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Toxic Elements in Aquatic Sediments: Distinguishing Natural Variability from Anthropogenic Effects

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Abstract

Regressions of aluminum against potentially toxic elements in the sediments of freshwater aquatic systems in Louisiana were used to distinguish natural variability from anthropogenic pollution when elemental concentrations exceeded screening effects levels. The data were analyzed using geometric mean model II regression methods to minimize, insofar as possible, bias that would have resulted from the use of model I regression. Most cadmium concentrations exceeded the threshold effects level, but there was no evidence of an anthropogenic impact. In Bayou Trepagnier, high concentrations of Cr, Cu, Pb, Ni, and Zn appeared to reflect anthropogenic pollution from a petrochemical facility. In Capitol Lake, high Pb concentrations were clearly associated with anthropogenic impacts, presumably from street runoff. Concentrations of potentially toxic elements varied naturally by as much as two orders of magnitude; hence it was important to filter out natural variability in order to identify anthropogenic effects. The aluminum content of the sediment accounted for more than 50% of natural variability in most cases. Because model I regression systematically under-estimates the magnitude of the slope of the regression line when the independent variable is not under the control of the investigator, use of model II regression methods in this application is necessary to facilitate hypothesis testing and to avoid incorrectly associating naturally high elemental concentrations with human impacts.

Keywords

Bias; Metals; Model II regression; Screening values; Sediments

1 Introduction

Issues concerning contamination of the sediments of aquatic systems by potentially toxic elements have become increasingly relevant to scientists, policy makers, and citizens in recent years. Contaminated sediments, which have been detected in every major US watershed (EPA 2004), are a threat to water quality, aquatic ecosystems, and human health. Some of this contamination is unrelated to human actions, but instead it is the result of natural chemical and physical weathering of igneous and metamorphic rocks and soils located upstream (Kennish 1992). However, a wide range of human activities have been

linked to contamination of sediments, including manufacturing processes, agricultural practices, and vehicular traffic on roadways.

Sediment analysis is important for several reasons. First, it can help to identify metals that are released into water bodies from anthropogenic point sources and are then adsorbed rapidly by particulate matter, which makes detecting their presence difficult by water-monitoring methods alone (Thomas and Meybeck 1992). Also, locating contaminated sediments is necessary given that they may be a secondary source of pollution when they are disturbed and become re-suspended within a water body (Forstner and Heise 2006). Furthermore, changes in measured concentrations of potentially toxic elements in sediments over time may be a useful indicator of the effectiveness of environmental policies and remedial measures (Matteucci et al. 2005).

One of the challenges associated with analyzing sediment quality data and interpreting the results is how to identify accurately the spikes or readings of higher-than-expected levels of particular pollutants in certain locations. Given the natural geographic variability of naturally occurring elements such as cadmium, lead, and arsenic, it may be difficult to ascertain the contribution of human activities to these elements in locations where their concentrations are naturally high. Certainly if sediment monitoring is to help identify water bodies that are affected by human activities and may need to be more closely regulated, it is useful to examine and improve upon the statistical methods often employed to interpret concentrations and to draw conclusions with respect to remedial actions.

Our research objective was to identify and reduce the effects of key confounding factors that limit the utility of regression analyses in sorting out the effects of human activity from naturally occurring conditions on potentially toxic elements in the sediments of aquatic systems. These confounding factors arise when certain statistical assumptions, such as control over the independent variable, are violated, thus producing biased estimates of the slope and intercept of the regression line. Reducing these confounding factors will result in increased accuracy in identifying those locations where human activities have impacted the concentrations of potentially toxic elements. Our objectives address one of the key observations concerning the current state of sediment monitoring presented by the EPA in the 2002 National Sediment Quality Survey report to Congress; that is the need for more refined evaluation methods and better monitoring and assessment tools to improve contaminated sediment management (EPA 2004). This is very relevant to analysts in many state environmental agencies, who need to identify as accurately as possible locations requiring either additional monitoring or remedial action, and who must make these decisions in the context of significant limitations of technical resources and personnel.

