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Puget Sound Estuary Program

ELLIOTT BAY ACTION PROGRAM:

Analysis of Toxic Problem Areas

FINAL REPORT

July 1988

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U.S. Environmental Protection Agency
Region X - Office of Puget Sound
Seattle, Washington

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ELLIOTT BAY ACTION PROGRAM: ANALYSIS OF TOXIC PROBLEM AREAS

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Science Applications Int'l. Corp.	Organic compounds in sediments except volatile compounds
Battelle Columbus Laboratory	Volatile organic compounds
Am Test	Sulfides

The Elliott Bay Toxics Action Program has benefited from the participation of an Interagency Work Group (IAWG) and a Citizen's Advisory Committee (CAC). Duties of the IAWG and CAC members included: 1) reviewing program documents, agency policies, and proposed actions; 2) providing data reports

and other technical information to EPA; and 3) disseminating action program information to respective interest groups or constituencies. We thank the IAWG and CAC members for their past and continuing efforts. We are especially grateful to Ms. Joan Thomas, Mr. Gary Brugger, and Mr. Dan Cargill for chairing the IAWG, and to Mr. David Schneidler and Ms. Janet Anderson for co-chairing the CAC. Members of the IAWG and CAC are listed below.

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EXECUTIVE SUMMARY

The goal of the Elliott Bay Toxics Action Program is to identify and control toxic contamination in Elliott Bay and the lower Duwamish River system. Under this program, federal, state, and local agencies cooperate to respond to toxic contamination problems. Response actions may include regulatory control of point and nonpoint sources of contaminants, and treatment, capping, or removal of highly contaminated sediments.

In this report, the results of a field investigation (Tetra Tech 1985e) of the nearshore region of the Elliott Bay/Duwamish River system are evaluated to achieve the following objectives:

- Define spatial patterns and quantitative relationships of sediment contamination, toxicity, and biological effects
- Identify problem areas of sediment contamination and associated biological effects
- Rank problem areas relative to priority for evaluation of potential contaminant sources and possible remedial action
- Identify potential problem chemicals (i.e., chemicals that display high concentrations in association with biological effects).

A standardized assessment technique used in several other urban bay projects (e.g., Tetra Tech 1985a; PTI and Tetra Tech 1988) was used to identify problem sediments. Information presented in this report will be used in conjunction with the results of a field survey of contaminant sources to evaluate potential sources and develop recommended source controls in the Elliott Bay/Duwamish River system. A revised action plan will be developed based in part on an update of an interim work plan developed earlier in this program (Tetra Tech 1985b). Although these data may not be sufficient alone for initiating enforcement action against specific entities, they provide a basis for demonstrating potential environmental effects of contaminant sources. As such, they may be especially valuable for targeting priority drainage areas for more focused investigations of sources and ultimately initiation of source controls.

The use of these data in controlling contaminant sources or restoring areas of contaminated sediments depends in part on coordination of the activities of the Elliott Bay Action Team with other sediment programs. The evaluation of problem areas as part of the Elliott Bay Toxics Action Program was performed in the context of several other major sediment programs. These include the following programs which are described in the main text: the Puget Sound Dredged Disposal Analysis, the Harbor Island Superfund Project, and the Sediment Criteria Element (P-2) of the Comprehensive Management Plan for Puget Sound. The future use of the data presented in

this report to implement corrective actions will depend in part on ongoing activities of the latter two programs.

The project area is described in the next section. The decision-making approach for problem evaluation, the spatial distribution of contaminants and effects in the Elliott Bay system, and the ranking of problem areas are described in the following sections.

PROJECT AREA

Elliott Bay is an embayment of approximately 21 km^2 in central Puget Sound, Washington. The project area includes the shallow areas (<20 m deep) of the bay east of a line from Alki Point to West Point and the lower Duwamish River upstream to the Head of Navigation (Figure ES-1). The inner bay receives fresh water from the Duwamish River and most of the stormwater runoff from about 67 km^2 of highly developed land in metropolitan Seattle.

The lower Duwamish River is a salt-wedge estuary, influenced by tidal action over a 16-km downstream reach (including all of the riverine habitat within the project area). Saltwater intrusion occurs in the portions of the Duwamish River within the project area for all river flow rates and tides. Near its mouth, the river is divided by Harbor Island into the East and West Waterways. In this area, and upstream to several kilometers beyond the Head of Navigation, the river passes through heavily industrialized areas. The entire Duwamish River drainage basin presently covers about 1,250 km^2, including large expanses of agricultural and forested land.

DECISION-MAKING APPROACH

The approach to identification and ranking of problem areas relies on empirical measurements of the environmental hazard of contaminated areas. The primary information used in the decision process includes:

- Sediment characteristics
  - Contaminant concentrations
  - Conventional physical/chemical characteristics (e.g., grain size distribution, sulfides, total organic carbon content).
- Biological effects
  - Benthic invertebrate community structure
  - Sediment toxicity bioassays using amphipods
  - Concentrations of PCBs, chlorinated pesticides, and mercury in muscle tissue of English sole
  - Prevalence of liver lesions in English sole.

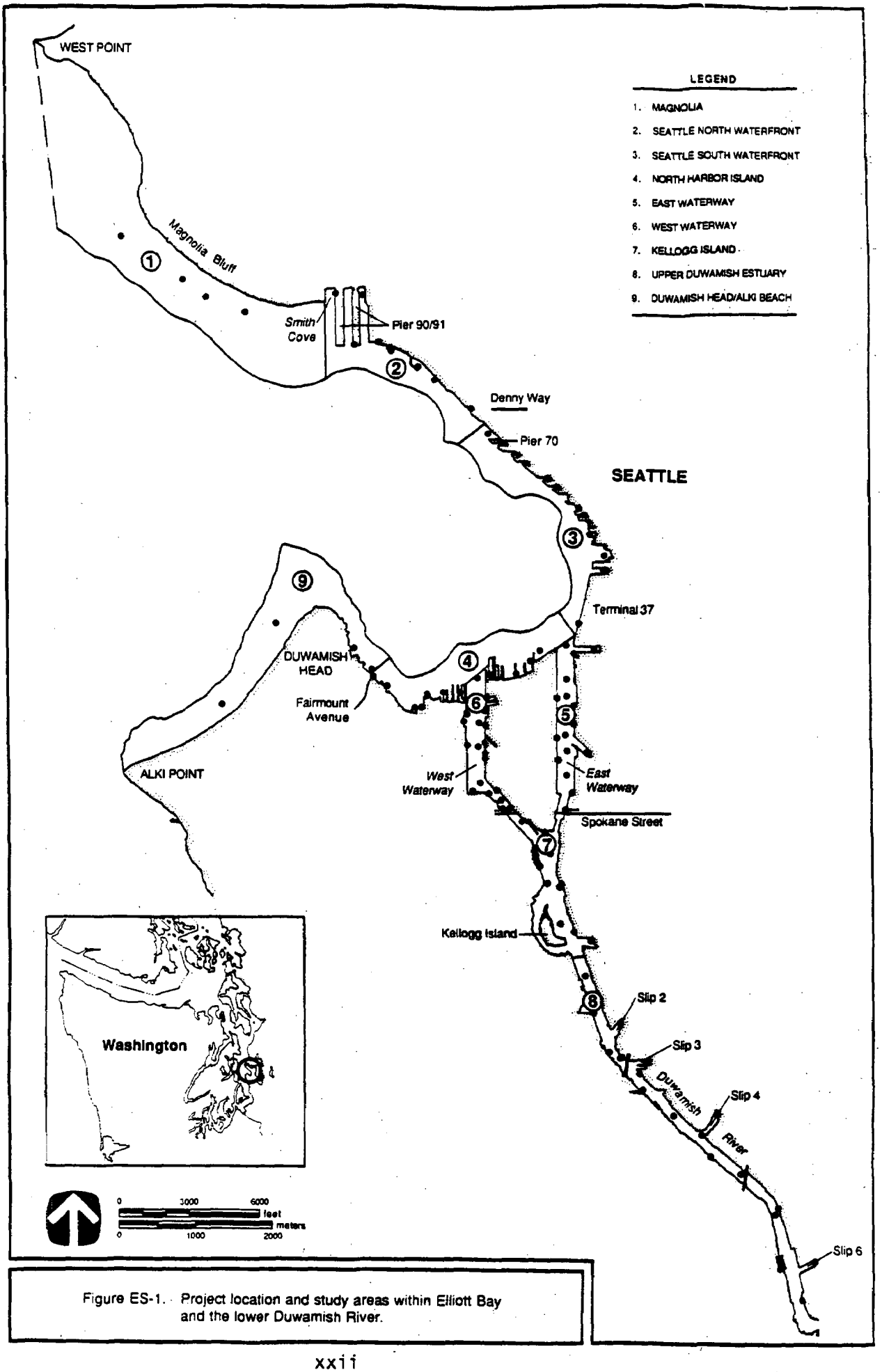


Figure ES-1. Project location and study areas within Elliott Bay and the lower Duwamish River.

Tetra Tech (1984, 1985a, 1986e) described the rationale for selecting these five major kinds of data to characterize the environmental hazard of contaminated sediments.

The environmental data on sediment contamination and biological effects were organized into a matrix of biological and toxicological indices used to compare study areas. This Action Assessment Matrix uses multiple independent indices termed "elevations above reference" (EAR) to indicate the magnitudes of contaminant levels and biological effects relative to reference conditions. A decision to proceed with source evaluation and ranking of problem areas is limited to sites that exceed a minimum action level defined by one or more significant EAR. The action-level guidelines provide a consistent framework for defining toxic problem areas based on the weight of evidence from evaluation of the selected hazard indicators. In the case of a single significantly elevated index, the magnitude of the elevation must provide sufficient evidence of a problem to outweigh the absence of significant elevations in multiple indicators.

REFERENCE AREAS

Reference areas included nine reference embayments in Puget Sound (including Port Susan) for sediment chemistry, Point Pully for fish pathology and bioaccumulation, and Port Susan for sediment bioassays and benthic infauna. Sediment chemical concentrations in Port Susan generally fell within the range of other Puget Sound reference areas. Point Pully was selected because of its proximity to Elliott Bay and the previously demonstrated low prevalences of major liver lesions in English sole. Port Susan was chosen to represent a relatively uncontaminated bay in east-central Puget Sound with a major riverine input (i.e., the Stillaguamish River). Data collected during this study generally confirmed the adequacy of Port Susan and Point Pully as reference areas. Nevertheless, at Station PS-02 in Port Susan, an observation of 24 percent mean mortality of amphipods suggested that sediments at this site may be marginally toxic to amphipods based on the criterion of $\geq$25 percent mortality proposed by Mearns et al. (1986).

SEDIMENT CHEMISTRY

Sediment samples from over 100 subtidal and intertidal stations (Figure ES-2) were analyzed for over 80 metals and organic compounds and conventional variables. In general, chemical contamination was spatially heterogeneous. The areas of the most severe contamination were localized, suggesting the importance of local contaminant sources. The Seattle South waterfront, the North Harbor Island area, and the West Waterway were among the most severely contaminated study areas. Stations within these areas accounted for many of the highest concentrations of metals and organic compounds observed in the study (e.g., Stations SS-09, SS-08, SS-03, NH-03, NH-04, NH-06, NH-08, WW-12, WW-14, and WW-19 in Figure ES-2). Other stations with relatively high concentrations included EW-05 and EW-14 in the East Waterway, Station AB-01 along Alki Beach, and Stations DR-08 and DR-12 in the upper Duwamish River. In contrast, stations in outer Elliott Bay (i.e., along Magnolia Bluff and Alki Beach, excluding inner bay Station AB-01) were the least contaminated overall.

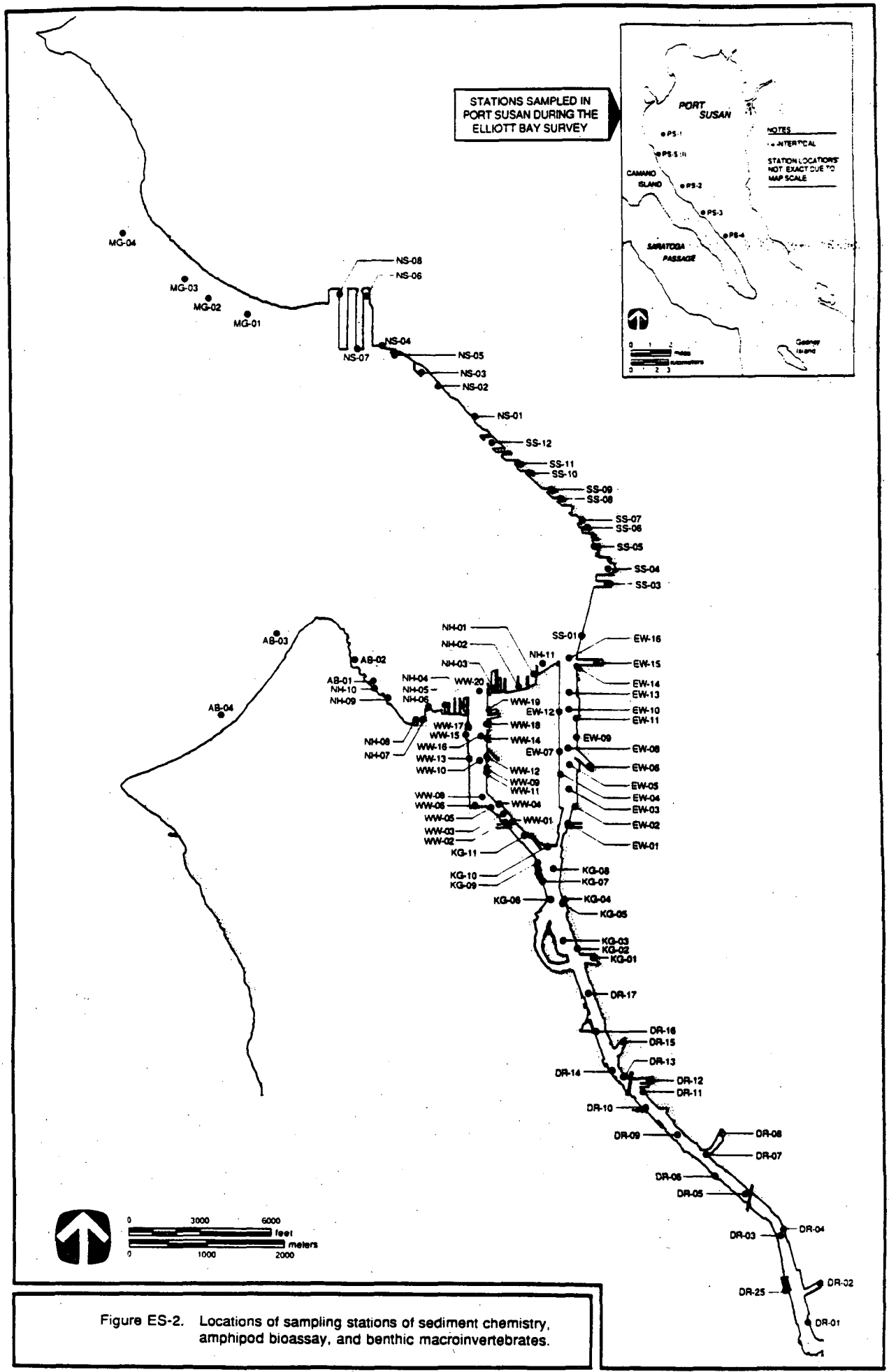


Figure ES-2. Locations of sampling stations of sediment chemistry, amphipod bioassay, and benthic macroinvertebrates.

Concentrations of copper, lead, mercury, and zinc were among the most elevated of the metals detected in the study area. Maximum EAR values for these chemicals ranged from 320 (for copper and zinc) to 7,700 (lead), whereas median EAR values were between 8 and 15. Concentrations of other metals that were somewhat less elevated but nonetheless of concern included arsenic (maximum EAR = 170), silver (maximum EAR = 92), cadmium, chromium, and nickel. Maximum copper concentrations [up to 2,050 mg/kg dry weight (DW)] occurred near the mouth of the West Waterway (Areas NH and WW) and along the Seattle South waterfront. Maximum lead concentrations (up to 71,100 mg/kg DW) occurred along the Seattle South waterfront and on the east side of the West Waterway. Maximum zinc concentrations (up to 6,010 mg/kg DW) occurred along the Seattle South waterfront. The highest mercury concentrations occurred at relatively isolated stations [AB-01 (28.8 mg/kg DW), NH-03, and EW-05] with generally elevated concentrations along the Seattle South waterfront.

Polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCBs) occurred at the highest concentration and were the most frequently detected of the organic contaminants. Other organic compounds occurred at high concentrations at isolated stations. Maximum EAR values for PAH and PCBs ranged from nearly 1,000 (for PCBs) to 15,000 (for low molecular weight PAH, or LPAH) to over 40,000 (for high molecular weight PAH, or HPAH). Median EAR for these compound classes ranged between 32 and 80. Other organic compounds that were infrequently found at elevated concentrations (maximum EAR >100) included 1,4-dichlorobenzene (maximum EAR = 8,900), benzyl alcohol (maximum EAR = 880), 4-methylphenol, pentachlorophenol, butyl benzyl phthalate, and retene. PAH concentrations were most elevated along the Seattle South waterfront (up to 3,800,000 ug/kg DW total PAH), but were also highly elevated in the North Harbor Island study area, the East and West Waterways, and at isolated stations in other areas. PCB concentrations were most elevated in the upper Duwamish River (up to 5,800 ug/kg DW) and along the Seattle South waterfront, but high concentrations occurred throughout the Duwamish River and in the North Harbor Island study area.

Pairwise Pearson correlations were performed to examine covariance in the distribution of selected contaminants. Except among PAH and related compounds, few correlations among chemicals were observed on a study-wide basis. When correlations were performed on a smaller scale for individual study areas, strong correlations were observed, particularly among metals. These results are consistent with the presumed importance of sources that predominate in localized areas.

Based on a quality assurance/quality control (QA/QC) review of the chemical data, a substantial portion of the data set was qualified for reasons of varying severity. The QA/QC review included control actions that are not included in U.S. EPA Contract Laboratory Program or Puget Sound Estuary Program guidelines for data review (e.g., in accordance with guidance from U.S. EPA Region X, all organic compounds detected at <1,000 ug/kg DW were qualified as estimates based on analyses of sediment reference materials). The data quality issue that most affected data analysis was high detection limits (i.e., low analytical sensitivity) for certain organic compounds (most notably chlorinated phenols, chlorinated benzenes, hexachlorobutadiene, benzyl alcohol, and benzoic acid). These high detection limits resulted from low surrogate recoveries, as detection

limits of acid/neutral compounds were adjusted on a chemical-specific basis to reflect surrogate recoveries. Analysis of identified problem areas, which had relatively high chemical concentrations, was largely unaffected by the issue of detection limits and analytical sensitivity.

BIOACCUMULATION

Chemical analyses for PCBs, selected chlorinated pesticides, and mercury were performed for 60 English sole muscle tissue samples (5 individual fish were analyzed for each of 12 trawl stations, including the Point Pully reference area). Tissue PCB concentrations were significantly elevated above reference levels over much of the study area, with the highest mean concentrations (390-470 ug/kg wet weight) observed in the Duwamish River (especially in the East and West Waterways). PCB concentrations tended to decrease with distance from the mouth of the Duwamish River. Pesticide bioaccumulation was not of concern with the exception of p,p'-DDE, which was detected in a single fish collected along the Seattle South waterfront (410 ug/kg wet weight). Mercury bioaccumulation was not significantly elevated above Point Pully reference levels in fish from any of the Elliott Bay/Duwamish River trawl stations.

SEDIMENT TOXICITY BIOASSAYS

The acute toxicity of field-collected sediments was determined using the amphipod (Rhepoxynius abronius) bioassay. Sediments from 17 of the 102 project area sites tested caused significant mortality ($P<0.001$) in the amphipod bioassay when compared with the Port Susan reference area. The two most toxic areas in Elliott Bay were North Harbor Island (mean mortality = 60 percent) and the East Waterway (mean mortality = 43 percent). The range of mean mortality within each study area was large, indicating considerable spatial heterogeneity. For example, the mean mortality at a station ranged from 9 to 100 percent within the North Harbor Island study area, and from 3 to 100 percent within the East Waterway. Sediment toxicity in the Magnolia and Alki Beach areas was low (<7 percent mean mortality at each of seven stations). One site (Station AB-01) just east of Duwamish Head displayed a mean amphipod mortality of 47 percent. Overall, there was good agreement between the present study and previous bioassay studies in Elliott Bay.

BENTHIC MACROINVERTEBRATE COMMUNITIES

Benthic macroinvertebrate samples from 78 stations in Elliott Bay and Port Susan were collected, and specimens were identified to major taxonomic levels and enumerated. Samples from 20 of the stations were further identified to the lowest possible taxonomic level. Abundances of major taxa at the Elliott Bay stations differed significantly ($P<0.001$) from the abundances in the Port Susan reference area. Significantly enhanced abundances ($P<0.001$) were detected in 78 comparisons, and significantly depressed abundances were detected in 73 comparisons.

Of the 74 stations sampled for benthic infauna, one or more significant depressions ($P<0.001$) in abundances of major taxa selected for problem definition (i.e., Polychaeta, Crustacea, Pelecypoda, Gastropoda) were detected at 40 of the stations. The most impacted areas in the Elliott Bay study area were North Harbor Island, West Waterway, and the Kellogg Island

segment. Stations within those segments accounted for 73 percent of the depressions detected among all Elliott Bay stations. Pelecypods and crustaceans appeared to be the most sensitive indicators among the major taxonomic groups.

The lowest numbers of taxa (at stations where organisms were identified to the species level) occurred at Stations NH-03, EW-05, NS-08, and KG-01, all of which exhibited two or more significant depressions ($P<0.001$) in the abundances of major taxa. A normal classification analysis of the species-level data separated stations into groups. Those groups corresponded to the groups based on numbers of major taxa that exhibited significantly depressed abundances ($P<0.001$) recorded among the stations.

FISH PATHOLOGY

Three major kinds of hepatic lesions (neoplasms, foci of cellular alteration, and megalocytic hepatosis) found in livers of English sole were used to characterize environmental conditions at 11 transect stations in the study area. Although the exact causes of these lesions are unknown, previous studies have demonstrated correlations between high lesion prevalences and toxic contamination of sediments. The spatial distributions of the three kinds of hepatic lesions indicate that most abnormalities were confined to inner Elliott Bay and the Duwamish River. The only study areas without significant ($P\leq0.001$) elevation of the prevalence of at least one kind of lesion were Alki Beach and Magnolia. Within inner Elliott Bay, most serious abnormalities were confined largely to the areas in or near the Duwamish River. Comparisons of length-at-age between fish with and without hepatic lesions suggested that the presence of lesions may be associated with reductions in fish growth only for females at ages greater than 5 years old. Prevalences of neoplasms and foci of cellular alteration were correlated positively ($P\leq0.05$) with fish age. Spatial distributions of lesion prevalences found in the present study were consistent with historical data collected by Malins et al. (1984).

CONTAMINANT, TOXICITY, AND BIOLOGICAL EFFECTS RELATIONSHIPS

Biological effects as measured by the amphipod toxicity bioassay and significant reductions in abundances of benthic infauna taxa were generally associated with higher concentrations of contaminants in sediments. Scatterplots of biological effects vs. concentrations of selected physical/chemical variables were examined. A strong relationship with an apparent threshold in the biological response of most benthic taxa evaluated was found for selected chemicals: LPAH, HPAH, PCBs, copper, arsenic, cadmium, and sulfides. Moreover, consistently low abundances of selected benthic taxa were observed above the concentration of these chemicals generally corresponding to Puget Sound Apparent Effect Thresholds (AET). These AET were developed from independent data sets. For other organic compounds evaluated, the number of stations with detected values was too small or the distribution of the data too skewed to show a strong association with biological variables. The abundance of the pollution-tolerant polychaete Capitella capitata displayed a linear increase with sulfides concentration in sediments and no apparent relationship with copper, PCBs, or grain size. The magnitude of amphipod mortality was generally high at higher concentrations of copper and

sulfides, but was not clearly correlated to total organic carbon (TOC) content, grain size, or the other chemical variables evaluated.

Biological effects at several stations in Area SS along the Seattle South waterfront were less than expected based on the severity of chemical contamination at these sites (especially Stations SS-03, SS-08, and SS-09). Other highly contaminated sites where statistically significant biological effects were not found ($P>0.001$) included Stations EW-14 and AB-01. However, at Station AB-01 the mean amphipod mortality was 47 percent; this test result was not statistically significant ($P<0.001$) because of substantial variability among replicates (a range of 25 to 80 percent mortality).

The abundances of several benthic taxa evaluated were consistently low at stations with $\geq$50 percent amphipod mortality in the toxicity bioassay. In contrast, C. capitata reached high abundances at stations with high levels of amphipod mortality, but was relatively rare at stations with low amphipod mortality. Concordance between statistically significant responses in the toxicity bioassay and depressions of infaunal taxa among the 74 stations where both were measured was not greater than that expected by chance alone. However, lack of concordance at low to moderate levels of contamination is not surprising given the wide range and levels of contaminants in the Elliott Bay system and the different endpoints measured by these two indicators. High concordance between these biological indicators was observed at highly contaminated stations.

Linear correlations between PCB bioaccumulation and PCB sediment contamination (i.e., wet weight bioaccumulation data vs. dry weight sediment data and lipid-normalized bioaccumulation data vs. TOC-normalized sediment data) were not significant ($P>0.05$).

PRIORITIZATION OF PROBLEM AREAS AND CONTAMINANTS

The selected data for indicators of sediment contamination, toxicity, and biological effects were integrated to evaluate toxic contamination problems in the project area. In the first phase of problem identification, all of the nearshore region inside a line from Pier 91 to Duwamish Head was defined as a problem area (Tier I) based on significant elevations of sediment contaminants and liver lesions in English sole. Seventy-two stations were designated as higher priority problem stations (Tier II). Tier I problem areas that were not also identified as Tier II areas are considered lower priority problems that may require further evaluation of potential sources and corrective actions at a future date. Sixty-one of the Tier II stations were grouped into the following multi-station problem areas: DRI (Slip 4), EW (East Waterway), KGI and KGII (near Kellogg Island), NHI and NHII (North Harbor Island, the mouth of the West Waterway, and west to just beyond Longfellow Slough outlet), NSI (Denny Way CSO), NSII (Pier 90/91), SS (Seattle South waterfront), WWI (southern segment of West Waterway), and WWII (northern segment of West Waterway).

Ranking of Tier II problem areas and stations identified five areas (SS, NHI, NHII, WWI, and WWII) and 33 single stations as the highest priority sites (Figure ES-3). Of the latter, the following stations were outside the five highest priority areas: Stations NS-01, EW-05, AB-01, KG-01, KG-05,

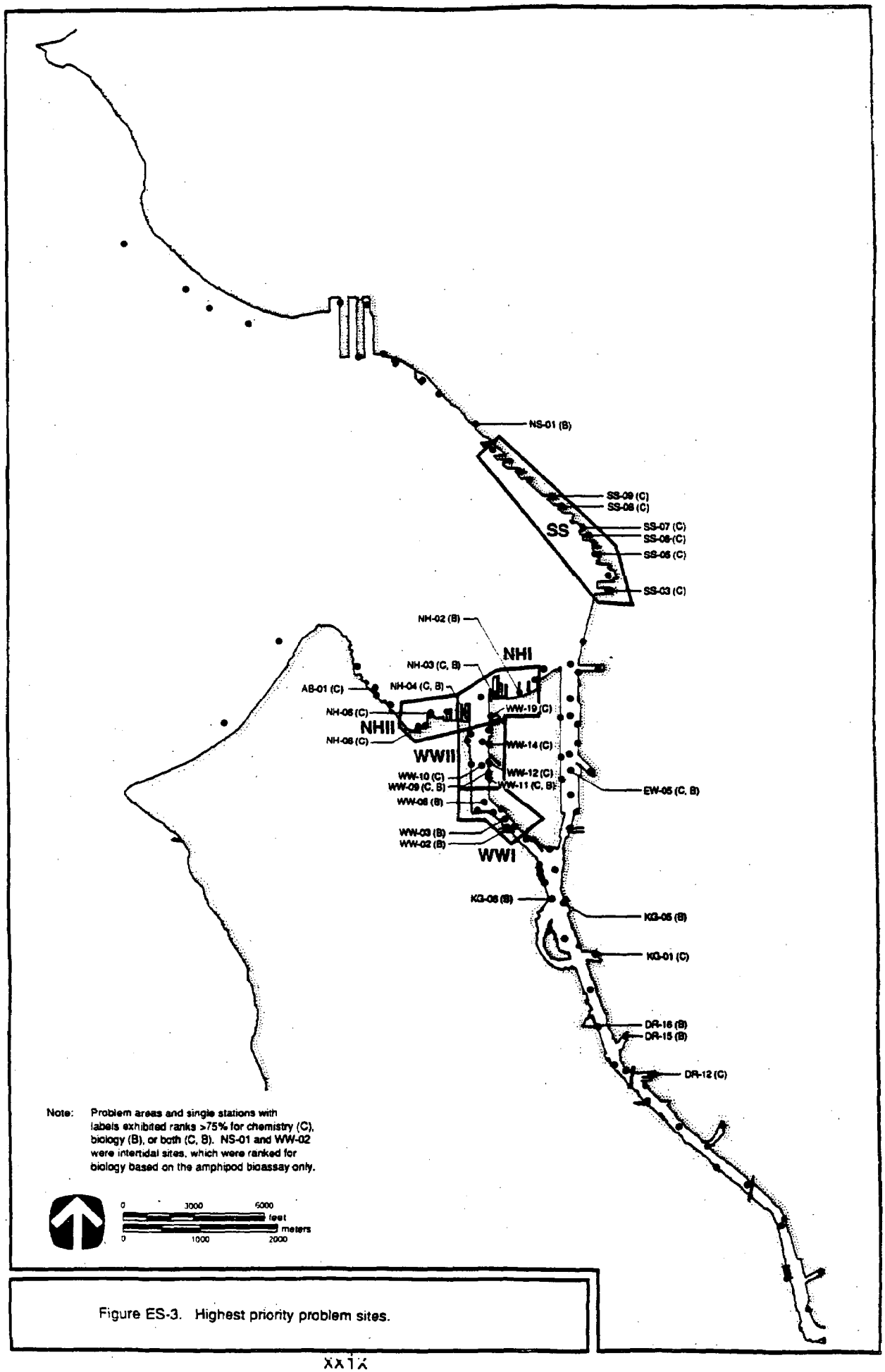


Figure ES-3. Highest priority problem sites.

KG-06, DR-12, DR-15, and DR-16. Each of the major problem areas is characterized in the following sections.

Problem Area SS

This area is highly contaminated overall (especially by PAH), with localized patches of extreme contamination. Stations SS-08 and SS-09 in this area account for the highest concentrations of several metals (e.g., lead, cadmium, zinc) and organic compounds (e.g., PAH, 1,4-dichlorobenzene) observed in this study; maximum concentrations of other metals occurred at other stations in this problem area (e.g., arsenic at Station SS-03). Sediments in this area were enriched in organic matter, with TOC concentrations typically greater than 5 percent and as high as 27 percent. Benthic infaunal depressions were found at Stations SS-04, SS-09, and SS-08, with greater than 80 percent depressions of Pelecypoda at the first two sites ($P<0.001$). Significant sediment toxicity to amphipods was found at Station SS-06, where mortality was 45 percent ($P<0.001$). Overall, biological effects in this area were confined to selected stations and did not exhibit the widespread occurrence that might be expected based on consideration of the chemistry data.

Problem Area NHI

Problem Area NHI, which encompasses two shipyard facilities at the mouth of the West Waterway, was heavily contaminated with several metals (most notably copper, but also mercury, lead, zinc, and arsenic), PAH, and PCBs. The most elevated concentrations of organic compounds and metals were observed near Station NH-03 and two historical stations located east of that station. On the west side of the West Waterway mouth, Station NH-04 contained high concentrations of copper, pentachlorophenol, and PAH, among other chemicals. Problem Area NHI exhibited severe depressions in the abundances of major taxa of benthic infauna (especially Pelecypoda) at all stations. Abundances of all four major taxa evaluated were severely depressed at Station NH-03. Significant amphipod mortality above 85 percent was found at Stations NH-03 and NH-04.

Problem Area NHII

PAH and related compounds (including alkylated PAH, carbazole, and biphenyl) were the predominant contaminants in Problem Area NHII. The most extreme contamination was observed at Stations NH-06 and NH-08, located near the Wyckoff creosote facility and the outflow of Longfellow Slough, respectively. These two stations were very similar in terms of PAH composition and concentration. Benthic infaunal effects in Problem Area NHII were less than in most other problem areas, although Station NH-08 exhibited severe depressions of pelecypods and crustaceans. Overall sediment toxicity was highest in this area, with Station NH-08 displaying 100 percent mortality.

Problem Area WWI

Chemical contamination was severe but patchy in this area, and included a relatively isolated but high historical concentration of PCBs in the southwest corner of the waterway, a high benzyl alcohol concentration at Station WW-02, and high concentrations of PAH at Station WW-04. Effects on

benthic infauna were moderate overall for this area. However, Station WW-03 was one of two stations in this study where severe (>80 percent) depressions in abundances of all four major taxa were observed. Sediment toxicity in Area WWI was generally low, except at Station WW-02, where 82 percent mortality was observed.

Problem Area WWII

The most distinctive chemical feature of this area was extreme lead contamination along the east side of the West Waterway (near the SW Lander Street discharges). PAH concentrations were generally elevated, but gradients or pronounced maxima were not apparent. PCB contamination was moderate and patchy in this area. Severe effects on benthic infauna were restricted to depressions in the abundances of pelecypods and crustaceans at several stations within this area. Sediment toxicity was relatively low in this area overall. Nevertheless, mean amphipod mortality above 40 percent was observed at Stations WW-09 and WW-11.

INTRODUCTION

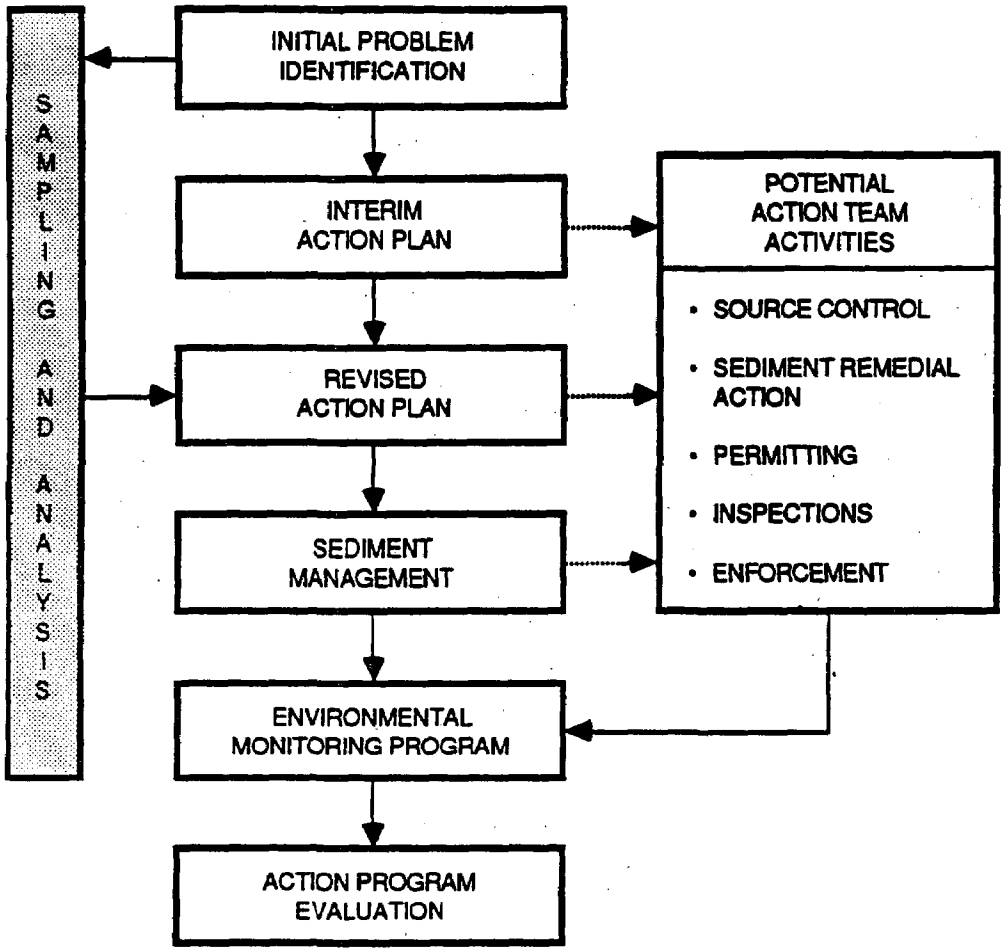
The U.S. Environmental Protection Agency (EPA) and the Washington Department of Ecology initiated the Elliott Bay Toxics Action Program to correct problems associated with toxic contamination of Elliott Bay and the lower Duwamish River (Figure 1). Previous studies (e.g., Malins et al. 1980, 1982; Romberg et al. 1984) have demonstrated widespread contamination of the nearshore region of the bay and river by a variety of toxic chemicals associated with discharges of industrial and municipal wastewater, stormwater, combined sewer overflows, and uncontrolled spills. A preliminary evaluation of toxic problem areas (Tetra Tech 1986e) and a review of existing plans for corrective actions (Tetra Tech 1985c) formed the basis for development of an interim work plan for the Elliott Bay Toxics Action Program (Tetra Tech 1985b). Under this program, remedial actions may include source controls designed to reduce emissions of toxic chemicals and possibly future cleanup of contaminated sediments.

An assessment of chemical contamination and adverse biological effects is provided in this report, including a ranking of problem areas in terms of priority for evaluation of potential contaminant sources. The field surveys described in this report were designed to fill data gaps and to provide a detailed assessment of environmental hazards. By identifying the worst problem areas based on multiple indicators of chemical contamination and bioeffects, this assessment allows resources for pollutant source investigations and remedial actions to be assigned to the highest priority areas. Nevertheless, the ranking of problem areas presented in this report may be modified by consideration of the economic and technical feasibility of potential remedial actions (e.g., Tetra Tech 1988c).

Development of a remedial action plan requires that the following kinds of questions be answered for areas within the bay/river system:

1. What is the magnitude of sediment contamination?
2. What is the extent of contamination of aquatic organisms?
3. Has the contamination resulted in adverse biological effects?
4. Can the contaminant sources be identified?
5. Would remedial action reduce the threat to the environment?

Answering Questions 1-5 involves development of an information base, that includes data on sources, fates, and effects of contaminants. Data on fates and environmental effects of contaminants are presented in this report. The evaluation of pollutant sources and an updated summary of remedial actions developed by an interagency work group will be presented in separate documents. An assessment of human health risks associated with chemical contamination of fisheries resources in the Elliott Bay system will be performed as part of a Puget Sound-wide study funded by EPA.



NOTE: Analyses of environmental data used to define problem areas are presented in this report.

Figure 1. Elements of the Elliott Bay Toxics Action Program.

The evaluation of problem areas as part of the Elliott Bay Toxics Action Program was performed in context with the following major sediment management programs:

- **Puget Sound Dredged Disposal Analysis (PSDDA)**--A multiagency program to develop evaluation procedures for disposal of dredged material and to identify disposal sites. A recent baseline survey of the designated disposal site in inner Elliott Bay analyzed sediment chemistry, benthic infauna abundances, sediment toxicity, and bioaccumulation of toxic chemicals by benthic infauna. PSDDA is not intended to identify contaminated problem areas or proposed cleanup actions.

- **Harbor Island Superfund Study**--As part of this U.S. EPA Superfund project, contaminated sites on Harbor Island and potential sources of contaminants to the East and West Waterways and Elliott Bay are being identified. Stabilization or cleanup of upland sites may be required to prevent offsite transport of contaminants. During the first phase of the Harbor Island Superfund study, U.S. EPA will also review information generated by the Elliott Bay Action Program with regard to contaminated sediments and potential sources of contaminants. Future phases of the study may entail further evaluation of contaminated sediments and, as appropriate, plans for remedial action.

- **Sediment Criteria Element (P-2) of the Comprehensive Management Plan for Puget Sound**--As directed under the plan developed by the Puget Sound Water Quality Authority, the Washington Department of Ecology is developing regulatory criteria for identifying and designating sediments that have observable acute or chronic effects on biological resources or that pose a significant health hazard to humans.

The latter program is designed to identify problem sediments in the environment throughout Puget Sound. Interim sediment criteria will be proposed by the Washington Department of Ecology by 31 July 1988, with adoption of final regulations by 30 June 1989. Development of the sediment criteria will rely partly on previous efforts to develop sediment quality values such as the U.S. EPA urban bay action programs (including the present project), the Commencement Bay Superfund Program, and PSDDA. A review of other plans and activities related to water quality management in Elliott Bay is provided in Tetra Tech (1985c).

The project area and its physical setting are described below. The decision-making approach used to identify and prioritize contamination problems is presented in the next major section. The second section also provides a summary of the study design and methods used to collect field data. Results of individual study components are presented in the third section, including analyses of 1) sediment contamination, 2) benthic macroinvertebrates, 3) sediment toxicity as measured by the amphipod bioassay using Rhepoxynius abronius, 4) bottomfish ecology, 5) histopathology of

English sole (Parophrys vetulus) livers, and 6) bioaccumulation of toxic substances in English sole muscle tissue. In the fourth section, relationships among contamination, toxicity, and biological effects are evaluated. Data for selected indicators are then integrated and evaluated within the decision-making framework to develop a prioritization of problem areas and contaminants.

SITE DESCRIPTION

Elliott Bay is an embayment of approximately 21 km^2 in central Puget Sound, Washington (Figure 2). The bay opens toward the main basin of Puget Sound to the west, with Seattle situated on the surrounding shore. The inner bay receives fresh water from the Duwamish River, which is channelized in the last 10 km of its downstream reach. Near its mouth, the river is divided by Harbor Island into the East and West Waterways. In this area, and upstream to several kilometers beyond the Head of Navigation, the river passes through the heavily industrialized portions of Seattle. The Duwamish River drainage basin presently covers about 1,250 km^2 (Santos and Stoner 1977). The major commercial district of Seattle is located on the northeastern shore of Elliott Bay. Much of the remainder of the shoreline is covered by residential development or recreational areas.

Drainage patterns and study areas within the bay/river system are described in the following sections. Background information on physical oceanography and beneficial uses of the bay is provided in Tetra Tech (1986e).

DRAINAGE PATTERNS

The immediate drainage basin of Elliott Bay and the lower Duwamish River consists of about 67 km^2 of highly developed land in metropolitan Seattle. The wider Duwamish/Green River basin includes large expanses of agricultural land and undeveloped forests. Boundaries of the immediate drainage basin considered in this study are roughly defined by Beacon Avenue on the east side and 35th Avenue S.W. on the west side. The basin includes residential areas in the southern portions of the Queen Anne and Magnolia neighborhoods, and most of West Seattle; the industrial areas along the Duwamish Waterway; the I-5 corridor from James Street to about S. Dawson Street; and the downtown business district.

The residential areas are generally served by partially separated storm and sanitary systems. Much of the surface runoff from streets and surrounding land surfaces is collected in storm sewers and discharged directly to Elliott Bay or the lower Duwamish River. Runoff from rooftops is generally discharged into the combined sewer system and treated at the three area wastewater plants. Runoff from the business district is served mainly by combined sewers, and is transported to the West Point plant via Municipality of Metropolitan Seattle's (Metro) interceptor system. Runoff from I-5 is collected in two large storm drains and discharged to the Duwamish Waterway at Slip 4 and Diagonal Way. The remaining industrial areas, excluding Harbor Island, are served by combined sewers, and private and municipal storm drains. Presently, several storm sewer separation projects are underway or are planned for business/industrial areas. Harbor Island has its own storm sewer system which discharges to the East and West Waterways.

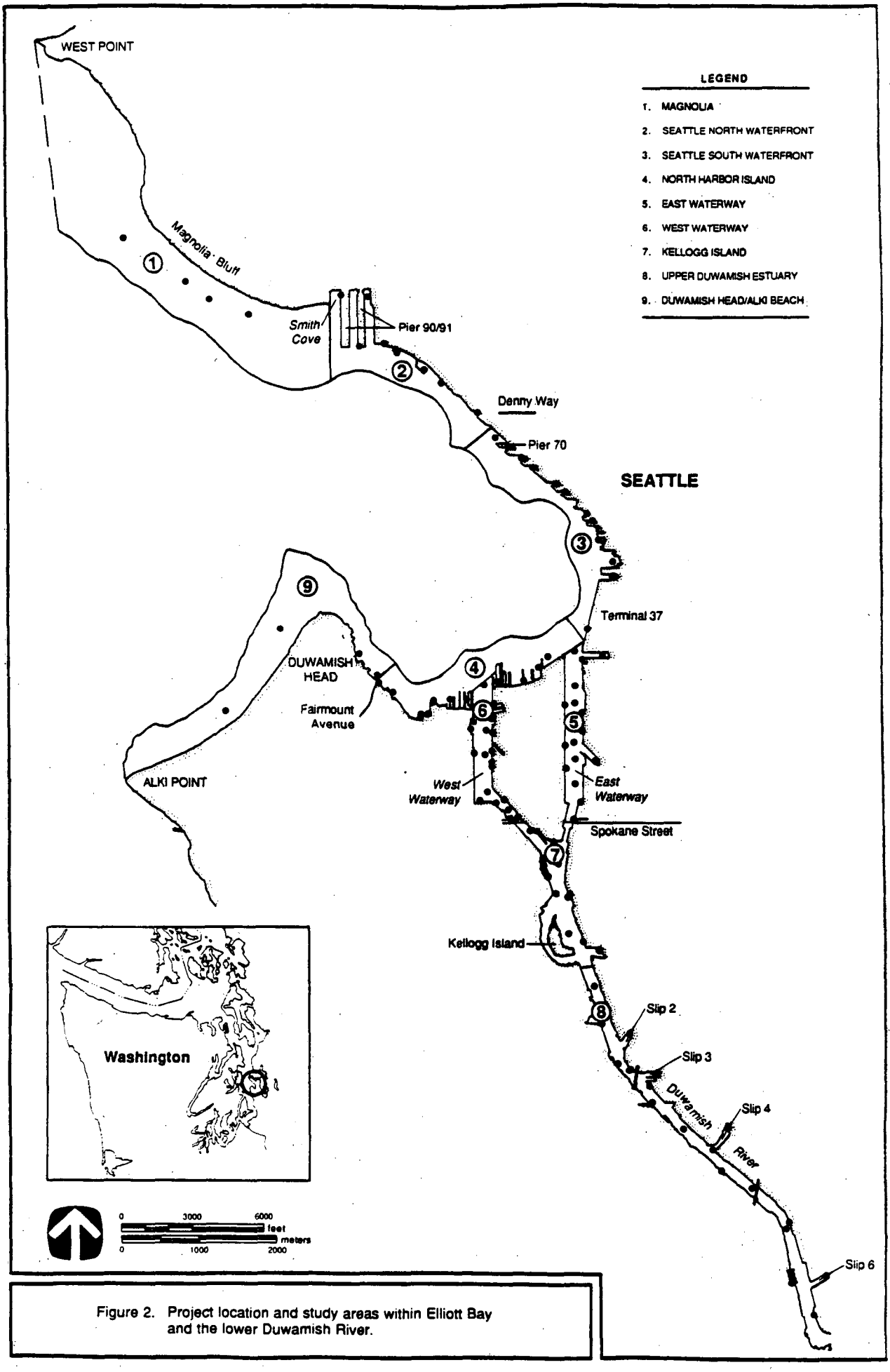


Figure 2. Project location and study areas within Elliott Bay and the lower Duwamish River.

The Duwamish River discharges at an annual average rate of 47 m^3/sec and contributes much of the suspended particulate matter entering Elliott Bay. The Duwamish River is a salt-wedge estuary, influenced by tidal action over its lower 16 km (including all of the riverine study area which extends to the Head of Navigation located approximately 10 km upstream from the mouth of the West Waterway). Saltwater intrusion occurs in the portions of the Duwamish River within the project area for all river flow rates and tides. The leading edge of the saltwater intrusion, called the wedge toe, is defined as the farthest point upstream where salinity of the wedge water is at least 25 ppt. Stoner (1967) found that when river discharge was less than 28 m^3/sec, the toe of the salt wedge did not intrude past 12.6 km (East Marginal Way Bridge), but it intruded at least that far on most flood tides when discharge was less than 18 m^3/sec. During some periods of low discharge and high tides, salt has been observed as far upstream as 16.4 km, and on rare occasions 21 km (Stoner et al. 1975). The salt wedge and overlying river water were fairly discrete (highly stratified) at river discharge rates above 28 m^3/sec, but at lower rates, the first 6 km of the estuary were partly mixed.

STUDY AREAS

A major objective of this report is to identify spatial patterns in the distribution of contaminants, sediment toxicity, and biological responses in the nearshore region of Elliott Bay and the lower Duwamish River. Sediment sampling was limited to areas of approximately 50 m water depth or less because previous studies (e.g., Malins et al. 1980, 1982; Romberg et al. 1984, 1987) have demonstrated that the most contaminated sediments are typically in these relatively shallow areas. To facilitate spatial analysis, the nearshore region (i.e., less than about 50 m deep) has been divided into nine smaller areas based on geographic features and locations of major sources of contaminants [i.e., storm drains and combined sewer overflows (CSOs) (Figure 2)]. Area boundaries and major features are as follows:

1. Magnolia (MG) - West Point, south to Smith Cove

2. Seattle Waterfront North (NS) - Terminal 90/91 to Pier 70; Interbay CSO at Terminal 90/91, Denny Way CSO, Myrtle Edwards public fishing pier

3. Seattle Waterfront South (SS) - Pier 70 to Terminal 37; main Seattle waterfront, ferry terminals, King Street and Connecticut Street CSOs, Seattle Aquarium, public fishing pier

4. North Harbor Island (NH) - Southern end of Elliott Bay from T37 west to Fairmount Avenue; northern Harbor Island, outflow of Longfellow Slough

5. East Waterway (EW) - Mouth to Spokane Street bridge; Hanford and Lander CSOs

6. West Waterway (WW) - Mouth to Spokane Street bridge; S.W. Lander and S.W. Florida CSOs

7. Kellogg Island (KG) - Spokane Street bridge to Kellogg Island/ Slip 1; Hanford-1 CSO

8. Upper Duwamish Estuary (DR) - Kellogg Island/Slip 1 to head of navigation; Michigan Street CSO, Georgetown flume

9. Duwamish Head/Alki Beach (AB) - Eastern shoreline of Duwamish Head, north of Fairmount Avenue S.W., to Alki Point

In this report, the phrase "Elliott Bay system" refers to the entire project area defined above.

METHODS

Descriptions of the field, laboratory, and data management methods are provided in the following sections. Before these methods are presented, the general approach used to define and rank toxic problem areas is summarized. The decision-making approach provides perspective on the uses of the various kinds of data that were collected and the rationale for specific variables.

DECISION-MAKING FRAMEWORK

Information on the extent of toxic contamination and adverse environmental effects formed the basis for prioritization of areas for cleanup or source control. The decision-making framework developed for the Elliott Bay Toxics Action Program incorporates a preponderance-of-evidence approach to problem identification. Study areas that exhibit high values for indices of contamination and adverse effects relative to a reference site receive a ranking of "high priority" for evaluation of pollutant sources and remedial action.

Overview

The decision-making process to evaluate toxic contamination problems is shown in Figure 3. This process ultimately focuses regulatory effort and remedial actions on localized areas of severe contamination and biological effects. Major steps in the process to identify and rank toxic chemical problems are as follows:

- Characterize sediment contamination, sediment toxicity, and biological effects
- Quantify relationships among sediment contamination, sediment toxicity, and biological effects
- Apply action levels to determine problem areas
- Determine problem chemicals in problem areas
- Define spatial extent of problem areas
- Evaluate sources contributing to problem areas
- Evaluate, prioritize, and recommend problem areas and sources for potential remedial action.

Four major premises underlie this approach. First, it was determined that no single measure of environmental conditions could be used in all cases to define adequately the requirements for potential remedial action. Therefore, recommendations for remedial action investigations are based on several measures of sediment contamination and biological effects. When results of these independent measures corroborate one another (i.e., there

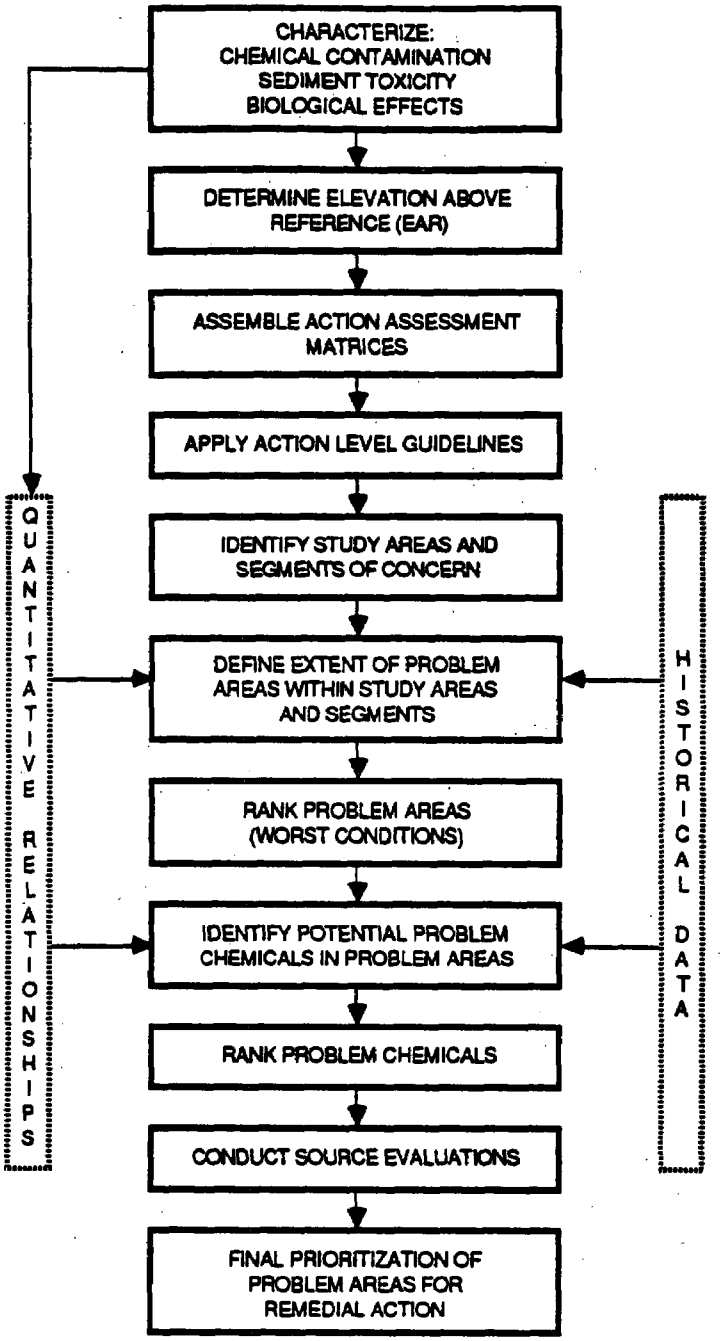


Figure 3. Decision-making approach for the Elliott Bay Action Program.

is a preponderance of evidence), a problem area is defined. There may be special circumstances where corroboration is not needed because a single indicator provides an exceptional basis for recommending that the site be evaluated for potential source control or remedial action.

Multiple contamination and effects variables were used in the preponderance-of-evidence approach for several reasons. First, chemical data are needed to characterize the extent of contamination and to relate contaminant distributions to potential sources. Second, direct measures of biological effects are needed because some chemicals present at high concentrations may not be bioavailable. Conversely, biological effects may result from chemicals that are not analyzed for. Several biological variables (e.g., mortality of amphipods exposed to sediments in the laboratory, abundances of indigenous benthic infauna organisms, and liver lesions in English sole) were used to account for effects at various levels of biological organization (i.e., cellular/tissue, whole organism, community). Also, different biological variables may demonstrate different sensitivities to specific chemicals or combinations of chemicals.

Second, action-level guidelines provide a consistent means for defining problem areas based on significant contamination and effects. These guidelines are developed in consultation with the Elliott Bay Work Group, an interagency task force consisting of representatives from federal, state, and local agencies.

Third, it is assumed that adverse biological effects are linked to environmental conditions that result from source emissions and that these links may be characterized empirically. Relationships between sources and effects will be quantified where possible, for example, by correlations of specific contaminant concentrations and distributions with the occurrence of adverse biological effects (see Tetra Tech 1988b). However, proof of specific causal agents is not provided by these studies. Direct cause-effect relationships in the sense of laboratory verification studies are not within the scope of the Elliott Bay investigation. Nevertheless, analysis of a wide range of contaminants should increase the probability of measuring either the causative substances, or related substances from the same source and with the same distribution in the environment.

Finally, a fourth premise is that the recommended remedial actions may vary from location to location. For example, only removal of contaminated sediments may be recommended where contamination originated only from past sources and biological effects are apparent. In contrast, source control may be recommended where contamination originates from an ongoing source even though biological effects may not be apparent. In other cases, both sediment removal and source control may be recommended. To prevent recontamination of newly cleaned areas, sediment remedial actions should be implemented only after sources have been controlled.

Chemical, Biological, and Toxicological Indices

The primary kinds of data used in the decision-making process are listed below:

- **Sediment Quality**
  - Contaminant concentrations
  - Apparent effects thresholds (AET), relating sediment contamination and predicted biological effects
- **Bioaccumulation**
  - Contaminant concentrations in muscle tissue of English sole
- **Sediment Toxicity**
  - Amphipod mortality (10-day bioassay)
- **Benthic Infauna**
  - Polychaete abundance
  - Crustacean abundance
  - Pelecypod abundance
  - Gastropod abundance
- **Fish Pathology**
  - Lesion prevalence in livers of English sole.

The rationale for using the five general kinds of data is provided in Tetra Tech (1985a, 1986e). Puget Sound AET were used as sediment quality values to evaluate chemical data relative to predicted biological effects (see PRIORITIZATION OF PROBLEM AREAS AND CONTAMINANTS). Although many other variables were evaluated throughout the decision-making process, those shown above formed the basis for problem identification and priority ranking. Justification for specific variables is provided below and in later sections (see RESULTS for individual data types).

Target Chemicals--

A list of chemical contaminants analyzed for in sediments collected during the Elliott Bay studies is given in Table 1. Most of the substances on this list have at least one of the following two properties: they can bioaccumulate, possibly with adverse biological effects in the food chain if bioaccumulated, or they can produce adverse biological effects even when not bioaccumulated. EPA priority pollutants that may be currently or historically discharged into the study area are included on the list. Compounds not on the EPA list of priority pollutants also have been considered on the basis of their local significance. Several conventional sediment quality variables were measured [e.g., total organic carbon (TOC) content, grain size]. These conventional variables provide a means of comparing areas with different bulk chemical or physical properties. Also, observed biological effects could result from a characteristic of the system unrelated to the selected organic compounds or metals of concern (e.g., the deleterious effects of sediment anoxia on benthic communities).

TABLE 1. LIST OF CONTAMINANTS AND CONVENTIONAL VARIABLES FOR ANALYSIS IN ELLIOTT BAY PROJECT

Low molecular weight PAH
- naphthalene
- acenaphthylene
- acenaphthene
- fluorene
- phenanthrene
- anthracene

High molecular weight PAH
- fluoranthene
- pyrene
- benz(a)anthracene
- chrysene
- benzofluoranthenes
- benzo(a)pyrene
- indeno(1,2,3-c,d)pyrene
- dibenzo(a,h)anthracene
- benzo(g,h,i)perylene

Total PCBs

Neutral halogenated compounds
- 1,2-dichlorobenzene
- 1,3-dichlorobenzene
- 1,4-dichlorobenzene
- 1,2,4-trichlorobenzene
- hexachlorobenzene (HCB)
- 2-chloronaphthalene
- trichlorobutadienes[a,b]
- tetrachlorobutadienes[a,b]
- pentachlorobutadienes[a,b]
- hexachlorobutadiene

Phthalate esters
- dimethyl phthalate
- diethyl phthalate
- di-n-butyl phthalate
- butyl benzyl phthalate
- bis(2-ethylhexyl)phthalate
- di-n-octyl phthalate

Pesticides
- p,p'-DDE
- p,p'-DDD
- p,p'-DDT
- aldrin
- chlordane
- dieldrin
- endrin
- endrin aldehyde
- heptachlor
- alpha-HCH
- beta-HCH
- delta-HCH
- gamma-HCH (lindane)

Phenols
- phenol
- 2-methylphenol[a]
- 4-methylphenol[a]
- 2,4-dimethylphenol
- 2-chlorophenol
- 2,4-dichlorophenol
- 4-chloro-3-methylphenol
- 2,4,6-trichlorophenol
- 2,4,5-trichlorophenol[a]
- pentachlorophenol (PCP)

Miscellaneous extractable compounds
- 1-methylphenanthrene[a,b]
- 2-methylphenanthrene[a,b]
- 3-methylphenanthrene[a,b]
- 2-methylnaphthalene[a]
- biphenyl[a,b]
- dibenzothiophene[a,b]
- dibenzofuran[a]
- benzyl alcohol[a]
- benzoic acid[a]
- carbazole[a,b]
- coprostanol[a,b]
- alpha-tocopheryl acetate[a,b]
- retene[a,b]
- isophorone

Volatile organic compounds
- acrolein
- acrylonitrile
- benzene
- bromodichloromethane
- bromoform
- bromomethane
- carbon tetrachloride
- chlorobenzene

TABLE 1. (Continued)

chloroethane	Metals
2-chloroethylvinylether	antimony
chloroform	arsenic
chloromethane	cadmium
dibromochloromethane	chromium
dichloromethane	copper
1,1-dichloroethane	iron[a]
1,2-dichloroethane	lead
1,1-dichloroethene	manganese[a]
trans-1,2-dichloroethene	mercury
1,2-dichloropropane	nickel
cis-1,3-dichloropropene	selenium
trans-1,3-dichloropropene	silver
ethylbenzene	zinc
1,1,2,2-tetrachloroethane	
tetrachloroethene	Conventional variables[a]
1,1,1-trichloroethane	total organic carbon
1,1,2-trichloroethane	total solids
trichloroethene	percent fine-grained material
toluene	total nitrogen
total xylenes[a]	water-soluble sulfides
vinyl chloride	total volatile solids
	oil and grease

[a] Not a U.S. EPA priority pollutant. Chemicals without footnotes are U.S. EPA priority pollutants; no sediment conventional variables are priority pollutants.

[b] Tentatively identified organic compounds.

The target contaminants measured during the Elliott Bay project have the potential to cause observed sediment toxicity or biological effects. However, the ability to identify poorly-understood chemical interactions (e.g., synergism and antagonism) is limited. Although interactive effects may not be distinguishable from other kinds of effects, they may be measured through the use of biological indicators explained below.

Biological Variables--

Selection of individual biological and toxicological variables was based on the following considerations:

- Analysis of several levels of potential biological effects
  - Bioaccumulation at the tissue level
  - Pathology at the tissue level
  - Acute lethality of test sediments to whole-organisms
  - Chronic effects at the community level in benthic infauna
- Use of each variable in past Puget Sound studies
- Documented sensitivity of each variable to contaminants
- Ability to quantify each variable within the resource and time constraints of the program.

Response variables were selected to characterize several important toxic effects in resident organisms of Elliott Bay. Although a study of effects on fish populations was beyond the scope of the current project, a study of effects on individual fishes is possible through an assessment of liver lesion prevalence. Benthic macroinvertebrates were selected because of their sensitivity to sediment contamination, their importance in local trophic relationships, and their ability to establish site-specific response gradients relative to sediment contamination.

The use of Rhepoxynius abronius to determine the acute lethality of field-collected sediments has been documented by numerous authors (e.g., Swartz et al. 1982, 1985; Chapman et al. 1982a,b; Mearns et al. 1986). This amphipod species is a sensitive indicator of contaminated areas both by its absence from some natural populations in such areas (Swartz et al. 1982; Comiskey et al. 1984), and by its response to contaminated sediments in laboratory studies (Swartz et al. 1985).

