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Assessment of Contaminated Sediments in Slip C Duluth Harbor, Minnesota

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Submitted to

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DISCLAIMER

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LIST OF ACRONYMS AND ABBREVIATIONS

2Metnap	2-Methylnaphthalene
Acene	Acenaphthene
Aceny	Acenaphthylene
Anth	Anthracene
AOC	Area of Concern
ARCS	Assessment and Remediation of Contaminated Sediments
ATSDR	Agency for Toxic Substances and Disease Registry
AVS	Acid Volatile Sulfide
b_0	Intercept of a Linear Regression Analysis Line
b_1	Slope of a Linear Regression Analysis Line
Bena	Benzo[a]anthracene
Benap	Benzo[a]pyrene
Benb	Benzo[b&j]fluoranthene
Bene	Benzo[e]pyrene
Beng	Benzo[g,h,i]perylene
Benk	Benzo[k]fluoranthene
BOD	Biochemical Oxygen Demand
CAC	Citizen’s Action Committee
Chry	Chrysene
cm	Centimeter
Co.	Company
Corp.	Corporation
Cs	Cesium
Diben	Dibenzo[a,h]anthracene
DROs	Diesel Range Organics
DSH	Duluth/Superior Harbor (code name for sediment samples collected in 1993)
EC_{50}	Median Effective Concentration at which an effect occurred to 50% of the test organisms within a given length of time
EPA	Environmental Protection Agency
Fig.	Figure
Fluo	Fluorene
Flut	Fluoranthene
GC/ECD	Gas Chromatography/Electron Capture Detection
GC/MS SIM	Gas Chromatography/Mass Spectrometry Selected Ion Monitoring
GLNPO	Great Lakes National Program Office
GPS	Global Positioning System
Indp	Indeno[1,2,3-cd]pyrene
IT Corp.	International Technology Corporation
IUPAC	International Union of Pure and Applied Chemistry
kg	Kilogram
LEL	Lowest Effect Level
LUST	Leaking Underground Storage Tank

LIST OF ACRONYMS AND ABBREVIATIONS (continued)

m	Meter
MDH	Minnesota Department of Health
mg	Milligram
MPCA	Minnesota Pollution Control Agency
Naph	Naphthalene
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
PEC	Probable Effect Concentration
Phen	Phenanthrene
PRP	Potentially Responsible Party
Pyrn	Pyrene
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
QC	Quality Control
r^2	Coefficient of Determination
R/V	Research Vessel
RAP	Remedial Action Plan
RCF	Relative Contamination Factor
R-EMAP	Regional Environmental Monitoring and Assessment Program
RPD	Relative Percent Difference
SEM	Simultaneously Extractable Metals
SLPC	Slip C code name for 1997 sediment samples
SOP	Standard Operating Procedure
SQG	Sediment Quality Guideline
SUS	Slip C code name for 1994 sediment samples
TEL	Threshold Effect Level
TMA	Thermo Analytical
TMDL	Total Maximum Daily Load
TOC	Total Organic Carbon
µg	Microgram
UMD	University of Minnesota--Duluth
USEPA	United States Environmental Protection Agency
VIC	Voluntary Investigative Clean-up
WDNR	Wisconsin Department of Natural Resources
WLSSD	Western Lake Superior Sanitary District
wt.	Weight
WWI	World War I

ABSTRACT

A sediment remediation scoping project was conducted in a contaminated boat slip in the Duluth, MN Harbor. Previous sediment investigations of this boat slip, Slip C, showed elevated levels of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), DDT metabolites, toxaphene, mercury, cadmium, copper, lead, and zinc. A sediment survey was conducted in June 1997 to collect additional sediment samples to further delineate the spatial extent of PAH, PCB, lead, and mercury contamination, as well as the distribution of total organic carbon (TOC) and particle size classes. Total PAHs, lead, and mercury were found to co-vary, with the strongest linear relationship between total PAHs and lead ($r^2 = 0.877$). The percentage composition of PAH compounds throughout the samples were fairly uniform, which may be indicative of a common source material of PAHs, such as from the combustion of fossil fuels. High levels of TOC (up to 30%) were found in the sediments in front of a compressed wood product plant that historically discharged industrial effluent into the slip until 1978. Lead, mercury, and total PAHs displayed a logarithmic correlation to TOC. Particle size proved to be an important indicator because the finer-grained sediments were more contaminated than the sandy, coarser-grained sediments. Lead had the best correlation with the different particle size classes, followed by total PAHs, mercury, and TOC. PCBs did not correlate well with any of the other parameters, possibly due to the small number of samples analyzed for PCBs, narrow range of corresponding TOC values, and highly elevated PCB concentrations in the core sections from one sample. Contaminant data were compared to several sediment quality assessment values/guidelines from other jurisdictions. The greatest exceedances of the guideline values occurred in the inner portion of the slip, which had more historical sources of contamination. The outer slip is more sandy and a portion of it is periodically dredged. Contaminant data were pooled with data collected in 1994 in order to produce contaminant isopleths for the 0-15, 15-30, and 30-45 cm depth intervals. These figures provided an effective visual picture of the distribution of contaminants. No potentially responsible parties were identified due to the historical nature of much of the contamination and current nonpoint sources, although this will be investigated further with the identification of historical business operations. Decisions on whether to remediate this site will be postponed until sediment quality objectives are developed for the St. Louis River Area of Concern (AOC) in late 1999, a sediment bioaccumulation study is completed in this slip in late 1999, and further work is done to assess groundwater and soil contamination adjacent to the slip. A sediment management plan for Slip C will be incorporated into an environmental management plan for the Duluth waterfront.

INDEX WORDS: Sediment assessment, sediment chemistry, remediation, Duluth Harbor, Area of Concern.

INTRODUCTION

Contaminated sediments contribute to many impaired uses at Great Lakes Areas of Concern (AOCs) including: fish advisories, habitat impairments, and restrictions on dredging. All of the current 42 AOCs are impacted by sediment contamination based on the application of sediment quality guidelines (Zarull *et al*. in press). In many cases, contaminated sediments represent a nonpoint source of pollutants to these AOCs, and may pose an unacceptable risk to aquatic organisms, aquatic-dependent wildlife, and human health. Successful remediation of contaminated sediments is essential for restoring impaired uses and contributing to the de-listing of AOCs.

The EPA's Assessment and Remediation of Contaminated Sediments (ARCS) Program provided a set of sediment assessment, risk assessment, modeling, and remediation tools for contaminated sediment investigations (USEPA 1993, 1994 a,b). The sediment assessment techniques recommended by the ARCS program promoted using a weight-of-evidence approach to conduct sediment chemistry analyses, sediment toxicity tests, and benthological community surveys on synoptic, surficially-collected sediment samples (USEPA 1994a). In particular, the sediment quality triad approach (Long and Chapman 1985; Long 1989; Chapman 1992) provided both a qualitative and quantitative means by which these data could be integrated together. The ARCS program also provided guidance on field sampling and chemical analysis procedures for deeper core segments (USEPA 1994a).

The work products and recommendations of the ARCS program have been implemented in the St. Louis River AOC, located in northeastern Minnesota.   The Minnesota Pollution Control Agency (MPCA), and its collaborators, as well as the Wisconsin Department of Natural Resources (WDNR), U.S Army Corps of Engineers, and some potentially responsible parties have conducted a number of sediment assessment investigations in this transboundary waterway between Minnesota and Wisconsin (Fig. 1). For the most part, these studies have followed an ecosystem-based management approach, involving citizens and other stakeholders in the decision-making process (MacDonald and Crane in review).   These studies have shown that the AOC includes relatively clean areas, in addition to several areas contaminated with a variety of toxic and bioaccumulative substances. Mercury and polycyclic aromatic hydrocarbons (PAHs) are widespread contaminants of concern in depositional areas of the lower St. Louis River estuary, whereas metals, polychlorinated biphenyls (PCBs), dioxins and furans, organochlorine pesticides, tributyltin, and diesel range organics (DROs) tend to be more localized contaminants of concern (MPCA and WDNR 1992, 1995; Redman and Janisch 1995; Schubauer-Berigan and Crane 1996, 1997; Normandeau Associates 1996; TMA 1996; Crane *et al*. 1997; IT Corporation 1997; Breneman *et al*. in review). Several hot spot areas of elevated contamination occur in the Duluth/Superior Harbor, including two Superfund sites (i.e., the Interlake/Duluth Tar and USX sites), Hog Island Inlet/Newton Creek, several boat slips (e.g., Minnesota Slip, Slip C, Howard's Bay), in the vicinity of historical and current wastewater treatment plants, and other areas with historical sources of contamination (e.g., Grassy Point) (Fig. 1) (Schubauer-Berigan and Crane 1997; Crane *et al*. 1997). Additional background information on the extent of sediment contamination in the St. Louis River AOC is given in the Stage I Remedial Action Plan (RAP) (MPCA and WDNR 1992, 1995) and in MacDonald and Crane (in review).

During 1996, the MPCA solicited input from the Sediment Contamination Work Group of the St. Louis River Citizen's Action Committee (CAC) to assist them in selecting an appropriate site for a sediment remediation scoping project. The group selected Slip C, in the Duluth Harbor, as the best candidate site because: the contamination was well-contained within the slip; several surficial contaminants exceeded benchmark sediment quality guidelines (Persaud *et al*. 1993);

the sediments contained bioaccumulative contaminants (e.g., PCBs, mercury) in the surficial and deeper sediment layers; significant acute sediment toxicity had been observed at the site in the past; and the benthological community was composed of organisms associated with degraded environments (Schubauer-Berigan and Crane 1997; Crane *et al*. 1997). In addition, the site was manageable for the budget available for this study. The group felt this site had a high potential for being effectively remediated in the future.

The purpose of this sediment remediation scoping project was to further delineate the extent and depth of contamination in the inner half of Slip C. The primary contaminants of concern were eighteen PAH compounds, congener-specific PCBs, mercury, and lead. Total organic carbon (TOC) and particle size classes were also measured. If possible, the volume of contaminated sediments was to be estimated, and preliminary remediation options assessed. In addition, a sediment management plan was to be developed for this site.

DESCRIPTION OF STUDY SITE

Slip C is located in the northern section of the Duluth Harbor basin in Duluth, MN (Fig. 1). Historically, swampy areas were dredged in the late 1800s to form many of the existing boat slips in the Duluth/Superior Harbor, including Slip C (Walker and Hall 1976). Four smaller slips (i.e., Slip numbers 5-8) used to extend out from the western side of Slip C (Fig. 2); these slips have now all been filled in for upland development, except for a small remnant of Slip #7. The fill material was usually of unknown origin. In the case of Slip #7, at least a portion of the fill consisted of material from the demolition of a hospital building and a creamery (Barr Engineering Company 1994). It is now known that the fill material in Slip #7 was contaminated with PAHs, mercury, and metals.

Several commercial operations have been located along either Slip C, or its adjoining slips, during the past hundred years (Walker and Hall 1976). These companies included: Duluth Universal Milling Co. (1900 - 1940s), Marine Iron & Shipbuilding Co. (1905 - 1961), Great Lakes Dredging and Dock Co. (1908 - c.1940), Standard Oil Co. storage facility (1890 - 1910), Cutler-Magner salt dock (1902 - present), Great Lakes Towing Co. (1907 - early 1990s), Superwood Corp. (now owned by Georgia-Pacific Corp.) (1940s - present), and Duluth Timber Co. (1990s to present). Earlier this century, approximately thirty ships were built by Zenith Co. in the vicinity of Slip C and its side slips (Keith Yetter, Marine Tech, personal communication, 1998). A gas station used to be located along Railroad Street in front of the Superwood plant; it closed in the late 1970s. In addition, a city incinerator used to be located in the vicinity of the Superwood plant. Additional information about this incinerator is being sought as to the time period of its operation. A coal gasification plant once existed at Dakota Pier on the north end of nearby Rice's Point. This plant could have been a source of airborne contamination to Slip C, as well as through the disposal of waste material along the waterfront (Tim Musick, MPCA Duluth Regional Office, personal communication, 1999).

Slip C is currently bordered on the southwest side by the Duluth Timber Company, a firm that removes lumber from historic structures. On the northwest side, Georgia-Pacific Corporation and Cutler-Magner Company border the slip. Georgia-Pacific manufactures Superwood® that is made from the compression of fine wood fibers with phenolic resin and moisture inhibitors. Most of the Superwood® made at the Duluth plant is used to manufacture dash boards for automobiles (Tom Lochner, Georgia-Pacific Corp., personal communication, 1997). Cutler-Magner imports salt which is stored on their property.

A portion of the land northwest of the Georgia-Pacific plant is included in the MPCA's Voluntary Investigative Clean-up (VICs) program. Historically, this site was Slip #7, which was filled in during either 1973 or 1974 (Tom Lochner, Georgia-Pacific Corp., personal communication, 1998). The groundwater beneath this site has been found to be contaminated with PAHs, mercury, and metals. Land on the southeast side of the plant is included in the MPCA's Leaking Underground Storage Tank (LUST) program because of two ruptures that occurred in their underground oil line during September 1990 and September 1991. The LUST site has now been included under the VICs program so that a comprehensive evaluation of soil and groundwater contamination can be made before implementing clean-up measures. As a next step, monitoring wells will be installed to assess groundwater contamination in the surrounding area (Jonathan Smith, MPCA Duluth Regional Office, personal communication, 1998).

Navigational dredging in Slip C is maintained by commercial operations, as needed. Dredging last occurred in 1986 in front of Cutler-Magner's dock, and they only dredged the spots that soundings indicated would interfere with boat draft (Mark LaLiberte, Cutler-Magner Co., personal communication, 1999). The inner end of the slip has not been dredged for some time as Georgia-Pacific relies on rail and truck traffic to transport their compressed wood products. Marine Tech (formerly known as Zenith Dredge) moors two dredging scows along Duluth Timber's dock for long-term storage. Thus, most water uses of the slip are limited to the outer half of it.

There are no current wastewater effluent discharges into Slip C. Effluent and sanitary discharges from all of the neighboring businesses have been routed to WLSSD since approximately 1978. Historically, Superwood Corp. was the major discharger to Slip C (MPCA/WDNR 1992). A MPCA report, published in 1969, noted that both industrial and sanitary waste treatment was inadequate at Superwood Corp. The sanitary sewage of approximately 200 persons was treated by septic tank, and the industrial wastes were treated by settling ponds (MPCA 1969). At that time, the total discharge of effluents was approximately 450 gallons per minute with a high 5-day biochemical oxygen demand (BOD) of about 2,000 mg/L (MPCA 1969).

Stormwater runoff from the Georgia-Pacific wood yard currently drains through a weir into an outfall at the southern (most inland) end of the slip (outfall 001) (Fig. 3). Buckingham Creek, which provides stormwater drainage of a section of Duluth, flows along the northern side of the Georgia-Pacific plant into the remnant of Slip #7 (Fig. 3). Outfalls 002 and 003 discharge into the creek, whereas outfall 010 discharges cooling water directly into Slip C (Fig. 3). Buckingham Creek was recently enclosed in a culvert along Georgia-Pacific's property, and two extra sand traps were added to promote the deposition of particulate matter (Tom Lochner, Georgia-Pacific Corp., personal communication, 1998).

Several nonpoint sources could have contributed contamination to Slip C. These sources potentially include the runoff of contaminated fill material from former Slips #7 and 8; other land runoff (e.g., coal piles); groundwater transportation of contaminants from the surrounding property; ship, rail, and motor vehicle traffic; transport and deposition of sediment-derived contaminants from elsewhere in the harbor; and atmospheric transport and deposition of contaminants.

PREVIOUS SEDIMENT INVESTIGATIONS AT SLIP C

The MPCA, and its collaborators, have conducted three previous sediment investigations in the Duluth/Superior Harbor in which sediment samples were collected from Slip C. During 1993, a sediment investigation was conducted at 40 depositional sites in the Duluth/Superior Harbor; four of these sites were sampled within Slip C (Schubauer-Berigan and Crane 1997) (Fig. 4). This study indicated that overall contamination decreased from the inland end of the slip to the outer end of the slip. Contaminants of concern at the inland end of the slip included: PAHs, PCBs, DDT metabolites, toxaphene, mercury, cadmium, copper, lead, and zinc. Bacterial and acute sediment toxicity tests were run on the sediments. The two most inner samples were toxic in the initial 90% screen of the Microtox® test, but not in the EC_{50} run. The inner three samples caused genotoxicity of samples in the Mutatox® test. The sediments were not acutely toxic to the midge, *Chironomus tentans*, and the results were inconclusive for 10-day toxicity tests with the amphipod, *Hyalella azteca*, due to control failure.

A follow-up investigation was conducted during 1994 to further utilize a weight-of-evidence approach to assess contaminated sediments in Slip C (Crane *et al*. 1997). Eight sites were sampled in a transect of this slip (Fig. 5). Selected core sections were analyzed for a suite of contaminants at various 15 cm depth intervals. Four surficial sites were sampled for 10-day sediment toxicity testing with *C. tentans* and *H. azteca*. The results indicated significant acute toxicity to *C. tentans* at site SUS 3. The specific cause of toxicity could not be determined. The control for the *C. tentans* toxicity test of SUS 7 sediments barely failed the acceptable control survival requirements by 2%. Although the results were not analyzed statistically, the mean percent survival in SUS 7 (i.e., 0%) was highly depressed relative to the control (i.e., 68%). Similarly, the control survival for the *H. azteca* test on SUS 7 sediments barely failed the acceptable control survival by 2%; although the results were not analyzed statistically, the mean percent survival in SUS 7 (i.e., 45%) appeared to be highly depressed relative to the control (i.e., 78%). All of the surficial sites were sampled for benthological community structure. The benthological survey showed that oligochaetes were the dominant group in the inner half of the slip (sites SUS 1-6), comprising 70-90% of the fauna; tubificids made up 62-85% of the oligochaete community. Chironomids accounted for 53% of the fauna at SUS 7; this site was within the area dredged for Cutler-Magner Co. in 1986.

Two sites were sampled in Slip C during June 1995 as part of a Regional Environmental Monitoring and Assessment Program (R-EMAP) project. One site (#51) was located directly in front of Georgia-Pacific's plant, whereas the other site (#24) was located in front of the remnant of Slip #5 in the outer slip (Fig. 6). Sediment chemistry and toxicity tests were run on synoptic

0-5 cm composite sediment samples. In addition, benthological samples were collected at the same time. Neither sample was acutely toxic to 10-day exposures of *H. azteca* and *C. tentans*. Oligochaetes dominated site #51, whereas both chironomids and oligochaetes dominated site #24. Mercury was elevated at site #51, and simultaneously extractable metals (SEM) also exceeded acid volatile sulfides (AVS) at this site. Total PAHs were elevated at both sites, particularly at site #51 (i.e., 56 mg/kg dry wt.).

METHODS

Field Sampling

Sediment samples were collected during June 16-18, 1997 according to the procedures specified in the quality assurance project plan (QAPP) (Crane 1997), the GLNPO Health, Safety, and Environmental Compliance Manual (GLNPO 1997), and Smith and Rood (1994). The field crew consisted of staff provided by the Great Lakes National Program Office (GLNPO), Seward Services, the MPCA, and volunteer members of the St. Louis River CAC Sediment Contamination Work Group. GLNPO's specially designed research vessel, the R/V Mudpuppy, was used to sample the sediments.

A total of 19 sampling sites were selected, three of which were located in the slip southeast of Slip C, two of which were located in the slip north of Slip C, and fourteen of which were located in Slip C itself. The slips, other than Slip C, were sampled because no sediment contaminant data were available for these sites. The sampling design in Slip C was best represented by a rectangular grid pattern for an elliptical-shaped hot spot (Lubin *et. al*. 1995).

A sediment sounding was taken at each site to determine the approximate depth of the soft sediment layer. This was done using a long metal rod of known length, in which the pole was lowered into the sediment and pushed in until the point of refusal (WDNR 1995). A real-time, differential global positioning system (GPS) unit was used to determine station positions by receiving digital codes from three or more satellite systems, computing time and distance, and then calculating an earth-based position. The positional accuracy of the GPS measurements was between 0.5-5 m. GPS measurements were converted from degree/minute format to decimal format for preparation of the site maps.

The R/V Mudpuppy was anchored in place at each site by the use of specialized "spuds." A new Vibrocorer system, composed of lexan plastic, was used to collect sediment cores down to 1.6 m. Cores were processed on board the R/V Mudpuppy immediately after collection. Each core was sectioned at 15 cm intervals down to 60 cm. A physical description of each core section was made, including sections below 60 cm. Each section was homogenized and split for specific chemical analyses. The samples were stored on ice in a cooler while on board the R/V Mudpuppy. At the end of each day, the sediment samples were stored under refrigeration (in the dark) at the Duluth MPCA Regional office. Samples were delivered to the contract laboratories for chemical analyses within one week of collection. Selected sediment core sections were analyzed for either all or a portion of the following chemical/physical measurements: eighteen PAH compounds, 107 PCB congeners, mercury, lead, TOC, and particle size classes.

Laboratory Analytical Procedures

Sediment samples were analyzed by three different analytical laboratories. PCB congeners were analyzed by En Chem, whereas particle size was analyzed by the University of Minnesota-Duluth (UMD). PAH compounds, lead, mercury, and TOC were analyzed by the Minnesota Department of Health (MDH).

A subset of 107 PCB congeners were analyzed by capillary column GC/ECD according to En Chem's standard operating procedures (SOPs) (En Chem 1995). Eighteen target PAH compounds were measured by capillary column GC/MS SIM using MDH Method 513 (MDH 1997). Mercury was measured using flow injection atomic absorption spectrometry--cold vapor technique according to EPA Method 245.1 A (USEPA 1983). Total lead was determined by digesting the samples with concentrated nitric acid and analyzing them with stabilized temperature graphite furnace atomic absorption spectroscopy (MDH 1993a,b; USEPA 1991). TOC was measured on a Dohrmann DC-80 TOC analyzer (Rosemount Analytical 1990a,b; 1991). Percent moisture of samples run by MDH was done according to MDH Method 261 (MDH 1995). Particle size was measured using an Horiba LA-900 analyzer (Lodge 1996). The particle size results were reported as percentages of the following classes: sand and gravel (>53 µm), coarse silt (53 - 20 µm), medium silt (20 - 5 µm), fine silt (5 - 2 µm), coarse clay (2 - 0.2 µm), medium clay (0.2 - 0.08 µm), and fine clay (<0.08 µm).

Quality Assurance/Quality Control

The Quality Assurance/Quality Control (QA/QC) procedures followed in this study adhered to the site-specific QAPP (Crane 1997) which was based on guidance given in U.S. EPA (1995). Two field replicate samples were collected to assess field precision. Analytical data quality objectives were made to assess analytical precision, accuracy, and completeness. The sampling strategy was designed to generate representative data for Slip C. The analytical methods utilized in this study were similar to methods used in previous investigations so that the data would be directly comparable to them. All samples were extracted within the holding time period specified in the QAPP (Crane 1997)

Two field replicates were collected in Slip C at the SLPC 08 and SLPC 15 sites. In both cases, the R/V Mudpuppy was repositioned to collect the replicate sample. Due to the heterogeneity of the sediments, the replicate core lengths were quite different for both sites. At SLPC 08, the replicate sample was 2.3 times longer than the field sample; thus, only the chemical data from the 0-15 cm segment was averaged with the field sample. The physical description of both 0-15 cm core sections were similar (Tables 1 and 2). At SLPC 15, the replicate sample was nearly half the length of the field sample (Table 1). In addition, the R/V Mudpuppy moved more than when the SLPC 08 replicate core was collected. The SLPC 15 replicate sample was treated as a separate sample from the field sample because the physical descriptions of the sediments varied greatly [as shown in the particle size (Table 2) and TOC (Table 3) data].

The analysis of PAHs included several quality control (QC) measurements. The results of three reagent blank samples were all less than the reporting limits for individual PAH compounds. The recoveries for three fortified blank samples, in which each blank was spiked with the suite of PAH compounds at a concentration of 100 µg, ranged from 72 - 116%; this was within the QC limit of 50 - 120%. The initial and continuing instrument calibrations were within the QC criteria. Three surrogate compounds of 2-fluorobiphenyl, pyrene-d10, and benzo[a]anthracene-d12 were added to each sample; the recoveries ranged from 48 - 128%, which were nearly all within the QC limits of 40 - 120%. The following samples were selected for the matrix spikes: SLPC 01 (0-15 cm), SLPC 11 (0-15 cm), and SLPC 16 (15-30 cm). Each sample was spiked with 100 µg of each PAH compound; the recoveries ranged from 36 - 201%, which deviated from the QC limits of 50 - 120%. For SLPC 01 (0-15 cm), only naphthalene was below the acceptable QC limit. For SLPC 11 (0-15 cm), four PAH compounds slightly exceeded the QC limit. For SLPC 16 (15-30 cm), six PAH compounds exceeded the QC limit with phenanthrene having the highest exceedance. This indicates that the sample matrix may bias the surrogate results for these two samples. Analytical duplicates were run on SLPC 03 (0-15 cm), SLPC 10 (0-15 cm), and SLPC 15R (30-45 cm). For SLPC 03 (0-15 cm), the Selective Ion Monitoring (SIM) part of the analysis was lost; the full scan analysis had several compounds below the full scan reporting limit of the working calibration curve. Thus, the results of this analytical duplicate were not compared to the corresponding sample. For the other two analytical duplicates, the relative percent difference (RPD) for individual PAH compounds ranged from 5 - 40% for SLPC 10 (0-15 cm) and 1 - 54% for SLPC 15R (30-45 cm), with one exceedance for fluorene. The RPDs for the field replicate of SLPC 08 ranged from 2 - 40%; this was within the QC limit of <50% RPD.

Similar types of QC samples were run with the PCB congener samples. The method blank that was extracted and analyzed with the samples had two small hits for congeners #1 (1.2 µg/kg) and #4 (2.0 µg/kg). The initial and continuing instrument calibrations were within the QC criteria. Congeners #14, 65, and 166 were used as surrogate compounds for each sample. All surrogate recoveries were between 62 - 89%, which were within the QC limits of 40 - 120%. Sample SLPC 17 (0-15 cm) was chosen for the matrix spike. Eleven congeners of interest were added to the matrix spike at a concentration of 10 µg/kg, wet weight. The matrix spike recoveries ranged from 47.3 - 85.5%, which were nearly all within the QC limits of 50 - 120%. Sample SLPC 17 (0-15 cm) was also chosen for the analytical duplicate. All congener relative percent differences (RPD) between the sample and duplicate results were between 0 - 44.5%, which were below the QC limit of 50% RPD. The control spike, consisting of blank sand fortified with eleven congeners of interest (at 10 µg/kg, wet weight), was extracted and analyzed with the samples; the recoveries ranged from 68.0 - 89%, which were within the QC limits of 50 - 120%.

Data Analysis

The analytical data were obtained electronically from each laboratory as Excel spreadsheets. The results of analytical duplicates were averaged with the field sample results, providing all data quality objectives had been met. As described in the previous section, only the field replicate for SLPC 08 was averaged together with the sample for the 0-15 cm segment. All manipulations of the data sets were double-checked to ensure that no errors had occurred. The relationships between different chemical and physical parameters were analyzed statistically by linear regression analysis. Any data points that were on or outside the 95% prediction intervals were designated as outliers and were removed from the regression analysis. The intercept (b_0), slope (b_1), and coefficient of determination (r^2) were reported for each regression analysis.

The dry weight analytical data for lead, mercury, PAHs, PCBs, and TOC were combined with previously collected data sets from 1993, 1994, and 1995 (Schubauer-Berigan and Crane 1997; Crane *et al*. 1997; Breneman *et al.* in review). This was done in order to evaluate graphical techniques by which the data could be plotted in either two-dimensional or three-dimensional space. The most appropriate use of this data set was to generate two-dimensional contaminant isopleths for similar depth intervals (i.e., 0-15, 15-30, and 30-45 cm). Only data from the 1994 study (Crane *et al*. 1997), and this study, qualified for use in the graphics due to their similar depth intervals. Surfer software was used to make the isopleth figures, and AutoCad Release 14 was used to finalize the figures with sample site labels.

Data Archival

The field and laboratory sediment data from this study will be submitted electronically to GLNPO's regional contaminated sediment database. The MPCA used this study to participate in a pilot project with GLNPO to test out their new field and laboratory data fields for the sediment database. The database will be available for public use when it is completed.

RESULTS AND DISCUSSION

Field Sampling Information

The field sampling information for the sediment cores is given in Table 1. Sites SLPC 01 through SLPC 03 corresponded to the surficial samples collected in the slip southeast of Slip C, whereas sites SLPC 06 through SLPC 19 were sampled in Slip C (Figs. 7-8). Sediment samples could not be obtained in the slip north of Slip C (i.e., SLPC 04 and SLPC 05) due to the gravely nature of the sediments and presence of logs. Nearly all of the Slip C sites were sampled as planned. The positions of SLPC 09 and SLPC 10 were adjusted westward because two dredging scows were docked in the area that was initially going to be sampled. A cohesive sediment core could not be collected at SLPC 18 the first time it was sampled, necessitating movement of the boat closer to SLPC 17.

Particle Size

Particle size analyses were conducted on all samples in which PAHs and/or PCBs were measured. Due to cost constraints, particle size was not done on samples in which only lead and mercury were measured. In general, the sediments in the inner portion of Slip C had a higher percentage of silt and coarse clay than the outer sites, which were more sandy (Table 2). In comparison, the surficial sediments in the slip southeast of Slip C were predominately sand (i.e., > 96% sand); the incidence of sediment scouring is probably higher in this slip due to active ship traffic. Thus, silty material may be transported out of this slip due to resuspension caused by ship propellers. None of the sediment samples, from either slip, contained a fine or medium clay fraction.