2 Evaluating Sediment Quality

Section 503 of the Water Resources Development Act of 1992 (WRDA) defines contaminated sediment as that “which contains chemical substances in excess of appropriate geochemical, toxicological, or sediment quality criteria or measures; or is otherwise considered by the EPA to pose a threat to human health or the environment” (EPA 1992). The WRDA mandates that the US Environmental Protection Agency (EPA), in consultation

with the National Oceanic and Atmospheric Administration (NOAA) and the US Army Corps of Engineers (USACE), conduct regular comprehensive national surveys of sediment quality and submit reports to Congress (EPA 1997). These National Sediment Quality surveys aggregate data derived from a variety of sediment and water quality monitoring efforts at the state and federal levels over past years. In the two subsequent reports to Congress (2001 and 2004), the EPA surmised that contamination of sediments is a problem in all regions of the US and determined that metals and persistent organic chemicals are the most commonly observed pollutants. This contamination is associated with discharges from point sources, non-point source surface run-off, and atmospheric deposition, and from the rerelease of pollutants through natural and human actions that have the effect of disturbing or remixing sediments at the bottom of water bodies (EPA 2001; 1–1).

In addition to the National Sediment Quality Survey, several programs have been established for the comprehensive monitoring of sediments. These include EPA's Environmental Monitoring and Assessment Program (EMAP), NOAA's National Status and Trends Program, and EPA's Great Lakes National Program Office. These programs collect data on the physical and chemical characteristics of sediments, the bioavailability of contaminants, the levels of contaminant residues in the tissues of aquatic organisms, and the health of benthic communities.

Suggested criteria or guidelines to evaluate sediment contamination in water bodies have been offered by EPA, NOAA, as well as several states, including Virginia and Washington, whose officials are interested in protecting designated areas such as Puget Sound and the Chesapeake Bay. The EPA criteria used in the National Sediment Quality Survey and NOAA's Screening Quick Reference Tables (SQRT) are not regulatory in nature, but have been developed to aid state regulatory agencies in assessing sediment quality in specific water bodies and in considering the potential impacts of contaminated sediment on water quality, fish and other organisms, and ultimately on human health (EPA 2001) (Buchman 1999).

The NOAA guidelines compare sediment contaminant concentrations to “applicable EPA Ambient Water Quality Criteria (AWQC) for the protection of aquatic organisms”, although “promulgated criteria similar to the AWQC are generally not available for contaminated sediments” (Buchman 1999, p. 1). NOAA's screening values are based on comparisons with levels of inorganic contaminants found in natural soils of the United States, to estimate which contaminants may be elevated and thus represent potential contaminant sources to aquatic habitats of concern. NOAA's SQRT tables present multiple screening values to convey the range of concentrations that have been linked to adverse effects on aquatic life. For freshwater sediment, this spectrum ranges from likely non-toxic levels of contamination or “background” levels of compounds; to conservative measures of threshold levels—the lowest threshold effects; to the less conservative level, the threshold effects level; to the probable effects level (PEL); and to the upper effects threshold (UET), which may indicate toxic levels of contamination. For marine sediment, the screening values range from the lowest threshold effects level (TEL), to effects range-low (ERL), to a probable effects level (PEL), to the effects range median (ERM), and to the apparent effects threshold (AET). Screening with TEL's indicates that the pollutant poses no potential threat. Upper thresholds

(e.g., PEL's) identify pollutant concentrations above which effects can be expected and may be approaching toxic levels (Buchman 1999, p. 12).