As described below, the chemical, biological, and toxicological data were used to develop indices of environmental quality. These indices allowed evaluation of the data relative to relatively uncontaminated reference areas.

Elevation Above Reference Indices--

Environmental quality indices were developed to rank areas based on observed contamination and biological effects. The indices have the general form of a ratio between the average value of a variable at a site in the Elliott Bay system and the value of the same variable at a reference site. The ratios are structured so that the value of the index increases as the deviation from reference conditions increases. Thus, each ratio is termed an Elevation Above Reference (EAR) index. For most variables, the measured average value at the study site is divided by the value at the reference area to obtain the EAR. For benthic infauna, EAR are derived as the inverse ratio of values (i.e., reference divided by Elliott Bay site) to reflect the magnitude of adverse effects on benthic populations. Chemical effects on infauna are expected to be manifested as decreases in taxa abundance relative to reference. An increase in the EAR for infauna would therefore reflect a decrease in absolute value of the variable but an increase in adverse effect relative to reference conditions.

It should be noted that these indices were not used in lieu of the original data (e.g., contaminant concentrations), but in addition to these data. The original data were used to identify statistically detectable increases in sediment contamination, sediment toxicity, or biological variables, and to determine quantitative relationships among these variables. The EAR indices were used to reduce large data sets into interpretable numbers that reflect the magnitudes of the different variables among areas.

EAR were used to rank sites based on synoptic biological and chemical data from the 1985 Elliott Bay Action Program survey. In the absence of matched biological and chemical data (i.e., for historical sediment chemistry data), existing Puget Sound AET were used to evaluate sediment chemistry data and identify problem chemicals. Historical chemistry data were also used to establish boundaries of problem areas. The use of sediment chemistry EAR (rather than existing Puget Sound AET) to rank problem areas ensured that high chemical contamination independent of observed biological effects was taken into account in ranking sites for evaluation of potential sources. The use of site-specific biological effects data for Elliott Bay provided complementary information for identifying and ranking problem sediments.

Action Assessment Matrix

The environmental contamination and effects indices (i.e., EAR) were organized into an Action Assessment Matrix used to compare study areas or stations. A simplified hypothetical example of an Action Assessment Matrix is shown in Table 2. This example matrix is presented to demonstrate how information from multiple indicators can be integrated for an overall evaluation and prioritization of different study areas. For this example, only general indices such as "sediment contamination", or "benthic macroinvertebrates" are used. In the actual application of the approach, multiple indices for specific types of sediment contamination were evaluated, including separate measures for organic compounds and metals (see PRIORITIZATION OF PROBLEM AREAS AND CONTAMINANTS). Similarly, the benthic macroinvertebrates category was replaced by more specific measures of benthic community structure.

TABLE 2. THEORETICAL EXAMPLE OF ACTION ASSESSMENT MATRIX[a]

Indicator	EAR Values for Study Sites					Reference Value
	A	B	C	D	E	
Sediment contamination	1,300	45	800	75	8	1,000 ppb
Toxicity	8.5	2.0	10.0	4.5	2.2	10% mortality
Bioaccumulation	900	20	1,100	200	13	10 ppb
Pathology	5.2	2.6	8.0	2.8	2.0	5% prevalence
Benthic macroinvertebrates	4.0	1.2	5.0	1.3	1.1	60 individuals/m^2

[a] EAR values for indicator variables are shown for Sites A-E. Benthic macroinvertebrate factors represent the reduction in numbers of individuals at the study site relative to the reference site. Factors for all of the other indices represent increases relative to the reference site values shown.

- Indicates indicator value for the specified area is significantly different from reference value.

Evaluation of information in this format enables the decision-maker to answer the following questions:

- Is there a significant increase in sediment contamination, sediment toxicity, or biological effects at any study site?
- What combination of indicators is significant?
- What are the relative magnitudes of the elevated indices (i.e., which represent the greatest relative hazard)?

The term "significant" is generally used in this report to mean statistically significant at the 99.9 percent confidence level (alpha = 0.001). Because replicate data for sediment chemistry were not collected at every station, an alternative criterion for significance was developed. Following the approach used earlier in Commencement Bay and Elliott Bay (Tetra Tech 1985a, 1986e), a significant elevation of a chemical concentration in sediments was defined as exceedance of the maximum concentration of that chemical in all Puget Sound reference areas.

Action-Level Guidelines

The decision to evaluate potential sources of contamination and the need for possible remedial alternatives applies only to those sites that exceed a minimum action level. An "action level" is a level of contamination or effects that defines a problem area. It is assumed that an area requires no action unless at least one of the indicators of contamination, toxicity, or biological effects is significantly elevated above reference levels.

The action levels used to define problem areas in the Elliott Bay system are shown in Table 3. The action-level guidelines are summarized as follows:

- Significant EAR for THREE OR MORE INDICES identifies a problem area requiring evaluation of sources and potential remedial action
- For ANY TWO INDICES showing significant elevations, the decision to proceed with source and remedial action evaluations depends on the actual combination of indices and the degree to which they are site-specific
- When only a SINGLE INDEX is significantly elevated, a problem area may be defined when additional criteria are met (i.e., the magnitude of the index is sufficiently above the significance threshold to warrant further evaluation).

It is conceivable (but not likely) that significant sediment toxicity or biological effects occur in areas without apparent contamination by toxic substances. In such cases, it would be important to evaluate the possibility that the observed conditions result from variables not measured in the field studies. An attempt would be made to distinguish the biological problem area from surrounding areas using chemical characteristics, and to identify sources based on these distinguishing chemical characteristics.

TABLE 3. ACTION-LEVEL GUIDELINES

Condition Observed	Threshold Required for Action
I. Any **THREE OR MORE** significantly elevated indices[a]	Threshold exceeded, continue with source and remedial action evaluation.
II. **TWO** significantly elevated indices	
1. Sediments contaminated, but below HAET and 90th percentile **PLUS:** Bioaccumulation elevated relative to that at the reference area, **OR** Sediment toxicity with no more than 40% mortality, **OR** Benthic community structure indicates altered assemblage, but less than 80% depression	No immediate action. Recommend site for future monitoring.
2. Sediments contaminated but below HAET and 90th percentile **PLUS** elevated fish pathology	Threshold for source evaluation exceeded if elevated contaminants are considered to be biologically available. If not, recommend site for future monitoring.
III. **SINGLE** significantly elevated index	
1. Sediment contamination	If the magnitude of contamination exceeds the 90th percentile for all study areas or the HAET, proceed with source and remedial action evaluation.
2. Sediment toxicity	Greater than 40% response (mortality).
3. Benthic community structure	80% depression or greater.
4. Fish pathology **OR** bioaccumulation	Insufficient as a sole indicator. Recommend site for future monitoring. Check adjacent areas for significant contamination, toxicity, and/or biological effects.

[a] Combinations of significant indices are from independent data types (i.e., sediment chemistry, bioaccumulation, sediment toxicity, benthic infauna, fish pathology).

Significant indices are defined as follows:

Sediment Chemistry = Chemical concentration at study site exceeds highest value observed at all Puget Sound reference areas.

Sediment Toxicity, Benthic Infauna, Bioaccumulation, and Pathology = Statistically significant difference between study area and reference area ($P<0.001$) at one or more stations within area.

Ranking of Problem Areas

Ranking of problem areas was based on a systematic method of assigning scores to sampling sites based on the significance and severity (i.e., EAR) of the various chemical and biological variables. Criteria for scoring problem areas in terms of priority for evaluation of sources and remedial actions are shown in Table 4. Based on these criteria, higher priority would be assigned to an area with many elevated indices (i.e., EAR) than to an area with few. Because the values of the individual indices are assumed to represent relative environmental hazards, areas with higher values of the indices are scored higher. Two ranking schemes were used. The first used sediment chemistry indicators only, primarily to characterize the extent and magnitude of contamination. The second used all biological indicators to measure the response to chemical contamination. For ranking based on biological variables, scores for bioaccumulation and pathology were assigned to each subtidal station based on trawl data for the corresponding area in which the station was located. Biological scores for intertidal stations were based only on the results of the amphipod bioassay since other biological variables were not measured at intertidal stations. Scores assigned to a station for individual biological indicators (i.e., bioassay, infauna, bioaccumulation, pathology) were summed to obtain an overall biological-effects score for the station. The total biological-effects score for a station was normalized to the maximum possible score attainable with the available data. This normalization step was necessary to avoid biasing ranks for some study areas towards lower values just because certain data were missing. The maximum possible score for biological effects when all variables were measured was 16 (= sum of 4 for amphipod bioassay, 4 for benthic macroinvertebrates, 4 for bioaccumulation, and 4 for pathology). The range of possible normalized scores for biology is from 0-1 (or 0-100 expressed as a percentage). The various areas were then ranked according to the magnitudes of their overall biological-effects scores.

Similarly, scores assigned to the sediment chemistry indicators (i.e., metals and organic compounds) were summed and normalized to the maximum possible score to obtain an overall chemical-contamination score for each station. The maximum possible score for sediment chemistry was 8 (= sum of 4 for metals and 4 for organic compounds). A ranking of problem stations was then developed based on their relative chemical-contamination scores.

Total chemical and biological scores for each multi-station problem area were calculated as the averages of the corresponding total scores for individual stations within the area. Separate rankings of multi-station problem areas were developed based on the total chemical and biological scores. If the final ranking based on biological effects for a single station or a multi-station problem area differed substantially from that based on sediment chemistry, then the higher-ranking score was given precedence. Thus, some high priority sites were designated strictly on the basis of chemical contamination (i.e., no corresponding biological problems apparent) or strictly on the basis of biological conditions (i.e., no chemical contamination apparent).

TABLE 4. SUMMARY OF SCORING CRITERIA FOR SEDIMENT CONTAMINATION, TOXICITY, AND BIOLOGICAL EFFECTS INDICATORS

Indicator	Criteria	Score
Metals (one or more)	Concentration not significant	0
	Significant; EAR <10	1
	Significant; EAR 10-<50	2
	Significant; EAR 50-<100	3
	Significant; EAR >100	4
Organic Compounds (one or more)	Concentration not significant	0
	Significant; EAR <10	1
	Significant; EAR 10-<100	2
	Significant; EAR 100-<1,000	3
	Significant; EAR >1,000	4
Toxicity[a]	No significant bioassay response	0
	Amphipod bioassay significant	2
	>40% response in bioassay	4
Macroinvertebrates[b]	No significant depressions	0
	1 significant depression	1
	2 significant depressions	2
	>3 significant depressions	3
	≥95% depression for ≥1 variable	4
Bioaccumulation (fish muscle)	No significant chemicals	0
	1 significant chemical	1
	2 significant chemicals	2
	>3 significant chemicals	3
	EAR >50 for ≥1 chemical	4
Fish Pathology[c]	No significant lesion types	0
	1 significant lesion type	1
	2 significant lesion types	2
	>3 significant lesion types	3
	≥5% prevalence of hepatic neoplasms	4

[a] Toxicity based on amphipod mortality bioassay.

[b] Variables considered were polychaete abundance, crustacean abundance, gastropod abundance, and pelecypod abundance.

[c] Lesions considered were hepatic neoplasms, foci of cellular alteration (preneoplastic nodules), and megalocytic hepatosis.

Quantitative Relationships

The development of quantitative relationships among possible causative factors, sediment toxicity, and benthic effects identifies threshold concentrations above which changes in the biological indicators are detectable. The basic concept of increased biological effects or sediment toxicity resulting from increased concentrations of a single chemical in sediments is depicted in Figure 4. Four study areas that have statistically elevated effects are shown in the figure. Although there is an elevation in contamination relative to reference conditions at four of the remaining five study areas, there are no statistically detectable increases in the effect indicator above background conditions. Thus, the level of sediment contamination corresponding to Area X (arrow) represents an apparent threshold above which significant effects occur. The contamination of sediments by multiple chemicals may result in a more complex relationship than the example in Figure 4. Such relationships are discussed in detail later (see CONTAMINANT, TOXICITY, AND BIOLOGICAL EFFECTS RELATIONSHIPS).

AET have been identified using synoptic chemical and biological data sets from throughout Puget Sound (Tetra Tech 1986c, 1987). Puget Sound AET are used in this study to identify potential problem areas based on chemical data collected in other studies [e.g., Metro, National Oceanic and Atmospheric Administration (NOAA)] where appropriate biological data were unavailable. The concept of AET and the data sets used in deriving AET are explained below. The Elliott Bay data collected during this study are being compiled along with other recent data from Puget Sound into the EPA Sediment Quality Values database (SEDQUAL). This database will be used as part of an ongoing study to update Puget Sound AET.

The focus of the AET approach is to identify concentrations of contaminants that are associated exclusively with sediments having statistically significant biological effects (relative to appropriate reference sediments). Thus, to generate AET values, chemical data are classified according to the absence or presence of significant biological effects to determine concentrations of contaminants above which statistically significant biological effects would always be expected to occur. AET were originally developed to identify problem sediments in the Commencement Bay Nearshore/Tideflats Remedial Investigation (Tetra Tech 1985a). AET have been subsequently revised with an expanded database (200 stations) and their accuracy has been evaluated using biological and chemical data for geographically diverse areas of Puget Sound (Tetra Tech 1986c, 1987). The AET method and accuracy tests in Puget Sound are described in detail in those documents.

AET have been established for 64 organic and inorganic toxic chemicals using matched chemical and biological data for several biological indicators and embayments in Puget Sound. Because of patchy biological and chemical conditions in the environment, it was important that chemical analyses be performed on the same or nearly the same sediment that was used in bioassays and benthic infaunal analyses. AET are available for predicting significant effects based on the following biological indicators:

- Depressions in abundances of major taxonomic groups of benthic infauna (i.e., Crustacea, Mollusca, Polychaeta, and total abundance)

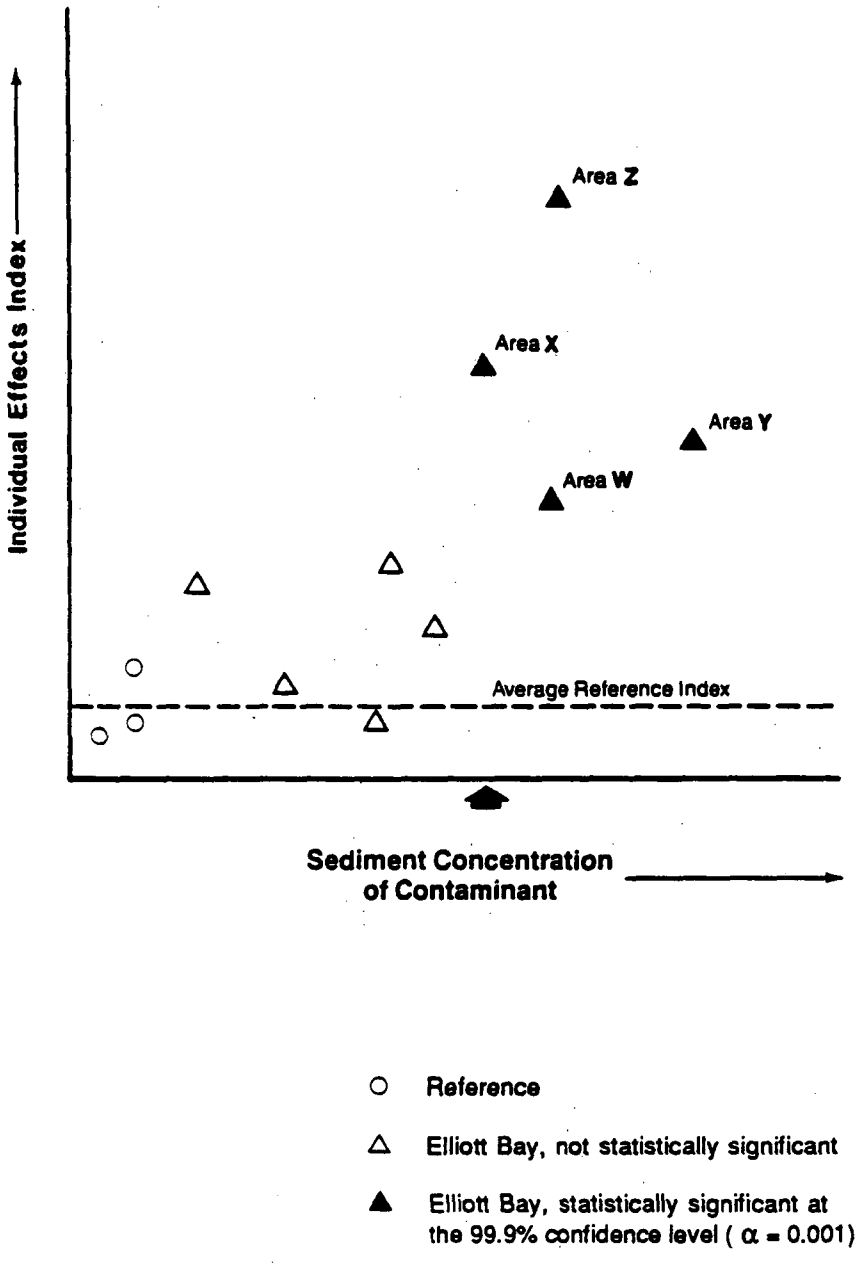


Figure 4. Theoretical example of relationship between sediment contamination and an effects index.

- Amphipod mortality bioassay using Rhepoxynius abronius
- Oyster larvae abnormality bioassay using Crassostrea gigas
- Microtox bioluminescence bioassay using Photobacterium phosphoreum.

For each chemical, a separate AET was developed for each biological indicator, resulting in four sets of AET. A list of the different AET generated thus far for Puget Sound is provided in Table 5, along with the lowest AET (LAET) and highest AET (HAET) among these four indicators. The derivation of these AET is described in more detail in Tetra Tech (1986c).

The AET method has been shown to be sensitive in correctly predicting impacted stations in Puget Sound, but in doing so the approach also predicts impacts at some stations that do not exhibit adverse effects (i.e., the approach is not completely efficient in only identifying impacted stations). Because the objective for using AET in this study was to identify potential problem chemicals and problem areas (in conjunction with established action level guidelines), the ability to correctly predict all impacted stations (sensitivity) is more important than the ability to predict only impacted stations (efficiency).

Spatial Resolution of Effects

Using the Action Assessment Matrix, contamination and effects were analyzed at several levels of spatial resolution (e.g., study areas within the project area or individual stations). Detailed examination of each sampling station was necessary because spatial heterogeneity of sediment contamination was relatively high.

Quantitative relationships among sediment contaminants, sediment toxicity, and benthic macroinvertebrates were examined to evaluate small-scale response gradients. AET were used to predict the occurrence of biological problems at stations where chemistry data were available but biological data were not.

Source Evaluation

The objective of source evaluation is to identify sources of contamination, and in turn to guide remedial activities. A limited evaluation of sources is presented in this report based upon the spatial distribution of contamination, the geochemical properties of observed contaminants, and characteristics of known or potential sources. A more complete evaluation of sources will be presented in a separate report (Tetra Tech 1988b).

OVERVIEW OF FIELD STUDY DESIGN

The general design of the field study is described in this section. A summary of data types and samples collected in the Elliott Bay system and the reference area is shown in Table 6. All of the Elliott Bay and initial Port Susan data were collected during September-October 1985. A second sampling of Port Susan occurred during September-October 1986 as part of the Everett

TABLE 5. PUGET SOUND AET (DRY WEIGHT)[a,b]
(ug/kg dry weight for organic compounds; mg/kg dry weight for metals)

Chemical	Amphipod AET[c]	Oyster AET[d]	Benthic AET[e]	Microtox AET[f]	LAET	HAET
Low molecular weight PAH	5,500[g,h,i]	5,200	6,100[i]	5,200	5,200	6,100
naphthalene	2,400[h,i]	2,100	2,100	2,100	2,100	2,400
acenaphthylene	560	>560	640[i]	>560	560	640
acenaphthene	980[h,i]	500	500	500	500	980
fluorene	1,800[h,i]	540	640[i]	540	540	1,800
phenanthrene	5,400[h,i]	1,500	3,200[i]	1,500	1,500	5,400
anthracene	1,900[g,h,i]	960	1,300[i]	960	960	1,900
High molecular weight PAH	38,000[h,i]	17,000	>51,000[i]	12,000	12,000	38,000
fluoranthene	9,800[h,i]	2,500	6,300[i]	1,700	1,700	9,800
pyrene	11,000[h,i]	3,300	>7,300[i]	2,600	2,600	11,000
benz(a)anthracene	3,000[h,i]	1,600	4,500[i]	1,300	1,300	4,500
chrysene	5,000[h,i]	2,800	6,700[i]	1,400	1,400	6,700
benzofluoranthenes	3,700	3,600	8,000[i]	3,200	3,200	8,000
benzo(a)pyrene	2,400	1,600	6,800[i]	1,600	1,600	6,800
indeno(1,2,3-c,d)pyrene	880[h,i]	690	>5,200[i]	600	600	880
dibenzo(a,h)anthracene	510[h,i]	230	1,200[i]	230	230	1,200
benzo(g,h,i)perylene	860[h,i]	720	5,400[i]	670	670	5,400
Total PCBs	2,500[i]	1,100	1,100	130	130	2,500
Total chlorinated benzenes	680[i]	400	400	170	170	680
1,3-dichlorobenzene	>170	>170	>170	>170		
1,4-dichlorobenzene	260	120	120	110	110	260
1,2-dichlorobenzene	>350	50	50	35	35	50
1,2,4-trichlorobenzene	51	64	64	31	31	64
hexachlorobenzene (HCB)	130	230	230	70	70	230
Total phthalates	>5,200[i]	3,400	>70,000[i]	3,300	3,300	3,400
dimethyl phthalate	>700[h,i]	160	160	71	71	160
diethyl phthalate	>1,200[h,i]	>73	200[h,i]	>48	200	200
di-n-butyl phthalate	>5,100	1,400	>5,100	1,400	1,400	1,400
butyl benzyl phthalate	>470	>470	470	63	63	470
bis(2-ethylhexyl)phthalate	>3,100	1,900	1,900	1,900	1,900	1,900
di-n-octyl phthalate	>590[i]	>420	>68,000[i]	--		
Pesticides						
p,p'-DDE	15	--	9	--	9	15
p,p'-DDD	43	--	2	--	2	43
p,p'-DDT	3.9	>6	11[i]	--	3.9	11

TABLE 5. (Continued)

Chemical	Amphipod AET[c]	Oyster AET[d]	Benthic AET[e]	Microtox AET[f]	LAET	HAET
Phenols						
phenol	670[h,i]	420	1,200	1,200	420	1,200
2-methylphenol	63	63	>72	>72	63	63
4-methylphenol	1,200	670	670	670	670	1,200
2,4-dimethylphenol	>72[h,i]	29	29	29	29	29
pentachlorophenol	>140	>140	>140	>140		
2-methoxyphenol	930	930	930	930	930	930
Miscellaneous extractables						
hexachlorobutadiene	290	270	270	120	120	290
1-methylphenanthrene	310	370	370	370	310	370
2-methylnaphthalene	670	670	670	670	670	670
biphenyl	260	260	270	270	260	270
dibenzothiophene	240	240	250	250	240	250
dibenzofuran	540	540	540	540	540	540
benzyl alcohol	73	73	73	57	57	73
benzoic acid	>690	650	650	650	650	650
N-nitrosodiphenylamine	220	130	75	40	40	220
Volatile organics						
tetrachloroethene	>210	140	140	140	140	140
ethylbenzene	>50	37	37	33	33	37
total xylenes	>160	120	120	100	100	120
Metals						
antimony	5.3	26	3.2	26	3.2	26
arsenic	93	700	85	700	85	700
cadmium	6.7	9.6	5.8	9.6	5.8	9.6
chromium	>130	>37	59	27	27	59
copper	800[i]	390	310	390	310	800
lead	700[i]	660	300	530	300	700
mercury	2.1[i]	0.59	0.88	0.41	0.41	2.1
nickel	>120[i]	39	49	28	28	49
silver	>3.7[i]	>0.56	5.2	>0.56	5.2	5.2
zinc	870[i]	1,600	260	1,600	260	1,600

[a] ">" indicates that a definite AET could not be established because the highest concentration occurred at a station without biological effects (hence, it is not clear from available data if biological effects always occur above this concentration, as specified in the definition of AET). For the purposes of problem identification in Elliott Bay, these values were excluded when LAET (low AET) and HAET (high AET) were generated.

[b] The following data sets were used to generate the AET in this table:

1. Battelle (1986)
2. Chan et al. (1985, unpublished)
3. Comiskey et al. (1984)
4. Osborn et al. (1985)

TABLE 5. (Continued)

5. Romberg et al. (1984)
6. Tetra Tech (1985a)
7. Tetra Tech (1986d)
8. Trial and Michaud (1985)
9. U.S. Department of the Navy (1985).

[c] Based on 160 stations.

[d] Based on 56 stations (all from Commencement Bay Remedial Investigation).

[e] Based on 104 stations.

[f] Based on 50 stations (all from Commencement Bay Remedial Investigation).

[g] A higher AET (24,000 ug/kg for low molecular weight PAH and 13,000 ug/kg for anthracene) could be established based on data from an Eagle Harbor station. However, the low molecular weight PAH composition at this station is considered atypical of Puget Sound sediments because of the unusually high relative proportion of anthracene. Thus, the low molecular weight PAH and anthracene AET shown are based on the next highest station in the data set.

[h] The value shown exceeds the Puget Sound AET established in Tetra Tech (1986c) and results from the addition of Eagle Harbor Preliminary Investigation data (Tetra Tech 1986d).

[i] The value shown exceeds AET established from Commencement Bay Remedial Investigation data (Tetra Tech 1985a) and results from the addition of Puget Sound data presented in Tetra Tech (1986c).

TABLE 6. SUMMARY OF FIELD STUDY DESIGN

Indicator	Variables	Sample Type	No. Replicates	No. Stations	
				Elliott Bay	Reference[a]
Sediment chemistry	selected chemicals and conventional variables[b]	composite 0-2 cm[c]	1	102	5
Toxicity bioassay	% mortality	composite 0-2 cm[c]	5	102	4
Benthic infauna	major taxa abundances	0.1-m^2 grab	5	74	4
	species abundances	0.1-m^2 grab	5	16	4
Bioaccumulation	PCBs, pesticides, mercury	English sole (>22 cm) fillet	5	11	1
Fish histopathology	lesion prevalences	English sole liver	1[d]	11	1

[a] Reference area for sediment chemistry, bioassay, and benthic macroinvertebrates was Port Susan. Reference area for bioaccumulation and fish pathology was Point Pully.

[b] See Table 1.

[c] Chemistry and bioassay samples were aliquots of the same composite sample.

[d] 60 fish per sample.

Harbor Action Program. Results of the 1986 sampling were compared with the 1985 results and used to evaluate Port Susan as a reference area. Similar methods were used during both years for Port Susan variables discussed in later sections of this report.

Station Locations

The locations of stations sampled during the Elliott Bay project are presented in Figures 5 and 6. Subtidal stations for sampling of sediments were located in shallow water [generally 5-15 m (corrected to mean lower low water; Appendix B)] near shore. Detailed information on station locations is provided in Appendix B, and large-scale maps are included in the source evaluation report (Tetra Tech 1988b). Trawl stations for sampling English sole (Parophrys vetulus) were located near areas sampled for sediments at water depths generally ≤33 m.

The rationale for station locations is provided in the sampling and analysis plan for the Elliott Bay Action Program (Tetra Tech 1985e) and sections below. Briefly, stations were selected to:

- Fill data gaps from previous studies
- Define known areas of contamination more precisely
- Determine large-scale gradients of contamination and bioeffects in relation to known sources
- Detect localized areas of contamination and bioeffects near potential sources.

Note that the triad of sediment chemistry, amphipod bioassay, and benthic infauna was sampled at all sediment stations except those in the upper Duwamish River (Stations DR-01 to DR-17 and DR-25 in Figure 5). The Duwamish River stations were not sampled for benthos because of the likelihood of estuarine gradients in community composition that would confound interpretation of the data (Tetra Tech 1985e). Based on the availability of an extensive database for the area offshore of the Denny Way CSO (e.g., Romberg et al. 1984), U.S. EPA limited the sampling effort for the present study to a single intertidal station (i.e., NS-01 in Figure 5). At the time of the interim action plan (Tetra Tech 1985b), U.S. EPA concluded that sufficient data were available to classify the Denny Way CSO area as a high-priority problem area.

Port Susan was selected as a reference area for sediment chemistry, bioassays, and benthic variables. Port Susan was chosen to represent a bay in east-central Puget Sound with a relatively unurbanized watershed and a major riverine inflow (i.e., the Stillaguamish River) (Tetra Tech 1985e). Previous studies (Malins et al. 1980) indicated that sediments of Port Susan were relatively uncontaminated compared to Elliott Bay and other urbanized embayments of Puget Sound. Point Pully was used as a reference area for bioaccumulation and histopathology. Point Pully was chosen because of its proximity to Elliott Bay and because previous studies (Landolt et al. 1984) demonstrated low prevalences of major liver lesions in English sole from this area.

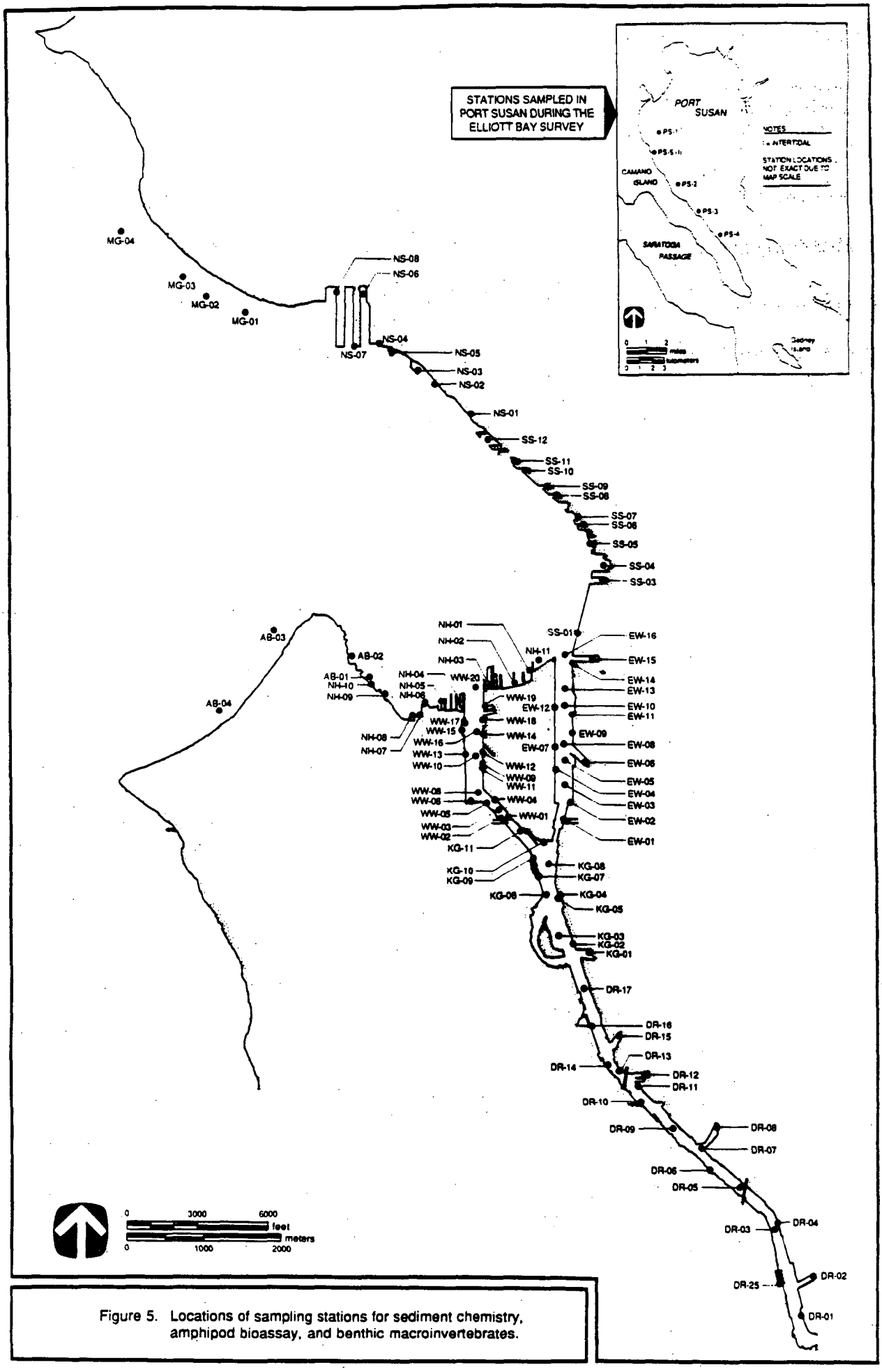


Figure 5. Locations of sampling stations for sediment chemistry, amphipod bioassay, and benthic macroinvertebrates.

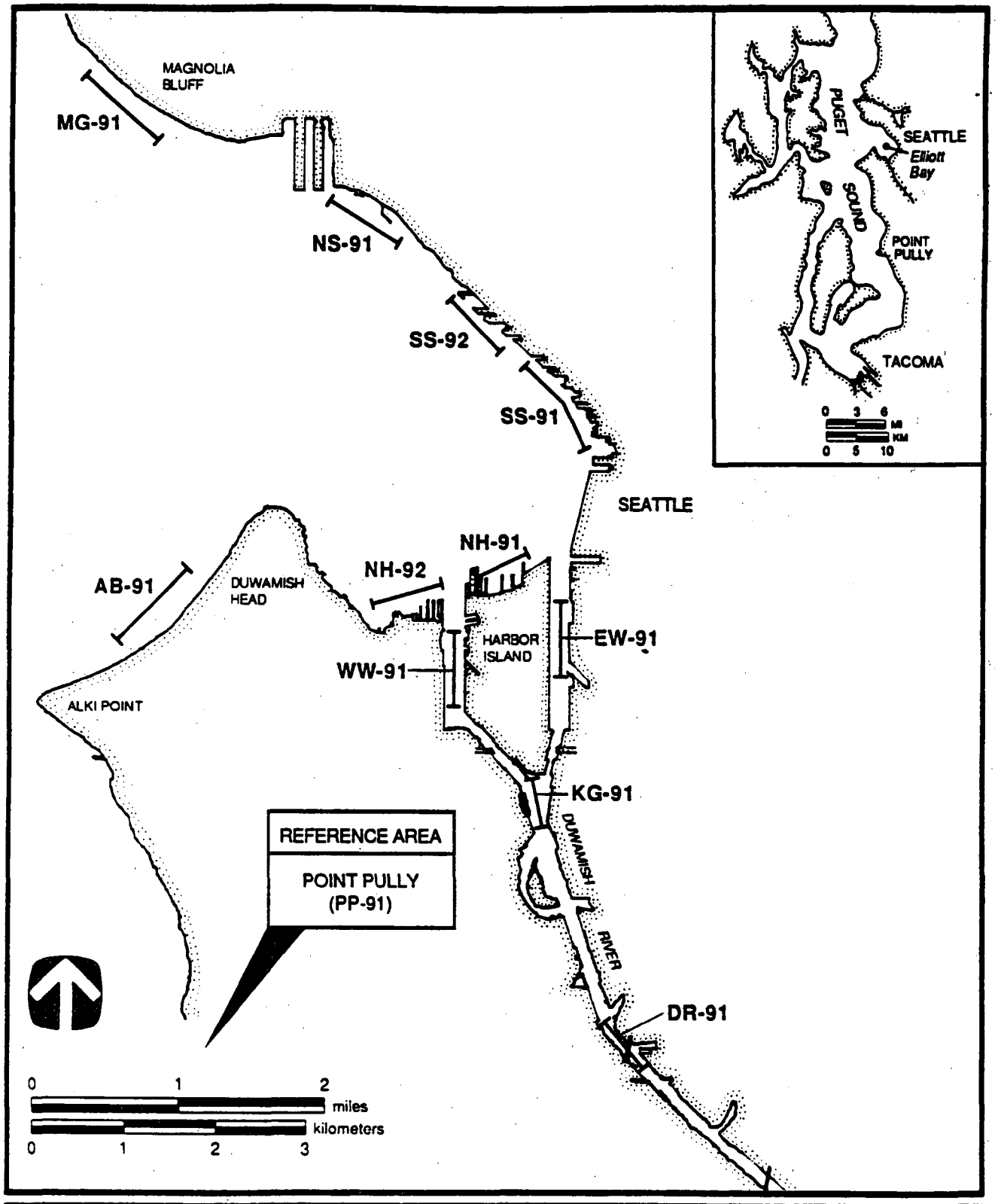


Figure 6. Locations of trawl transects in Elliott Bay.

In nearshore areas of Elliott Bay and in the Duwamish River, station locations were determined by line-of-sight fixes on stationary shoreline features. In offshore areas of Elliott Bay and in Port Susan, LORAN C navigational coordinates were recorded for each station. Wherever possible, a variable range marker (VRM) was used with LORAN C to determine ranges between two reference points, or to determine distances to shore objects. In addition, photographic records of all position alignments and ranges were made at all stations, and depth soundings were recorded. Station positioning methods were sufficiently accurate to define locations within a 15-m radius at most stations and within a 8-m radius at stations that were located in areas where the vessel could be tied to a stationary object. The research vessel was anchored at the stations whenever possible during the survey, and station locations were verified before each sample was collected.

Data Analysis Methods

Chemical Contamination--

The magnitude and spatial extent of contamination of sediments was determined by comparisons of chemical concentrations among Elliott Bay study areas and with Puget Sound reference conditions. EAR values were calculated using Carr Inlet data, and the "significance" of EAR values was assessed by comparison to the maximum values reported in Puget Sound reference areas (including Carr Inlet and Port Susan).

Averaged data from six Carr Inlet stations sampled in 1984 were used to calculate EAR for Elliott Bay and Duwamish River sediments. Recent Carr Inlet data were used as the basis for calculating EAR for the following reasons:

- The most complete reference data set is available for Carr Inlet, including synoptic data for metals, a wide range of organic compounds, grain size, organic carbon content, and other conventional variables
- The lowest detection limits for most substances of concern in Puget Sound embayments are available for Carr Inlet
- EAR for chemical variables measured in other urban embayments (e.g., Commencement Bay) have been calculated with these data, and therefore, will be directly comparable with the values calculated for this study
- In almost all cases where chemicals were detected in multiple reference areas, the Carr Inlet samples had comparable or lower values. Therefore, Carr Inlet is considered representative of Puget Sound reference conditions.

Because replicate data for sediment chemistry were not collected at every station, tests for statistically significant differences between Elliott Bay/Duwamish River samples and reference area samples could not be conducted. Instead, data from a wide range of Puget Sound reference areas (collected from 1976 to 1986, including the Port Susan data from the present

study) were used as the criteria for determining whether EAR were "significant" (i.e., whether the contamination exceeded all Puget Sound reference conditions). Port Susan data from this study were added to reference data compiled previously (Tetra Tech 1985a). If a chemical was not detected in a reference area sample, detection limits were used to define reference conditions for that chemical. Detection limits greater than 50 ug/kg dry weight (DW) for organic compounds in Port Susan sediments were excluded from the reference area concentration ranges to minimize the bias resulting from less sensitive chemical analyses. Such detection limits observed in other studies were previously excluded from Puget Sound reference area data (Tetra Tech 1985a).

Pairwise Pearson correlations (Sokal and Rohlf 1981) were performed to examine covariance in the distribution of selected contaminants. These correlations were performed on a study-wide basis and for most individual study areas. Only those contaminants that were detected four or more times in at least one study area were selected for analysis. Evaluation of correlations focused on chemical pairs that had correlation coefficients ≥ 0.7. Scatterplots (i.e., graphs of the concentration of one chemical vs. that of another chemical) were examined, and correlations that were apparently driven by anomalously high chemical concentrations at single stations were not reported.

The relatively high detection limits reported for a number of organic compounds in this study necessitated several special measures during data analysis. Low molecular weight polynuclear aromatic hydrocarbon (LPAH) and high molecular weight polynuclear aromatic hydrocarbon (HPAH) sums in this study do not include detection limits except for reference area (Port Susan) samples. For most samples, detection limits would not affect the PAH sums, but certain samples had detection limits sufficiently high to produce sums that would be misleading. PAH detection limits for Port Susan samples (all less than 50 ug/kg DW) were retained in PAH sums to maximize consistency with data treatment for other reference areas.

High detection limits observed for a number of semivolatile [acid/neutral] target compounds in this study would have resulted in 50th percentile (median) and 90th-percentile concentrations that were likely not representative of chemical conditions in the study area. For this reason, detection limits greater than 100 ug/kg DW for semivolatile organic compounds and PCBs, or greater than 25 ug/kg DW for single component pesticides, were not used in determining percentile concentrations. However, detection limits were not excluded from the analysis of spatial patterns of contamination.

Biological Effects--

Selected biological variables within each of the four categories of data (i.e., amphipod bioassay, benthic infauna, bioaccumulation, and liver histopathology) were used to test for statistical differences between study area stations and the reference area (Port Susan or Point Pully). Use of statistical criteria ensured that between-site differences were judged objectively. The statistical design used to test for significant differences between control and test stations adjusted the individual error rate for multiple comparisons. This reduced the probability of a Type I error (i.e., the probability of defining a significant difference from reference when

none actually exists). The null hypothesis was that the mean value of a variable at the test station was equal to the mean value of that variable at the reference station. This null hypothesis was tested versus several alternative hypotheses, depending on the biological variable being tested. In environmental studies, control of the Type I error rate becomes increasingly important as the regulatory and legal consequences of incorrectly identifying a difference between mean values become important.

Correction of the error rate for multiple comparisons was necessary because the repetitive use of data collected at a control station results in non-independence among the pairwise comparisons (Winer 1971). If the individual error rate for each comparison is not corrected, then the probability of falsely identifying at least one significant difference between the test and reference stations within the entire data set increases with the number of pairwise comparisons made. For example, if the selected pairwise significance level is P=0.05, and 20 hypotheses are tested (each using the same reference data), then the probability that all of the significant differences identified in the 20 comparisons are correct is $(0.95)^{20}$, or 35.8 percent. This probability decreases as the number of tests increases.

In these studies, the number of pairwise comparisons varied from 11 to 102 among the four biological variables. Selecting an experimentwise error rate of P=0.05, and dividing that rate by the number of comparisons would have yielded individual error rates between P=0.005 to P=0.0005. However, a pairwise comparison error rate of P=0.001 was selected for all four variables, for two reasons. First, a significance level of P=0.001 was sufficiently conservative to assure with 90.3 to 98.9 percent probability that all identified significant differences were true differences. Second, use of the same error rate for tests of all four biological variables ensured comparability among the test results.

For the benthic macroinvertebrate data, an unpaired two-sample t-test was used to test for a statistically significant difference (P<0.001) between each study site (n=5) and the pooled reference stations (n=20 for the four stations combined). Before applying the parametric tests, the F_{max} test was used to determine whether the sample variances were homogeneous for each paired comparison. Because the variances were heterogeneous in most of the pairwise comparisons, the abundances of infaunal taxa (i.e., polychaetes, crustaceans, pelecypods, and gastropods) used to test for between-site differences were log-transformed [$\log_{10}$ (x+1)]. If the variances of the log-transformed data were heterogeneous between the study site and the reference site (F_{max} test; P<0.05), an approximate t-test was applied to the data (Sokal and Rohlf 1981). Comparisons of benthic infaunal assemblages among stations in Elliott Bay and among Elliott Bay, Port Susan, and other reference areas within Puget Sound are also described. Based on species-level data for 20 stations within the Elliott Bay system, faunal similarities among stations were determined using a normal classification analysis. All data were log transformed [$\log_{10}$(x+1)] prior to analysis. The classification analysis involved two steps. First, similarity values were generated for all possible pairs of stations included in the analysis using the Bray-Curtis Similarity Index (see Boesch 1977). This index uses both species composition and the abundances of the individual species to estimate between-site similarity. The group average clustering strategy was then

applied to the matrix of similarity values to generate a dendrogram of stations, from which groups of stations (i.e., stations that are most similar in species composition and abundance) were determined.

For the amphipod (Rhepoxynius abronius) bioassay data, a two-sample analysis of variance (ANOVA), which is statistically equivalent to a t-test, was used to test for a significant difference ($P<0.001$) between each study site station ($n=5$) and the pooled reference stations ($n=20$ for the four stations combined). Following the approach of Mearns et al. (1986), the data were transformed using an arcsine transformation only when the variances were heterogeneous. Homogeneity of variances was tested using the F_{max} test ($P<0.05$). The mean mortality and 95 percent confidence limits for reference area samples from Port Susan were compared with similar statistics for other reference areas used during previous studies. Amphipod mortality in Elliott Bay sediments was compared with reference-area mortality rather than with native-sediment controls (i.e., West Beach, Whidbey Island) to account for possible effects of simply removing amphipods from their native sediments.

There is evidence that the R. abronius bioassay is subject to limited grain-size effects and attempts have been made to quantify and compensate for these effects (DeWitt et al. in press). However, the present data showed no predictive relationship between amphipod mortality and grain-size (percent fines) within Elliott Bay, Port Susan, or the combined data set (see RESULTS, Sediment Bioassays). Accordingly, the data were analyzed without any correction for possible sediment grain size effects.

Lesion prevalence and male proportion (i.e., an index of fish sex ratio) were compared between Elliott Bay transects and Point Pully using the G-test of independence ($P<0.001$) with Williams' correction factor (Sokal and Rohlf 1981). Fish age was compared between Elliott Bay transects and Point Pully using the Mann-Whitney U-test. The similarity among the prevalences of all three lesions across all transects was determined using Kendall's coefficient concordance (W). Within Elliott Bay, the proportion of males having each kind of hepatic lesion was compared with the corresponding proportion of females using the G-test of independence with Williams' correction factor. Positive association between the prevalence of each kind of lesion and fish age was tested using Spearman's coefficient of rank correlation (r_s). Length-at-age was compared between fish with and without hepatic lesions using the Mann-Whitney U-test.

For bioaccumulation, pairwise t-tests were used to test for statistically significant ($P<0.001$) elevations of PCB and mercury tissue concentrations at each Elliott Bay/Duwamish River trawl station ($n=5$) relative to the Point Pully reference station ($n=5$). Before applying the t-tests, the F_{max} test was used to determine whether sample variances were homogenous for each paired comparison. Because variances were heterogeneous for PCBs in most of the pairwise comparisons, the PCB data were $\log_{10}$-transformed. Variances for mercury data were homogenous and no transformation was required. The effect of lipid normalization on the data distributions was examined for mercury and PCB bioaccumulation.

SEDIMENT CHEMISTRY

Field Sampling

Field collection procedures followed the recommendations of the Puget Sound Estuary Program (PSEP) (Tetra Tech 1986f). Full details of the sampling design and techniques are provided in Tetra Tech (1985d,e). Sediment samples were collected during September-October 1985 using a chain-rigged van Veen grab sampler with a cross-sectional area of 0.1 m^2. Following deployment, the closed grab was retrieved and placed in a sampling tray. The hinged lids of the van Veen sampler were opened to inspect the sample.

Care was taken to ensure recovery of an intact surface sediment layer, with four major criteria used for rejection of a sample:

- Overflowing sediments, with sediment touching the top of the closed cover
- Water leaking from the sides or bottom (i.e., indicating that the interstitial water in the sample was being flushed with overlying seawater), or visible scour of the sediment surface near the edges of the sampler
- Turbid water overlying the sediments
- Insufficient penetration depth.

After the field supervisor determined maximum penetration depth and sample acceptability, qualitative observations were recorded on field log sheets for sediment color, odor, texture, and the presence of recognizable organisms. An HNu photoionization detector was used to monitor all sediment samples for harmful vapors.

When it was determined that the grab triggered incorrectly, that the sample was disturbed, or that some of the sample was lost, a new sample was taken. More than one grab at the same station sometimes was necessary to obtain an acceptable depth of penetration. In medium to coarse sand, a minimum penetration depth of 5 cm was considered acceptable. In fine sand and sandy silt, a penetration depth of 7 cm was the minimum acceptable depth. When attempts to sample a station were unsuccessful, another nearby station was selected and documented. Standardized collection data (i.e., collection date and time, station location, depth, and replicate number) were recorded for each sample.

Once onboard, samples were held in a vertical position by blocks and the overlying water was carefully drained off by an aspirator hooked to the ship's hose. Subsamples for volatile organic analyses were taken by placing 40-cm^3 glass vials (duplicates) at the undisturbed sediment surface and filling them using a stainless steel spatula. Subsamples for sulfide analysis were immediately removed from the sampler and placed in a weighed plastic container with 50 mL of sulfur antioxidant buffer (SAOB).

The remaining subsamples were taken from a homogenized sample. Each sampling horizon from the upper 2 cm of sediment away from the edge of the van Veen sampler was carefully removed with a stainless steel spatula, transferred to a stainless steel bowl, and homogenized by stirring with a stainless steel spoon (sampling equipment was rinsed with site water and methylene chloride between sampling events). Samples were stirred until uniform color and textural homogeneity were observed. Homogenized subsamples were collected as follows:

- 500 cm^3 was transferred to a precleaned glass jar with a tetrafluoroethene (TFE) cap liner for organic analysis
- 125 cm^3 was transferred to a precleaned glass jar for metals analysis
- 100 cm^3 was transferred to a freon-rinsed glass jar for oil and grease analysis, total organic carbon and nitrogen
- 100 cm^3 was transferred to a Ziploc bag for grain size analysis
- 1,500 cm^3 was transferred to a polyethylene bag for bioassays.

Intertidal samples were collected from shore using a stainless steel spatula. Otherwise, intertidal and subtidal sediment samples were processed and analyzed in similar fashion. All sediment samples for chemical analysis were stored on ice on the ship and were transported directly to the laboratory (for sulfide and volatile organic compound analyses) or were stored frozen before delivery to the laboratory (for the remaining chemical analyses). Chain-of-custody procedures were followed for all samples.

Laboratory Analysis for Metals

The following 11 of the 13 EPA priority pollutant metals were analyzed for all 107 sediment samples for this study: antimony, arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, and zinc. The remaining two priority pollutant metals, beryllium and thallium, were not analyzed because historical data did not suggest that these metals were of concern in the study area. Iron and manganese were also analyzed. Analyses were performed at Battelle Northwest Marine Research Laboratory in Sequim, Washington.

Samples were prepared by thawing the frozen sediment, homogenizing, freeze-drying, and grinding each sample. The sample was then either subjected to a total acid digestion for atomic absorption (AA) analysis, or pressed into a pellet for x-ray fluorescence (XRF) analysis. Total acid digestion was performed by combining 1 mL of 4:1 nitric acid:perchloric acid (HNO_3:$HClO_4$) with a 0.200-gram sample in a polytetrafluoroethylene (PTFE) bomb at 130° C for 4 hours. After the sample was cooled, 3 mL of hydrofluoric acid (HF) was added and the bomb was heated overnight at 130° C. After cooling, 20 mL of 2.5 percent boric acid (H_3BO_3) was added and the bomb was heated again at 130° C for 8 hours. After the weight and volume of the digestate were determined, the solution was analyzed for silver, cadmium, antimony, and selenium by Zeeman graphite furnace atomic absorption

(GFAA) using the method of standard addition for calibration. Mercury was determined on aliquots by cold vapor atomic absorption (CVAA). The mercury detector was calibrated with standard solutions.

XRF was used to quantify arsenic, chromium, copper, iron, manganese, nickel, lead, and zinc. Thin film standards (Neilson 1977) were used to calibrate the XRF analyzer. Although the analysis of these metals by XRF differs from the methods specified in the quality assurance project plan (Tetra Tech 1985d), it is stated in PSEP protocols (Tetra Tech 1986f) that XRF may be used if accuracy and precision can be demonstrated to the levels specified by the program.

Laboratory Analysis for Semivolatile Organic Compounds (Acid/Neutral and Pesticide/PCB)

Analyses for 37 of the 57 EPA priority pollutant semivolatile (acid/neutral) organic compounds, six additional Hazardous Substance List compounds, PCBs, and 13 priority pollutant chlorinated pesticides were performed on all 107 sediment samples collected for this study. Priority pollutant bases and halogenated ethers were not included in the analyses, in accordance with recommendations of PSEP (Tetra Tech 1986f). The excluded compounds have been detected infrequently in Puget Sound studies. Gas chromatograph/mass spectrometer (GC/MS) searches for additional non-priority pollutant compounds or compound classes (i.e., tentatively identified organic compounds) were also performed on all sediment extracts; these compounds were specified to the laboratory prior to analysis. Analyses were performed by Science Applications International Corporation in La Jolla, California.

The procedure used to analyze acid/neutral compounds was derived from Tetra Tech (1986a). Briefly, the extraction and cleanup procedure for acid/neutral compounds included addition of 38 stable isotope-labeled surrogate compounds to sediment samples, 24-hour Soxhlet extraction with methylene chloride/ methanol (2:1, vol/vol), separatory funnel extraction, extract drying (Na_2SO_4) and concentration (Kuderna-Danish apparatus), removal of elemental sulfur with metallic mercury (extracts were shaken with mercury for $\geq$4 hours and then filtered), automated gel permeation chromatography (GPC), reverse-phase column chromatography (C_{18} phase eluted with methanol), and analysis by isotope dilution GC/MS. Compounds without labeled analogs (identified below) were quantified using the nearest eluting, most chemically similar labeled compound as a recovery standard.

Compound Without Labeled Analog	Labeled Compound Used as a Recovery Standard
2-methylphenol	d4-2-chlorophenol
4-methylphenol	d4-2-chlorophenol
benzoic acid	d3-1,2,4-trichlorobenzene
benzyl alcohol	d4-1,4-dichlorobenzene
2-methylnaphthalene	d7-2-chloronaphthalene
dibenzo(a,h)anthracene	d12-benzo(g,h,i)perylene
indeno(1,2,3-cd)pyrene	d12-benzo(g,h,i)perylene

Recovery corrections were applied to detection limits as well as detected values to account for the effect of analytical losses on overall analytical sensitivity. Poor surrogate recoveries for a number of compounds (especially chlorinated benzenes and chlorinated phenols) resulted in high detection limits for these compounds.

Extracts used for gas chromatography/electron capture detection (GC/ECD) analysis of PCBs and pesticides were subsamples of the acid/neutral extracts that were taken after GPC cleanup. The portion of the extract for PCBs/pesticides was exchanged into hexane, subjected to alumina column cleanup [per the EPA Contract Laboratory Program (CLP) procedure; (U.S. EPA 1986)], and analyzed by dual capillary column (0.25-mm i.d. x 30 m) GC/ECD (Durabond DB-5 as the analytical column and DB-1701 as the confirmation column).

Laboratory Analysis for Volatile Organic Compounds

The analytical laboratory (Battelle-Columbus, Columbus, Ohio) gave the following report: "Just prior to analysis, the samples were mixed and 10.0 grams of the homogenous sediment was transferred to a clean 40-mL vial. Ten milliliters of reagent water with 250 ng each of d_4-1,2-dichloroethane, d_6-benzene, d_5-ethylbenzene and bromofluorobenzene was then added to facilitate the purging of the sample. The vial was placed in a 110° C heated sand bath and purged for analysis in accordance with the Speis (1980) Method" (Battelle 1985).

No conclusive documentation is available to explain mixing of sediments prior to volatile organic analysis (VOA). PSEP protocols warn that many of the volatile compounds of interest could be lost during mixing and compositing. The analytical laboratory confirmed that vigorous mixing of volatile organic samples is *not a standard or recommended procedure.* However, samples may have been gently stirred once to homogenize the sediment prior to analysis (Gebhart, J., 30 December 1987, personal communication).

The analyses were performed using a Tekmar LSC-I liquid sample concentrator interfaced to a Finnigan 3200 GC/MS and Finnigan/INCOS Model 2300 data system. Quantification was performed by the internal standard method using d_6-benzene. The MS was operated in the electron impact (EI) ionization mode with an electron energy of 70 eV and set to scan from 35 to 350 amu/2 sec. A 6-ft x 2-mm ID glass column, packed with 1 percent SP-1000 on Carbopack B and interfaced to the ion source by a standard glass jet separator, was used in the GC.

Ancillary Analyses

Methods used for the analysis of conventional variables are briefly described below:

- Grain size - Approximately 25 grams of homogenized wet sediment was treated with hydrogen peroxide to remove organic material. Sediment was then wet-sieved through a 0.0625-mm screen and the fines were collected in a cylinder. Sand and gravel fractions (0.0625 to >2 mm) were wet-sieved and then dried to constant weight at 90° C. The silt-clay fraction

(<0.004 to 0.0625 mm) was treated with a preweighed dispersant and analyzed by pipetting 20 mL at 30-second intervals for 10-inch depth, and 59-minute intervals for 5-cm depth. Pipetted samples were dried at 90° C to constant weight and then corrected for dispersant weight. Results were calculated based on total weight of the eight fractions. The following size fractions were evaluated:

gravel - >2 mm
very coarse sand - 1-2 mm
coarse sand - 0.5-1 mm
medium sand - 0.25-0.5 mm
fine sand - 0.125-0.25 mm
very fine sand 0.0625-0.125 mm
silt - 0.004-0.0625 mm
clay - <0.004 mm.

- Total solids - Frozen sediment was thawed, homogenized, weighed, and dried to a constant weight at 103° C. The ratio of dry sediment weight to wet sediment weight was reported as a percent.

- Total Volatile Solids - Samples were thawed and dried to a constant weight at 103° C, and then combusted at 550° C. The percent change in weight between the dried and combusted sample was determined.

- Total Organic Carbon (TOC) and Total Nitrogen (TN) - Samples were freeze-dried, ground to a fine particle size, treated with hydrochloric acid, and analyzed using a Carlo-Erba instrument. TOC and TN results were reported as the percent of unacidified sample DW.

- Oil and Grease - Approximately 25 grams of thawed and homogenized wet sediment was mixed with 25 grams of magnesium sulfate monohydrate and extracted twice with carbon tetrachloride. Absorbance was measured at 2,930 cm^{-1} on an infrared spectrophotometer, and compared to the standard curve prepared from the oil reference standard described in EPA Method 413.2. Concentrations were reported as mg/kg DW.

- Water-Soluble Sulfides - Water-soluble sulfides were measured according to the method described in Green and Schnitker (1974), with one exception: 0.005 M $Pb(ClO_4)_2$ was used for sample titration rather than 0.001 M $Cd(NO_3)_2$.

The methods used to analyze conventional variables, except those used for analysis of water-soluble sulfides and grain size, followed the methods recommended in PSEP protocols (Tetra Tech 1986f). A specific method for water-soluble sulfides is not presented in PSEP protocols, but analysis of water-soluble sulfides is recommended for estimation of biologically available sulfides. The PSEP method for grain size analysis specifies that the sieves used in wet-sieving particles greater than 65 um are to be dried after each use. This process will allow particles less than 65 um that

adhere to the sieve surface to be removed and added to the sample fraction analyzed for percent silt and clay. However, only wet sieving was conducted for this sample set (Crecelius, E., 2 March 1987, personal communication). The consequences of not following the sieve drying step and particle collection step cannot be evaluated from the data. The initial weights of samples were not provided by the laboratory and therefore sample recoveries following sieving could not be calculated.

Battelle Northwest Marine Research Laboratory (Sequim, Washington) performed the above analyses with the exception of water-soluble sulfides, which were analyzed by Am Test (Redmond, Washington).

Quality Assurance/Quality Control Results

Reviews of sediment chemistry data were performed in accordance with PSEP guidelines (Tetra Tech 1986f). Quality assurance/quality control (QA/QC) reviews of chemistry included assessments of accuracy [using standard reference materials (SRM), matrix spikes, and surrogate recoveries, when applicable], precision (using analytical replicates), initial and ongoing calibration and tuning, blank results, sample holding times, and initial performance tests or validation data for certain non-CLP procedures.

Detailed QA reports were prepared for chemical analyses and were compiled in a single document (Tetra Tech 1988a). These reports will not be reproduced in this section, but are summarized below.

Metals--

The data are considered acceptable as qualified. SRM-1646, certified by the National Bureau of Standards (NBS), was analyzed with each batch of 20 samples. Spike recoveries were determined for antimony and selenium because these elements were not certified in the SRM analyzed. Silver was also not certified in the SRM. However, the analytical laboratory had confidence in the silver results based on intercalibration comparisons with other laboratories, and comparison with neutron activation analysis (Crecelius, E., 5 December 1986, personal communication), and therefore did not perform spike recoveries for silver. It was recommended in a U.S. EPA Region X policy decision (Gakstatter, J., 24 November 1987, personal communication) that the data for compounds not certified in the SRM be considered estimates and qualified in the database. Under this recommendation, antimony, selenium, and silver would be qualified with an "E" (estimated) in the database.

The matrix spike recovery data for selenium and antimony were within the control limit criteria (75-125 percent) established by PSEP (Tetra Tech 1986f). Therefore, qualifying all data for these compounds did not appear warranted and data qualifiers were not assigned to sample results for these compounds. However, all sample results for silver were assigned an "E" qualifier because matrix spike data were not available to evaluate accuracy. In some samples, precision data for silver and antimony exceeded the control limit established by PSEP. In these cases, an "E" qualifier was assigned to silver and antimony data. Reanalyses of antimony by XRF in several samples from Elliott Bay and Carr Inlet indicated that the antimony data generated

by GFAA in this study are not suitable for use in identifying or ranking problem areas (see next section).

Detected values for manganese, zinc, and chromium were qualified as estimates based on low recoveries for the SRM during accuracy analysis. In addition, because the 28-day maximum sample holding time recommended by PSEP was exceeded for all samples, positive sample results for mercury were assigned an "E" qualifier.

Assessment of the Effect of Analytical Procedures on Metals Results--

The analytical methods used to determine metals in this study were designed to measure the total concentrations of metals in sediments (including mineral-bound components), in contrast to methods that rely on partial digestion. A small study was conducted to examine the implications of using the "total metals" methods, especially when comparing results to historical reference area data generated by "strong acid" methods (e.g., reference area data from Carr Inlet).

Two archived Carr Inlet samples collected during the Commencement Bay Remedial Investigation (Tetra Tech 1985a) were analyzed in triplicate by "total metals" methods used in the present study and by the "strong acid" method (per EPA CLP) used during the Commencement Bay study. In addition, selected samples collected during the present study were reanalyzed by the "strong acid" method for comparison purposes. The results are presented in Table 7.

Although differences were observed for a number of metals analyzed by both methods, the consistently largest differences were observed for chromium (Table 7). In both Carr Inlet samples, mean chromium concentrations by "total metals" methods (in this case, XRF) were over 4 times the mean concentrations determined by the "strong acid" technique. Samples with higher overall chromium concentrations from Port Susan and Elliott Bay/ Duwamish River tended to have approximately a factor of 2 difference between "total metals" and "strong acid" results.

Differences between antimony results by "total metals" vs. "strong acid" methods could not be determined for Carr Inlet samples because antimony was consistently undetected by the "strong acid" procedure (Table 7). However, data reported for Samples CR-11 and CR-13 during the Commencement Bay Remedial Investigation were roughly 15 times lower than the "total metals" values in Table 7. Similarly, for Duwamish River Samples WW-12 and EW-15, the "total metals" procedure (including HF digestion and analysis by GFAA) resulted in concentrations roughly 10-20 times higher than concentrations determined by the "strong acid" procedure. This marked discrepancy prompted reanalysis by an independent and more reliable technique for antimony (i.e., XRF). Comparisons between XRF and the "total metals" procedure used in this study were confounding (Table 7), but suggest that antimony concentrations observed during this study could be considerable overestimates (e.g., by a factor of approximately 5).