TOC

TOC ranged from 0.34 - 1.1% in the slip southeast of Slip C and from 0.81 - 30% in Slip C (Table 3). The sediments in the inland portion of Slip C contained a large amount of detrital material (i.e., wood fibers and wood chips), resulting mostly from historical operations of the Superwood plant. The manufacturing performed by Superwood Corp. and Georgia-Pacific Corp. has remained consistent, since operations began around 1948; this process includes mechanically refining wood into fiber, adding phenolic resin and wax, and pressing it in a hot press (James Holmes III, Georgia-Pacific Corp., memorandum, 1999). Thus, the release of wood-derived material in Superwood's effluent was a major contributor to elevated TOC levels in Slip C sediments. Correspondingly, TOC was highest (up to 30%) in the core sections collected at SLPC 14 and SLPC 15, in front of the former Superwood plant (Table 3).

General Contaminant Results

As with previous sediment investigations in Slip C, elevated concentrations of lead, mercury, total PAHs, and total PCBs were found in both surficial sediments and deeper core sections (Table 3). Lead and mercury concentrations that were less than the detection limit were reported in Table 3 at one-half the detection limit for SLPC 08 (15-26 cm) and SLPC 08R (30-45 cm), respectively.

The contaminant concentrations in Table 3 were compared to two classes of empirically-derived sediment quality guidelines: a threshold level, or lowest effect level, and a probable effect concentration (Table 3). Threshold effect level (TEL) values are intended to estimate the concentration of a chemical below which adverse biological effects only rarely occur (Smith *et al.* 1996). Lowest effect level (LEL) values indicate the level of sediment contamination that can be tolerated by the majority of benthic organisms (Persaud *et al*. 1993). Probable effect concentrations (PECs) are intended to estimate the concentration of a chemical above which adverse biological effects frequently occur (Ingersoll and MacDonald 1998). TEL values for lead, mercury, and total PCBs were used in Table 3; since a TEL value for total PAHs was not available, the LEL value was used. PEC values were available for each of the contaminants of concern.

Low levels of contamination were found in the slip southeast of Slip C, whereas multiple exceedances of the TEL and LEL values were common at most of the Slip C sites and depth intervals. Total PAHs and lead were the predominant contaminants of concern due to the number of exceedances of the PEC values. Thus, at sites SLPC 11-14, SLPC 15R, and SLPC 17, the surficial sediments were sufficiently contaminated to present a greater probability of risk to the benthic community. However, other site-specific factors in the sediment matrix (e.g., type of contaminant source such as fly ash or oil, TOC, particle size) may affect the bioavailability of these contaminants to aquatic organisms. In addition, PCBs and mercury remained as contaminants of concern due to their potential to bioaccumulate in organisms.

Relative contamination factors (RCFs) were calculated by dividing the contaminant concentration by its associated sediment quality guideline value. This was done based on using the threshold/lowest effect level guidelines (Table 4) and the PEC guidelines (Table 5). A cumulative mean low level or probable effect level RCF value was calculated for each core section. Since PAHs and PCBs were not measured at every site, the mean values were skewed towards those chemicals in which data were available. Mean RCF values greater than one implied a higher probability of either low level or adverse effects impacting the benthological community. From this data set, there were no instances in which a high individual chemical RCF was diluted by low chemical RCFs to result in a mean RCF less than one.

Nearly all of the inland Slip C sites, throughout the core profiles, had mean low level RCFs exceeding one. Of these sites, SLPC 13 had the most contaminated sediments in the 0-15 and 15-30 cm depth intervals. SLPC 15 had the most contaminated sediments in the 30-45 cm core segment. SLPC 13 was located by the outfall for Georgia-Pacific’s yard runoff, whereas SLPC 15 was located in front of the Georgia-Pacific plant. These sites also had a mean probable effect concentration RCF greater or equal to one. Most of the other samples had mean probable effect concentration RCFs of less than one. Thus, there appeared to be intermediate levels of contamination at most of the Slip C sample sites.

Distribution of PAH Compounds

The distribution of eighteen PAH compounds was determined in this study (Table 6). Sediment samples were selected for PAH analyses based on either physical observations of the sample (e.g., presence of an oil sheen) or to fill data gaps (e.g., sites SLPC 01 through SLPC 03).

Individual PAH concentrations were converted to a percentage of the total concentration for each sample (Table 7). Fluoranthene (18.1%), pyrene (13.5%), phenanthrene (12.1%), and chrysene (7.9%) made up the greatest proportion of total PAHs. Fluoranthene is a constituent of coal tar and petroleum-derived asphalt; it is a universal product of the combustion of organic matter and is present in fossil fuel products. Pyrene and chrysene are ubiquitous products of incomplete combustion, whereas phenanthrene most likely results from the incomplete combustion of a variety of organic compounds, including wood and fossil fuels. All four compounds are strongly adsorbed to sediments and to particulate matter when released into the water column (U.S. Library of Medicine, Health, and Safety Database 1999).

All other PAH compounds, on average, constituted less than 6.8% each of the total PAHs. Dibenzo[a,h]anthracene (0.9%) and acenaphthylene (0.4%) made up the lowest percentage of total PAHs. Dibenzo[a,h]anthracene is a ubiquitous product of incomplete combustion. Acenapthylene is a component of crude oil and coal tar, as well as being a product of combustion which may be produced and released to the environment during natural fires. The other PAH compounds generally result from the incomplete combustion of fossil fuels (U.S. Library of Medicine, Health, and Safety Database 1999).

The low molecular weight PAHs generally constituted less than 2.8% each of total PAHs, except for phenanthrene that made up 12.1% of PAHs. The other low molecular weight PAHs were: 2-

methylnapthalene, acenapthene, acenapthylene, anthracene, fluorene, and naphthalene. The remaining PAH compounds made up the high molecular weight fraction; most of them constituted over 5.5% each of total PAHs, except for benzo[k]fluoranthene (2.5%) and dibenzo[a,h]anthracene (0.9%).

The percentage of PAH compounds appeared fairly uniform between depth intervals, between spatial locations in Slip C, and between Slip C and the slip southeast of it. This uniform distribution would suggest that photolysis and microbial degradation are not active degradation pathways for the sorbed PAH compounds. In addition, this may be indicative of a common type of source material, such as coal combustion products, for contributing most of the PAH contamination in these slips. The Duluth/Superior Harbor area had a high historical use of coal during the past 100 years through the storage and transport of coal along the waterfront, the presence of several coal gasification plants (including one a half-mile from Slip C), and the manufacture of coal-powered ships, especially during WWI. The release of some PAH compounds may also have resulted at the Superwood plant from the combustion of the wood fines, oversized chips, and chip wash residue as boiler fuel.

The individual PAH concentrations were compared to available sediment quality guidelines that represented either a lower level or probable level of effects (Table 6). No sediment quality guidelines were available for benzo[b&j]fluoranthene or benzo[e]pyrene. No probable effect level guidelines were available for benzo[g,h,i]perylene, benzo[k]fluoranthene, or indeno[1,2,3-cd]pyrene. For the other PAH compounds, the greatest probable effect level exceedances occurred for phenanthrene, pyrene, fluoranthene, benzo[a]anthracene, chrysene, and benzo[a]pyrene (Table 6). These last three compounds, in addition to benzo[b]fluoranthene, benzo[k]fluoranthene, dibenz[a,h]anthracene, and indeno[1,2,3-cd]pyrene, have caused tumors in laboratory animals through ingestion, dermal, and inhalation exposure pathways (ATSDR 1990). Human exposure to these compounds in Slip C is minimal because swimming and wading do not occur in this slip, and fishing probably occurs infrequently there. In addition, fish metabolize PAHs so they would not bioaccumulate in their tissues as readily as for benthic invertebrates. Inhalation would not be an important human exposure pathway because most of the PAH compounds are strongly sorbed to the sediments and would not be partitioning much to the water column, with subsequent volatilization to the air. An exposure assessment, combined with a toxicity assessment, would need to be done to quantitate human health risks at this site. A similar process could be used to assess ecological risks to aquatic receptors.

Distribution of PCB Congeners

The distribution of PCB congeners at six Slip C sites is given in Table 8. The highest congener concentrations for the SLPC 17 and SLPC 18 samples were the coeluting congener pair of IUPAC numbers 77/110. For the SLPC 09 samples, this was the second most prevalent congener group, with congener #4 being the most predominant. However, the small hits for congeners #1 and 4, found in the method blanks, were not subtracted from the sample results. Considering this, #77/110 would be the most prevalent congeners in the SLPC 09 samples. Other prevalent congeners in all samples were IUPAC numbers: 95, 101/90, 118, 132/168/105, and 163/138 (see Table 9 for associated congener nomenclature). In general, these compounds were mostly highly chlorinated penta- and hexachlorobiphenyls. These compounds would be more resistant to degradation in the environment than lower chlorinated congeners, and would be more likely to be associated with higher PCB Aroclor mixtures such as Aroclor 1260.

Chemical-Physical Relationships

The contaminant data were examined for trends with other contaminant and physical parameters. The data set included the Slip C sites, as well as three sites in the slip southeast of Slip C. The non-Slip C sites provided lower bound contaminant values for use in the regression analyses. Total PAHs were strongly correlated to lead ($r^2 = 0.877$) (Fig. 9) and moderately correlated to mercury ($r^2 = 0.770$) (Fig. 10). Thus, lead could be used as a good indicator of PAH contamination in Slip C. Mercury and lead were more moderately correlated to each other ($r^2 = 0.744$) (Fig. 11). Mercury and lead are both components of coal, and PAHs result from the incomplete combustion of fossil fuels, like coal. Thus, some of the contamination in Slip C may result from fossil fuel sources, such as fly ash and petroleum products. Some of the sediment samples had a visible oil sheen and were oily; it is not known whether two fuel oil leaks at Georgia-Pacific's plant in the early 1990s contributed to this sediment contamination. A gas station was located in the area historically, and it is not known if used oil could have been dumped in the slip by it, or other historical businesses.

For the outlier data that were removed from Figs. 9-11, these data were either clustered in Slip C at SLPC 13 (0-15, 15-30 cm), SLPC 15 (15-30 cm), and/or SLPC 19 (0-15 cm). The SLPC 13 and 15 outliers had elevated PAH concentrations, whereas mercury was elevated in the SLPC 19 (0-15 cm outlier. Of the sites sampled in Slip C, SLPC 13 was located at the most shallow water depth (i.e., 4.5 m). Both this site and SLPC 15 had deep soft sediment layers (i.e., 1.4-1.8 m), whereas the soft sediment layer in SLPC 19 was much less (i.e., 0.5 m) (Table 1). SLPC 13 was located at the most inland section of Slip C by the yard runoff outflow for the south section of Georgia-Pacific's property. The particle size distribution in the surficial sediments from SLPC 13 contained a much higher coarse grain fraction (>53 μm) than SLPC 12 or 14. These results are consistent with general observations of outfalls that the coarser material settles out closer to the outfall and finer material settles out further away from the outfall. There may also be more resuspension of material below the outfall that would promote the mixing of the upper sediment layers. The lead, mercury, PAH, and TOC levels were highest in the surficial sediments of SLPC 13, but the 15-30 cm section was also elevated for these parameters (Table 3). Radioisotope dating of a sediment core with ^{210}lead could provide more information about the extent of sediment mixing at this site.

The coarse grain fraction in the upper two sections of SLPC 15 was also high, but it is not known if any historical discharges occurred in this area. SLPC 19 was located in the area dredged for Cutler-Magner Co. in 1986. This site was also located in front of former Slip #6 which was filled in around 1993 (Mark LaLiberte, Cutler-Magner Co., personal communication, 1998)]. The elevated mercury levels in these surficial sediments may have resulted from the exposure of deeper, more contaminated sediments during the 1986 dredging, from the displacement of contaminated sediments from the edge of Slip #6 when it was filled, and/or from the runoff of fill material from Slip #6 into Slip C.

Total PCBs did not correlate to total PAHs ($r^2 = 0.0194$), lead ($r^2 = 0.0351$), or mercury ($r^2 = 0.0875$) (Figs. A-1 through A-3, Appendix A). This lack of correlation may have been partly attributable to the small sample size of PCBs used in the regression analyses (i.e., n = 5 for PAHs; n = 6 for lead and mercury). Therefore, the combined 1993 (Schubauer-Berigan and Crane 1997) and 1994 (Crane *et al.* 1997) data sets for Slip C were also examined for relationships between total PCBs and total PAHs, as well as total PCBs and mercury. There were insufficient lead data to compare to total PCBs. The results of these regression analyses also demonstrated a lack of correlation with total PAHs ($r^2 = 0.428$, n = 18, Fig. A-4) and mercury ($r^2 = 0.230$, n = 42, Fig. A-5) (Appendix A). Since total PCBs did not correlate to the other three contaminants, they must have entered Slip C through a different source material. In particular, a high pocket of PCB contamination was found between sites SLPC 17 and SLPC 18. This area encompassed a 1994 sample site, SUS 5 (15-23 cm), which had the highest PCB concentration of 1140 µg/kg reported in Slip C (Crane *et al*. 1997).

Hydrophobic organic contaminants, such as PAHs and PCBs, preferentially partition to organic rich sedimentary particles in lakes and rivers (Chevreuil *et al.* 1987). For example, the concentration of PCBs correlated well with percent organic carbon ($r^2 = 0.86$) and the percent silt-clay fraction ($r^2 = 0.96$) in surficial sediments from northeast Lake Michigan (Simmons *et al*. 1980). However, PCBs were not associated with TOC in Slip C ($r^2 = 0.0169$) based on the 1997 data set (Fig. A-6, Appendix A). Likewise, no correlation was observed between sediment PCB concentrations and the percentage of clay or organic matter in sediments from the upper Great Lakes (Glooschenko *et al*. 1976). A more detailed examination of the correlation between total PCBs and TOC, based on the 1993 and 1994 data sets for Slip C, showed a stronger correlation of $r^2 = 0.707$, n = 42 (Fig. A-7, Appendix A). The 1993 and 1994 data sets spanned a wider range of TOC values (i.e., 0.09 - 19%) than for the 1997 TOC values (i.e., 2.2 - 5.4%). Thus, the lack of a correlation in the 1997 data set may have been attributable to the small number of samples, narrow range of TOC values, and highly elevated PCB concentrations in the SLPC 18 core sections (i.e., 0-15, 15-30 cm).

Total PAHs were linearly related to TOC up to about 10% TOC ($r^2 = 0.876$) (Fig. 12) after which point the data became more scattered. Thus, with this data set, normalization of PAH concentrations by TOC should only be done when TOC is less than 10%. This also corresponds to the use of some organic carbon normalized sediment quality guidelines for PAHs which limit their use to sites with TOC less than 10% (Persaud *et al*. 1993). For the whole data set, the logarithm of the corresponding TOC values accounted for over 76% of the variance in total PAHs ($r^2 = 0.766$) (Fig. 13). Lead and mercury also displayed a logarithmic relationship with TOC ($r^2 = 0.793$ and 0.773, respectively) (Figs. 14-15).

Lead, mercury, total PAHs, total PCBs, and TOC were compared to their corresponding particle size classes. Particle size proved to be an important indicator because the finer-grained sediments were more contaminated than the sandy, coarser-grained sediments. Lead had the best correlation with the different particle size classes (Figs. 16-21), followed by total PAHs, mercury, and TOC (Table 10, Figs. B-1 through B-9 in Appendix B). For lead, the correlations were stronger for the sand and gravel (>53 µm) and silt (52 - 2 µm) fractions than they were for individual silt fractions and coarse clay fraction (2 - 0.2 µm) (Figs. 16-21).

Sediment Kriging Graphics

The contaminant data were merged with the results of a 1994 hot spot study in Slip C (Crane *et al*. 1997) in order to examine spatial trends in the data. Contaminant isopleths, for selected depth intervals, were done for lead (Fig. 22), mercury (Fig. 23), total PAHs (Fig. 24), total PCBs (Fig. 25), and TOC (Fig. 26) through a sediment kriging technique. The figures provided an effective way to visualize a large quantity of data in three different depth segments. For all chemical parameters, the bulk of the chemical contamination was concentrated in the inner half of the slip. This demonstrates that these sediments are fairly stable and are not being transported very much, through advective transport, out of the slip.

The ^{137}Cs dating of a sediment core (DSH 38) taken from the middle of Slip C in 1993 showed a classic ^{137}Cs profile with easily distinguishable peaks and edges; this suggests that not much mixing has occurred in the sediments from this site in recent years (Schubauer-Berigan and Crane 1997). The sedimentation rates for this particular core, which was located near SLPC 08, were as follows: 1954-1964, 2.03 ± 0.51 cm/year; 1964-1993, 0.56 ± 0.15 cm/year; 1954-1993, 0.94 ± 0.1 cm/year (Schubauer-Berigan and Crane 1997). The diversion of Superwood's effluent to WLSSD in 1978 probably resulted in the greatest decrease in sedimentation rates in the slip caused by the reduction of wood particle waste entering the slip. This reduction in organic matter entering the slip is reflected in the lower TOC concentrations in the surficial sediments (Fig. 26). The wide range of surficial TOC concentrations (i.e., 0.91 - 15%) observed in Slip C is still greater than the surficial TOC ranges observed in some nearby hot spot areas such as Minnesota Slip (i.e., 1.6 - 4.8%), Howard's Bay (i.e., 0.9 - 5.2%), and around the embayment encompassing WLSSD, Miller Creek, and Coffee Creek (i.e., 1.7 - 5.6%) (Schubauer-Berigan and Crane 1997).

Assuming the 1964-1993 sedimentation rate could be extrapolated to 1997, the upper 18.5 ± 5 cm sediment section would correspond to the period from 1964-1997. The next 20.3 ± 5.1 cm core section would correspond to the period from 1954-1964; this could encompass the 18.5 - 38.8 cm core section. Since these sedimentation rates were based on a core taken near the middle of Slip C, the sedimentation rate would probably be much greater in the inland end of the slip due to more point source discharges. Radioisotope dating of some inland sediment cores, using ^{210}lead, would provide useful information about whether the sediments are being redistributed based on smearing in the ^{210}lead profile.

All of the data used for the lead isopleth figures were based on this investigation since total lead was not measured in the 1994 hot spot survey (Schubauer-Berigan and Crane 1997). For all three core sections, the highest concentrations of lead occurred in the area bordered by SLPC 11, SLPC 12, SLPC 13, SLPC 14, SLPC 15, and SLPC 15R (Fig. 22). This corresponded to the most inland section of Slip C. At SLPC 13, the concentration of lead increased 64.4% from the 30-45 cm segment to the 15-30 cm segment; similarly, the concentration of lead increased 58.3% from the 15-30 cm segment to the 0-15 cm segment. This pattern implies there was a more recent source of lead to the surficial sediments, such as from outfall 001. In addition, the surficial sediments at SLPC 17 were higher in lead and PAHs than the historical sediments, implying a current source of material to these sediments, such as from the filling of former Slip #7 or discharge of cooling water and stormwater runoff at the Buckingham Creek outlet.

For the mercury plots, the highest concentration of mercury (i.e., 0.97 mg/kg) observed in this slip occurred in the 30-45 cm segment of SUS 2 (Schubauer-Berigan and Crane 1997). This area became progressively cleaner in the 15-30 cm (i.e., 0.47 mg/kg) and 0-15 cm (i.e., 0.19 mg/kg) segments. However, other areas became more contaminated with mercury in the surficial sediments compared to the deeper layers. In particular, there appears to be a more recent source of mercury contamination at SLPC 19 (Fig. 23); the surficial concentration of mercury at this site was 0.6 mg/kg compared to 0.18 mg/kg in the 15-30 cm core segment and 0.16 mg/kg in the 30-45 cm core segment (Table 3).

For the PAH graphics given in Fig. 24, not as much data were available for the 15-30 cm and 30-45 cm plots due to the high cost of analyzing sediment samples for PAHs. Thus, more detail in the distribution of PAHs is given in the 0-15 cm graphic. Due to the triangulation pattern used in the sediment kriging process, single data points of high contamination surrounded by much lower contaminated data points may not be designated by its corresponding color on the concentration scale. Such was the case with SLPC 15 and SLPC 15R that were located next to each other, but had total PAH concentrations that varied by 4,283 – 22,350 μg/kg from each other. From Fig. 24, a larger area of PAH contaminated sediments appeared in the 15-30 cm core segment versus the 30-45 cm core segment, and higher levels of contamination occurred in the surficial sections of SUS 3 and SLPC 17. In addition, total PAH contamination at SLPC 13 increased 125.5% in the 15-30 cm core section compared to the 30-45 cm core section; PAHs increased 10% in the 0-15 cm core segment compared to the 15-30 cm core section at this site. The level of PAH contamination at SLPC 13 (0-15 cm) is of concern because it is more than double the probable effect concentration for PAHs.

The data for PCBs (Fig. 25) were more sparse due to the incompatibility of adding the 1993 field data (which were collected in 30 cm increments) to the graphics data set. Since PCBs were not associated with the other contaminants, no extrapolations can be made about their presence in other parts of the slip. PCBs were generally highest in the 15-30 cm segment in front of the former Superwood plant. In addition, a high pocket of PCB contamination occurred near SLPC 18. The transect of PCB samples collected from Slip C in 1993 also showed higher historical levels of PCBs in the sediments in front of the former Superwood plant (Schubauer-Berigan and Crane 1997). This spatial distribution of PCB contamination does not necessarily imply that the contamination was due to the former Superwood plant (now owned by Georgia-Pacific Corp.).

Volume of Contaminated Sediments

Determination of the volume of contaminated sediments is dependent on setting contaminant clean-up goals for Slip C. By doing this, volume estimates can be generated for those sediments exceeding the clean-up goals. From the available data, the inner slip is clearly the most contaminated section warranting additional evaluation of remediation options. The MPCA, and its collaborators, are in the process of developing sediment quality objectives that will be one piece of information, in addition to toxicology, bioaccumulation, and benthological data that will be considered for setting clean-up goals. The distribution of contaminants down to 45 cm has been well determined in Slip C. For this study, physical observations of unsampled core sections down to as much as 90 cm revealed physical indications of contamination (e.g., oil sheen, odor, detrital material) (Table 1).

Previous sediment investigations at Slip C have demonstrated deeper areas of contamination. Of four sediment cores collected in Slip C during 1993, the most inland core (DSH 29) was contaminated with mercury and PCBs down to 157 cm (Fig. 4) (Schubauer-Berigan and Crane 1997). In addition, mercury was found to be contaminated down to 74 cm at the second most inland core (DSH 37) (Schubauer-Berigan and Crane 1997). For the 1994 hot spot investigation, the sediments were contaminated with mercury and PCBs down to 126 cm at SUS 2 and to 115 cm at SUS 4; PCBs were also elevated down to 54 cm at SUS 5 (Fig. 5) (Crane *et al*. 1997). The sediment contamination in Slip C is very heterogeneous and may require a more sophisticated integration of contaminant volume estimates than just multiplying the area by a single depth interval.

Preliminary Remediation Options

Decisions on whether to remediate contaminated sediments in Slip C will be postponed until sediment quality objectives are developed for the St. Louis River AOC in late 1999, a sediment bioaccumulation study is completed in this slip in late 1999, and further work is done to assess groundwater and soil contamination adjacent to the slip. In addition, future land and water uses around Slip C need to be assessed. Lastly, a determination of potentially responsible parties needs to be made, if possible.

The MPCA will use the weight-of-evidence data available for this site, with input from community stakeholders, to decide on the course of actions to be taken at this site. If it is decided the slip warrants remediation, the following remediation options should be considered further through a feasibility study:

- natural recovery (i.e., no action alternative)
- dredging and removing the contaminated sediments to an upland landfill appropriate to the level of sediment contamination or to a confined disposal facility (e.g., Erie Pier)
- capping the contaminated sediments
- *in situ* treatment of contaminated sediments
- *in situ* containment of contaminated sediments
- filling in the most contaminated area of Slip C and developing it for upland uses
- some combination of the above remediation options.

The development and implementation of any remediation options will be highly dependent on whether any potentially responsible parties (PRPs) can be held legally responsible for contamination in Slip C. If no PRPs can be named for this site, then local, state, and federal sources of money will need to be competitively sought to remediate this site if options, other than natural recovery, are selected.

Sediment Management Plan

A sediment management plan for Slip C will be developed within the context of an environmental management plan for the entire Duluth waterfront. The waterfront has many historical sources of contamination resulting from the filling in of former wetlands with unknown fill material to expand the waterfront; from former industry, business, and municipal sources of contamination; and from nonpoint sources. Thus, a multimedia approach is warranted to address contamination along the waterfront and to prioritize where clean-up actions should take place. The MPCA's Duluth Regional Office will lead the effort to develop an environmental management plan for the waterfront, which may be expanded to eventually include the entire St. Louis River AOC. Stakeholder involvement will be sought to develop shared goals and situational alliances that will ultimately result in a consistent and effective management plan for reducing multimedia sources of contamination in this section of the watershed. In addition, this plan will play an important role in developing total maximum daily loads (TMDLs) for mercury and other contaminants in the St. Louis River.

RECOMMENDATIONS

Based on the results of this investigation, the following recommendations can be made for managing contaminated sediments in Slip C.

- Compare existing sediment chemistry data for Slip C with sediment quality objectives that will be developed for the St. Louis River AOC by the fall of 1999.
- Assess the bioaccumulation of Hg, PAH compounds, and PCB congeners in *Lumbriculus variegatus* organisms exposed to Slip C sediments. This project will be completed by the fall of 1999.
- Assess the need for remediating soil and groundwater contamination on Georgia-Pacific's property by Slip C.
- Implement source control measures to reduce contaminant inflows into Slip C through point and nonpoint sources.
- Monitor the loading of contaminants entering Slip C from the Buckingham Creek outfall and Georgia-Pacific's yard runoff outfall to ensure existing source control measures are working.
- Conduct ^{210}Lead dating on at least two sediment cores from Slip C in order to determine historical time periods in the cores; the distribution of an indicator chemical like mercury would be measured in the same core segments. This information would be used to assess the level of mixing in the cores, as well as to determine the sediment depth at which major changes occurred in the immediate watershed (e.g., depth at which nearby commercial business operations started, changed, and ended).
- Analyze some sediments for the presence of phenolic resins, phenols, and formaldehyde as an indicator of waste products released by the former Superwood Corp. Phenols would also be present due to coal tar contamination as well.
- Discuss present and future water and land uses around Slip C with current business owners, the City of Duluth, the Metropolitan Interstate Commission's Harbor Technical

Advisory Committee, the St. Louis River CAC Sediment Contamination Work Group, and other interested stakeholders. This would have implications for determining what kinds of remediation options would be feasible for maintaining existing and future water uses in Slip C.

- Develop contaminant clean-up goals based on integrating sediment quality objectives with the weight-of-evidence information available for sediment chemistry, sediment toxicity, benthological, and bioaccumulation data for this site.
- Conduct a feasibility study of viable remediation options for Slip C.
- Determine the extent of sediment contamination at the former coal gasification plant at Dakota Pier, and examine the data for any similar trends in the distribution of PAHs, lead, and mercury with the Slip C sediments.
- Determine if any current, or historical companies, can be designated as potentially responsible parties for sediment contamination in Slip C.
- Develop an overall environmental management plan for the Duluth waterfront that ties together known air, soil, sediment, and groundwater contamination sources with setting priorities for the remediation of known sediment hot spots.

Implementation of the above recommendations will depend on the availability of funding and staff, as well as cooperative ventures developed with potentially responsible parties or other interested stakeholders.

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TABLES

TABLE 1. Description of field results.

Site Location	Sampling Date (mo/d/yr)	Latitude	Longitude	Water Depth (m)	Soft Sediment Depth (m)	Core Length (cm)	Core Section (cm)	Core Section Description
SLPC 01	6/16/97	46.77057	-92.10852	9.3	0.3	45	0-15	small amount of fibrous material and fine grained sand on top, rest of core is brown sand
							15-55	uniform brown sand w/ rocks and shells present
SLPC 02	6/16/97	46.77090	-92.10582	2.3	0	50	0-15	brown sand
							15-60	uniform brown sand w/ bottom 15 cm more hard packed
SLPC 03	6/16/97	46.76871	-92.11148	2.6	0.1	75	0-15	brown sand
							15-85	uniform brown sand
SLPC 06	6/16/97	46.77356	-92.10617	6.3	1	72	0-15	brown sand w/ some fines, thin layer of wood chips on top
							15-30	brown sand with some detrital material
							30-45	brown sand with some detrital material and 5 cm layer of silty material
							45-60	brown sand with detrital material throughout, lower layer contained clay
SLPC 07	6/16/97	46.77322	-92.10674	6.5	0.8	36	0-15	brown sand/silt
							15-30	brown sand/silt, more organic material than upper section
							30-36	brown sand/silt w/ some fibrous material
SLPC 08	6/16/97	46.77282	-92.10776	7.1	0.3	26	0-15	dark brown sand/silt, fibrous material, wood chips
							15-26	coarse brown sand w/ some gravel and detritus, tar streaks
SLPC 08R	6/16/97	46.77282	-92.10776	7.4	0.3	61	0-15	dark brown sand/silt, large wood chips
							15-30	brown sand, piece of shingle in sample (discarded)
							30-45	uniform brown sand
							45-60	uniform brown sand
SLPC 09	6/17/97	46.77234	-92.10810	7.1	0.5	87	0-15	grey-brown, pudding-like consistency, fine silt/sand, some wood chips and detritus
							15-30	firm brown silt/clay w/ detrital material throughout and large chunks of wood
							30-45	brown sand w/ some detrital material (wood)
							45-60	brown sand w/ small amount of detrital material

R = Field replicate

TABLE 1. Continued.