Although not regulatory, the NOAA screening guidelines are useful to state regulators evaluating sediment quality in the larger context of water quality and the designated uses of water bodies within the states. Section 305-b of the Clean Water Act requires states to evaluate whether water quality within the state meets appropriate standards for five designated uses. The designated uses are aquatic life, swimming, fish consumption, shellfish consumption, and drinking water. (Drinking water use carries the most stringent standards, conforming to criteria for public drinking water supplies.) State officials usually compare data on sediment quality to the NOAA screening guidelines, and if there is an exceedance, they may decide to conduct follow-up monitoring of the site. For example, Virginia officials assessing a water body designated for supporting aquatic life would compare the measured concentration levels of specific pollutants to the NOAA effects range-medium (ER-M) for marine or freshwater sediments. If they find one or more exceedance of an ER-M value, they would conduct further biological monitoring to assess the water body's support of aquatic life (VADEQ 2007). Officials in Louisiana would follow a similar protocol (Chris Piehler, LDEQ, 2007, personal communication).

It should be pointed out that total metal content used as a screening guideline may not provide a true toxicity evaluation. Heavy metals are present in various forms: dissolved, adsorbed, bound to carbonate and iron and manganese oxides, insoluble organic matter forms, and within the structure of primary minerals (Shannon and White 1991). In addition, sediment organic matter and clay content, pH, and redox status are also important physiochemical properties influencing the availability or toxicity of heavy metals.

3 Materials and Methods

3.1 Sample Collection and Chemical Analysis

A total of 198 10-cm sediment cores were collected from a wide range of lakes and rivers by the Louisiana Department of Environmental Quality (DEQ) during the year 2002 (Fig. 1). The cores were taken as part of a study of mercury pollution and included samples from 45 of 64 Louisiana parishes. The elemental analyses reported here were carried out on preserved sections of the cores subsequent to completion of the mercury study. The organic matter content of the sediment samples averaged 3.5% (range <0.1% to 8.5%). The texture of the majority of the sediment samples were fine grain silt or silty clay. Less than 20% of the sediment samples were coarse texture consisting of sand or sandy loam material.

Elements were extracted from aliquots of about 0.75 g of dry sediment by digestion in 10 ml of concentrated trace metal grade nitric acid at ~120°C for 8 h. The acid plus extracted solids were diluted to 50 ml with deionized water and the mixture shaken vigorously and allowed to settle 14 h until the supernatant was clear (Hou et al. 2006).

Elemental analyses were carried out on the clear supernatant using a Spectro CIROS inductively coupled plasma (ICP) in a certified soil testing laboratory, which used internal reference standard and outside laboratory calibration for QA/QC. The method detection

limit for Al, As, Cd, Cr, Cu, Mg, Ni, Pb, Se, and Zn was 0.00009, 0.003, 0.0003, 0.0006, 0.001, 0.00002, 0.0008, 0.002, 0.004, and 0.0004 ppm, respectively. On average, the ratio of standard deviation to mean for each sample was about 2.96%, 3.85%, 3.17%, 2.28%, 2.17%, 2.73%, 2.78%, 3.28%, 3.87%, and 3.90% for Al, As, Cd, Cr, Cu, Mg, Ni, Pb, Se, and Zn, respectively. Seventy of the samples contained more than 3% Fe and these were automatically diluted by the instrument. Unfortunately, corrections for dilution were made incorrectly by the analytical chemist and results from those 70 samples were therefore excluded in the subsequent data analysis. In the remaining samples, concentrations of cadmium, copper, arsenic, zinc, and selenium were sometimes below the limit of detection. Concentrations judged to be less than the limit of reliable quantitation were ignored. The average number of useful data was 111, with a range from 86 (zinc) to 128 (lead, nickel, and chromium). We compared the results of the DEQ study with previously reported data obtained from two overtly contaminated bodies of water, Capitol Lake near the State Capitol in Baton Rouge (DeLaune et al. 1989) and Bayou Trepagnier, the recipient of discharges from a petrochemical facility near the Bonnet Carré Floodway (DeLaune et al. 1987).

3.2 Statistical Methods

The analyses reported here focused on the metals cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb), nickel (Ni), and zinc (Zn), the metalloid arsenic (As), and the nonmetal selenium (Se). Following the approach advocated by Pardue et al. (1992), we examined the relationships between elemental concentrations and aluminum.