The XRF analysis of antimony aroused sufficient uncertainty about the "total metals" antimony concentrations reported in this study that antimony data were not used to define or rank problem areas. However, antimony

TABLE 7. COMPARISON OF ANALYTICAL METHODS FOR SELECTED METALS

	Sample	Technique	Antimony	Arsenic	Cadmium	Chromium	Copper	Lead	Nickel	Silver	Zinc
Reference Area Samples	CR-11 (n=3)	Total metal[a]	1.91 ± 0.16[b]	4.47 ± 0.79	0.09 ± 0.01	99 ± 26	9.8 ± 1.6	4.4 ± 1.2	17.7 ± 3.1	0.043 ± 0	28.2 ± 1.7
	CR-11 (n=3)	Strong acid[c]	U0.92 ± 0	2.07 ± 0.09	0.13 ± 0.01	19 ± 1.5	6.1 ± 0	3.6 ± 0.1	13.8 ± 1.3	0.027 ± 0.002	19.3 ± 0.58
	CR-13 (n=3)	Total metal	1.40 ± 0.18	3.69 ± 1.1	0.19 ± 0.02	84 ± 10	12.6 ± 0.36	8.1 ± 0.55	20.6 ± 0.85	0.076 ± 0.029	34 ± 2
	CR-13 (n=3)	Strong acid	U0.92 ± 0	2.48 ± 0.52	0.22 ± 0.01	19 ± 1.5	6.73 ± 1.4	2.2 ± 0.60	15.1 ± 1.3	0.022 ± 0.007	19 ± 0.6
	PS-01 (n=1)	Total metal	2.66			236	49.8	10.4	139		
	PS-01 (n=3)	Strong acid	U0.92 ± 0			133 ± 2	43.3 ± 1.1	5.6 ± 2.4	130 ± 2		
Elliott Bay/ Duwamish River Samples	WW-12 (n=1)	Total metal	1,200			555	618	1,180	100		
	WW-12 (n=2)	Strong acid	59 ± 6.6			266 ± 12	920 ± 33	1,510 ± 69	87 ± 3.6		
	WW-12 (n=1)	XRF[d]	240								
	EW-15 (n=1)	Total metal	150			223	176	210	63.8		
	EW-15 (n=2)	Strong acid	14 ± 1.2			115 ± 2.8	305 ± 33	330 ± 40	45.9 ± 2.7		
	EW-15 (n=1)	XRF	32								
	NH-04 (n=1)	Total metal	504								
	NH-04 (n=1)	XRF	120								
	KG-06 (n=1)	Total metal	192								
	KG-06 (n=1)	XRF	27								
	WW-14 (n=1)	Total metal	1,370								
	WW-14 (n=1)	XRF	217								
	SS-09 (n=1)	Total metal	680								
	SS-09 (n=1)	XRF	547								

[a] Methods used in the present study: digestion with nitric, perchloric, and hydrofluoric acids and analysis by AA (for antimony, cadmium, and silver) or x-ray fluorescence (for arsenic, chromium, copper, lead, nickel, and zinc).

[b] Mean ± standard deviation. All concentrations are in mg/kg DW.

[c] EPA CLP procedure involving digestion with nitric acid and hydrogen peroxide.

[d] X-ray fluorescence.

distributions are described in the RESULTS section because of their potential value in assessing relative antimony contamination in Elliott Bay. The XRF results for antimony were sufficiently elevated in some samples to establish that antimony may be of concern in Elliott Bay and may warrant further investigation.

Because analytical procedures can clearly have an effect on chromium results, AET generated from historical data (i.e., by strong acid digestion) were not used in this study. Nevertheless, the results of the analytical comparisons in Table 7 do not provide a basis for excluding chromium data. Therefore, these data were included in problem area identification and ranking.

Semivolatile Organic Compounds--

The data are considered acceptable as qualified. Qualifiers were assigned to sample results for reasons that vary in severity. Acid/neutral compound data from 68 samples and pesticide/PCB data from 26 samples were assigned "E" qualifiers because the extracts were held longer than the PSEP-recommended maximum holding time (Tetra Tech 1986f). During the initial and continuing GC/MS and GC/ECD calibrations, the relative percent difference (RPD) between response factors for several acid/neutral and pesticide compounds exceeded the control limit criteria. Sample data associated with calibrations out of the control limits were therefore assigned an "E" qualifier and are considered estimates. In some cases, precision data exceeded the established control limits. Sample results for compounds that did not meet the required level of precision outlined in PSEP protocols (Tetra Tech 1986f) were assigned an "E" qualifier. All sample data for endrin aldehyde and total PCBs are considered estimates and were assigned an "E" qualifier due to low recoveries of matrix spikes (recoveries for all six PCB matrix spikes ranged from 0-39 percent). Because of excessive laboratory contamination for diethylphthalate, di-n-butylphthalate, and bis(2-ethylhexyl)phthalate, all sample data for these phthalates were rejected and do not appear in the database.

An EPA policy decision (Gakstatter, J., 10 December 1987, personal communication) required the qualification, as estimates, of all acid/neutral compounds detected at <1,000 ug/kg DW. This qualification was based upon results of analyses of two sediment reference materials. One reference material had moderate contaminant concentrations (e.g., roughly 100 to 150 ug/kg DW for PAH), whereas the other reference material was more contaminated (roughly 300 to 4,000 ug/kg DW for PAH). For compounds detected in either reference material, recovery was typically >75 percent (an acceptable level of accuracy under PSEP guidelines). However, the laboratory failed to detect a large proportion of the compounds known to be present in the reference materials at concentrations between roughly 100 and 500 ug/kg DW; in these cases, detection limits were typically at or above the known concentrations of target compounds. Thus, the accuracy for detected compounds was acceptable across a range of concentrations, but the inability to consistently detect compounds known to be present at <1,000 ug/kg DW resulted in the qualification of acid/neutral compounds detected at <1,000 ug/kg DW.

Volatile Organic Compounds--

Detected volatile organic data were considered estimates and assigned an "E" qualifier in the database, because it is not known whether a multi-point calibration was performed by the analytical laboratory. Information provided by the laboratory indicated that a single point calibration was performed at least two times a day. Data for three compounds (i.e., methylene chloride, trichlorofluoromethane, and 1,1,1-trichloroethane) were rejected due to excessive blank contamination.

The following practices occurred during the analysis of volatile organic compounds in Elliott Bay sediment samples that may have compromised data quality:

- The PSEP-recommended holding time of 14 days was exceeded for 31 of the 50 samples analyzed.
- An evaluation of accuracy indicated percent recovery of surrogates outside PSEP control limits (Tetra Tech 1986f) at three stations.
- Failure of the laboratory computer resulted in loss of surrogate recovery data at three stations.
- An insufficient number of replicate samples were analyzed (i.e., 2 percent frequency of analysis) for the determination of precision.

The above factors necessitated qualification of all detected volatile organic data as estimates.

Ancillary Analyses--

Quality assurance review was performed for the following conventional variables: total solids (TS), total volatile solids (TVS), total organic carbon (TOC), total nitrogen (TN), oil and grease (OG), water-soluble sulfides, and grain size. Given the nature of the variables evaluated and the methods of analysis, data are considered acceptable as qualified. All TOC data were qualified with an "E" and are considered estimates based on SRM results. The mean TOC value determined for the SRM was 2.86 ± 0.07 percent (n=6), which was slightly below the certified range (2.99 ± 0.09 percent). No other data were qualified.

BIOACCUMULATION

Field Sampling

English sole (Parophrys vetulus) were sampled at 11 transects in Elliott Bay and at 1 transect at Point Pully, a nonurban reference area (see Figure 6). Point Pully was used as a reference area because previous studies have found that the area is relatively uncontaminated (Nevissi et al. 1984). In addition, Pierce et al. (1978) and Landolt et al. (1984) found no serious hepatic lesions in English sole (n=18 and 163, respectively) collected from that general area.

Most sampling was conducted between 16 and 25 September 1985. However, Transect SS-91 was revisited on 17 October 1985 to collect additional fish. Fish were collected using a 7.6-m (headrope) Marinovich otter trawl having a body mesh size of 3.2 cm (stretched) and cod-end liner mesh size of 0.8 cm (stretched). Trawling was conducted along each transect at a constant vessel speed of approximately 2.5 kn during daylight hours (0730-1730 h).

Five of 60 English sole (>220 mm) that were collected for histopathological analysis (see FISH ECOLOGY AND HISTOPATHOLOGY) were selected for analysis of PCBs, EPA priority pollutant pesticides, and mercury in raw muscle tissue. After removal of liver and otoliths, each fish was wrapped in aluminum foil and stored on ice. In the laboratory, fillets of dorsal muscle tissue were excised and skinned with a stainless steel spatula in preparation for analysis.

Laboratory Analysis for Mercury

Mercury was the only EPA priority pollutant metal analyzed in fish tissue because of its high potential for bioaccumulation. Muscle tissue was homogenized and subjected to nitric acid/perchloric acid digestion at Battelle Northwest Marine Research Laboratory (Sequim, Washington). The digestate was analyzed by cold vapor atomic absorption spectrophotometry.

Laboratory Analysis for PCBs/Pesticides

Extraction and Cleanup--

The analytical procedure used by Battelle Northwest Marine Research Laboratory was derived from Tetra Tech (1986b), "Analytical Methods for U.S. EPA Priority Pollutants and 301(h) Pesticides in Tissues from Estuarine and Marine Organisms." Only the sections relevant to analysis of PCBs and pesticides were followed. The procedure involves Soxhlet extraction with CH_2Cl_2/MeOH (2:1, vol/vol), extract cleanup by GPC (Biobeads S-X3; elution with CH_2Cl_2) and alumina column chromatography, and capillary column GC/ECD. Several notable exceptions to the Tetra Tech (1986b) procedure were cited in the laboratory's cover letter:

- Soxhlet extraction was carried out for 12 hours rather than the specified 24 hours
- Rotary evaporation was used for extract concentration rather than the specified Kuderna-Danish (K-D) apparatus.

These two modifications did not appear to affect laboratory performance based on results of initial laboratory performance tests with standard reference materials (SRM) and spiked blanks.

GC/ECD Analysis and Quantification--

Pesticides and PCBs were analyzed by capillary column GC/ECD with a DB-5 quantification column (0.25-mm i.d. x 30 m, J & W Scientific) and a SP-608 (Supelco, Inc.) confirmation column. The 80-minute temperature program used for these samples allowed for a high degree of chromatographic

resolution [roughly 76 peaks were resolved in a PCB standard consisting of Aroclor 1242:1254:1260 (1:1:1, wt/wt/wt)].

The quantification procedure used for PCBs is described in Tetra Tech (1986b). The procedure involves peak-by-peak quantification using an internal standard. Relative response factors for resolved peaks in a PCB standard containing Aroclors 1242, 1254, and 1260 (the range of PCB congeners expected in environmental samples) were determined by measuring the individual peak concentrations by GC/MS and then using dilutions of the same standard for initial and ongoing GC/ECD calibrations.

Extracts containing pesticides identified on the DB-5 column were rerun on the SP-608 confirmation column. The sole p,p'-DDE identification on the DB-5 column (Sample SS-91-643) was confirmed on the SP-608 column and by GC/MS.

Quality Assurance/Quality Control Results

Reviews of bioaccumulation data were performed in accordance with PSEP guidelines (Tetra Tech 1986f). QA/QC reviews included assessments of accuracy (using standard reference materials, matrix spikes, and surrogate recoveries, when applicable), precision (using analytical replicates), initial and ongoing calibration and tuning, blank results, sample holding times, and initial performance tests or validation data for PCB bioaccumulation.

Detailed QA reports were prepared for chemical analyses and were compiled in a single document (Tetra Tech 1988a). These reports will not be reproduced in this section, but are summarized below.

Mercury Bioaccumulation--

Mercury data exhibited accuracy and precision within the guidelines established by PSEP (Tetra Tech 1986f). However, because the 28-day maximum sample holding time recommended by PSEP was exceeded for all of the tissue samples analyzed, sample results for mercury are considered to be estimates and were assigned an "E" qualifier. No raw data accompanied the results; therefore, this data set was not reviewed for calculation algorithm or transcription errors.

PCB/Pesticide Bioaccumulation--

Sample holding times exceeded PSEP guidelines; however, qualification was not considered necessary because the target analytes (particularly PCBs) are not very susceptible to microbial or chemical alteration. The relatively high concentrations of PCBs in samples may have precluded detection of pesticides at low to moderate levels. An "E" qualifier was applied to samples associated with ongoing calibrations that were outside control limits. Matrix spike recoveries were low; however, samples were not qualified based upon low matrix spike recoveries for three reasons:

1. Surrogate recoveries strongly suggest that the sample batch in which the matrix spikes were included had considerably lower recovery than the majority of the samples

2. Average 4,4'-dibromooctafluorobiphenyl (DBOFB) recoveries for trawl stations were typically above 50 percent despite low recoveries in the latter batches

3. Isodrin recoveries were above 50 percent in roughly 95 percent of all individual samples.

Overall, these data are considered acceptable.

SEDIMENT BIOASSAY

Field Sampling

Sediment toxicity tests with Rhepoxynius abronius were performed using sediments from 102 stations in the Elliott Bay system and 4 stations in the reference area (Port Susan). A subsample of the composite sediment sample collected for chemical analyses was tested for toxicity using the amphipod bioassay. Field collection methods for sediment samples are described above (see SEDIMENT CHEMISTRY, Field Sampling).

The infaunal amphipod R. abronius was collected subtidally from West Beach on Whidbey Island (Washington) using a bottom dredge. Amphipods were maintained and transported in clean coolers with ice, and were returned to the laboratory within 18 hours of collection.

Laboratory Analysis

Following their arrival in the laboratory, amphipods were kept in holding containers filled with fresh seawater (28 ppt salinity) and clean sediment and maintained at 15 ± 1^{o} C under continuous light until used in testing. Cultures were aerated but not fed during acclimation and were held for not more than 10 days. Prior to testing amphipods were sorted by hand from sediments and identifications were confirmed using a Wild M5 dissecting microscope. Damaged, dead, or unhealthy individuals were discarded.

Acute lethality of amphipods exposed for 10 days to whole, fresh (unfrozen) sediments was measured using the methodology of Swartz et al. (1982, 1985) as modified in the PSEP protocols (Tetra Tech 1986f). A 2-cm layer of test sediment was placed in 1-L glass jars and covered with 800 mL of clean seawater (28 ppt salinity). Each beaker was seeded (randomly and blindly) with 20 amphipods and aerated. Six replicates (20 amphipods each) were run per test sediment. Five beakers served to determine toxicity, while the sixth beaker served as a reference for daily measurement of water chemistry (i.e., pH, dissolved oxygen, salinity, and temperature). Testing was conducted at 15 ± 1^{o} C under constant light. Test containers were checked daily to establish early trends in mortality and sediment avoidance, and also to gently sink any amphipods that had left the sediments overnight and become trapped by surface tension at the air/water interface. A negative (clean) control sediment from the amphipod collection site at West Beach, Whidbey Island was run concurrently with each series of test sediments. In addition, clean seawater sediment spiked with $CdCl_2$ was used as a positive control to ensure that response criteria (lethality) were operative.

Amphipod bioassays were initiated on all sediments within a 2-week period following field collection of sediments.

Bioassay tests were terminated after 10 days, when sediments were sieved (0.5-mm screen), and live and dead amphipods were removed and counted. Amphipods were considered dead when there was no response to physical stimulation and microscopic examination revealed no evidence of pleopod or other movement. Missing amphipods were assumed to have died and decomposed prior to the termination of the bioassay (Swartz et al. 1982, 1985).

Quality Assurance/Quality Control Results

Mean mortality ranged from 0 to 10 percent in the clean sediment (Whidbey Island) controls. A mean mortality of 10 percent is considered acceptable for amphipod sediment bioassay controls (Swartz et al. 1985). ANOVA indicated no significant differences ($P>0.05$) in mean mortality values among the clean sediment controls. Mortality in cadmium-spiked sediments was 100 percent, which is consistent with the expected mortality rate. Interstitial salinities in the sediment samples were acceptable according to Puget Sound Protocols (Tetra Tech and E.V.S. Consultants 1986), and none required adjustment. Dissolved oxygen concentrations in water overlying the sediments in the bioassay chambers were acceptably high.

Because of a labeling error in the field, the bioassay results from the intertidal Station PS-05 and replicates at Station PS-01 in Port Susan could not be distinguished. Therefore, these data were deleted from the database.

The amphipod bioassay results are considered acceptable for use in problem area identification. However, it should be noted that the data for the following stations showed high variance due to an extreme outlier replicate: NS-02, NS-06, KG-07, DR-05, EW-03, EW-14, NH-01, WW-12 (Figure 5).

BENTHIC MACROINVERTEBRATES

Field Sampling

Benthic macroinvertebrates were collected at 74 subtidal stations in the Elliott Bay study area and at four subtidal stations in the Port Susan reference area between 25 September and 16 October 1985 (see Figure 5). Among the 78 stations, water depths ranged from 4.3 m to 21.4 m (corrected to mean lower low water; Appendix B). A majority of the stations were located at depths of 8.8-12.2 m, but it was not possible to sample within this depth range at all stations because of differences in shoreline bathymetry.

Five replicate grab samples were collected at each station, for a total of 390 samples. All grab samples were collected using a 0.1-m^2 modified van Veen grab sampler. In the field, samples were washed on a sieve with 1.0-mm mesh openings and fixed with a 10-percent solution of buffered formalin. Sample tracking records followed each sample through all stages of sample collection and laboratory processing.

The field sampling methods used to collect benthic macroinvertebrate samples during the Elliott Bay survey are outlined in the Puget Sound

Protocols (Tetra Tech 1986g) and the Elliott Bay Quality Assurance Project Plan (Tetra Tech 1985d). The following discussion summarizes those procedures. Following deployment and retrieval of the van Veen grab, it was placed in a sieve stand and the sediment sample was inspected carefully to determine the acceptability of the sample. Samples were rejected if excessive leakage or surface disturbance occurred. Samples were also rejected if they did not meet or exceed the following minimum penetration depths:

- Medium to coarse sand and gravel - 4 to 5 cm
- Fine sand and sandy silt - 7 to 10 cm
- Silt - 10 cm.

When a sample was judged to be acceptable, the following qualitative sediment characteristics were recorded:

- Penetration depth
- Sediment texture
- Sediment color
- Presence and strength of odors
- Degree of leakage and/or surface disturbance
- Presence of debris or shell fragments.

After the foregoing observations were recorded, the sampler was opened and the sediment was released into the top section of the sieving stand. The sediment was then washed from above with a gentle spray of seawater, and the larger masses of sediment were broken apart. Sediment was rinsed into a sieve box located in the lower level of the sieving stand. The sediment in the sieve box was then completely washed until materials no longer passed through the 1.0-mm mesh screen. That portion retained on the screen was placed in a plastic sample bag having external and internal labels. Samples were then fixed in the field with a 10-percent solution of Borax-buffered formalin.

Laboratory Analysis

In the laboratory, benthic macroinvertebrate samples were washed on a 0.5-mm sieve and transferred to a 70-percent solution of isopropyl alcohol. Organisms from each sample were sorted into the following major taxonomic groups and enumerated: Porifera, Hydrozoa, Anthozoa, Platyhelminthes, Nematoda, Nemertea, Sipuncula, Polychaeta, Oligochaeta, Pelecypoda, Acmaeidae, Gastropoda, Opisthobranchia, Acarina, Pycnogonida, Cirripedia, Nebaliacea, Amphipoda, Ostracoda, Mysidacea, Decapoda, Isopoda, Cumacea, Tanaidacea, other Crustacea, Priapulida, Phoronida, Bryzoa, Brachiopoda, Echinodermata, and Holothuroidea. Planktonic organisms that occurred in the samples were not enumerated. Colonial organisms that occurred in the samples were noted as "present" but also were not enumerated.

Quality control checks of sample sorting were performed by resorting 20 percent of each sample. If the 20-percent resort indicated a calculated difference of 5.0 percent or greater in total sample abundance for all taxa combined, the entire sample was resorted. Independent quality control checks of sorting procedures (including checks of 20-percent aliquots) and checks of abundance counts for the major taxonomic groups were also performed. Samples that failed either quality control check were resorted completely.

Of the 390 samples (i.e,. 78 stations) scheduled for analysis, organisms in 290 samples (i.e., 58 stations) were sorted into major taxonomic groups and enumerated by the sorters. Organisms in the remaining 100 samples (i.e., 20 stations) were identified to the lowest possible taxonomic level and enumerated. The 20 stations selected for detailed taxonomy were chosen to represent widespread geographic locations within the project area. Other criteria used to select these 20 stations included proximity to suspected contaminant sources and high values of mean mortality in the amphipod bioassay. Specimens of each species (or lowest possible taxon) that occurred in the Elliott Bay study area were placed in reference museums prepared by the taxonomists.

Quality Assurance/Quality Control Results

QA/QC procedures resulted in an acceptable data set without qualification. As part of QA/QC, the adequacy of collecting five 0.1-m^2 grab samples was assessed by plotting the cumulative number of species collected per replicate at the Port Susan reference stations and at two randomly-selected stations from Elliott Bay (Figure 7). Reference area stations were used in this analysis because they were considered more typical of benthic communities than the potentially impacted stations in Elliott Bay. In general, the cumulative number of new taxa collected in successive grab samples declines and appears to approach an asymptote by the fifth replicate at most stations. (Station PS-04 is a possible exception.) This condition indicates that a reasonably full complement of taxa were collected at both the Port Susan and Elliott Bay stations using five replicate 0.1-m^2 samples.

FISH ECOLOGY AND HISTOPATHOLOGY

Field Sampling

Field sampling methods were described earlier (see BIOACCUMULATION, Field Sampling). English sole larger than 220-mm total length (TL) were selected for histopathological analysis. This size limit was used to ensure that most fish were greater than 2 years old. A selection criterion based indirectly on age was used because English sole younger than 2 years old have substantially lower prevalences of hepatic lesions than older fish (Malins et al. 1982). The present study therefore focused on those fish most likely to be afflicted with hepatic lesions.

Sixty English sole of appropriate length were collected at every transect except Transect SS-91, where 54 fish were sampled. A total of 714 fish was collected during the overall study. Immediately after collection, each selected fish was sacrificed by a blow to the head, measured to the nearest millimeter (TL), examined for grossly visible external abnormalities

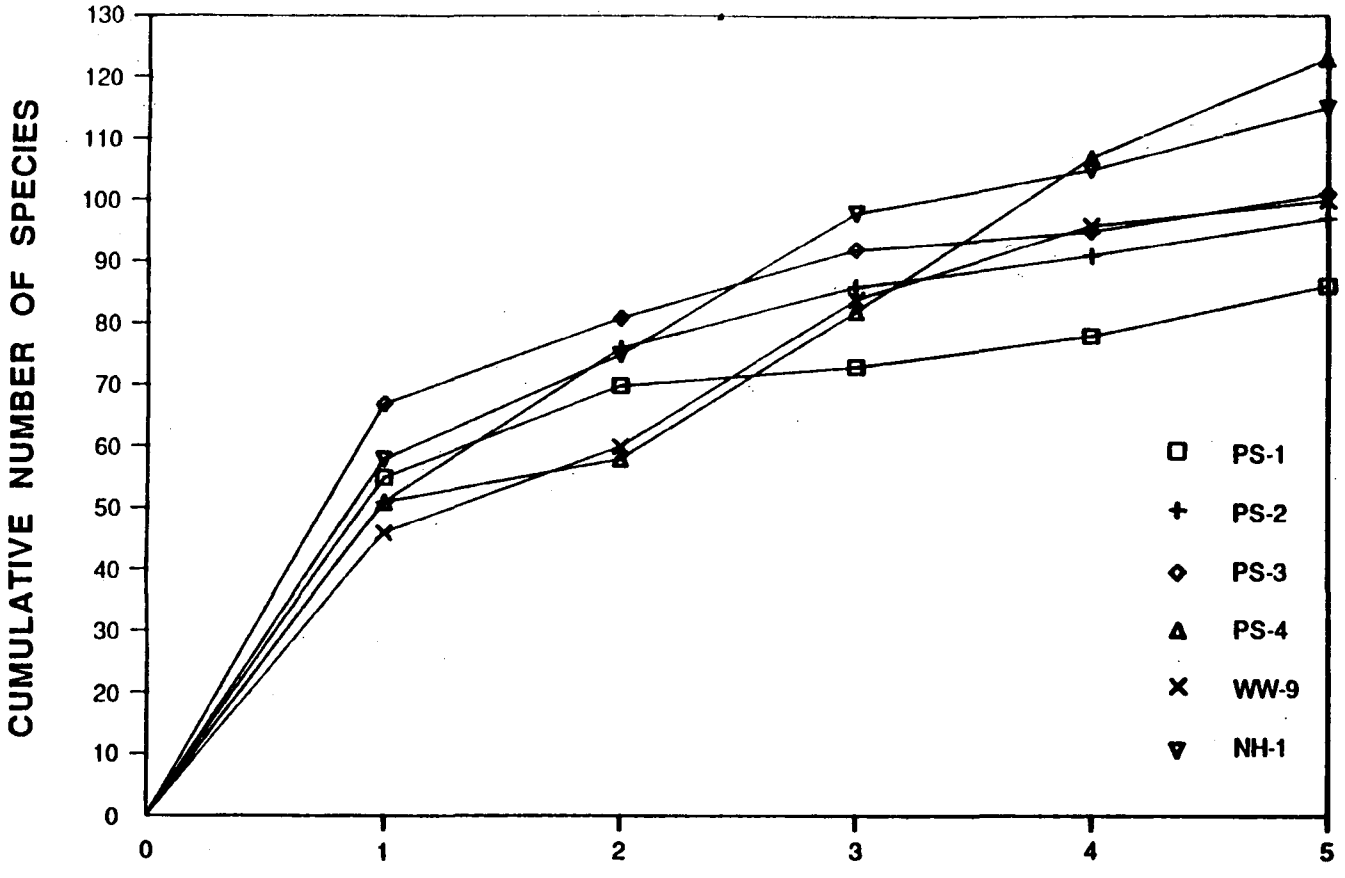


Figure 7. Cumulative numbers of species collected over successive replicate benthic grab samples at four stations in Port Susan and at two stations in Elliott Bay in 1985.

(e.g., fin erosion, skin tumors, scoliosis, parasites), and transferred to the shipboard laboratory for liver removal.

In the shipboard laboratory, the liver of each fish was removed in its entirety, cut into multiple sections, and examined for the presence of grossly visible lesions. If lesions or discontinuities were noted, a subsample was taken from the affected area for histopathological analysis. If the liver appeared to be normal, a subsample was taken from the center of the organ at its broadest point. Each subsample was fixed in 10 percent neutral-buffered formalin. After the liver was removed from each individual, the sex of the fish was noted and the otoliths (sagittae) were removed for subsequent age determination.

All fishes in the remainder of the catch at each transect were identified to species and counted. All English sole not selected for histopathological analysis were measured (nearest mm TL) and counted.

Laboratory Analysis

Each formalin-fixed liver was dehydrated in a graded series of ethanol, cleared in xylene, and embedded in paraffin. Embedded livers were sectioned at 4 um using a rotary microtome and stained using hematoxylin and eosin (H&E). Prepared slides were examined using conventional light microscopy. Each slide was coded, so the pathologist did not know where the corresponding fish was captured. Lesion identifications were confirmed by M.S. Myers (Chief Pathologist, Northwest and Alaska Fisheries Center) to ensure their consistency with the identifications made by Malins et al. (1980, 1982, 1984).

Three major kinds of idiopathic hepatic lesion were evaluated: neoplasms, foci of cellular alteration, and megalocytic hepatosis. Briefly, neoplasms include both benign and malignant tumors. Foci of cellular alteration are discrete clusters of altered cells that have specific staining characteristics and are suspected of being preneoplastic. Megalocytic hepatosis is a specific degenerative condition characterized by a marked increase in both nuclear and cellular diameters in the absence of cellular inflammatory responses.

Prevalences of all three major lesions have been found to be elevated in English sole from urban embayments of Puget Sound (e.g., Malins et al. 1984; Becker et al. 1987). In addition, Myers et al. (1987) found consistent patterns of co-occurrence of these lesions in English sole from Eagle Harbor. Based on those patterns of co-occurrence and comparisons with similar lesions induced in rodents following laboratory exposure to chemicals, Myers et al. (1987) concluded that megalocytic hepatosis, foci of cellular alteration, and neoplasms may be related sequentially in the progression towards hepatic neoplasia in English sole. In that scenario, the following steps are thought to occur:

- Megalocytic hepatosis and associated degenerative lesions are induced as the initial, subchronic to chronic manifestations of the cytotoxic effects of hepatocarcinogens. These lesions form the proper stimulus for a proliferative response.

- In the above environment favoring proliferation, foci of cellular alteration develop. Because these lesions are selectively resistant to the cytotoxic effects of hepatocarcinogens, they have a growth advantage over normal hepatocytes.

- Autonomous, neoplastic hepatocytes arise from the non-autonomous foci of cellular alteration to form neoplasms. This final transformation is probably a complex, multistep process of mutation followed by selection.

Quality Assurance/Quality Control Results

Lesion identifications were confirmed by Mark Myers of the National Marine Fisheries Service. To ensure consistent identification of lesions between the two pathologists for this project, each examined one-half the slides from each station. For all three major kinds of lesions, the numbers of each lesion identified by the two pathologist were very similar, implying consistent diagnostic criteria. In addition, the relative prevalences of lesions among stations and among lesion types identified during this study were similar to results from previous studies by National Marine Fisheries Service (Malins et al. 1980). The final histopathology data were considered acceptable without qualification.

DATA MANAGEMENT

To facilitate data storage, quality control, and analysis, recent and historical data from the Urban Bay Action Programs have been incorporated into a DBase III-compatible microcomputer database. This database system is based on the same software, data formats, and files as the SEDQUAL system. The database software performs a wide variety of retrievals, reports, and analyses. It also allows data to be transferred directly to other software (e.g., SPSS/PC+ and Lotus 1-2-3) for statistical analyses and graphic displays. A library system is incorporated into the database to document data sources, changes to data, and other information to be linked to sample measurements.

Data Organization

Data are linked so that related kinds of information can be retrieved together for interdisciplinary analyses. For example, sediment chemistry, infauna abundances, and bioassay data can be retrieved into a single table, based on common samples or stations. During data retrievals, data can be summarized across laboratory replicates and field replicates as requested by the user.

The database design requires that only actual measurements be recorded. For example, if cadmium was measured at all stations but one during a survey, no value for cadmium need be stored for that single station. This reduces ambiguity and complexity of the database as well as storage requirements and retrieval speed. For biological effects data, a distinction is made between "not significant" (as compared to a reference area) and "not evaluated."

Each data value is associated with a single survey and station. The survey identifies the sampling program responsible for data collection. The station coordinates identify a unique geographic position sampled during that survey. Stations are described by an identifier, latitude and longitude, and basin and subbasin codes. Samples collected at each station are further identified by a unique sample ID, the date of collection, and field replicate number. Data of any type can be retrieved by:

- Date - all dates or a specified range
- Survey - any survey or only data from one or more specific surveys
- Station - any station or only data from one or more specific stations
- Basin and subbasin - any basin/subbasin or only data from one or more specific basin/subbasin.

These criteria allow any subset of the data to be retrieved or combined for analysis.

Data Analysis

Procedures for summarization of data are programmed into the database, providing consistent treatment and formatting of the data for analysis and interpretation. These procedures include, for example, the ability to rank observations by station or chemical; create new variables (such as sums of HPAH and LPAH); construct species lists by replicate, sample, or station; and compare data to AET or other sediment quality values. Statistical analyses were carried out using SPSS/PC+, and Lotus 1-2-3 was used for other analyses and data manipulations.

Data Entry and Quality Control

Quality control of the data was based upon technical evaluation of the data, automated error-checking procedures in the database, and consistent and reliable automated procedures for retrieving and summarizing the data. All additions of data and modifications to data are documented, and the appropriate document reference code linked to the affected samples. The date is automatically inserted in all permanent output from the database. Technical review of the data is carried out before data entry and during analysis and interpretation. Automated error-checking procedures are used to screen data to preclude erroneous codes, duplicate data, and insufficiently or incorrectly identified data (e.g., measurements that are not assigned to a previously defined station). All access to the database is carried out through a series of menus and prompts, ensuring that all summaries and analyses are carried out in a consistent and replicable manner.

RESULTS

Results of field investigations in the Elliott Bay system and Port Susan are presented in the following sections on sediment chemistry, bioaccumulation, sediment bioassays, benthic macroinvertebrates, and fish ecology and histopathology. An evaluation of data collected during the present study and comparisons with recent data from previous studies is provided in each section.

SEDIMENT CHEMISTRY

The following section provides a summary of chemical results for over 100 subtidal and intertidal sediment samples collected in Elliott Bay and the Duwamish River. An additional five samples collected from the Port Susan reference area were also analyzed. Chemical data were collected for 11 EPA priority pollutant metals, 37 acid/neutral EPA priority pollutant organic compounds, PCBs, 13 EPA priority pollutant chlorinated pesticides, 6 additional Hazardous Substance List compounds, and selected tentatively identified compounds (TICs) (see Table 1). Twenty-eight of the samples were also analyzed for EPA priority pollutant volatile organic compounds. In addition, sediment conventional variables (e.g., grain size distribution and total organic carbon content) were analyzed and are discussed in this section. The objectives of this section are to:

- Provide a chemical perspective of the Elliott Bay/Duwamish River study area, including the general distributions, concentration ranges, and frequencies of detection of chemical contaminants
- Determine the magnitude of contamination relative to reference area conditions and to determine the significance of this contamination relative to Puget Sound reference areas
- Summarize spatial correlations among frequently detected chemicals and to define groups of chemicals with similar distribution patterns
- Compile historical data to supplement the sediment chemistry results of the present study.

All chemical data and sediment conventional data are presented in Appendix A.

Normalization of Chemical Concentrations

Sediment concentrations presented in this report are typically expressed as the weight of contaminant per dry weight of sediment (e.g., ug/kg dry weight or DW). Normalization of sediment concentrations to other variables [e.g., percent organic carbon or percent of fine-grained material (silt plus clay)] can aid in the interpretation of contaminant distributions by focusing on the most contaminated fractions of sediment, thus reducing the

significance of variations in less important components of sediment texture and composition. The following is a brief description of each type of normalization.

Dry Weight Normalization--

Most sedimentary contaminants are associated primarily with the solid material in bulk sediments, not with the interstitial water. Thus, dry weight contaminant concentrations are preferred to wet-weight concentrations. Use of dry weight concentrations precludes the possibility that variations in sedimentary moisture content will obscure informative trends in chemical data.

Total Organic Carbon Normalization--

Chemical concentration gradients, particularly of nonpolar, nonionic compounds, have been observed to correlate well with sedimentary organic carbon content (e.g., Choi and Chen 1976). This observation is commonly interpreted in one of two ways:

1. Organic matter is the "active fraction" of sediment and serves as a sorptive sink for neutral, and possibly polar or metallic, compounds

2. Carbon-rich particles may be an important transport medium for contaminants [e.g., HPAH may be associated with soot particles (Prahl and Carpenter 1983)].

The occurrence of multiple contaminant sources in a localized area can obscure gradients of concentrations normalized to TOC content.

Normalization to Percent Fine-Grained (<63 um) Particles--

On a limited spatial basis, contaminant concentrations are often inversely correlated with particle size (e.g., Lee 1985). Thus, contaminants (especially metals) may be concentrated in the fine-grained particles of bulk sediments. This observation is often explained in terms of surface area, in that finer particles have greater specific surface area, and thus greater sorption capacity, than larger particles. However, organic carbon content also tends to vary inversely with particle size in natural sediments (Choi and Chen 1976). Thus, normalizing to percent fines may be effectively equivalent to normalizing to organic carbon content in natural sediments. Grain size relationships can be confounded by anthropogenic processes such as sandblasting, which can result in coarse-grained sediments with high metals concentrations.

Evaluation of the Reference Area

Port Susan appeared to be a suitable reference area based on available chemical data. The Port Susan sediment chemistry data are compared to data from Elliott Bay and other Puget Sound reference areas later in this section (Sediment Metals of Concern and Organic Compounds of Concern). As discussed later, Port Susan Station PS-05 was excluded from reference area comparisons because of anomalously high concentrations of several metals and organic

compounds. Exclusion of this intertidal station does not affect interpretation of reference area biological data because amphipod bioassay and benthic infaunal data were not collected at Station PS-05.

Conventional Sediment Characteristics

Conventional sediment variables measured for this study included grain size distribution (as percent sand, silt, and clay), "oil and grease" concentrations, total organic carbon, nitrogen, and sulfides.

Grain Size--

Average percentages of fine-grained material in the nine study areas and Port Susan are presented in Figure 8. Grain size distributions generally did not follow spatial trends and areas are not easily discriminated based on the summary information presented in Figure 8. Ranges of grain size distributions were extremely wide in all areas except Alki Beach (Area AB), which had sediments with markedly coarser particle size distributions (ranging from roughly 5 to 40 percent fine-grained material). The lack of apparent gradients is not surprising, as the sampling design was oriented toward characterization of contaminants near potential sources rather than characterization of sediment transport; for example, samples in the Duwamish River were not collected from a consistent channel position.

A more detailed summary of grain size distributions is presented in Figures 9, 10, 11, and 12. One general trend apparent from Figure 9 is that intertidal sediments tended to be coarse-grained (e.g., <20 percent fines in virtually all cases). In contrast, sediment samples collected in slips and other relatively quiescent areas (e.g., near piers) tended to be predominantly fine-grained (e.g., >70 percent fine-grained material).

Grain size distributions and organic carbon content of the reference (Port Susan) sediments are presented in Figure 13. Stations PS-01 through PS-04 form a transect away from the mouth of the Stillaguamish River (Station PS-05 is intertidal and is not a part of this transect). Based on the information in Figure 13, it is apparent that finer particles relatively high in organic carbon content settled near the mouth of the river whereas coarser particles with lower TOC content were prevalent farther from the river mouth.

Oil and Grease--

Average "oil and grease" concentrations (mg/kg DW) for the nine study areas and Port Susan are presented in Figure 14. These concentrations are a broad indicator of the amount of solvent-extractable organic matter in sediments, but do not provide information on chemical-specific contamination. Mean concentrations were highest along the Seattle South waterfront (Area SS), although the highest individual station concentrations were in the Duwamish River (Area DR) and East Waterway (Area EW). Within Area SS, the maximum concentrations were at Stations SS-08 and SS-09 (5,200 to 5,470 mg/kg DW), with generally decreasing concentrations moving away from these stations in either direction. Concentrations in the East Waterway were patchy; the maximum, 7,800 mg/kg DW, was observed at Station EW-05. Concentrations in the Duwamish River (Area DR) were also patchy, with a

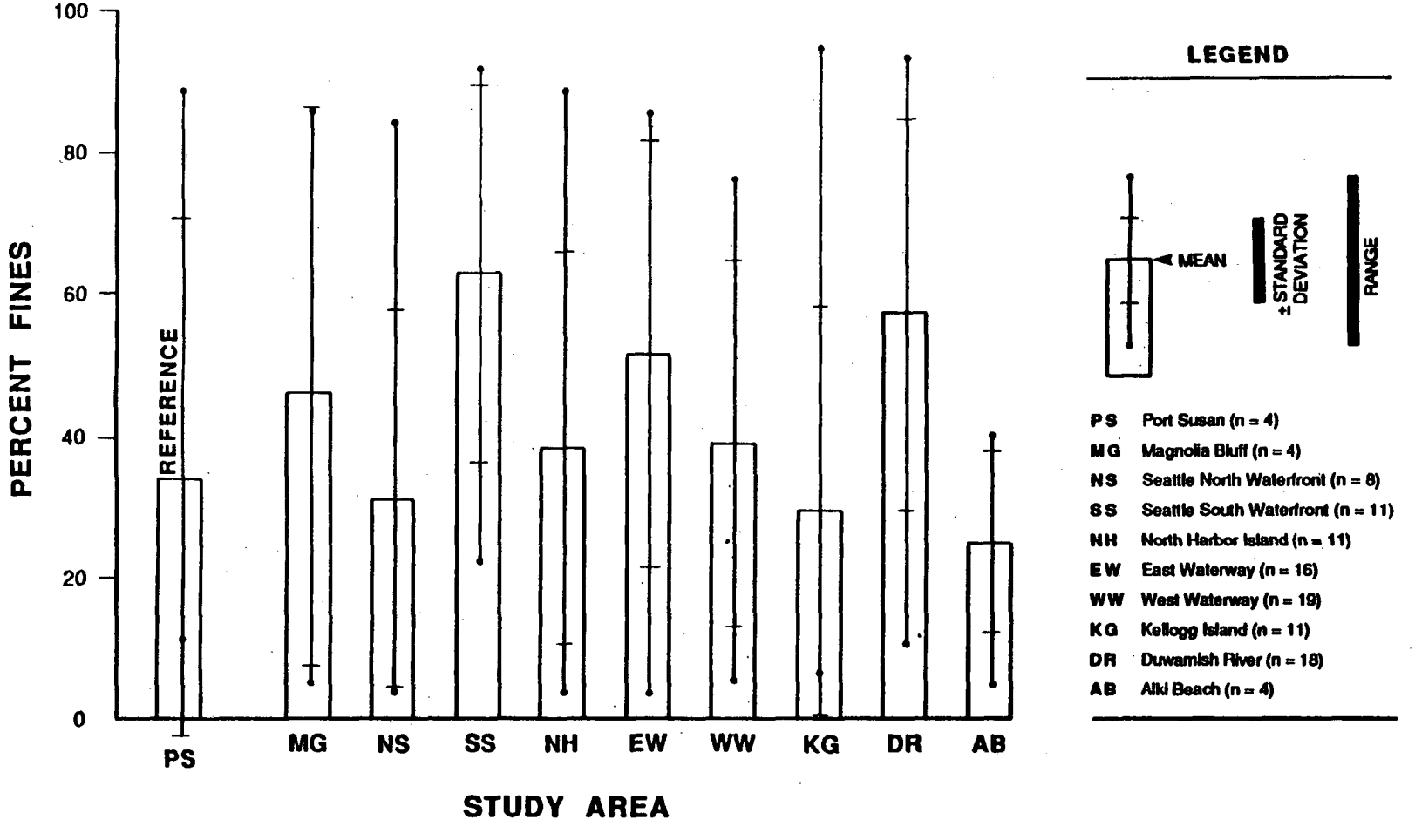


Figure 8. Average percent fine-grained material (silt plus clay) in sediments of Elliott Bay, the Duwamish River, and Port Susan.

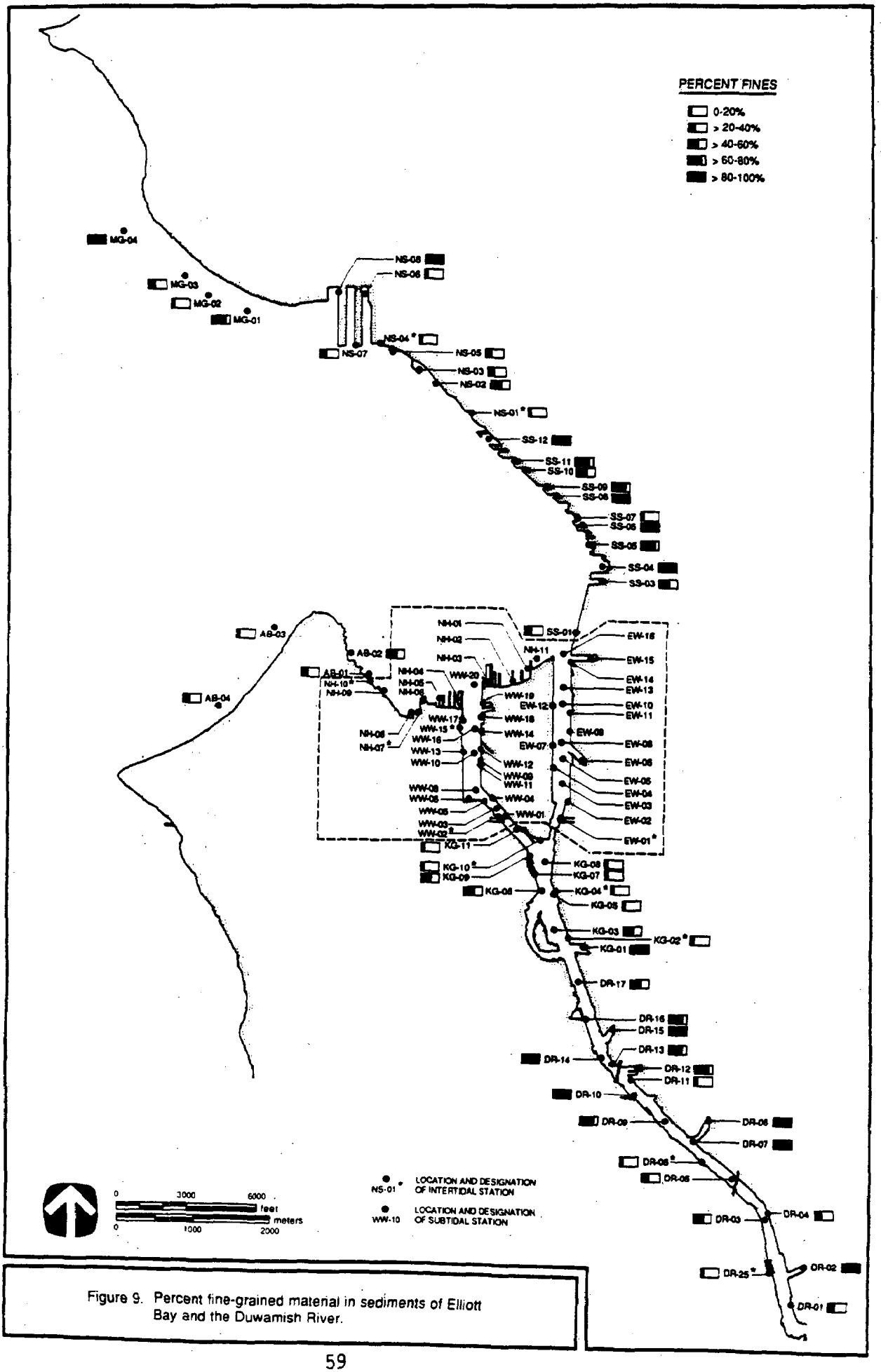


Figure 9. Percent fine-grained material in sediments of Elliott Bay and the Duwamish River.

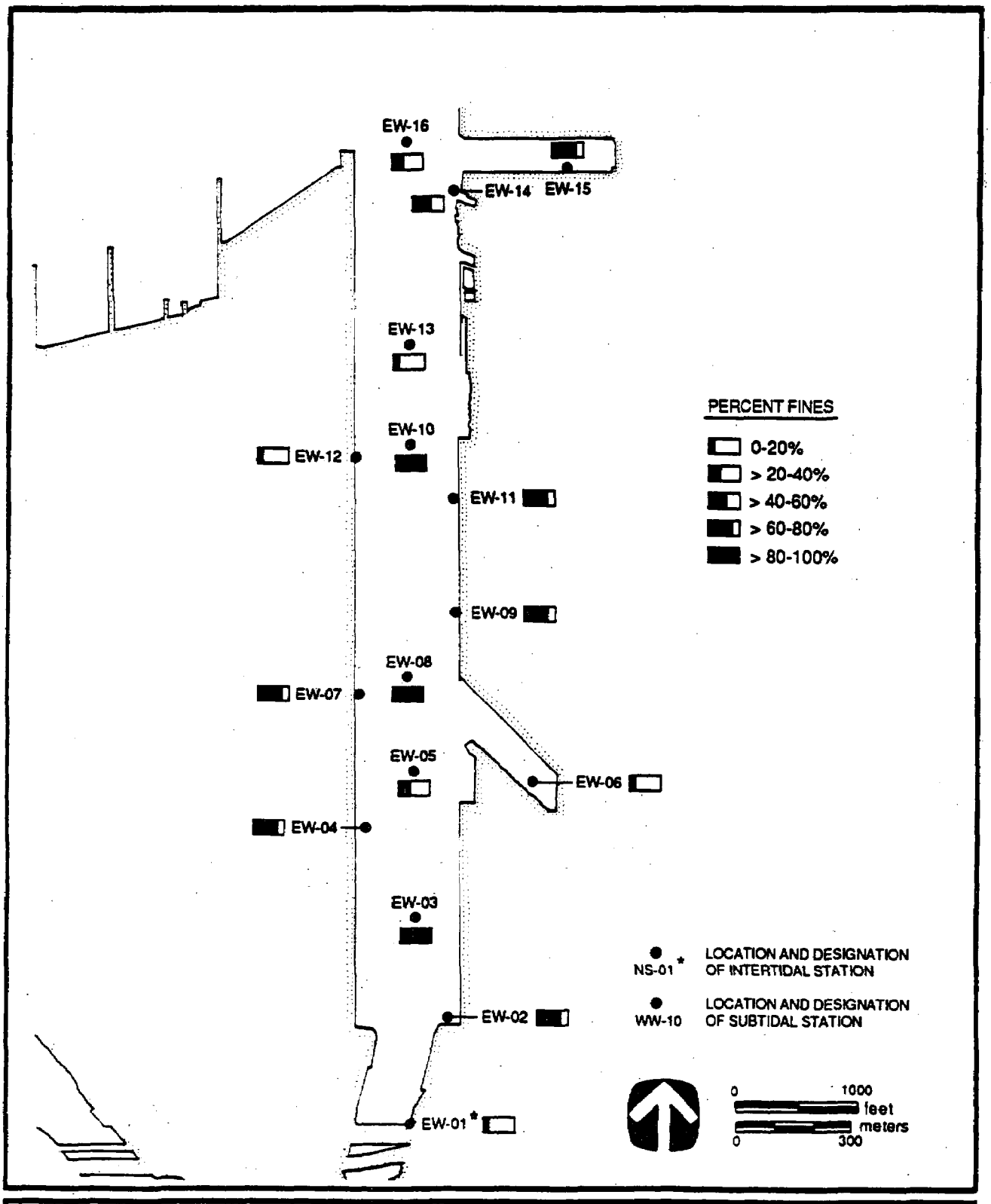


Figure 10. Percent fine-grained material in sediments of the East Waterway.

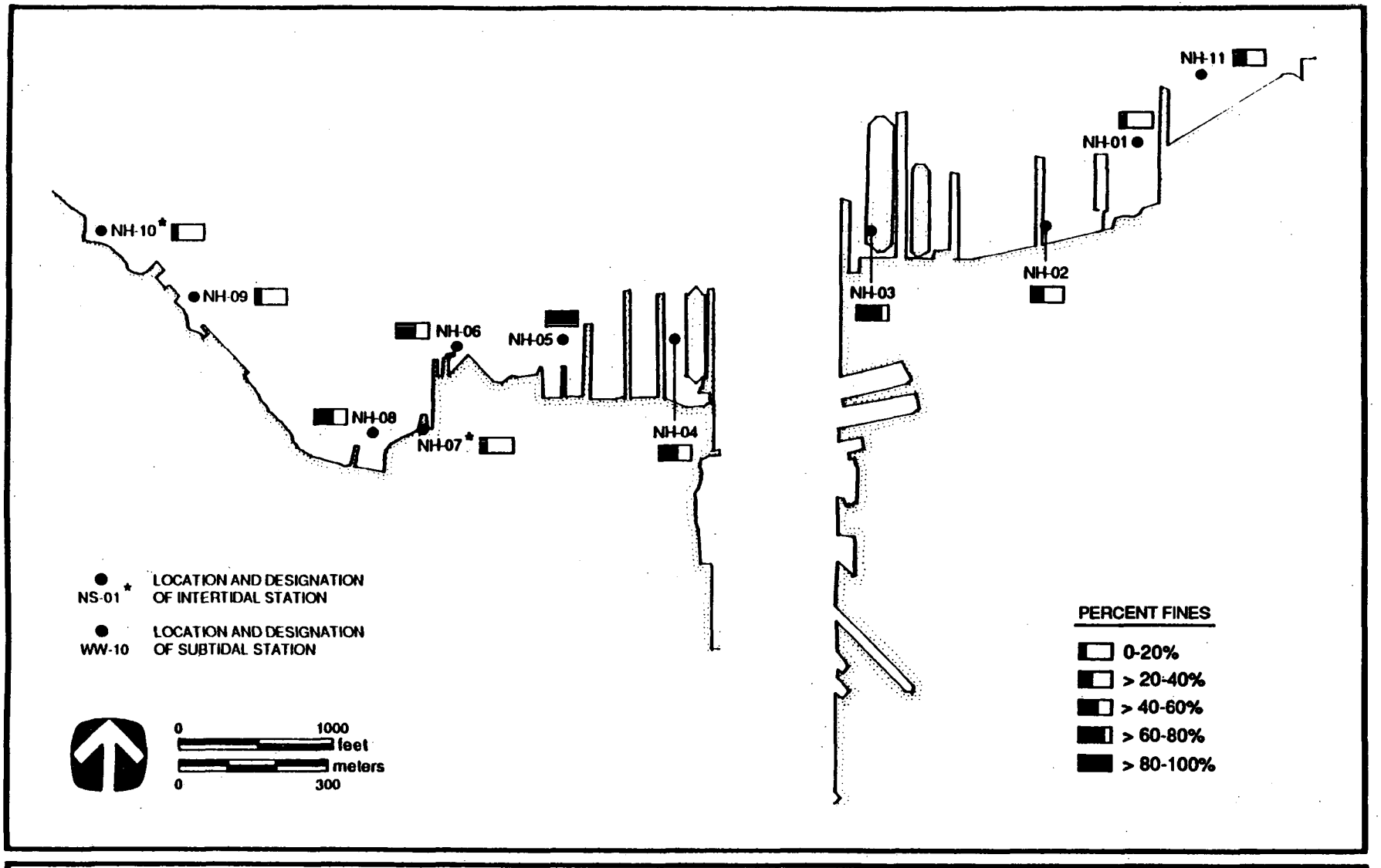


Figure 11. Percent fine-grained material in sediments of North Harbor Island.

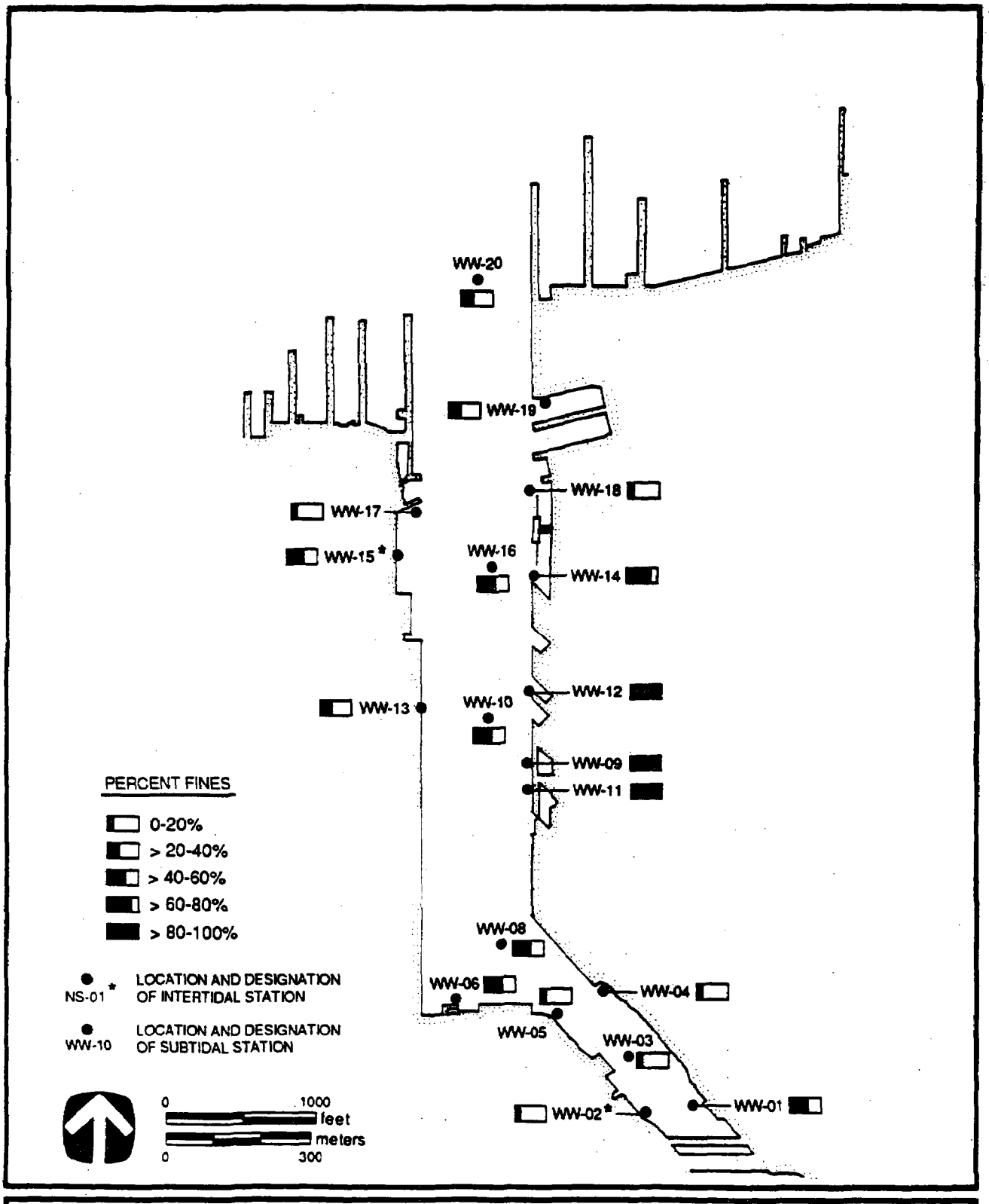


Figure 12. Percent fine-grained material in sediments of the West Waterway.

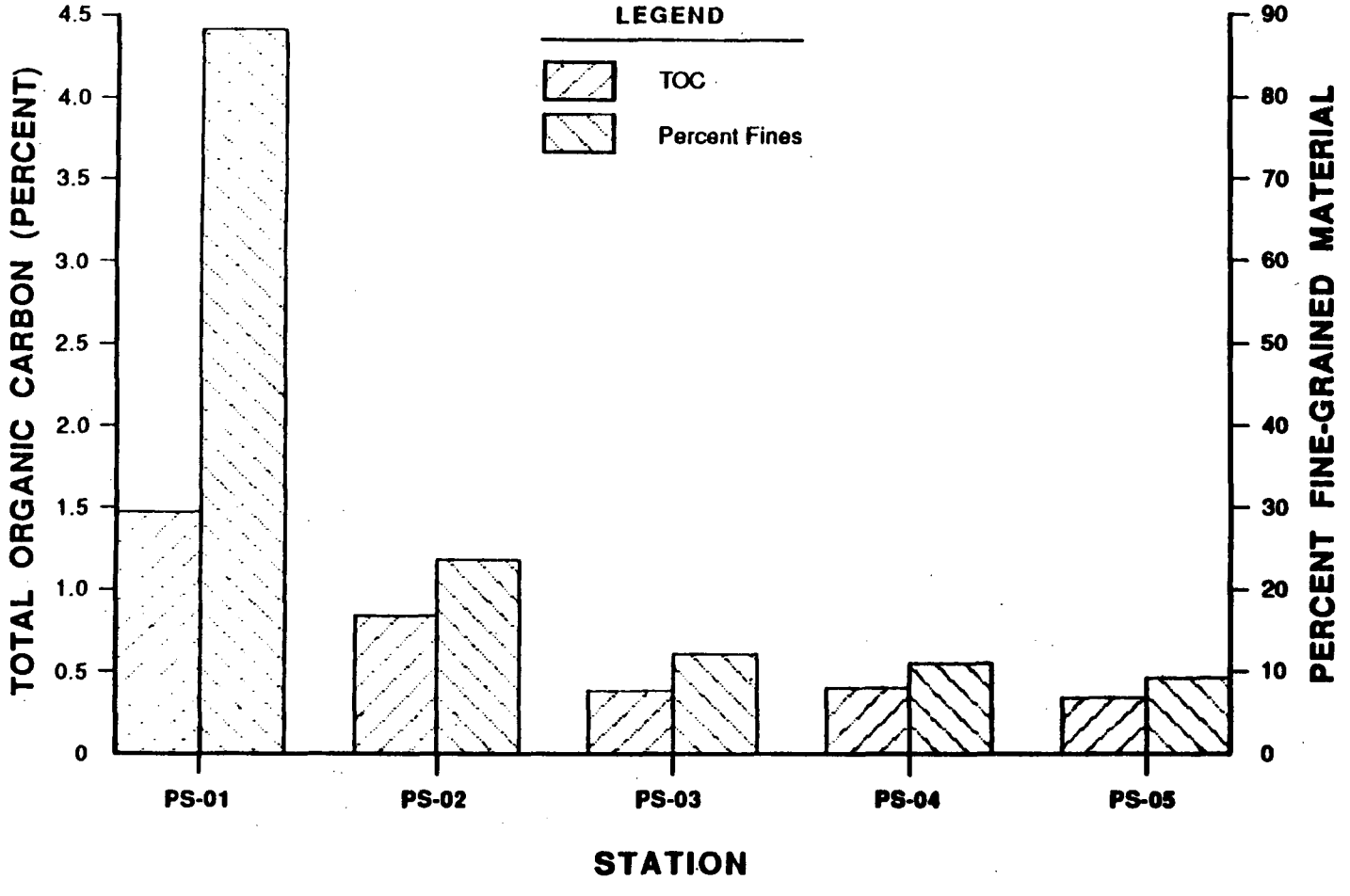


Figure 13. Grain size and total organic carbon content of Port Susan sediments.

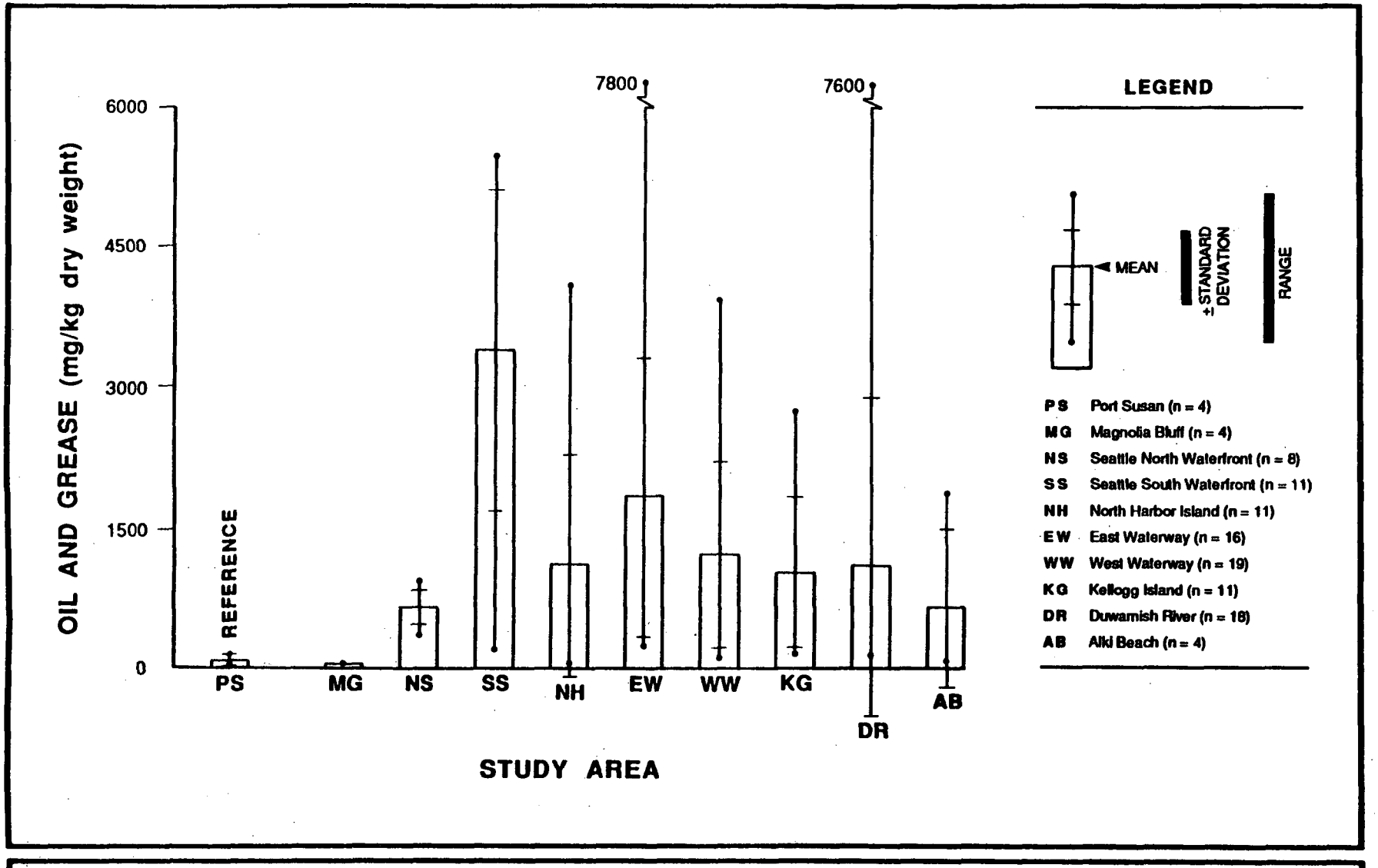


Figure 14. Average oil and grease concentrations (mg/kg dry wt.) in sediments of Elliott Bay, the Duwamish River, and Port Susan.

pronounced maximum at Station DR-10 (7,600 mg/kg DW). Maximum concentrations in Areas NH and WW were roughly 4,000 mg/kg DW. Magnolia bluff (Area MG) was the only area in Elliott Bay with "oil and grease" concentrations within the range of the reference area (Port Susan).