Site Location	Sampling Date (mo/d/yr)	Latitude	Longitude	Water Depth (m)	Soft Sediment Depth (m)	Core Length (cm)	Core Section (cm)	Core Section Description
SLPC 10	6/17/97	46.77208	-92.10935	5.9	1.5	63	0-15	grey-brown, pudding-like consistency, silty, oil sheen, some detrital material
							15-30	brown sand/silt, firmer texture than upper section, detrital material
							30-45	uniform brown sand w/ some detrital material
							45-60	homogeneous clay/sand w/ lots of detrital material
SLPC 11	6/17/97	46.77128	-92.11111	6.4	1.5	75	0-15	grey-brown, pudding-like consistency, silty, slight oil sheen, some detrital material
							15-30	brown sand w/ lots of detrital material, wood chunks
							30-45	brown silt w/ lots of detrital material
							45-60	brown silt, increased clay content w/ depth, odor, small amount of detrital material
SLPC 12	6/17/97	46.77075	-92.11054	5.9	0.8	118	0-15	grey-brown, pudding-like consistency, silty, fine detritus
							15-30	brown silt, pudding-like consistency, some detritus
							30-45	brown silt, firm, pudding-like consistency, some detritus, odor
							45-60	brown clay/sand w/ wood particles, odor, one rock
							60-75	brown, more clay than 45-60 cm section, wood fibers, odor
SLPC 13	6/17/97	46.77050	-92.11125	4.5	1.4	86	0-15	grey-brown, pudding-like consistency, silty, some detritus, oil sheen
							15-30	grey-brown, firm pudding-like texture, silty/sand, oil sheen, lots of detrital material
							30-45	brown silt w/ lots of detrital material
							45-60	dark brown sand/silt/clay, detritus, odor
							60-75	dark silt and detritus

TABLE 1. Continued.

Site Location	Sampling Date (mo/d/yr)	Latitude	Longitude	Water Depth (m)	Soft Sediment Depth (m)	Core Length (cm)	Core Section (cm)	Core Section Description
SLPC 14	6/18/97	46.77084	-92.10675	5.9	0.9	55	0-15	brown silt, pudding-like consistency, some detritus
							15-30	brown silt, firm pudding-like texture, lots of detrital material
							30-45	brown silt/sand, firm texture, lots of detrital material
							45-55	dark brown sand/silt, some gravel, lots of woody detrital material, oil sheen
SLPC 15	6/18/97	46.77157	-92.11048	5.9	1.8	90	0-15	brown sand/silt, detritus, oil sheen
							15-30	brown silt, lots of detrital material, some wood chunks
							30-45	brown silt, mostly detrital material, some twigs
							45-60	brown silt/clay, detrital material
							60-75	brown, mostly sand, some silt/clay, odor, sawdust
							75-90	brown sand/gravel, clay layer on bottom, small amount of detrital material, odor
SLPC 15R	6/18/97	46.77157	-92.11048	6.4	1.5	47	0-15	brown silt, pudding-like consistency, lots of detrital material
							15-30	brown silt, firm, lots of detrital material
							30-45	brown sand/silt, firm, lots of detrital material, odor
							45-47	brown sand/silt, firm, mostly detrital material
SLPC 16	6/18/97	46.77195	-92.10976	5.2	0.6	33	0-15	brown silt, oil sheen, lots of detrital material
							15-30	brown sand w/ some detrital material
							30-33	brown sand, small amount of detrital material
SLPC 17	6/18/97	46.77254	-92.10886	6	1.4	79	0-15	brown silt, oil sheen, lots of detrital material, pudding-like consistency
							15-30	firm brown silt/sand with lots of detrital material
							30-45	firm brown sand/silt with detrital material
							45-60	brown sand/silt with detrital material, some pebbles
							60-75	mostly brown sand w/some detrital material

R = Field replicate

TABLE 1. Continued.

Site Location	Sampling Date (mo/d/yr)	Latitude	Longitude	Water Depth (m)	Soft Sediment Depth (m)	Core Length (cm)	Core Section (cm)	Core Section Description
SLPC 18	6/18/97	46.77259	-92.10864	6.2	0.8	46	0-15	brown, silty, soupy, oil sheen, twigs, small amount of detrital material
							15-30	brown, silty, odor, lots of detrital material, some sand
							30-45	brown sand, some silt, detrital material
SLPC 19	6/18/97	46.77320	-92.10774	7.7	0.5	52	0-15	brown, soupy, silty, twigs, detrital material, oil sheen
							15-30	brown silt/sand, detrital material
							30-45	brown, sand/silt, detrital material
							45-52	brown sand, gravel, wood chunks, odor

TABLE 2. Particle size distribution of sediment samples.

			Percent Composition of Different Size Ranges				
Site Location	Core Section (cm)	Estimated Median Diameter (µm)	Sand & Gravel >53 µm	Coarse Silt 53-20 µm	Medium Silt 20-5 µm	Fine Silt 5-2 µm	Coarse Clay 2-0.2 µm
SLPC 01	0-15	>53	96.2	1.8	0.9	0.4	0.7
SLPC 02	0-15	>53	97.6	0.8	0.7	0.3	0.6
SLPC 03	0-15	>53	96.2	1.1	1.4	0.4	0.9
SLPC 06	0-15	>53	93.5	1.5	2.3	0.9	1.8
SLPC 07	0-15	>53	86.5	4.5	4.6	1.5	2.9
SLPC 08 (mean; SD)	0-15*	>53	95.0 (2.2)	1.7 (1.1)	1.8 (0.7)	0.5 (0.1)	1.0 (0.2)
SLPC 09	0-15	>53	62.7	11.8	14.3	3.8	7.4
	15-30	>53	78.3	6.7	8.0	2.3	4.6
SLPC 10	0-15	>53	68.9	11.4	10.6	3.1	5.9
	15-30**	>53	89.1	3.5	4.0	1.1	2.2
SLPC 11	0-15	37	41.7	17.0	23.7	6.0	11.6
	15-30	>53	56.4	13.4	17.4	4.4	8.4
SLPC 12	0-15	18	26.8	19.2	30.8	7.9	15.3
	15-30	28	33.8	21.2	25.0	7.0	12.9
SLPC 13	0-15	>53	50.3	17.2	18.3	5.0	9.2
	15-30	>53	56.2	24.6	11.0	2.9	5.3
	30-45	>53	66.7	14.5	11.5	2.9	4.4
SLPC 14	0-15	32	36.9	20.9	24.8	6.2	11.2
	15-30	33	36.3	22.5	25.1	6.3	9.8
	30-45***	>53	63.2	12.6	14.4	3.8	6.1
SLPC 15	0-15**	>53	71.7	7.8	11.5	3.1	5.8
	15-30	>53	61.8	11.2	15.6	4.3	7.0
	30-45	33	37.9	19.8	26.0	6.5	9.8
SLPC 15R	0-15	>53	50.6	14.4	19.2	3.8	12.0
	15-30	33	39.3	18.0	25.0	7.1	10.7
	30-45	>53	70.7	9.4	11.4	3.2	5.3
SLPC 16	0-15	>53	74.8	7.0	10.1	2.8	5.2
	15-30	>53	96.0	0.9	1.8	0.5	0.8
SLPC 17	0-15	>53	56.7	19.9	13.4	2.1	7.9
	15-30	>53	82.9	5.6	6.2	1.8	3.5
	30-45	>53	91.9	2.9	2.9	0.9	1.5
	45-60**	>53	83.9	5.7	5.9	1.6	2.9
SLPC 18	0-15***	>53	69.5	10.3	11.2	3.2	5.8
	15-30	>53	90.9	2.1	4.0	1.1	1.9
SLPC 19	0-15**	>53	62.6	11.9	14.1	3.7	7.7

SD = Standard deviation

R = Field replicate

* Mean of field replicates

** Mean of analytical duplicates, based on full preparation

*** Mean of analytical duplicates, based on elutriate

TABLE 3. Comparison of contaminant data with low/threshold effect level and probable effect concentration sediment quality guidelines (SQGs). Values in bold exceed the low level SQGs, whereas values in bold shading exceed the probable effect concentration SQGs.

Site Location	Core Depth (cm)	Lead (mg/kg)	Mercury (mg/kg)	Total PAHs (µg/kg)	Total PCBs (µg/kg)	TOC (%)
SLPC 01	0-15	12	0.04	**4726**		1.1
SLPC 02	0-15	7.6	0.02	2238		0.34
SLPC 03	0-15	9.4	0.02	2925		0.79
SLPC 06	0-15	10	0.03	3450		0.91
SLPC 07	0-15	25	0.12	**6623**		1.9
SLPC 08 (mean)	0-15	0.36	0.08	3486		1.4
SLPC 09	0-15	**75**	**0.24**	**14285**	**99**	4
SLPC 10	0-15	**75**	**0.22**	**15996**		3.4
SLPC 11	0-15	**130**	**0.31**	**28229**		7.6
SLPC 12	0-15	**140**	**0.34**	**25625**		8.4
SLPC 13	0-15	**190**	**0.27**	**48996**		10
SLPC 14	0-15	**150**	**0.37**	**32036**		9.5
SLPC 15	0-15	**68**	**0.19**	**19717**		4.3
SLPC 15R	0-15	**130**	**0.4**	**24000**		15
SLPC 16	0-15	**81**	**0.24**	**12441**		1.8
SLPC 17	0-15	**100**	**0.26**	**27855**	**111**	5.4
SLPC 18	0-15	**83**	**0.3**	**14933**	**258**	4.3
SLPC 19	0-15	**96**	**0.6**	**14314**		5.1
SLPC 07	15-30	0.2	**0.17**			
SLPC 08	15-26	0.05	0.09			
SLPC 08R	15-30	0.94	0.08			
SLPC 09	15-30	**77**	**0.22**	**9534**	**66.9**	2.9
SLPC 10	15-30	**70**	**0.17**	**9196**		1.8
SLPC 11	15-30	**120**	**0.26**	**22562**		7.2
SLPC 12	15-30	**150**	**0.36**	**29450**		13
SLPC 13	15-30	**120**	**0.18**	**44537**		8
SLPC 14	15-30	**140**	**0.39**	**28200**		30
SLPC 15	15-30	**110**	**0.35**	**35841**		11
SLPC 15R	15-30	**120**	**0.33**	**25428**		21
SLPC 16	15-30	**43**	0.07	**4988**		1.9
SLPC 17	15-30	**65**	**0.34**	**8823**	**96.8**	2.6
SLPC 18	15-30	**81**	0.15		**269**	2.2
SLPC 19	15-30	**43**	**0.18**			
SLPC 07	30-36	0.15	**0.22**			
SLPC 08R	30-45	1.5	0.0025			
SLPC 09	30-45	**47**	0.09			
SLPC 10	30-45	**69**	**0.2**			
SLPC 11	30-45	**150**	**0.34**			
SLPC 12	30-45	**160**	**0.45**			

TABLE 3. Continued.

Site Location	Core Depth (cm)	Lead (mg/kg)	Mercury (mg/kg)	Total PAHs (µg/kg)	Total PCBs (µg/kg)	TOC (%)
SLPC 13	30-45	**73**	**0.25**	**19753**		14
SLPC 14	30-45	**92**	**0.36**	**22597**		13
SLPC 15	30-45	**170**	**0.49**	**43639**		19
SLPC 15R	30-45	**89**	**0.3**	**21289**		9.9
SLPC 16	30-33	**38**	0.1			
SLPC 17	30-45	**56**	0.14	**7980**		1.9
SLPC 18	30-45	**44**	0.06			
SLPC 19	30-45	**69**	0.16			
SLPC 15	45-60	**150**	**0.4**			
SLPC 15R	45-47	**200**	**0.5**			
SLPC 17	45-60	**88**	0.16	**14032**		2.5
Sediment Quality Guidelines:						
LEL				4000		
TEL		35	0.174		34.1	
PEC		128	1.06	22800	676	

R = Field replicate
LEL = Lowest effect level (Persaud *et al*. 1993)
TEL = Threshold effect level (Smith *et al*. 1996)
PEC = Probable effect concentration (Ingersoll and MacDonald 1998)

TABLE 4. Summary of relative contamination factors (RCFs) for contaminant concentrations normalized to low level effect sediment quality guidelines. Bold values exceed an RCF of 1.

Site Location	**Core Section (cm)**	**Lead TEL RCF**	**Mercury TEL RCF**	**PAH LEL RCF**	**PCB TEL RCF**	**Mean Low Level RCF**
SLPC 01	0-15	0.3	0.2	**1.2**		0.6
SLPC 02	0-15	0.2	0.1	0.6		0.3
SLPC 03	0-15	0.3	0.1	0.7		0.4
SLPC 06	0-15	0.3	0.2	0.9		0.4
SLPC 07	0-15	0.7	0.7	**1.7**		**1.0**
SLPC 08 (mean)	0-15	0.01	0.5	0.9		0.4
SLPC 09	0-15	**2.1**	**1.4**	**3.6**	**2.9**	**2.5**
SLPC 10	0-15	**2.1**	**1.3**	**4.0**		**2.5**
SLPC 11	0-15	**3.7**	**1.8**	**7.1**		**4.2**
SLPC 12	0-15	**4.0**	**2.0**	**6.4**		**4.1**
SLPC 13	0-15	**5.4**	**1.6**	**12.2**		**6.4**
SLPC 14	0-15	**4.3**	**2.1**	**8.0**		**4.8**
SLPC 15	0-15	**1.9**	**1.1**	**4.9**		**2.7**
SLPC 15R	0-15	**3.7**	**2.3**	**6.0**		**4.0**
SLPC 16	0-15	**2.3**	**1.4**	**3.1**		**2.3**
SLPC 17	0-15	**2.9**	**1.5**	**7.0**	**3.3**	**3.6**
SLPC 18	0-15	**2.4**	**1.7**	**3.7**	**7.6**	**3.8**
SLPC 19	0-15	**2.7**	**3.4**	**3.6**		**3.3**
SLPC 07	15-30	0.01	**1.0**			0.5
SLPC 08	15-26	0.001	0.5			0.3
SLPC 08R	15-30	0.03	0.5			0.2
SLPC 09	15-30	**2.2**	**1.3**	**2.4**	**2.0**	**2.0**
SLPC 10	15-30	**2.0**	**1.0**	**2.3**		**1.8**
SLPC 11	15-30	**3.4**	**1.5**	**5.6**		**3.5**
SLPC 12	15-30	**4.3**	**2.1**	**7.4**		**4.6**
SLPC 13	15-30	**3.4**	**1.0**	**11.1**		**5.2**
SLPC 14	15-30	**4.0**	**2.2**	**7.1**		**4.4**
SLPC 15	15-30	**3.1**	**2.0**	**9.0**		**4.7**
SLPC 15R	15-30	**3.4**	**1.9**	**6.4**		**3.9**
SLPC 16	15-30	**1.2**	0.4	**1.2**		**1.0**
SLPC 17	15-30	**1.9**	**2.0**	**2.2**	**2.8**	**2.2**
SLPC 18	15-30	**2.3**	0.9		**7.9**	**3.7**
SLPC 19	15-30	**1.2**	**1.0**			**1.1**
SLPC 07	30-36	0.004	**1.3**			0.6
SLPC 08R	30-45	0.04	0.01			0.03
SLPC 09	30-45	**1.3**	0.5			0.9
SLPC 10	30-45	**2.0**	**1.1**			**1.6**
SLPC 11	30-45	**4.3**	**2.0**			**3.1**
SLPC 12	30-45	**4.6**	**2.6**			**3.6**

TABLE 4. Continued.

Site Location	**Core Section (cm)**	**Lead TEL RCF**	**Mercury TEL RCF**	**PAH LEL RCF**	**PCB TEL RCF**	**Mean Low Level RCF**
SLPC 13	30-45	**2.1**	**1.4**	**4.9**		**2.8**
SLPC 14	30-45	**2.6**	**2.1**	**5.6**		**3.4**
SLPC 15	30-45	**4.9**	**2.8**	**10.9**		**6.2**
SLPC 15R	30-45	**2.5**	**1.7**	**5.3**		**3.2**
SLPC 16	30-33	**1.1**	0.6			0.8
SLPC 17	30-45	**1.6**	0.8	**2.0**		**1.5**
SLPC 18	30-45	**1.3**	0.3			0.8
SLPC 19	30-45	**2.0**	0.9			**1.4**
SLPC 15	45-60	**4.3**	**2.3**			**3.3**
SLPC 15R	45-47	**5.7**	**2.9**			**4.3**
SLPC 17	45-60	**2.5**	0.9	**3.5**		**2.3**

R = Field replicate
LEL = Lowest effect level (Persaud *et al*. 1993)
RCF = Relative contamination factor
TEL = Threshold effect level (Smith *et al*. 1996)

TABLE 5. Summary of relative contamination factors (RCFs) for contaminant concentrations normalized to probable effect level sediment quality guidelines. Bold values exceed an RCF of 1.

Site Location	**Core Section (cm)**	**Lead PEC RCF**	**Mercury PEC RCF**	**PAH PEC RCF**	**PCB PEC RCF**	**Mean PEC RCF**
SLPC 01	0-15	0.09	0.04	0.2		0.1
SLPC 02	0-15	0.06	0.02	0.1		0.1
SLPC 03	0-15	0.07	0.02	0.1		0.1
SLPC 06	0-15	0.08	0.03	0.2		0.1
SLPC 07	0-15	0.2	0.1	0.3		0.2
SLPC 08 (mean)	0-15	0.003	0.08	0.2		0.1
SLPC 09	0-15	0.6	0.2	0.6	0.1	0.4
SLPC 10	0-15	0.6	0.2	0.7		0.5
SLPC 11	0-15	**1.0**	0.3	**1.2**		0.8
SLPC 12	0-15	**1.1**	0.3	**1.1**		0.8
SLPC 13	0-15	**1.5**	0.3	**2.1**		**1.3**
SLPC 14	0-15	**1.2**	0.3	**1.4**		**1.0**
SLPC 15	0-15	0.5	0.2	0.9		0.5
SLPC 15R	0-15	**1.0**	0.4	**1.1**		0.8
SLPC 16	0-15	0.6	0.2	0.5		0.5
SLPC 17	0-15	0.8	0.2	**1.2**	0.2	0.6
SLPC 18	0-15	0.6	0.3	0.7	0.4	0.5
SLPC 19	0-15	0.8	0.6	0.6		0.6
SLPC 07	15-30	0.002	0.2			0.1
SLPC 08	15-26	0.0004	0.08			0.04
SLPC 08R	15-30	0.01	0.08			0.04
SLPC 09	15-30	0.6	0.2	0.4	0.1	0.3
SLPC 10	15-30	0.5	0.2	0.4		0.4
SLPC 11	15-30	0.9	0.2	**1.0**		0.7
SLPC 12	15-30	**1.2**	0.3	**1.3**		0.9
SLPC 13	15-30	0.9	0.2	**2.0**		**1.0**
SLPC 14	15-30	**1.1**	0.4	**1.2**		0.9
SLPC 15	15-30	0.9	0.3	**1.6**		0.9
SLPC 15R	15-30	0.9	0.3	**1.1**		0.8
SLPC 16	15-30	0.3	0.07	0.2		0.2
SLPC 17	15-30	0.5	0.3	0.4	0.1	0.3
SLPC 18	15-30	0.6	0.1		0.4	0.4
SLPC 19	15-30	0.3	0.2			0.3
SLPC 07	30-36	0.001	0.2			0.1
SLPC 08R	30-45	0.01	0.002			0.007
SLPC 09	30-45	0.4	0.08			0.2
SLPC 10	30-45	0.5	0.2			0.4
SLPC 11	30-45	**1.2**	0.3			0.7
SLPC 12	30-45	**1.3**	0.4			0.8
SLPC 13	30-45	0.6	0.2	0.9		0.6

TABLE 5. Continued.

Site Location	**Core Section (cm)**	**Lead PEC RCF**	**Mercury PEC RCF**	**PAH PEC RCF**	**PCB PEC RCF**	**Mean PEC RCF**
SLPC 14	30-45	0.7	0.3	**1.0**		0.7
SLPC 15	30-45	**1.3**	0.5	**1.9**		**1.2**
SLPC 15R	30-45	0.7	0.3	0.9		0.6
SLPC 16	30-33	0.3	0.09			0.2
SLPC 17	30-45	0.4	0.1	0.4		0.3
SLPC 18	30-45	0.3	0.06			0.2
SLPC 19	30-45	0.5	0.2			0.3
SLPC 15	45-60	**1.2**	0.4			0.8
SLPC 15R	45-47	**1.6**	0.5			**1.0**
SLPC 17	45-60	0.7	0.2	0.6		0.5

R = Field replicate
PEC = Probable effect concentration (Ingersoll and MacDonald 1998)
RCF = Relative contamination factor

TABLE 6. Summary of PAH concentrations for selected sediment samples. PAH concentrations in bold itallics exceeded a low level sediment quality guideline (SQG) value, whereas shaded values exceeded a higher level SQG number.

Site	Core Section	PAHs (µg/kg dry weight)																		
Location	**(cm)**	**2Metnap**	**Acene**	**Aceny**	**Anth**	**Bena**	**Benap**	**Benb**	**Bene**	**Beng**	**Benk**	**Chry**	**Diben**	**Flut**	**Fluo**	**Indp**	**Naph**	**Phen**	**Pyrn**	**Total**
SLPC 01	0-15	69	***63***	18	143	***407***	307	208	214	***195***	157	***372***	43	***944***	86	***212***	58	***627***	***602***	***4720***
SLPC 02	0-15	25	***29***	4.5	58	172	166	111	114	115	82	161	27	449	42	138	15	222	307	2240
SLPC 03	0-15	25	***48***	4.5	129	232	169	106	110	103	81	199	25	602	65	112	31	425	459	2920
SLPC 06	0-15	25	***57***	4.5	104	280	191	136	125	123	103	247	34	***779***	65	137	51	528	458	3450
SLPC 07	0-15	52	***59***	25	181	***551***	***520***	465	282	***277***	233	***525***	59	***1258***	111	***308***	72	***777***	***868***	***6623***
SLPC 08*																				
mean	0-15	54	***58***	11	99	279	203	145	139	151	112	233	33	655	82	161	51	454	***566***	3490
SD	0-15	6.3	0.85	3.2	9.3	53	42	31	33	38	28	50	5.6	71	5.7	39	8.6	11	51	490
SLPC 09	0-15	***149***	***110***	***66***	***310***	***1086***	***1055***	863	962	***1128***	***396***	***1086***	***130***	***2358***	178	***1187***	148	***1372***	***1703***	***14280***
SLPC 10**																				
mean	0-15	***112***	***139***	***49***	***349***	***1162***	***1139***	985	1043	***963***	***478***	***1239***	***138***	***2906***	*215*	***1090***	115	***1791***	***2082***	***16000***
SD	0-15	20	12	1.7	46	142	179	96	129	145	133	77	5.9	382	7.4	172	20	381	248	2120
SLPC 11	0-15	***421***	***294***	***92***	***530***	***1555***	***1821***	1607	1627	***1720***	***902***	***2459***	***251***	***5229***	***455***	***1895***	***377***	***3109***	***3885***	***28230***
SLPC 12	0-15	***198***	***168***	***99***	***435***	***1581***	***1939***	1691	1747	***1851***	***539***	***2487***	***239***	***4452***	***263***	***2032***	***216***	***2280***	***3412***	***25620***
SLPC 13	0-15	***438***	***660***	***129***	***1372***	***2623***	***3250***	2533	2634	***3001***	***1308***	***4115***	***969***	***8632***	***1083***	***3355***	***430***	***5808***	***6656***	***49000***
SLPC 14	0-15	***270***	***390***	***96***	***719***	***1750***	***2185***	1864	1801	***1975***	***855***	***2836***	***320***	***5666***	***520***	***2230***	***257***	***3909***	***4394***	***32040***
SLPC 15	0-15	***109***	***292***	***49***	***647***	***1277***	***1309***	1070	1068	***1142***	***545***	***1616***	***183***	***3600***	***409***	***1277***	115	***2391***	***2616***	***19720***
SLPC 15R	0-15	***347***	***357***	***128***	***843***	***1324***	***1579***	1456	1572	***1574***	***346***	***1691***	***170***	***4084***	***427***	***1764***	***349***	***2960***	***3031***	***24000***
SLPC 16	0-15	***98***	***131***	***69***	***270***	***774***	***938***	785	825	***921***	***252***	***1034***	***125***	***2148***	188	***898***	138	***1175***	***1672***	***12440***
SLPC 17	0-15	***249***	***421***	***101***	***795***	***2044***	***1673***	1368	1427	***1489***	***775***	***2264***	***272***	***5043***	***737***	***1658***	***245***	***3419***	***3874***	***27850***
SLPC 18	0-15	***182***	***143***	***67***	***325***	***1126***	***1069***	945	933	***933***	***351***	***1190***	***128***	***2588***	***221***	***973***	***179***	***1623***	***1958***	***14930***
SLPC 19	0-15	***218***	***230***	***64***	***472***	***768***	***923***	817	796	***898***	***298***	***1103***	***116***	***2444***	***398***	***829***	***192***	***2111***	***1636***	***14310***
SLPC 09	15-30	***102***	***78***	36	190	***727***	***732***	636	658	***567***	228	***764***	***74***	***1669***	116	***660***	102	***944***	***1252***	***9534***
SLPC 10	15-30	***72***	***84***	21	215	***824***	***657***	558	567	***481***	172	***845***	***62***	***1637***	119	***586***	70	***1034***	***1192***	***9196***

TABLE 6. Continued.

Site Location	Core Section (cm)	PAHs (µg/kg dry weight)																		
		2Metnap	**Acene**	**Aceny**	**Anth**	**Bena**	**Benap**	**Benb**	**Bene**	**Beng**	**Benk**	**Chry**	**Diben**	**Flut**	**Fluo**	**Indp**	**Naph**	**Phen**	**Pyrn**	**Total**
SLPC 11	15-30	***203***	***266***	***81***	***637***	***1276***	***1616***	1345	1356	***1443***	***667***	***1942***	***215***	***3975***	***345***	***1571***	***181***	***2360***	***3083***	***22560***
SLPC 12	15-30	***384***	***313***	***140***	***692***	***1113***	***2137***	1840	1900	***2191***	***941***	***1838***	***278***	***5205***	***431***	***2340***	***357***	***3232***	***4117***	***29450***
SLPC 13	15-30	***271***	***680***	***125***	***1471***	***2705***	***2654***	1851	2044	***2286***	***1358***	***3865***	***726***	***8166***	***956***	***2478***	***248***	***5943***	***6711***	***44540***
SLPC 14	15-30	***274***	***779***	***99***	***688***	***1309***	***1766***	1823	1668	***911***	***362***	***1898***	***222***	***4692***	***992***	***1830***	***187***	***4871***	***3829***	***28200***
SLPC 15	15-30	***382***	***798***	***180***	***1225***	***1796***	***2182***	1763	1818	***1936***	***1026***	***2721***	***318***	***6510***	***962***	***2037***	***465***	***4730***	***4991***	***35840***
SLPC 15R	15-30	***573***	***530***	***211***	***556***	***1232***	***1454***	1320	1368	***1364***	***431***	***2168***	***190***	***4660***	***555***	***1486***	***497***	***3264***	***3570***	***25430***
SLPC 16	15-30	***139***	***79***	32	127	***482***	274	239	203	165	105	***441***	55	**987**	104	172	99	***627***	***657***	***4990***
SLPC 17	15-30	***138***	***112***	35	195	***579***	***637***	595	598	***505***	174	***649***	***75***	***1540***	159	***597***	130	***959***	***1146***	***8823***
SLPC 13	30-45	***304***	***342***	***66***	***445***	***1002***	***1272***	1151	1184	***1097***	***289***	***1696***	***142***	***3309***	***414***	***1331***	152	***2947***	***2610***	***19750***
SLPC 14	30-45	***442***	***795***	***76***	***957***	***920***	***1358***	1179	1220	***1135***	***467***	***1135***	***183***	***3751***	***1015***	***1418***	***265***	***3493***	***2790***	***22600***
SLPC 15	30-45	***832***	***609***	***305***	***1336***	***1700***	***2707***	2194	2468	***2842***	***1305***	***2958***	***345***	***7752***	***1091***	***2985***	***661***	***5346***	***6202***	***43640***
SLPC 15R**																				
mean	30-45	***227***	***388***	***103***	***682***	***992***	***1337***	1136	1154	***1224***	***394***	***1898***	***189***	***3778***	***512***	***1376***	***277***	***2670***	***2953***	***21290***
SD	30-45	14	***55***	0	100	100	147	131	155	***202***	76	75	23	304	197	***240***	9.4	456	177	2110
SLPC 17	30-45	64	***72***	26	170	***589***	***592***	532	540	***470***	176	***621***	***69***	***1470***	105	***568***	51	***796***	***1070***	***7980***
SLPC 17	45-60	***239***	***116***	***53***	***258***	***999***	***994***	839	866	***995***	***337***	***1179***	***119***	***2408***	183	***938***	153	***1448***	***1907***	***14030***
Sediment Quality Guidelines (µg/kg):																				
LEL					220	320	370			170	240	340	60	750	190	200		560	490	4000
PEC			650		845	1050	1450					1290		2230	536		561	1170	1520	22800
ERL		70	16	44													160			
PEL (MacDonald 1993)		450											320							
PEL (MacDonald 1994)				128																

TABLE 6. Continued.

* Mean of field replicates
** Mean of analytical duplicates
SD = Standard deviation
R = Field replicate
LEL = Lowest effect level (Persaud and Jaagumagi 1993)
PEC = Probable effect concentration (Ingersoll and MacDonald 1998)
ERL = Effects range low (Long and Morgan 1990)
PEL = Probable effect level (MacDonald 1993, 1994)

PAH Codes:
2Metnap = 2-Methylnaphthalene
Acene = Acenaphthene
Aceny = Acenaphthylene
Anth = Anthracene
Bena = Benzo[a]anthracene
Benap = Benzo[a]pyrene
Benb = Benzo[b&j]fluoranthene
Bene = Benzo[e]pyrene
Beng = Benzo[g,h,i]perylene
Benk = Benzo[k]fluoranthene
Chry = Chrysene
Diben = Dibenzo[a,h]anthracene
Flut = Fluoranthene
Fluo = Fluorene
Indp = Indeno[1,2,3-cd]pyrene
Naph = Naphthalene
Phen = Phenanthrene
Pyrn = Pyrene

TABLE 7. Percentage composition of PAH compounds in sediment samples.