First, a regression line was fit to the element versus Al data. We used a model II geometric mean regression to minimize, insofar as possible, bias associated with the use of a model I regression, because the independent variable (Al) was not under our control (Laws 1997; Ricker 1973). In ordinary model I regression, the least squares slope (b_I) is given by the equation

$$b_I = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sum (x - \bar{x})^2} \quad (1)$$

where x and y are the average values of the independent variable x and dependent variable y , respectively. The geometric mean model II slope (b_{II}) is related to b_I by the equation

$$b_{II} = \frac{b_I}{|r|} \quad (2)$$

where $|r|$ is the absolute value of the correlation coefficient r . The intercept (a_{II}) of the regression line is calculated from the equation

$$a_{II} = \bar{y} - b_{II} \bar{x} \quad (3)$$

Noise tends to be positively correlated with the magnitude of the signal (Fig. 2) and because our elemental concentrations spanned several orders of magnitude, this tendency would have confounded the interpretation of error bounds. We were able to overcome this problem by log transforming the data, i.e., by regressing $\log(\text{Al})$ against the logarithm of an element's concentration. We accepted the assumption that deviations from the regression line were normally distributed if the type I error probability was greater than 5% using a Lilliefors test for goodness of fit to a normal distribution. All of the log-transformed datasets satisfied the assumption that the deviations from the model II regression line were normally distributed.

Using the model II regression lines fit to the DEQ dataset, we then examined the Capitol Lake and Bayou Trepagnier data for evidence of metal contamination. For a single sample (X_0, Y_0) drawn from an independent dataset, the variance of Y_0 about the regression line is given by the equation

$$V(Y_0) = V(Y|X) \left(1 + \frac{1}{N} + \frac{(X_0 - \bar{X})^2}{\sum (X - \bar{X})^2} \right) \quad (4)$$

where $V(Y|X)$ is the variance of the original (i.e., DEQ) data about the regression line, N is the number of data in the original dataset, X_0 is the X coordinate (i.e., logarithm of the Al concentration) of the single sample, and $\bar{X}$ is the mean value of all the X coordinates in the original dataset (Laws 1997). The square root of Eq. 4, multiplied by the appropriate t statistics, gives the upper and lower 95% and 99% confidence limits for the deviation of a single data from the regression line. Judgments about metal contamination in the Capitol Lake and Bayou Trepagnier datasets were based on the percentage of samples that fell above the upper 95% and 99% confidence limits so calculated.

4 Results

Results are shown in Figs. 3, 4, 5, 6, 7, 8, 9 and 10. The left-hand panels show the regressions of elements against aluminum. The horizontal lines are National Oceanic and Atmospheric Administration threshold effects levels and probable effects levels for metals and metalloids in freshwater sediments (Buchman 1999). The dashed and dotted curves are the 95% and 99% confidence intervals, respectively, about the regression lines for a single data from an independent dataset. The right-hand panels show the relationship between the pH of the interstitial water of the DEQ samples and the deviations from the regression line in the left-hand panel. The deviations were negatively correlated (Spearman's rank correlation coefficient, $p < 0.05$) with pH for metals in periodic table groups 12 and 14 (Cd, Zn, and Pb) and positively correlated with pH ($p < 0.05$) for metals in groups 6, 10, and 11 (Cr, Ni, and Cu). There was no significant correlation between the deviations and pH for As and Se.

For comparative purposes, we show metal concentrations reported by DeLaune et al. (1989, 1987) in sediments that they considered to be contaminated with Cr, Pb, and Zn. Our analysis clearly flags some of their Cr and Zn concentrations (Figs. 5 and 10) and most of their Pb concentrations (Fig. 7) as abnormally high, but would also include some of their Cu

and Ni concentrations (Figs. 6 and 8) in the same category. Many of the Pb concentrations from both Capitol Lake and Bayou Trepagnier are well above the NOAA probable effects level and more than an order of magnitude higher than the upper 95% and 99% confidence limits from our regression line.