Total Organic Carbon--

TOC concentrations (summarized in Figure 15) demonstrated similar trends as observed for oil and grease concentrations (Figure 14). The correlation between TOC and oil and grease concentrations for all stations was moderate ($r=0.59$, $n=107$, $P<0.05$). Area SS (the Seattle South waterfront) had the highest mean TOC concentration (7.3 percent) and the highest individual concentration (26.6 percent at Station SS-08). The next highest TOC concentration in the study (10.3 percent), was found at adjacent Station SS-09. Average TOC concentrations for other areas were less than 3 percent. TOC concentrations along Magnolia Bluff were very low; all individual MG stations had lower TOC concentrations than those found in the reference area (Port Susan). TOC concentrations are presented in more detail in Figures 16, 17, 18, and 19. Gradients in TOC concentrations were not readily apparent in study areas other than Port Susan.

An inverse relationship between particle size and TOC content has been reported in other studies (e.g., Choi and Chen 1976) and is expected when hydrodynamic sorting is a predominant process. However, the correlation between TOC and percent fine-grained material was poor overall ($r=0.31$, $n=107$, $P<0.05$) and in most study areas. In part, the poor correlation may be attributed to the presence of relatively coarse-grained sediments located near discharges of material rich in organic matter (e.g., CSOs). The North Harbor Island (NH) area was an exception, in that a moderately strong correlation was observed between TOC and percent fine-grained material ($r=0.79$, $n=11$, $P<0.05$). Because this area is at the mouth of the Duwamish River, hydrodynamic sorting may be responsible for the better correlation relative to other study areas.

TOC concentrations correlated well with total volatile solids (TVS) concentrations ($r=0.93$, $n=107$, $P<0.05$), based on a regression that included all sediment stations. The following regression equation related TOC to TVS:

$$TVS = 1.54(TOC) + 3.11.$$

Water-Soluble Sulfides--

Distributions of water-soluble sulfides in sediments are summarized in Figure 20. Sulfide concentrations correlated moderately well with total organic carbon concentrations (Figure 15) ($r=0.65$, $n=107$, $P<0.05$). Because sulfides are indicative of sulfate-reducing (oxygen-poor) conditions, it is not unusual for sulfide concentrations to be relatively high in areas that are rich in organic matter and high in oxygen demand. The highest mean and individual sulfide concentrations were found along the Seattle South waterfront (Area SS), an area with consistently high sulfide concentrations that maximized at Station SS-06 (1,500 mg/kg DW). High values were also observed in the East Waterway [particularly Stations EW-05 and EW-06 (1,100 and 740 mg/kg DW, respectively)], in the North Harbor Island area [especially

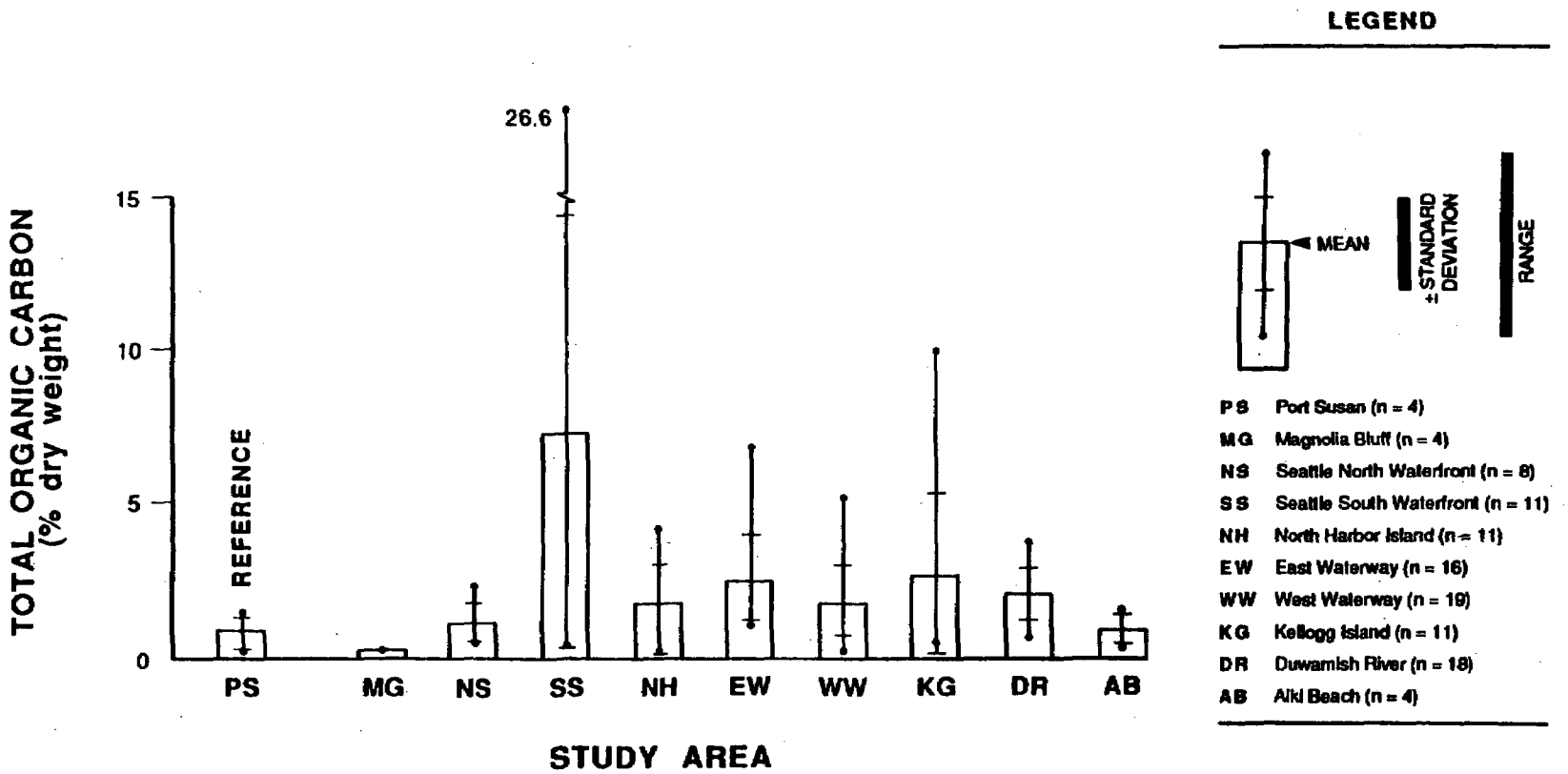


Figure 15. Average total organic carbon (TOC) content (as percent dry wt.) in sediments of Elliott Bay, the Duwamish River, and Port Susan.

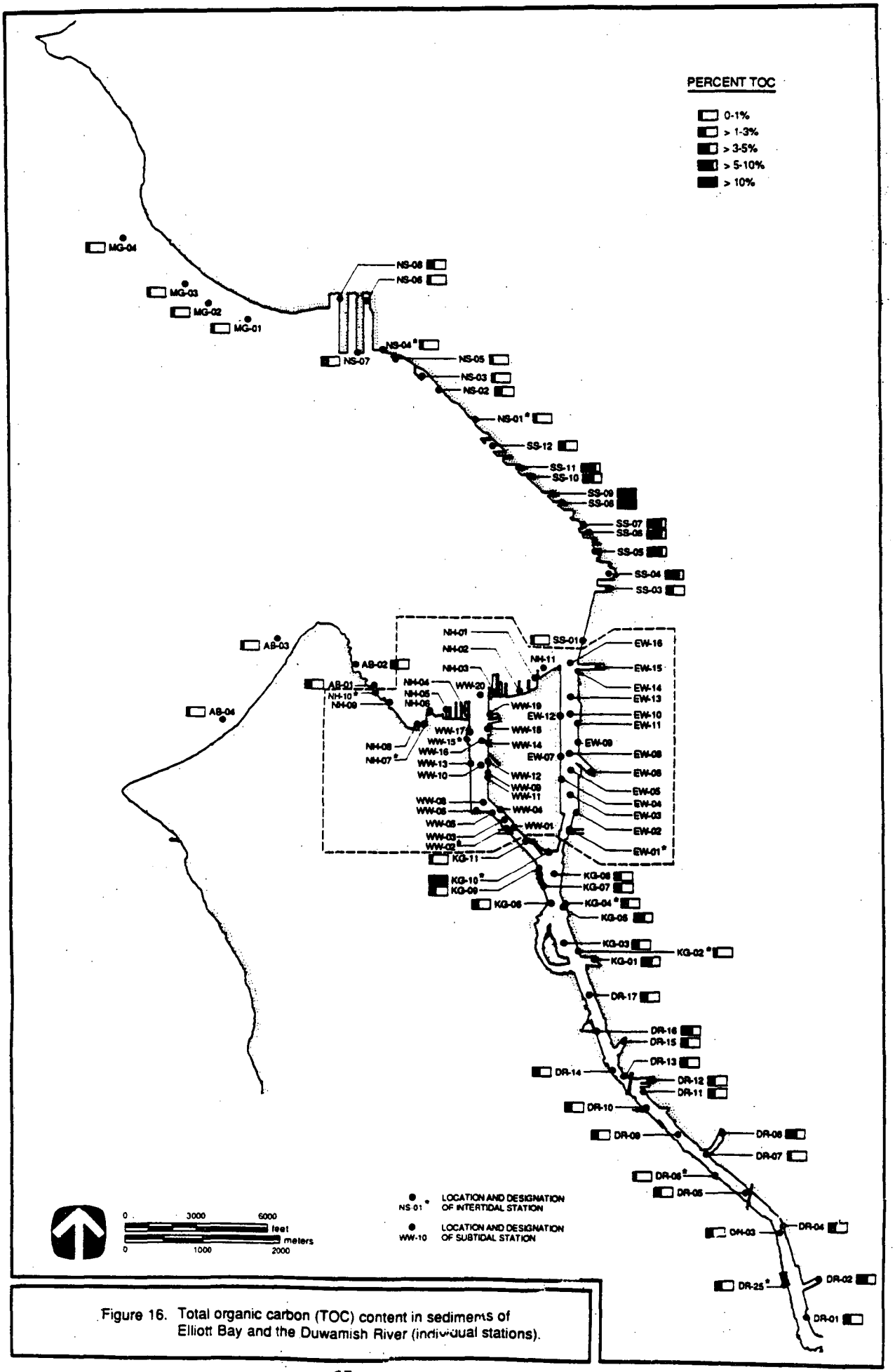


Figure 16. Total organic carbon (TOC) content in sediments of Elliott Bay and the Duwamish River (individual stations).

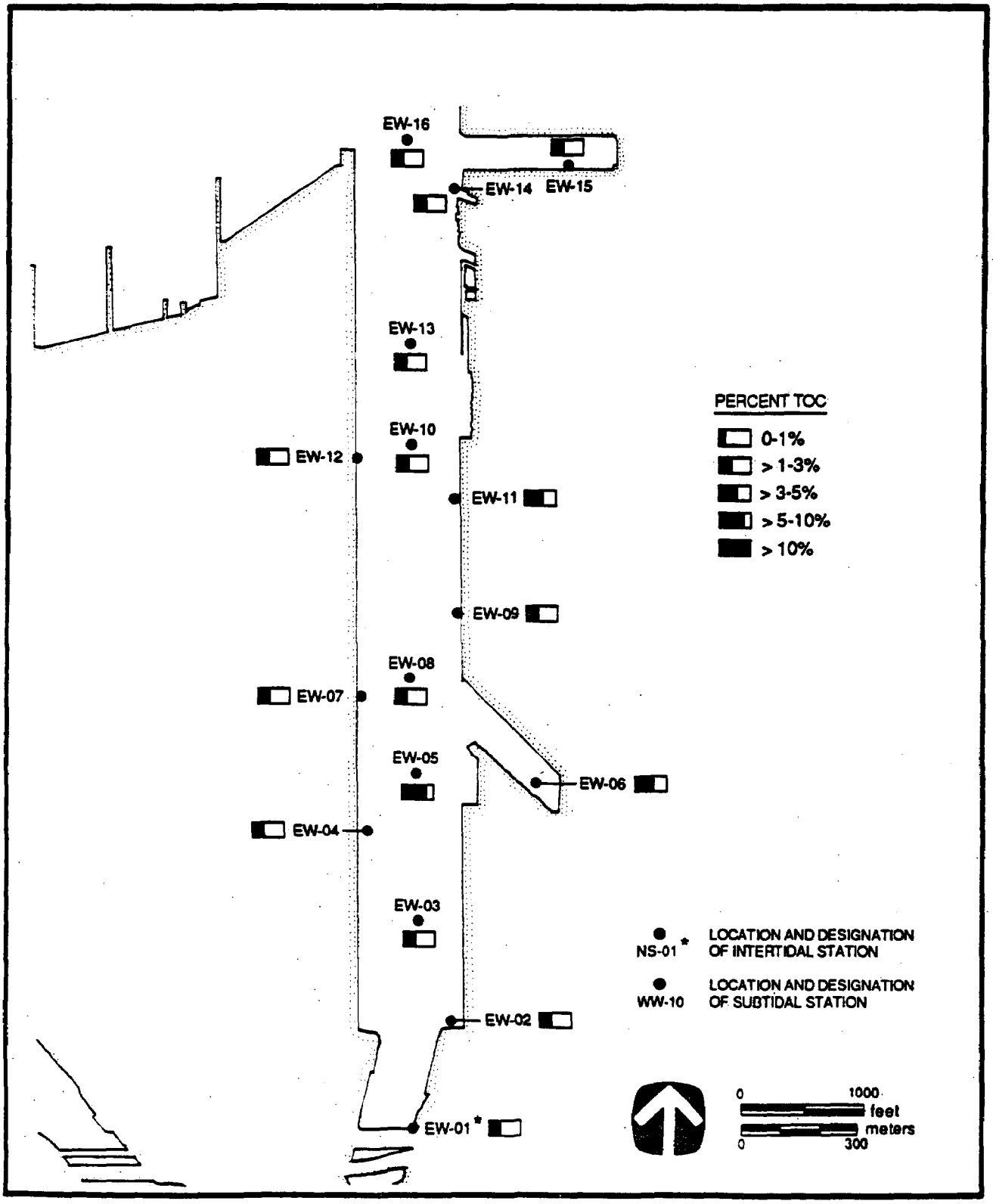


Figure 17. Total organic carbon (TOC) content in sediments of the East Waterway.

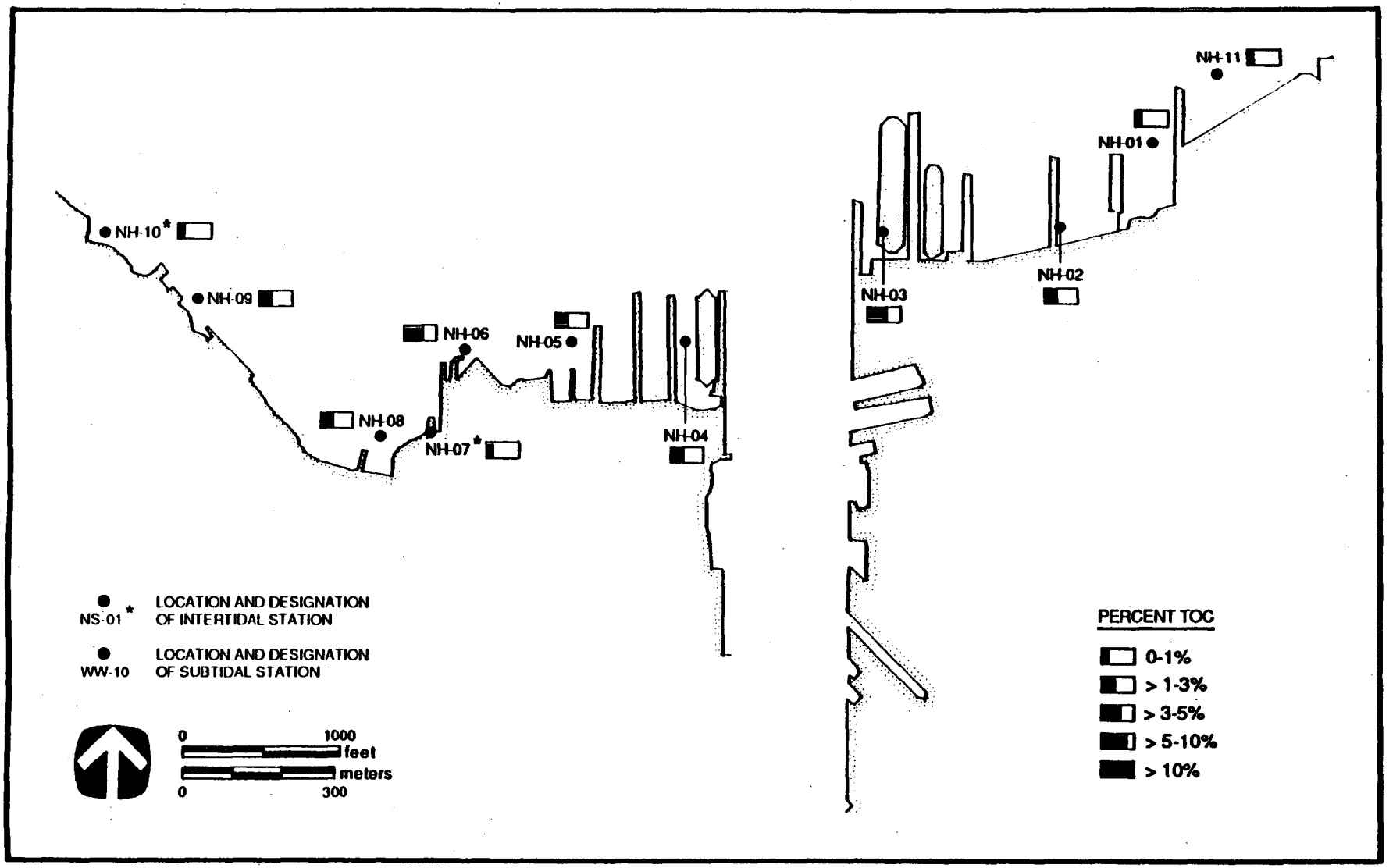


Figure 18. Total organic carbon (TOC) content in sediments of North Harbor Island.

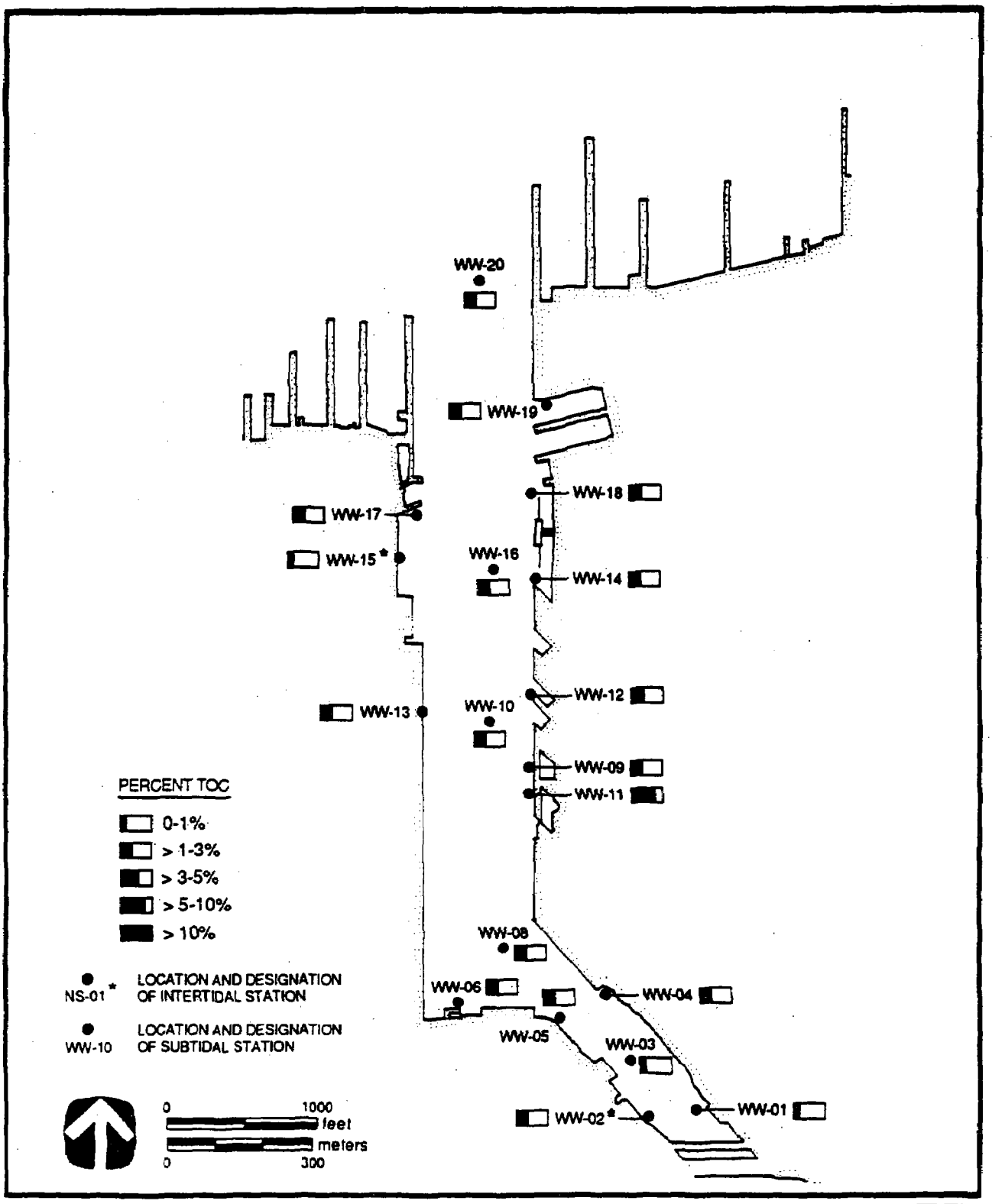


Figure 19. Total organic carbon (TOC) content in sediments of the West Waterway.

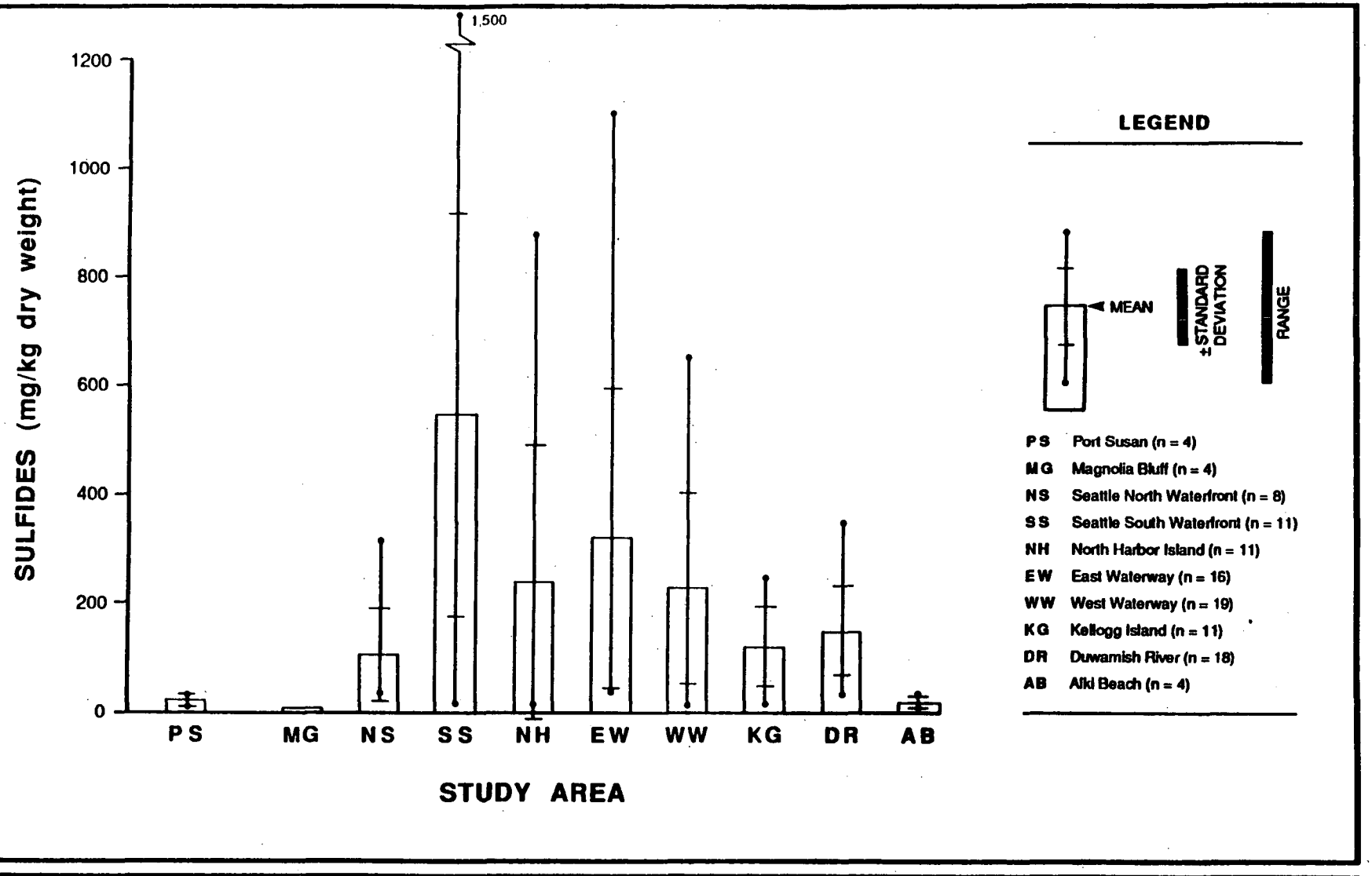


Figure 20. Average sulfide concentrations (mg/kg dry wt.) in sediments of Elliott Bay, the Duwamish River, and Port Susan.

Station NH-03 (870 mg/kg DW)], and along the east side of the West Waterway [particularly Station WW-09 (650 mg/kg DW)]. Sulfides concentrations along Magnolia Bluff, Alki Beach, and in the reference area were relatively low and consistent.

Sediment Chemistry: Metals

Concentration ranges and detection frequencies for the 13 elements analyzed in this study are presented in Table 8. Eleven of the 13 EPA priority pollutant metals are included in this group; beryllium and thallium were not analyzed because historical data did not suggest that these metals were of concern in the study area.

Most metals were detected in all samples (Table 8). Concentration ranges were very broad for many metals, ranging from reference area concentrations to some of the highest concentrations reported in Puget Sound sediments. For example, concentration ranges of antimony, lead, and mercury spanned three to four orders of magnitude. Maximum values occurred most often along the Seattle South waterfront (Area SS; arsenic, cadmium, chromium, lead, nickel, selenium, and zinc), although other areas had maximum concentrations of certain metals (Table 8). Station SS-09 was noteworthy in that three metals, cadmium, lead, and zinc, maximized there. The maximum mercury concentration was found in the Alki Beach area (Station AB-01), the maximum copper concentration was found in Area NH (Station NH-03), and the maximum antimony concentration was found in the West Waterway (Station WW-14). High levels of contamination by most metals occurred in more than one area. The distributions of the metals of greatest concern are described in the following section.

Sediment Metals of Concern--

Metals of concern are defined as those metals that occur at concentrations exceeding Puget Sound reference areas. It is assumed that the range of reference concentrations provides a reasonable measure of the possible variability of concentrations in relatively uncontaminated sediments.

The range of trace metal concentrations in Puget Sound reference areas are presented in Table 9. Metals concentrations from Port Susan sediments collected for this study (Stations PS-01 to PS-04) are included among the reference values summarized in Table 9. Station PS-05 was excluded from compilations of reference stations because it had anomalously high concentrations of several metals (as well as organic compounds). Chromium was the most notable metal at Station PS-05; the chromium concentration of 886 mg/kg DW at Station PS-05 was over 3 times that of any other Port Susan station and was uncharacteristically high for natural mineral assemblages. The exclusion of Station PS-05 from reference area chemical characterization does not have serious consequences for data interpretation, because this intertidal station was not included in the bioassay comparisons or in the benthic infaunal comparisons. Other Port Susan stations had metals concentrations that were generally characteristic of other Puget Sound reference areas (Table 9), although chromium and nickel concentrations were 2-3 times existing reference values. This was expected as the chemical analyses used in this study yielded a more complete measurement of mineral-bound crustal elements (such as chromium and nickel) than analyses used in previous

TABLE 8. CONCENTRATIONS OF METALS IN SURFACE SEDIMENTS OF ELLIOTT BAY, DUWAMISH RIVER, AND PORT SUSAN

Chemical	Range (mg/kg dry wt)	Detection Frequency	Location of Maximum
Antimony	U0.29[a] - 1,370	106/107	WW-14
Arsenic	2.37 - 584	107/107	SS-03
Cadmium	0.07 - 17.2	107/107	SS-09
Chromium	E32[a] - E1,080	107/107	SS-10
Copper	9.3 - 2,050	107/107	NH-03
Iron	15,900 - 112,000	107/107	WW-19
Lead	7.2 - 71,100	107/107	SS-09
Manganese	E258 - E3,390	107/107	NS-04
Mercury	E0.012 - E28.8	107/107	AB-01
Nickel	18.2 - 366	107/107	SS-10
Selenium	U0.11 - 0.93[b]	78/107	SS-06
Silver	U0.02 - E8.27	102/107	NS-01
Zinc	E32.7 - E6,010	107/107	SS-09

[a] Qualifiers:

U = Undetected at the detection limit shown.

E = Estimated value.

[b] Maximum observed value does not exceed range of values for Puget Sound reference areas.

TABLE 9. SUMMARY OF METAL CONCENTRATIONS IN SEDIMENTS FROM PUGET SOUND REFERENCE AREAS

Chemical	Range (mg/kg dry wt)[a]	Detection Frequency	Reference Sites[b]
Antimony	U0.1[c]-2.76 (0.92-2.76)	19/39	1,2,3,4,7,8,9,10,11
Arsenic	1.9-17 (6.41-11)	41/41	1,2,3,4,7,8,9,10,11
Cadmium	0.047-1.9 (0.07-0.15)	31/31	1,2,3,4,6,9,10,11
Chromium	9.6-E255 (E132-E255)	45/45	1-11
Copper	5-74 (16.2-49)	35/35	1,2,3,4,5,6,9,10,11
Lead	U0.1-24 (7.2-11)	28/35	1,2,3,4,5,6,9,10,11
Mercury	0.01-0.28 (E0.015-E0.110)	45/45	1-11
Nickel	4-140 (63.2-140)	33/33	1,2,3,4,5,9,10,11
Selenium	U0.1-1.0 (U0.14-0.22)	21/31	1,2,3,4,6,9,10,11
Silver	U0.02-3.3 (U0.02-E0.1)	31/33	1,2,3,4,5,9,10,11
Zinc	15-E101 (E57.2-E101)	33/33	1,2,3,4,5,9,10,11

[a] The range of Port Susan concentrations from this study is shown in parentheses. Port Susan concentrations from this study were the highest of all reference area sites for antimony, chromium, nickel, and zinc. The highest values for reference areas without Port Susan were 1.7 (antimony), 130 (chromium), 47 (nickel), and 100 (zinc). Station PS-05 (this study) was excluded from this table for reasons discussed in text.

[b] Reference sites:
1. Carr Inlet
2. Samish Bay
3. Dabob Bay
4. Case Inlet
5. Port Madison
6. Port Susan
7. Nisqually Delta
8. Hood Canal
9. Sequim Bay
10. Port Susan (this study)
11. Port Susan (1986)

[c] U = Undetected at the method detection limit shown.

References:

(Site 1) Tetra Tech (1985a); Crecelius et al. (1975)
(Site 2) Battelle (1986)
(Site 3) Battelle (1986)
(Site 4) Crecelius et al. (1975); Malins et al. (1980)
(Site 5) Malins et al. (1980)
(Site 6) Malins et al. (1982)
(Site 7) Crecelius et al. (1975)
(Site 8) Crecelius et al. (1975)
(Site 9) Battelle (1985)
(Site 10) This study
(Site 11) PTI and Tetra Tech (1988).

studies. In fact, the "total metals" technique (used in this study) and the "strong acid" technique (common in past studies) were recently compared with Carr Inlet, Port Susan, and Elliott Bay sediments. The results indicate that the different analytical procedures can account for the relatively higher chromium concentrations observed in Port Susan sediments during this study but not the higher nickel concentrations (see METHODS, Sediment Chemistry, Assessment of the Effect of Analytical Procedures on Metals Results).

Ten of the eleven EPA priority pollutant metals analyzed in this study were found at concentrations exceeding the highest Puget Sound reference concentrations (Tables 8 and 9). Among these ten metals of concern, nickel will not be considered in detail because only one station (SS-10) had a nickel concentration that exceeded the range of Puget Sound reference concentrations (Table 9). Selenium concentrations did not exceed Puget Sound reference area values and are thus not considered of concern in this study.

A summary of the distributions of the metals of concern is presented in Table 10. In this table, EAR are used to describe chemical distributions. Each EAR is the ratio of the dry weight concentration of a chemical divided by the average concentration determined for six Carr Inlet stations (Tetra Tech 1985a). Table 11 summarizes the most contaminated study areas and stations in terms of EAR values; areas with EAR between 100 and 1,000 are presented in Table 11 as well as areas with EAR values of greater than 1,000. Descriptions of the distributions of metals of concern are described below for the most contaminated study areas. Concentrations normalized to fine-grained material were examined in the most contaminated study areas, but will not be discussed unless they suggest gradients not apparent for dry weight concentrations.

Antimony--Absolute antimony concentrations reported for samples in this study are probably overestimates, as determined by subsequent XRF analyses (see METHODS, Sediment Chemistry, Assessment of the Effect of Analytical Procedures on Metals Results). Nonetheless, the data are presented in this section to yield information on the areas with the highest relative concentrations. Antimony data were not used for problem identification or ranking.

Antimony EAR values for all study areas are presented in Figure 21, and EAR values for individual stations in the most contaminated areas are presented in Figure 22. The two highest concentrations in the study were found in the West Waterway (1,370 mg/kg DW at Station WW-14 and 1160 mg/kg DW at Station WW-12; Figure 22). Other stations on the east side of the West Waterway (e.g., WW-09, WW-11, WW-16, WW-18, WW-19) were also elevated. High concentrations were also found at NH stations adjacent to the mouth of the West Waterway (Station NH-04 = 504 mg/kg DW and NH-03 = 249 mg/kg DW) with rapidly decreasing concentrations moving away from these stations (Figure 22). Other high concentrations were found along the Seattle South waterfront, at Stations SS-03 (690 mg/kg DW) and SS-09 (680 mg/kg DW). These two stations were not adjacent, and intervening stations had order-of-magnitude lower concentrations that did not appear to follow a concentration gradient on a dry-weight or percent fines normalized basis. Other stations with high concentrations were EW-15 (the remainder of the East Waterway stations were

TABLE 10. RANGE IN EAR FOR INORGANIC CONTAMINANTS OF CONCERN IN SEDIMENTS OF ELLIOTT BAY AND THE DUWAMISH RIVER

Chemical	EAR[a] Range	Median	Threshold[b]	Areas wnere Threshold Exceeded by 10 Times[c]
Antimony	2.6 - 12,000	240	25	AB,DR,EW,KG,NH,NS,SS,WW
Arsenic	0.7 - 170	4.6	5.0	DR,NH,SS,WW
Cadmium	0.07 - 18	0.73	2.0	--
Chromium	2.2 - 72	6.6	17	--
Copper	1.5 - 320	15	12	NH,SS,WW
Lead	0.78 - 7,700	15	2.6	AB,DR,EW,KG,NH,SS,WW
Mercury	0.30 - 720	8.1	7.0	AB,EW,NH,SS
Nickel	1.1 - 21	2.3	8.1	--
Silver	0.24 - 92	7.0	37	--
Zinc	1.7 - 320	12	5.4	NH,SS,WW

[a] Dry-weight concentration in study area sediments divided by the average concentration measured in six Carr Inlet sediments (Tetra Tech 1985a).

[b] The threshold EAR is defined as the ratio of the maximum reference sediment concentration in Puget Sound divided by the average for six Carr Inlet reference sediments. Above the threshold EAR, the dry-weight concentration of a study area sediment contaminant would exceed the maximum concentration reported for any Puget Sound reference site listed in Table 9.

[c] The contaminant EAR in sediments from at least one station in each listed area exceeded the threshold level by at least one order of magnitude. The factor of 10 is arbitrary, but is useful for indicating the areas of greatest contamination. It was not used in problem area identification or ranking. Sediments in the underlined areas had the highest observed concentrations.

TABLE 11. SUMMARY OF METALS WITH EAR BETWEEN 100-1,000 AND >1,000 IN SEDIMENTS OF ELLIOTT BAY AND THE DUWAMISH RIVER[a]

Chemical	Station
EAR = 100-1,000	
Arsenic	DR-12, SS-03
Copper	NH-03, NH-04, SS-03, WW-19
Lead	WW-12, WW-14
Mercury	AB-01, NH-03
Zinc	SS-03, SS-09
EAR >1,000	
Lead	SS-09
Chemical	Area[b]
EAR = 100-1,000	
Lead	SS
Mercury	AB

[a] Antimony has been excluded from this table.

[b] Concentrations averaged over all stations in the area indicated.

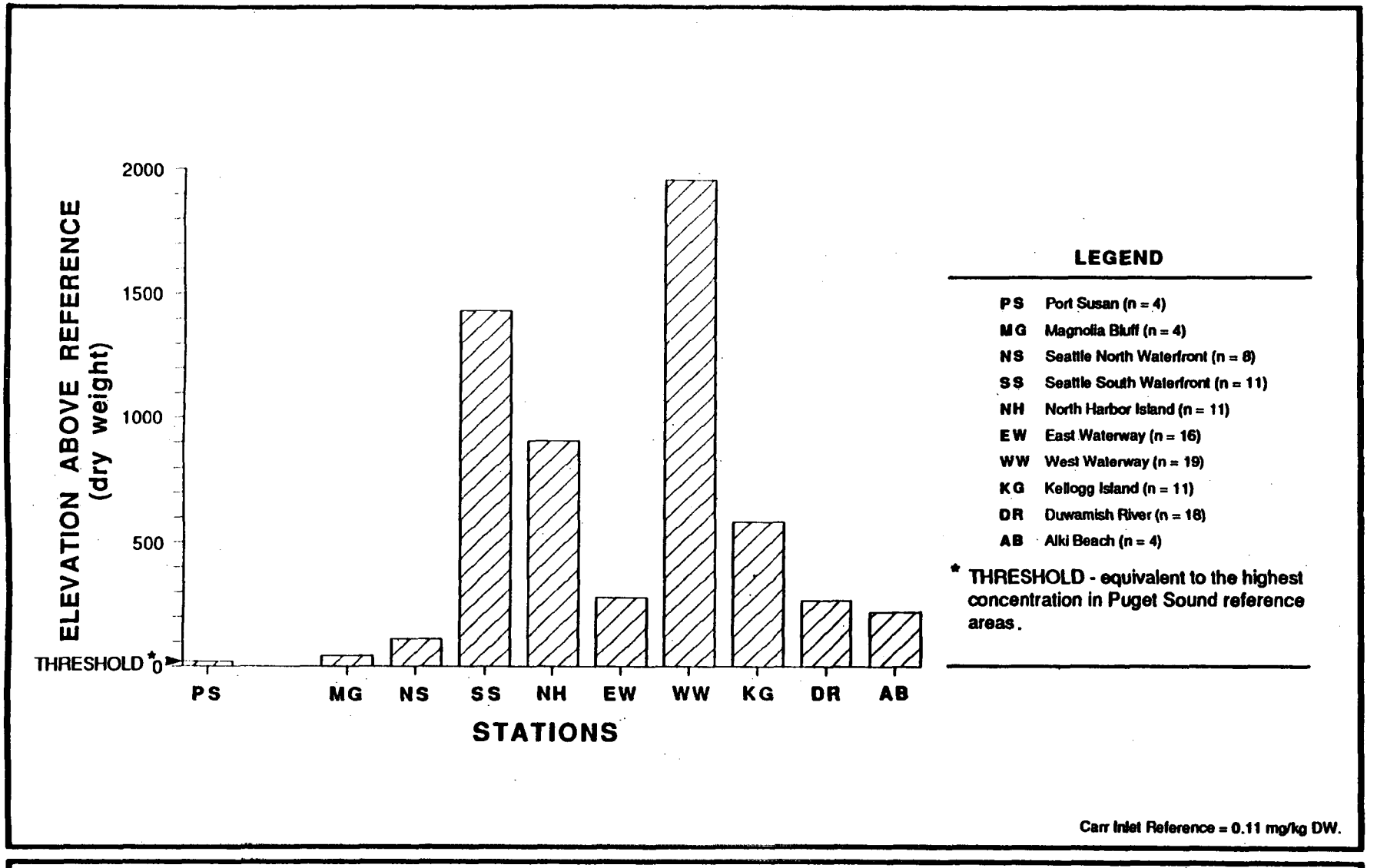


Figure 21. Mean elevations above reference (EAR) of antimony in sediments from all study areas.

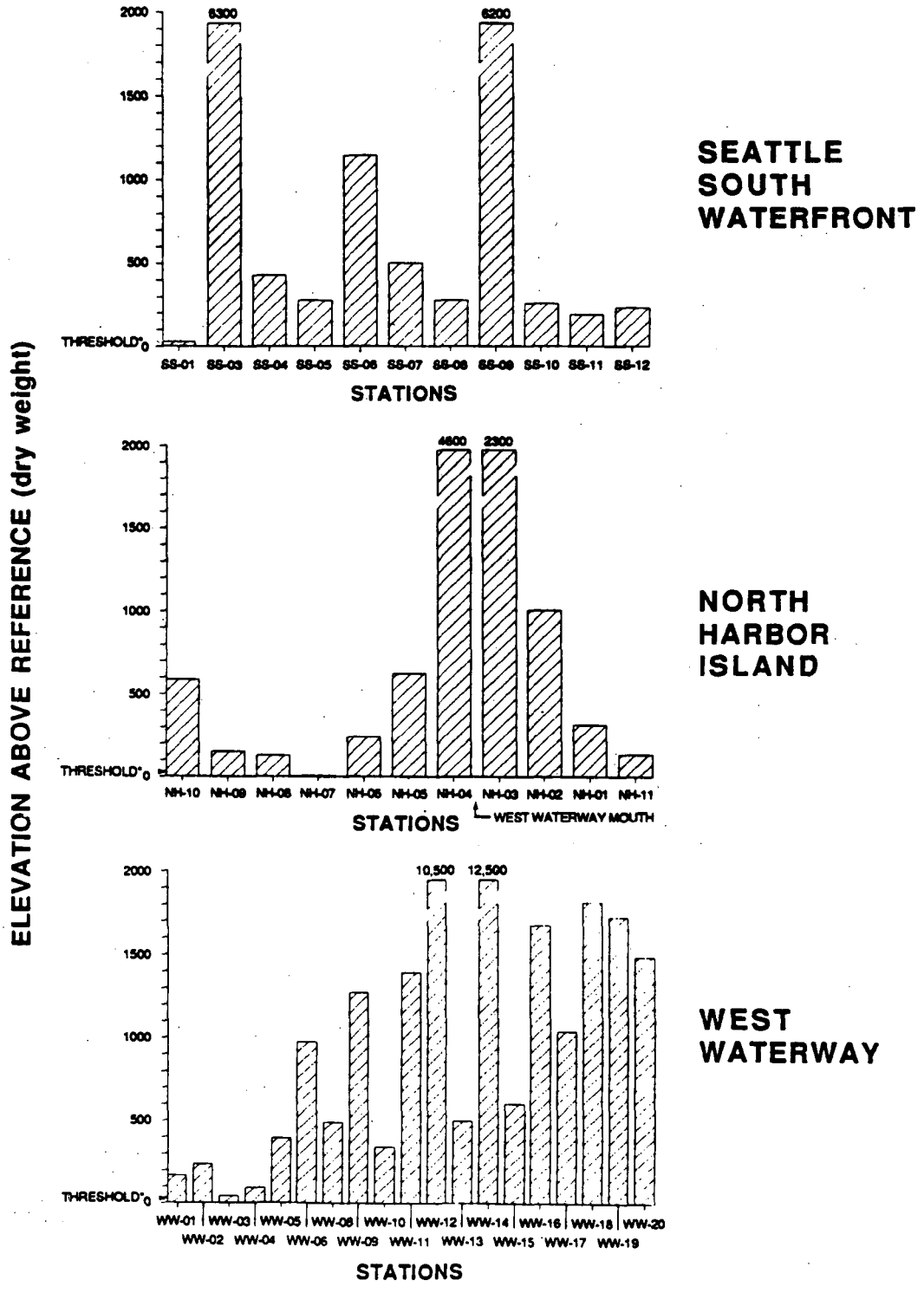


Figure 22. Elevations above reference (EAR) of antimony at individual stations in the most contaminated study areas.

considerably less contaminated) and Stations KG-06 and KG-07 near Kellogg Island.

Arsenic--Arsenic concentrations were not highly elevated in the study area; the areas of highest contamination appeared to be geographically isolated. The highest concentration in the study was found at Station SS-03, along the Seattle South waterfront (584 mg/kg DW; EAR = 173). The adjacent station, SS-04, had a far lower concentration (28.5 mg/kg DW). The next highest concentration was observed in the Duwamish River, at Station DR-12 (449 mg/kg DW). Concentrations of arsenic at stations adjacent to Station DR-12 were near reference values. The West Waterway had somewhat elevated concentrations. For example, Station WW-12 had an arsenic concentration of 239 mg/kg DW. Stations NH-04 and NH-03, at the mouth of the West Waterway, had concentrations of 174 and 119 mg/kg DW, respectively.

Cadmium--The highest cadmium concentration was observed at Station SS-09 (17.2 mg/kg DW; EAR = 18), although adjacent stations had concentrations within the range of Puget Sound reference areas (i.e., <2 mg/kg DW; Table 9). Station SS-03, far removed from Station SS-09, had a concentration of 7.16 mg/kg DW. The next highest concentrations were found at Stations EW-05 (12.4 mg/kg DW) and EW-06 (6.32 mg/kg DW) in the East Waterway. The nearest East Waterway stations were within Puget Sound reference levels.

Chromium--Mean EAR values for study areas in Elliott Bay and the Duwamish River were very consistent and ranged from 5 to 10, with the exception of Area SS, which had an EAR of 16. These mean EAR values were all within the range of Puget Sound reference areas. The highest chromium concentration, 1,080 mg/kg DW, occurred at Station SS-10. Nearby Station SS-09 had a concentration of 304 mg/kg DW. Other SS stations had concentrations within the range of Puget Sound reference areas; concentration gradients were not readily apparent in this area.

A chromium concentration of 555 mg/kg DW was reported at Station WW-12 in the West Waterway, with concentrations at adjacent stations below 200 mg/kg DW. All other concentrations in the study were within the Puget Sound reference range.

Copper--Copper concentrations were most elevated in and near the mouth of the West Waterway (Areas NH and WW) and along the Seattle South waterfront (Area SS) (Figure 23). The highest concentrations were observed at Stations NH-03 (2,050 mg/kg DW; EAR = 320) and NH-04 (1,770 mg/kg DW; EAR = 280) at the mouth of the West Waterway (Figure 24). As was the case for antimony and arsenic, concentrations at NH stations decreased with distance from the mouth of the waterway. Station WW-19, also near the mouth of the waterway, had the next highest copper concentration (1,300 mg/kg DW). Other stations along the east side of the West Waterway also had elevated concentrations (Figure 24), although a smooth gradient was not apparent. Station WW-19 clearly had the highest concentration in the waterway based on dry weight or percent fines normalization.

Along the Seattle South waterfront, Station SS-03 had a concentration of 1,040 mg/kg DW, relatively coarse-grained Station SS-07 had a concentration of 525 mg/kg DW, and Station SS-09 had a concentration of 350 mg/kg DW.

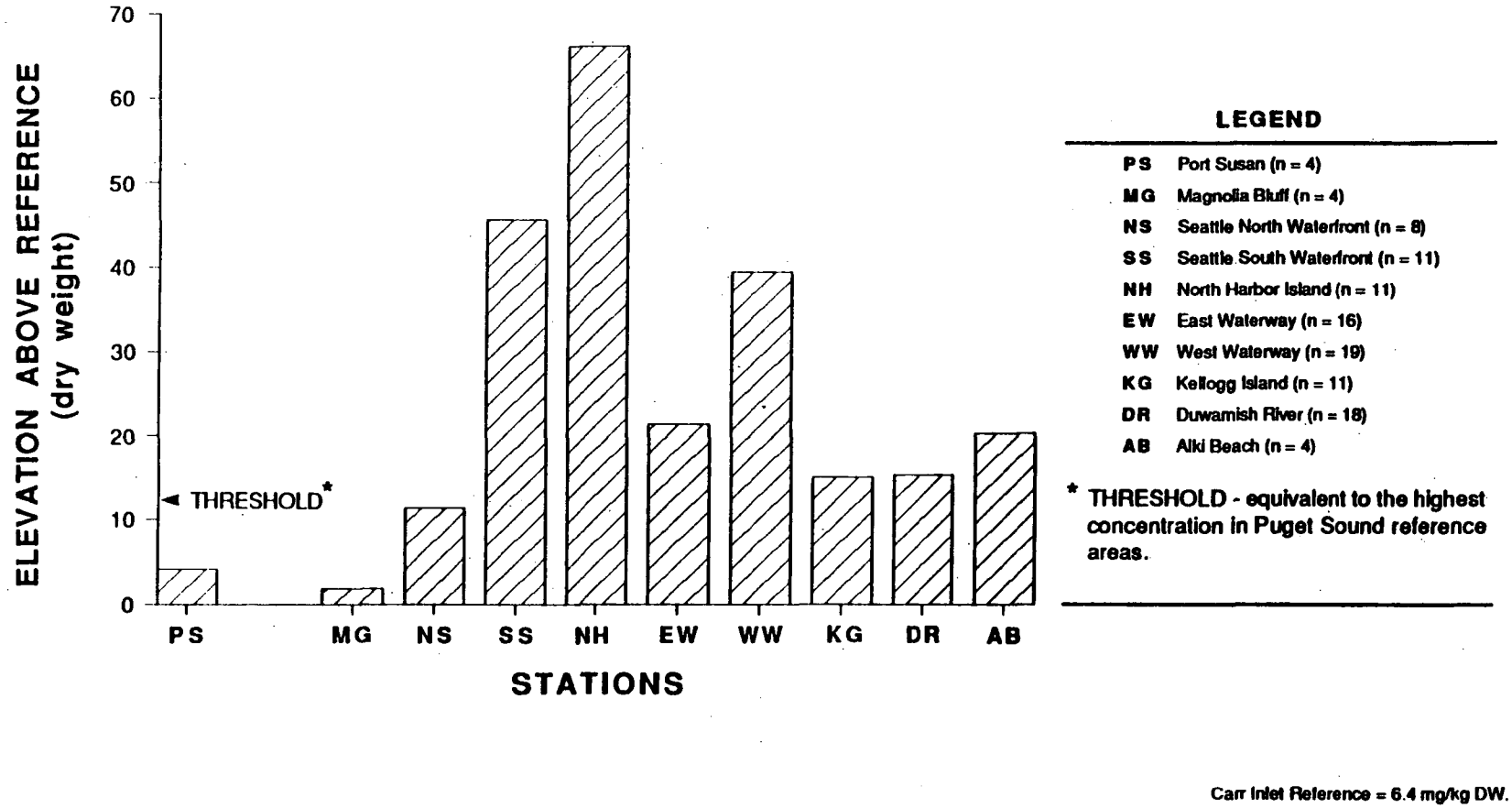


Figure 23. Mean elevations above reference (EAR) of copper in sediments from all study areas.

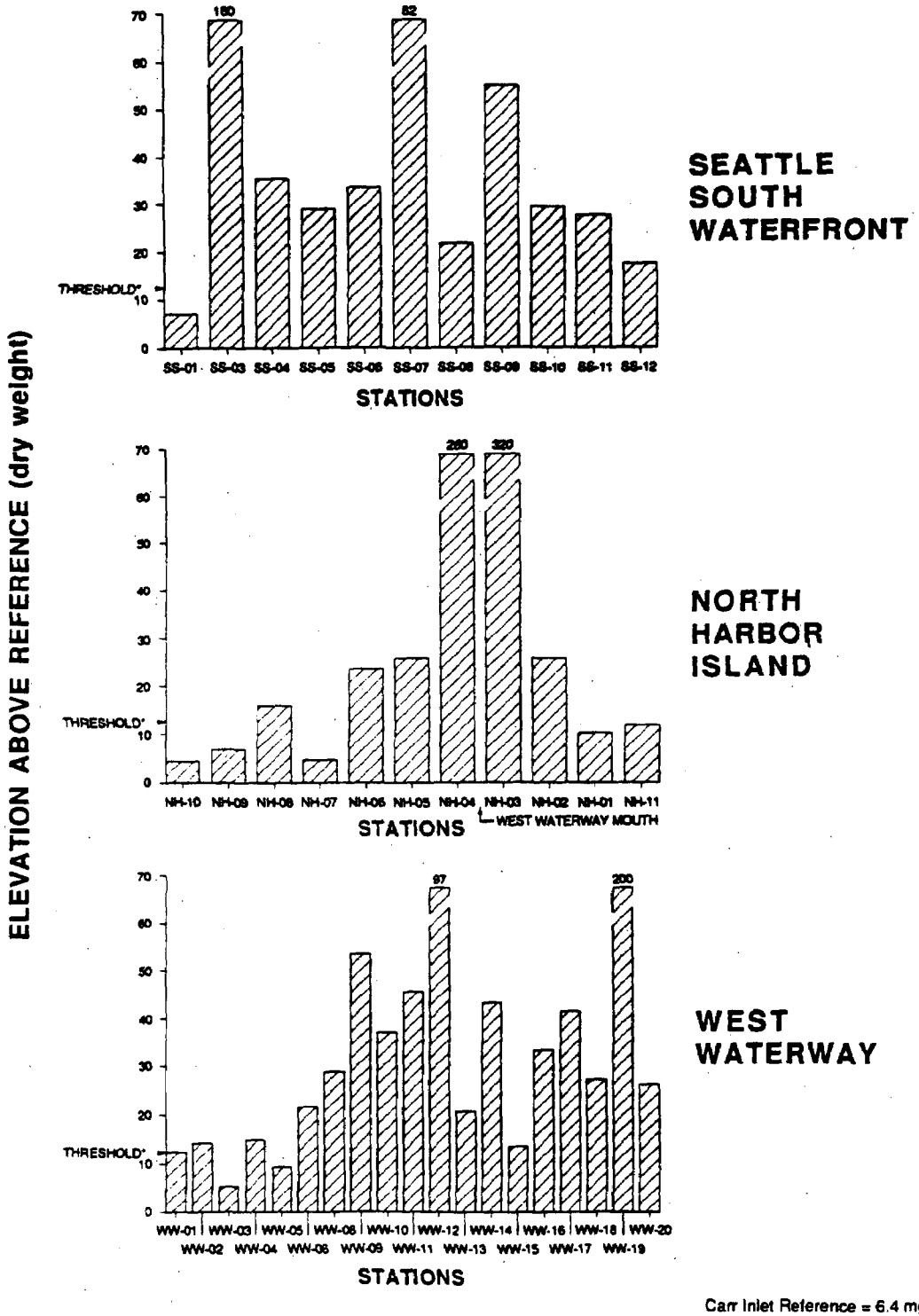


Figure 24. Elevations above reference of copper at individual stations in the most contaminated study areas.

However, these stations were not adjacent and copper concentrations along the waterfront were, in general, patchy (Figure 24). Based on normalization to percent fine-grained material, Station SS-07 had a higher copper concentration than Station SS-03, but no gradients were apparent with this normalization. Other areas were less contaminated, but EAR values of greater than 50 were observed at Alki Beach (Station AB-01, 440 mg/kg DW) and in the Duwamish River (Station DR-12, 386 mg/kg DW). Concentrations at stations in the vicinity of these samples were typically within or near the range of Puget Sound reference stations.

Lead--An extreme range of lead concentrations was observed in this study. The Seattle South waterfront and the West Waterway were the most contaminated areas (Figure 25). The highest concentration, observed at Station SS-09, was over 7 percent lead (71,000 mg/kg DW; EAR = 7,700). Lead concentrations at adjacent SS stations were over 200 times lower (Figure 26) and were relatively constant throughout the rest of the area. Station SS-03, far removed from Station SS-09, had the next highest lead concentration in this area (646 mg/kg DW).

Very high lead concentrations were reported on the east side of the West Waterway. Concentrations appeared to decrease with distance from Station WW-14 (8,730 mg/kg DW; EAR = 950). Moving south from Station WW-14, concentrations decreased from 1,180 mg/kg DW (WW-12) to roughly 700 mg/kg DW (WW-11 and WW-09). Station NH-03, at the mouth of the West Waterway, had a lead concentration of 550 mg/kg DW (Figure 26). Patchy areas of moderate concentrations (e.g., EAR >30) were found in other areas, such as the East Waterway (Station EW-05), Kellogg Island (Stations KG-04 and KG-05), and other areas in the Duwamish River (Station DR-12).

Mercury--Mercury concentrations in this study ranged over three orders of magnitude (see Table 8) but were patchy in the areas of highest contamination. The highest concentration was observed in the Alki Beach area, at Station AB-01 (28.8 mg/kg DW; EAR = 720) (Figures 27 and 28). Adjacent stations had concentrations within the range of Puget Sound reference areas (Figure 28). A mercury concentration of 10.5 (EAR = 260) was observed at Station NH-03, near the mouth of the West Waterway. Adjacent stations had concentrations that were roughly 10 times lower on a dry weight or fines normalized basis (Figure 28). An isolated high concentration also occurred in the East Waterway (EW-05; 3.82 mg/kg DW). Concentrations along the Seattle South waterfront were generally elevated, except at Station SS-01 (Figure 28); SS station concentrations ranged from 0.905 to 3.89 mg/kg DW (excluding Station SS-01), with a mean EAR of 41.

Silver--Silver concentrations were most elevated along the Seattle waterfront. The highest concentration was located at intertidal Station NS-01 (8.27 mg/kg DW; EAR = 92) even though the sediment at this station was very coarse-grained, with less than 4 percent fine-grained material. Concentrations decreased moving south along the waterfront, from Station SS-12 (4.98 mg/kg DW) to Station SS-08 (1.99 mg/kg DW), and then increased at Stations SS-07, SS-06, and SS-05 (between 4.72 and 5.85 mg/kg DW). Other concentrations were typically within the range of Puget Sound reference areas (i.e., <3.3 mg/kg DW; see Table 9).

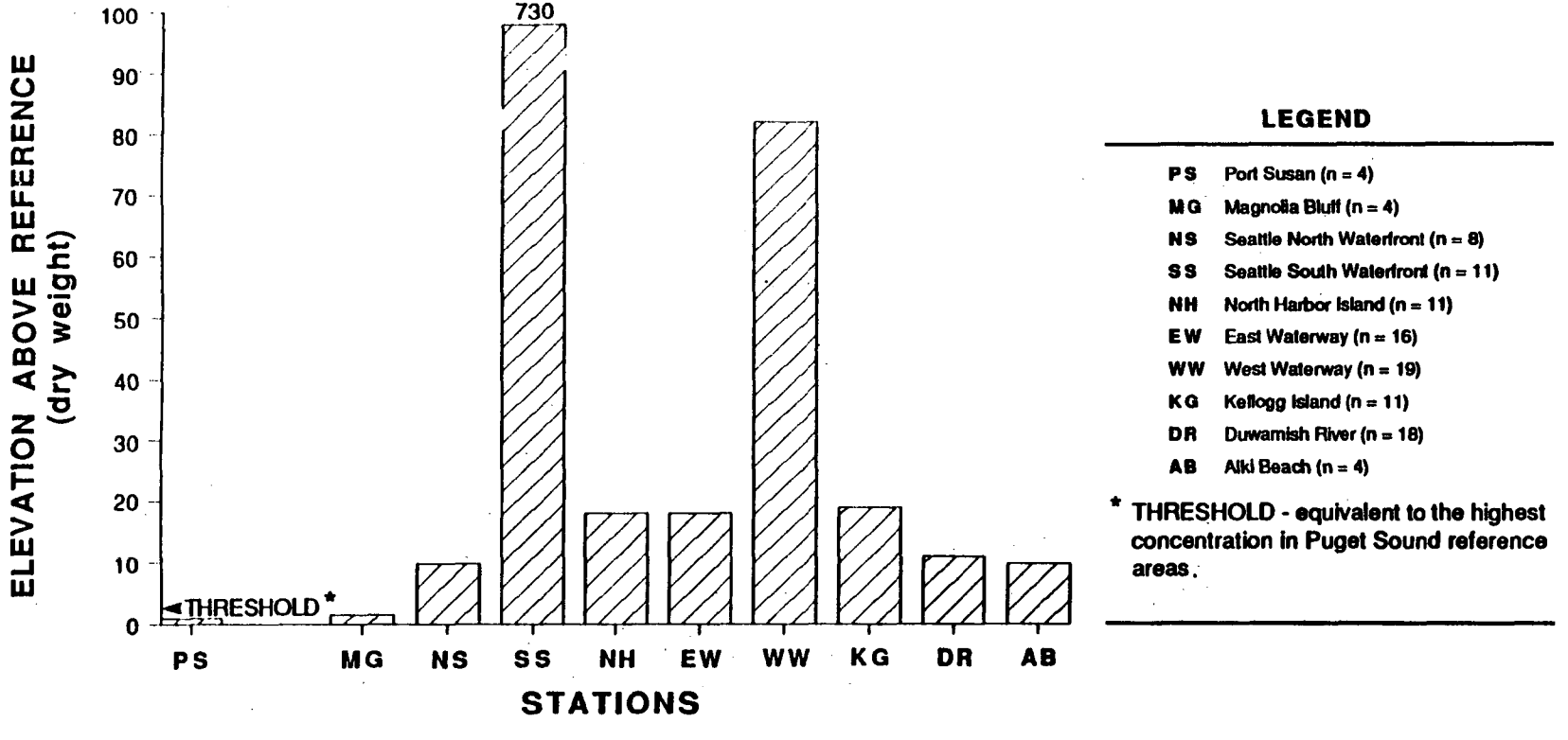


Figure 25. Mean elevations above reference (EAR) of lead in sediments from all study areas.

