative invertebrate samples for population and community analyses were collected from 36 muddy lake bottom sites in Clear Lake using a 6 inch Ekman dredge (volume = 3540 cm^3) during September 1992. Sampling sites were arranged along transects within each arm such that the greatest number of sites was in the region of the steepest gradient of sediment Hg concentrations (Figure 1). Each community sample consisted of two Ekman grabs, yielding a volume of 7080 cm^3 for each sample. Invertebrates were sieved using a 0.5 mm sieve bucket, fixed in 5% formalin and preserved in 70% ethanol. Wet weights were measured using an Ohaus Analytical Balance (detection limit = 0.0001g) after extraneous surface moisture was removed by blotting dry for 1 minute.

A summary of the analytical techniques for sediment Hg, Total Organic Carbon (TOC) and grain size are provided here, but are described more fully in Suchanek *et al.* (in prep a). Sediment total Hg levels were analyzed for 36 stations (see Figure 1) using standard cold vapor atomic absorption. MeHg levels were analyzed at 24 stations using aqueous phase ethylation, followed by cryogenic gas chromatography with cold vapor atomic fluorescence detection, as developed by Bloom and Porcella (1989). All meHg analyses were performed by Brooks Rand, Ltd., Seattle, WA, utilizing ultra-clean methodology. TOC was analyzed in lake sediments by modified EPA SW-846 Method 9060A utilizing a TOC analyzer. Grain size was determined with EPA method D 422-63, which utilizes sieving for grain sizes above 75 μm and an air dispersion sedimentation sorting process, with detection by hydrometer, for smaller grain size fractions.

Data (both numerical abundance and weights) were analyzed with ANOVA, curve fitting routines and multiple regression analyses using the statistical visualization program JMP version 3.0 for Macintosh (SAS Institute, Inc.). Stepwise multiple regression analyses were then performed on numerical abundance data for each species fitted to a Poisson distribution using the S-PLUS program for DOS-Windows (version 3.1) by StatSci, Inc. Because the relationships between independent variables were complex, local (smoothing) regression models in the LOESS routine of S-PLUS were also used to produce "*conditioning plots*" to evaluate the behavior of meHg on individual taxa as a function of the most statistically significant variables in the analysis. Invertebrate biomass was used to calculate Shannon-Wiener (ln) diversity, Simpson diversity and Evenness.

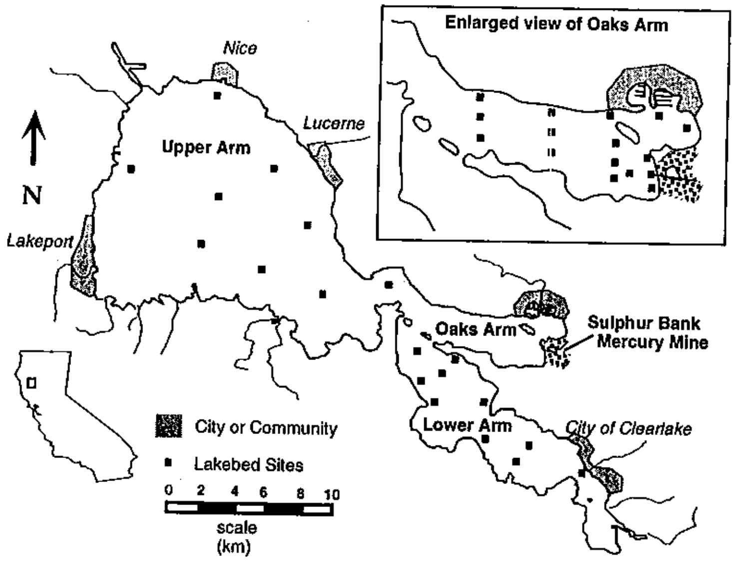

Fig. 1. Location map for study sites near the Sulphur Bank Mercury Mine at Clear Lake, California.

3. Results and Discussion

Profundal sediments within Clear Lake are composed primarily of soft flocculent muds with predominantly clay-sized particles (Suchanek *et al.* 1993) and do not support a rich infauna. Sediment total Hg levels range from 0.27 μg/g (in the Lower Arm ca. 22.4 km from the mine) to 183 μg/g (about 0.88 km from the mine) and meHg levels range from 0.18 μg/kg (22.4 km from the mine) to 15.9 μg/kg (1.1 km from the mine) (Suchanek *et al.*, in prep a).