Magnesium (Fig. 11) is an alkaline earth metal whose concentration we would not expect to be impacted by human activities. On a log-log plot its concentration was highly correlated with aluminum ($r=0.81$), but Pb, Ni, and Se ($r=0.85$, 0.92 , and 0.95 , respectively) were even more highly correlated. Deviations from the log-log Mg–Al regression line; however, were more highly correlated with pH ($p=0.006$) than was the case for any other metal, with higher Mg concentrations associated with higher pH.

5 Discussion

For several decades geochemists have used regression analysis with Al as the independent variable to identify baseline concentrations of potentially toxic heavy metals (Pardue et al. 1992; Schropp et al. 1990; Windom et al. 1989). This is an approach with great potential for sorting out anthropogenic effects from natural variability as long as potentially confounding factors are dealt with appropriately. These include, inter alia, the following: first, when the independent variable X is not under the control of the investigator, a standard model I regression will give a biased estimate of the slope and intercept of the underlying relationship (Laws and Archie 1981). The nature of the bias is to systematically underestimate the magnitude of the slope of the linear relationship between X and Y . The alternative is to use model II regression methods and of these Ricker (1973) has argued that the geometric mean or reduced major axis method is the best with respect to minimizing bias. Assuming a positive correlation between X and Y , fitting a model I regression line to the data will tend to inappropriately flag as high outliers values of Y associated with large values of X .

Second, if the deviations from a regression line follow a normal distribution, 5% of them will tend to lie outside the standard 95% confidence intervals. There is no reason to flag such numbers as outliers. They are just as much a part of the normal distribution of deviations as the data inside the 95% confidence intervals. In our analysis we found that all of the DEQ data, when log transformed, adhered to the assumption of a normal distribution of deviations from the model II regression line. There is obviously no way to ensure that any particular statistical procedure cleanly separates normally distributed errors from outliers, but the approach we have used (Lilliefors test) is far less prone to type I error than flagging 5% of the data as outliers because they lie outside the 95% confidence intervals.

Third, we tested the distribution of deviations in each dataset for normality and used transformations of the original data to obtain a distribution of deviations consistent with the assumption of normality. Confidence intervals are meaningless unless the distribution of deviations can be associated with a particular distribution function. The expectation value of the deviations should be zero, and the variance of the deviations should be independent of the magnitude of the X variable. The latter assumption is clearly violated by the

untransformed Ni vs. Al data in Fig. 2 but is satisfied by the analogous transformed data in Fig. 8.

Comparison of our results with the NOAA TEL and PEL standards is provocative. With the exception of one Cd value, none of the metal or metalloid concentrations from the 2002 DEQ survey fell above the probable effects level. However, all of the Pb values measured in Capitol Lake sediments (DeLaune et al. 1989) and many of the Pb, some of the Ni, two of the Cd, and one of the Cr concentrations in the sediments of Bayou Trepagnier (DeLaune et al. 1987) exceeded the PEL. Of these high values, all of the Pb concentrations and several of the Ni concentrations were above the upper confidence limit for uncontaminated sediments (Figs. 7 and 8), but none of the high Cd and Cr values exceeded the corresponding upper confidence limits (Figs. 4 and 5). Based on this analysis, the high Pb concentrations in the sediments of Capitol Lake and Bayou Trepagnier would be attributed to anthropogenic effects, but the highest Cr concentration and the two highest Cd concentrations would not.