		Percentage (%) Composition of PAH Compounds in Sample Sediments																		
Site Code	**Core Section (cm)**	**2Metnap (%)**	**Acene (%)**	**Aceny (%)**	**Anth (%)**	**Bena (%)**	**Benap (%)**	**Benb (%)**	**Bene (%)**	**Beng (%)**	**Benk (%)**	**Chry (%)**	**Diben (%)**	**Flut (%)**	**Fluo (%)**	**Indp (%)**	**Naph (%)**	**Phen (%)**	**Pyrn (%)**	**T. PAHs (%)**
SLPC 01	0-15	1.5	1.3	0.4	3.0	8.6	6.5	4.4	4.5	4.1	3.3	7.9	0.9	20.0	1.8	4.5	1.2	13.3	12.7	100
SLPC 02	0-15	1.1	1.3	0.2	2.6	7.7	7.4	5.0	5.1	5.1	3.7	7.2	1.2	20.1	1.9	6.2	0.7	9.9	13.7	100
SLPC 03	0-15	0.9	1.6	0.2	4.4	7.9	5.8	3.6	3.8	3.5	2.8	6.8	0.9	20.6	2.2	3.8	1.1	14.5	15.7	100
SLPC 06	0-15	0.7	1.7	0.1	3.0	8.1	5.5	3.9	3.6	3.6	3.0	7.2	1.0	22.6	1.9	4.0	1.5	15.3	13.3	100
SLPC 07	0-15	0.8	0.9	0.4	2.7	8.3	7.9	7.0	4.3	4.2	3.5	7.9	0.9	19.0	1.7	4.7	1.1	11.7	13.1	100
SLPC 08*	0-15	1.6	1.7	0.3	2.8	8.0	5.8	4.2	4.0	4.3	3.2	6.7	0.9	18.8	2.4	4.6	1.5	13.0	16.2	100
SLPC 09	0-15	1.0	0.8	0.5	2.2	7.6	7.4	6.0	6.7	7.9	2.8	7.6	0.9	16.5	1.2	8.3	1.0	9.6	11.9	100
SLPC 10**	0-15	0.7	0.9	0.3	2.2	7.3	7.1	6.2	6.5	6.0	3.0	7.7	0.9	18.2	1.3	6.8	0.7	11.2	13.0	100
SLPC 11	0-15	1.5	1.0	0.3	1.9	5.5	6.5	5.7	5.8	6.1	3.2	8.7	0.9	18.5	1.6	6.7	1.3	11.0	13.8	100
SLPC 12	0-15	0.8	0.7	0.4	1.7	6.2	7.6	6.6	6.8	7.2	2.1	9.7	0.9	17.4	1.0	7.9	0.8	8.9	13.3	100
SLPC 13	0-15	0.9	1.3	0.3	2.8	5.4	6.6	5.2	5.4	6.1	2.7	8.4	2.0	17.6	2.2	6.8	0.9	11.9	13.6	100
SLPC 14	0-15	0.8	1.2	0.3	2.2	5.5	6.8	5.8	5.6	6.2	2.7	8.9	1.0	17.7	1.6	7.0	0.8	12.2	13.7	100
SLPC 15	0-15	0.6	1.5	0.2	3.3	6.5	6.6	5.4	5.4	5.8	2.8	8.2	0.9	18.3	2.1	6.5	0.6	12.1	13.3	100
SLPC 15R	0-15	1.4	1.5	0.5	3.5	5.5	6.6	6.1	6.5	6.6	1.4	7.0	0.7	17.0	1.8	7.4	1.5	12.3	12.6	100
SLPC 16	0-15	0.8	1.1	0.6	2.2	6.2	7.5	6.3	6.6	7.4	2.0	8.3	1.0	17.3	1.5	7.2	1.1	9.4	13.4	100
SLPC 17	0-15	0.9	1.5	0.4	2.9	7.3	6.0	4.9	5.1	5.3	2.8	8.1	1.0	18.1	2.6	6.0	0.9	12.3	13.9	100
SLPC 18	0-15	1.2	1.0	0.5	2.2	7.5	7.2	6.3	6.2	6.2	2.3	8.0	0.9	17.3	1.5	6.5	1.2	10.9	13.1	100
SLPC 19	0-15	1.5	1.6	0.4	3.3	5.4	6.4	5.7	5.6	6.3	2.1	7.7	0.8	17.1	2.8	5.8	1.3	14.7	11.4	100
SLPC 09	15-30	1.1	0.8	0.4	2.0	7.6	7.7	6.7	6.9	5.9	2.4	8.0	0.8	17.5	1.2	6.9	1.1	9.9	13.1	100
SLPC 10	15-30	0.8	0.9	0.2	2.3	9.0	7.1	6.1	6.2	5.2	1.9	9.2	0.7	17.8	1.3	6.4	0.8	11.2	13.0	100
SLPC 11	15-30	0.9	1.2	0.4	2.8	5.7	7.2	6.0	6.0	6.4	3.0	8.6	1.0	17.6	1.5	7.0	0.8	10.5	13.7	100
SLPC 12	15-30	1.3	1.1	0.5	2.3	3.8	7.3	6.2	6.5	7.4	3.2	6.2	0.9	17.7	1.5	7.9	1.2	11.0	14.0	100
SLPC 13	15-30	0.6	1.5	0.3	3.3	6.1	6.0	4.2	4.6	5.1	3.0	8.7	1.6	18.3	2.1	5.6	0.6	13.3	15.1	100
SLPC 14	15-30	1.0	2.8	0.4	2.4	4.6	6.3	6.5	5.9	3.2	1.3	6.7	0.8	16.6	3.5	6.5	0.7	17.3	13.6	100
SLPC 15	15-30	1.1	2.2	0.5	3.4	5.0	6.1	4.9	5.1	5.4	2.9	7.6	0.9	18.2	2.7	5.7	1.3	13.2	13.9	100
SLPC 15R	15-30	2.3	2.1	0.8	2.2	4.8	5.7	5.2	5.4	5.4	1.7	8.5	0.7	18.3	2.2	5.8	2.0	12.8	14.0	100
SLPC 16	15-30	2.8	1.6	0.6	2.6	9.7	5.5	4.8	4.1	3.3	2.1	8.8	1.1	19.8	2.1	3.4	2.0	12.6	13.2	100
SLPC 17	15-30	1.6	1.3	0.4	2.2	6.6	7.2	6.7	6.8	5.7	2.0	7.4	0.8	17.5	1.8	6.8	1.5	10.9	13.0	100

TABLE 7. Continued.

		Percentage (%) Composition of PAH Compounds in Sample Sediments																		
Site Code	**Core Section (cm)**	**2Metnap (%)**	**Acene (%)**	**Aceny (%)**	**Anth (%)**	**Bena (%)**	**Benap (%)**	**Benb (%)**	**Bene (%)**	**Beng (%)**	**Benk (%)**	**Chry (%)**	**Diben (%)**	**Flut (%)**	**Fluo (%)**	**Indp (%)**	**Naph (%)**	**Phen (%)**	**Pyrn (%)**	**T. PAHs (%)**
SLPC 13	30-45	1.5	1.7	0.3	2.3	5.1	6.4	5.8	6.0	5.6	1.5	8.6	0.7	16.8	2.1	6.7	0.8	14.9	13.2	100
SLPC 14	30-45	2.0	3.5	0.3	4.2	4.1	6.0	5.2	5.4	5.0	2.1	5.0	0.8	16.6	4.5	6.3	1.2	15.5	12.3	100
SLPC 15	30-45	1.9	1.4	0.7	3.1	3.9	6.2	5.0	5.7	6.5	3.0	6.8	0.8	17.8	2.5	6.8	1.5	12.3	14.2	100
SLPC 15R**	30-45	1.1	1.8	0.5	3.2	4.7	6.3	5.3	5.4	5.7	1.8	8.9	0.9	17.7	2.4	6.5	1.3	12.5	13.9	100
SLPC 17	30-45	0.8	0.9	0.3	2.1	7.4	7.4	6.7	6.8	5.9	2.2	7.8	0.9	18.4	1.3	7.1	0.6	10.0	13.4	100
SLPC 17	45-60	1.7	0.8	0.4	1.8	7.1	7.1	6.0	6.2	7.1	2.4	8.4	0.8	17.2	1.3	6.7	1.1	10.3	13.6	100
Mean		1.2	1.4	0.4	2.7	6.5	6.7	5.6	5.6	5.6	2.5	7.9	0.9	18.1	2.0	6.3	1.1	12.1	13.5	
SD		0.5	0.6	0.1	0.6	1.5	0.7	0.9	0.9	1.2	0.6	1.0	0.2	1.3	0.7	1.2	0.4	2.0	0.9	
CV		42	42	38	24	24	10	16	17	21	25	12	26	7.0	35	19	33	16	6.8	
Range: Low		0.6	0.7	0.1	1.7	3.8	5.5	3.6	3.6	3.2	1.3	5.0	0.7	16.5	1.0	3.4	0.6	8.9	11.4	
Range: High		2.8	3.5	0.8	4.4	9.7	7.9	7.0	6.9	7.9	3.7	9.7	2.0	22.6	4.5	8.3	2.0	17.3	16.2	

* Mean of field replicates

** Mean of analytical duplicates

R = Field replicate

Standard deviation

CV = Coefficient of variation

PAH Codes:
2Metnap = 2-Methylnaphthalene
Acene = Acenaphthene
Aceny = Acenaphthylene
Anth = Anthracene
Bena = Benzo[a]anthracene
Benap = Benzo[a]pyrene
Benb = Benzo[b&j]fluoranthene
Bene = Benzo[e]pyrene
Beng = Benzo[g,h,i]perylene
Benk = Benzo[k]fluoranthene
Chry = Chrysene
Diben = Dibenzo[a,h]anthracene
Flut = Fluoranthene
Fluo = Fluorene
Indp = Indeno[1,2,3-cd]pyrene
Naph = Naphthalene
Phen = Phenanthrene
Pyrn = Pyrene

TABLE 8. Distribution of PCB congeners in selected samples from Slip C.

	PCB Congener Concentrations (μg/kg)					
PCB IUPAC Number	**SLPC 09 0-15 cm**	**SLPC 09 15-30 cm**	**SLPC 17* 0-15 cm**	**SLPC 17 15-30 cm**	**SLPC 18 0-15 cm**	**SLPC 18 15-30 cm**
1	4.5	2.7	2.7	3.0	4.6	2.5
4	7.4	4.9	7.1	5.3	7.1	4.3
7	0.2	0.17	0.22	0.17	0.22	0.15
6	1.3	0.87	0.82	0.92	1.3	0.83
8	0.22	0.19	0.24	0.18	0.24	0.17
5	1.9	1.1	1.9	1.3	1.8	1.2
19	0.91	0.55	0.68	0.56	0.82	0.53
18	0.17	0.14	0.28	0.14	0.51	0.58
17	0.18	0.15	0.20	0.15	0.19	0.14
27/24	0.32	0.27	0.34	0.26	0.33	0.24
32/16	0.90	0.29	0.58	0.67	0.92	0.58
26	0.91	0.71	0.91	0.80	3.3	5.2
25	0.15	0.13	0.16	0.13	0.42	0.66
31	0.94	0.92	1.1	0.99	1.4	1.4
28	0.86	0.59	0.87	0.73	1.2	0.85
33	0.33	0.28	0.36	0.28	0.35	1.3
53	0.50	0.44	0.55	0.43	1.5	0.39
22	0.16	0.26	0.17	0.27	0.41	0.33
45	0.18	0.15	0.37	0.15	0.19	0.46
46	0.51	0.12	0.43	0.37	0.59	0.33
52	2.2	1.7	3.4	3.1	11	15
49	2.4	1.7	3.1	2.8	7.4	8.6
47	0.64	0.54	0.91	1.1	2.7	2.4
48	0.14	0.12	0.15	0.12	0.15	0.11
44	1.6	1.3	2.3	1.7	6.1	7.9
59	0.14	0.12	0.15	0.12	0.15	0.11
37/42	0.6	0.5	0.65	0.50	2.3	2.0
71	0.35	0.13	0.52	0.49	1.1	0.67
64/41	0.63	0.25	0.75	0.70	1.5	1.8
40	0.32	0.13	0.27	0.36	0.74	0.83
63	0.15	0.13	0.16	0.12	0.33	0.31
74	0.85	0.62	0.89	0.70	1.7	1.9
70	1.6	1.1	2.0	1.7	5.8	6.2

* Mean of field sample and analytical duplicate

TABLE 8. Continued.

	PCB Congener Concentrations (μg/kg)					
PCB IUPAC Number	**SLPC 09 0-15 cm**	**SLPC 09 15-30 cm**	**SLPC 17* 0-15 cm**	**SLPC 17 15-30 cm**	**SLPC 18 0-15 cm**	**SLPC 18 15-30 cm**
76	0.14	0.12	0.15	0.12	0.15	0.11
66	0.19	0.16	0.21	0.16	0.20	0.14
95	3.9	2.9	5.1	4.7	16	16
91	0.78	0.51	1.1	0.92	3.1	2.5
56/60	0.30	0.25	0.78	0.50	1.3	1.0
92	0.74	0.54	1.1	1.0	3.6	3.9
84	1.3	0.96	1.9	1.6	6.0	5.8
101/90	3.5	2.5	4.6	4.4	15	15
99	1.8	1.3	2.3	2.1	8.2	7.9
119	0.42	0.14	0.60	0.38	0.79	0.76
97	1.4	0.92	1.8	1.7	6.0	5.7
81/87	2.9	1.9	3.6	3.2	12	11
85	1	0.64	1.3	1.0	3.1	2.5
136	0.82	0.6	1.0	0.89	2.6	2.3
77/110	5.9	4.1	7.7	7.2	26	28
82	0.44	0.28	0.55	0.49	1.8	1.6
151	0.89	0.58	0.99	0.91	2.1	2.0
135/144	0.28	0.66	0.30	0.23	0.29	0.21
107	0.6	0.46	0.72	0.66	2.0	2.1
123/149	0.28	0.24	0.30	0.23	0.30	0.21
118	3.4	2.3	4.4	4.1	14	15
114	0.27	0.12	0.34	0.11	0.57	0.51
146	0.9	0.67	1.1	0.96	2.2	2.4
153/184	3.6	2.3	4.1	3.9	9.3	9.9
132/168/105	3.1	2	3.8	3.5	11	12
141	0.89	0.55	0.96	0.91	2.2	2.3
137	0.3	0.12	0.32	0.32	0.87	0.87
176	0.77	0.46	1.1	0.72	0.11	0.075
163/138	4.6	2.8	5.3	5.1	14	15
158	0.51	0.3	0.61	0.57	1.6	1.7
126/178	0.38	0.24	0.4	0.29	0.42	0.52
182/187	1.5	0.97	1.6	1.1	1.7	2.2
183	1.2	0.77	1.1	0.88	1.5	1.6

* Mean of field sample and analytical duplicate

TABLE 8. Continued.

PCB IUPAC Number	SLPC 09 0-15 cm	SLPC 09 15-30 cm	SLPC 17* 0-15 cm	SLPC 17 15-30 cm	SLPC 18 0-15 cm	SLPC 18 15-30 cm
	PCB Congener Concentrations (μg/kg)					
128	1.1	0.73	1.2	1.1	2.9	3.1
167	0.39	0.3	0.50	0.36	0.81	0.87
185	0.28	0.11	0.22	0.11	0.27	0.26
174	1.3	0.77	1.3	1.0	1.6	1.8
177	0.76	0.5	0.79	0.67	0.98	1.0
202/171	1.5	0.85	0.87	0.61	0.28	0.2
156	0.15	0.13	0.60	0.54	1.4	2.9
157	0.15	0.13	0.17	0.13	0.95	1.1
172	0.28	0.12	0.15	0.23	0.33	0.39
197	0.30	0.25	0.32	0.25	0.32	0.22
180	2.6	1.5	2.5	2.0	3.0	4.1
199	0.13	0.11	0.14	0.11	0.14	0.2
169	< PQL	< PQL	< PQL	< PQL	< PQL	< PQL
170	1.5	0.85	1.5	1.2	2	2.6
190	0.15	0.13	0.16	0.12	0.16	0.11
201	0.91	0.65	0.91	0.55	0.79	1.3
196/203	1.2	0.85	1.2	0.74	1.1	2
189	0.17	0.14	0.18	0.14	0.18	0.13
208	0.08	0.21	0.29	0.065	0.085	0.060
195	0.54	0.17	0.22	0.17	0.46	0.62
194	0.94	0.6	0.87	0.57	0.81	1.5
206	0.79	0.66	0.88	0.44	0.71	0.92
209	0.7	0.6	0.75	0.60	0.75	0.55
SUM	99.0	66.9	111	96.8	258	269

* Mean of field sample and analytical duplicate
PQL = Probable quantitation limit

TABLE 9. Nomenclature of predominant PCB congeners in Slip C.

IUPAC Number	PCB Congener Name
77/110	3,3’4,4’-Tetrachlorobiphenyl
	2,3,3’,4’,6-Pentachlorobiphenyl
95	2,2’,3,5’,6-Pentachlorobiphenyl
101/90	2,2’,4,5,5’-Pentachlorobiphenyl
	2,2’,3,4’,5-Pentachlorobiphenyl
118	2,3’,4,4’,5-Pentachlorobiphenyl
132/168/105	2,2’,3,3’,4,6’-Hexachlorobiphenyl
	2,3’,4,4’,5’,6-Hexachlorobiphenyl
	2,3,3’,4,4’-Pentachlorobiphenyl
163/138	2,3,3’,4’,5,6-Hexachlorobiphenyl
	2,2’,3,4,4’,5’-Hexachlorobiphenyl

TABLE 10. Results of regression analyses of chemical parameters with particle size classes. Regression relationships are in the form of $y = b_0 + b_1(x)$*, with variables defined below.*

Chemical Parameter (y variable)	**Intercept (b_0)**	**Slope (b_1)**	**Particle Size Class (x variable)**	**r^2 value**	**N**	**Outlier(s) at 95% Prediction Intervals**
Total PAHs	47	-0.44	Sand and Gravel (>53 µm)	0.787	32	SLPC 13 (0-15, 15-30 cm)
Total PAHs	3.3	0.54	Silt (53 - 2 µm)	0.802	32	SLPC 13 (0-15, 15-30 cm)
Total PAHs	4.2	2.2	Coarse Clay (2 - 0.2 µm)	0.678	32	SLPC 13 (0-15, 15-30 cm)
Mercury	0.56	-0.0048	Sand and Gravel (>53 µm)	0.715	34	SLPC 19 (0-15 cm)
Mercury	0.083	0.0058	Silt (53 - 2 µm)	0.711	34	SLPC 19 (0-15 cm)
Mercury	0.086	0.025	Coarse Clay (2 - 0.2 µm)	0.676	34	SLPC 19 (0-15 cm)
TOC	20	-0.20	Sand and Gravel (>53 µm)	0.612	34	SLPC 14 (15-30 cm)
TOC	-0.068	0.25	Silt (53 - 2 µm)	0.630	34	SLPC 14 (15-30 cm)
TOC	0.66	0.97	Coarse Clay (2 - 0.2 µm)	0.500	34	SLPC 14 (15-30 cm)
Total PCBs	-22	2.4	Sand and Gravel (>53 µm)	0.115	6	none
Total PCBs	210	-2.7	Silt (53 - 2 µm)	0.104	6	none
Total PCBs	230	-15	Coarse Clay (2 - 0.2 µm)	0.155	6	none

N = Number of samples used in the regression analysis.

FIGURES

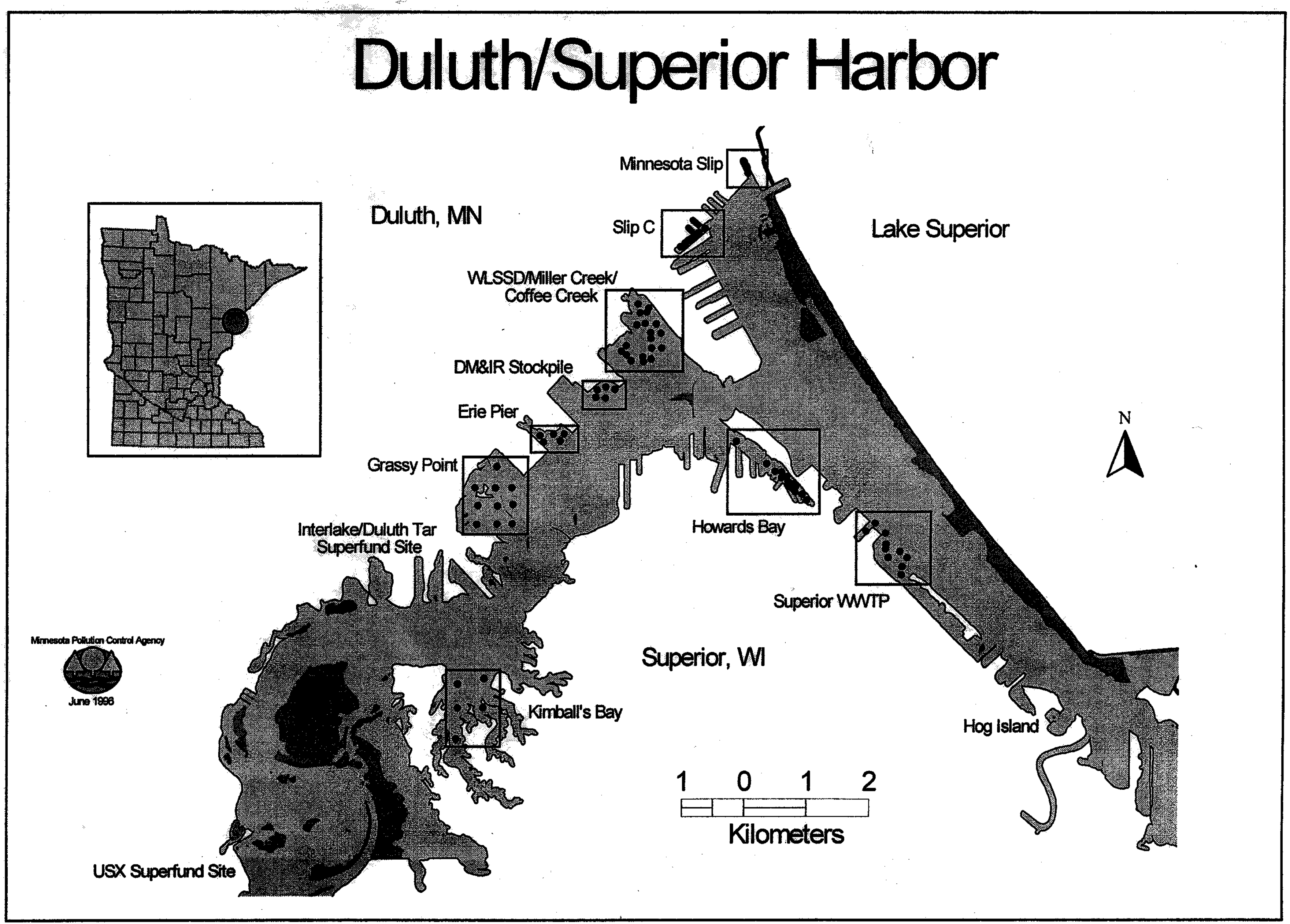

FIG. 1. Map of the St. Louis River AOC showing locations of contaminated areas plus a reference area at Kimball's Bay.

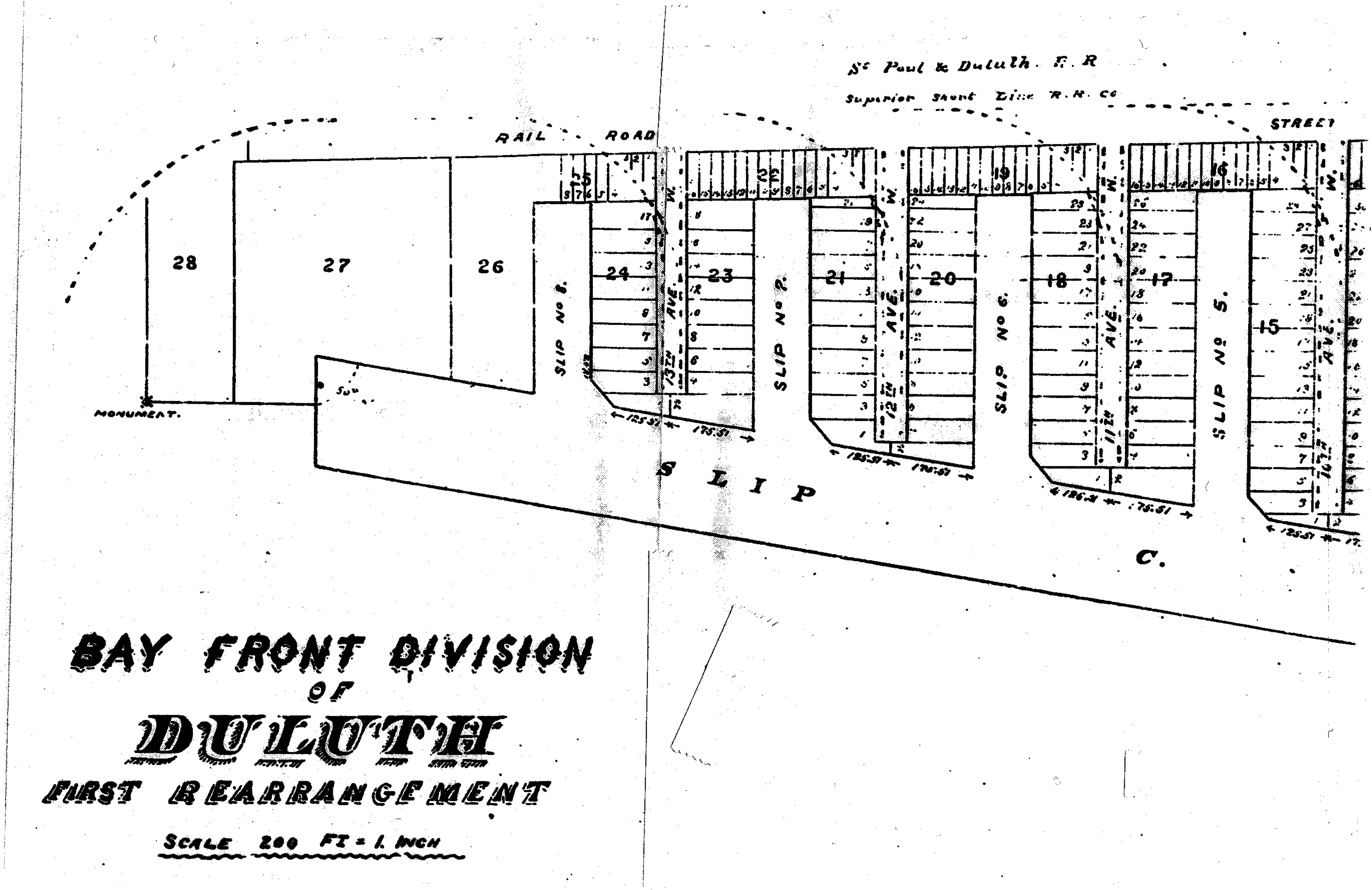

FIG. 2. *Historical map of Slip C showing Slip numbers 5-8.*

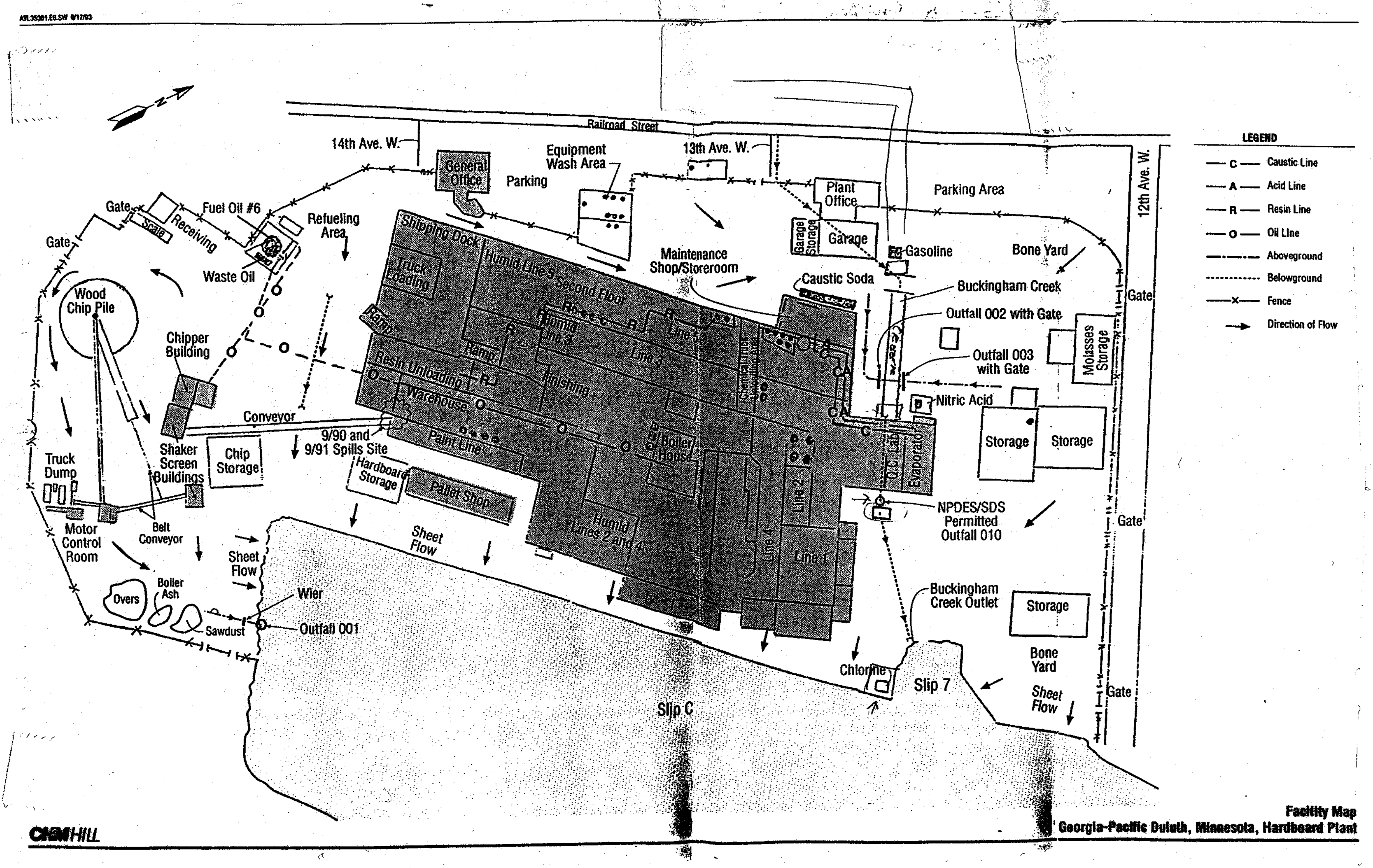

FIG. 3. Map of the Georgia-Pacific plant in Duluth, MN circa 1993. Note: boiler ash and sawdust are no longer stored by outfall 001.