The five most abundant taxa found within profundal sediments of Clear Lake during this study and analyzed for population estimates and community diversity indices are provided in Table I.

TABLE I

Most common benthic invertebrate taxa found within profundal sediments at Clear Lake.

TAXON [common name]	TROPHIC STATUS [diet]	ABUNDANCE PER SAMPLE MEAN ± SD	ABUNDANCE PER SAMPLE RANGE	BIOMASS PER SAMPLE (g) MEAN ± SD	BIOMASS PER SAMPLE (g) RANGE
Annelida					
Hirudinea					
Placobdella translucen. [leech]	predator/scavenger	2.8 ± 7.0	0-39	0.012 ± 0.025	0-0.089
Oligochaeta					
oligochaete spp. [aquatic worm]	detritivore [sediments]	153.3 ± 94.2	12-398	0.694 ± 0.444	0.028-2.094
Arthropoda					
Insect larvae					
Chaoborus astictopus [phantom midge]	predator (zooplankton)	2.6 ± 4.5	0-21	0.003 ± 0.005	0-0.021
Chironomus spp. [midge]	detritivore [sediments]	20.4 ± 31.6	0-115	0.161 ± 0.164	0-0.703
Procladius bellus [midge]	predator [chironomids, zooplankton]	17.1 ± 20.9	0-78	0.027 ± 0.031	0-0.109

Population-Level Responses:

The five taxa of profundal invertebrates were highly variable (spanning over two orders of magnitude) in their numerical abundance and biomass among the 36 stations analyzed from Clear Lake. However, numerical abundance was usually tightly correlated with biomass (R^2 for *Chironomus* = 0.748, *Procladius* = 0.844, *Chaoborus* = 0.803, pooled oligochaetes = 0.683, *Placobdella* = 0.581). Most taxa usually occurred in relatively low numbers (i.e. less than ca. 20 per sample), except oligochaetes, which sometimes reached nearly 400 individuals per sample. Because numerical abundance and biomass were correlated, and because numerical counts were more easily fitted to a Poisson distribution, most analyses evaluating population responses to environmental variables were performed on numerical abundance values.

Benthic invertebrate populations, as measured by numerical abundance and biomass, are plotted as a function of sediment total Hg levels (Figure 2) and meHg levels (Figure 3). Initial viewing of these plots indicates that *Chironomus* appear to decline exponentially with increasing sediment Hg (especially total Hg), whereas *Procladius* appear to increase in response to sediment Hg levels (Figures 2A,B; 3A,B). The phantom midge, *Chaoborus*, also appeared to decline exponentially or linearly as a function of sediment Hg levels (Figures 2C, 3C). The taxon with the greatest biomass and highest numerical abundance was oligochaetes. Several oligochaete genera exist within the sediments of Clear Lake, but all were pooled in this study. There was no clear relationship between sediment Hg levels and oligochaete populations (Figures 2D, 3D). On the other hand, *Placobdella* leeches exhibited an exponential decline with increasing sediment Hg levels (Figure 2E, 3E).

Although there appear to be striking declines in the populations of several taxa as a function of sediment Hg levels, other environmental factors complicate the picture. Stepwise multiple regression models were used to determine the relative significance of depth, grain size, TOC, meHg and total Hg on numerical abundance and biomass for each taxon (*Chironomus*, *Procladius*, *Chaoborus*, oligochaetes and *Placobdella*).

Results from these analyses indicate that Clear Lake benthic invertebrate populations are responding to a variety of environmental variables, with the most influential factors being depth, grain size and meHg. One major difficulty that arose in analyzing the responses of these taxa to environmental variables was the fact that sediment Hg concentrations are partially confounded with grain size ($P < 0.001$, $R^2 = 0.274$). Further complicating the analysis is the fact that meHg is even more strongly confounded with total Hg ($P < 0.001$, $R^2 = 0.387$). This created some problems in establishing a basis for causality, but despite these difficulties, some clear trends emerged from further analyses.