Thirteen percent of the DEQ arsenic values fell between the TEL and PEL for freshwater sediments, but none of those exceeded the upper confidence limits for natural samples (Fig. 3). Most of the Cd concentrations in both the DEQ survey and Bayou Trepagnier exceeded the TEL for Cd (Fig. 4) and the Bayou Trepagnier data appear more-or-less evenly dispersed among the DEQ results. Thus, although most of the Cd values lie above the TEL, our analysis does not implicate anthropogenic effects. Fifty-eight percent of the Cr concentrations from Bayou Trepagnier lay between the TEL and PEL (Fig. 5) and about half of those exceeded the upper confidence limit for uncontaminated sediments. Our analysis is therefore consistent with DeLaune et al. (1987) conclusion that the bayou is contaminated with Cr. Thirteen percent of the DEQ chromium concentrations also exceeded the TEL, but all of these lay within the confidence limits for uncontaminated sediments. Of the Cu concentrations, 43% of the Bayou Trepagnier values exceeded the TEL, but only four of 128 DEQ values (Fig. 6). The fact that three of the 114 DEQ Cu concentrations exceeded the upper 95% confidence limit (Fig. 6) is to be expected for a normal distribution of values, but the fact that six of 73 Bayou Trepagnier Cu concentrations exceeded the same limit (and that three of those six also exceeded the upper 99% confidence limit) is not. Thus, there is evidence of Cu contamination of the sediments in Bayou Trepagnier. Of the DEQ lead values, only four of 128 exceeded the TEL and three of those lay marginally above the upper 95% confidence limit for uncontaminated sediments (Fig. 7). Thus, there is no evidence of Pb contamination in the DEQ dataset. Twenty percent of the DEQ nickel values exceeded the TEL (Fig. 8), but all of these lay within the confidence limits for uncontaminated sediments. Many of the Bayou Trepagnier Ni values lay between the TEL and PEL and overall 18% of the Bayou Trepagnier Ni concentrations exceeded the upper 95% confidence limit for uncontaminated sediments. Thus, there is good evidence that the sediments of Bayou Trepagnier are contaminated with Ni. Only five of 128 DEQ zinc values exceeded the TEL for zinc (Fig. 10) and only three of those lay above the upper 95% confidence interval for uncontaminated sediments. Sixty percent of the Bayou Trepagnier Zn values exceeded the TEL and 12% and 5% exceeded the upper 95% and 99% confidence limits, respectively, for uncontaminated sediments. Thus, our analysis supports Delaune et al.'s (1987) conclusion that Bayou Trepagnier is contaminated with zinc.

Of the elements examined in this study, there was a correlation between deviations from the regression lines and pH for all of the metals. Deviations for metals with group numbers less than 12 (Mg, Cr, Ni, and Cu) were positively correlated with pH. Deviations for metals with higher group numbers (Cd, Zn, and Pb) were negatively correlated with pH. Without knowing more about the chemistry of the sediments, it is problematic to interpret these patterns. Furthermore, comparison of the magnitude of the deviations explained by pH effects with the range of concentrations accounted for by aluminum indicates that Al accounts for far more natural variability than pH and it is unlikely that taking pH into account would enhance the ability of government agencies to separate anthropogenic impacts from natural variability.

6 Synthesis

The results presented here indicate that the concentrations of potentially toxic elements in freshwater sediments can naturally vary by as much as two orders of magnitude and that a substantial portion (>50% in seven of the nine cases examined here) of that natural variability can be accounted for by the concentrations of aluminum in the sediment. Whether the relationships between aluminum and other elements reflect direct or indirect effects, the use of regression lines and their associated confidence intervals, when appropriately calculated so as to avoid bias, is a promising mechanism for distinguishing natural variability from anthropogenic impacts. The distinction is an important one given the fact that metal concentrations may exceed screening values through apparently natural mechanisms (e.g., Cd in Fig. 4) and the appropriate response of government agencies to concentrations above the TEL (for example) will depend to some extent on whether the high values are judged to be natural or the result of human impacts. In the case of Bayou Trepagnier, our analysis is consistent with the conclusions of DeLaune and Gambrell (1996) that the bayou is polluted with Cr, Pb, and Zn, but we also found evidence of Cu and Ni contamination. One of the most important cautions in this use of regression analysis is to avoid model I regression, which systematically underestimates the magnitude of the slope of the regression line when the independent variable (in this case Al) is not under the control of the investigator. This bias creates two kinds of problems. First, the bias will alter the distribution of deviations from the regression line. In the case of Cd, for example, the null hypothesis that the deviations from the model II regression line were normally distributed was easily accepted ($p=0.14$), but if the same data were fit with a model I regression line, the assumption of normality was rejected ($p=0.03$). Error bounds become meaningless if the data are not normally distributed. Second, when the correlation between the two variables is positive, use of model I regression and associated error bounds will cause naturally high concentrations of elements to be flagged as outliers and hence inappropriately attributed to anthropogenic effects. When the absolute value of the correlation coefficient is close to 1, there is little difference between the geometric mean model II slope and the model I slope (Eq. 2). The distinction becomes important when there is more scatter in the data (e.g., Fig. 10). While there is no way to guarantee the absence of bias when the independent variable is not under the control of the investigator, model II regression, and in particular the use of the geometric mean method, is the best way to minimize the likelihood of artifacts caused by bias (Ricker 1973).