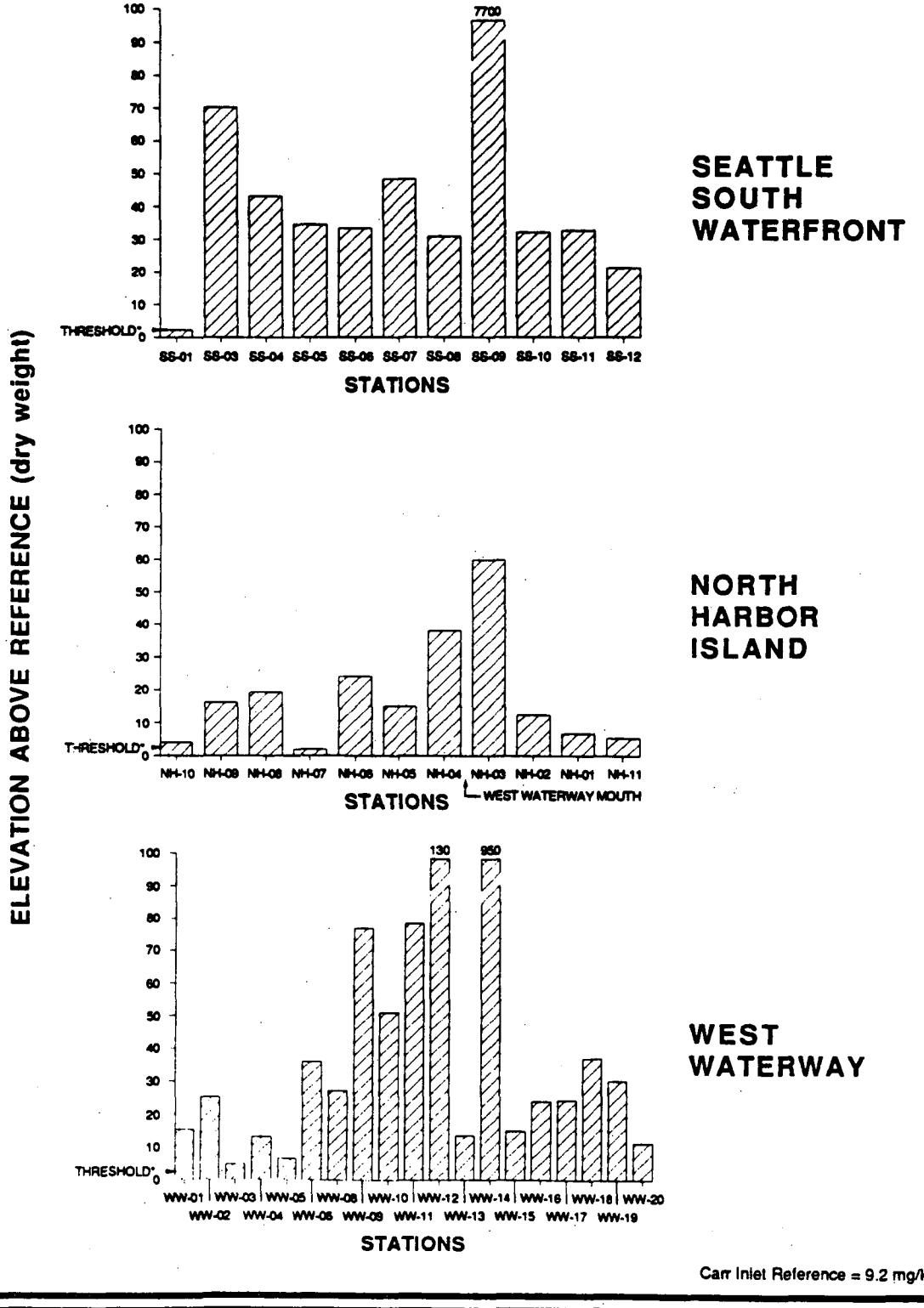


Figure 26. Elevations above reference (EAR) of lead at individual stations in the most contaminated study areas.

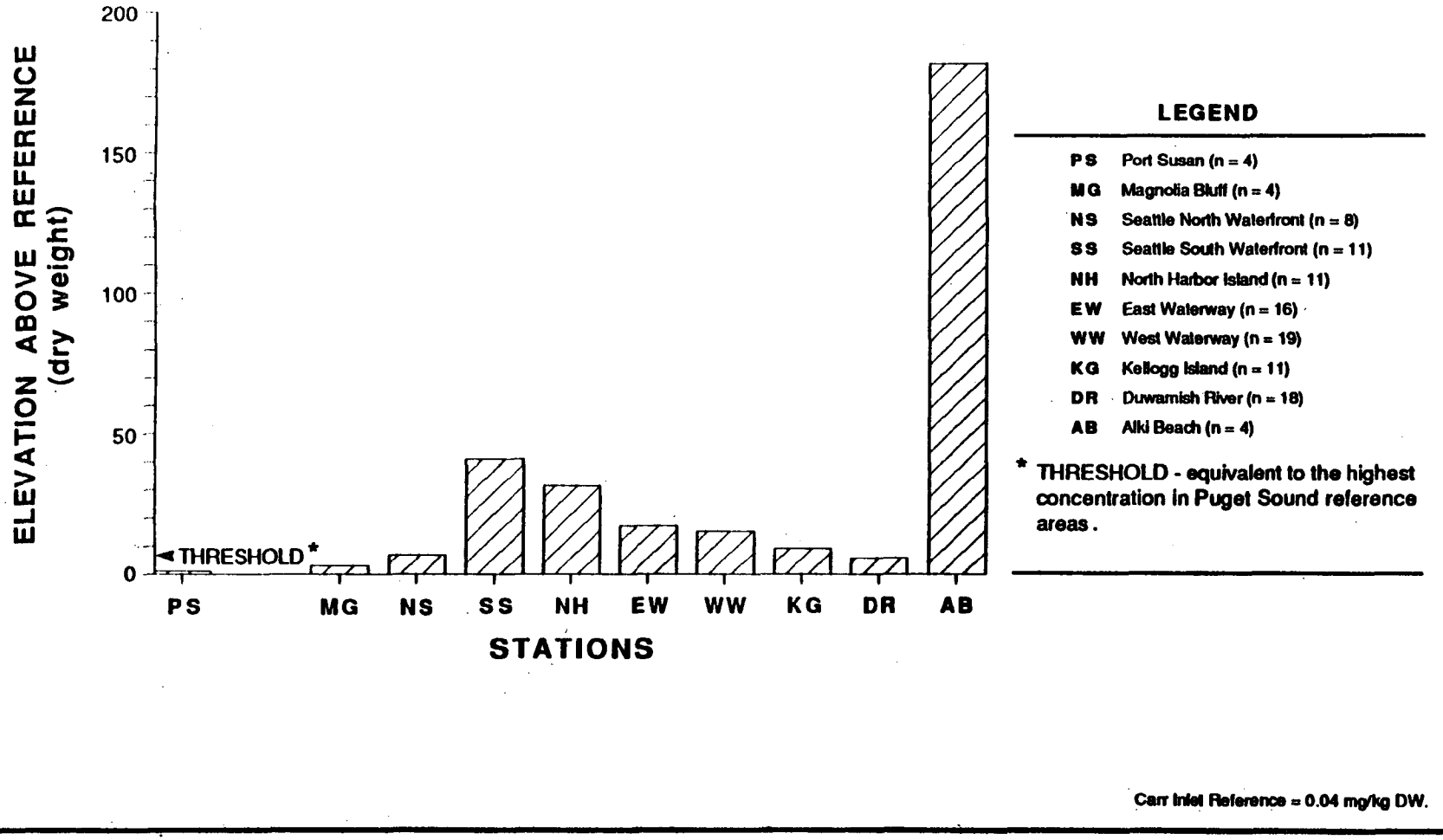


Figure 27. Mean elevations above reference (EAR) of mercury in sediments from all study areas.

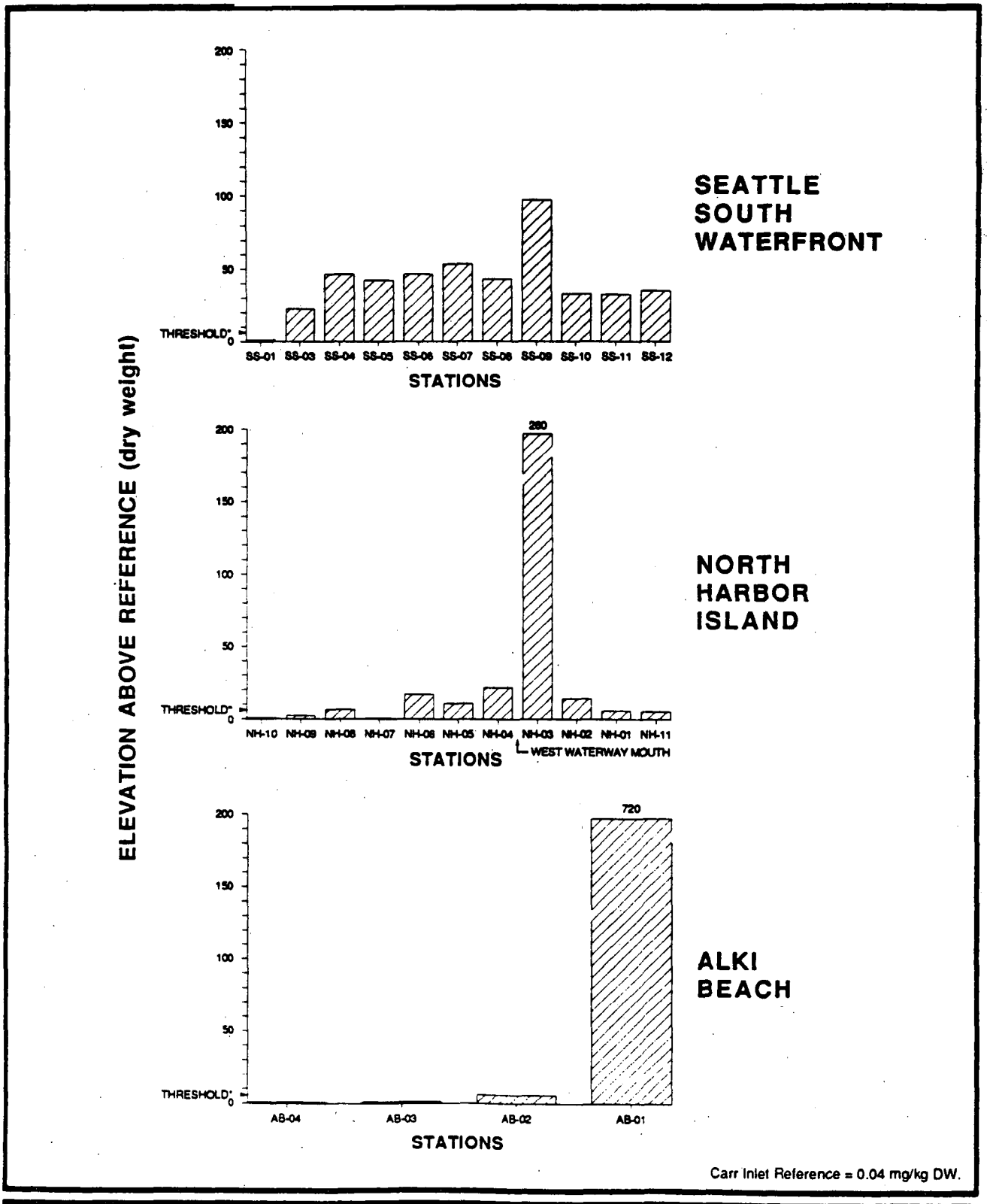


Figure 28. Elevations above reference (EAR) of mercury at individual stations in the most contaminated study areas.

Zinc--Zinc concentrations were elevated above Puget Sound reference conditions in much of the study area, although the most highly elevated concentrations were along the Seattle South waterfront (Figure 29). The maximum concentration, 6,010 mg/kg DW (EAR = 320), occurred at Station SS-09. The next highest concentration in the study was observed at Station SS-03 (4,830 mg/kg DW). Zinc concentrations at intervening stations were relatively constant and were more than 10 times lower than observed at Stations SS-09 and SS-03 (Figure 30).

The area near the mouth of the West Waterway also had highly elevated zinc concentrations, particularly Stations NH-03 and NH-04 (1,300 and 994 mg/kg DW, respectively) at the mouth, and Stations WW-12 and WW-19 (1,170 and 705 mg/kg DW, respectively) on the east side of the waterway (Figure 30). West of the mouth of the waterway, concentrations were greater than 600 mg/kg at Stations NH-06 and NH-08. However, these two stations were not adjacent and were separated by a less contaminated, coarse-grained sediment station (Figure 30).

High zinc concentrations were observed in isolated areas of contamination in the Duwamish River (e.g., near 1,000 mg/kg DW at KG-01 and DR-15). Somewhat lower concentrations (between 400 and 800 mg/kg DW) were observed in the East Waterway (Stations EW-05, EW-06 and EW-15).

Sediment Chemistry: Organic Compounds

The ranges in concentration (ug/kg DW) and detection frequencies of semivolatile compounds detected at least once in the study area are presented in Table 12.

Acid and neutral priority pollutants that were searched for but not found in any samples were 2-chlorophenol, 2,4-dichlorophenol, 2,4,5- and 2,4,6-trichlorophenol, 4-chloro-3-methylphenol, 2-chloronaphthalene, 1,2- and 1,3-dichlorobenzene, hexachlorobenzene, isophorone, and hexachlorobutadiene. Priority pollutant pesticides that were searched for but not detected in any samples included alpha-, beta-, and gamma-hexachlorocyclohexane (HCH). TIOs searched for but not found were tri-, tetra-, and pentachlorobutadienes, coprostanol, and alpha-tocopheryl acetate.

Relatively high detection limits may have precluded the detection of certain semivolatile organic compounds at moderate to high concentrations. Among the undetected or infrequently detected compounds that had high detection limits were all chlorinated benzenes, hexachlorobutadiene, several substituted phenols (e.g., pentachlorophenol and other chlorinated phenols), benzoic acid, and benzyl alcohol. Acid/neutral organic compounds for which detection limits exceeded existing Puget Sound AET (when available) for more than roughly half the stations are presented in Table 13. For the compounds in Table 13, characterization of spatial concentration gradients is inconclusive in most areas. The implications of detection limits for data analysis will be discussed on a chemical-by-chemical basis in the following section, when appropriate.

The 16 EPA priority pollutant PAH (2-6 rings) were the most frequently detected organic compounds in the study and occurred at the highest concentrations of all organic compounds (Table 12). Wide concentration ranges

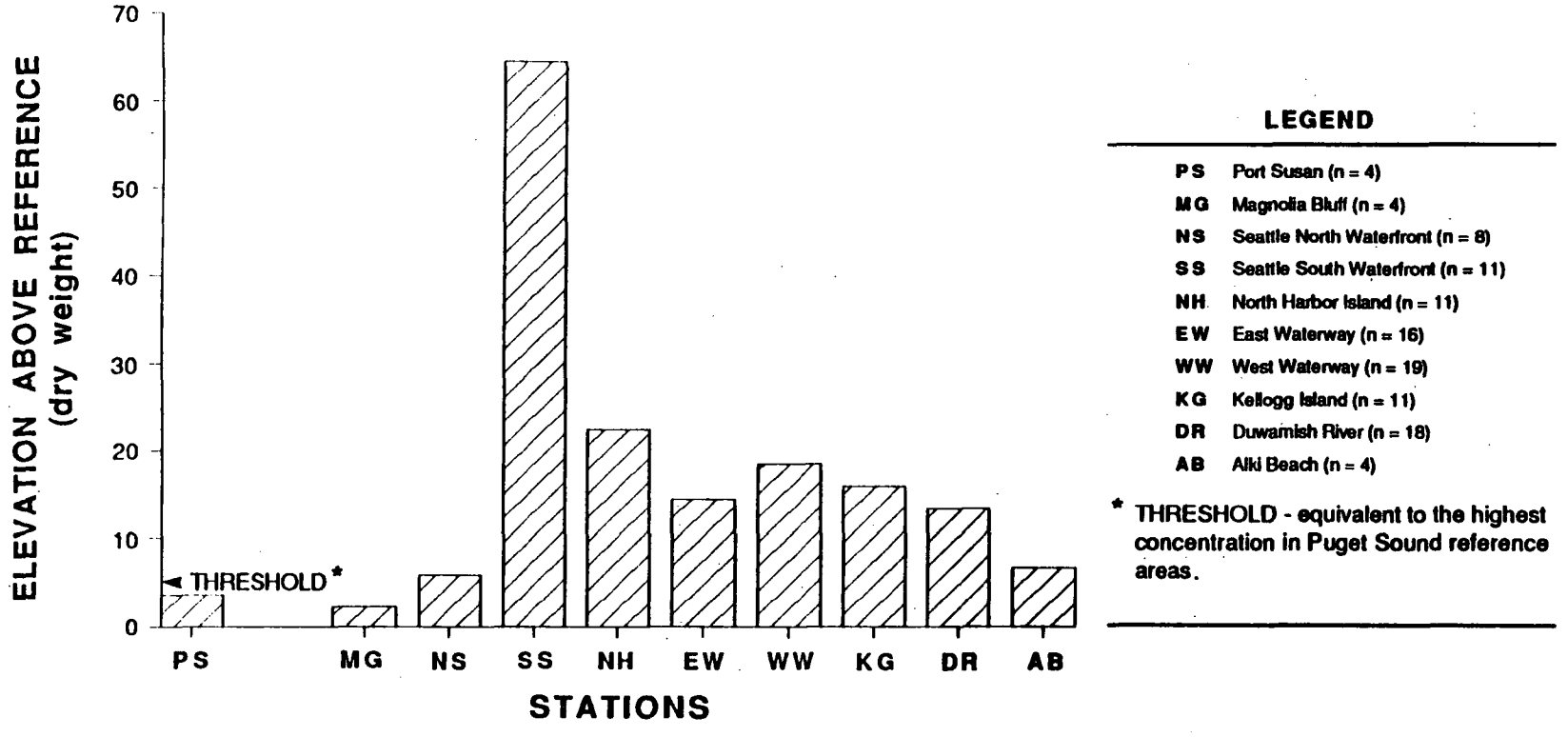


Figure 29. Mean elevations above reference (EAR) of zinc in sediments from all study areas.

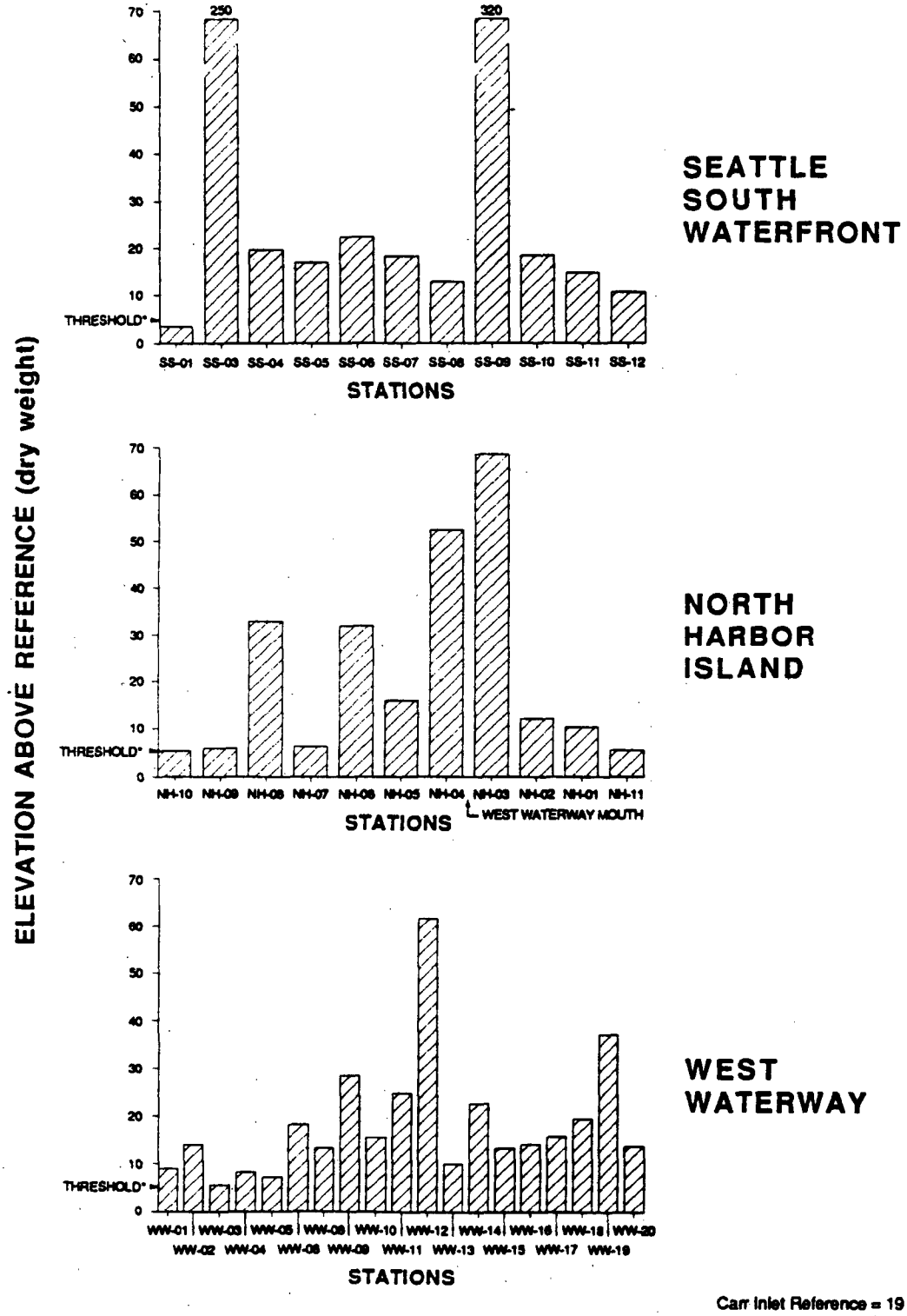


Figure 30. Elevations above reference (EAR) of zinc at individual stations in the most contaminated study areas.

TABLE 12. CONCENTRATIONS OF DETECTED SEMIVOLATILE ORGANIC COMPOUNDS IN SURFACE SEDIMENTS OF ELLIOTT BAY, DUWAMISH RIVER, AND PORT SUSAN[a]

Chemical	Range (ug/kg dry wt)[b]	Detection Frequency	Location of Maximum[b]
Low molecular weight PAH	E7 - 630,000	105/107	SS-08
naphthalene	XE2 - 15,000	66/107	NH-06
acenaphthylene	E1.7 - X37,000	62/107	SS-08
acenaphthene	U6 - 33,000	62/107	SS-08
fluorene	U3 - 37,000	65/107	SS-08
phenanthrene	E5.2 - 330,000	105/107	SS-08
anthracene	E2 - 190,000	93/107	SS-08
High molecular weight PAH	E24 - E3,200,000	107/107	SS-08
fluoranthene	E9.4 - 1,300,000	107/107	SS-08
pyrene	E8.0 - 740,000	107/107	SS-08
benz(a)anthracene	U2 - 300,000	101/107	SS-08
chrysene	U2.4 - 350,000	102/107	SS-08
benzofluoranthenes	E9.3 - 300,000	94/107	SS-08
benzo(a)pyrene	U3 - E100,000	92/107	SS-08
indeno(1,2,3-c,d)pyrene	E1.0 - E40,000	85/107	SS-08
dibenzo(a,h)anthracene	E1.0 - E12,000	63/107	SS-08
benzo(g,h,i)perylene	E1.2 - E32,000	83/107	SS-08
Total PCBs	E59 - E5,800	79/106	DR-08
Chlorinated benzenes			
1,4-dichlorobenzene	U1.0 - X31,000	7/107	SS-09
1,2,4-trichlorobenzene	U39 - E15[c]	1/107	DR-03
Phthalates			
dimethyl phthalate	E0.70 - X1,400	41/107	SS-11
butyl benzyl phthalate	U1 - 1,800	60/107	EW-07, EW-08, EW-09
di-n-octyl phthalate	U1 - Z9,900	40/106	NS-06
Pesticides			
p,p'-DDE	U1.1 - 62	4/107	DR-10
p,p'-DDD	U1.7 - E140	9/107	SS-09
p,p'-DDT	U1.4 - E270	6/107	KG-06
aldrin	U1.0 - E90	2/107	NH-10
delta-HCH	U0.8 - L17	1/107	WW-06
dieldrin	U1.3 - E51	1/106	NH-10
endrin	U1.4 - E8[c]	1/107	NH-10
endrin aldehyde	U1.9 - 68	2/107	DR-08
heptachlor	U0.9 - E6[c]	1/107	NH-10
chlordane	U6.4 - L200	1/106	EW-05

TABLE 12. (Continued)

Chemical	Range (ug/kg dry wt)[b]	Detection Frequency	Location of Maximum[b]
Phenols			
phenol	XE0.9 - X1,200	36/107	DR-25
2-methylphenol	U3 - E280	2/107	DR-25
4-methylphenol	E2 - 2,600	32/107	WW-19
2,4-dimethylphenol	U2.6 - E210	2/107	SS-07
pentachlorophenol	U38 - X6,000	8/107	NH-04
Miscellaneous extractables and tentatively identified compounds			
benzyl alcohol	E5.2 - E8,800	5/107	WW-02
benzoic acid	U25 - 6,300	1/106	KG-10
dibenzofuran	U2.9 - 7,100	80/107	SS-08
2-methylnaphthalene	E0.3 - 3,300	66/107	SS-08
1-methylphenanthrene	U[d] - E100,000	70/107	SS-08
2-methylphenanthrene	U[d] - E110,000	71/107	SS-08
3-methylphenanthrene	U[d] - E97,000	69/107	SS-08
biphenyl	U[d] - E1,800	27/107	NH-06
retene	U[d] - E10,000	56/107	KG-10
carbazole	U[d] - E1,200	45/107	NH-06

[a] Qualifiers:

U = Substance undetected at the detection limit shown.
E = Estimated value.
X = The surrogate recovery for this compound was low (<10 percent). Hence, the recovery correction was at least a factor of 10.
L = The reported concentration is the mean of a detected value and a detection limit.
Z = Value corrected for blank contributions; the resulting value still exceeds the detection limit.

[b] Maximum is the highest detected value even if maximum detection limits were higher.

[c] Maximum detected concentration does not exceed the maximum concentration in Puget Sound reference areas.

[d] This tentatively identified organic compound was not found during a mass spectral search of a sample extract. Actual detection limits for tentatively identified compounds were not assigned in these cases.

TABLE 13. INFREQUENTLY DETECTED ACID/NEUTRAL COMPOUNDS WITH HIGH DETECTION LIMITS[a]

Chemical	LAET[b] (ug/kg DW)	No. Samples with Detection Limits ≥100	≥1,000	≥10,000	Range of Detection Limit
1,2-dichlorobenzene	35	65	24	0	U2 - U7,300
1,3-dichlorobenzene	>170	83	27	0	U2 - U7,300
1,4-dichlorobenzene	110	71	27	0	U2 - U7,300
1,2,4-trichlorobenzene	31	73	35	14	U39 - U73,000
hexachlorobenzene	70	66	25	3	U18 - U99,000
hexachlorobutadiene	120	105	56	22	U34 - U150,000
2,4-dichlorophenol	NA[c]	45	26	12	U9 - U20,000
2,4,5-trichlorophenol	NA	41	24	5	U8 - U14,000
2,4,6-trichlorophenol	NA	39	24	6	U7 - U19,000
pentachlorophenol	>140	94	62	17	U38 - U84,000
2,4-dimethylphenol	29	44	17	0	U3 - U7,300
benzoic acid	650	56	28	11	U25 - U46,000
benzyl alcohol	57	81	15	4	U33 - U22,000

[a] Criteria for inclusion in this table: compound is undetected in more than roughly half the samples in the study at detection limits above the lowest Puget Sound AET (Tetra Tech 1986c, 1987) or above 100 ug/kg DW if no AET value is available.

[b] Lowest of AET values based on benthic infaunal abundances and amphipod, oyster larvae, and Microtox bioassays; taken from Tetra Tech (1986c, 1987). The ">" values shown in this table are considered less reliable than unqualified AET and were not used during problem identification.

[c] Not available.

(e.g., over five orders of magnitude) were observed for individual PAH. Maximum concentrations of individual PAH (except naphthalene) were observed along the Seattle South waterfront (Station SS-08); naphthalene maximized at Station NH-06 (west of the mouth of the West Waterway) (Table 12). The total PAH concentration at Station SS-08 was roughly 4,000,000 ug/kg DW (i.e., 0.4 percent DW). Among the TIOs typically associated with PAH, alkylated PAH (e.g., methyl naphthalene and methyl phenanthrenes), and dibenzofuran also maximized at Station SS-08. Maximum concentrations of biphenyl and carbazole were found at Station NH-06.

The Seattle South waterfront had maximum concentrations of chemicals other than PAH. For example, 1,4-dichlorobenzene and p,p'-DDD maximized at Station SS-09 (as did cadmium, lead, and zinc) (see Tables 8 and 12). Maximum concentrations of a number of chemicals were found in various sections of the Duwamish River. The maximum PCB concentration was observed in the Duwamish River (Station DR-08), as were the maximum concentrations of several chlorinated pesticides (e.g., p,p'-DDE at Station DR-10 and endrin aldehyde at Station DR-08). Phenol and 2-methylphenol concentrations maximized at intertidal Station DR-25.

Compounds detected infrequently (i.e., one or two times) in the study included 1,2,4-trichlorobenzene, 2-methylphenol, 2,4-dimethylphenol, benzoic acid, and seven chlorinated pesticides (aldrin, delta-HCH, dieldrin, endrin, endrin aldehyde, heptachlor, and chlordane) (see Table 12). These compounds will not be considered for describing spatial correlations among chemicals, but will be included in the chemical characterization of problem areas (see PRIORITIZATION OF PROBLEM AREAS AND CONTAMINANTS).

Volatile organic compounds were measured at 28 of the 107 sediment stations. The concentration ranges and detection frequencies of compounds detected at least once are presented in Table 14. In general, concentration ranges were narrow and compounds were detected infrequently. Total xylenes (i.e., ortho-, meta-, and para- isomers) were most frequently detected among volatile organic compounds; the maximum concentration occurred in the West Waterway (Station WW-11). Trichloroethene was the next most frequently detected compound, but never exceeded 4 ug/kg DW (near detection limits). Other volatile organic compounds were detected only once or twice, and at relatively low concentrations. The maximum values were found near Kellogg Island; Station KG-05 had maximum concentrations of five of the eight volatile pollutants detected in this study. Data for three volatile compounds were rejected because of potentially high laboratory contamination (see METHODS, Sediment Chemistry, Quality Assurance/Quality Control Results).

Organic Compounds of Concern--

As described for metals, chemicals of concern are those chemicals that occur at concentrations exceeding the range of Puget Sound reference areas. The range of concentrations of organic compounds in Puget Sound reference areas are summarized in Table 15. Concentrations in Port Susan sediments analyzed for this study (PS-01 to PS-04) are included in Table 15. Station PS-05 (this study) was excluded from this table because it had PAH concentrations that were far above those characteristic of reference areas. In fact, the high molecular weight PAH concentration at Station PS-05, 28,000 ug/kg DW, exceeded existing AET based on amphipod mortality, oyster larvae

TABLE 14. CONCENTRATIONS OF VOLATILE ORGANIC COMPOUNDS IN SURFACE SEDIMENTS OF ELLIOTT BAY AND THE DUWAMISH RIVER[a]

Chemical	Range (ug/kg dry wt)[b]	Detection Frequency	Location of Maximum[b]
Total xylenes	E0.1 - E64	24/28	WW-11
Trichloroethene	E0.5 - E3.4	6/28	EW-09
Trans-1,2-dichloroethene	E0.8 - E8.9	2/28	KG-05
Toluene	U0.6 - Z54	3/28	KG-05
Ethyl benzene	U0.7 - Z10	1/28	NH-08
Chlorobenzene	U0.2 - Z26	2/28	KG-05
Tetrachloroethene	U0.1 - Z8.3	1/28	KG-05
1,1-Dichloroethane	U0.6 - E1.1	1/28	KG-05

[a] Only compounds that were detected one or more times are listed.

Qualifiers:

U = Substance undetected at the detection limit shown.
Z = Value corrected for blank contributions; the resulting value still exceeds the detection limit.
E = Estimated value.

[b] Maximum is highest detected value even if maximum detection limit was higher.

TABLE 15. SUMMARY OF ORGANIC COMPOUND CONCENTRATIONS IN SEDIMENTS FROM PUGET SOUND REFERENCE AREAS[a]

Chemical	Range (ug/kg dry wt)[b]	Detection Frequency	Reference Sites[c]
Low molecular weight PAH	4-L71 (L45-L71)	13/13	1,8,9
naphthalene	U0.5-U40 (X2-U26)	12/27	1,2,3,4,5,6,8,9
acenaphthylene	U0.1-U40 (U4.1-U9.3)	2/27	1,2,3,4,5,6,8,9
acenaphthene	U0.1-U40 (U6.7-U14)	4/27	1,2,3,4,5,6,8,9
fluorene	U0.1-40 (U6.7-U13)	7/28	All
phenanthrene	4-170 (E5.2-E17)	18/24	1,2,3,6,7,8,9
anthracene	U0.5-U40 (E2-U20)	11/24	1,2,3,6,7,8,9
High molecular weight PAH	34-L100 (E48-L100)	13/13	1,8,9
fluoranthene	5-100 (E9.4-E19)	24/29	All
pyrene	5-120 (E8.0-E19)	23/29	All
benz(a)anthracene	2-U40 (E2.8-E6.5)	15/24	1,2,3,6,7,8,9
chrysene	4-U40 (E5.0-E13)	15/24	1,2,3,6,7,8,9
benzo(b)fluoranthene	U5-94 (U5.9-E8.3)	15/25	1,2,3,4,5,6,7,8
benzo(k)fluoranthene	E4.8-94 (E4.8-U7.5)	15/25	1,2,3,4,5,6,7,8
benzo(a)pyrene	U0.37-40 (U3.8-E15)	16/21	1,3,4,5,6,7,8,9
indeno(1,2,3-c,d)pyrene	U0.37-30 (E2.2-U8.2)	10/19	1,4,5,6,7,8,9
dibenzo(a,h)anthracene	U0.4-E10 (E1-U13)	3/12	1,8,9
benzo(g,h,i)perylene	E1.2-20 (E1.2-U7.6)	8/13	1,7,8,9
Total PCBs	3.1-U50[d] (U120-U170)	7/22	1,2,3,4,6,7,9
Chlorinated benzenes			
1,4-dichlorobenzene	U0.06-U40[d] (U20-U120)	1/23	1,2,3,4,5,8,9
1,2,4-trichlorobenzene	U0.5-U16[d] (U75-U190)	0/9	1,9
Phthalate esters			
dimethyl phthalate	U0.5-U50 (E0.7-U7.5)	1/12	1,8,9
butyl benzyl phthalate	U0.5-U25 (U3.7-E14)	3/12	1,8,9
di-n-octyl phthalate	U0.5-E56 (E3.0-E56)	4/12	1,8,9
Pesticides[e]			
p,p'-DDE	U1.6-U10 (U1.6-U2.1)	0/8	1,8,9
p,p'-DDD	U1.9-U10 (U1.9-U2.6)	0/9	1,8,9
p,p'-DDT	U1.0-U10 (U1.7-U2.3)	0/8	1,8,9
aldrin	U0.5-U10 (U1.4-U1.9)	0/9	1,8,9
chlordane	U5-U50 (U23-U31)	0/13	1,8,9
endrin aldehyde	U2.3-U10 (U2.3-U3.2)	0/5	1,8
delta-HCH	U0.5-U10 (U1.0-U1.4)	0/9	1,8,9
dieldrin	U1-U10 (U1.3-U1.8)	0/9	1,8,9
endrin	U1-U10 (U1.8-U2.4)	0/9	1,8,9
heptachlor	U0.5-U10 (U1.3-U1.8)	0/9	1,8,9

TABLE 15. (Continued)

Chemical	Range (ug/kg dry wt)[b]	Detection Frequency	Reference Sites[c]
Phenols			
phenol	U0.5-62[f] (U3.3-E33)	5/17	1,2,3,8
2-methylphenol	U0.7-U50 (U3.3-U11)	0/11	--
4-methylphenol	U0.8-290 (E2-U8.3)	7/11	1,8,9
2,4-dimethylphenol	U1-U14 (U4.7-U14)	0/13	1,8,9
pentachlorophenol	0.1-U50[d] (U38-U220)	1/10	1,8,9
Miscellaneous extractables			
benzyl alcohol	U3.4-U20[d] (U58-U340)	0/6	1,8,9
benzoic acid	U7.2-430[d] (U46-U110)	4/6	1,8,9
dibenzofuran	U5-E14 (U6.6-E14)	4/11	1,8,9
2-methylnaphthalene	E0.3-U22 (E0.3-U22)	10/17	1,4,5,6,8,9
1-methylphenanthrene[g]	U[h]-E7.1	1/4	8
2-methylphenanthrene[g]	U[h]-E5.8	1/4	8
3-methylphenanthrene[g]	U[h]	0/4	8
biphenyl[g]	U[h]	0/4	8
retene[g]	U[h]-E130	6/10	1,8
carbazole[g]	U[h]	0/4	8

[a] This table includes only chemicals that were detected in the present study.

Qualifiers:

L = The sum has incorporated detection limits for one or more PAH compounds and is considered a maximum estimate.
U = Undetected at the detection limit shown.
E = Estimated value.
X = The surrogate recovery for this compound was low (<10 percent).

[b] The range of Port Susan concentrations from this study is in parentheses. Station PS-05 (this study) had anomalously high concentrations of numerous chemicals and was excluded from this table for reasons discussed in text.

[c] Reference sites:
1. Carr Inlet
2. Samish Bay
3. Dabob Bay
4. Case Inlet
5. Port Madison
6. Port Susan
7. Nisqually Delta
8. Port Susan (this study)
9. Port Susan (1986)

[d] Detection limits for this chemical or chemical group that exceeded 50 ug/kg have been excluded for the purpose of reference area comparisons; this is consistent with treatment of reference area data in Tetra Tech (1985a).

[e] Higher detection limits for single component pesticides (U25) were reported for Main Sediment Quality Survey samples from Carr Inlet in Tetra Tech (1985a). However, these detection limits were based on GC/MS analysis, which is less sensitive than GC/ECD and was considered undesirable for characterizing reference areas. GC/ECD analyses for Carr Inlet samples in the Preliminary Survey (Tetra Tech 1985a) resulted in the U10 values.

TABLE 15. (Continued)

[f] An anomalously high phenol value of 1,800 ug/kg dry wt was found at one Carr Inlet station (Tetra Tech 1985a). For the purpose of reference area comparison, this value has been excluded. Data from Site 9 were excluded because laboratory contamination of phenol was observed during analysis of these reference area samples

[g] Tentatively identified compound.

[h] U - This tentatively identified compound was not found during a mass spectral search of reference sample extracts. Actual detection limits for tentatively identified compounds were not assigned in these cases.

References:

(Site 1) Tetra Tech (1985a); Mowrer et al. (1977)
(Site 2) Battelle (1986)
(Site 3) Battelle (1986); Prahl and Carpenter (1979)
(Site 4) Malins et al. (1980); Mowrer et al. (1977)
(Site 5) Malins et al. (1980)
(Site 6) Malins et al. (1982)
(Site 7) Barrick and Prahl (1987); Mowrer et al. (1977)
(Site 8) This study; Port Susan Stations PS-01 through PS-04
(Site 9) PTI and Tetra Tech (1988).

abnormality, and Microtox bioassays (Tetra Tech 1987). The remaining four Port Susan stations from this study had concentrations of PAH that were roughly two orders of magnitude lower and concentrations of other organic compounds that were typically within the existing range of Puget Sound reference areas (Table 15).

The three semivolatile organic compounds that did not exceed the range of reference concentrations were 1,2,4-trichlorobenzene, endrin, and heptachlor (see Tables 12 and 15); these three compounds were detected only once in the study (see Table 12). These compounds are thus of relatively minor concern and will not be discussed further.

Puget Sound reference area data were not available for most volatile organic compounds. In the absence of reference area data, volatile contaminants were considered of concern only if they exceeded a concentration of 10 ug/kg DW at one or more stations. The concentration of 10 ug/kg was chosen as a reasonable detection limit for relatively uncontaminated sediments (e.g., Tetra Tech 1986f). Based on this assigned concentration, the volatile organic compounds of concern are total xylenes, toluene, and chlorobenzene. Of these compounds, only total xylenes were detected more than three times in the study. The highest concentrations of chlorobenzene and toluene were qualified with a Z, indicating that these compounds were also found in blanks. Although concentrations exceeded those of corresponding blanks, the blank contamination of volatile compounds is often variable. Hence, these data are considered less reliable than total xylene data. Volatile organic compounds will not be discussed further in this section but were considered during problem area identification.

Distributions of selected contaminants of concern are summarized in terms of EAR values in Table 16. Summaries of distributions of organic chemicals with EAR between 100 and 1,000 are presented in Tables 17 and 18; distributions of chemicals with EAR greater than 1,000 are presented in Tables 19 and 20. The distributions of the organic chemicals of concern that were highly elevated and fairly widespread in the study area are described below.

Polycyclic Aromatic Hydrocarbons--To facilitate data analysis and to maximize comparability with data analyses performed for other Puget Sound studies, the 16 individual EPA priority pollutants were treated as two groups: LPAH and HPAH. This grouping was considered to be a reasonable data reduction method because the concentrations of individual PAH within each group tended to correlate well. It is also a reasonable grouping for potential source correlations, as relatively high concentrations of LPAH are characteristic of petroleum-derived materials whereas relatively high concentrations of HPAH are more characteristic of combustion-derived materials (e.g., Readman et al. 1982; Prahl and Carpenter 1983; Tetra Tech 1985a).

A Pearson correlation analysis including all individual PAH data was performed (see Appendix C) and scatterplots of the correlations were analyzed. Correlation coefficients (r) among the six LPAH (using dry weight concentrations) ranged from a relatively poor 0.29 to a very strong >0.99 ($P<0.05$). However, of all 16 unique correlations among these six chemicals, 11 had r values of greater than 0.95. The correlations of naphthalene with

TABLE 16. RANGE IN EAR FOR SELECTED ORGANIC CONTAMINANTS OF CONCERN IN SEDIMENTS OF ELLIOTT BAY AND THE DUWAMISH RIVER[a]

Chemical	EAR[b] Range	Median[c]	Threshold[d]	Areas where Threshold Exceeded by 10 Times[e]
LPAH	0.2 - 15,000	32	1.7	AB,DR,EW,KG,NH,NS,SS,WW
HPAH	0.3 - 41,000	75	1.3	AB,DR,EW,KG,NH,SS,WW
Total PCBs	9.8 - 970	80	8.3	DR,EW,KG,NH,SS,WW
1,4-Dichlorobenzene	0.3 - 8,900	17	11	SS
Dimethyl phthalate	0.02 - 35	0.5	1.3	SS,WW
Butyl benzyl phthalate	0.06 - 110	1.2	1.5	DR,EW,KG,SS
Di-n-octyl phthalate	0.05 - 490	0.9	2.8	DR,NS,SS
p,p'-DDD	0.17 - 14	0.97	1.0	NH, SS
p,p'-DDT	0.14 - 27	0.87	1.0	EW, KG, SS
Phenol	0.03 - 36	0.67	1.9	DR
4-Methylphenol	0.15 - 200	2.0	22	--
Pentachlorophenol	1.1 - 180	2.8	1.5	EW,NH
Benzyl alcohol	0.5 - 880	8.3	2.0	EW,SS,WW
Dibenzofuran	0.8 - 1,900	24	3.8	AB,DR,EW,KG,NH,NS,SS,WW
2-Methylnaphthalene	0.1 - 900	12	6.0	AB,EW,KG,NH,SS,WW
Retene	U[f] - 370	3.3	4.8	EW,KG,SS

[a] This table includes only compounds that were detected five times or more in the study. Certain TIOs were not included because of the unavailability of reference concentrations.

[b] Dry-weight concentration in study area sediments divided by the average concentration measured in six Carr Inlet sediments (taken from Tetra Tech 1985a).

[c] Medians are based on data after exclusion of detection limits >100 ug/kg DW for acid/neutral compounds and PCBs, and >25 ug/kg DW for single component pesticides.

[d] The threshold EAR is defined as the ratio of the maximum reference sediment concentration in Puget Sound divided by the average for six Carr Inlet reference sediments. Above the threshold EAR, the dry-weight concentration of a study area sediment contaminant would exceed the maximum concentration (or detection limit) reported for any Puget Sound reference site listed in Table 15.

[e] The contaminant EAR in sediments from at least one station in each listed area exceeded the threshold level by at least one order of magnitude. The factor of 10 is arbitrary, but is useful for indicating the areas of greatest contamination. It was not used in problem area identification or ranking. Sediments in the underlined areas had the highest observed concentrations.

[f] Retene is a tentatively identified compound for which detected limits are not reported. Hence, the lower end of the range is unknown.

TABLE 17. SUMMARY OF SEMIVOLATILE ORGANIC CHEMICALS WITH EAR BETWEEN 100-1,000 IN SEDIMENTS OF ELLIOTT BAY AND THE DUWAMISH RIVER (USING AREA MEANS)[a]

Chemical	Area
Low molecular weight PAH	EW, NH
naphthalene	AB, NH, SS
acenaphthene	EW, NH
fluorene	EW, NH
phenanthrene	AB, EW, NH, WW
anthracene	AB, EW, NH
High molecular weight PAH	AB, EW, NH, NS, WW
fluoranthene	AB, EW, NH, NS, WW
pyrene	AB, EW, NH, NS, WW
benz(a)anthracene	AB, EW, NH, NS, WW
chrysene	EW, NH, WW
benzofluoranthenes	AB, EW, NH, NS, WW
benzo(a)pyrene	AB, EW, NH, NS, WW
indeno(1,2,3-c,d)pyrene	AB, EW, NH, NS, WW
dibenzo(a,h)anthracene	NH, SS
benzo(g,h,i)perylene	AB, EW, NH
Total PCBs	DR, EW, KG, NH, SS
2-Methylnaphthalene	KG, NH, SS
Dibenzofuran	EW, NH, SS
Benzyl alcohol	WW
1,4-Dichlorobenzene	SS

[a] Concentrations averaged over all stations in the area indicated.

Detection limits >100 ug/kg DW have been excluded from these means.

TABLE 18. SUMMARY OF SEMIVOLATILE ORGANIC CHEMICALS WITH EAR BETWEEN 100-1,000 IN SEDIMENTS OF ELLIOTT BAY AND THE DUWAMISH RIVER (USING INDIVIDUAL STATIONS)

Chemical	Station
Low molecular weight PAH	AB-01, DR-16, EW-02, EW-04, EW-06, EW-14, NH-03, NH-04, NH-05, NH-08, NS-07, SS-03 to SS-07, SS-09, SS-10, SS-11, WW-04, WW-09, WW-12
naphthalene	AB-01, AB-02, NH-03, NH-05, SS-04 to SS-11
acenaphthylene	EW-06, EW-14, NH-04, NH-06, NH-08, SS-04 to SS-07, SS-09, SS-10
acenaphthene	AB-01, DR-16, EW-12, EW-14, NH-03, NH-04, NH-05, NS-08, SS-03 to SS-07, SS-09, WW-04, WW-09
fluorene	AB-01, DR-16, EW-06, EW-14, NH-03 to NH-05, NS-07, SS-03 to SS-07, SS-09, WW-04, WW-09
phenanthrene	AB-01, AB-02, DR-12, DR-16, EW-04, EW-06, EW-11, EW-12, EW-14, KG-01, KG-07, NH-02 to NH-05, NS-02, NS-07, NS-08, SS-03 to SS-07, SS-09 to SS-11, WW-04, WW-06, WW-09 to WW-14, WW-16 to WW-18
anthracene	AB-01, DR-16, EW-02, EW-04, EW-06, EW-11, EW-14, NH-03 to NH-05, NH-08, NS-07, NS-08, SS-03 to SS-05, SS-07, SS-09 to SS-11, WW-04, WW-09, WW-11, WW-12, WW-14, WW-16
High molecular weight PAH	AB-01, AB-02, DR-16, EW-02 to EW-04, EW-06, EW-07, EW-09, EW-11, EW-14, EW-15, KG-01, KG-07, KG-09, NH-01 to NH-05, NS-07, NS-08, SS-03 to SS-07, SS-10, SS-11, WW-04, WW-06, WW-09 to WW-14, WW-16 to WW-19
fluoranthene	AB-01, DR-02, DR-12, DR-16, EW-02, EW-04, EW-06, EW-07, EW-09, EW-11, KG-01, KG-07, NH-01 to NH-05, NH-08, NS-07, NS-08, SS-03 to SS-07, SS-09 to SS-11, WW-06, WW-09 to WW-14, WW-16 to WW-19
pyrene	AB-01, AB-02, DR-12, DR-16, EW-02, EW-04, EW-06, EW-07, EW-09, EW-11, EW-12, EW-15, KG-01, KG-07, KG-09, NH-01 to NH-05, NS-07, NS-08, SS-03 to SS-05, SS-07, SS-10 to SS-12, WW-04, WW-06, WW-09 to WW-14, WW-16 to WW-19

TABLE 18. (Continued)

Chemical	Station
benz(a)anthracene	AB-01, AB-02, DR-08, DR-16, EW-02 to EW-04, EW-06, EW-07, EW-09 to EW-12, EW-14, EW-15, KG-01, KG-07, KG-09, NH-01 to NH-05, NS-07, NS-08, SS-03 to SS-07, SS-10 to SS-12, WW-04, WW-06 to WW-14, WW-16 to WW-19
chrysene	AB-01, EW-02, EW-04, EW-06 to EW-12, EW-14, EW-15, KG-01, KG-07, KG-09, NH-01 to NH-05, NS-07, NS-08, SS-03 to SS-07, SS-10 to SS-12, WW-04, WW-06, WW-09 to WW-14, WW-16 to WW-19
benzofluoranthenes	AB-01, AB-02, DR-16, EW-02 to EW-04, EW-06 to EW-09, EW-11, EW-12, EW-14, EW-15, KG-01, KG-09, NH-01 to NH-05, NS-07, NS-08, SS-03 to SS-05, SS-07, SS-10, SS-11, WW-04, WW-06 to WW-14, WW-16 to WW-20
benzo(a)pyrene	AB-01, AB-02, DR-08, DR-16, EW-02 to EW-04, EW-06 to EW-09, EW-11, EW-14, EW-15, KG-01, KG-09, NH-01 to NH-05, NH-08, NS-07, NS-08, SS-03 to SS-07, SS-10, SS-11, WW-04, WW-06, WW-09 to WW-14, WW-16 to WW-19
indeno(1,2,3-cd)pyrene	AB-01, DR-08, DR-12, DR-16, EW-02, EW-04, EW-06, EW-07, EW-11, EW-14, EW-15, KG-01, NH-01, NH-04, NH-05, NH-08, NS-07, NS-08, SS-03 to SS-07, SS-09 to SS-11, WW-04, WW-09, WW-11, WW-14, WW-17 to WW-20
dibenzo(a,h)anthracene	AB-01, DR-16, EW-06, EW-14, NH-03, NH-04, NH-06, NH-08, NS-07, SS-03 to SS-07, SS-09, WW-04, WW-17
benzo(g,h,i)perylene	AB-01, DR-08, DR-12, DR-16, EW-04, EW-06, EW-11, EW-14, EW-15, KG-01, NH-01, NH-04 to NH-06, NH-08, NS-07, NS-08, SS-03 to SS-07, SS-09 to SS-11, WW-04, WW-09, WW-11, WW-17, WW-18
Total PCBs	DR-03, DR-08, DR-10 to DR-14, DR-16, DR-17, EW-02, EW-03, EW-05, EW-06, EW-11, KG-06, NH-03, NH-06, NH-08, SS-04, SS-09, WW-05, WW-06, WW-08, WW-09, WW-16
2-Methylnaphthalene	AB-01, KG-06, KG-10, NH-05, NH-06, NH-08, SS-06 to SS-08

TABLE 18. (Continued)

Chemical	Station
Dibenzofuran	AB-01, DR-16, EW-02, KG-10, NH-03, NH-05, NH-06, NH-08, SS-03 to SS-07, SS-09, WW-04
Retene	KG-10
1,4-Dichlorobenzene	SS-03
4-Methylphenol	KG-09, WW-19
PCP	NH-04
Benzyl alcohol	SS-03, WW-02
Butyl benzyl phthalate	EW-07 to EW-09
Di-n-octyl phthalate	NS-06

TABLE 19. SUMMARY OF SEMIVOLATILE ORGANIC CHEMICALS WITH EAR >1,000 IN SEDIMENTS OF ELLIOTT BAY AND THE DUWAMISH RIVER (USING AREA MEANS)

Chemical	Area[a]
Low molecular weight PAH	SS
acenaphthylene	SS
acenaphthene	SS
fluorene	SS
phenanthrene	SS
anthracene	SS
High molecular weight PAH	SS
fluoranthene	SS
pyrene	SS
benz(a)anthracene	SS
chrysene	SS
benzofluoranthenes	SS
benzo(a)pyrene	SS
indeno(1,2,3-c,d)pyrene	SS
benzo(g,h,i)perylene	SS

[a] Concentrations averaged over all stations in the area indicated.

Detection limits >100 ug/kg DW have been excluded from these means.

TABLE 20. SUMMARY OF SEMIVOLATILE ORGANIC CHEMICALS WITH EAR >1,000 IN SEDIMENTS OF ELLIOTT BAY AND THE DUWAMISH RIVER (USING INDIVIDUAL STATIONS)

Chemical	Station
Low molecular weight PAH	NH-06, SS-08
naphthalene	NH-06, NH-08
acenaphthylene	SS-08
acenaphthene	EW-02, NH-06, NH-08, SS-08
fluorene	EW-02, NH-06, NH-08, SS-08
phenanthrene	EW-02, NH-06, NH-08, SS-08
anthracene	NH-06, SS-06, SS-08
High molecular weight PAH	NH-06, NH-08, SS-08, SS-09
fluoranthene	EW-14, NH-06, SS-08, WW-04
pyrene	EW-14, NH-06, NH-08, SS-06, SS-08, SS-09
benz(a)anthracene	NH-06, NH-08, SS-08, SS-09
chrysene	NH-06, NH-08, SS-08, SS-09
benzofluoranthenes	NH-06, NH-08, SS-06, SS-08, SS-09
benzo(a)pyrene	NH-06, SS-08, SS-09
indeno(1,2,3-cd)pyrene	NH-03, NH-06, SS-08
dibenzo(a,h)anthracene	SS-08
benzo(g,h,i)perylene	NH-03, SS-08
Dibenzofuran	SS-08
1,4-Dichlorobenzene	SS-09

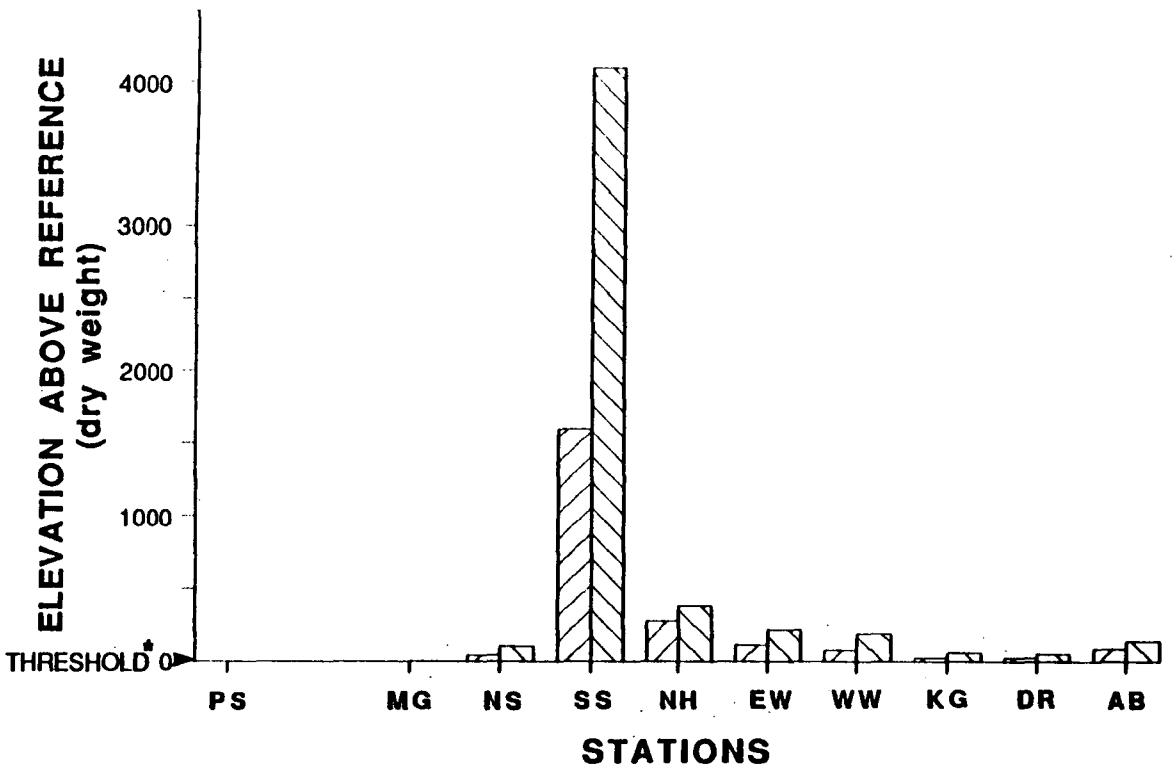
other LPAH were consistently the poorest, and had correlation coefficients ranging from 0.29 to 0.44. When naphthalene was correlated with total LPAH in individual study areas with more than five naphthalene detections, regressions were stronger and r values ranged from 0.75 to 0.98. Special attention will be given to naphthalene in data analysis to account for its poorer covariation with other LPAH. Concentrations normalized to organic carbon content did not generally yield improved correlations, and in many cases, correlations were worse. Organic carbon normalized concentrations of PAH were examined but will not be discussed because they did not indicate spatial gradients that were not apparent based on dry weight concentrations.

Correlations among the 10 individual HPAH were uniformly strong, and all had r values greater than 0.90 ($P<0.05$). Although the strength of these correlations was enhanced by extreme PAH concentrations at Station SS-08, correlations were strong even in the absence of that outstanding station. Correlation coefficients without Station SS-08 ranged from 0.56 to 0.99 for individual HPAH.

LPAH concentrations were generally elevated (e.g., EAR >30) over most of the study area. The areas of most severe contamination were the Seattle South waterfront and NH stations (west of the mouth of the West Waterway) (Tables 17-20) (Figure 31). The highest LPAH concentration occurred at Station SS-08 (630,000 ug/kg DW; EAR = 15,500). The mean LPAH concentration of SS stations was 65,000 ug/kg DW (EAR = 1,600). A clear concentration gradient was apparent at stations surrounding Station SS-08 (Figure 32); the concentration gradient was not linear, as Station SS-08 was over 40 times more contaminated than adjacent stations. Nonetheless, Stations SS-03 to SS-11 all had EAR values greater than 100.

Stations west of the mouth of the West Waterway (Area NH) also had very high LPAH concentrations, although concentration gradients along shore were not continuous. Highly contaminated Stations NH-06 (57,000 ug/kg DW; EAR = 1,400) and NH-08 (37,000 ug/kg DW; EAR = 910) were separated by a far lower concentration at intertidal Station NH-07 (230 ug/kg DW) (Figure 32). The sediments at Station NH-07 were far more coarse-grained (over 90 percent sand) than Stations NH-06 and NH-08 (roughly 53 percent silt and clay). Concentrations from 5,000 to 10,000 ug/kg (EAR >100) occurred at Stations NH-04, NH-05, and Station AB-01 located along Alki Beach. A similarly high concentration was observed at Station NH-03 (8,200 ug/kg DW) on the east side of the mouth of the West Waterway. Elevated LPAH concentrations were observed in the West Waterway (EAR >100 at Stations WW-04, WW-09, and WW-12), and sites of isolated, severe contamination (EAR >100) were observed in the East Waterway (Stations EW-02, EW-04, EW-06, and EW-14), the Duwamish River (Station DR-16), and along the Seattle North waterfront (Station NS-07) (Figure 33). Only a few stations in the study had detected concentrations within the range of reference sediments (Stations AB-03, MG-01, MG-04, and DR-06), and all individual LPAH were undetected at Station MG-03 and intertidal Station WW-15.

Naphthalene distributions differed somewhat from overall LPAH distributions. The maximum naphthalene concentration (15,000 ug/kg DW; EAR = 2,600) was located at Station NH-06, west of the mouth of West Waterway; the maximum LPAH concentration occurred at Station SS-08. However, the relative



LEGEND

LPAH

HPAH

- **PS** Port Susan (n = 4)
- **MG** Magnolia Bluff (n = 4)
- **NS** Seattle North Waterfront (n = 8)
- **SS** Seattle South Waterfront (n = 11)
- **NH** North Harbor Island (n = 11)
- **EW** East Waterway (n = 16)
- **WW** West Waterway (n = 19)
- **KG** Kellogg Island (n = 11)
- **DR** Duwamish River (n = 18)
- **AB** Alki Beach (n = 4)

* THRESHOLD - equivalent to the highest concentration in Puget Sound reference areas.

Carr Inlet Reference = 41 µg/kg DW (LPAH) and 79 µg/kg DW (HPAH).

Figure 31. Mean elevations above reference (EAR) of LPAH and HPAH in sediments from all study areas.

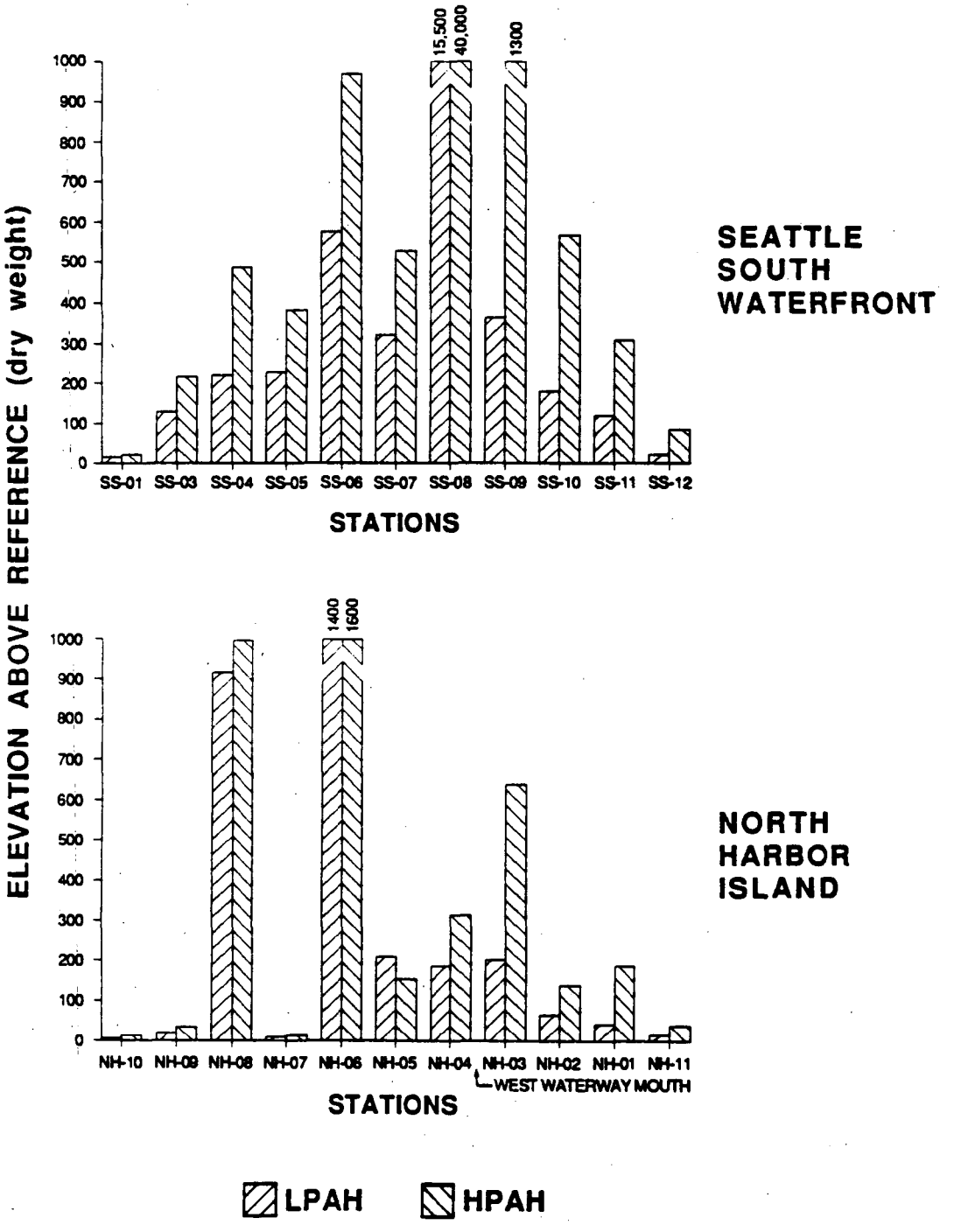


Figure 32. Elevations above reference (EAR) of LPAH and HPAH at individual stations in the most contaminated study areas.