Table II provides a summary of the Poisson fitted regression analyses. It should be noted that the results reported in this table reflect significance values from a conservatively approximated F-test (S-PLUS routine First, Poisson regression analyses were performed for each taxon against meHg and total Hg. These individual regression results indicate that only the positive relationship of the midge *Procladius* and the negative relationship of the leech *Placobdella* were statistically significant.

Next, stepwise multiple Poisson regression analyses were used to select variables influencing abundances (and biomass) based on depth, grain size, TOC and meHg considered together. Then this same procedure was followed using the same independent variables and total Hg. MeHg and total Hg were not run together because of their strong correlation.

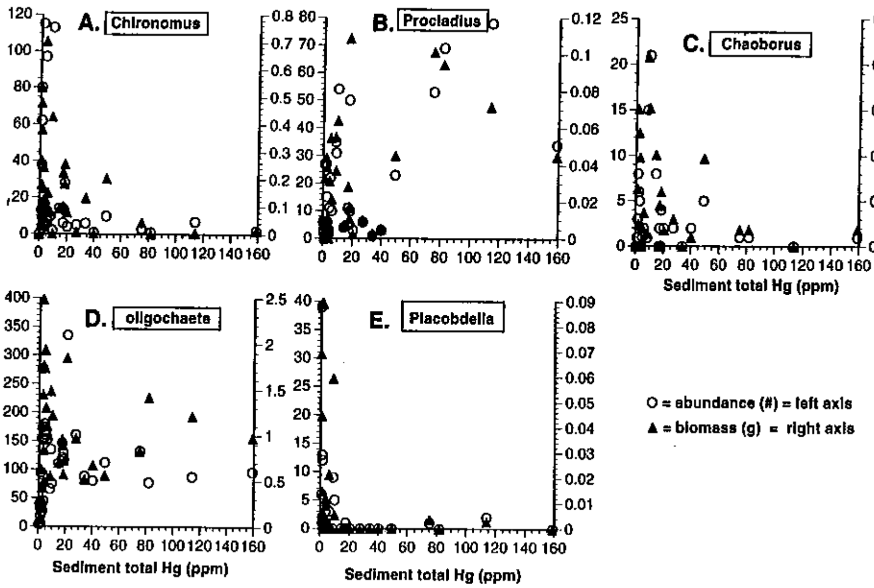

Fig. 2. Benthic invertebrate abundance and biomass as a function of sediment total Hg. A= Chironomus, B= Procladius, C= Chaoborus, D= Oligochaetes, E= Placobdella

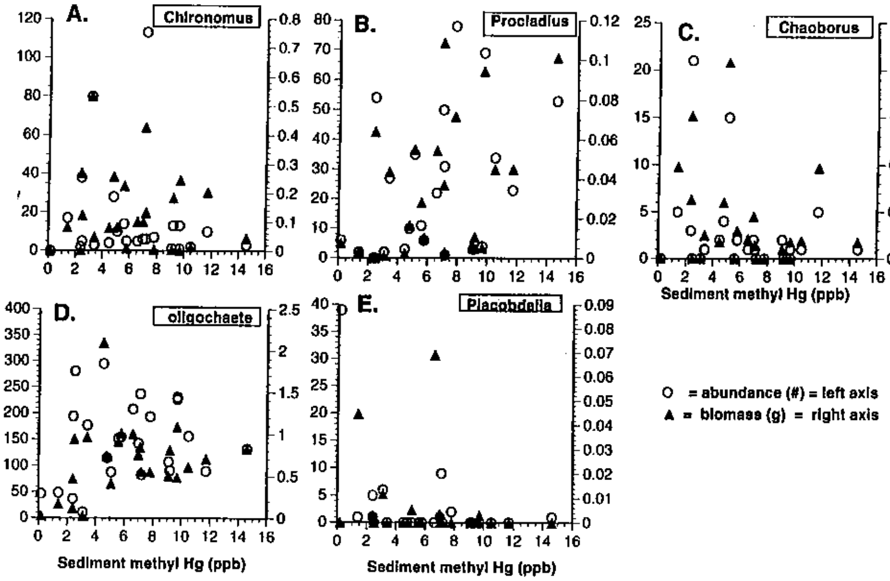

Fig. 3. Benthic invertebrate abundance and biomass as a function of sediment meHg. A= Chironomus, B= Procladius, C= Chaoborus, D= Oligochaetes, E= Placobdella