Finally, while the assumption of a normal distribution of deviations about the model II regression line could be accepted in all the DEQ datasets, the satisfaction of this criterion by no means guarantees the absence of anthropogenic effects. However, since pollution would presumably be uncorrelated with the presence of aluminum, anthropogenic impacts would be expected to reduce the correlation between Al and the metals of interest. In the DEQ dataset, the two metals least correlated with Al were Zn ($r=0.31$) and As ($r=0.34$). Most of the data in these two datasets fell below the TEL and none was higher than the PEL (Figs. 3 and 10). All other correlation coefficients (0.72 to 0.95) were comparable to the correlation between Mg and Al (0.81), for which an anthropogenic impact seems unlikely. Thus, we feel reasonably confident that our characterization of the DEQ sediment samples as uncontaminated is basically correct.

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Fig. 1.
Sample locations sites in relationship to Louisiana river basins

Fig. 2.
Relationship between untransformed Al and Ni concentrations illustrating the positive correlation between the variance of the data and the magnitude of the metal concentrations in the DEQ dataset

Fig. 3.

Left-hand panel Relationships between Al and As in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations

Fig. 4.

Left-hand panel Relationships between Al and Cd in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. The *plus symbols* indicate data from Bayou Trepagnier reported by DeLaune et al. (1987). *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations

Fig. 5.

Left-hand panel Relationships between Al and Cr in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. The *plus symbols* indicate data from Bayou Trepagnier reported by DeLaune et al. (1987). *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations

Fig. 6.

Left-hand panel Relationships between Al and Cu in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. The *plus symbols* indicate data from Bayou Trepagnier reported by DeLaune and Gambrell (1996). *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations

Fig. 7.

Left-hand panel Relationships between Al and Pb in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. The *plus* and *unfilled square* symbols indicate data from Bayou Trepagnier and Capitol Lake reported by DeLaune and Gambrell (1996) and DeLaune et al. (1989). *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations

Fig. 8.

Left-hand panel Relationships between Al and Ni in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. The *plus symbols* indicate data from Bayou Trepagnier reported by DeLaune et al. (1987). *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations

Fig. 9.

Left-hand panel Relationships between Al and Se in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations

Fig. 10.

Left-hand panel Relationships between Al and Zn in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. The *plus symbols* indicate data from Bayou Trepagnier reported by DeLaune and Gambrell (1996). *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations

Fig. 11.

Left-hand panel Relationships between Al and Mg in lake and river sediment samples collected by Louisiana DEQ in 2002 (*unfilled triangle*). *Solid line* is geometric mean regression to the data. The *dashed* and *dotted lines* are confidence intervals within which a single data from an independent dataset would be expected to fall 95% and 99% of the time, respectively. *Horizontal lines* are the NOAA threshold effects level and probable effects level for freshwater sediment. *Right-hand panel* Deviations from regression lines versus pH. The pH data have been binned. The *error bars* are standard errors of the corresponding deviations