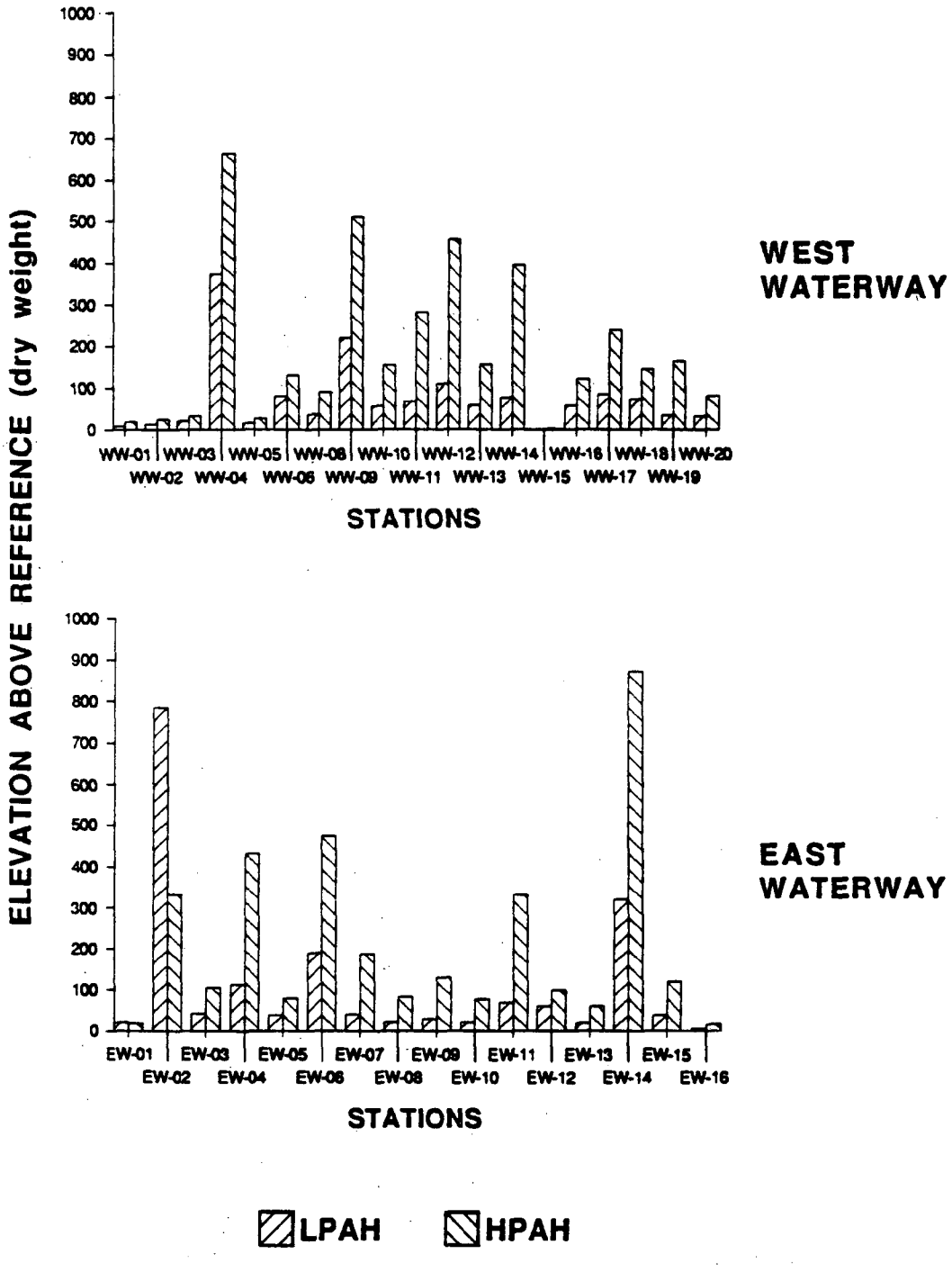


Figure 33. Elevations above reference (EAR) of LPAH and HPAH at individual stations in highly contaminated study areas.

distributions of naphthalene and LPAH were otherwise similar in the most contaminated areas (i.e., Areas SS and NH).

High molecular weight PAH had similar distributions to LPAH, but HPAH typically occurred at higher concentrations and were more elevated above Carr Inlet reference concentrations than LPAH (Figure 31). The correlation between LPAH and HPAH was very strong on a study-wide basis ($r=0.997$, $n=105$, $P<0.05$; dry weight concentrations). Although correlations between LPAH and HPAH were strong overall, scatterplots of LPAH vs. HPAH in each of the study areas revealed several noteworthy exceptions within areas. An anomalously high ratio of LPAH/HPAH was apparent at Station EW-02 (Figure 33). An anomalously low LPAH/HPAH ratio was noted at Station NS-07.

As was the case for LPAH contamination, HPAH contamination was most severe along the Seattle South waterfront and at NH stations (see Tables 17-20). EAR values along the Seattle South waterfront (Stations SS-03 to SS-12) ranged from 78 to 41,000 (maximum at Station SS-08). The mean EAR in this area was 4,100. Concentrations decreased sharply moving away in either direction from Station SS-08, as was the case for LPAH (Figure 32). EAR values greater than 1,000 were observed at Stations SS-08 and SS-09, and greater than 500 at Stations SS-06, SS-07, and SS-10.

In Area NH, EAR values of near or greater than 1,000 for HPAH were observed at Stations NH-06 (EAR = 1,600) and NH-08 (Figure 32). As was the case for LPAH, these stations were separated by a coarse-grained intertidal station with a much lower concentration (NH-07; EAR = 18). Nearby Station AB-01 had an EAR of 440, but was flanked by less contaminated stations. Station NH-03, on the opposite side of the mouth of West Waterway, had an EAR of roughly 50.

Other areas with mean HPAH concentrations that exceeded an EAR of 100 were the East and West Waterways and the Seattle North waterfront (see Table 17). Within these areas, individual stations with EAR greater than 500 were EW-14 (69,000 ug/kg DW), WW-04, WW-09, and NS-07. Although the EAR plotted for West Waterway stations in Figure 33 appear to follow a gradient that decreases in concentration toward the mouth, this is an artifact of the linear presentation of the figure. Stations WW-01 to WW-20 were not actually positioned along a straight line in the waterway and PAH concentration gradients were not apparent when concentrations were plotted on a map, although concentrations were generally elevated. All individual stations with EAR between 100 and 1,000 are listed in Table 18, and those with EAR greater than 1,000 are listed in Table 20.

Polychlorinated Biphenyls--PCBs were detected in roughly 75 percent of the samples in the study. However, detection limits were generally high (>100 ug/kg DW) and may have precluded detection of low-level contamination. Roughly 24 percent of the stations in this study had EAR values of over 100 for PCBs (see Table 17) and the median EAR was 80 (see Table 16). PCB distributions were generally patchy but were most elevated in the Duwamish River and along the Seattle South waterfront. The mean EAR for PCBs in the Duwamish River (Area DR) was 160 (using detected values only) (Figure 34). The highest concentration at an individual station was observed in the Duwamish River at Station DR-08 (5,800 ug/kg DW; EAR = 970) (Figure 35). On an organic carbon normalized basis, concentrations tended to decrease moving

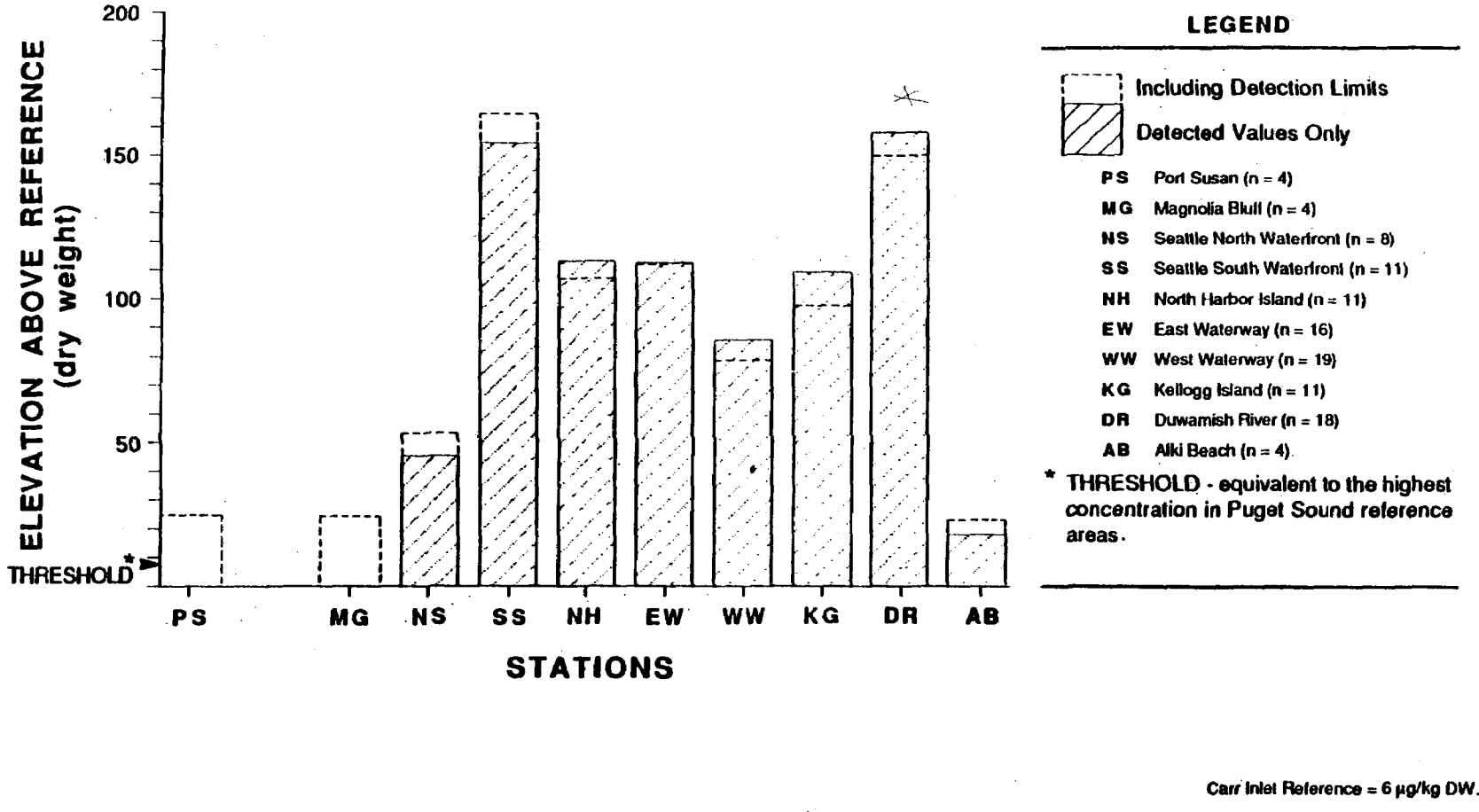


Figure 34. Mean elevations above reference (EAR) of PCBs in sediments from all study areas.

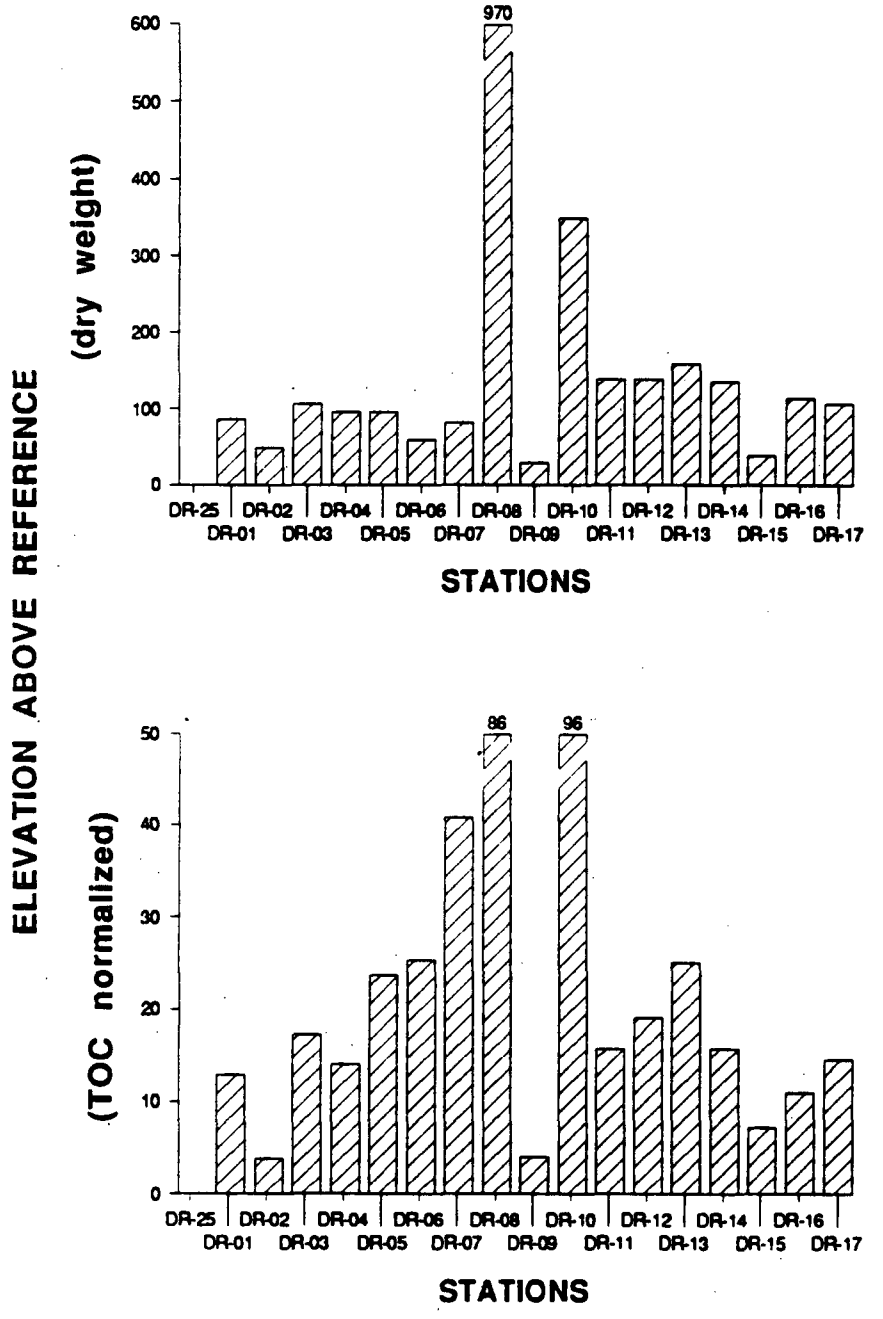


Figure 35. Elevations above reference (EAR) of PCBs in the Duwamish River (Area DR).

upstream from Station DR-08 (i.e., from Stations DR-07 to DR-03) (Figure 35), possibly suggesting upriver transport related to salt-wedge intrusion. Along this gradient, EAR on a dry weight basis were near or above 100 at Stations DR-03, DR-04, and DR-05. Another area of relatively heavy contamination (i.e., EAR >100) in Area DR consisted of a group of contiguous stations including DR-10 (2100 ug/kg DW), DR-11, DR-12, DR-13, DR-14, DR-16, and DR-17 (Figure 35).

The Seattle South waterfront had a mean EAR of 160 (detected values only), including several stations with EAR greater than 100 (Figure 36). Station SS-09 had a concentration of 3,300 ug/kg DW and Station SS-04 had a concentration of 1,600 ug/kg DW. Although a gradient was not clear on a dry weight basis, total organic carbon normalized concentrations tended to decrease moving north from Station SS-03 to SS-07 (Figure 36). A maximum occurred at Station SS-09.

EAR values greater than 100 were also found in the East Waterway, which had a mean EAR of 115 (PCBs detected at all stations), a maximum concentration of 2,500 ug/kg DW (Station EW-05), and a concentration of 1,500 ug/kg DW at nearby Station EW-06 (Figure 37). Other stations with EAR values greater than 100 in the East Waterway were EW-02, EW-03, and EW-11 (all roughly 1,000 ug/kg DW; Table 18). On an organic carbon normalized basis, concentrations were more uniform than on a dry weight basis, and appeared to decrease moving toward the mouth of the East Waterway (Figure 37). The nearest upriver stations (e.g., KG-08) do not appear to continue this trend upriver. The correlation between TOC and PCB concentrations in the East Waterway was unusually strong relative to other study areas with elevated PCB contamination ($r=0.92$, $n=16$, $P<0.05$).

The West Waterway tended to have lower concentrations than the East Waterway, with a mean EAR of 88 (using only detected values) and a maximum concentration of 1,500 ug/kg DW (Station WW-09). PCB concentrations at stations on the east side of the West Waterway ranged from 270 to 1,500 ug/kg DW, with no clear gradient in concentration on a dry weight or organic carbon normalized basis (Figure 38). Station WW-05, located in another section of the West Waterway, had a PCB concentration of 1,200 ug/kg DW. In another area of the Duwamish River, an isolated high concentration was found near Kellogg Island (Station KG-06; 3,100 ug/kg DW).

The mean EAR for NH stations at which PCBs were detected was 120. Only three individual stations had EAR of 100 or greater: Stations NH-03 (3,300 ug/kg DW; EAR = 550), NH-08 (1,300 ug/kg DW; EAR = 220), and NH-06 (600 ug/kg DW; EAR = 100) (Figure 38).

Lower PCB concentrations were reported along the Seattle North waterfront and along Alki Beach (Figure 34). PCBs were undetected at all four Magnolia Bluff stations at moderate to high detection limits (100-200 ug/kg DW).

Phenols--Analyses of phenolic compound distributions were impeded because of high detection limits (see Table 13). Although high detection limits resulting from poor surrogate recoveries were obtained for all target chlorinated phenols and 2,4-dimethylphenol, the most problematic detection

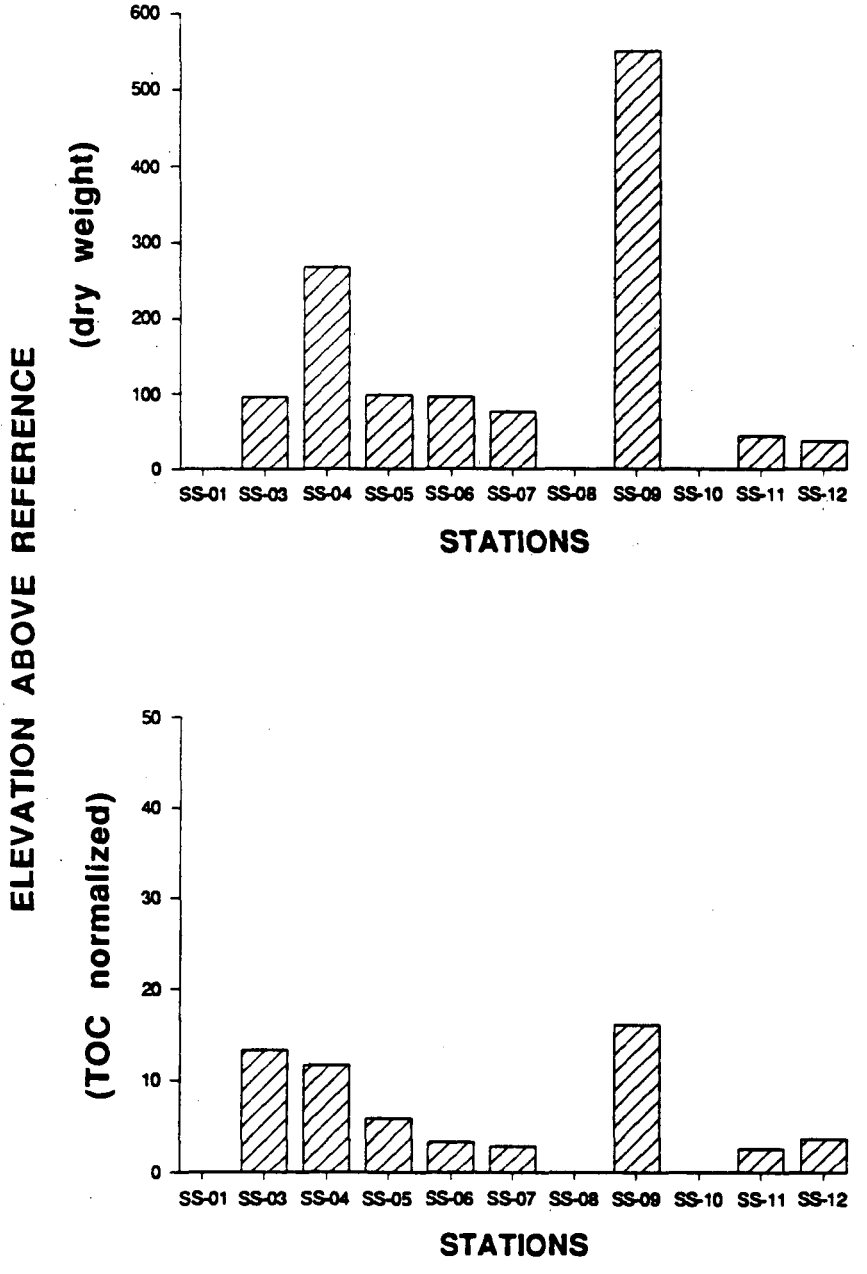


Figure 36. Elevations above reference (EAR) of PCBs along the Seattle South Waterfront.

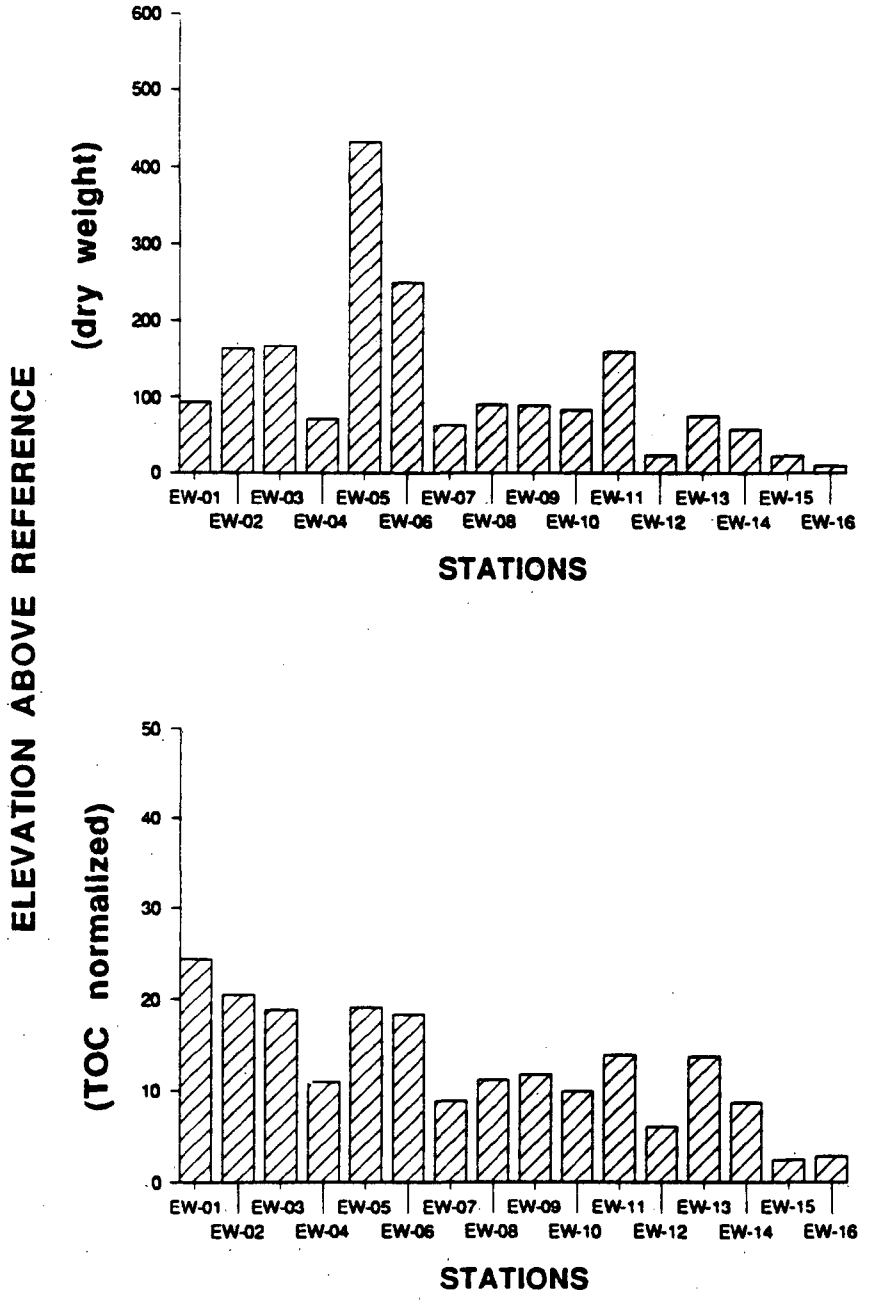


Figure 37. Elevations above reference (EAR) of PCBs in the East Waterway.

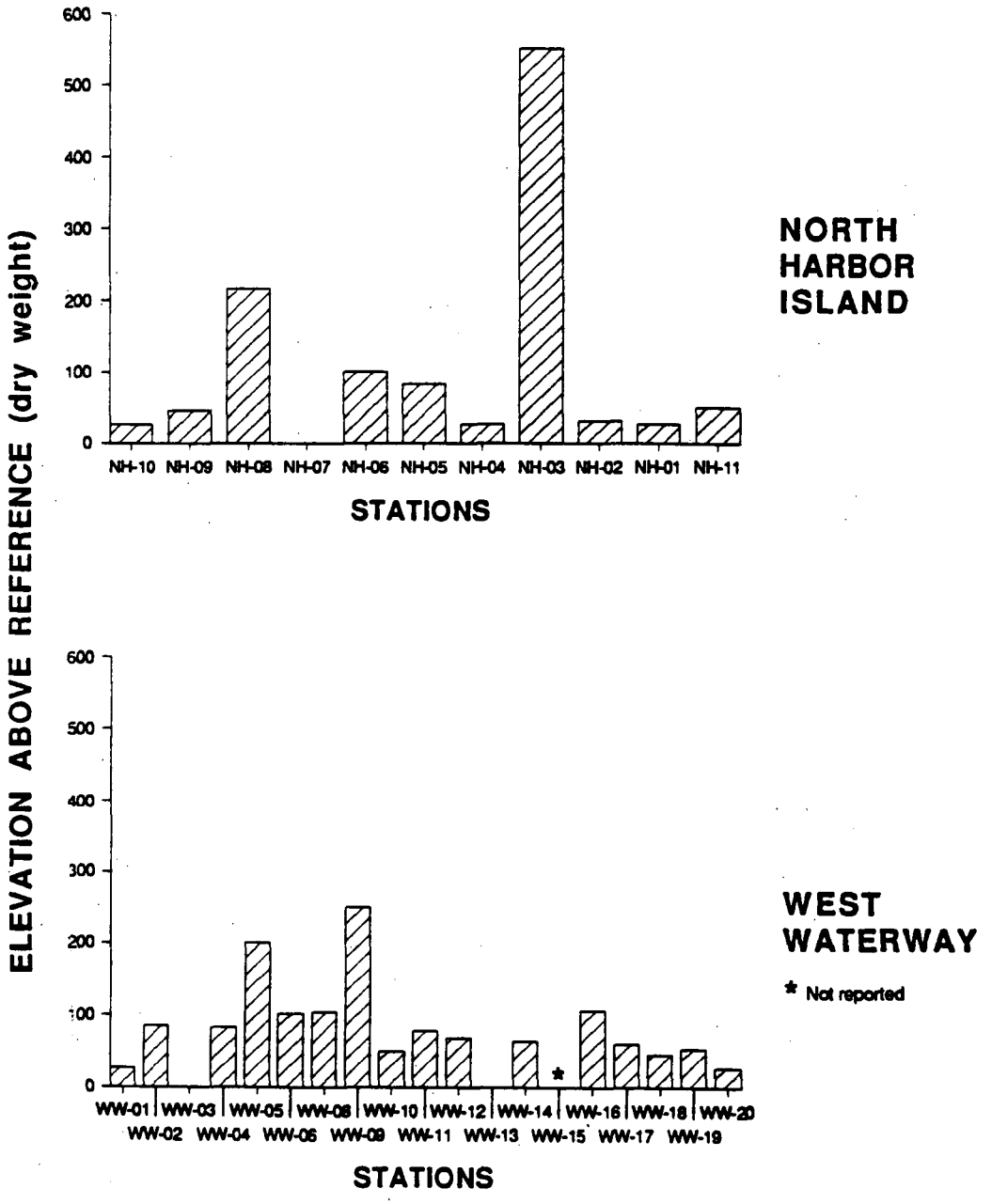


Figure 38. Elevations above reference (EAR) of PCBs in North Harbor Island and the West Waterway.

limits were for pentachlorophenol (over half the samples had detection limits over 1,000 ug/kg for pentachlorophenol; see Table 13).

Pentachlorophenol (PCP) was detected eight times in the study with a maximum concentration near the mouth of the West Waterway (Station NH-04; 6,000 ug/kg DW; EAR = 180) (see Table 12). A nearby station in the West Waterway (Station WW-17) had a concentration of 360 ug/kg DW. High detection limits in this area do not allow for further analysis. Another area of PCP contamination was at the mouth of the East Waterway. Station EW-16 had a concentration of 690 ug/kg DW and EW-15 had a concentration of 95 ug/kg DW. Station NH-01, east of the mouth, had a concentration of 100 ug/kg DW. PCP was undetected at other stations at the mouth of the East Waterway (Stations SS-01 and NH-11) at reasonable detection limits (56 and 75 ug/kg DW). Three relatively isolated detections of PCP occurred at Station AB-04 (110 ug/kg DW), coarse-grained intertidal Station NS-04 (330 ug/kg DW), and Station SS-05 (47 ug/kg DW). PCP was undetected at relatively high detection limits (e.g., 160 to 4,600 ug/kg DW) at adjacent stations in these areas (i.e., Alki Beach and the Seattle waterfront).

Phenol was detected at 36 stations but had a relatively narrow concentration range (see Table 12). The maximum concentration (1,200 ug/kg DW; EAR = 36) occurred at intertidal Station DR-25 in the Duwamish River. Phenol was undetected at adjacent stations at low detection limits (e.g., <50 ug/kg DW). Other isolated stations of moderate phenol concentration (roughly 400 ug/kg DW; EAR = 12) were Station SS-09, intertidal Station KG-10, and Station PS-05 (Port Susan), the latter of which had been excluded from reference area comparisons because of elevated chemistry. Other phenol concentrations that exceeded reference conditions were relatively isolated. Concentrations near 100 ug/kg DW were detected in or near the West Waterway (Station NH-04 and intertidal Station WW-15) and along the Seattle North waterfront (Station NS-07).

4-Methylphenol was detected 32 times in the study, although the concentration range was relatively narrow. The maximum concentration occurred at Station WW-19, on the east side of the West Waterway (2,600 ug/kg DW, EAR = 200). Moderate concentrations occurred at intertidal Station WW-15 on the west side of the waterway (540 ug/kg DW) and at NH stations near the mouth (Stations NH-04 and NH-06, 1,000 and 170 ug/kg DW, respectively). Concentrations of greater than 1,000 ug/kg DW were observed at intertidal Station NS-04, intertidal Station DR-25, and at Station KG-09 near Kellogg Island. Adjacent Station KG-11 had a concentration of 610 ug/kg DW. All other detected concentrations were equivalent to EAR less than 30.

Chlorinated Benzenes--1,4-Dichlorobenzene, detected seven times, was the only chlorinated benzene detected more than once and the only detected dichlorobenzene. High detection limits for chlorinated benzenes (see Table 13) precluded comprehensive data analysis for these compounds. More than half of the samples had detection limits greater than 100 ug/kg DW for each of the chlorinated benzenes.

1,4-Dichlorobenzene had a wide concentration range in this study, but only one extremely high concentration was observed (Station SS-09, 31,000 ug/kg DW, EAR = 8,900). The next highest concentration, 380 ug/kg at Station SS-03, also occurred along the Seattle South waterfront but was not

located near Station SS-09. 1,4-Dichlorobenzene was undetected at other SS stations over a wide range of detection limits (2 to 7,300 ug/kg DW). Isolated areas of contamination were observed in the Duwamish River at adjacent Stations WW-04 and WW-05 (90 and 59 ug/kg DW, respectively) and much further upriver at Station DR-15 (100 ug/kg DW). Detection limits at adjacent stations in these areas were relatively low (i.e., below the detected concentrations). All other detected concentrations were less than 40 ug/kg DW.

Phthalate Esters--Data for three phthalate esters were rejected because of high blank contamination (diethyl phthalate, di-n-butyl phthalate, and bis(2-ethylhexyl)phthalate; see METHODS, Sediment Chemistry, Quality Assurance/Quality Control Results). The remaining phthalates were dimethyl phthalate, butyl benzyl phthalate, and di-n-octyl phthalate. These compounds did not correlate well enough in the overall study to justify their treatment as one group during data analysis (using detected values only, dimethyl vs. butyl benzyl, $r=0.06$, $n=26$, $P>0.05$; di-n-octyl vs. butyl benzyl, $r=0.51$, $n=27$, $P<0.05$; dimethyl vs. di-n-octyl, $r=0.20$, $n=18$, $P>0.05$).

Butyl benzyl phthalate was the most commonly detected phthalate ester (detection frequency = 60/107; Table 12). Areas of relatively high concentration (EAR >50) were observed in the East Waterway and along the Seattle South waterfront. Three adjacent stations in the East Waterway (EW-07, EW-08, and EW-09) had the maximum concentration of 1,800 ug/kg DW (EAR = 180). Lower concentrations (760 to 1,300 ug/kg DW) were observed in this area at Stations EW-05 and EW-11. Notably, butyl benzyl phthalate and di-n-octyl phthalate correlated well in the East Waterway ($r=0.98$, $n=7$, $P<0.05$). Elevated concentrations also occurred along the Seattle South waterfront at Stations SS-04 and SS-05 (500 to 1,000 ug/kg DW). Adjacent stations had concentrations below 50 ug/kg DW. Except for an isolated high concentration at Station KG-06 (690 ug/kg DW; EAR = 41), other concentrations were relatively low (EAR <20).

Distributions of dimethyl phthalate were patchy. The highest observed concentration was found along the Seattle South waterfront (Station SS-11, 1,400 ug/kg DW; EAR = 35). Dimethyl phthalate was undetected at adjacent stations at high detection limits (600 to 2,200 ug/kg DW), but was detected at Station SS-09 (160 ug/kg DW) and at SS-03 (300 ug/kg DW) with low detection limits adjacent to Station SS-03. Similarly elevated concentrations were found in the West Waterway at Stations WW-09 (440 ug/kg DW) and WW-13 (1,000 ug/kg DW); these stations were located on opposite sides of the waterway. All other detected values in the study were less than 200 ug/kg DW (EAR = 5).

Di-n-octyl phthalate was detected 40 times in this study, but an EAR of 25 (500 ug/kg DW) was exceeded only 4 times. The highest concentration in the study was observed at Station NS-06 (9,900 ug/kg DW, blank-corrected; EAR = 490). Observations at other stations in the Seattle North waterfront area were typically detected concentrations or detection limits of less than 50 ug/kg DW. Intertidal Station DR-25 had the next highest concentration in the study (1,300 ug/kg DW; EAR = 65). Concentrations of di-n-octyl phthalate at adjacent stations were blank corrected down to low detection limits. Station SS-05, along the Seattle South waterfront, had a concentration of 1,100 ug/kg DW, although di-n-octyl phthalate was undetected at 5 ug/kg DW

at adjacent stations. Station KG-05 had a moderate concentration of 400 ug/kg DW. All other detections in the study were equivalent to an EAR of 15 or less.

Pesticides--Only three of the target pesticides were detected more than two times in this study: p,p'-DDT (six detections), p,p'-DDE (four detections), and p,p'-DDD (nine detections) (see Table 12). Elevated concentrations tended to be geographically isolated, and the pesticides did not tend to occur at the same stations. Only Station DR-10 had all three pesticides, whereas Stations DR-08 and SS-09 had p,p'-DDE and p,p'-DDD, Station EW-05 had p,p'-DDE and p,p'-DDT, and Station SS-04 had p,p'-DDD and p,p'-DDT.

Relatively high and isolated p,p'-DDT concentrations were observed in the East Waterway (Station EW-05, 84 ug/kg DW), along the Seattle South waterfront (Station SS-04, 180 ug/kg DW), and in the Duwamish River (Station KG-06, 270 ug/kg DW). DDT was undetected at adjacent stations at detection limits lower than 20 ug/kg DW. The highest p,p-DDE concentration was found at Station DR-10 (62 ug/kg DW). Relatively high p,p'-DDD concentrations were observed at Stations NH-03 (120 ug/kg DW) and SS-09 (140 ug/kg DW).

It is noteworthy that all the stations with high pesticide concentrations also had high PCB concentrations (>1,000 ug/kg PCBs at all stations discussed in this section). It is possible that PCBs could have acted as interferences during GC/ECD analysis and may have artificially increased pesticide concentrations. Confirmation of pesticide concentrations by GC/MS is recommended if future analyses of pesticides are conducted in these areas.

Miscellaneous Organic Compounds--Compounds assigned to this class include 2-methylnaphthalene, dibenzofuran, benzyl alcohol, benzoic acid, and the following TIOs detected in this study: alkylated phenanthrenes (1-, 2-, and 3-methylphenanthrene), biphenyl, carbazole, and retene. Detection frequencies for these compounds are presented in Table 12. High detection limits for benzoic acid and benzyl alcohol (see Table 13) impeded data analysis for these compounds.

Biphenyl and the alkylated PAH and heterocycles detected in this study (2-methylnaphthalene, methylphenanthrenes, dibenzofuran, and carbazole) tended to co-vary with PAH; therefore, their distributions will not be described in detail. Such covariation was expected, as these compounds are known to co-occur in fossil fuel products. Retene and benzyl alcohol have a wider range of potential sources and will be discussed separately.

Correlations of miscellaneous organic compounds vs. PAH are presented in Table 21 (correlations excluding anomalous Station SS-08 are also presented in Table 21). 2-Methylnaphthalene correlated well with the most structurally related PAH, naphthalene (Table 21). Similarly, 1-, 2-, and 3-methylphenanthrene correlated well with phenanthrene (Table 21). Although Station SS-08 was an outlier in these three phenanthrene correlations and resulted in deceptively high correlation coefficients, correlations run without SS-08 were still relatively strong (Table 21). Correlations of dibenzofuran, carbazole, and biphenyl vs. LPAH and HPAH were examined because these organic compounds co-occur with PAH (especially LPAH) in fossil fuel products such as petroleum and creosote (Clark and Brown 1977; Nestler 1974). Carbazole, an important creosote component (e.g., Nestler 1974; Krone

TABLE 21. CORRELATIONS BETWEEN PAH AND MISCELLANEOUS ORGANIC COMPOUNDS[a]

Compounds	All Detected Stations		Without SS-08[b]	
	r	n	r	n
naphthalene:				
vs. 2-methylnaphthalene	0.87	61	0.92	60
phenanthrene:				
vs. 1-methylphenanthrene	0.998	69	0.75	68
vs. 2-methylphenanthrene	0.998	70	0.68	69
vs. 3-methylphenanthrene	0.998	68	0.70	67
LPAH:				
vs. dibenzofuran	0.84	79	0.91	78
vs. biphenyl	0.94	27	(same)[c]	
vs. carbazole	0.83	45	(same)[c]	
vs. retene	0.08	55	(same)[c]	
HPAH:				
vs. dibenzofuran	0.80	80	0.65	79
vs. biphenyl	0.87	27	(same)[c]	
vs. carbazole	0.90	45	(same)[c]	
vs. retene	0.06	56	(same)[c]	

[a] Based on dry weight concentrations; detected values only.

[b] Station SS-08 excluded from correlation.

[c] Same as "all detected stations" - not detected at Station SS-08.

et al. 1986) and biphenyl correlated well with LPAH and HPAH (Table 21). Neither compound was detected at Station SS-08. Both compounds maximized at Station NH-06, as did naphthalene. Dibenzofuran also correlated well with LPAH and HPAH, even when the maximum concentration at Station SS-08 was excluded.

Retene is a useful geochemical marker for sub-bituminous coal and lignite found in the Green River area (Barrick et al. 1984), but is not prevalent in higher grade coals (e.g., anthracite). Unlike other compounds described in this section, retene correlated very poorly with PAH on a study-wide basis, even when outlier stations were eliminated (Table 21; $P>0.05$). Retene was not detected at the station with the highest PAH concentrations (SS-08); also, the highest retene concentration (10,000 ug/kg DW) was reported at Station KG-10, which had low PAH concentrations (total PAH = 1,900 ug/kg DW). Retene was undetected or detected at low concentrations (<25 ug/kg DW) at stations near KG-10. Other than Station KG-10, retene was detected at concentrations greater than 1,000 ug/kg DW at Stations KG-06, EW-05, and SS-09. Notably, detected retene concentrations correlated well with LPAH and HPAH in Area SS ($r=0.93$ and 0.91, respectively; $n=5$, $P<0.05$). However, as noted above, retene was not detected at the station in this area with the highest PAH concentration.

Benzyl alcohol was detected only five times, but was reported at relatively high concentrations in most cases. The highest concentration was found in the southern portion of the West Waterway at intertidal Station WW-02 (8,800 ug/kg DW). Another station in the West Waterway, WW-08, had a far lower concentration (140 ug/kg DW). An isolated concentration of 870 ug/kg DW occurred at Station EW-12 in the East Waterway. Along the Seattle South waterfront, Station SS-03 had a concentration of 1,300 ug/kg DW.

Spatial Correlations Among Chemicals

Pearson linear correlations were performed on a study-wide basis and for most individual study areas to examine the covariance of chemical distributions. Only detected data were used in this analysis. The range of correlations examined in detail was reduced by application of the following criteria:

- Chemicals had to be detected at least four times in at least one study area
- Correlation coefficients (r) had to be at least 0.7 (i.e., r^2 was at least 0.5)
- Based on examination of scatterplots, correlations were not apparently driven by stations with anomalously high concentrations.

Although these criteria are subjective, they provided a reasonable means for producing a reliable, if not comprehensive, summary of spatial covariance. The variables included in the correlation analysis that satisfied the first criterion specified above were all metals of concern, HPAH and LPAH (as group sums), PCBs, p,p'-DDD, 4-methylphenol, phenol, dimethyl phthalate,

butyl benzyl phthalate, di-n-octyl phthalate, and retene. TOC content and percent fine-grained material were also included in the analyses to examine trends between chemistry and sediment texture. Study-wide correlations (particularly among PAH and related alkylated PAH and heterocycles) that were discussed in the previous section will not be recounted here. Three individual study areas (Areas AB, MG, and NS) were not analyzed on an area-specific basis because contamination was not highly elevated or widespread in these areas.

On a study-wide basis, most correlations were poor or driven by outliers. An exception to this generalization was the correlation between chromium and nickel on a study-wide basis ($r=0.83$, $n=107$, $P<0.05$). Because concentrations of these two metals seldom exceeded reference levels, it is possible that the relatively consistent chromium/nickel ratio is primarily related to mineralogical composition rather than anthropogenic contamination.

Many strong correlations were observed when regression analyses were performed on an area basis rather than a study-wide basis. Apparently, the localized, heterogeneous contamination observed in this study required small-scale analyses of spatial covariance to resolve trends that were confounded during the study-wide analysis. Strong correlations may be useful during source evaluation for defining the chemical nature of sources. A summary of significant correlations that were relatively strong (i.e., $r \geq 0.7$ without apparent outliers) in at least two study areas is presented in Table 22. Strong correlations among metals were clearly far more prevalent than strong correlations among organic compounds. Correlations among copper, lead, and zinc were relatively strong in Areas DR, NH, and EW (Table 22). As expected, correlations between LPAH and HPAH were strong in most study areas. Strong correlations observed between retene and mercury may be related to particulate material derived from the Green River. The Green River passes through both mercury and coal mines, which are potential sources of these chemicals. Strong correlations between organic chemicals and TOC content or between metals and percent fine-grained material, which support normalization to these variables, were not typically observed even on a small scale basis. However, PAH correlated well with TOC in Areas NH and SS (Table 22), and a number of metals correlated well with percent fine-grained material in Area NH, and to a lesser extent, in Area KG.

Certain relatively strong correlations were observed for only single areas and are not listed in Table 22. These are described briefly below. Along the Seattle South waterfront, relatively strong correlations were observed between copper and arsenic, PAH (both LPAH and HPAH) and retene, and PCBs and mercury. In the North Harbor Island area, very strong correlations were observed between PAH (both LPAH and HPAH) and cadmium. Among the many strong correlations observed in the East Waterway were PCBs with several metals (lead, cadmium, and silver), and silver with cadmium, mercury, and copper. In the West Waterway, zinc correlated well with nickel and chromium. Lead and mercury correlated well in Area KG, and butyl benzyl phthalate and cadmium correlated well in Area DR.

Comparison with Recent Historical Data

Data from previous studies of Elliott Bay and the Duwamish River were compiled to confirm contaminant distributions found in this study and to

TABLE 22. STRONG CHEMICAL CORRELATIONS[a]

Chemicals	Area[b]					
	DR	EW	KG	NH	SS	WW
Copper - Lead	0.84[c] (18)[d]	0.76 (16)		0.91 (11)		
Copper - Zinc	0.98 (18)	0.79 (16)		0.90 (11)		0.72 (19)
Lead - Zinc	0.84 (18)	0.77 (16)		0.96 (11)		
Chromium - Nickel		0.85 (16)	0.79 (11)		0.98 (11)	0.93 (19)
Cadmium - Zinc		0.77 (16)	0.89 (11)		0.92 (11)	
Cadmium - Lead		0.92 (16)			0.86[e] (10)	0.91 (19)
Silver - Lead	0.78 (18)	0.89 (16)		0.87 (11)		
Silver - Zinc				0.91 (11)		0.91 (19)
HPAH - LPAH	0.98 (18)		0.86 (11)	0.97 (11)	0.85[e] (10)	0.88 (18)
Retene - Mercury		0.95 (10)			0.93 (5)	0.88 (7)
LPAH - TOC				0.74 (11)	0.83[e] (10)	
HPAH - TOC				0.81 (11)	0.89[e] (10)	

[a] Correlations included in this table meet the following criteria:

1. r value >0.7 (based on n >4)
2. scatterplot confirming strong correlation (i.e., not driven by a station with anomalously high concentrations)
3. apparently strong correlations in at least two study areas.

TABLE 22. (Continued)

[b] The most contaminated areas were the focus of spatial characterization, so Areas AB, MG, and NS are not included.

[c] Correlation coefficient (r).

[d] Number of observations (n); only detected values were included.

[e] Correlation excludes one anomalous station; inclusion of the station would result in a misleading higher correlation coefficient.

provide a more comprehensive assessment of contamination (especially in areas not sampled in this study, such as central Elliott Bay and the area near Denny Way CSO). Data from the following historical studies were compiled:

- Gamponia et al. (1986), a Metro report of sampling performed in the West Waterway and North Harbor Island area
- Metro (1987), a report on the baseline investigations performed near Duwamish Head in 1985-1986
- Romberg et al. (1984), a report on Metro's extensive environmental sampling as part of their Toxicant Pretreatment Planning Study (TPPS)
- Stober and Chew (1984), a report on the baseline investigations performed for Metro near Duwamish Head
- U.S. EPA (1982, 1983), two unpublished surveys performed by EPA in the Duwamish River in 1982 and 1983
- Malins et al. (1980, 1982), two reports presenting the results of sampling performed in Elliott Bay in support of pathology studies of resident organisms.

Sampling stations from these studies are plotted in Figures 39-42. In general, historical data tended to confirm the distributions reported in the present study. In the sections below, notable historical findings are discussed for chemicals or chemical groups of concern that were most elevated in the present study (phthalate ester concentrations were not compared because historical data were not corrected for potential laboratory contamination). The maps presented in this section focus on nearshore chemical distributions; not all available historical data from deeper Elliott Bay stations have been plotted in these maps. In a limited number of cases, concentrations for a station sampled more than once differed considerably. In such cases, the highest concentration was plotted. It was assumed that analytical variability (especially among different studies) and small-scale spatial heterogeneity were more likely responsible for such discrepancies than temporal trends.

Several historical stations had very elevated concentrations of a number of chemicals, in some cases exceeding the maximum concentrations observed in the present study. Several of these stations occurred in the North Harbor Island area: Station E42 (U.S. EPA 1982, 1983), and EPA Station E4 and Station 3 of Gamponia et al. (1986), both located east of Station NH-03. Other notable historical stations were Gamponia Station 9 in the West Waterway, and TPPS Station S0090, located near Station SS-05 along the Seattle South waterfront.

Copper--

Copper data for the present study and historical studies are presented in a contour map (Figure 43). Four historical stations near the mouth of the West Waterway had concentrations greater than 1,000 mg/kg DW. One

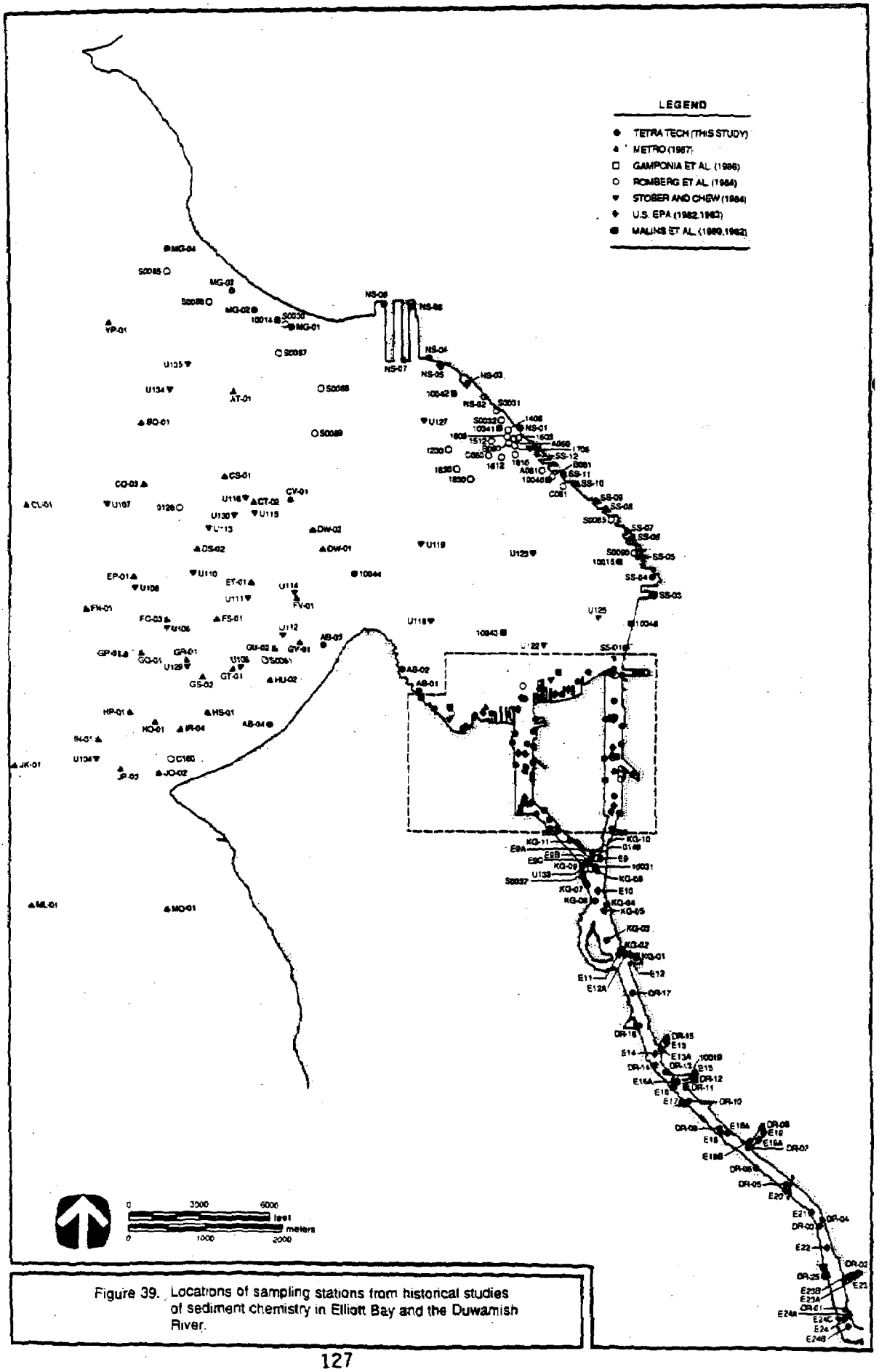


Figure 39. Locations of sampling stations from historical studies of sediment chemistry in Elliott Bay and the Duwamish River.

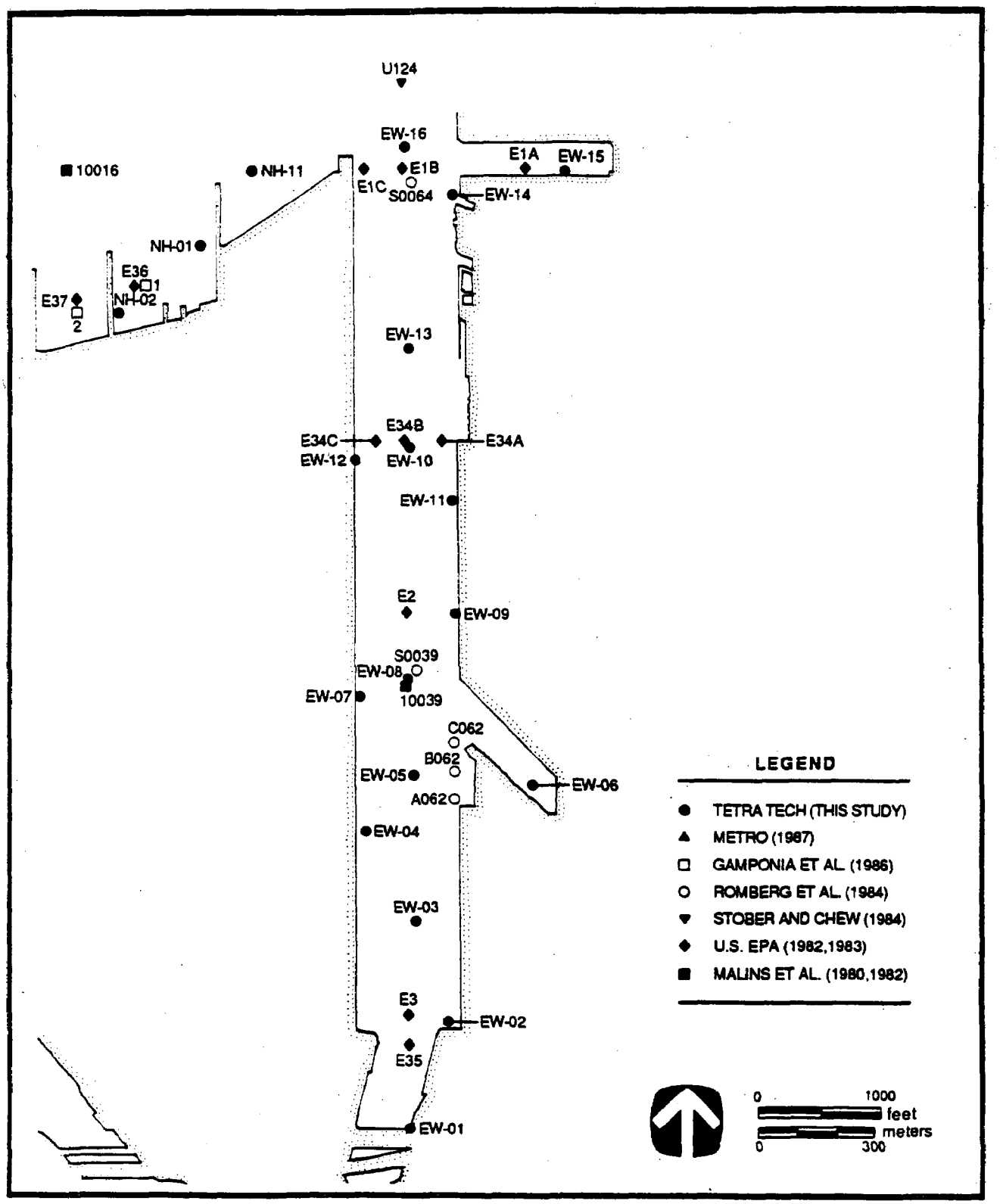


Figure 40. Locations of sampling stations from historical studies of sediment chemistry in the East Waterway.

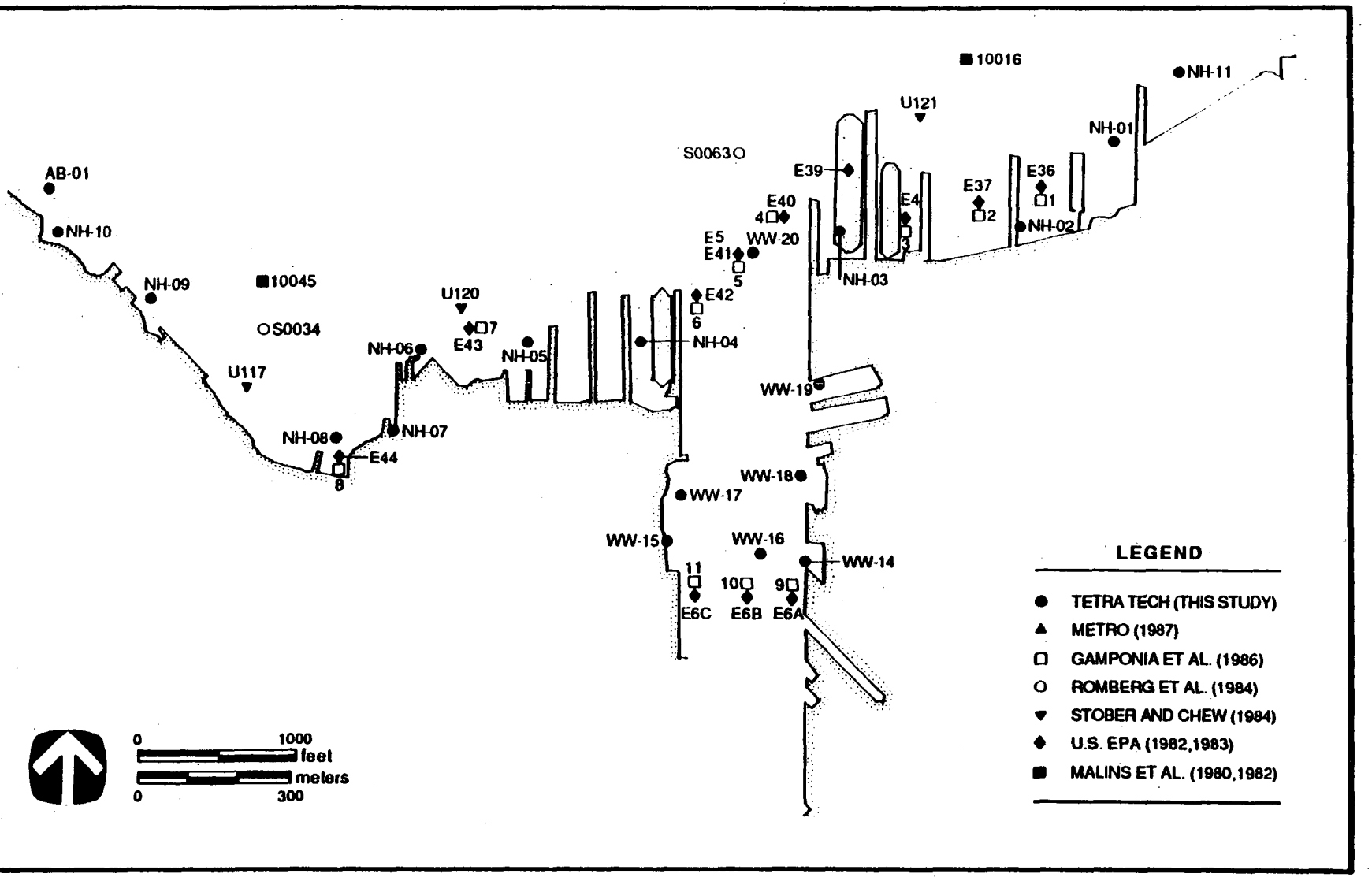


Figure 41. Locations of sampling stations from historical studies of sediment chemistry in the North Harbor Island area.

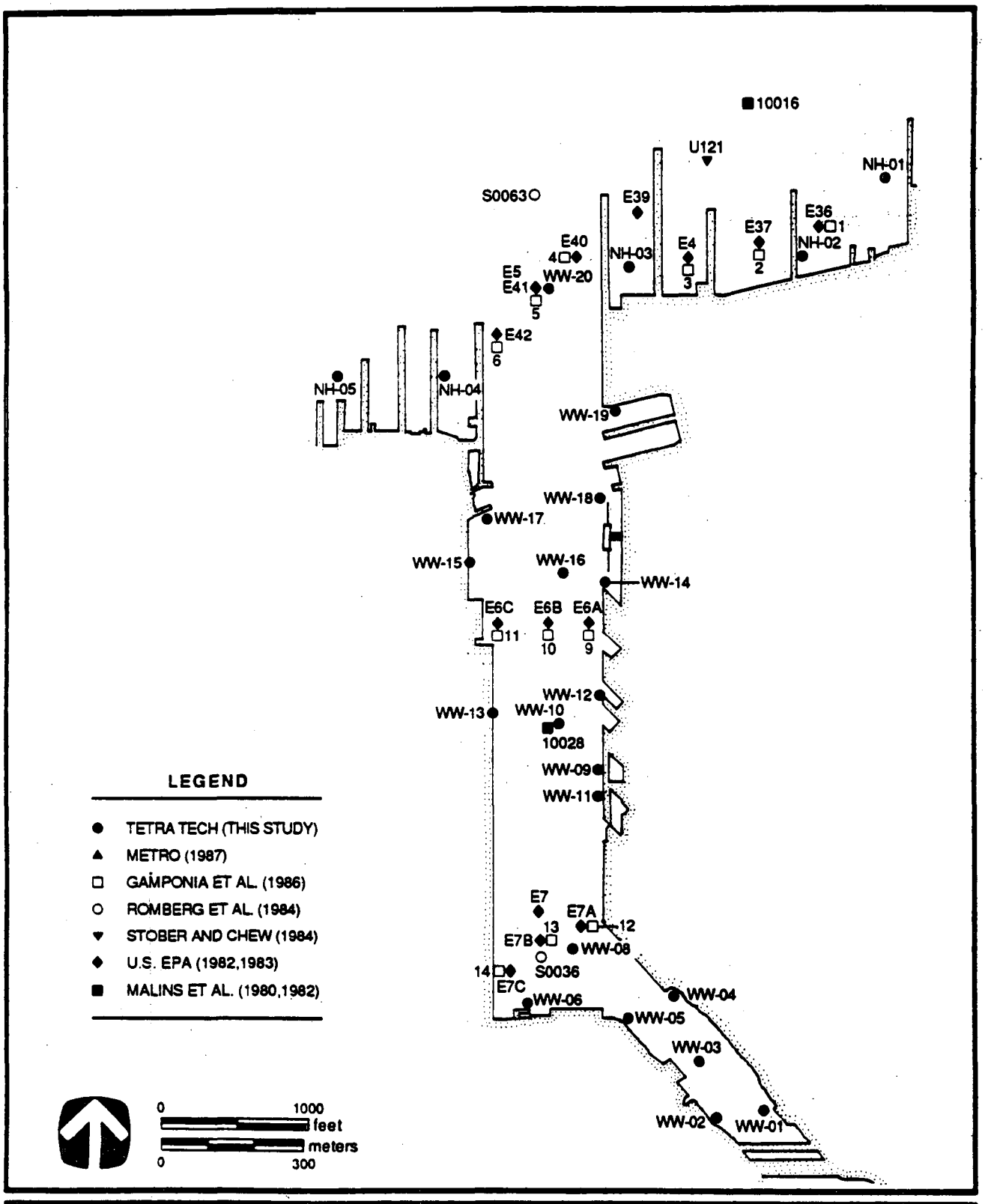


Figure 42. Locations of sampling stations from historical studies of sediment chemistry in the West Waterway.