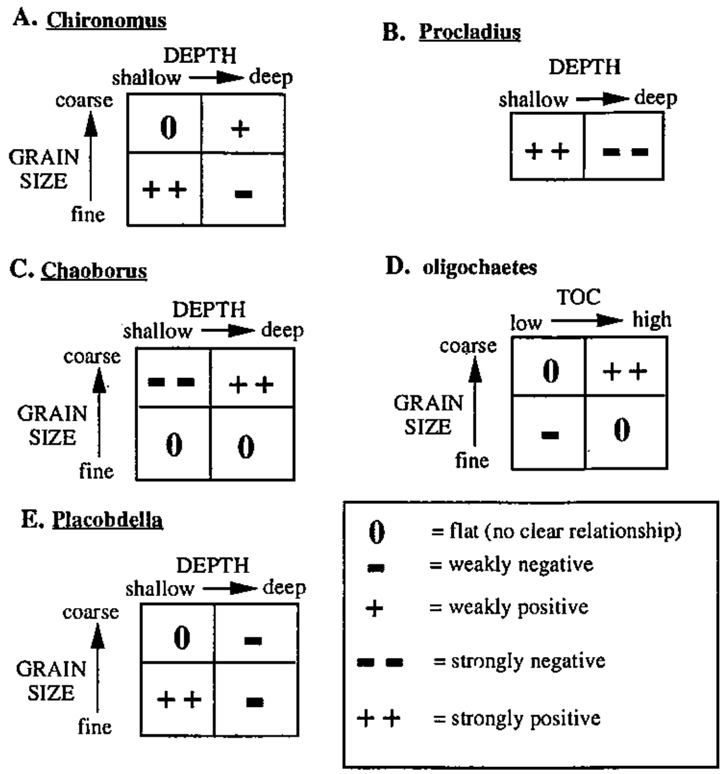

Fig. 4. Conditioning plots showing the relationship between changing population levels and sediment meHg concentrations as a function of the most significant independent variables as determined by stepwise multiple regression analysis.

under conditions of low grain size and shallow depth is strongly positive, but at deep depths, it becomes weakly negative. Furthermore, under the same deep depth regime, the relationship changes sign again with an increase in grain size. Similarly, there is a dramatic switch in the population response of *Procladius* to meHg under changing depth regimes. This indicates that the results obtained by fitting prescribed regression models to these types of data may not reveal more subtle and complex relationships within the system.

There are likely to be additive and multiplicative factors responsible for the distributions of these benthic invertebrate populations. Standard multiple regression statistics yield an overall appreciation of the gross level population responses that are strongly influenced by specific environmental variables. However, given the types of coconfounding present in these data, it is quite possible that several variables act in concert to influence the abundance and distribution of these populations, but the specific contributions from specific environmental variables cannot be clearly delineated. Sediment Hg appears to have some significant influence on these benthic invertebrate populations, especially for the leech *Placobdella* at deep depths. Whether other, more subtle, interactions involving Hg are present will be evaluated during an ongoing seasonal investigation at Clear Lake during 1994-1995.

Community-Level Responses:

Shannon-Wiener and Simpson diversity indices and Pielou's Evenness index each exhibited a decline in community diversity as a function of increasing sediment Hg concentrations, for both total Hg and meHg. Figure 5 shows that there is a tighter relationship between

Shannon-Wiener diversity and sediment total Hg than with sediment meHg. Although Simpson's index (not shown) is not as sensitive (i.e.- gives relatively less weight) to the presence of rarer species, both indices show virtually identical results. In either case, the regression lines plotted in Figure 5 represent a decline in diversity and evenness as a function of increasing Hg, which proved to be close to statistical significance at P = 0.1103. However, diversity showed greater significance with depth than either total Hg or meHg. These results are compatible with those of Moore *et al.* (1979) who found increasing species richness and diversity with distance from a mine (but indicated that other factors may be responsible for this trend) and Warwick (1991) who found reduced species richness at sites highly contaminated with Hg. It is unclear what influence a more in-depth and precise taxonomic identification of oligochaetes would have on these results.