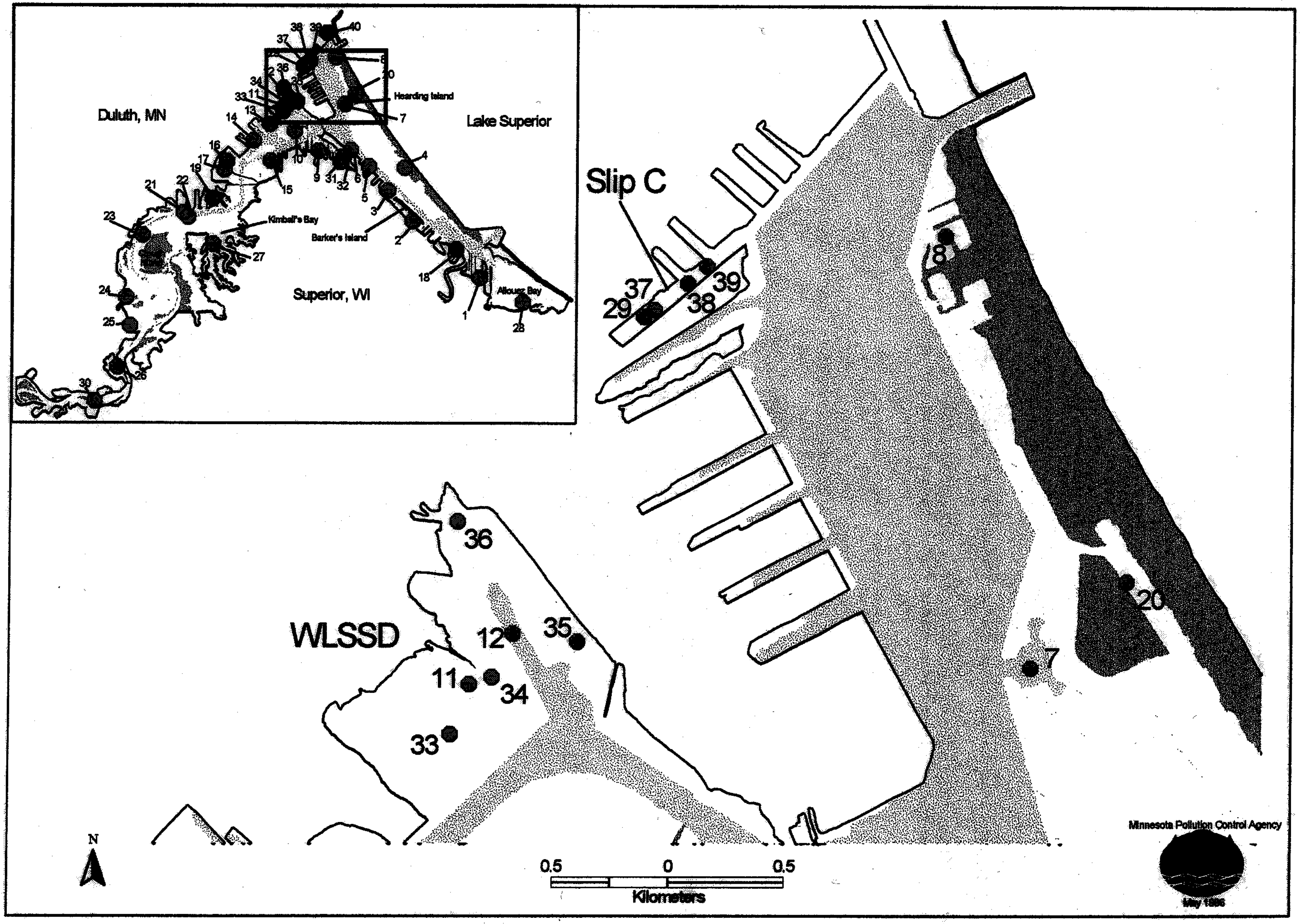

FIG. 4. *Map of the 1993 sediment sampling sites in Slip C (Schubauer-Berigan and Crane 1997).*

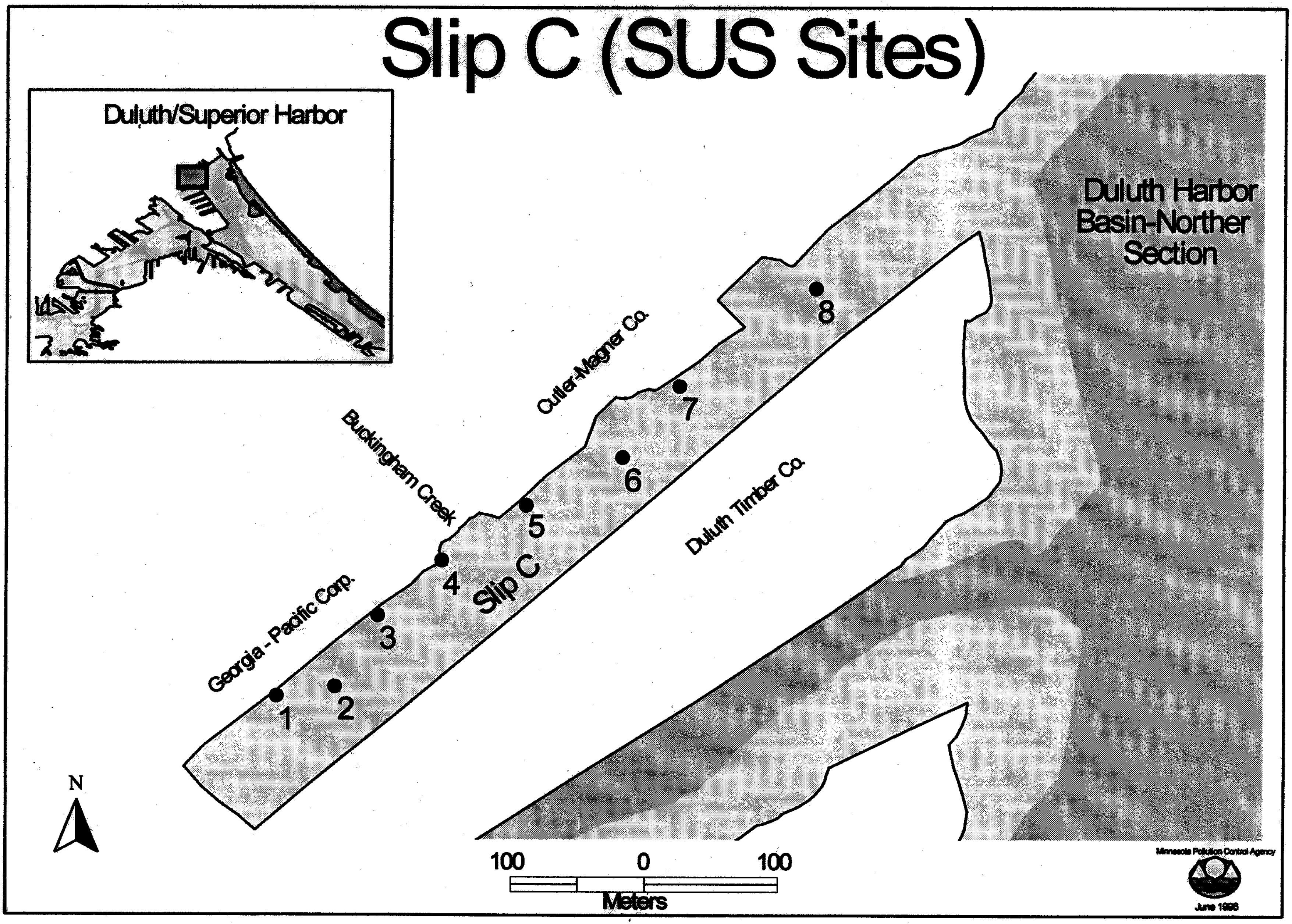

FIG. 5. *Map of the 1994 sediment sampling sites in Slip C (Crane et al. 1997).*

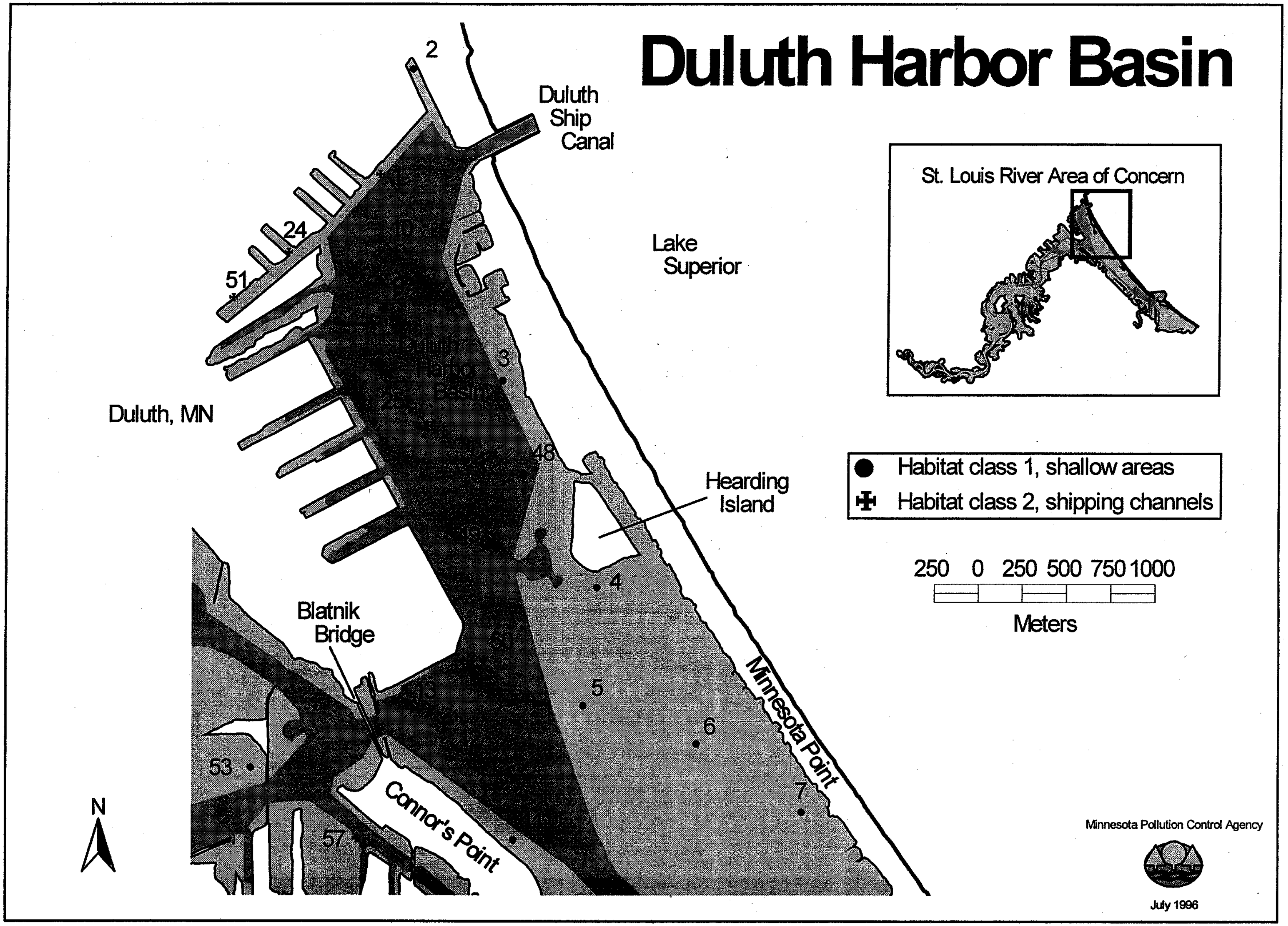

FIG. 6. *Map of the 1995 sediment sampling sites in Slip C as part of the R-EMAP project.*

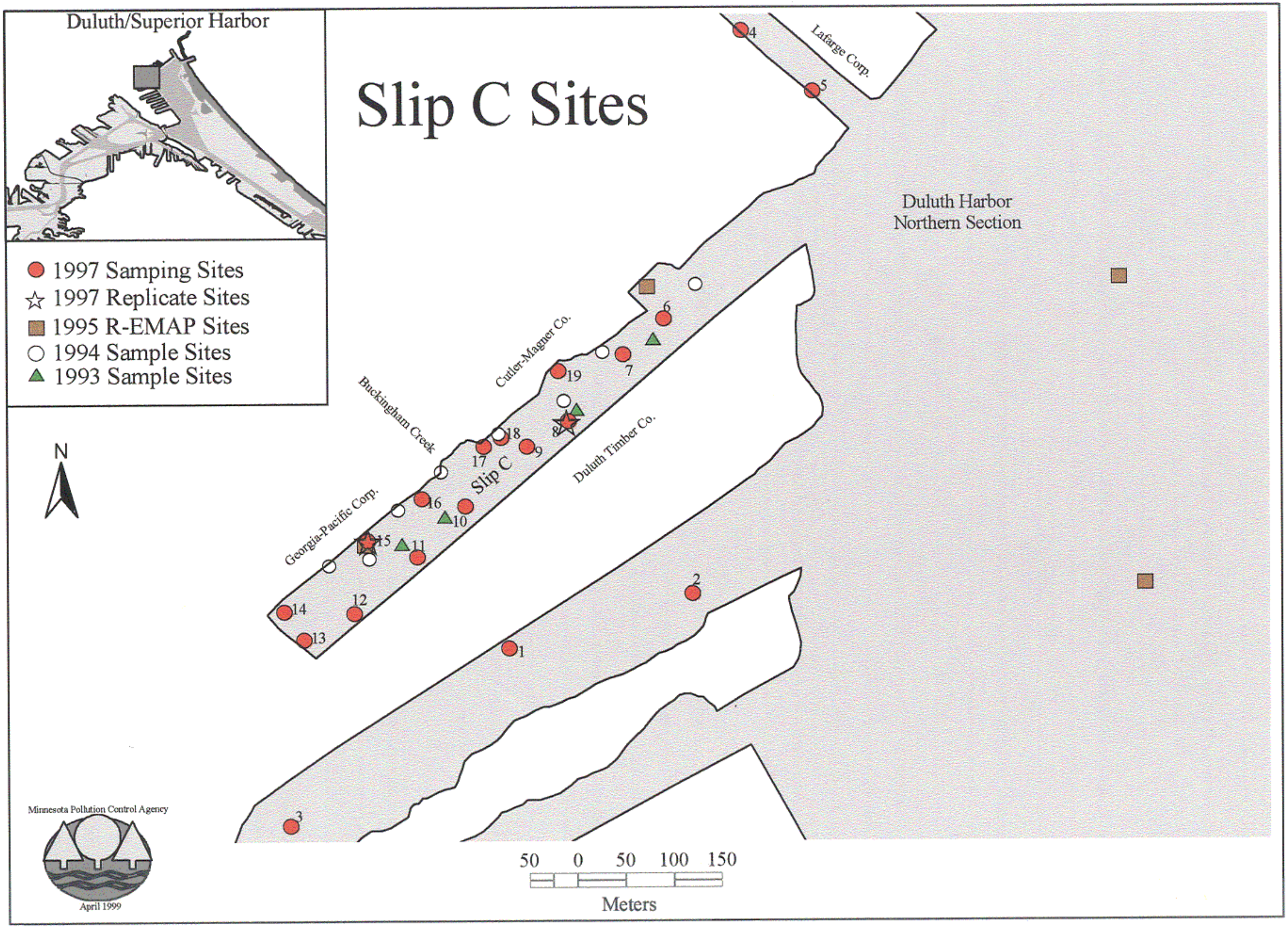

FIG. 7. Location of the 1997 sediment sampling sites in Slip C and the slip southeast of it.

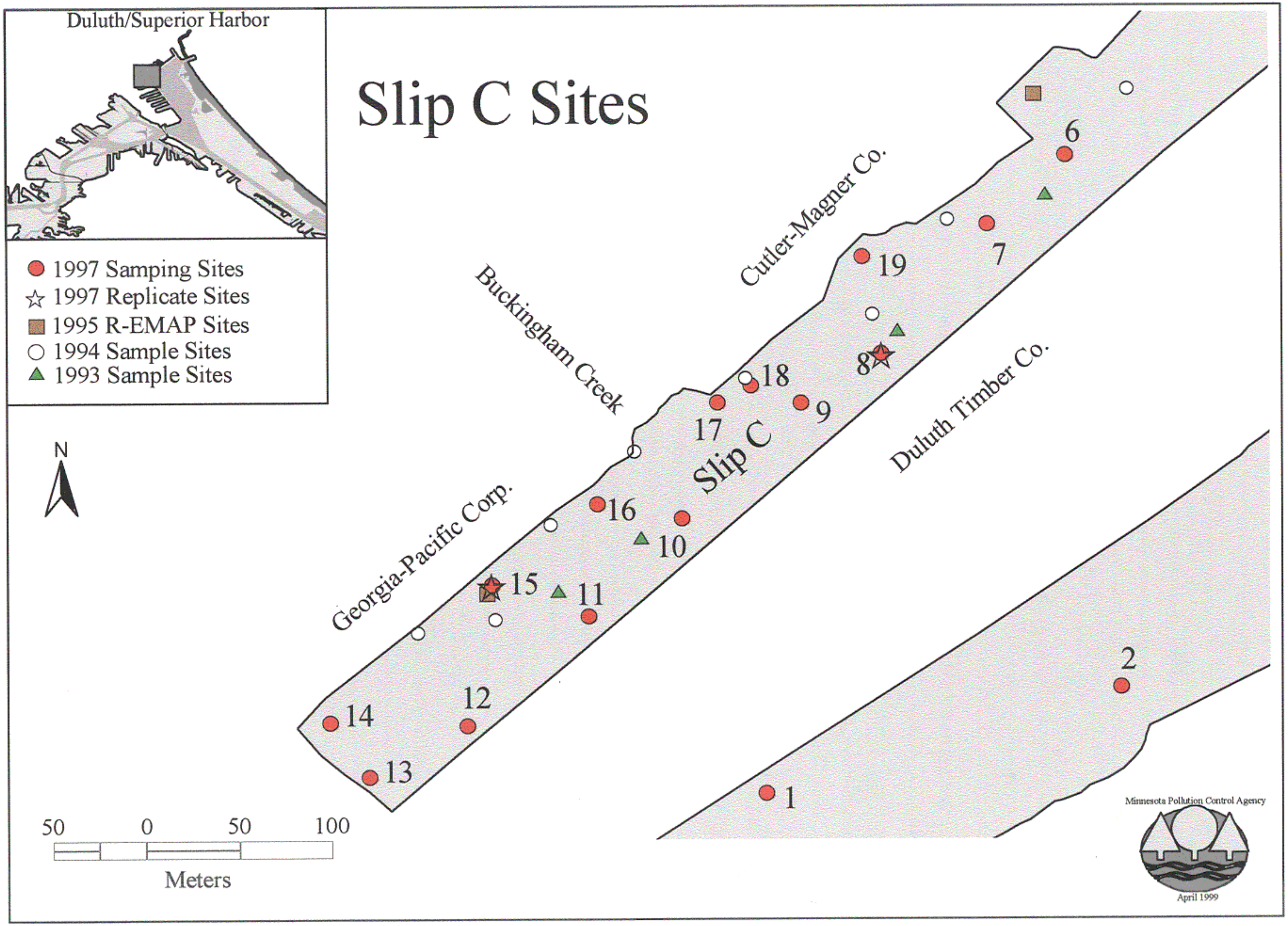

FIG. 8. Close-up map of the 1997 sediment sampling sites in Slip C.

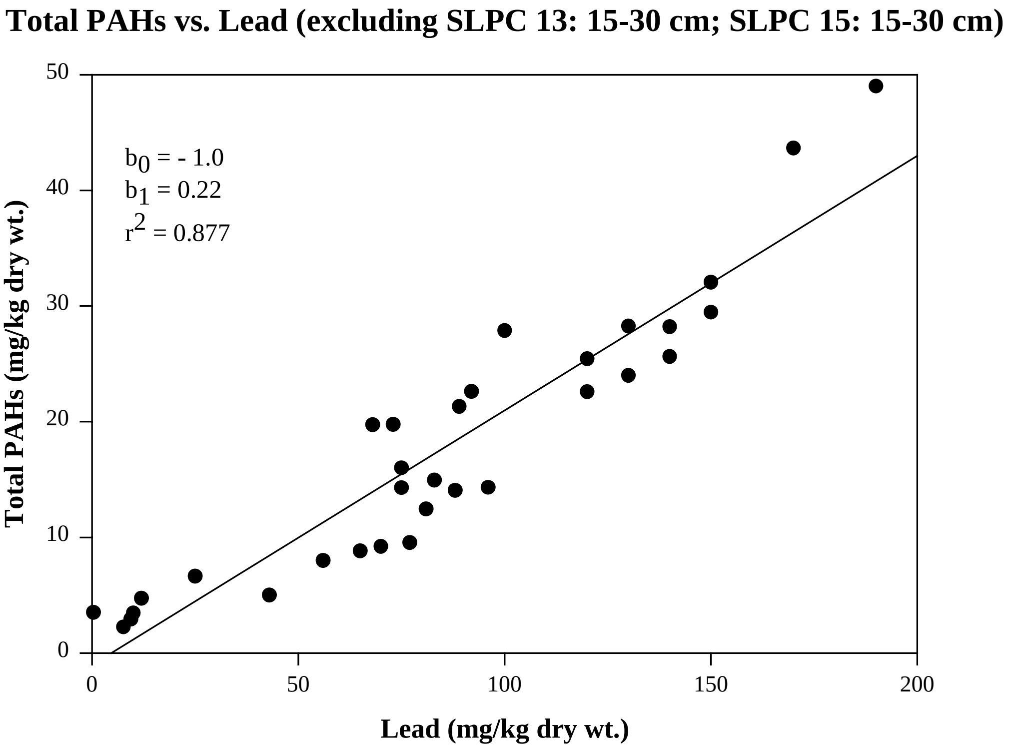

FIG. 9. Linear regression analysis of total PAHs versus lead.

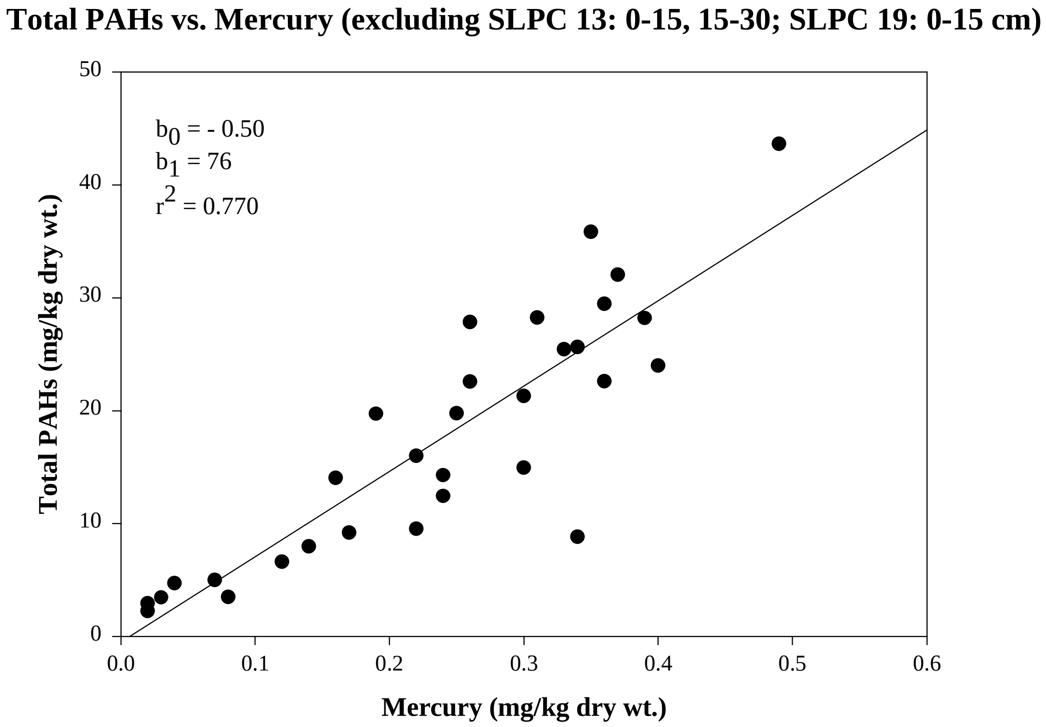

FIG. 10. Linear regression analysis of total PAHs versus mercury.

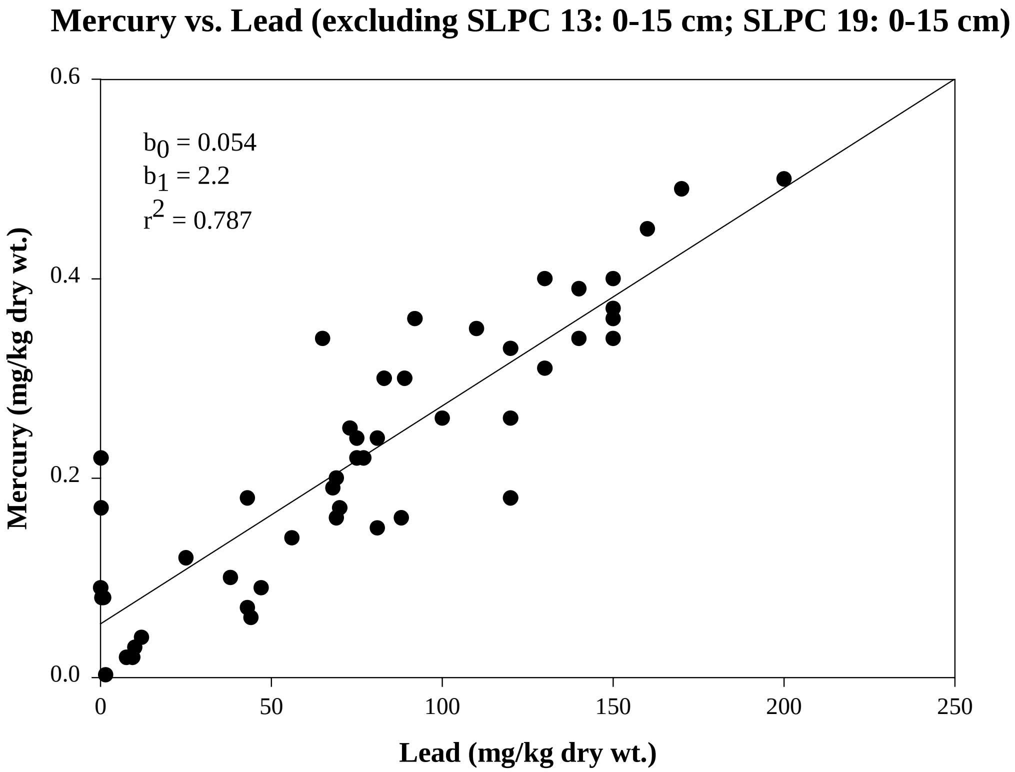

FIG. 11. Linear regression analysis of mercury versus lead.