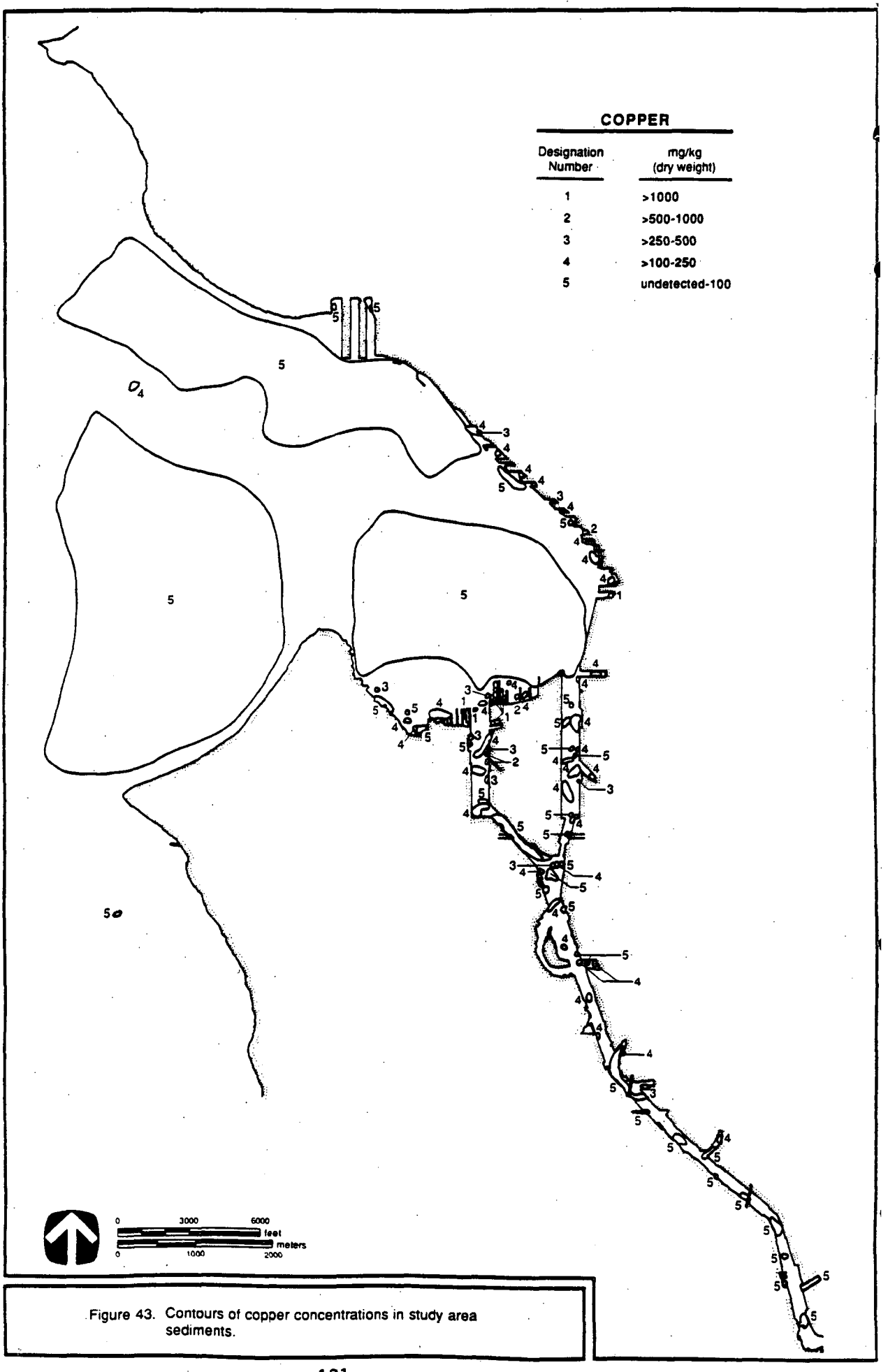


Figure 43. Contours of copper concentrations in study area sediments.

station was at the western side of the mouth (EPA Station E42, 1,050 mg/kg) and three other stations were on the east side of the mouth near Station NH-03 (1,220 to 2,800 mg/kg DW) (Gamponia et al. 1986; U.S. EPA 1982, 1983). Station 9 of Gamponia et al. (1986), located on the east side of the West Waterway, had a copper concentration of 860 mg/kg DW. Concentrations of a number of other metals (e.g., lead and zinc) were also highly elevated at this station and at Station E42.

Lead--

Historical lead concentrations (summarized in Figure 44) were generally consistent with those reported in this study. Among the noteworthy historical findings is Gamponia Station 9 on the east side of the West Waterway, which had a lead concentration of nearly 11,000 mg/kg DW (Station WW-14 in that area had a comparable concentration). Historical EPA Station E42 near the mouth of the West Waterway had a concentration of greater than 2,000 mg/kg DW (U.S. EPA 1982, 1983). Two historical stations east of Station NH-03 had lead concentrations between 500 and 1,000 mg/kg DW (Gamponia et al. 1986; U.S. EPA 1982,1983).

Several high historical concentrations were reported along the Seattle waterfront. TPPS Station 1603 near Denny Way CSO had a lead concentration of 670 mg/kg DW. Along the Seattle South waterfront, a concentration of 1,700 mg/kg DW was found at TPPS Station S0090. This concentration was over 5 times higher than the concentration at nearby Station SS-05.

Mercury--

Mercury distributions are summarized in Figure 45. Historical data tended to confirm the findings of this study. A high mercury concentration (12 mg/kg DW) was reported in the slip immediately to the east of Station NH-03 (Gamponia Station 3). Four other historical stations in the North Harbor Island area had mercury concentrations of greater than 1 mg/kg DW (Malins Station m10016 and Gamponia Stations 2, 4, and 6). A number of historical stations in the Denny Way CSO area (not sampled subtidally during the present study) had mercury concentrations of greater than 1 mg/kg DW, with a maximum of 3.6 mg/kg DW (TPPS Station 1612) during early studies (Romberg et al. 1984, Malins et al. 1980, 1982) and a maximum of 2.2 mg/kg DW during recent studies (Romberg et al. 1987). Few historical stations were taken along the Seattle South waterfront, but the two historical stations located between Stations SS-05 and SS-08 (present study) confirmed the high concentrations reported in this study (0.92 and 3.3 mg/kg DW; TPPS Stations S0065 and S0090). Data from U.S. EPA (1982, 1983) were reported as wet weight without additional information on total solids content; hence, these data were unusable.

Zinc--

A number of relatively high zinc concentrations were observed in historical studies (Figure 46). EPA Station E42 near the west side of the mouth of the West Waterway had a zinc concentration of 4,810 mg/kg DW (U.S. EPA 1982, 1983). Station 9 of Gamponia et al. (1986), located on the east side of the West Waterway, had a zinc concentration of greater than 1,500 mg/kg DW. Concentrations greater than 1,700 mg/kg DW east of Station

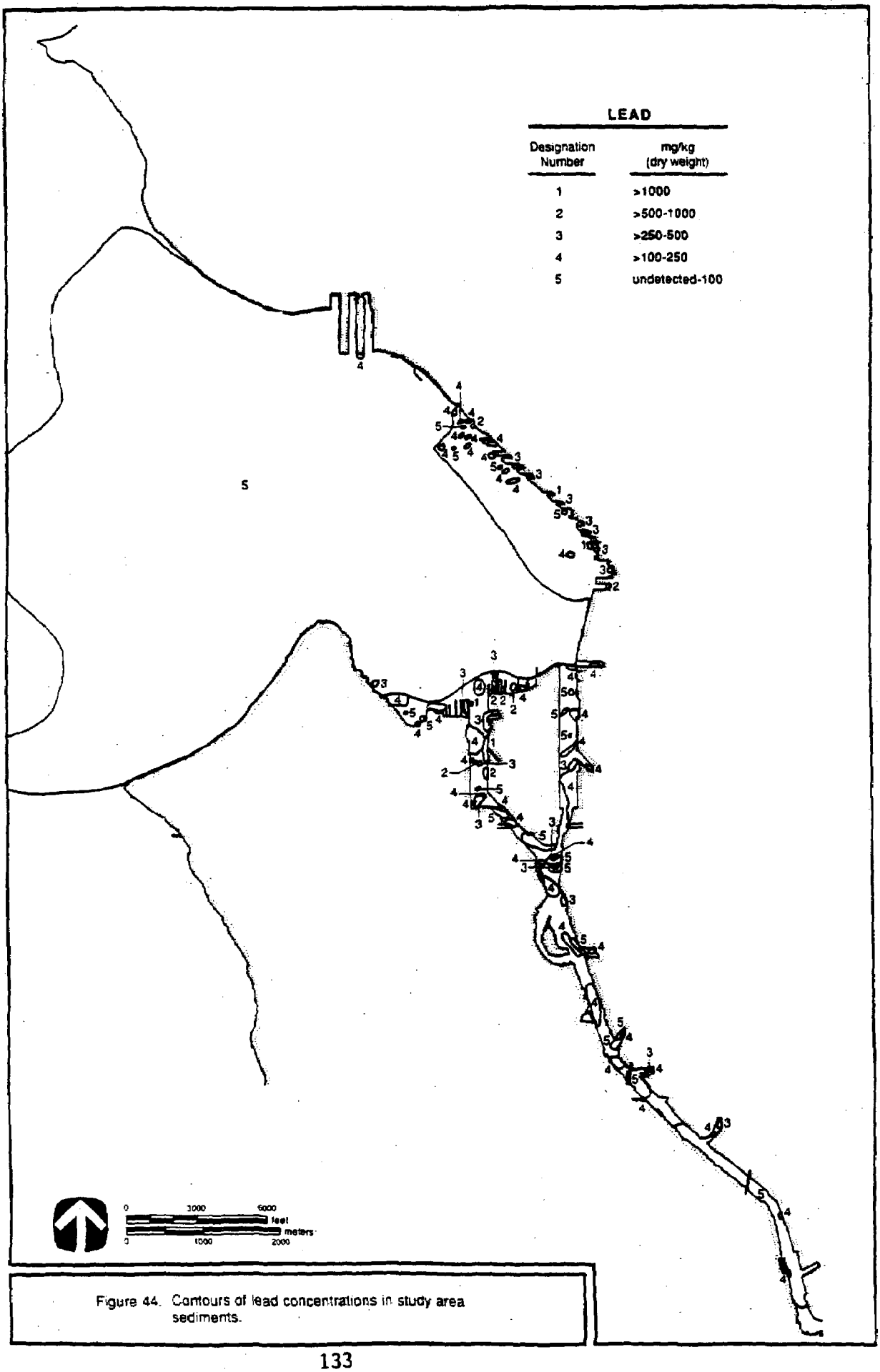


Figure 44. Contours of lead concentrations in study area sediments.

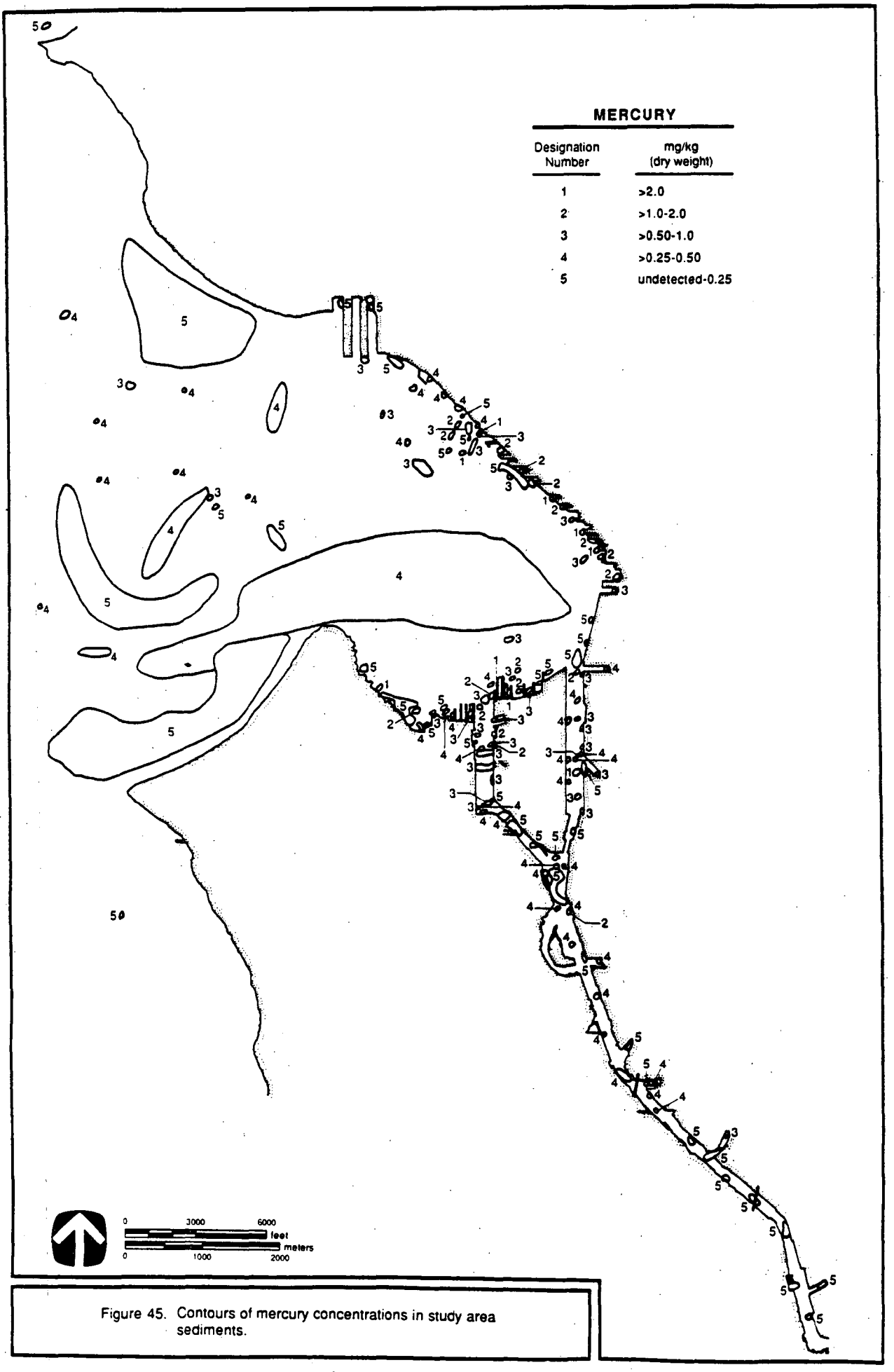


Figure 45. Contours of mercury concentrations in study area sediments.

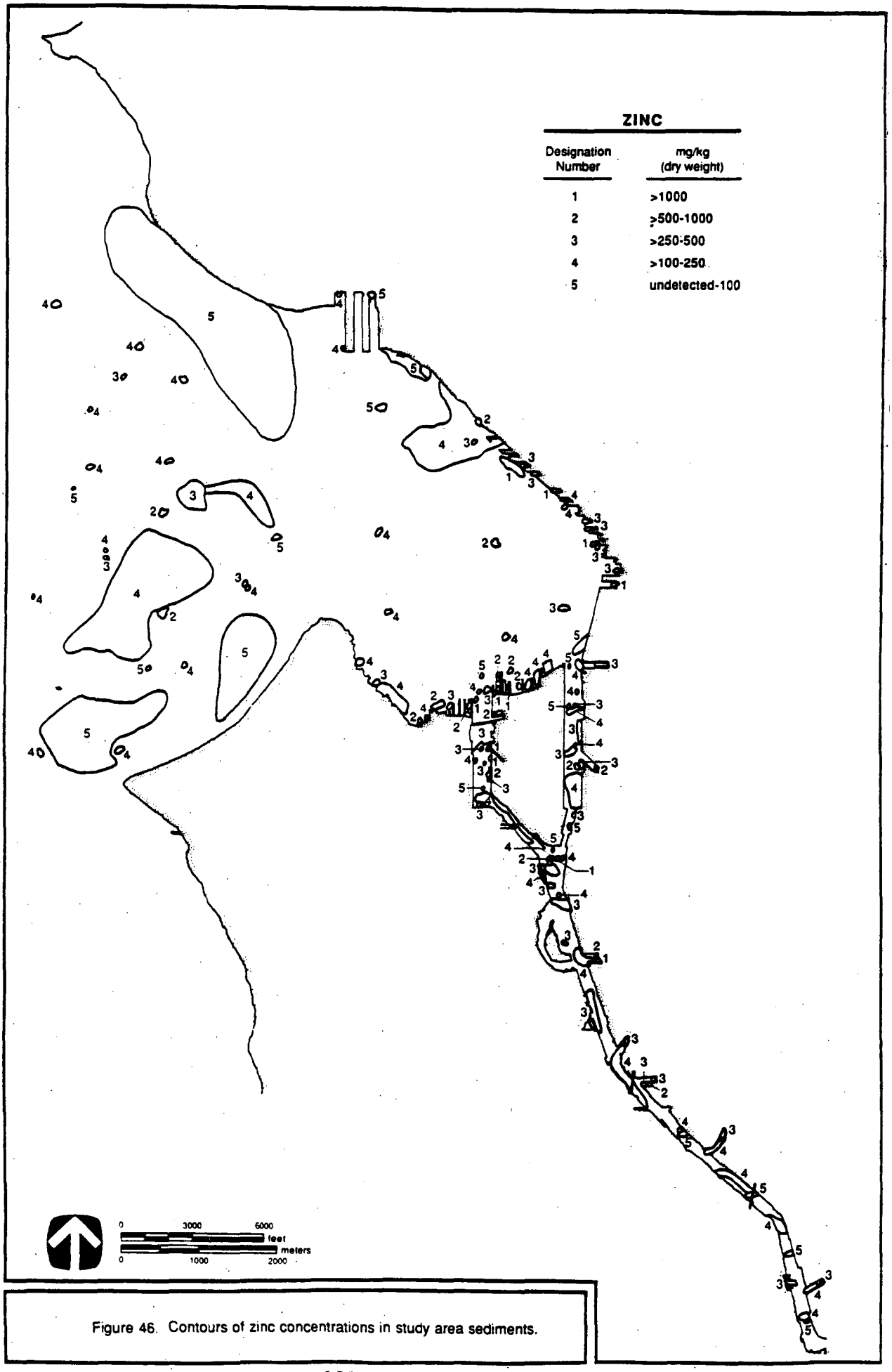


Figure 46. Contours of zinc concentrations in study area sediments.

NH-03 confirmed the high zinc concentrations at that station (Gamponia et al. 1986; U.S. EPA 1982, 1983). Other relatively high concentrations (>1,000 mg/kg DW) were observed near Kellogg Island (Romberg et al. 1984) and along the Seattle South waterfront, offshore of Stations SS-10 and SS-12 (TPPS Stations A061, B061, and C061) and near Station SS-05 (TPPS Station S0090, 4,700 mg/kg DW). The latter zinc concentration was anomalously high relative to nearby stations (by roughly an order of magnitude) but was within the range of other SS stations.

Other Metals--

A number of relatively high silver concentrations (up to 6 mg/kg DW) were reported in the area near the Denny Way CSO (Romberg et al. 1984). The only station taken in that area during the present study, intertidal Station NS-01, had the highest silver concentration observed in this study (over 8 mg/kg DW).

Cadmium concentrations reported by Malins et al. (1980, 1982) were considerably higher (e.g., in some cases, by an order of magnitude or greater) than concentrations at nearby stations from other studies. These apparently anomalous results did not significantly affect problem area identification or ranking. The highest cadmium concentration observed in all studies compiled was found at TPPS Station S0090 (27 mg/kg DW), located near Station SS-05 (2.39 mg/kg DW). Although this historical concentration was considerably higher than the concentration observed at Station SS-05, other SS stations had highly elevated cadmium concentrations (e.g., Station SS-09, 17 mg/kg DW).

Arsenic concentrations reported in historical studies were typically consistent with those of the present study; however, notably high values were reported in the North Harbor Island area. EPA Station E42, on the west side of the mouth of the West Waterway, had the highest arsenic concentration of any study compiled (1,420 mg/kg DW). Concentrations between 250 and 600 mg/kg DW were reported at historical stations east of Station NH-03.

LPAH--

Concentrations of LPAH from this study and historical studies are summarized in Figure 47. Detection limits were not available for PAH in all historical studies and therefore could not be included in LPAH and HPAH sums for those studies.

Historical LPAH concentrations were generally consistent with those of the present study. However, historical EPA Station E12, near Kellogg Island, had an extremely high LPAH concentration (42,000 ug/kg DW), whereas nearby Station KG-01 (this study) had a considerably lower concentration (2,100 ug/kg DW). A number of historical stations in the Denny Way area (not sampled subtidally in the present study) had LPAH concentrations ranging from 4,200 to 21,000 ug/kg DW in early studies (Romberg et al. 1984) and from 240 to 185,000 ug/kg DW in more recent studies (Romberg et al. 1987).

High LPAH concentrations were observed in Area NH in the present study and in historical studies. A number of stations east of the mouth of the

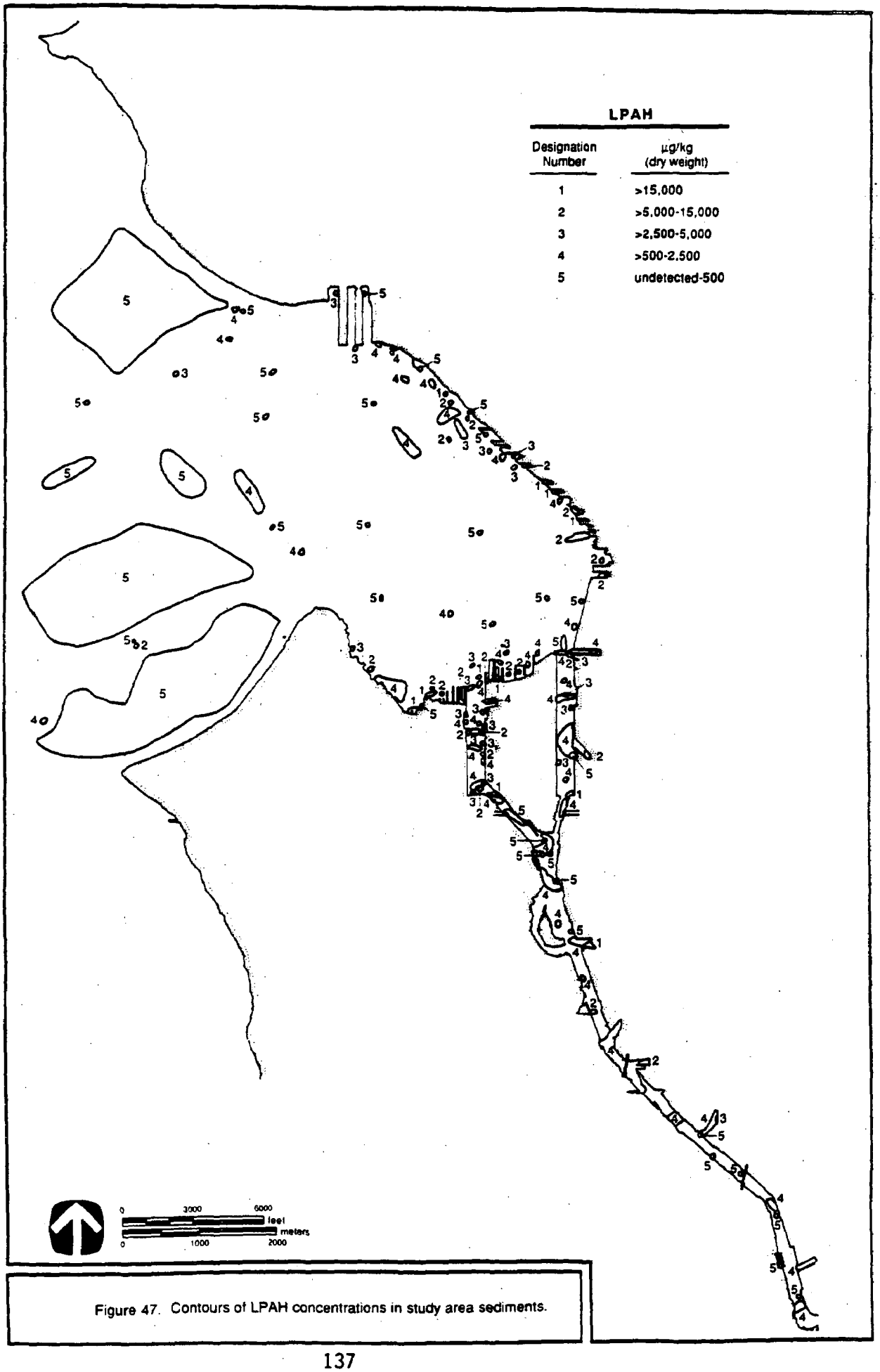


Figure 47. Contours of LPAH concentrations in study area sediments.

West Waterway had concentrations exceeding 15,000 ug/kg DW. The most extreme example is a station located near NH-03 with reported concentrations of 150,000 and 25,000 ug/kg DW (U.S. EPA 1982, 1983; Gamponia et al. 1986). On the other side of the West Waterway, high LPAH concentrations observed in the present study (Stations NH-06 and NH-08) were confirmed by historical data (U.S. EPA 1982, 1983).

HPAH--

Although HPAH concentrations were higher than LPAH concentrations, the trends observed for historical HPAH data were similar to those for LPAH data (Figure 48). In the North Harbor Island area, historical HPAH concentrations were reported over 450,000 ug/kg DW near Station NH-03, and over 150,000 ug/kg DW near NH-06. Concentrations in the Denny Way CSO area were reported as high as 130,000 ug/kg DW (Romberg et al. 1984) and 159,000 ug/kg DW (Romberg et al. 1987).

PCBs--

Interpretation of historical PCB data was impeded to some extent by high detection limits, especially for data reported in U.S. EPA (1982, 1983). The highest concentration in the present study (Station DR-08; 5,800 ug/kg DW) was confirmed by historical EPA Station E19 (5,600 ug/kg DW) (U.S. EPA 1982, 1983). Similar precision was observed between PCB concentrations for Station DR-10 (this study; 2,100 ug/kg DW) and historical EPA Station E17 (2,400 ug/kg DW) (U.S. EPA 1982, 1983). The data are presented in Figure 49.

The highest reported value from historical data was in the West Waterway (24,000 ug/kg DW; Gamponia Station 14). PCB concentrations at nearby stations from the present study (WW-06) and from historical studies were considerably lower (typically from 600 to 1,200 ug/kg DW). Furthermore, PCB concentrations reported by Gamponia et al. (1986) were higher than those reported by other studies in other areas of the West Waterway and in Area NH. Gamponia et al. (1986) reported a number of PCB concentrations greater than 1,000 ug/kg DW in Area NH, including a concentration of 14,000 ug/kg in a slip east of Station NH-03 (Station 3; adjacent EPA Station 4 had a concentration of 3,800 ug/kg DW). Elsewhere in Area NH, Gamponia et al. (1986) reported concentrations greater than 5,000 ug/kg DW at Station 1 (near NH-02, present study), Station 6, and Station 7 (near Station NH-06, present study). TPPS Station S0034 had a relatively isolated high PCB concentration of 3,100 ug/kg DW.

A number of stations with PCB concentrations between 1,000 and 4,000 ug/kg DW were reported in the Denny Way CSO area (Romberg et al. 1984). A concentration of 2,600 ug/kg was reported at TPPS Station S0090 (near Station SS-05), located along the Seattle South waterfront.

Other Organic Compounds--

A notable discrepancy between historical data and data from the present study was observed for 2,4-dimethylphenol. Gamponia et al. (1986) reported six observations in the general concentration range of 500-800 ug/kg DW in the North Harbor Island area. In contrast, in the present study, 2,4-di-

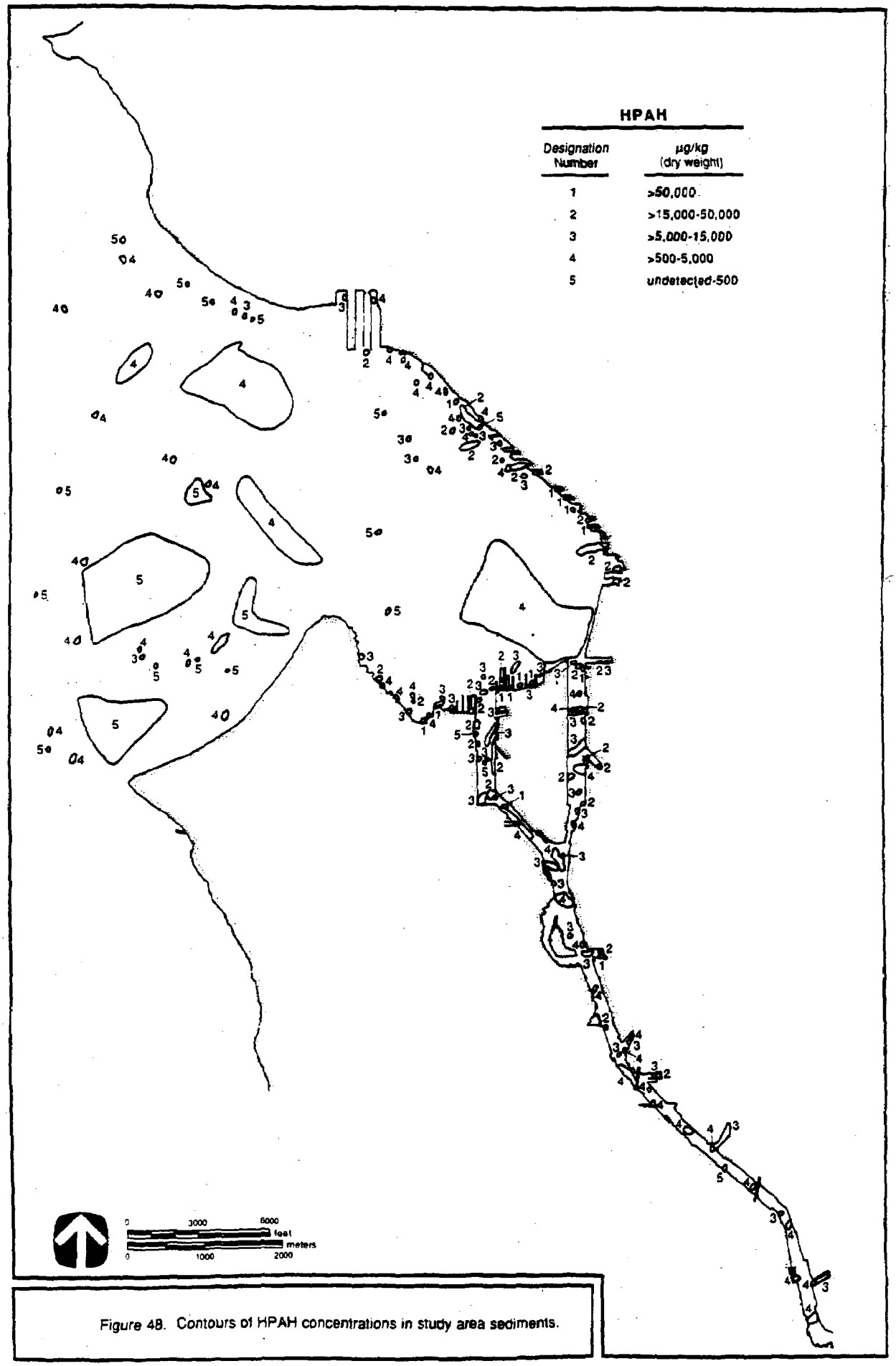


Figure 48. Contours of HPAH concentrations in study area sediments.

methylphenol was undetected at most stations in the same area at detection limits typically below 20 ug/kg DW.

Summary

- Contamination in the study area was spatially heterogeneous. The most severe sediment contamination was localized, suggesting the importance of local contaminant sources. Relatively small-scale gradients were not prevalent, although this may in part be a function of sample locations (i.e., samples were typically collected along shorelines rather than in offshore or cross-channel transects).

- The Seattle South waterfront, the North Harbor Island area, and the West Waterway were among the most severely contaminated study areas, and contained stations that accounted for many of the highest concentrations observed in the study (e.g., Stations SS-09, SS-08, SS-03, NH-03, NH-04, NH-06, NH-08, WW-12, WW-14, and WW-19). Highly-contaminated historical stations in these areas included Station 3 of Gamponia et al. (1986) and EPA Stations 4 and 42 in the North Harbor Island area, Stations 9 and 14 of Gamponia et al. (1986) in the West Waterway, and TPPS Station S0090 along the Seattle South waterfront. Other stations with relatively high concentrations included EW-05 and EW-14 in the East Waterway, Station AB-01 along Alki Beach, and Stations DR-08 and DR-12 in the upper Duwamish River. In contrast, stations in outer Elliott Bay (i.e., Areas MG and AB, excluding inner bay Station AB-01) were the least contaminated areas overall.

- Concentrations of copper, lead, mercury, and zinc were among the most elevated of the metals detected in the study area. Maximum EAR values for these chemicals ranged from 320 (for copper and zinc) to 7,700 (lead), whereas median EAR values were between 8 and 15. Concentrations of other metals that were somewhat less elevated but nonetheless of concern included arsenic (maximum EAR = 170), silver (maximum EAR = 92), cadmium, chromium, and nickel. Maximum copper concentrations (up to 2,050 mg/kg dry weight or DW) occurred near the mouth of the West Waterway (Areas NH and WW) and along the Seattle South waterfront (see Figure 43). Maximum lead concentrations (up to 71,100 mg/kg DW) occurred along the Seattle South waterfront and on the east side of the West Waterway (see Figure 44). Maximum zinc concentrations (up to 6,010 mg/kg DW) occurred along the Seattle South waterfront (see Figure 46). The highest mercury concentrations occurred at relatively isolated stations [AB-01 (28.8 mg/kg DW), NH-03, and EW-05] with generally elevated concentrations along the Seattle South waterfront (see Figure 45).

- PAH and PCBs occurred at the highest concentration and were the most frequently detected of the organic contaminants. Other organic compounds occurred at high concentrations at isolated stations. Maximum EAR values for PAH and PCBs

ranged from nearly 1,000 (for PCBs) to 15,000 (for LPAH) to over 40,000 (for HPAH). Median EAR for these compound classes ranged between 32 and 80. Other organic compounds that were infrequently found at elevated concentrations (maximum EAR >100) included 1,4-dichlorobenzene (maximum EAR = 8,900), benzyl alcohol (maximum EAR = 880), 4-methylphenol, pentachlorophenol, butyl benzyl phthalate, and retene. PAH concentrations were most elevated along the Seattle South waterfront (up to 3,800,000 ug/kg DW total PAH), but were also highly elevated in the North Harbor Island study area, the East and West Waterways, and at isolated stations in other areas (see Figures 47 and 48). PCB concentrations were most elevated in the upper Duwamish River (up to 5,800 ug/kg DW) and along the Seattle South waterfront, but high concentrations occurred throughout the Duwamish River and in the North Harbor Island study area (Figure 49). Relatively high detection limits reported for a number of organic compounds (most notably chlorinated phenols, chlorinated benzenes, hexachlorobutadiene, benzyl alcohol, and benzoic acid) impeded data analysis for these compounds.

- Except among PAH and related compounds, few correlations among chemicals were observed on a study-wide basis. When correlations were performed on a smaller scale for individual study areas, strong correlations were observed, particularly among metals. These results are consistent with the presumed importance of sources that predominate in localized areas.

BIOACCUMULATION

Bioaccumulation studies were conducted to determine if selected contaminants in sediment or water were accumulated in the tissues of indigenous organisms. This section summarizes the bioaccumulation of mercury, selected chlorinated pesticides, and PCBs in edible muscle tissue of English sole. The objectives of this section are to describe geographic trends in bioaccumulation and to determine whether tissue contaminants in the Elliott Bay study area were significantly elevated above concentrations observed at the reference area (Point Pully).

Normalization of Chemical Concentrations

A number of interrelated variables have been observed to influence the concentrations of lipophilic compounds in fish tissue, most notably tissue lipid content, sex, age, and season of collection (Phillips 1980). Of these variables, lipid content (estimated as total extractable organic matter) is often used for normalization, based on empirical relationships between pollutant concentrations and lipid content (e.g., Sloan et al. 1985), as well as theoretical (partitioning) considerations (e.g., Mackay 1982; Chiou 1985). Strong relationships between bioaccumulation factors and partition coefficients [e.g., octanol-water partition coefficients (k_{ow}) or triglyceride-water partition coefficients (k_{tw})] in controlled studies support the theory that hydrophobic chemicals partition into organism lipids from water as they would partition into an organic solvent. Therefore, lipid normaliza-

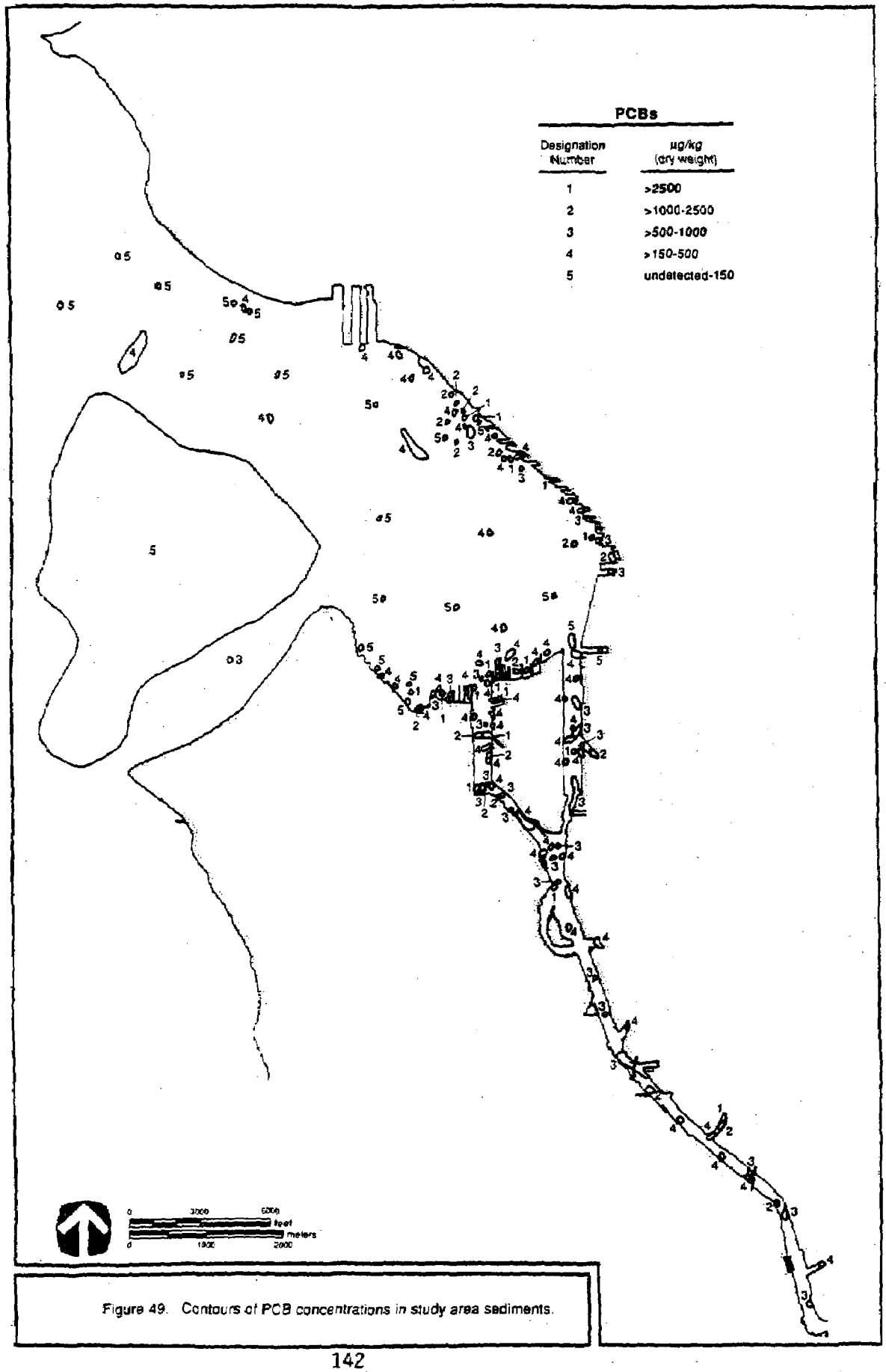


Figure 49. Contours of PCB concentrations in study area sediments.

tion was examined in this study to examine trends that may have been obscured on a wet weight basis. One important factor that can reduce the applicability of lipid-bioaccumulation relationships is deviation from equilibrium conditions in the environment (e.g., as related to the kinetics of uptake and depuration).

Evaluation of the Reference Area

Concentrations of mercury, PCBs, and pesticides in muscle tissue of English sole collected from the Point Pully reference area were within the range of values expected for areas of Puget Sound that are remote from contaminant sources. The mean concentration of mercury in Point Pully samples was 0.089 mg/kg wet weight, with a range of 0.056 to 0.118 mg/kg wet weight. The concentration of PCBs in Point Pully samples was 5.4 ug/kg wet weight, with a range of 2-19 ug/kg wet weight. EPA priority pollutant pesticides were not detected in muscle tissue of English sole from Point Pully.

By comparison, the mean concentration of mercury found in muscle tissue of English sole from other reference areas of Puget Sound was 0.04 mg/kg wet weight in Discovery Bay (Gahler et al. 1982) and <0.06 mg/kg wet weight in Carr Inlet (Tetra Tech 1985a). The mean concentration of PCBs in muscle tissue of English sole was <13 ug/kg wet weight in Discovery Bay (Gahler et al. 1982) and 36 ug/kg wet weight in Carr Inlet (Tetra Tech 1985a). EPA priority pollutant pesticides were not detected in the samples from Carr Inlet (Tetra Tech 1985a) and from Discovery Bay (Gahler et al. 1982), with two exceptions. p,p'-DDT and p,p'-DDE were detected in English sole muscle from Discovery Bay at low concentrations (<1 ug/kg wet weight and 3 ug/kg wet weight, respectively).

In summary, Point Pully appears to be an adequate reference area for evaluation of bioaccumulation in English sole.

Mercury in Fish Tissue

The results of the mercury analyses are presented in Table 23. The means and ranges of each station are based upon data for five individual fish (not including analytical replicates). The data do not suggest that mercury in tissue is of concern, as the reference station from Point Pully (PP-91) had the highest mean mercury concentration of all stations sampled (Table 23). Although maximum concentrations of mercury at 3 of 11 stations equalled or exceeded the maximum value observed at the reference station, the ranges were not broad and never exceeded 0.15 mg/kg wet weight. No Elliott Bay/Duwamish River test station had a mercury concentration that was statistically different from that at the reference station (t-test; $P>0.001$).

The F_{max} test revealed homogenous variances for all comparisons, suggesting that wet weight normalization was appropriate for statistical analysis. However, several additional analyses were conducted to examine whether normalizations other than wet weight might be appropriate for these data. Pearson correlation analyses were performed for mercury vs. lipid content and mercury vs. fish age. For both variables, correlations were very poor (mercury vs. lipids: $r=-0.08$, $P>0.05$, $n=60$; mercury vs. fish age: $r=0.32$, $P<0.05$, $n=60$). It is possible (but speculative) that such relation-

TABLE 23. MERCURY CONCENTRATIONS IN FISH COLLECTED FROM ELLIOTT BAY, DUWAMISH RIVER, AND POINT PULLY (mg/kg wet weight)

Station	Mean[a]	Range
AB-91	0.064	0.013 - 0.125
DR-91	0.071	0.053 - 0.099
EW-91	0.036	0.018 - 0.055
KG-91	0.068	0.048 - 0.097
MG-91	0.084	0.061 - 0.114
NH-91	0.059	0.022 - 0.102
NH-92	0.077	0.045 - 0.118
NS-91	0.074	0.058 - 0.099
PP-91[b]	0.089	0.056 - 0.118
SS-91	0.037	0.011 - 0.071
SS-92	0.060	0.023 - 0.099
WW-91	0.085	0.029 - 0.149

[a] Arithmetic mean.

[b] Reference station; no test stations were significantly different from the reference station (P>0.001).

ships could have existed but were not discernible because of the narrow range of observed mercury concentrations. Mercury data for all stations were evaluated for normality with the Kolmogorov-Smirnov (K-S) test (Sokal and Rohlf 1981). The data were normally distributed ($P>0.05$). Lipid normalization of the data skewed the data set toward the lower end of the concentration range and resulted in a distribution that was not normal (K-S test; $P<0.05$). These results indicate that lipid normalization was not preferable to wet weight normalization to satisfy the assumptions of the statistical tests used for comparisons with the reference area.

PCBs/Pesticides in Fish Tissue

This section focuses on PCB concentrations, as EPA priority pollutant pesticides were seldom detected in this study. Detection limits for single-component pesticides ranged from 1 to 50 ug/kg wet weight, but typically were less than 5 ug/kg wet weight. The only pesticide detected at greater than 10 ug/kg wet weight was p,p'-DDE (410 ug/kg wet weight) for a single fish at trawl Station SS-91 (along the Seattle South waterfront). For other fish in trawl Station SS-91, p,p'-DDE was undetected at a detection limit of 2 ug/kg wet weight. The 410 ug/kg concentration was confirmed by GC/MS.

Statistical comparisons between test stations and the reference station were conducted as for mercury bioaccumulation data. However, for PCB bioaccumulation based on wet weight concentrations, the F_{max} test revealed extremely heterogeneous variances for all trawl stations except AB-91 (alpha = 0.05). Observed F values exceeded the critical F value by a factor of 35 to >1,100. Comparable results were obtained for lipid normalized PCB data. Therefore, PCB concentrations (wet weight) were $\log_{10}$-transformed to better satisfy the assumption of homogeneous variances for the t-test. Log transformation resulted in homogenous variances for all comparisons (alpha = 0.05). Cumulative frequency plots of all individual fish (n=60) revealed that, for the overall data set, log transformation resulted in a more normal distribution than was observed for the untransformed wet weight PCB concentrations. However, neither the untransformed nor the transformed PCB data were normally distributed (K-S test, $P<0.05$).

Results of the t-tests using log-transformed PCB data (wet weight) are presented in Figure 50. Eight of the eleven trawl stations had mean PCB concentrations that were significantly greater than the reference area mean ($P<0.001$). Only trawl Stations AB-91, MG-91, and NH-92 were not significantly different than the reference station (PP-91).

Geometric mean concentrations (ug/kg wet weight) are presented in Figure 50 and in Table 24, along with along with data for lipid content and ages of fish in all trawls. Concentrations were highest in the Duwamish River and tended to decrease toward outer Elliott Bay. Specifically, PCB concentrations were highest in the East and West Waterways of the Duwamish River (460-470 ug/kg wet weight) and decreased slightly moving upriver (390-400 ug/kg wet weight at trawl Stations KG-91 and DR-91). Trawl Station NH-91, located north of Harbor Island, had a geometric mean concentration of 350 ug/kg wet weight; concentrations decreased rapidly moving west from Harbor Island (53 ug/kg wet weight at trawl Station NH-92 and 2.4 ug/kg wet weight at Station AB-91). Mean concentrations at three trawl stations along the Seattle waterfront ranged from 190 to 250 ug/kg wet weight, whereas trawl

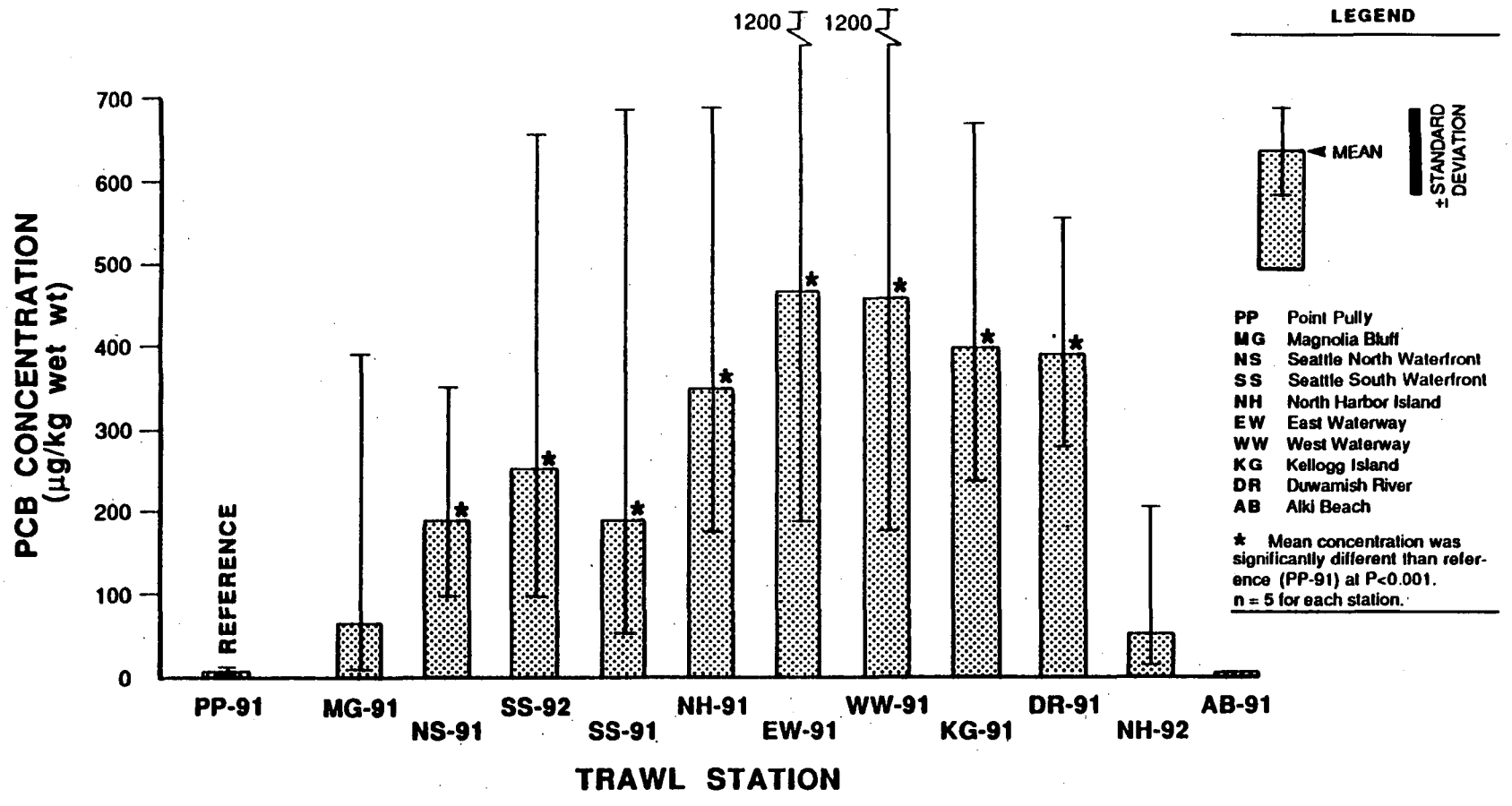


Figure 50. PCB concentrations (µg/kg wet wt.) in muscle tissue of English sole from Elliott Bay, the Duwamish River, and Point Pully. Means and standard deviations are based upon $\log_{10}$-transformed data.

TABLE 24. PCB CONCENTRATIONS, LIPID CONTENTS, AND AGES OF ELLIOTT BAY FISH

Station	PCB Concentration (ug/kg wet weight)		Lipid Content (percent of wet weight)		Age (yr)	
	Mean[a]	Range	Mean[b]	Range	Mean[b]	Range
AB-91	E2.4[c]	E1-E10	0.42	0.20-0.63	11	7-16
DR-91	E390	E280-E630	1.9	0.94-3.1	8.6	7-11
EW-91	470	230-2,060	1.3	0.59-1.8	5.0	3-9
KG-91	E400	E190-E730	1.9	0.94-2.9	9.0	7-10
MG-91	E63	E13-1,490	0.78	0.50-1.2	8.2	6-10
NH-91	E350	E150-690	2.9	1.2-4.2	6.0	3-9
NH-92	E53	E12-480	1.3	0.44-2.8	8.8	6-12
NS-91	E190	79-E420	1.2	0.25-1.9	6.6	4-8
PP-91	E5.4	E2-E19	0.85	0.64-1.0	8.8	8-10
SS-91	E190	E42-670	1.5	0.62-3.1	8.2	4-15
SS-92	E250	E53-530	2.1	1.5-3.2	5.0	4-7
WW-91	E460	100-1,030	0.68	0.38-1.0	7.2	3-11

[a] Geometric mean (based on the arithmetic mean of log-transformed samples). Log-transformed data were used to satisfy the assumptions of statistical tests.

[b] Arithmetic mean; appropriate because the data were normally distributed.

[c] E = Estimated concentration.

Station MG-91 had a considerably lower mean concentration (63 ug/kg wet weight). An anomalously high concentration was reported for an individual fish in the MG-91 trawl (1,490 ug/kg wet weight; Table 24). Although bioaccumulation data are often variable because fish are mobile and can have different exposure histories, the anomalous PCB concentration in one Magnolia fish was extreme (roughly 30 times higher than any other fish in the trawl).

To examine whether alternative normalization would be appropriate for these data, PCB concentrations were correlated against lipid content and fish age. The correlation coefficient (r) for PCB concentration (wet weight) vs. lipid content was 0.27; the correlation coefficient for PCB concentration vs. age was 0.08. To some extent, this lack of correlation is indicated in Table 24 [e.g., the fish trawl from Alki Beach (AB-91) had the lowest mean and range for PCB concentration but had the greatest mean and range for fish age]. Scatterplots revealed generally poor correlations and indicated that the low correlation coefficients did not result from a small number of anomalous cases.

Based on these data, geographic location of fish (and presumably, the PCB exposure associated with different geographic areas) is a more important factor in PCB bioaccumulation than lipid content or age (for the age classes sampled). Whereas PCB concentrations appeared to correspond to proximity to the Duwamish River, PCB concentrations did not correlate well with lipid content or age of fish over the entire data set.

Comparison with Recent Historical Data

The bioaccumulation data for English sole collected during this study were compared with data from recent studies by Malins et al. (1982), Romberg et al. (1984), and Landolt et al. (1985). Because of the limited number of observations of contaminant levels in muscle tissue of English sole from Elliott Bay, only qualitative comparisons of the results of this study with previous studies could be made.

Mercury concentrations in four composite samples of muscle tissue from trawl-caught English sole were analyzed during the Metro TPPS at three locations within the present study area [Alki Point (two samples), West Point, Denny Way CSO]. Numbers of individual fish represented in each sample were not given by the authors. The concentrations of mercury in the four samples ranged from 0.061 mg/kg (wet weight) at Alki Point to 0.125 mg/kg (wet weight) at the Denny Way CSO, with a mean concentration of 0.08 mg/kg (wet weight). The mean concentrations of mercury in English sole muscle tissue observed during the present study ranged from 0.036 mg/kg (wet weight) in the East Waterway to 0.089 mg/kg (wet weight) at Point Pully. These concentrations are comparable to those found by Romberg et al. (1984).

EPA priority pollutant pesticides were generally not detected in the English sole samples collected by Romberg et al. (1984) [mean detection limits from 0.01 to 3 ug/kg (wet weight) were reported]. The pesticides DDD and DDE were measured in several of the samples, with a maximum total concentration of 7.0 ug/kg (wet weight) in fish collected offshore of the Denny Way CSO. Because these were composite samples, concentrations of DDD and DDE in individual fish could be much greater than the reported values. Nevertheless, their results are consistent with those of the present study

[i.e., pesticides were generally not detected; the only high level observed was 410 ug/kg (wet weight) of p,p'-DDE in a single fish at Station SS-91].

In historical studies, mean concentrations of PCBs in muscle tissue of English sole ranged from 11 ug/kg (wet weight) to 2,100 ug/kg (wet weight), with a mean of about 400 ug/kg (wet weight; n=14 samples, some of which were composites). Romberg et al. (1984) found an average of 24 ug/kg (wet weight) of PCBs in English sole muscle at Alki Point, 290 ug/kg (wet weight) at Denny Way CSO, and 486 ug/kg (wet weight) at West Point. Malins et al. (1982) found a range of 270-2,100 ug/kg (wet weight) in four samples of English sole muscle from Elliott Bay (specific sampling locations not reported). PCB concentrations in muscle tissue samples from five individual English sole collected by Landolt et al. (1985) from Smith Cove ranged from 20 ug/kg to 47 ug/kg (wet weight), with a mean of 28 ug/kg (wet weight). A clear spatial pattern was not evident in the historical PCB data. The overall mean PCB concentration for historical studies is of the same order of magnitude as several of the highest mean concentrations found in the present investigation. The low concentrations reported from Smith Cove by Landolt et al. (1985) are consistent with the low values observed at the Magnolia area in the present study. The PCB value at West Point found by Romberg et al. (1984) is substantially higher than the mean PCB concentration reported here for the Magnolia area. The apparent discrepancy could be due to differences in specific sampling locations. The station sampled by Romberg et al. (1984) was north of West Point and could represent a local population of English sole that is somewhat distinct from that in the Magnolia area sampled during this study.

Summary

- Mercury bioaccumulation in English sole in the Elliott Bay/Duwamish River area was not significant relative to that near Point Pully; in fact, the reference area had the highest mean mercury concentration observed in the study.

- Pesticide bioaccumulation was not important in the study area with the exception of p,p'-DDE, which was detected in a single fish collected along the Seattle South waterfront (410 ug/kg wet weight).

- PCB bioaccumulation was significant over much of the study area, with the highest concentrations observed in the Duwamish River (specifically in the East and West Waterways). Concentrations tended to decrease with distance from the mouth of the Duwamish River.

SEDIMENT BIOASSAYS

The results of sediment toxicity tests using the amphipod Rhepoxynius abronius are presented in this section. First, amphipod bioassay results for Port Susan are compared with results from other reference areas used during previous studies. The amphipod mortality values for each station in the Elliott Bay system are then presented and compared statistically with the Port Susan values. Finally, results of the present study are compared with

those of previous studies on the toxicity of sediments in Elliott Bay to R. abronius.

Evaluation of the Reference Area

Mean values of amphipod survival and their 95 percent confidence limits are shown in Figure 51 for individual stations in Port Susan and other reference areas of Puget Sound. Data for the 1986 survey of Port Susan, which were collected as part of the Everett Harbor Toxics Action Program, are also shown in the figure. Mean amphipod survival for several of the Port Susan observations was low (<80 percent) relative to data for most other reference areas. Mean survival was also low (≤75 percent) at one station in Carr Inlet, where a single replicate was an extreme outlier, and at one station in Sequim Bay. The relatively low survival at some Port Susan stations can not be explained by a response of the amphipods to fine-grained sediments. The product-moment correlation between mean amphipod survival and percent fine-grained material was not significant ($r=0.38$, $P>0.05$, $n=7$). The range of percent fine-grained material in samples collected during 1985-1986 in Port Susan was 7.4-88 percent. Only a single sample contained more than 24 percent fine-grained material. Moreover, mean amphipod mortality for that sample (Station PS-01, 1985) was relatively low (13 percent).

The 1985 data for amphipod response to Port Susan sediments are considered to be adequate for use as reference data. At one of the Port Susan stations (PS-02), mean amphipod survival was only 76 percent, a value that indicates marginal toxicity compared to the criterion of ≤75.4 percent survival for toxic sediments in Mearns et al. (1986). However, the mean amphipod survival among all four stations sampled during 1985 was 84 percent. Moreover, contaminant concentrations in sediments of Port Susan were typically within the range of those observed at other reference areas in Puget Sound (see SEDIMENT CHEMISTRY). Thus, all of the 1985 bioassay data for Port Susan were pooled for statistical comparisons with data from sites in the Elliott Bay system.

The Elliott Bay bioassay data could have been compared with native sediment controls (i.e., West Beach, Whidbey Island) rather than with Port Susan to establish statistically significant elevations in mortality. Because of the relatively low levels of mean mortality (i.e., ≤10 percent) in native sediments, comparisons of Elliott Bay sediments to native-sediment controls would have resulted in identification of more stations with significantly elevated amphipod mortality. However, such comparisons may confound the effects of simply removing amphipods from native sediment with toxic effects or other site-specific factors in Elliott Bay. Comparisons with a separate reference area (i.e., Port Susan) were used to account for possible factors related to removal of amphipods from native sediments.

General Patterns of Amphipod Mortality

The mean amphipod mortality and the range of station-specific means for each study area within the Elliott Bay system and the reference area are shown in Figure 52. The highest overall mortalities were found in the North Harbor Island area (mean mortality = 60 percent) and in East Waterway (mean mortality = 43 percent). The maximum mortality (100 percent) was observed at

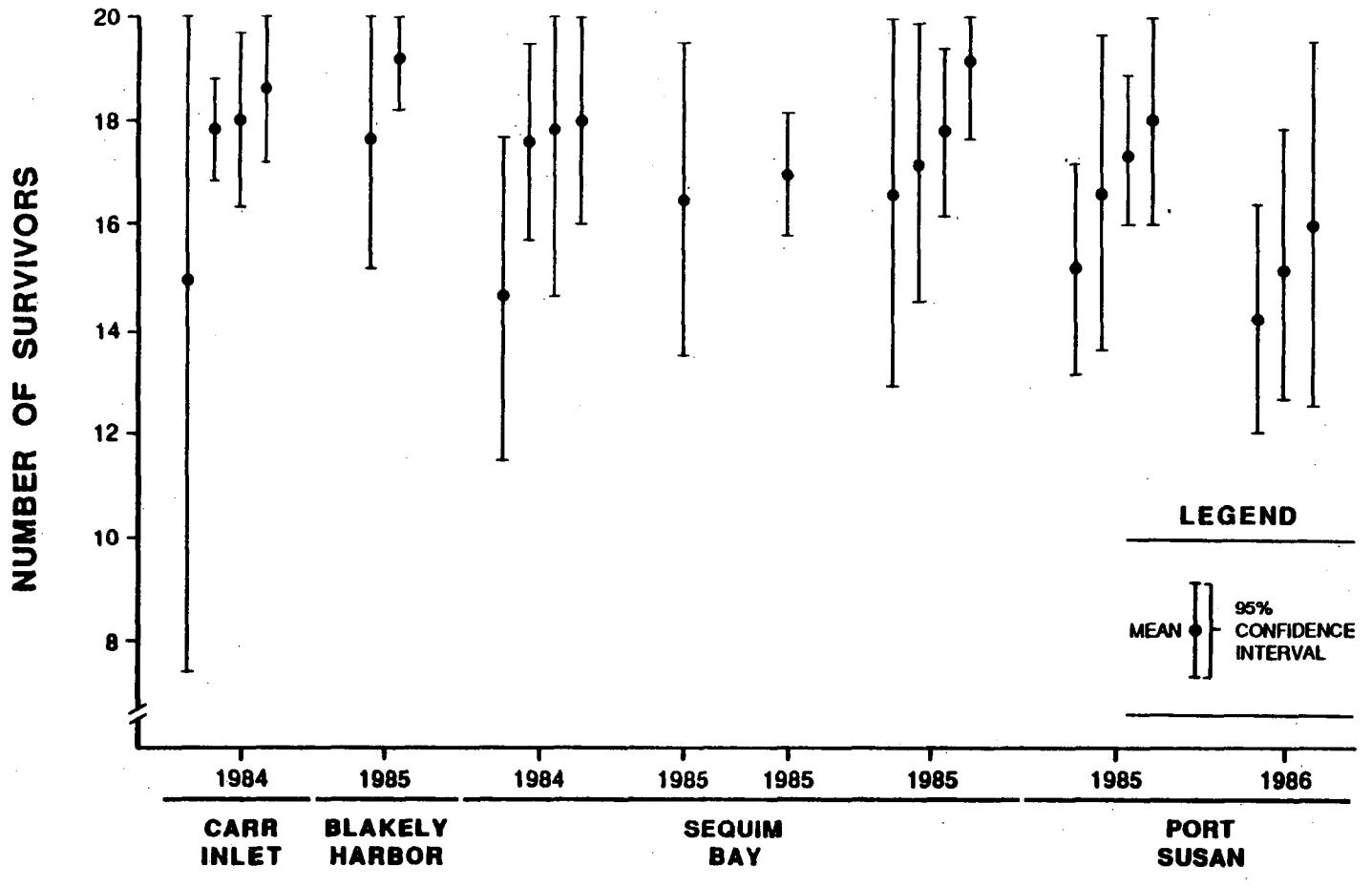


Figure 51. Amphipod bioassay data from Puget Sound reference areas.