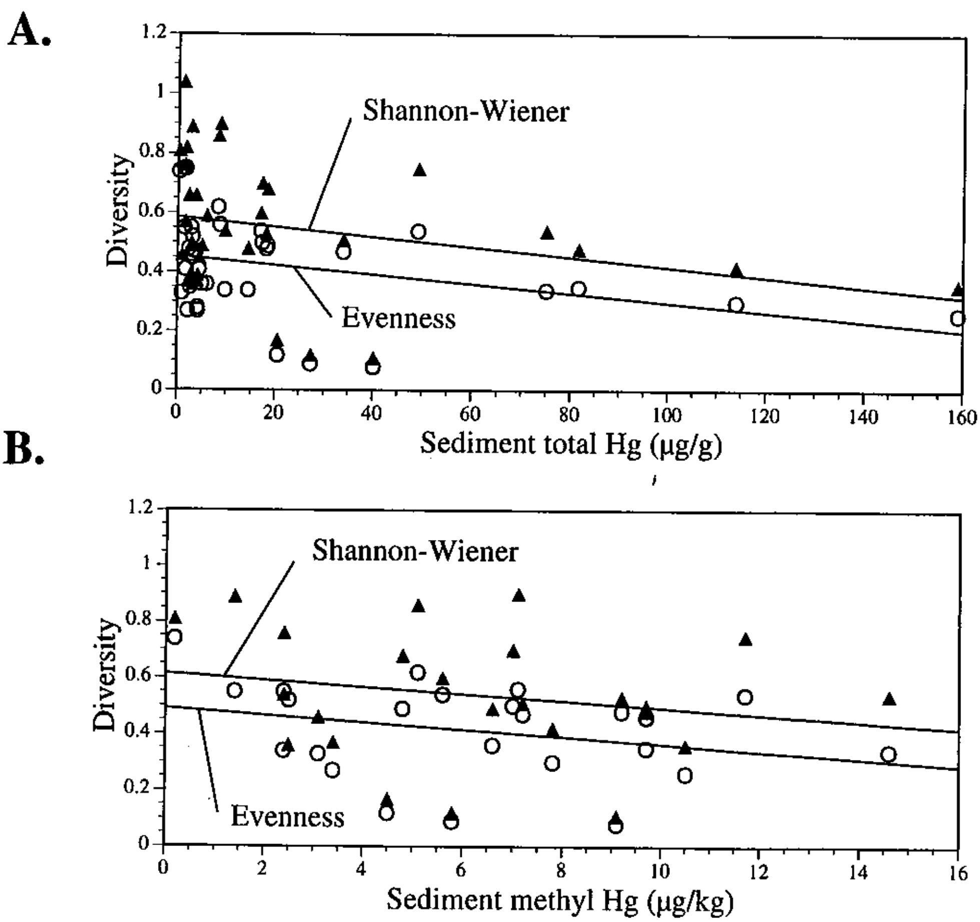

Fig. 5. Shannon-Wiener diversity and Evenness as a function of A= total sediment Hg concentrations, B= sediment meHg concentrations. Solid triangles = Shannon-Wiener; Open circles = Evenness

4. Conclusions

Populations of benthic invertebrates at Clear Lake showed complex relationships to sediment Hg levels and several environmental parameters including depth, grain size and TOC. Standard multiple regression statistics using Poisson fitted models indicated that each of the five taxa analyzed were responding most significantly to a unique combination of natural environmental variables and sediment Hg levels. While plots of population parameters versus sediment Hg levels yield visual relationships, multiple regression analyses produced statistically verifiable relationships to sediment Hg in only a few taxa.

Populations of the leech *Placobdella* yielded the most significant negative relationship to increasing sediment Hg (especially at deep depths), whereas the midge *Procladius* appears to have a positive relationship to increasing sediment Hg levels (especially at shallow depths). This positive relationship may indicate a species-specific resistance to Hg and/or be related to reduced competition from another chironomid midge (*Chironomus*) in regions of high sediment Hg. *Procladius*, *Chaoborus* and *Placobdella* all had significant relationships to depth, *Chironomus* responded most significantly to grain size and oligochaetes most significantly to TOC (and not depth), but each responded differently to sediment Hg levels at varying depth regimes.

Community level parameters (diversity and evenness) declined with increasing sediment Hg levels with considerable variation at low Hg levels. Simple and multiple regression analysis yielded a relationship between diversity/evenness that was nearly significant for sediment total Hg, but not close to significance for sediment meHg.

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