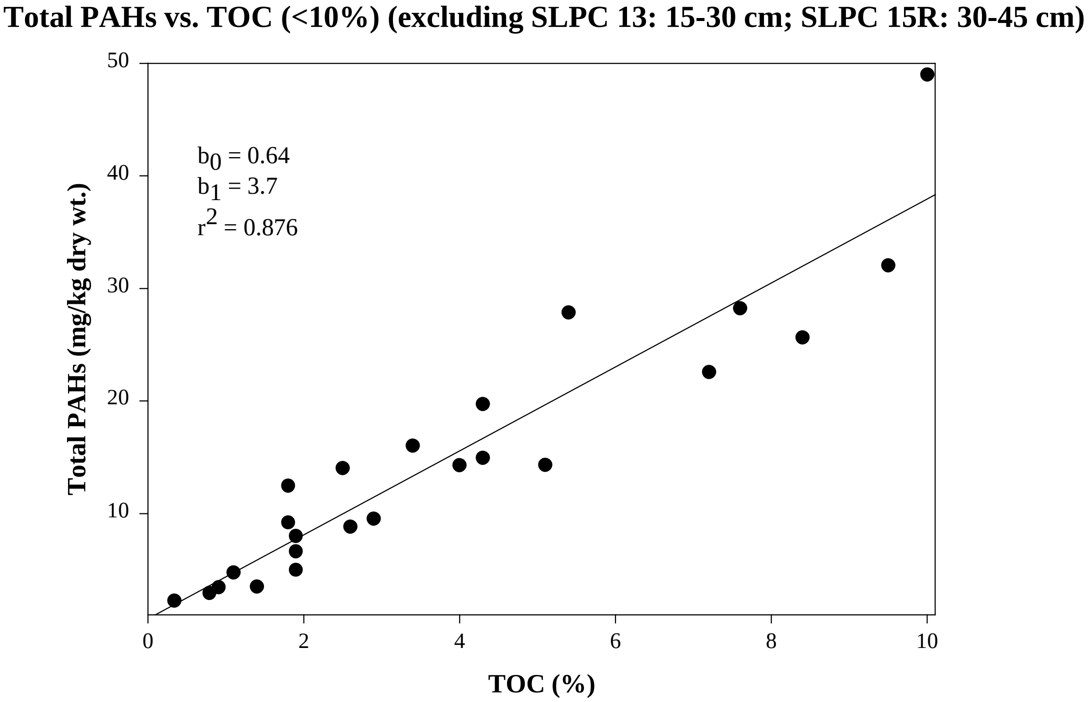

FIG. 12. Linear regression analysis of total PAHs versus TOC values less than 10%.

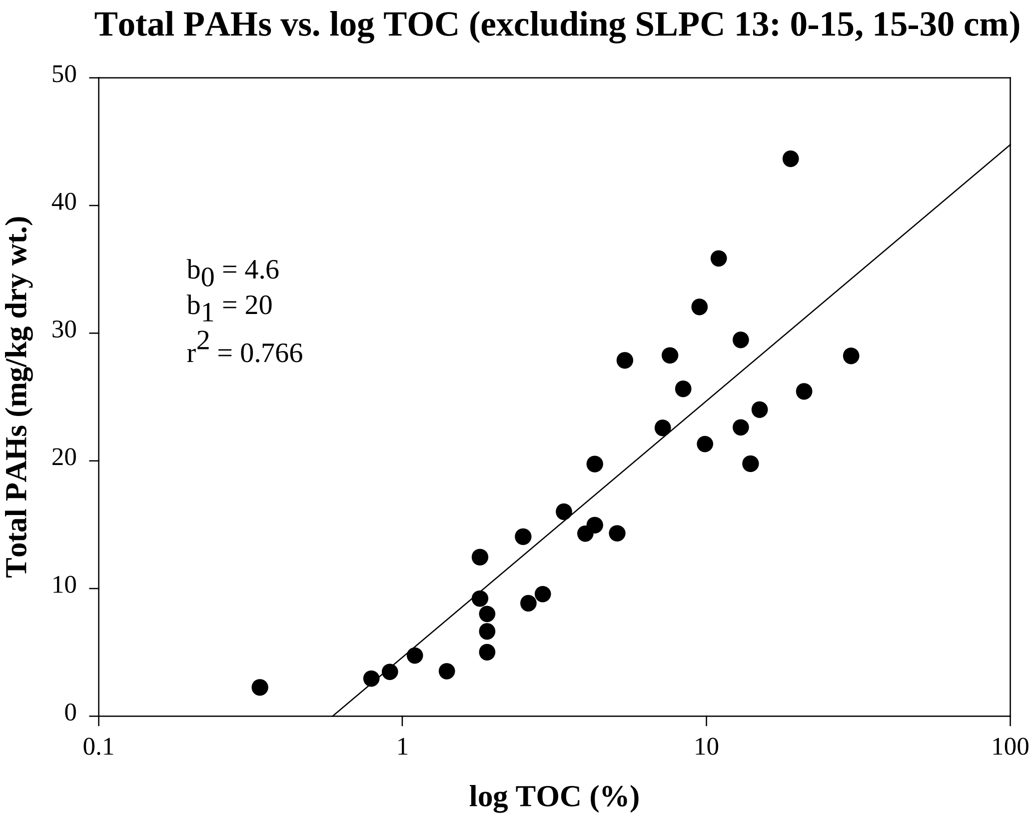

FIG. 13. Linear regression analysis of total PAHs versus the logarithm of TOC.

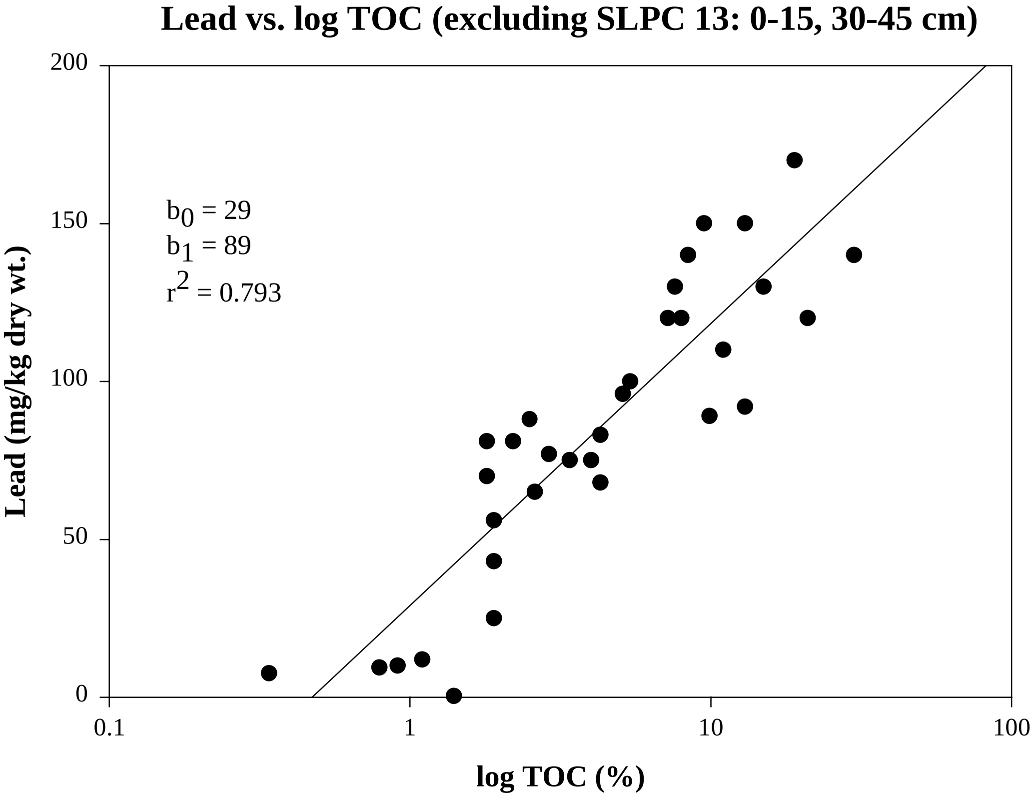

FIG. 14. Linear regression analysis of lead versus the logarithm of TOC.

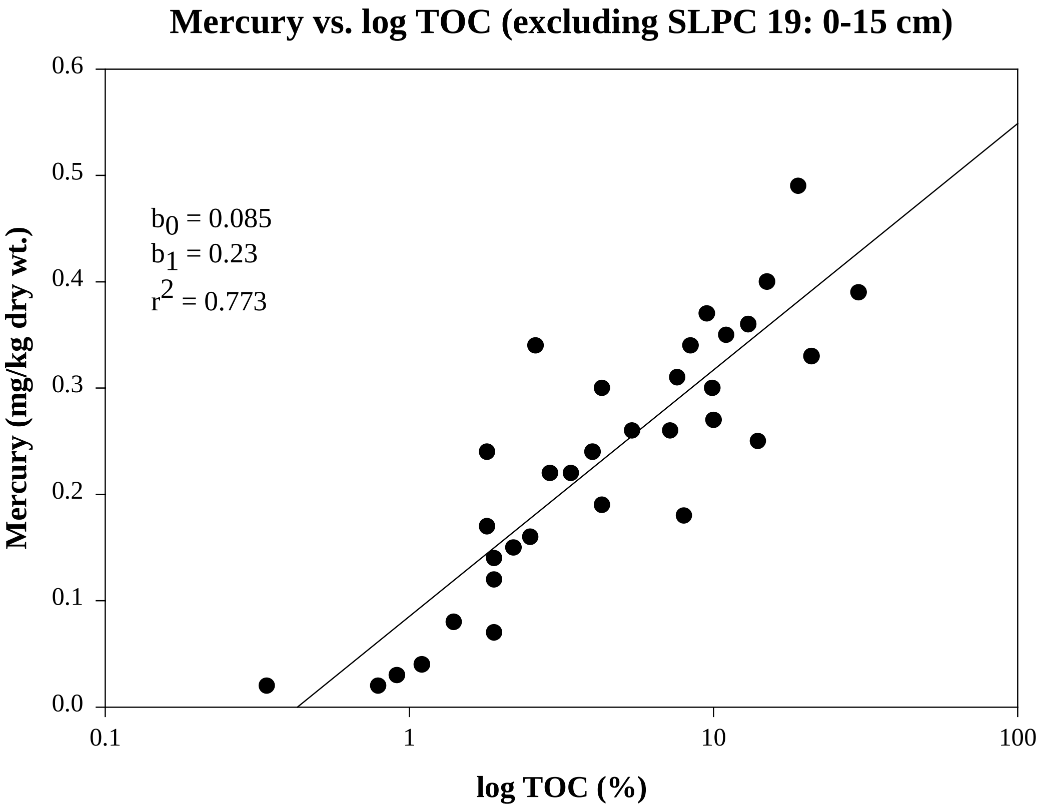

FIG. 15. Linear regression analysis of mercury versus the logarithm of TOC.

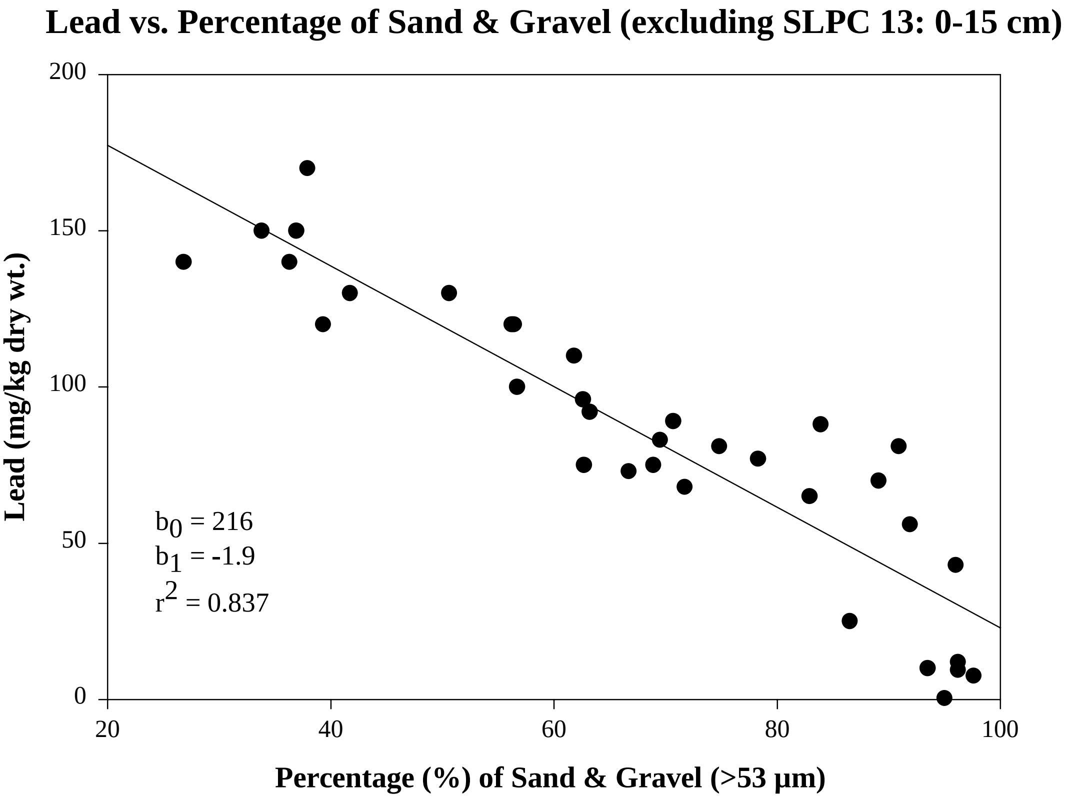

FIG. 16. Linear regression analysis of lead versus percentage of sand and gravel (>53 µm).

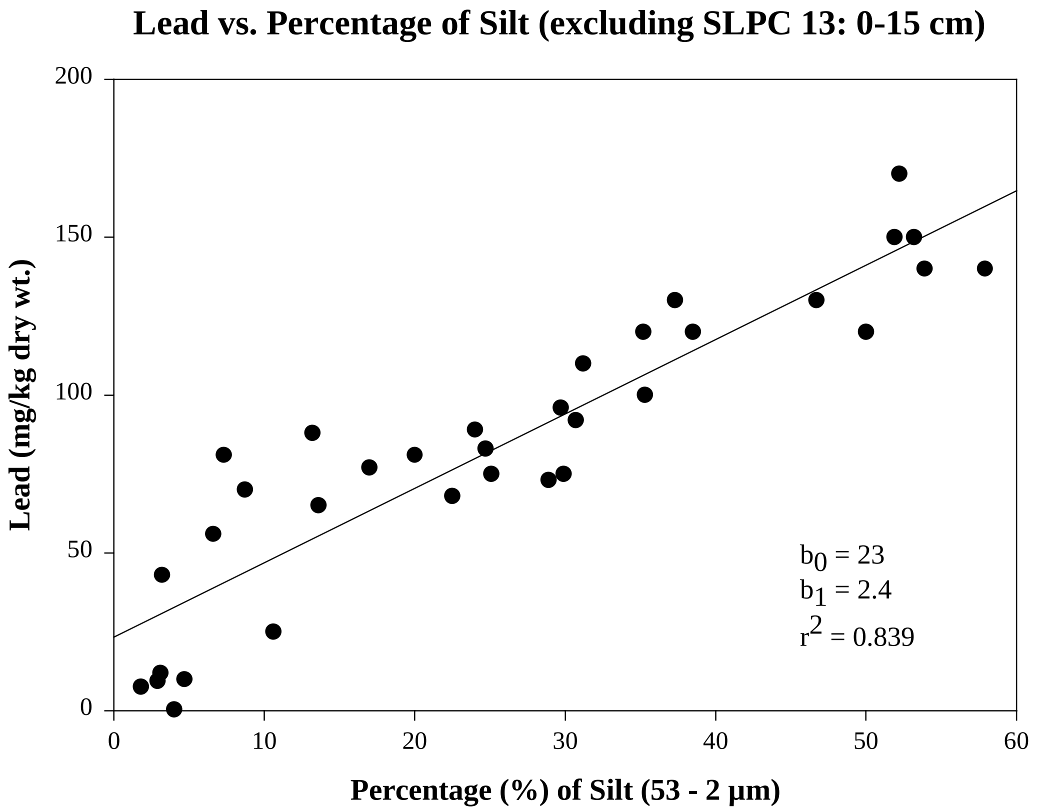

FIG. 17. Linear regression analysis of lead versus percentage of silt (52 - 2 μm).

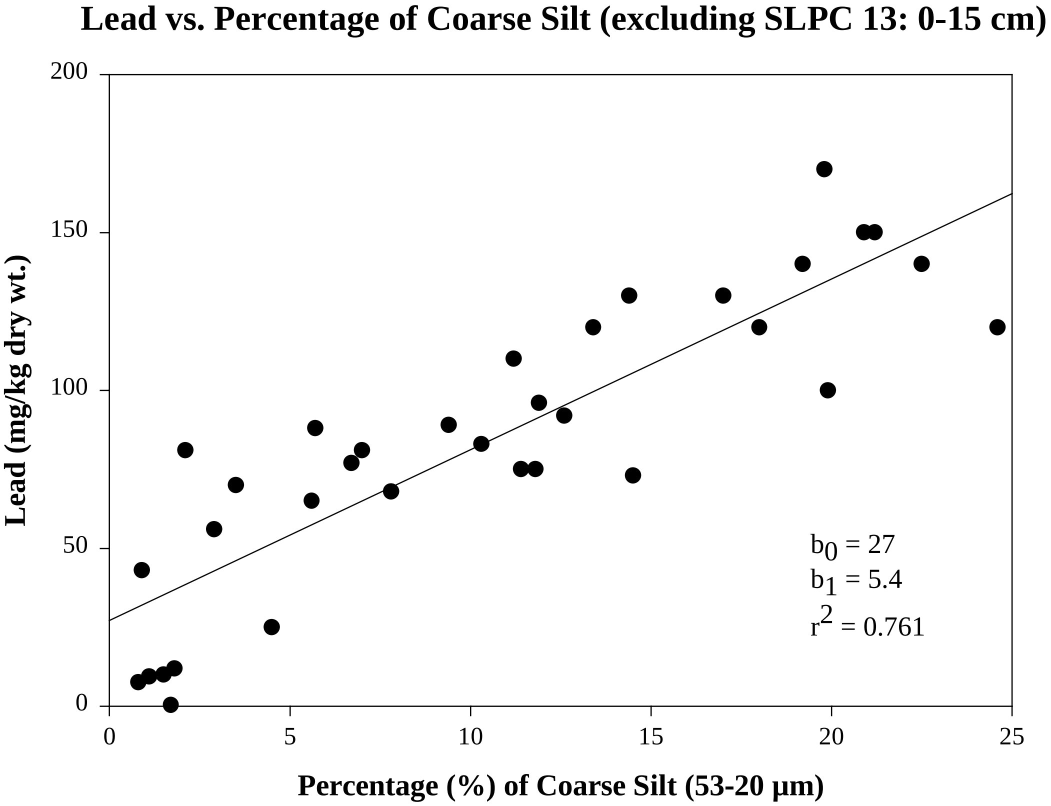

FIG. 18. Linear regression analysis of lead versus percentage of coarse silt (53 - 20 μm).

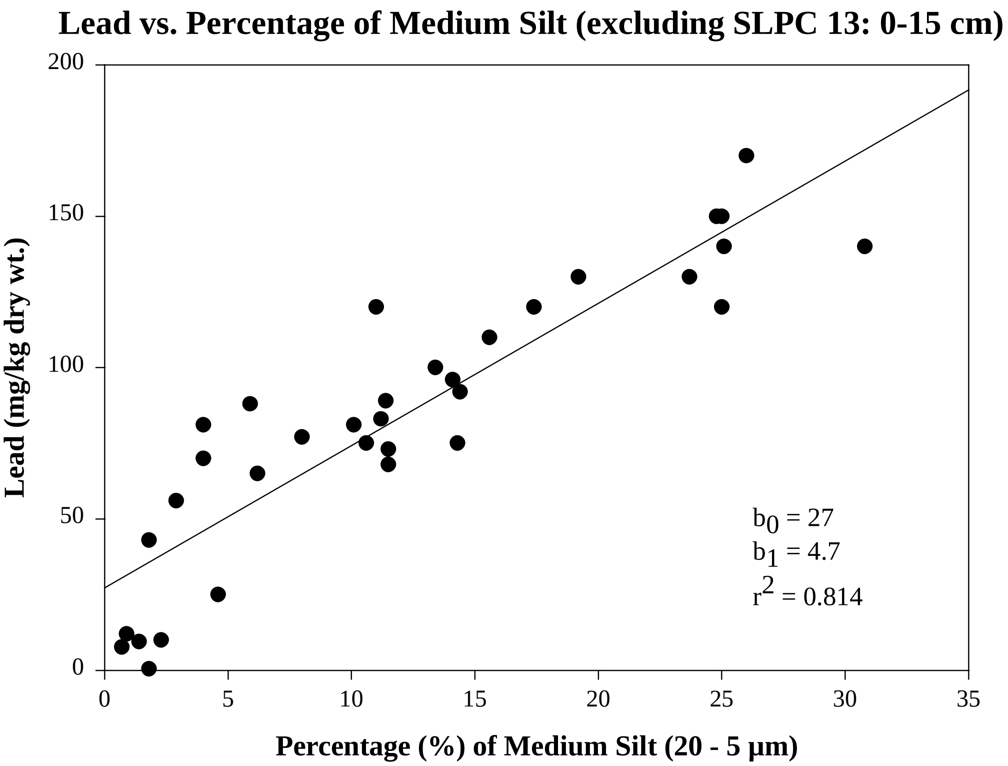

FIG. 19. Linear regression analysis of lead versus percentage of medium silt (20 - 5 μm).

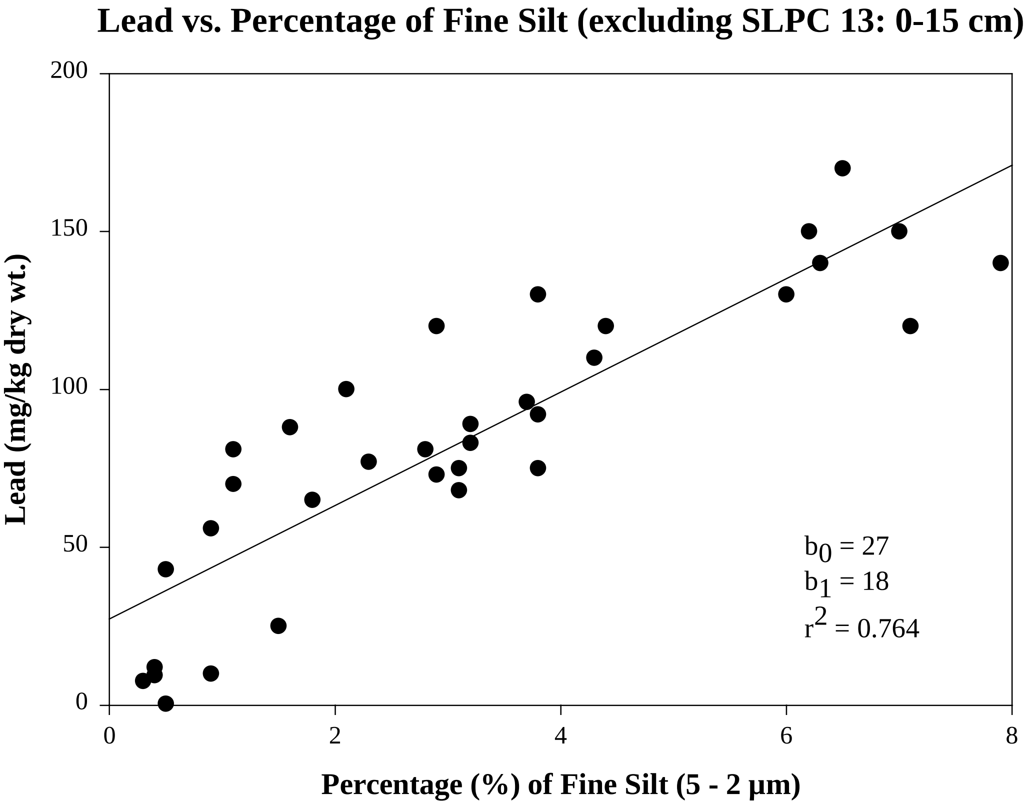

FIG. 20. Linear regression analysis of lead versus percentage of fine silt (5 - 2 μm).

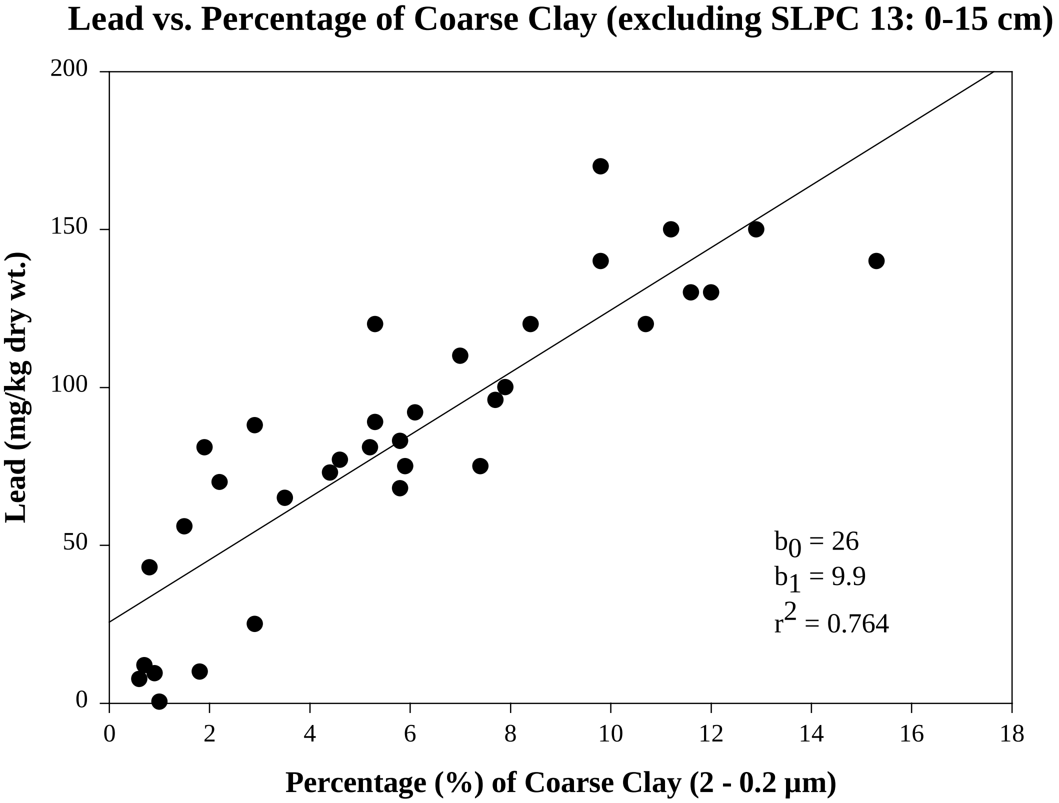

FIG. 21. Linear regression analysis of lead versus percentage of coarse clay (2 - 0.2 μm).

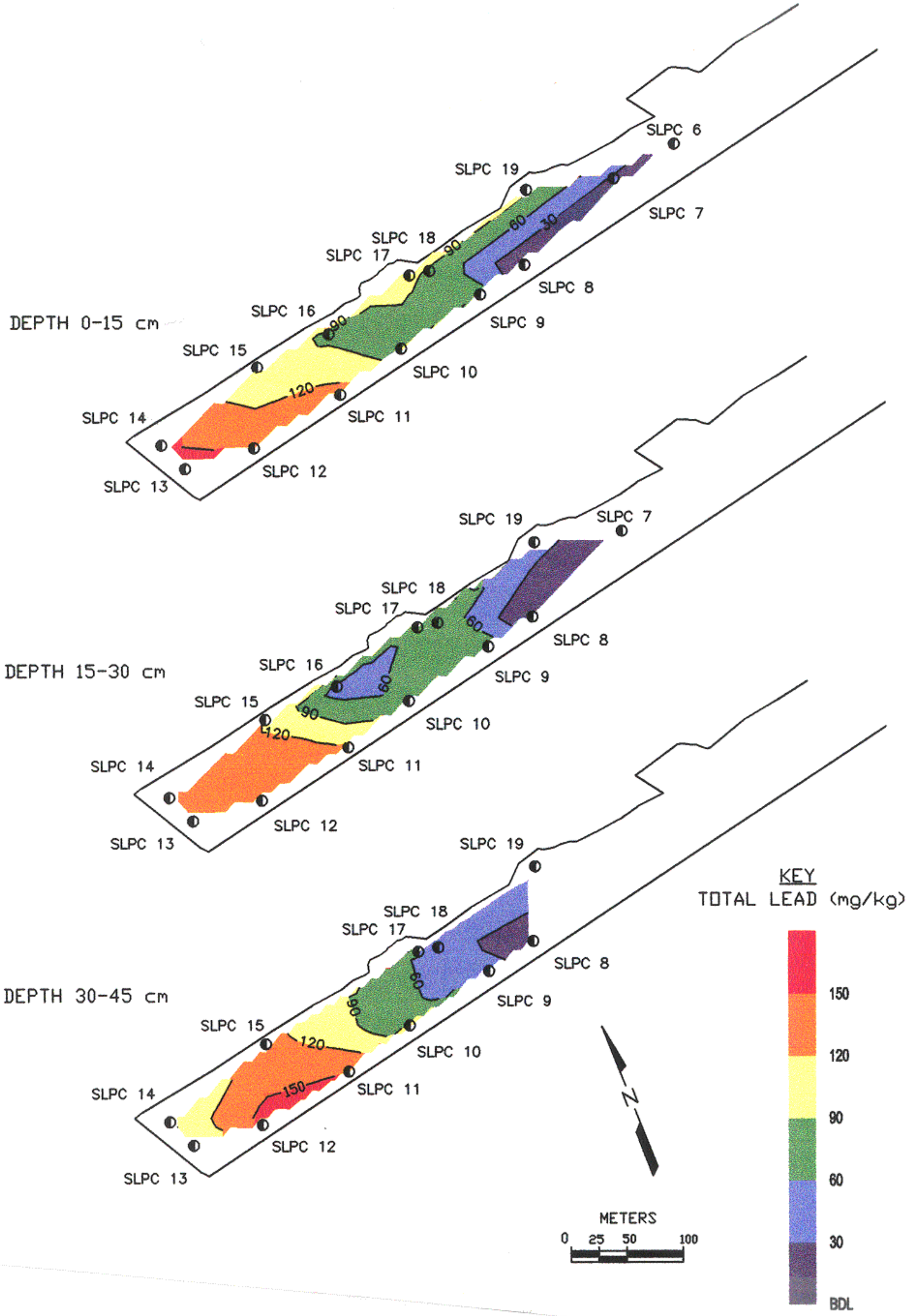

FIG. 22. Sediment kriging graphs for selected depth intervals of lead contamination in Slip C.

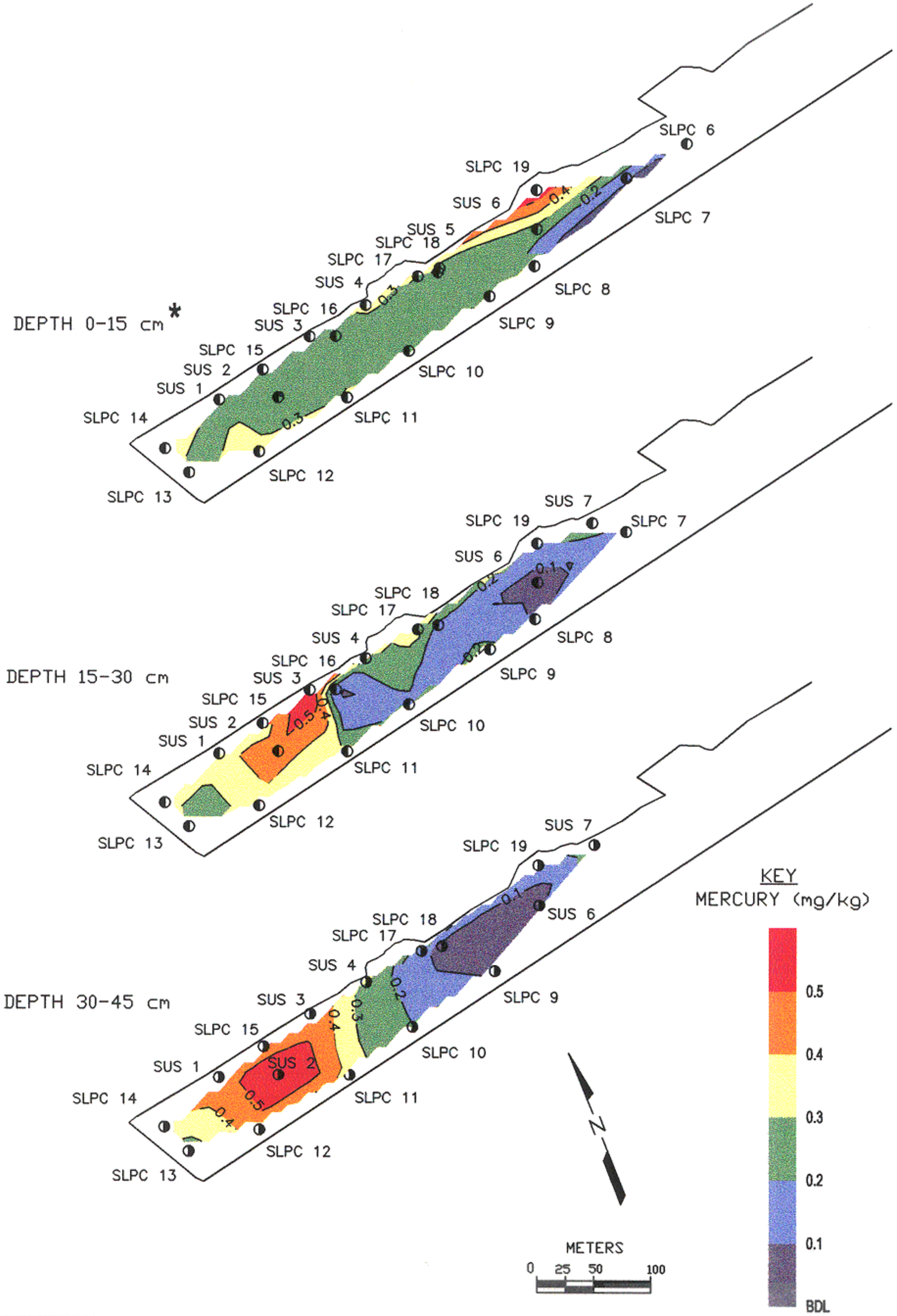

FIG. 23. *Sediment kriging graphs for selected depth intervals of mercury contamination in Slip C. *Depth intervals for the 1994 SUS code samples ranged from 0-15 cm to 0-21 cm.*

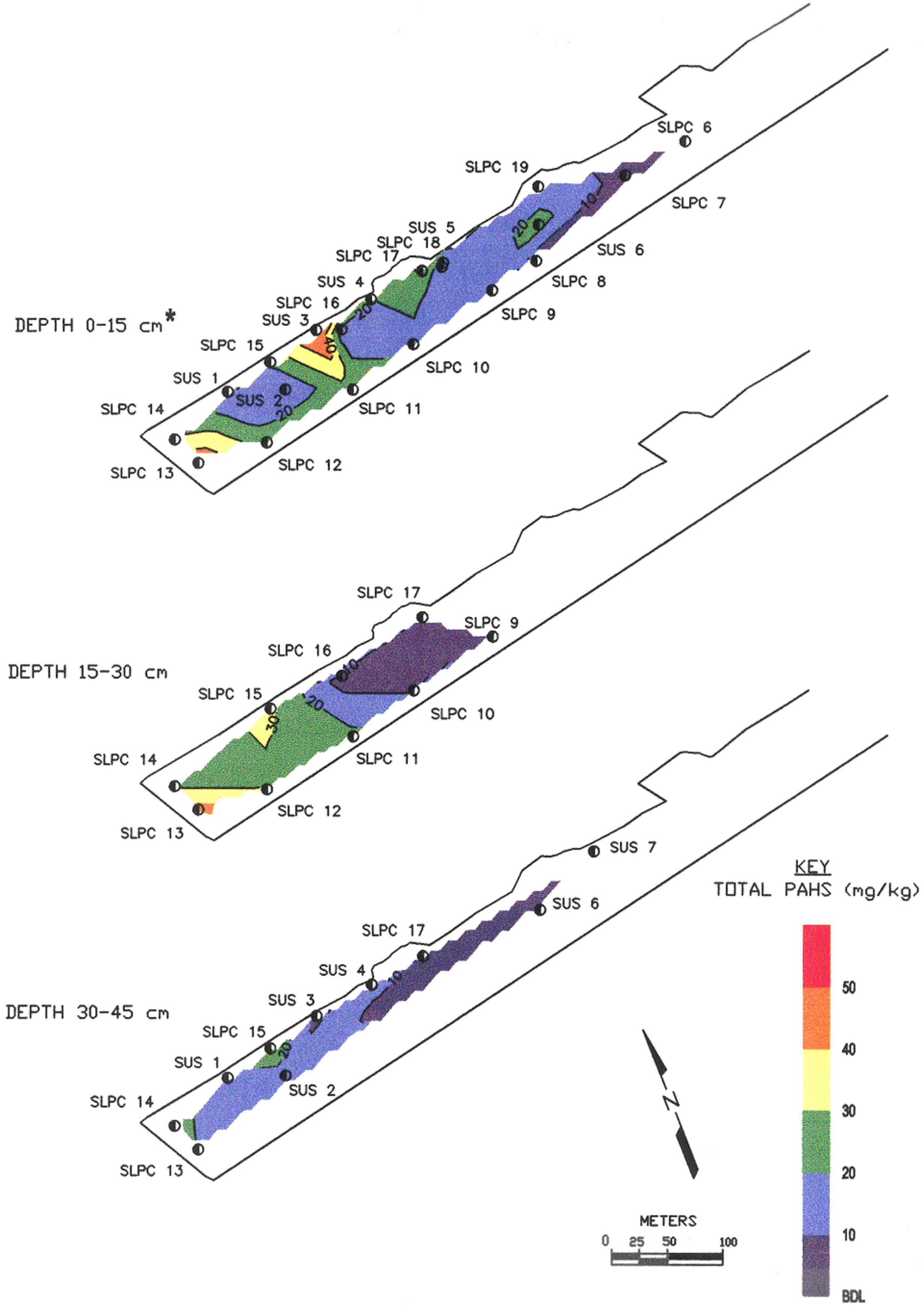

FIG. 24. Sediment kriging graphs for selected depth intervals of PAH contamination in Slip C.
**Depth intervals for the 1994 SUS code samples ranged from 0-15 cm to 0-21 cm.*

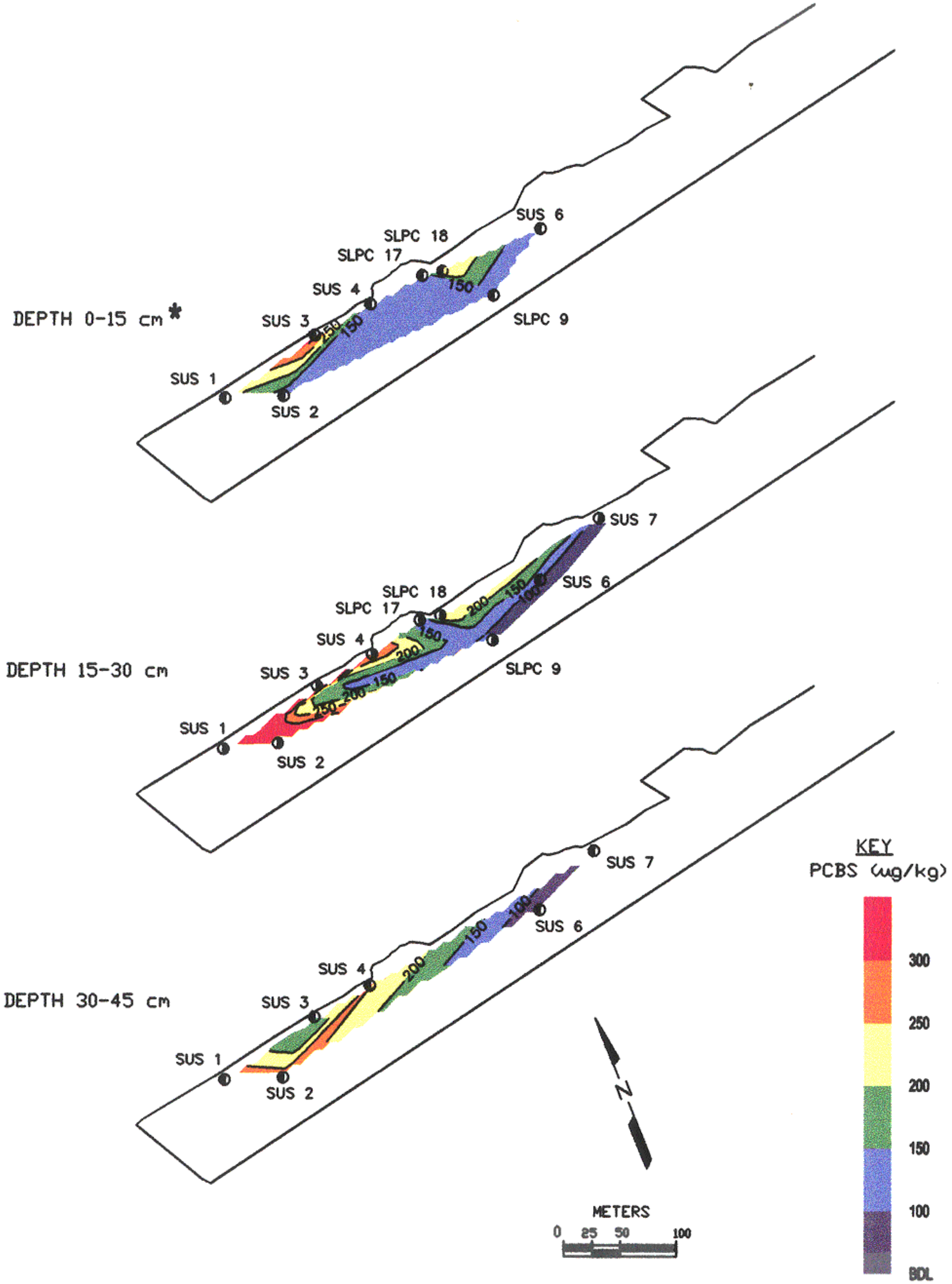

*FIG. 25. Sediment kriging graphs for selected depth intervals of PCB contamination in Slip C. *Depth intervals for the 1994 SUS code samples ranged from 0-15 cm to 0-21 cm.*

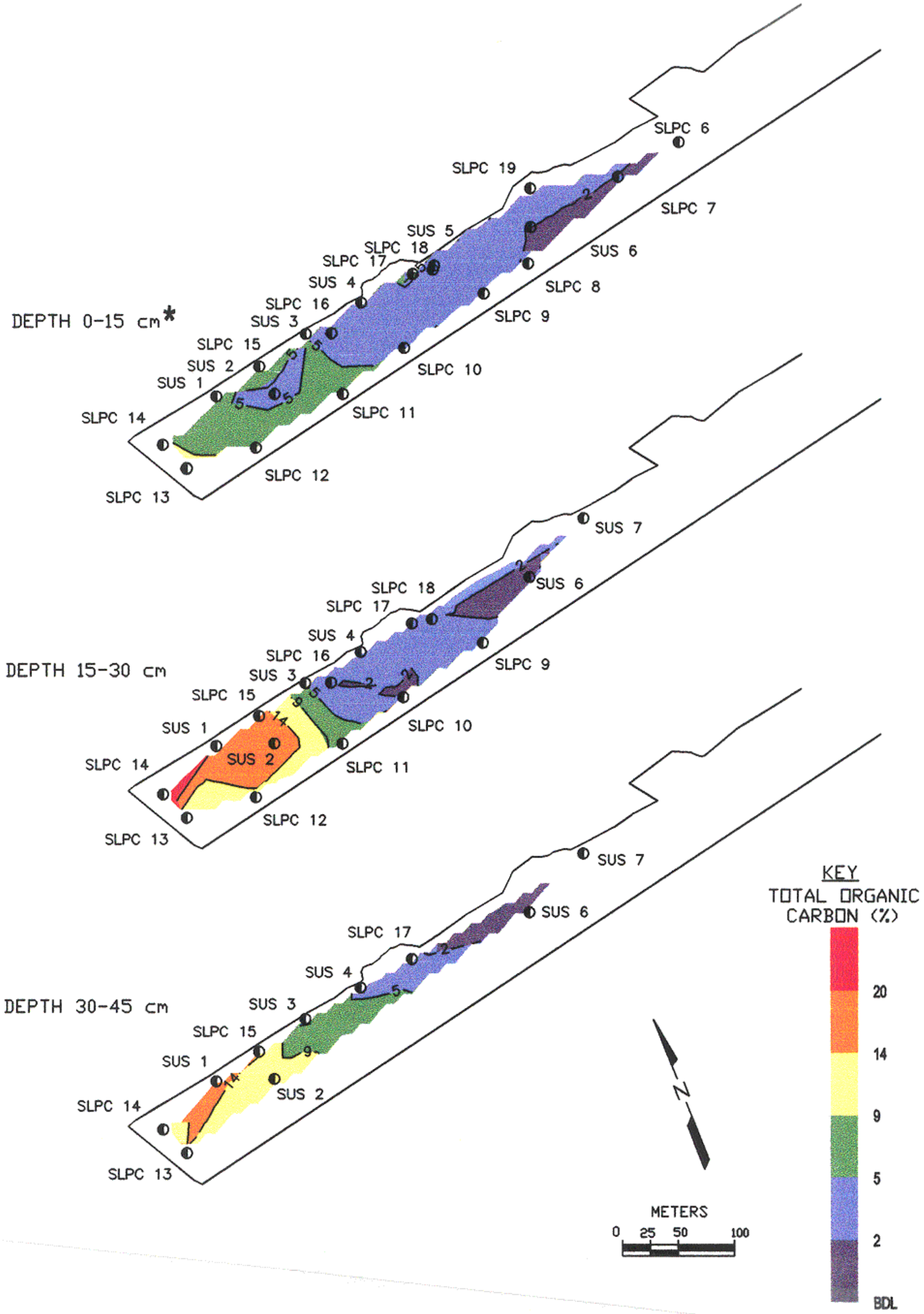

*FIG. 26. Sediment kriging graphs for selected depth intervals of TOC in Slip C. *Depth intervals for the 1994 SUS code samples ranged from 0-15 cm to 0-21 cm.*

APPENDIX A

Regression Analyses of Total PCBs with other Variables

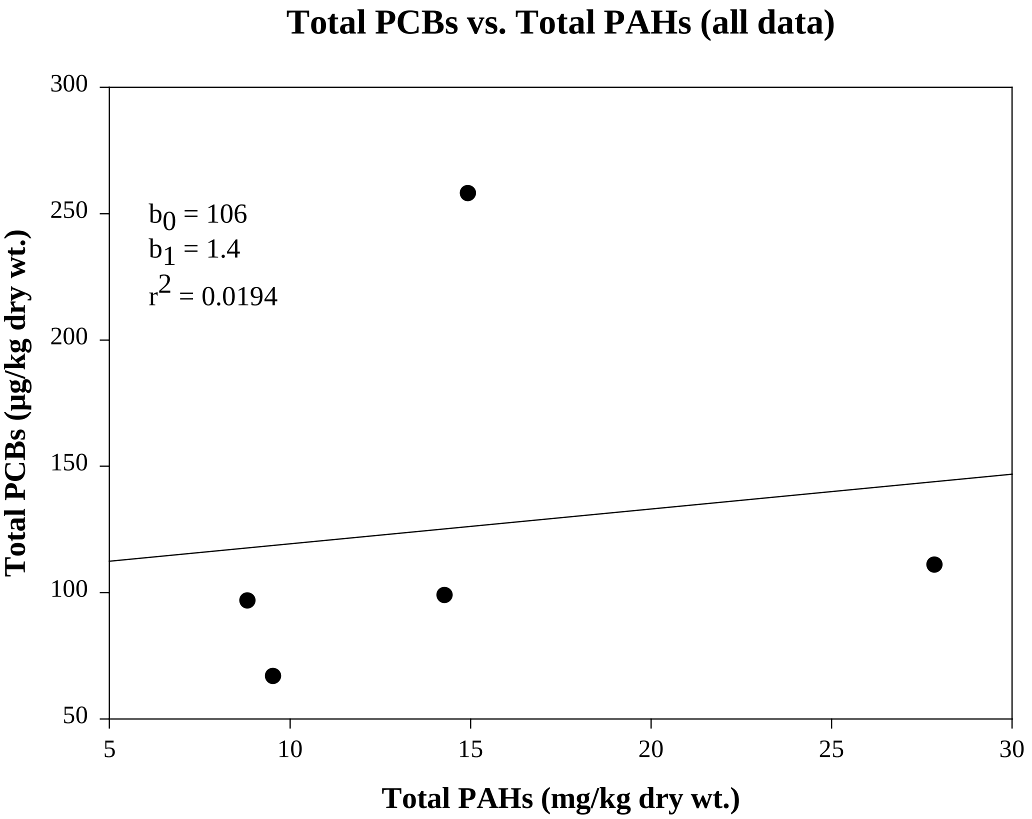

FIG. A-1. Linear regression analysis of total PCBs versus total PAHs.

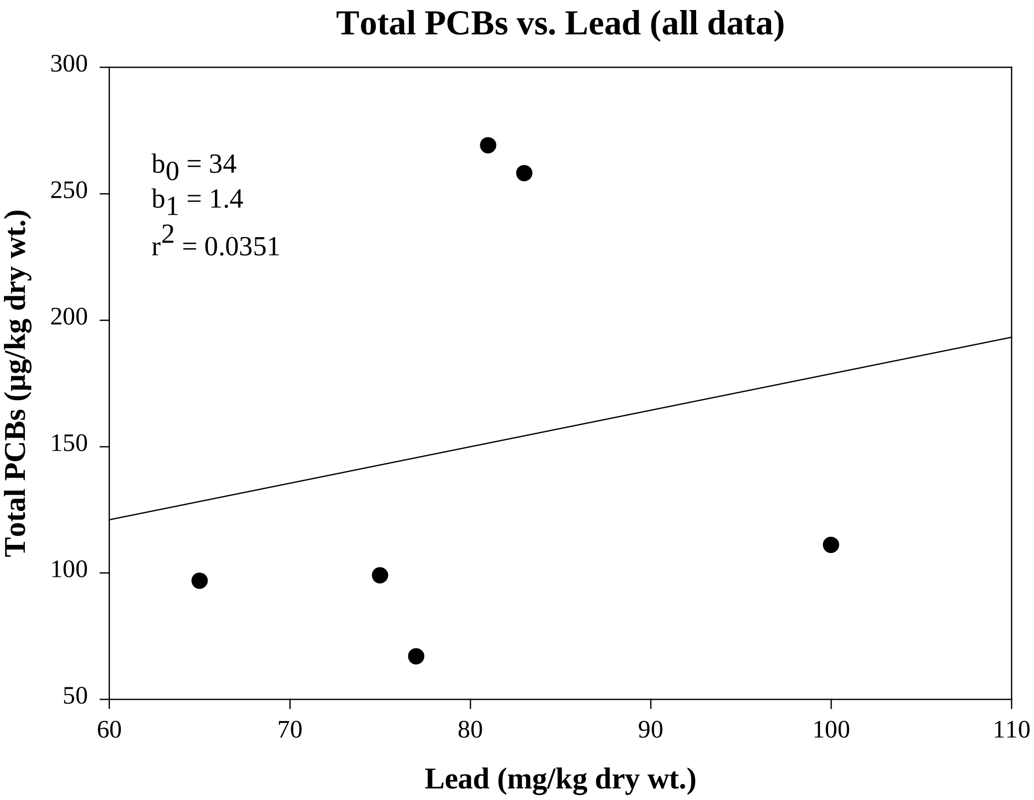

FIG. A-2. Linear regression analysis of total PCBs versus lead.

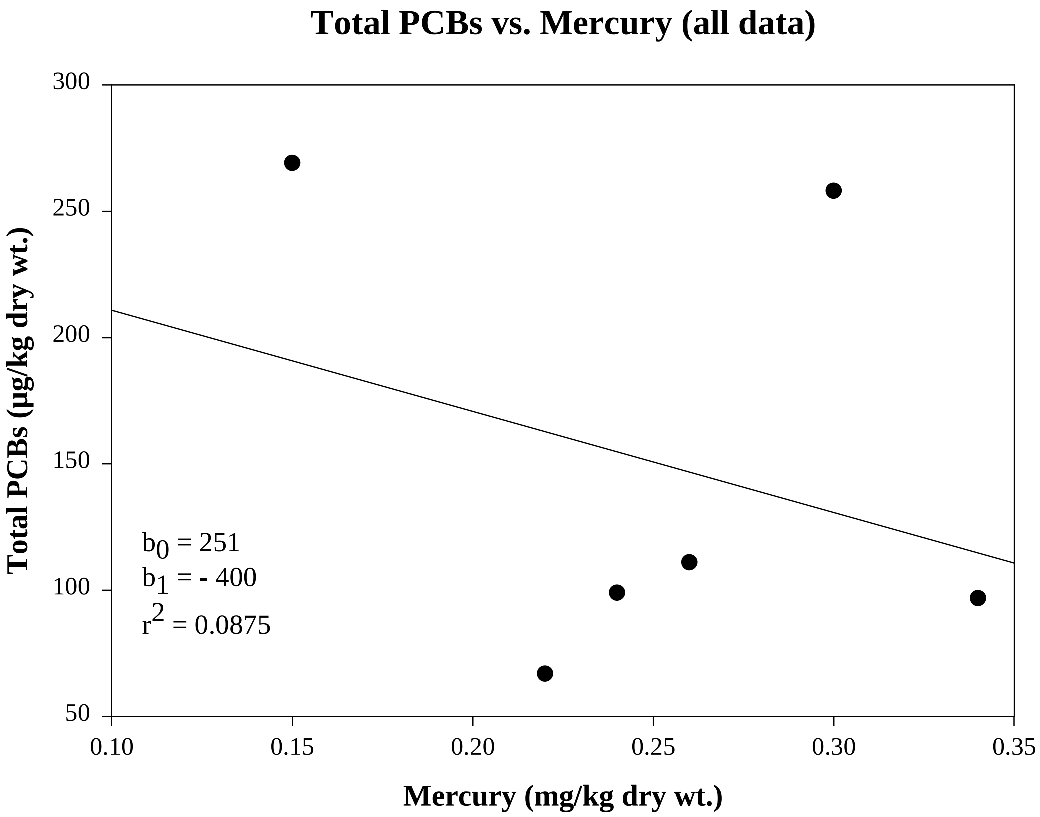

FIG. A-3. Linear regression analysis of total PCBs versus mercury.

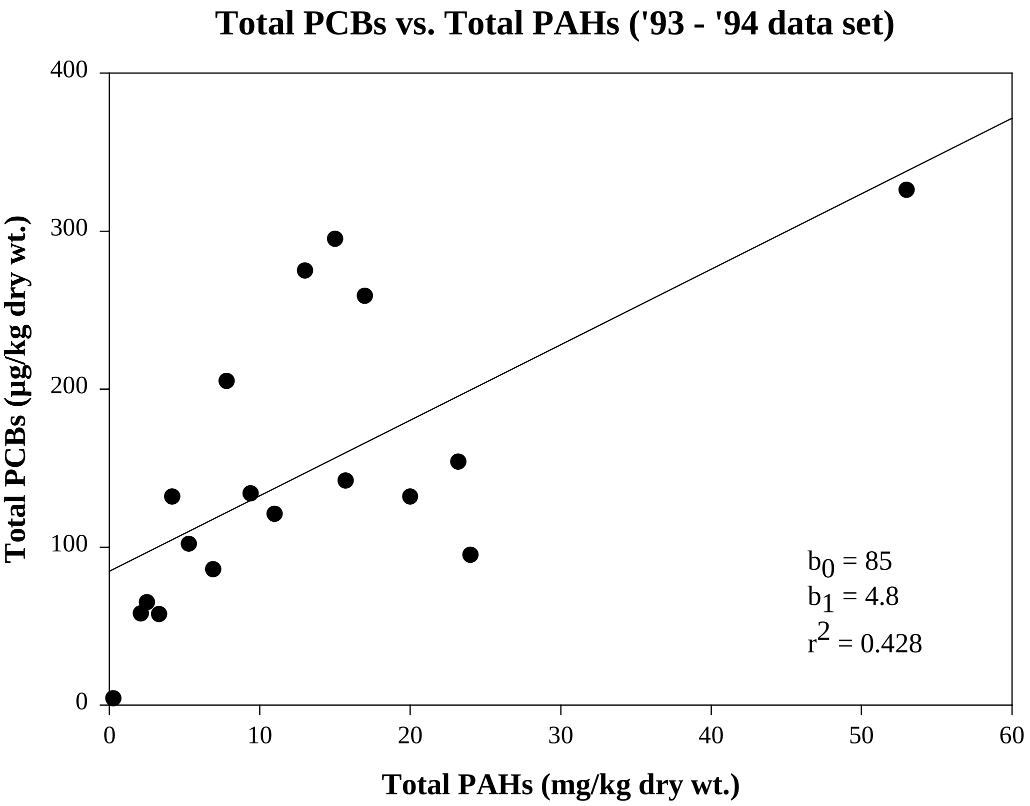

FIG. A-4. Linear regression analysis of total PCBs versus total PAHs for the 1993 and 1994 Slip C data sets.

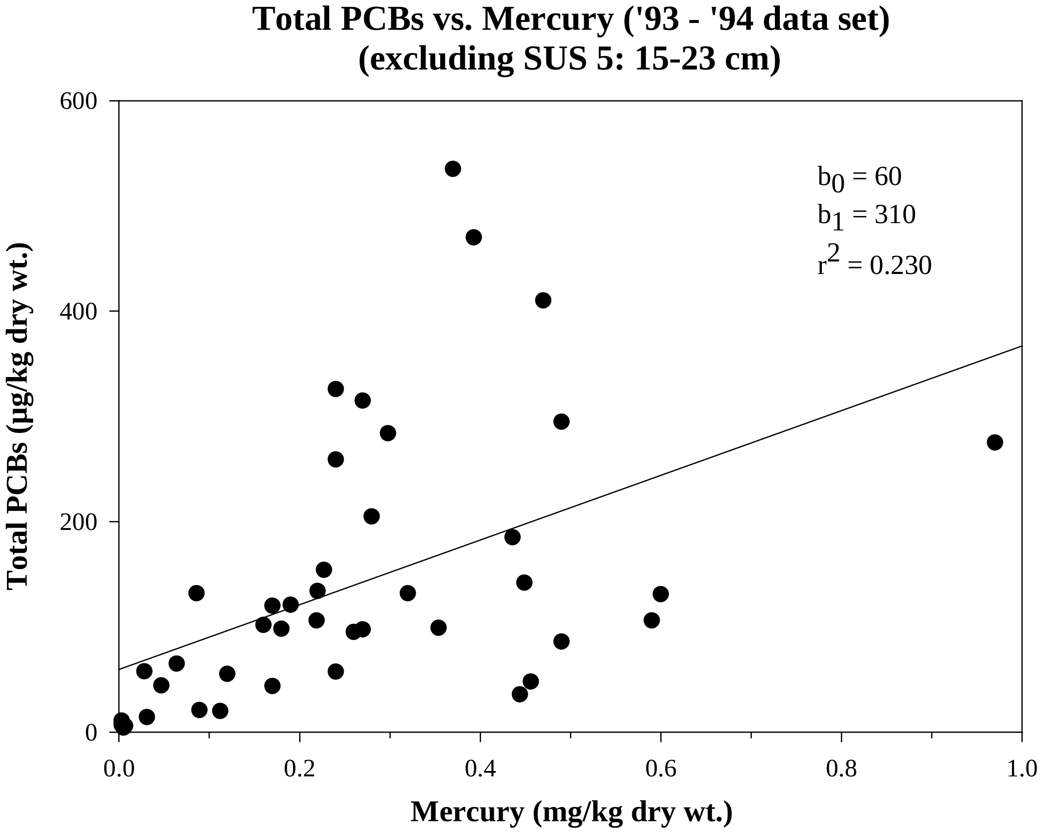

FIG. A-5. Linear regression analysis of total PCBs versus mercury for the 1993 and 1994 Slip C data sets.

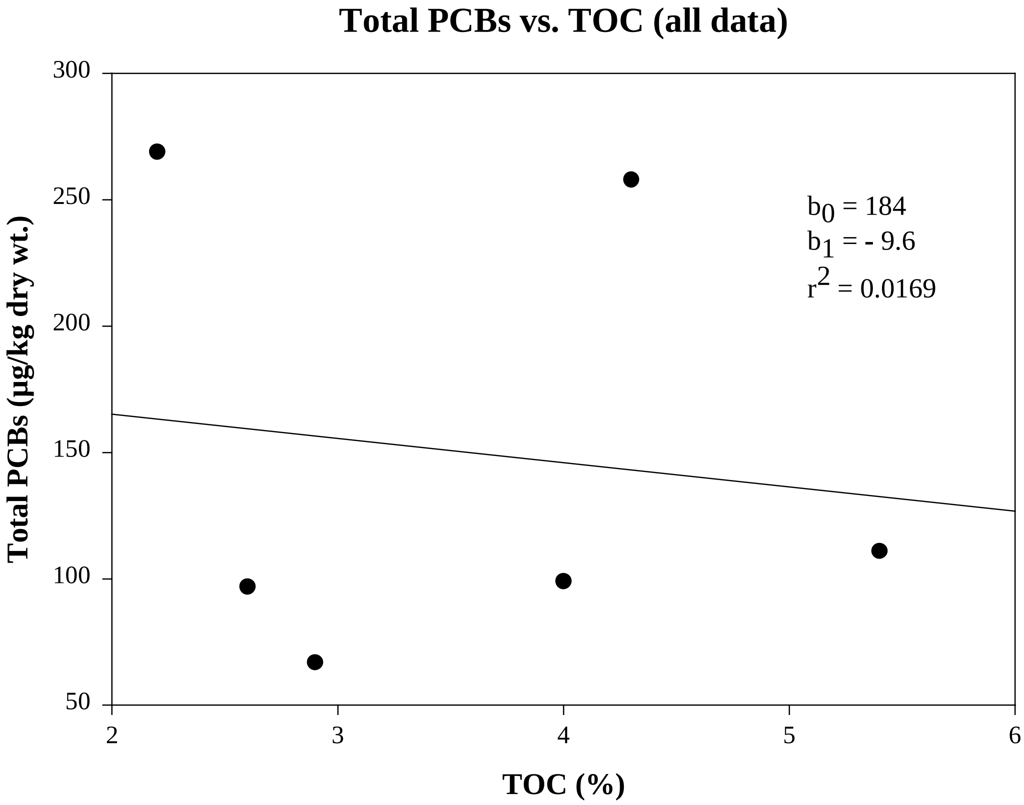

FIG. A-6. Linear regression analysis of total PCBs versus TOC.

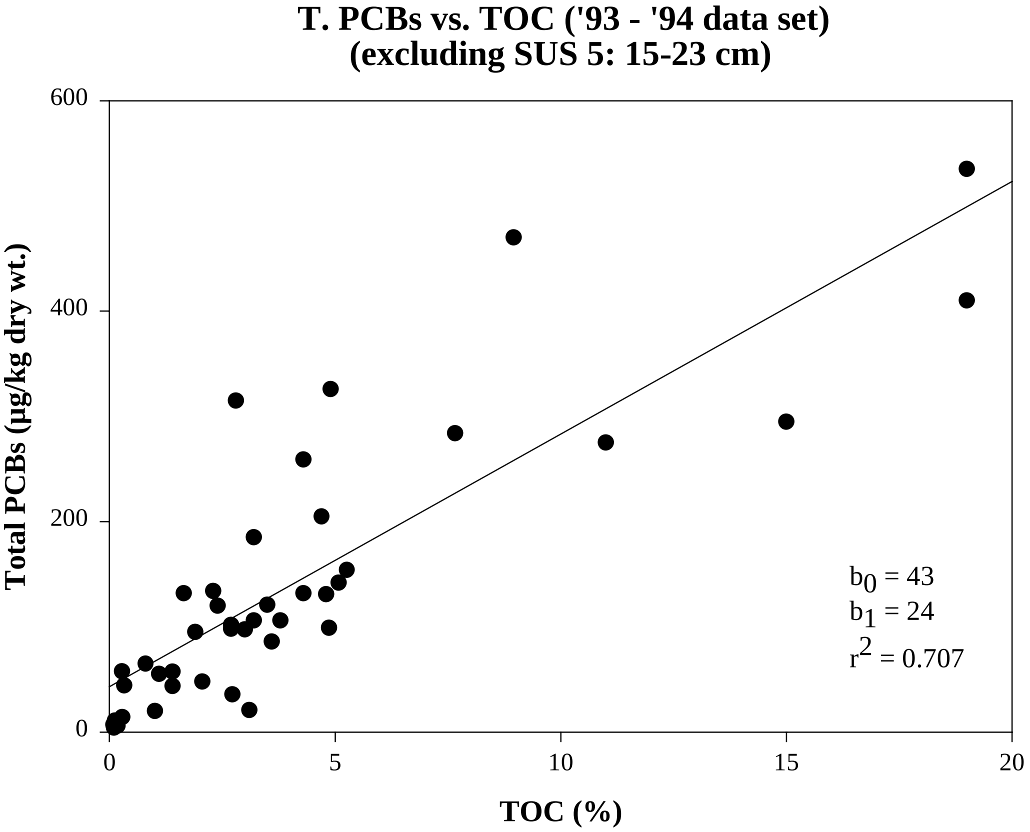

FIG. A-7. Linear regression analysis of total PCBs versus TOC for the 1993 and 1994 Slip C data sets.

APPENDIX B

Regression Analyses of PAHs, Mercury, and TOC with Particle Size Classes

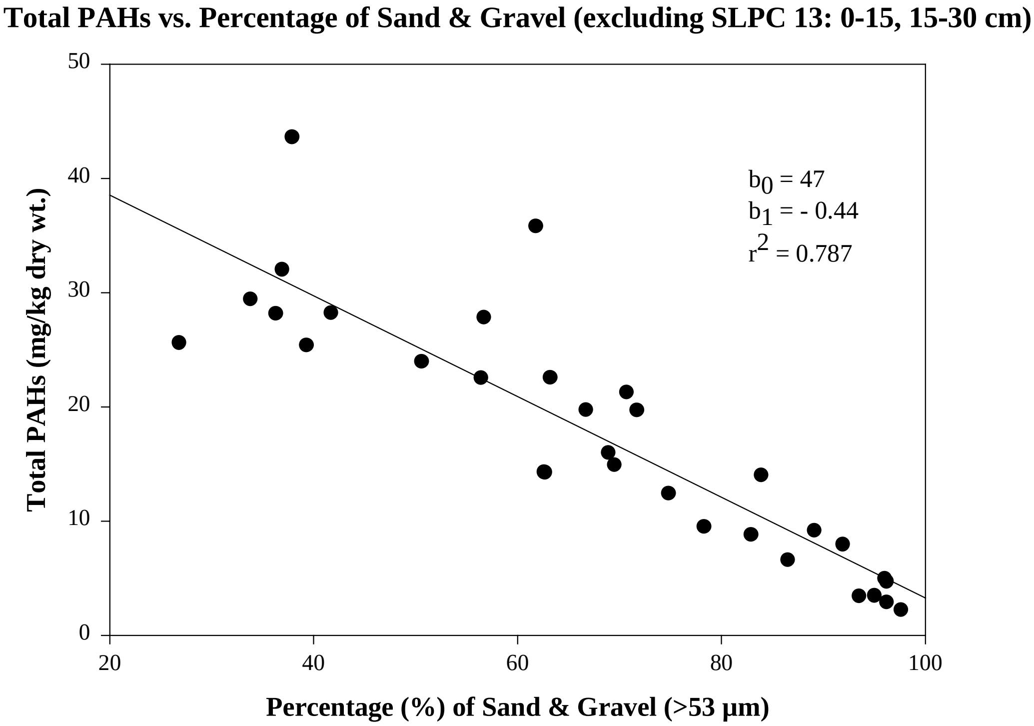

FIG. B-1. Linear regression analysis of PAHs versus percentage of sand and gravel (>53 μm).

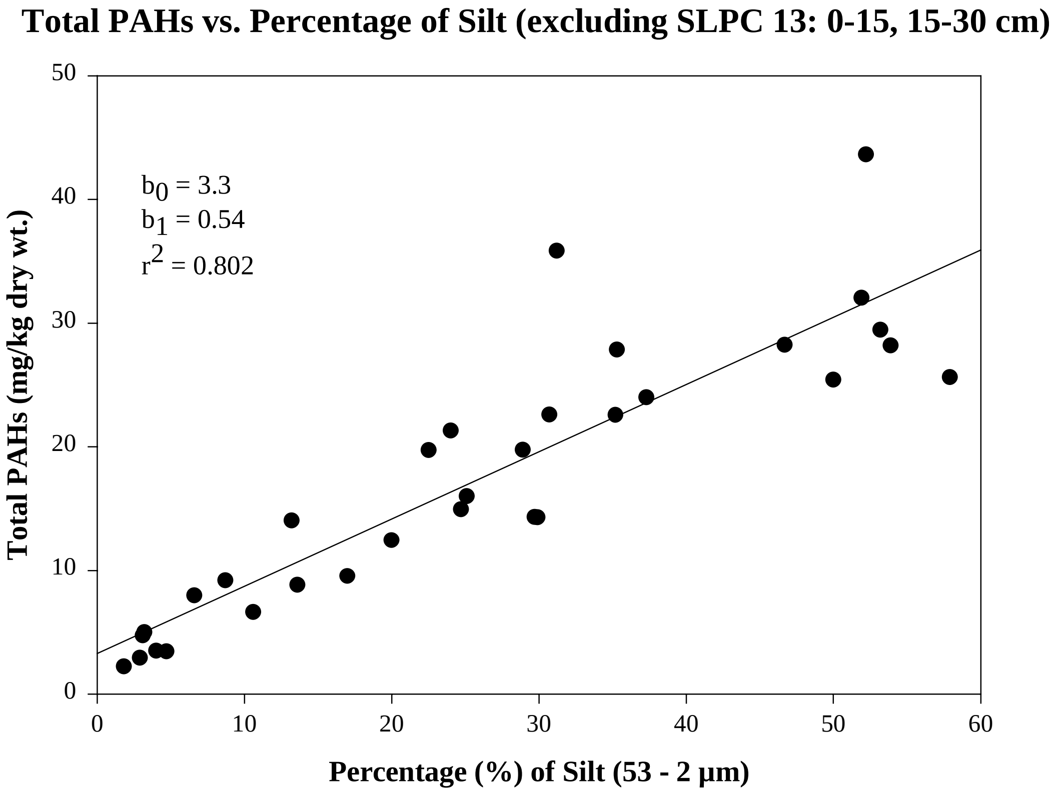

FIG. B-2. Linear regression analysis of PAHs versus percentage of silt (52 - 2 µm).

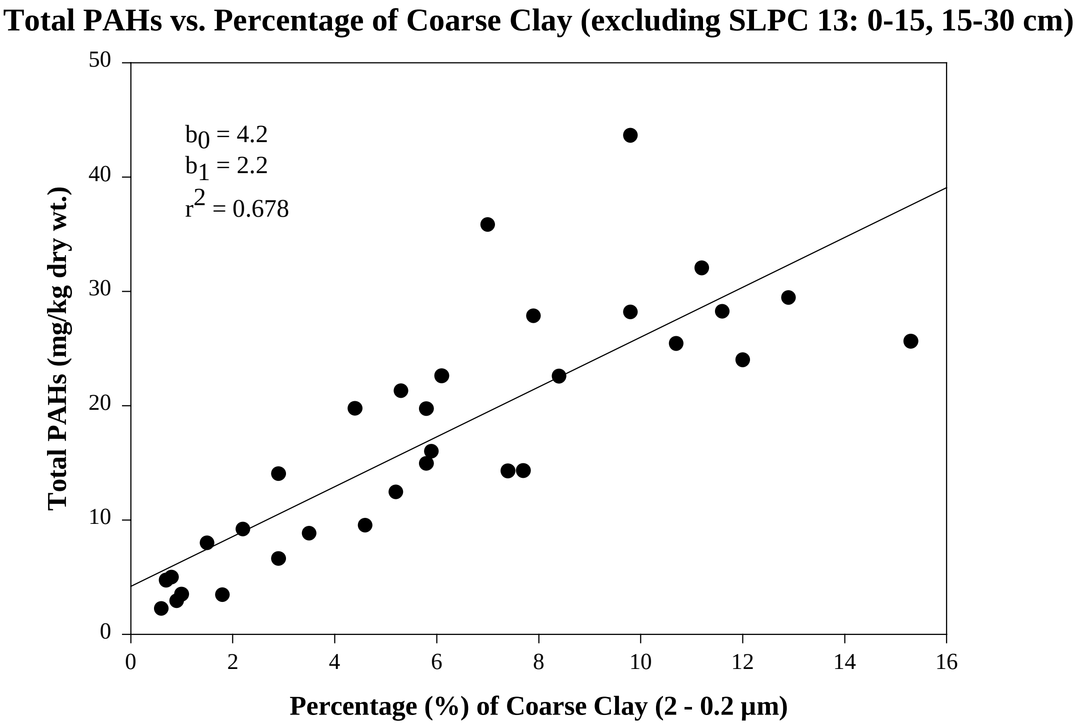

FIG. B-3. Linear regression analysis of PAHs versus percentage of coarse clay (2 - 0.2 µm).

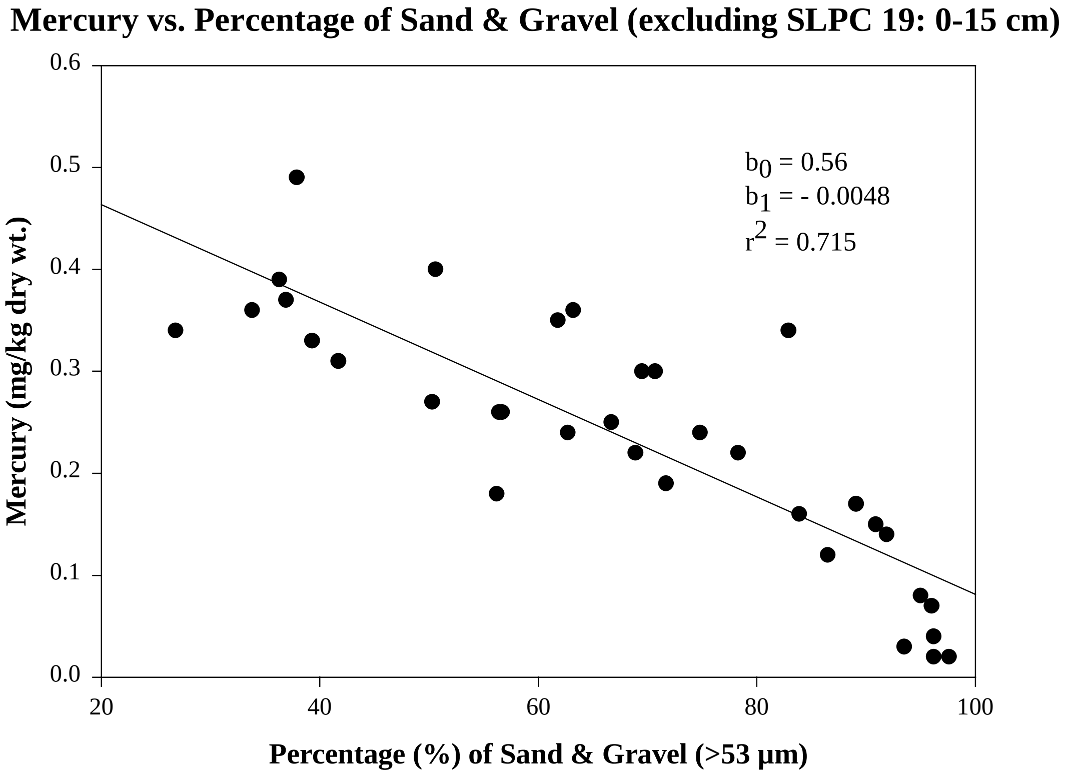

FIG. B-4. Linear regression analysis of mercury versus percentage of sand and gravel (>53 µm).

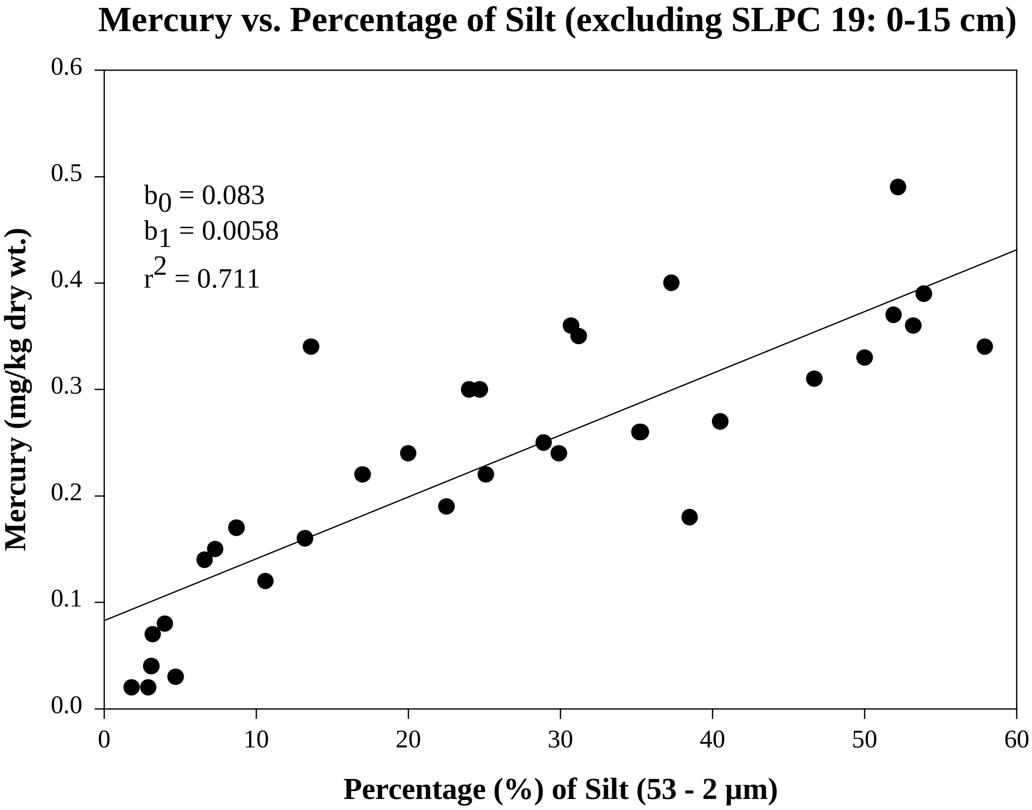

FIG. B-5. Linear regression analysis of mercury versus percentage of silt (52 - 2 µm).

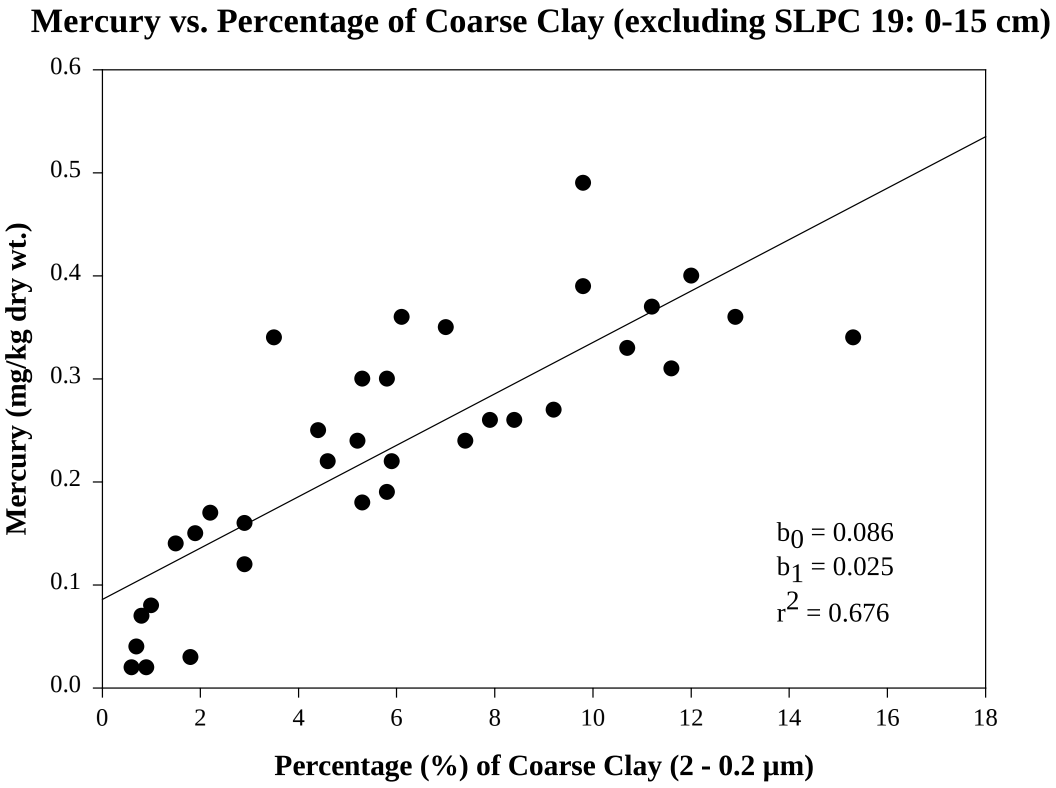

FIG. B-6. Linear regression analysis of mercury versus percentage of coarse clay (2 - 0.2 µm).

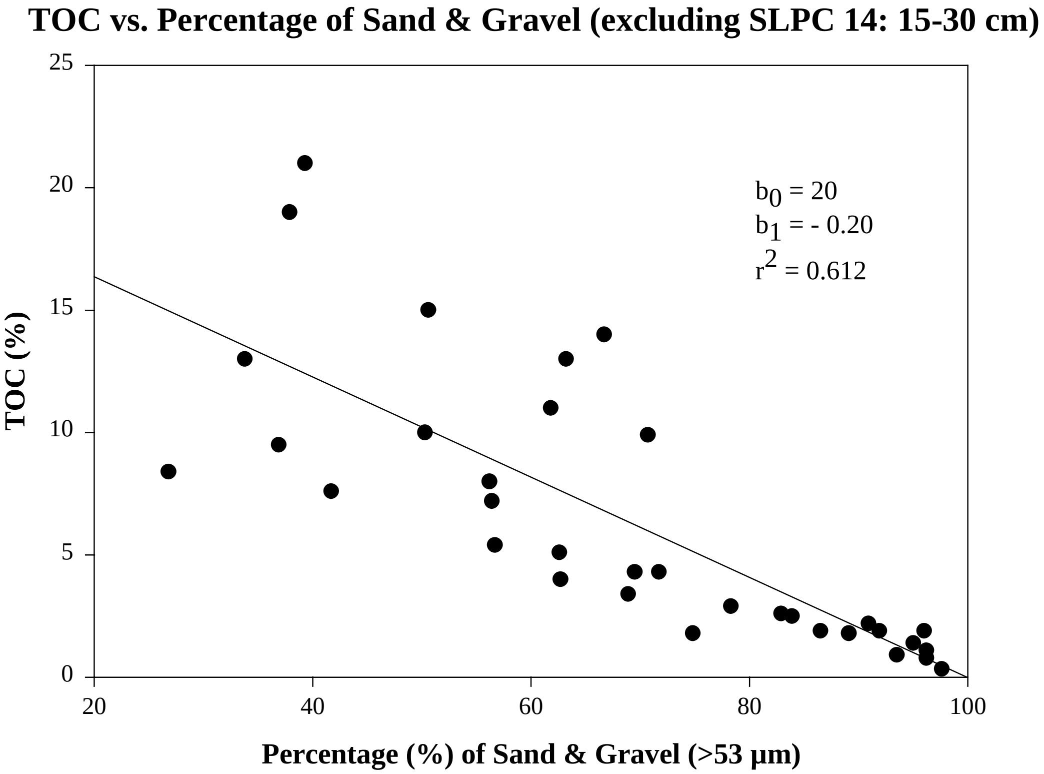

FIG. B-7. Linear regression analysis of TOC versus percentage of sand and gravel (>53 μm).

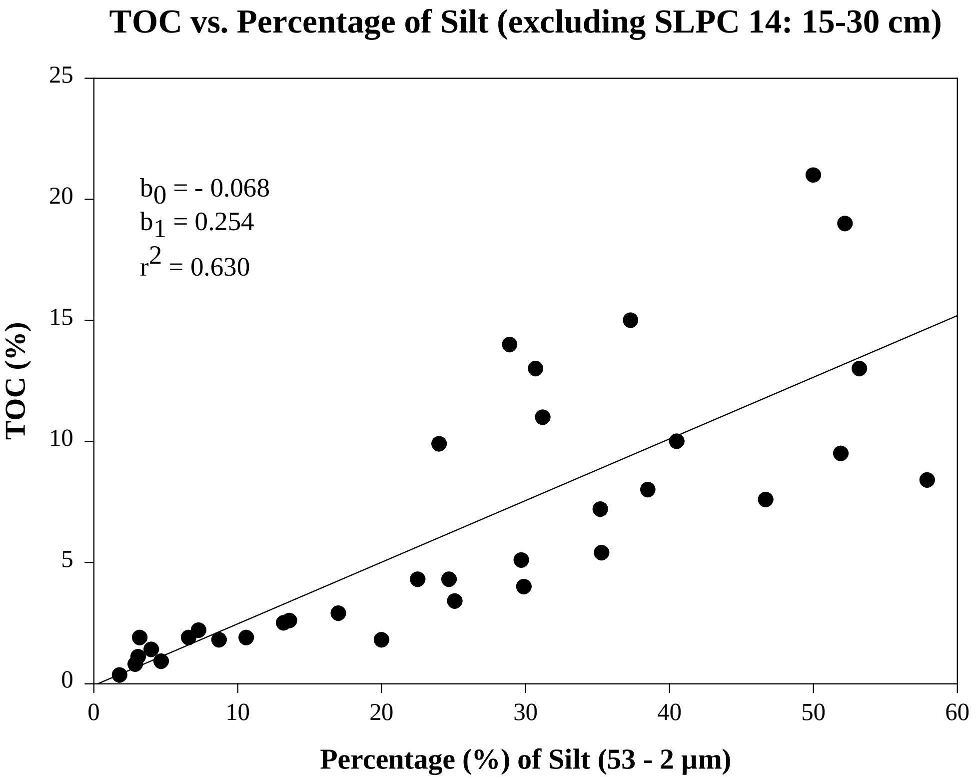

FIG. B-8. Linear regression analysis of TOC versus percentage of silt (52 - 2 µm).

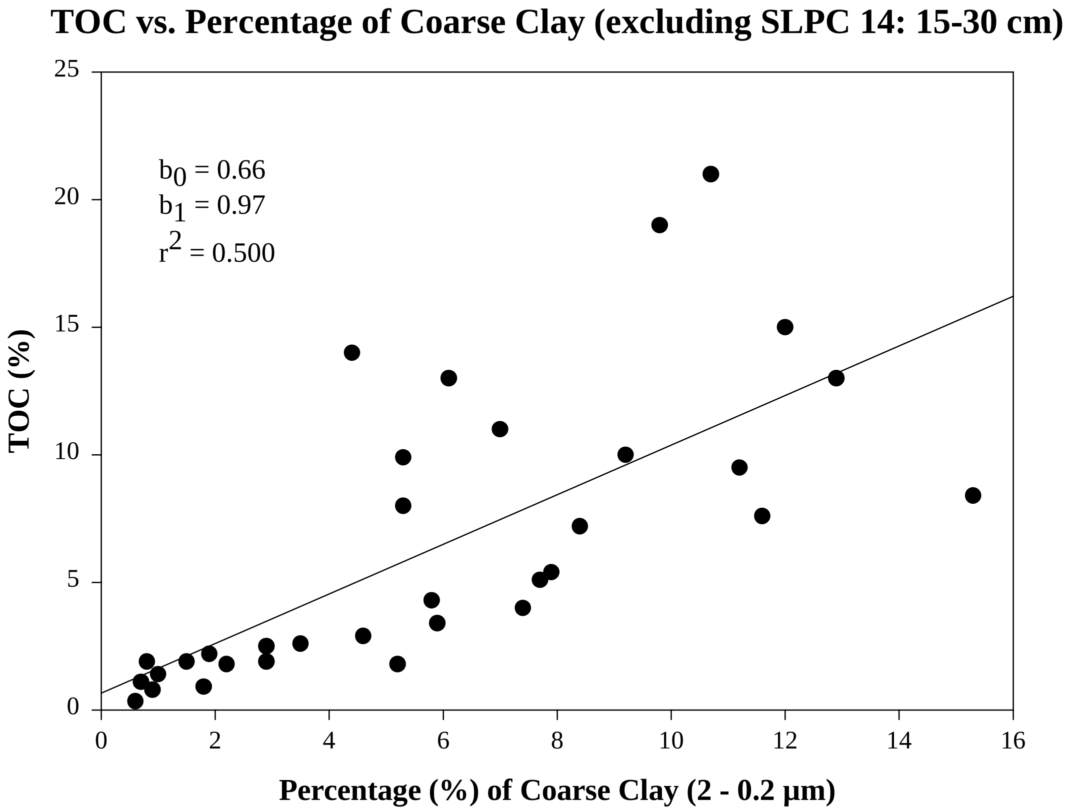

FIG. B-9. Linear regression analysis of TOC versus percentage of coarse clay (2 - 0.2 µm).