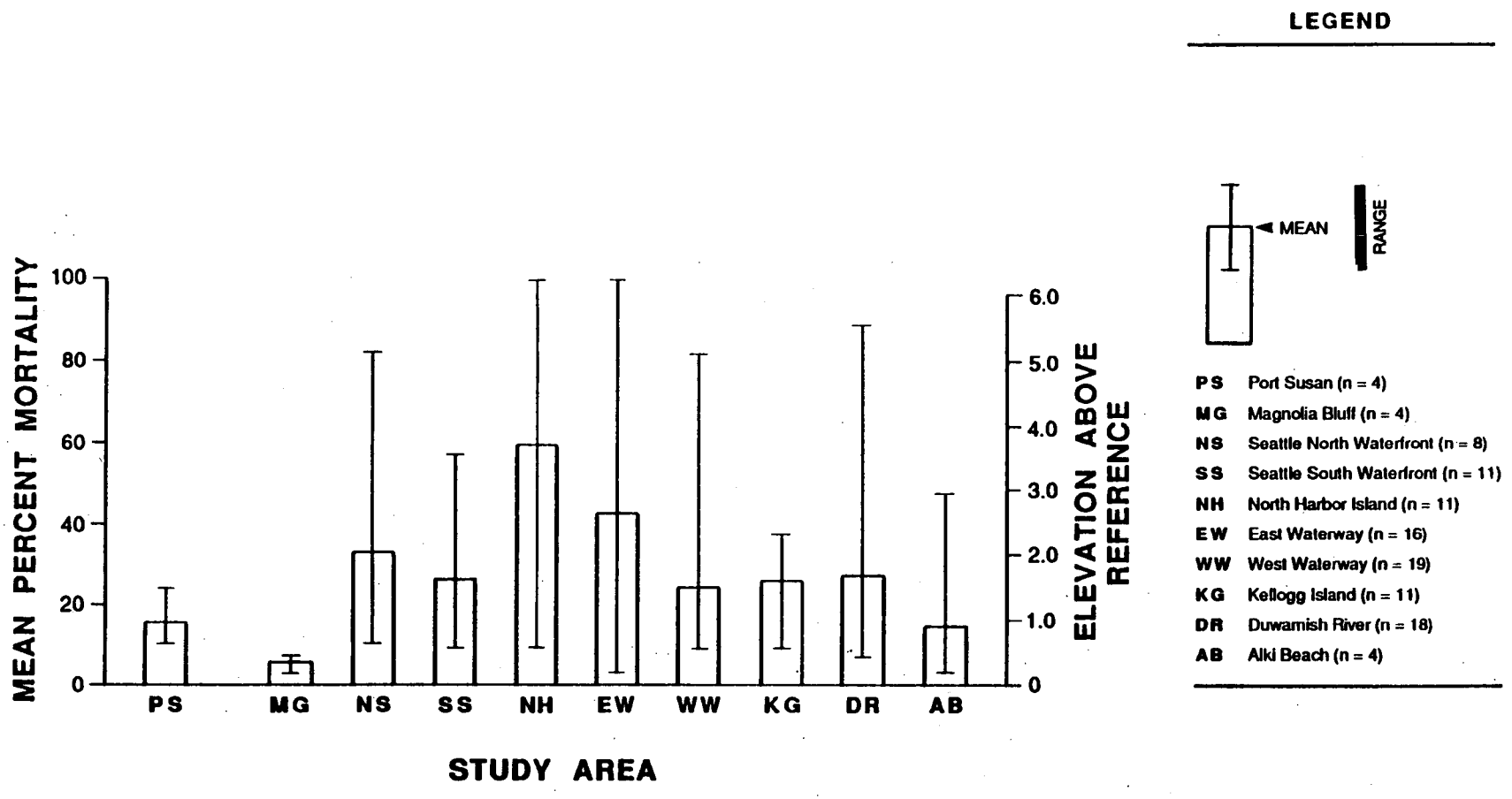


Figure 52. Mean and range of amphipod bioassay responses within study areas.

Stations NH-08 and EW-05. The range of mean mortality at stations within most study areas was large, indicating considerable spatial heterogeneity. Although relatively high mean mortalities (>35 percent) were observed within all study areas (except Magnolia), some stations within each area exhibited mean mortality values as low or lower than the lowest value (i.e., 10 percent) in Port Susan.

Comparison of the Elliott Bay System with Port Susan

Results of the amphipod bioassay tests for all stations sampled during the Elliott Bay investigation are summarized in Table 25. Statistical comparisons between Elliott Bay sites and the reference area (Port Susan 1985 data pooled) indicated that mortalities in 17 test sediments were significantly different from the Port Susan samples ($P<0.001$). Seven of the nine study areas tested contained one or more sampling sites with statistically significant amphipod mortality (Figure 53).

In 14 of the 28 samples that exhibited a mean amphipod mortality $\geq$40 percent, mean mortality was not statistically different from the mean reference value at $P<0.001$. However, all 28 of these samples did exhibit a significant difference from the reference area at $P<0.05$. The lack of significance at $P<0.001$ for mean mortality values over 40 percent can be explained by low statistical power (<0.6 at $P<0.001$), partly due to the relatively high mean mortality in the reference area. Also, the variance of the bioassay test is typically higher at intermediate mortality values (35-65 percent) compared with the extremes of the mortality range. The variance of the mean in the Elliott Bay amphipod bioassays was very high [standard deviation $\geq$28, corresponding to a standard error (SE) $\geq$12] at four stations: Stations SS-03, NH-02, DR-13, and DR-16. The relative influence of good reference survival vs. low variability on the statistical power of the amphipod bioassay is being investigated in a separate EPA project on refinement of sediment quality values.

Comparison with Recent Historical Data

Previous R. abronius sediment bioassay tests in Elliott Bay, which used acceptable protocols (cf. Swartz et al. 1985) and fresh sediments, are summarized by Evans-Hamilton and D.R. Systems (1987). Other kinds of bioassay tests performed on fresh sediments from the Elliott Bay system are summarized by Long (unpublished). The majority of Elliott Bay has not been tested for sediment toxicity to amphipods (see Figure 50).

The Magnolia stations (MG-01 to MG-04) were all non-toxic. Previous sediment bioassays in this area have shown a similar lack of toxicity to R. abronius.

Previous sampling along the Seattle Waterfront North (Stations NS-01 to NS-08) has been concentrated near the Denny Way CSO, where sediments have consistently been shown to be toxic. Evans-Hamilton and D.R. Systems (1987) determined that the north end of Pier 91 and the Denny Way CSO were sites of most concern based on the amphipod bioassay. In the present study, these two sites (represented by Stations NS-01 and NS-08, respectively) were the only stations that displayed significant toxicity ($P<0.001$) in the Seattle Waterfront North area.

TABLE 25. SUMMARY OF AMPHIPOD BIOASSAY RESULTS

Station	Range of Mortality (percent)	Mean Mortality[a] (percent)
AB-01	25-80	47 (9.3)
AB-02	0-15	6 (2.9)
AB-03	0-10	3 (2.0)
AB-04	0-5	3 (1.2)
DR-01	5-25	13 (3.7)
DR-02	20-80	38 (11.0)
DR-03	2.5-35	14.5 (6.5)
DR-04	10-30	18 (4.1)
DR-05	0-100	29 (18.3)
DR-06	0-15	8 (3.0)
DR-07	0-20	8 (3.7)
DR-08	0-45	25 (7.6)
DR-09	15-20	17 (1.2)
DR-10	0-10	7 (2.0)
DR-11	5-35	23 (5.1)
DR-12	5-25	17 (3.4)
DR-13	15-90	57 (16.3)
DR-14	15-60	32 (9.6)
DR-15	85-100	89 (2.9)*
DR-16	5-90	45 (14.6)
DR-17	0-20	6 (3.7)
DR-25	15-65	40 (9.7)
EW-01	0-10	3 (2.0)
EW-02	20-65	39 (8.3)
EW-03	5-100	29 (18.1)
EW-04	50-75	58 (5.1)*
EW-05	100[b]	100 (0)*
EW-06	30-55	39 (4.3)*
EW-07	50-80	63 (5.8)*
EW-08	35-90	65 (11.3)
EW-09	20-85	59 (10.9)
EW-10	30-90	58 (12.1)
EW-11	40-80	62 (7.2)*
EW-12	10-25	16 (2.4)
EW-13	10-45	24 (6.8)
EW-14	5-70	22 (12.1)
EW-15	10-20	16 (1.9)
EW-16	20-40	31 (3.7)

TABLE 25. (Continued)

Station	Range of Mortality (percent)	Mean Mortality[a] (percent)
KG-01	10-35	22 (4.1)
KG-02	10-60	37 (10.2)
KG-03	10-40	27 (5.4)
KG-04	5-35	18 (4.9)
KG-05	25-45	32 (3.7)
KG-06	5-15	9 (2.4)
KG-07	5-75	23 (13.3)
KG-08	5-35	16 (5.1)
KG-09	25-40	33 (2.5)*
KG-10	15-45	31 (5.3)
KG-11	25-40	32 (2.5)*
MG-01	5-10	7 (1.2)
MG-02	0-10	3 (2.0)
MG-03	0-10	7 (2.0)
MG-04	0-15	6 (2.9)
NH-01	0-65	20 (12.0)
NH-02	20-90	45 (12.6)
NH-03	85-100	94 (3.7)*
NH-04	85-95	87 (2.0)*
NH-05	70-100	80 (6.3)*
NH-06	75-100	83 (4.6)*
NH-07	5-15	9 (2.4)
NH-08	100[b]	100 (0)*
NH-09	30-90	58 (10.2)
NH-10	10-45	24 (5.8)
NH-11	30-95	55 (11.5)
NS-01	45-75	58 (6.2)*
NS-02	0-65	16 (12.4)
NS-03	0-25	13 (4.1)
NS-04	0-70	33 (13.7)
NS-05	0-15	10 (2.7)
NS-06	0-65	15 (12.6)
NS-07	10-65	36 (9.7)
NS-08	65-100	82 (6.8)*
PS-01	5-20	13 (2.5)
PS-02	15-35	24 (3.7)
PS-03	0-20	10 (3.5)
PS-04	0-30	17 (5.4)

TABLE 25. (Continued)

Station	Range of Mortality (percent)	Mean Mortality[a] (percent)
SS-01	0-20	9 (3.7)
SS-03	5-80	57 (14.5)
SS-04	0-45	13 (8.3)
SS-05	5-40	18 (6.0)
SS-06	30-65	45 (5.7)*
SS-07	15-35	30 (3.9)
SS-08	20-65	44 (8.3)
SS-09	15-45	29 (5.1)
SS-10	5-20	14 (2.9)
SS-11	0-15	10 (2.7)
SS-12	5-35	19 (4.8)
WW-01	5-25	15 (3.5)
WW-02	65-100	82 (6.6)*
WW-03	0-20	9 (3.3)
WW-04	0-25	11 (4.0)
WW-05	5-15	9 (2.4)
WW-06	10-40	19 (5.3)
WW-08	15-70	41 (11.3)
WW-09	30-90	60 (11.7)
WW-10	5-25	12 (3.4)
WW-11	30-70	41 (7.5)
WW-12	15-75	33 (10.8)
WW-13	5-40	15 (6.3)
WW-14	5-30	18 (5.4)
WW-15	5-20	13 (2.5)
WW-16	10-35	17 (4.6)
WW-17	10-25	16 (2.9)
WW-18	5-35	14 (5.3)
WW-19	10-25	18 (3.0)
WW-20	5-50	22 (7.8)
Controls - clean		
1	0-10	1 (1.0)[c]
2	0-20	10 (3.5)
3	0-10	5 (1.6)
4	0-5	1 (1.0)
5	0-15	2.2 (0.8)[d]
Control-Cd-spiked		
	100[b]	100 (0)

TABLE 25. (Continued)

[a] Mean mortality is based on five replicate samples per station, unless otherwise indicated. Standard error of each mean is given in parentheses.

[b] A mortality level of 100 percent was observed for each of the five replicates.

[c] Mean mortality is based on ten replicate samples per station.

[d] Mean mortality is based on twenty replicate samples per station.

* - Denotes that mean mortality differed significantly ($P<0.001$) from the mean mortality of pooled replicates from the four Port Susan stations.

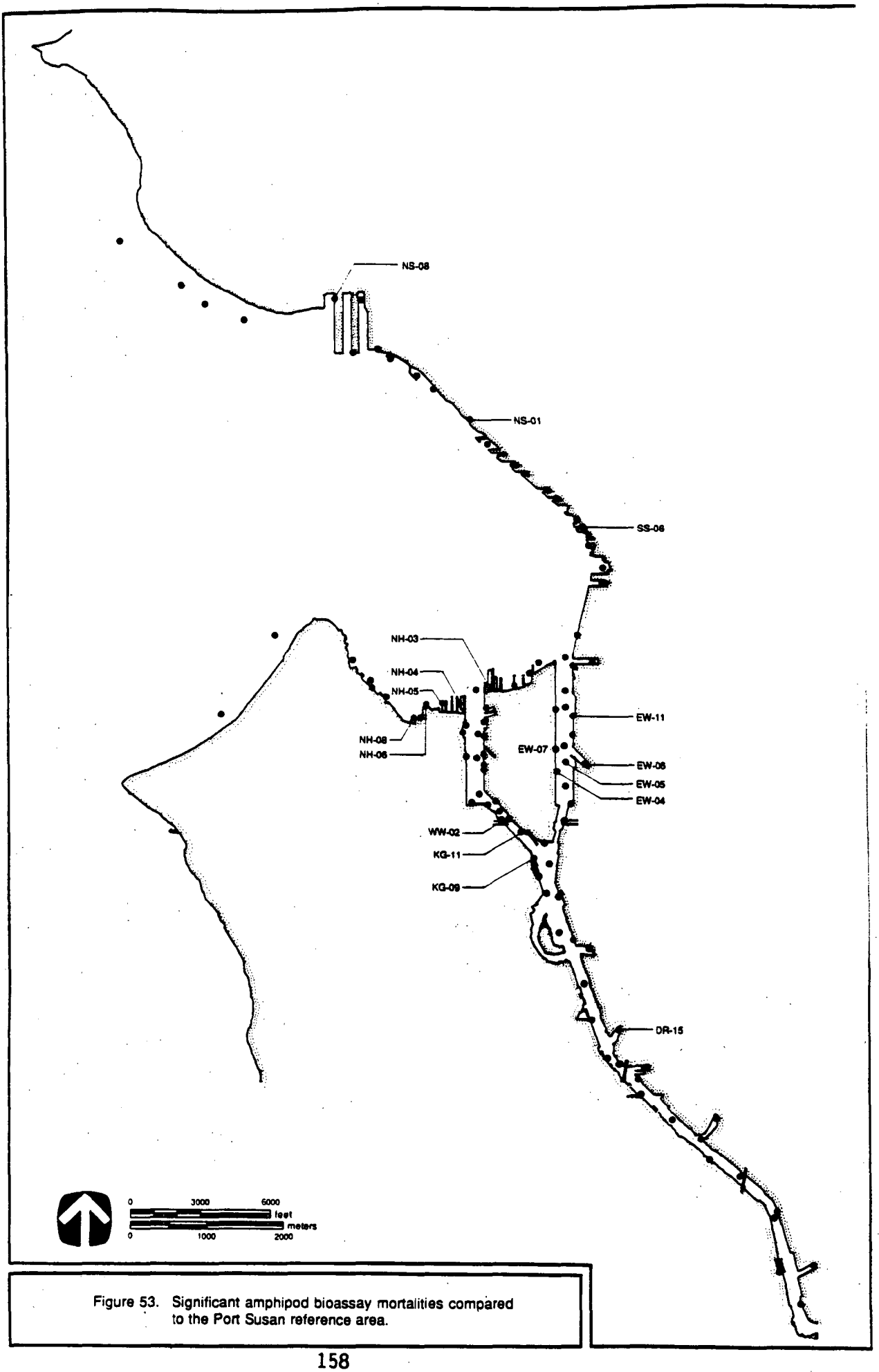


Figure 53. Significant amphipod bioassay mortalities compared to the Port Susan reference area.

The Seattle Waterfront South (Stations SS-03 to SS-12) has shown patchy toxicity, and has been less toxic than expected (Long 1984). Evans-Hamilton and D.R. Systems (1987) delineated three sites of most concern based on the amphipod bioassay. In the present study only one of these (SS-06) showed statistically significant toxicity ($P<0.001$). Nevertheless, two stations (SS-03 and SS-08) located at sites where high toxicity was found previously exhibited high values of mean mortality (>40 percent). Despite the high mortality levels, these stations were not statistically different ($P<0.001$) from the reference area. High variability (defined as SE >10) was observed at Station SS-03.

North Harbor Island (Stations NH-01 to NH-11) has been shown to have high toxicity, particularly around four stations which were significantly toxic ($P<0.001$) in the present study: NH-03, NH-04, NH-05, and NH-06. Three additional stations (NH-02, NH-09, and NH-11) had high toxicity in previous studies. In the present study, these three stations displayed high mean mortality (>40 percent) and high variability. All three sites exhibited statistical differences from the reference area at $P<0.05$, but not at $P<0.001$. Station NH-08 was significantly toxic ($P<0.001$) in the present study, whereas previous studies at this site had shown very low amphipod mortalities (Evans-Hamilton and D.R. Systems 1987).

East Waterway (Stations EW-01 to EW-16) showed high toxicity along the transect from EW-04 to EW-11. Although only five stations (EW-04, EW-05, EW-06, EW-09, EW-11) were statistically different from the reference area ($P<0.001$), three additional stations (EW-08, EW-09, EW-10) had mean mortalities of 58-65 percent and high variability. This transect has shown similar previous evidence of high toxicity (Evans-Hamilton and D.R. Systems 1987) that extended through two stations which showed low toxicity in the present study: Stations EW-12 and EW-13.

West Waterway (Stations WW-01 to WW-19) had only one area of significant toxicity ($P<0.001$) in the present study: Station WW-02. Previous studies have shown high toxicity at this site, and also at sites WW-08, WW-09 and WW-11 (Evans-Hamilton and D.R. Systems 1987). These three latter stations all had greater than 40 percent mortality in the present study, but were not statistically different ($P<0.001$) from the reference area. The amphipod tests at Stations WW-08 and WW-09 displayed high variability.

Kellogg Island (Stations KG-01 to KG-11) has shown previous high toxicity at the tip and immediately south of Harbor Island (Long unpublished; Evans-Hamilton and D.R. Systems 1987). The same pattern was shown in the present study, with significant toxicity at Stations KG-09 and KG-11 ($P<0.001$).

The Upper Duwamish Estuary (Stations DR-01 to DR-17) had three stations with mean mortalities greater than 40 percent, one of which (DR-15) was significantly more toxic than the reference area, while the other two (DR-13 and DR-16) were not significant due to high variability. Toxicity at all three stations is as expected from previous studies in which greater than 40 percent mortality was recorded (Evans-Hamilton and D.R. Systems 1987).

The final area, Duwamish Head/Alki Beach (Stations AB-01 to AB-04), had one station (AB-01) with greater than 40 percent mortality. This station was significantly different from reference at $P<0.05$, but not at $P<0.001$. The other three stations had low toxicity. These results are in accord with previous studies (Evans-Hamilton and D.R. Systems 1987).

In conclusion, the results of the present study are generally in accord with previous work. The only major differences were unexpectedly high toxicity of Station NH-08 and the low toxicity at Stations EW-12 and EW-13. It is possible that sediment toxicity at these three sites has changed due to dredging, sedimentation, changes in contaminant inputs, or other causes. However, it is also possible that these differences are simply a function of the patchy distribution of sediment toxicity in the waterways (Swartz et al. 1982). Results of the replicate tests conducted in the present study should be considered representative of present conditions at the stations tested.

Summary

- Sediments from 17 of the 102 Elliott Bay sites tested displayed significant toxicities ($P<0.001$) in the amphipod bioassay when compared with the Port Susan reference area (Figure 54; see Table 25)
- Overall, there was good agreement between the present study and previous bioassay studies in Elliott Bay (Figure 54)
- The two most toxic areas in Elliott Bay were North Harbor Island and East Waterway.

BENTHIC MACROINVERTEBRATES

The purposes of this section are to describe the general characteristics of benthic communities within the segments of Elliott Bay and in the Port Susan reference area, and to identify possible areas where benthic communities are impacted. Characterization of the benthic communities within Elliott Bay is based primarily on abundances of the major infaunal taxonomic groups (i.e., polychaetes, molluscs, and crustaceans). Complete species-level analyses of benthic communities were conducted at 16 selected stations in Elliott Bay and at all 4 stations in Port Susan to supplement the characterizations based on abundances of major taxa. Identifications of possible impacted areas in the Elliott Bay study area were based on statistical comparisons between the abundances of major taxa groups in Elliott Bay and those in the Port Susan reference area.

The following discussion is organized into several major topics. First, the adequacy of the reference area (i.e., Port Susan) is evaluated. Second, the general characteristics of infaunal communities within the segments of Elliott Bay and in Port Susan, are described, and abundances of major taxonomic groups are compared statistically to identify possible areas of impact. Third, species-level characteristics of the completely identified stations are described. Individual stations and segments within Elliott Bay that appear to be degraded and the degree of apparent degradation are then discussed.

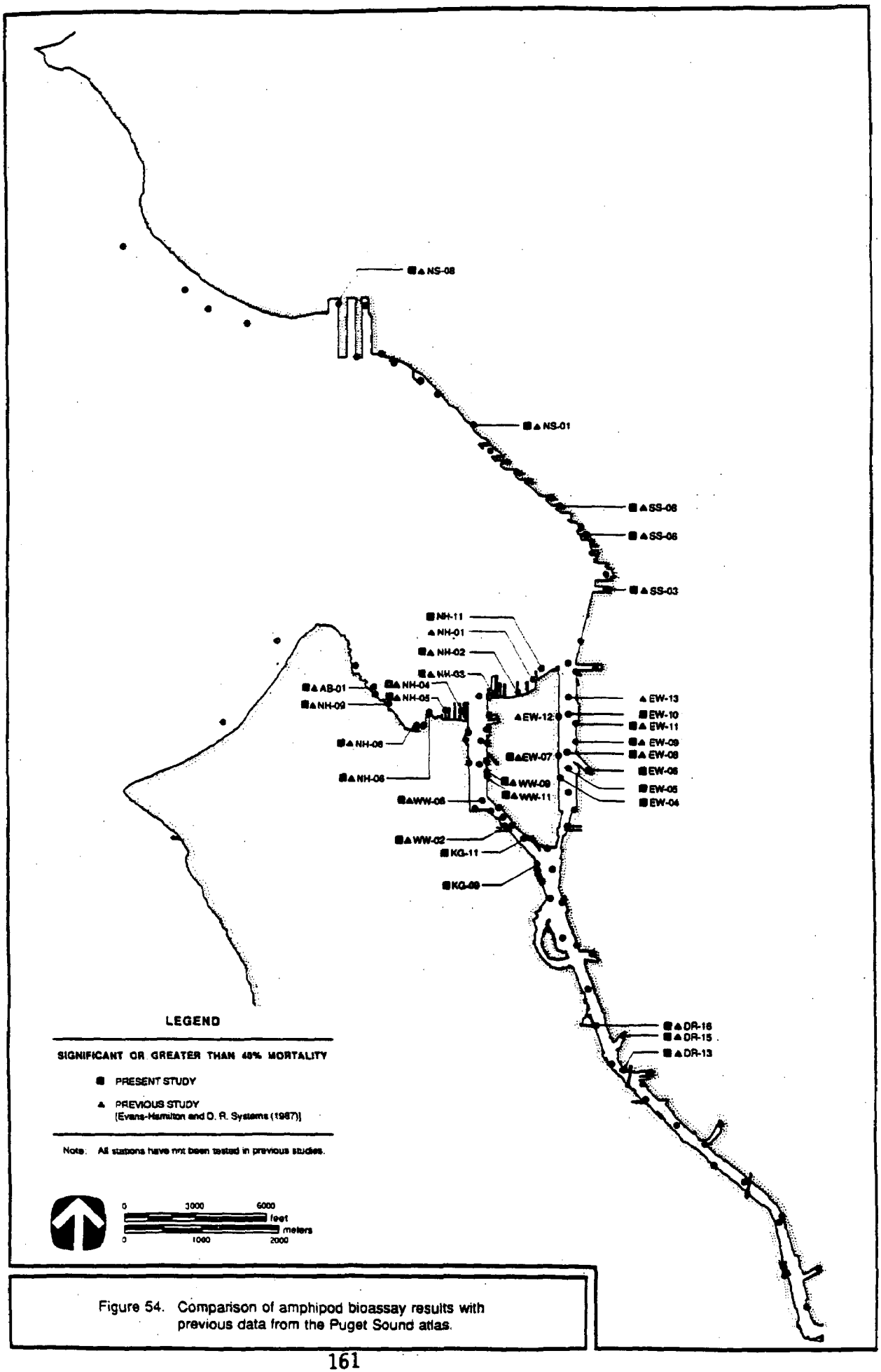


Figure 54. Comparison of amphipod bioassay results with previous data from the Puget Sound atlas.

Evaluation of the Reference Area

The ideal reference area for any investigation of anthropogenic impacts would be identical to the potentially impacted area, but would lack all anthropogenic influences. This condition is, of course, unachievable because no two areas are exactly alike, and because nearly all areas exhibit some evidence of human activities. Nevertheless, the reference area should exhibit physical, chemical, and biological characteristics that are as similar as possible to the study area (anthropogenic stresses excepted), so as not to unduly bias comparisons between the two areas. In this investigation, Port Susan was selected as the reference area for benthic communities in Elliott Bay because:

- It is one of only a few areas in northern Puget Sound with a major riverine input (i.e., the Stillaguamish River), similar to that of the Duwamish River in Elliott Bay
- In comparison with other bays in northern Puget Sound, Port Susan does not have any obvious sources of contamination (except slight organic enrichment from the Stillaguamish River) and it exhibits low concentrations of sediment contaminants
- It exhibits a range of sediment grain sizes.

A major difference between Port Susan and Elliott Bay is the wind and wave exposure regimes. Port Susan is a fairly narrow bay and is protected from the larger waves generated in the main Puget Sound basin, whereas, a large portion of the study area in Elliott Bay (e.g., Magnolia, Duwamish Head/Alki Beach) is exposed to these types of wind and wave conditions.

Another difference between the two areas is in the sampling design used for each area. Four stations were sampled in Port Susan in 1985. Stations PS-01 to PS-04 were located on the western side of Port Susan, along the 12-m isobath. (Stations PS-02, PS-03, and PS-04 were also sampled in 1986 in conjunction with the Everett Harbor investigation.) None of these stations was located in the upper reaches of the Stillaguamish estuary, whereas benthic infaunal stations in Elliott Bay were located in eight of the nine segments (delineated in this report) and extended to Kellogg Island in the Duwamish River (see Figure 5).

Port Susan is known to be an extremely productive estuary, which indicates that ample nutrients are available to support the flora and fauna. Indeed, a slight degree of organic enrichment may be occurring in Port Susan, possibly as a consequence of organic materials advected into the bay by the Stillaguamish River. Much of the watershed of the Stillaguamish River is agricultural land. However, no evidence of organic enrichment is evident in any of the data collected during this survey or in the 1986 Everett Harbor investigation, where Port Susan was also used as a reference area.

A range of grain-size characteristics were exhibited at the Port Susan stations, from sandy sediments at Station PS-04 (furthest from the Stillaguamish River mouth) to fine sands at Stations PS-02 and PS-03, to mixed silty-clays at Station PS-01 (closest to the river mouth) (see Appendix D).

Other conventional sediment variables (i.e., percent nitrogen, percent total organic carbon, and percent total solids) also exhibited fairly strong gradients in relation to distance from the river (see Appendix D). Sediments at stations sampled in other selected reference areas of Puget Sound are also predominantly sandy (Table 26). Mean concentrations of total organic carbon, sulfides, and total solids at the Port Susan stations were similar to the mean concentrations of those variables among the other reference areas listed in Table 26, and appear to be typical of unimpacted areas.

Abundances of the major taxonomic groups of benthic invertebrates at the Port Susan stations were also similar to those in other reference areas within Puget Sound. Mean total abundances and mean abundances of polychaetes, molluscs, and crustaceans were generally similar to mean abundances observed in Carr Inlet, in Blakely Harbor, at 15-22 m depth stations in Central Puget Sound, and at stations in Port Susan sampled in 1986 (Figure 55).

Comparisons of mean total abundances and mean abundances of the major taxonomic groups of benthic macroinvertebrates between the 1985 and the 1986 Port Susan stations revealed interannual differences (Figure 55). Mean total abundances were significantly lower in the samples collected in 1986 than those collected in 1985. Mean abundances among the major taxonomic groups appeared to be lower in 1986, but no significant differences ($P>0.05$) in mean abundances of the major taxonomic groups were detected between 1986 and 1985 samples. The consistent interannual differences in mean total abundances document the importance of using simultaneously collected data from reference and impact areas for impact assessment, as was done in this investigation.

Comparisons of the five most abundant taxa at each of the Port Susan stations indicate that species composition was fairly similar both within and between years (Table 27). Two to three species at each station were also among the abundant taxa at the other stations. This high degree of similarity documents that structurally similar assemblages of benthic macroinvertebrates were sampled at all four stations in Port Susan in 1985, and suggests that those assemblages were temporally stable. Comparisons of the five most abundant species at the 1985 Port Susan stations with those at the Carr Inlet stations reveals little similarity between these two areas (Table 27). This is not unexpected, however, because Port Susan and Carr Inlet are located in different regions of Puget Sound and exhibit different habitat characteristics (e.g., exposure, freshwater input).

Opportunistic and pollution-tolerant taxa (as defined by Pearson and Rosenberg 1978) constituted an average 17.4 percent of the fauna at stations in Port Susan (Table 28). This value was similar to the 21.1 percent of the Carr Inlet fauna represented by those same taxa. However, Prionospio steenstrupi and Macoma nasuta constituted most of the opportunistic and pollution-tolerant organisms in Carr Inlet, whereas Euphilomedes carcharodonta and Euphilomedes producta accounted for nearly all of those organisms in Port Susan. Euphilomedes spp. are known to increase in abundance only in areas where organic enrichment of the ecosystem is moderate (Word et al. 1977). If abundances of Euphilomedes spp. are not considered in the foregoing calculations, opportunistic and pollution-tolerant organisms would have constituted less than 5.0 percent of the benthic macroinvertebrates at all stations in Port Susan.

TABLE 26. SURFACE SEDIMENT CHARACTERISTICS AT BENTHIC INFAUNA STATIONS IN PORT SUSAN COMPARED WITH OTHER REFERENCE AREAS IN PUGET SOUND

Reference Area	Sediment Type[a]	Mean TOC (%)	Mean Sulfide (mg/L)	Mean Total Solids (%)	Depth Range (m)
Port Susan (1985, this study)	sand-clayey silts	0.78	22.8	66.4	10-12
Port Susan (1986)[b]	sand	0.34	U[c]	77.4	11-12
Carr Inlet[d]	sand	0.41	2.3	70.4	2-26
Blakely Harbor[e]	sand	1.65	15	67.8	10-18
Central Puget Sound (Seahurst)[f]	sand	1.51	--	--	15-22
Samish Bay[g]	silty sand/ clayey silt	1.65	--	--	10-30
Case Inlet[g]	sandy silt	2.2	--	--	21-41
Dabob Bay[g]	silty sand/ sandy silt	1.88	--	--	88-113
Sequim Bay[g]	sandy silt	2.35	--	--	19-26

[a] Sediment type designations after Shephard (1954).

[b] Data from PTI and Tetra Tech (1988).

[c] Undetected at a detection limit of 5 ppm.

[d] Data from Tetra Tech (1985a).

[e] Data from Tetra Tech (1986d).

[f] Data from Word et al. (1984).

[g] Data from Battelle (1986).

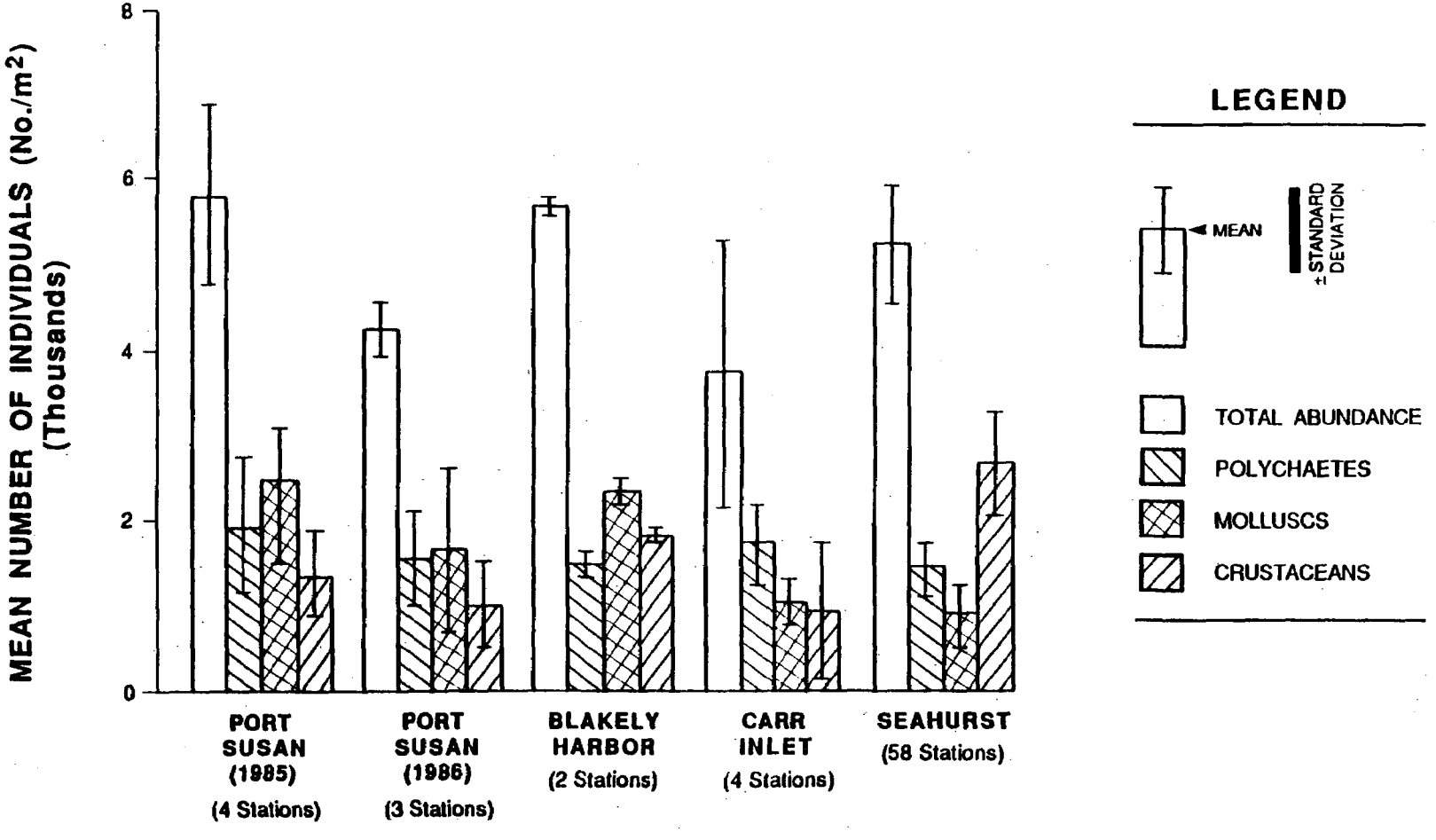


Figure 55. Mean total abundances (no./m^2) and mean abundances of major taxonomic groups of benthic invertebrates in Puget Sound reference areas.

TABLE 27. NUMERICALLY DOMINANT TAXA AT PORT SUSAN STATIONS SAMPLED IN 1985 AND 1986, AND AT CARR INLET STATIONS SAMPLED IN 1984

Taxon	Port Susan 1985				Port Susan 1986			Carr Inlet 1984			
	PS1	PS2	PS3	PS4	PS2	PS3	PS4	CR11	CR12	CR13	CR14
Protomedia prudens	o										
Psephidia lordi	o	o	o	o	o	o	o				
Terebellides stroemi	o	o									
Euphilomedes producta	o		o	o		o	o				
Lumbrineris spp.	o	o							o		
Axinopsida serricata		o	o	o	o				o	o	
Lumbrineris luti		o	o								
Euphilomedes carcharodonta			o	o	o	o	o		o		
Ampharete acutifrons				o							
Clinocardium nuttali					o						
Leitoscoloplos pugetensis					o						
Pectinaria granulata						o	o				
Macoma baltica						o					
Pista spp.							o				
Leptochelia dubia								o			
Phyllochaetopterus prolifica								o			
Prionospio steenstrupi								o	o	o	
Odostomia spp.								o		o	
Platynereis bicanaliculata								o			
Amphioda urtica									o		
Scalibregoma inflatum										o	o
Mitrella gouldi										o	
Macoma nasuta											o
Caprellidae											o
Caprella mendax											o
Spiophanes berkeleyorum											o

TABLE 28. COMPARISON OF ABUNDANCES (AS PERENCT OF FAUNA) OF OPPORTUNISTC AND POLLUTION-TOLERANT TAXA[a] AT STATIONS IN PORT SUSAN AND CARR INLET[b]

Taxon	Stations PS1	PS2	PS3	PS4	Carr Inlet[c]
Eteone longa (Po)[d]	0.19	0.53	0.04	0.07	0.05
Euphilomedes carcharodonta (Os)	0.0	3.80	9.90	16.10	2.97
Euphilomedes producta (Os)	5.80	3.20	7.60	9.50	0.14
Glycinde picta (Po)	0.08	0.19	0.0	0.07	0.54
Leitoscoloplos pugettensis (Po)	0.0	0.0	2.9	1.20	1.64
Macoma nasuta (Pe)	0.0	0.0	0.0	0.0	3.20
Mediomastus californiensis (Po)	0.08	0.19	0.08	0.24	1.61
Nephtys cornuta franciscana (Po)	0.0	0.0	0.0	0.0	0.68
Paraprionospio pinnata (Po)	0.04	0.0	0.0	0.0	0.71
Prionospio cirrifera (Po)	0.04	1.99	0.16	0.03	0.03
Prionospio steenstrupi (Po)	0.23	0.30	0.20	0.38	8.63
Tharyx spp. (Po)	0.70	0.70	0.30	0.20	0.45
Others (No. of taxa)	0.36 (5)	0.72 (4)	0.52 (4)	0.88 (6)	0.46 (5)
TOTAL	7.52	11.62	21.70	28.67	21.11

[a] As defined by Word et. al. (1977), Pearson and Rosenberg (1978), and Word (1980).

[b] Data from Tetra Tech (1985a).

[c] Mean value of four stations.

[d] Po = Polycheata, Os = Ostracoda, Pe = Pelecypoda

Overall, the foregoing comparisons of conditions in Port Susan in 1985 with conditions in other reference areas in Puget Sound, and with Port Susan in 1986, affirm the adequacy of Port Susan as a reference area for benthic macroinvertebrate communities in Elliott Bay. They demonstrate that sediment grain-size characteristics, the values of other conventional sediment variables, and abundances of major taxonomic groups of benthic invertebrates at the four Port Susan stations were similar to those in other reference areas. Abundances of opportunistic and pollution-tolerant taxa were found to be low, and comparable to the Carr Inlet reference area. Finally, the similarity between the numerically dominant taxa collected at the three Port Susan stations sampled in both 1985 and 1986 indicates that the structure of the benthic assemblages in Port Susan at a given time of year may be temporally stable over the long term. In this study, impacts to the benthos were inferred using statistical criteria to identify changes in the abundances of the major taxonomic groups of benthic invertebrates. When comparing benthic communities in potentially impacted areas with those in reference areas, it is often advisable to stratify between-station comparisons by habitat characteristics. Such comparisons may be stratified by sediment grain-size characteristics because sediment grain size is often an important determinant of benthic community structure (Sanders 1960; Johnson 1971; Gray 1974; Fresi et al. 1983).

As in Port Susan, sediments in Elliott Bay exhibited a wide variety of textural characteristics, which ranged from silty-clays to coarse sands. But in most areas of Elliott Bay, the sediments have been highly modified by anthropogenic inputs, and are no longer representative of "natural" conditions. Typically, the sediments smelled of hydrogen sulfide or petroleum, or both. Wood chips, scrap metal, oil droplets, and other debris were common in the grab samples. Field notes indicate that at least 73 percent of the stations sampled in Elliott Bay exhibited evidence of sediment modification (e.g., hydrogen sulfide, petroleum, foreign objects). Largely because of these anthropogenic modifications, sediment grain sizes at Port Susan stations do not cover the entire spectrum of sediment grain sizes in Elliott Bay, and stratification of the between station statistical comparisons would, in many cases, be artificial.

Results of species-level analyses of the benthic macroinvertebrate data also indicate that stratification of between-station comparisons by sediment characteristics would be inconsistent because it would not be possible to match grain size characteristics in many of the tests. Species composition of the benthic macroinvertebrate assemblages was fairly similar among the Port Susan stations (Table 27), despite the gradient of sediment grain size composition that occurred moving away from the river mouth (see Appendix D).

In summary, an a priori examination of the data on sediment characteristics and benthic community structure in Port Susan and Elliott Bay indicated that:

- Total abundances and abundances of the major taxonomic groups of benthic invertebrates in Port susan were comparable to abundances in other reference areas in Puget Sound, despite differences in species composition

- Species composition among Port Susan stations was temporally stable between 1985 and 1986

- The sediments in Elliott Bay are highly modified in many cases, to the extent that stratification of statistical tests based on sediment characteristics would be largely artificial

- The range of sediment characteristics in Port Susan was similar to the range of sediment characteristics in Elliott Bay, but the data set from Port Susan was not adequate to stratify by grain size for individual stations.

For these reasons, data on abundances of the major taxonomic groups of benthic infauna at the four stations in Port Susan were not stratified by habitat characteristics prior to statistical testing. Instead, the data were pooled, such that mean values of variables at each station in Elliott Bay were compared with mean values of variables across all four stations in Port Susan. Pooling the Port Susan data increases the number of replicate reference values used in each statistical test from 5 to 20.

Characteristics of Benthic Communities in Elliott Bay and Port Susan

During this study, 364,446 individuals were collected from 78 sampling stations in Port Susan and Elliott Bay (see Figure 5). Total abundances per station ranged from 322 to 25,046/m^2, and averaged 9,345/m^2. This range of total abundances is much greater than the range of total abundances in Carr Inlet (2,767 to 5,946/m^2) (Tetra Tech 1985a) and Eagle and Blakely Harbors (3,134 to 9,406/m^2) (Tetra Tech 1986d). However, it is similar to the range of total abundances that was observed in 50 benthic samples from Commencement Bay (13 to 33,887/m^2) (Tetra Tech 1985a). Total abundances at the Port Susan stations ranged from 5,040 to 7,232/m^2, x=5,799/m^2, and were comparable with those in Carr Inlet and Blakely Harbor (see Figure 55). Hence, total infaunal abundances at Elliott Bay stations were more variable than those of Port Susan and other reference areas in Puget Sound. This situation is illustrated graphically in Figure 56, where the mean number of individuals/m^2 collected in each segment of Elliott Bay is plotted. Abundances were variable among the segments, tending to be higher in the Magnolia, East Waterway, Kellogg Island, and Duwamish Head/Alki Beach segments than elsewhere (Figure 56).

Polychaetous annelids were the most abundant major taxonomic group among the Elliott Bay and Port Susan stations (x=5,202/m^2), followed by total crustaceans (x=2,103/m^2). [Crustaceans, exclusive of amphipods (x=1,731/m^2), were also the second most abundant major taxonomic group.] Bivalve molluscs ranked third in mean abundance among all stations (x=1,524/m^2). Amphipods (x=372/m^2) and gastropods (x=280/m^2) were ranked fourth and fifth in mean total abundance among all stations, respectively. Miscellaneous taxa and echinoderms ranked sixth and seventh in mean abundances and were generally very minor contributors to community composition at most stations. However, nematodes and oligochaetes were abundant at some stations in the Elliott Bay segments.

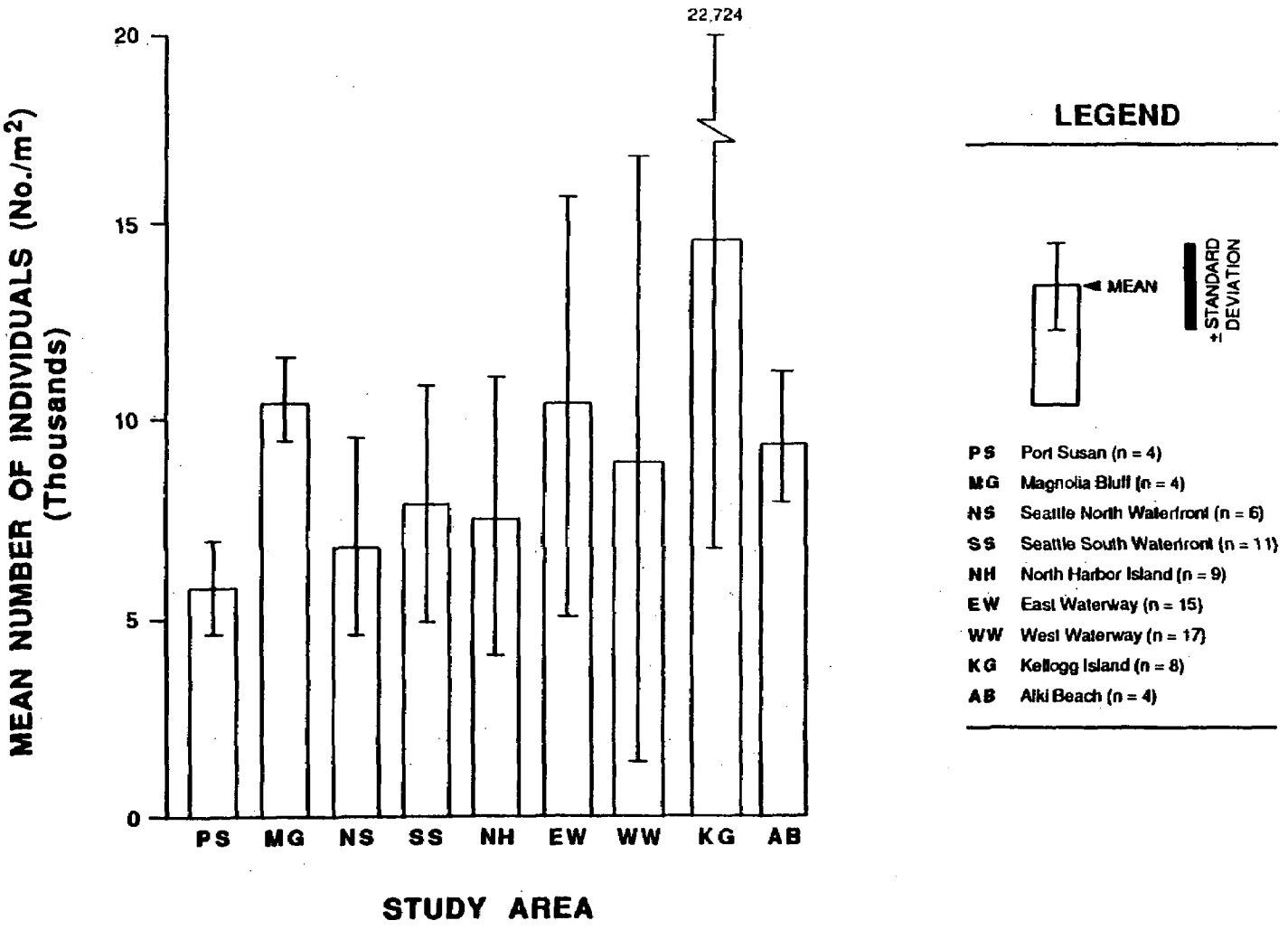


Figure 56. Mean number of individuals/m^2 in each study area segment.

Comparisons Between Reference and Potentially Impacted Areas

As discussed earlier, 74 stations in Elliott Bay (divided into eight segments) and 4 stations in Port Susan (reference area) were sampled for benthic infauna. Species-level identifications were available for only 20 of the 78 stations. The absence of identification of all organisms to the lowest possible taxonomic level at all stations precluded in-depth analyses (e.g., calculation of diversity indices) at all stations because basic measures of community structure (e.g., numbers of species, dominance) that are needed for these calculations could not be estimated for 58 of the 78 stations. In addition, information on pollution-sensitive, pollution-tolerant, and opportunistic taxa also were not available for 58 of the 78 stations. Thus, identification of potentially impacted areas in the Elliott Bay study area were based on comparisons of abundances of major taxa groups between stations in Port Susan and stations in Elliott Bay. Species-level data were used to further characterize and interpret the structure of the benthic assemblages at those stations where it was available.

As discussed above, total mean abundances among the Port Susan stations did not vary greatly (i.e., 5,040-7,232/m^2). Mean abundances of the major taxonomic groups (i.e., polychaetes, total crustaceans, amphipods, crustaceans other than amphipods, pelecypods, gastropods, echinoderms, and miscellaneous taxa) also did not vary greatly among the Port Susan stations (see Appendix E). In contrast, mean abundances of the major taxa and total infaunal abundances differed greatly among stations in Elliott Bay (see Appendix E). Statistical analyses of infaunal abundances were conducted during this study to determine whether any of the differences between abundances in Port Susan and at stations in Elliott Bay were significant.

Results of the t-tests are summarized in Figures 57-61 and Appendix E. Among the 370 paired comparisons that were performed (i.e., 74 stations x 5 taxa), 219 were not statistically significant, 78 indicated enhanced abundances, and 73 indicated depressed abundances (Figures 57-61). Concentrations of toxic substances in sediments have been correlated with reduced abundances of sensitive taxa (Wolfe et al. 1982; Rygg 1985, 1986) and may affect all taxa (Bilyard 1987). Extreme organic enrichment may also result in reduced abundances of infaunal taxa (Pearson and Rosenberg 1978). At lower levels of organic enrichment, numbers of infaunal organisms may become moderately to extremely abundant (Pearson and Rosenberg 1978). Thus, depressed abundances may be indicative of sediments with high levels of toxic substances, and enhanced abundances may be indicative of organically enriched conditions.

Results of the paired comparisons are addressed on a segment by segment basis in Appendix E, beginning with Magnolia (Segment 1) and ending with Duwamish Head/Alki Beach (Segment 9). The relative degree of impact at each test station was estimated by ranking stations according to the number of significant depressions in the abundance of the following major taxonomic groups: polychaetes, crustaceans, pelecypods, and gastropods (see Indices for Decision Criteria, for discussions of the rationale).

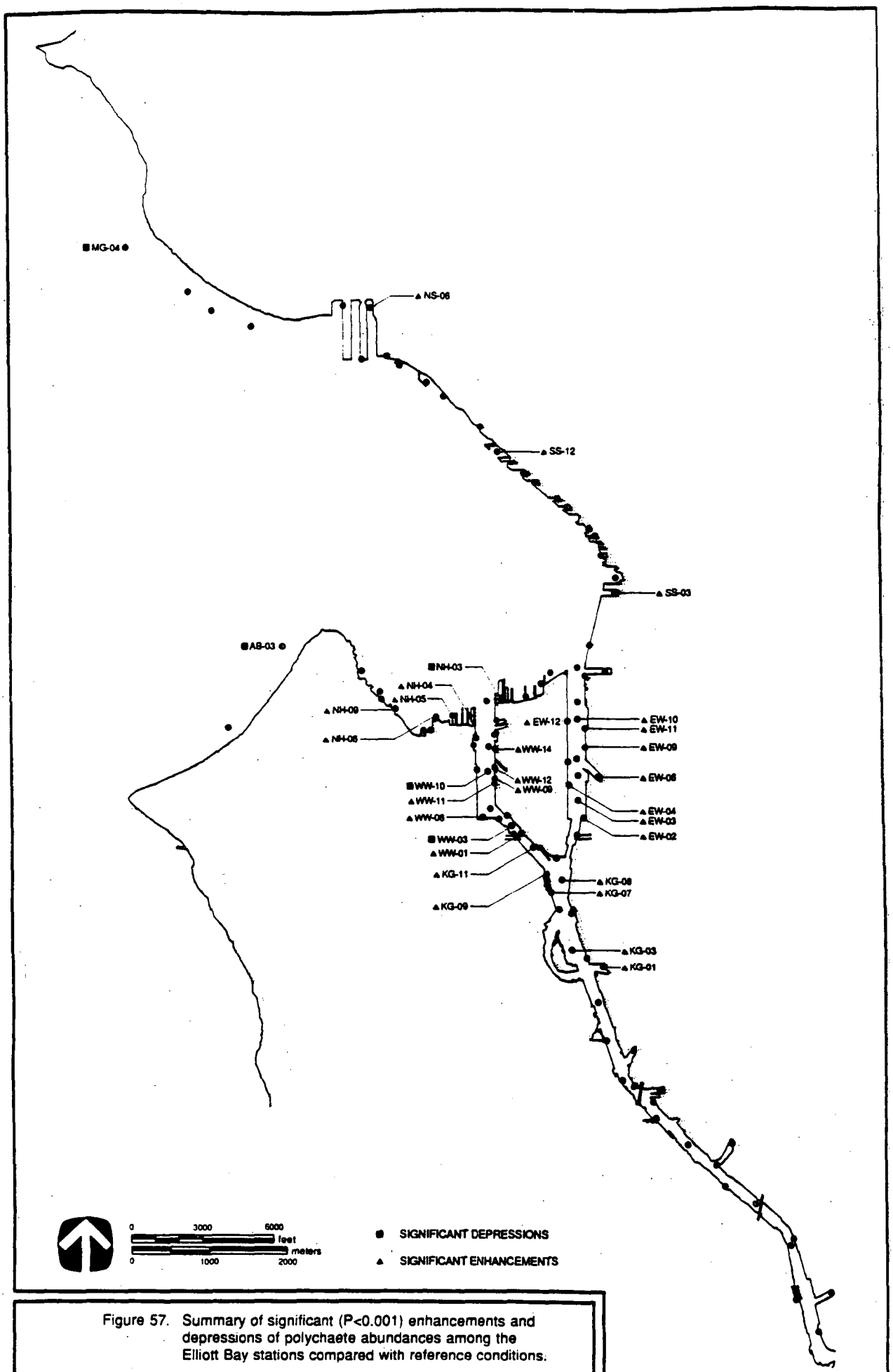


Figure 57. Summary of significant (P<0.001) enhancements and depressions of polychaete abundances among the Elliott Bay stations compared with reference conditions.

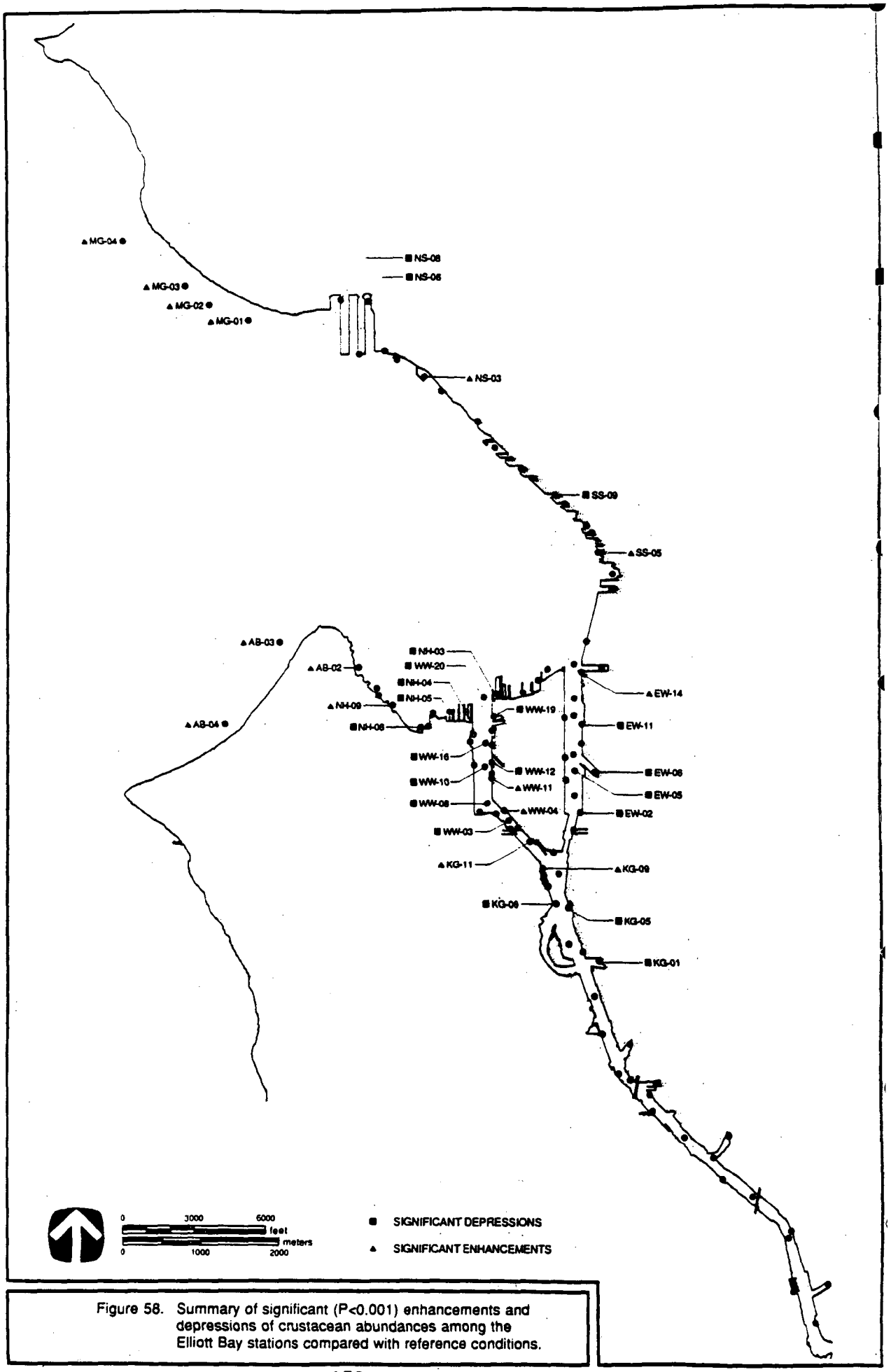


Figure 58. Summary of significant ($P<0.001$) enhancements and depressions of crustacean abundances among the Elliott Bay stations compared with reference conditions.

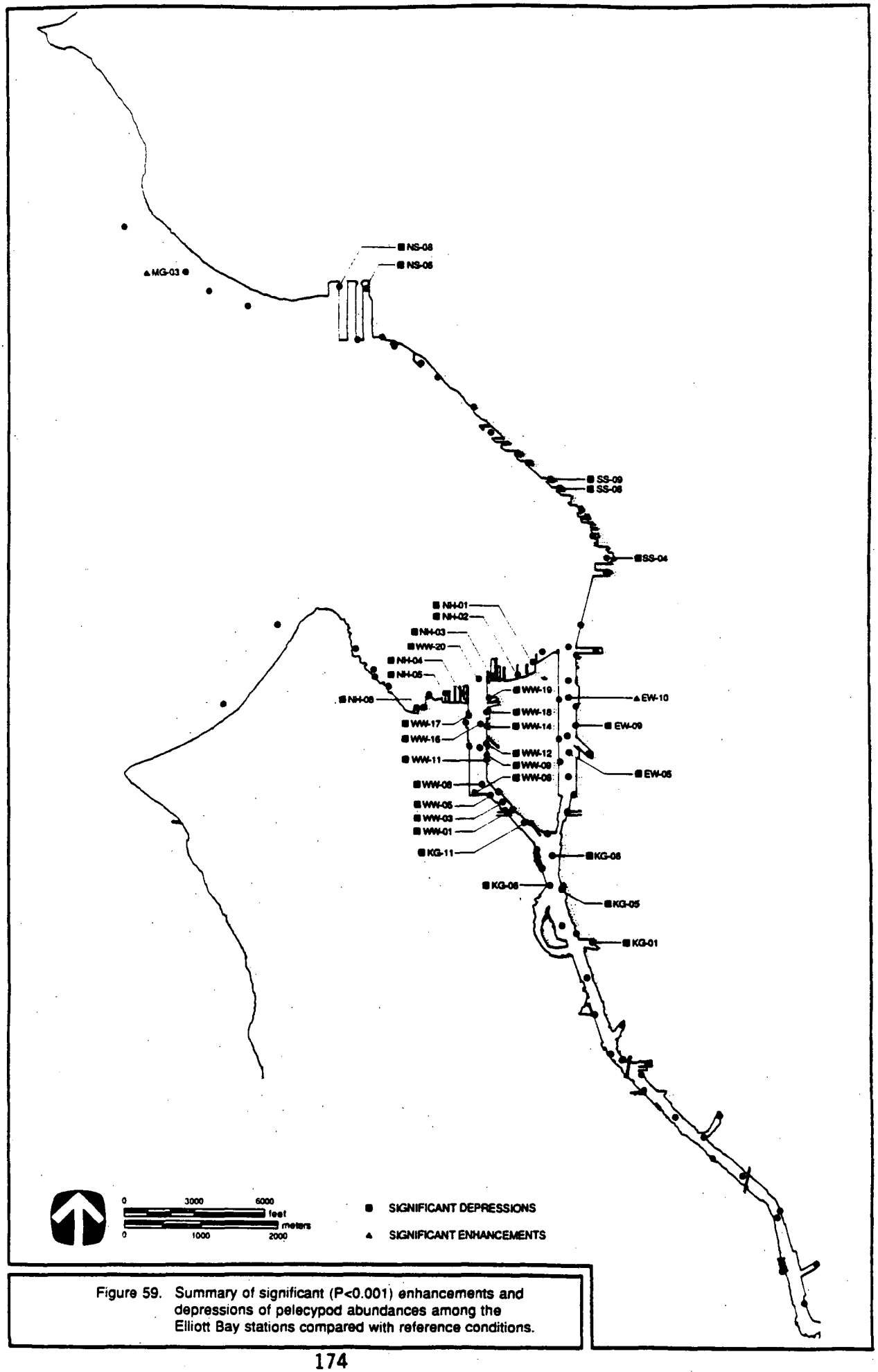


Figure 59. Summary of significant (P<0.001) enhancements and depressions of pelecypod abundances among the Elliott Bay stations compared with reference conditions.

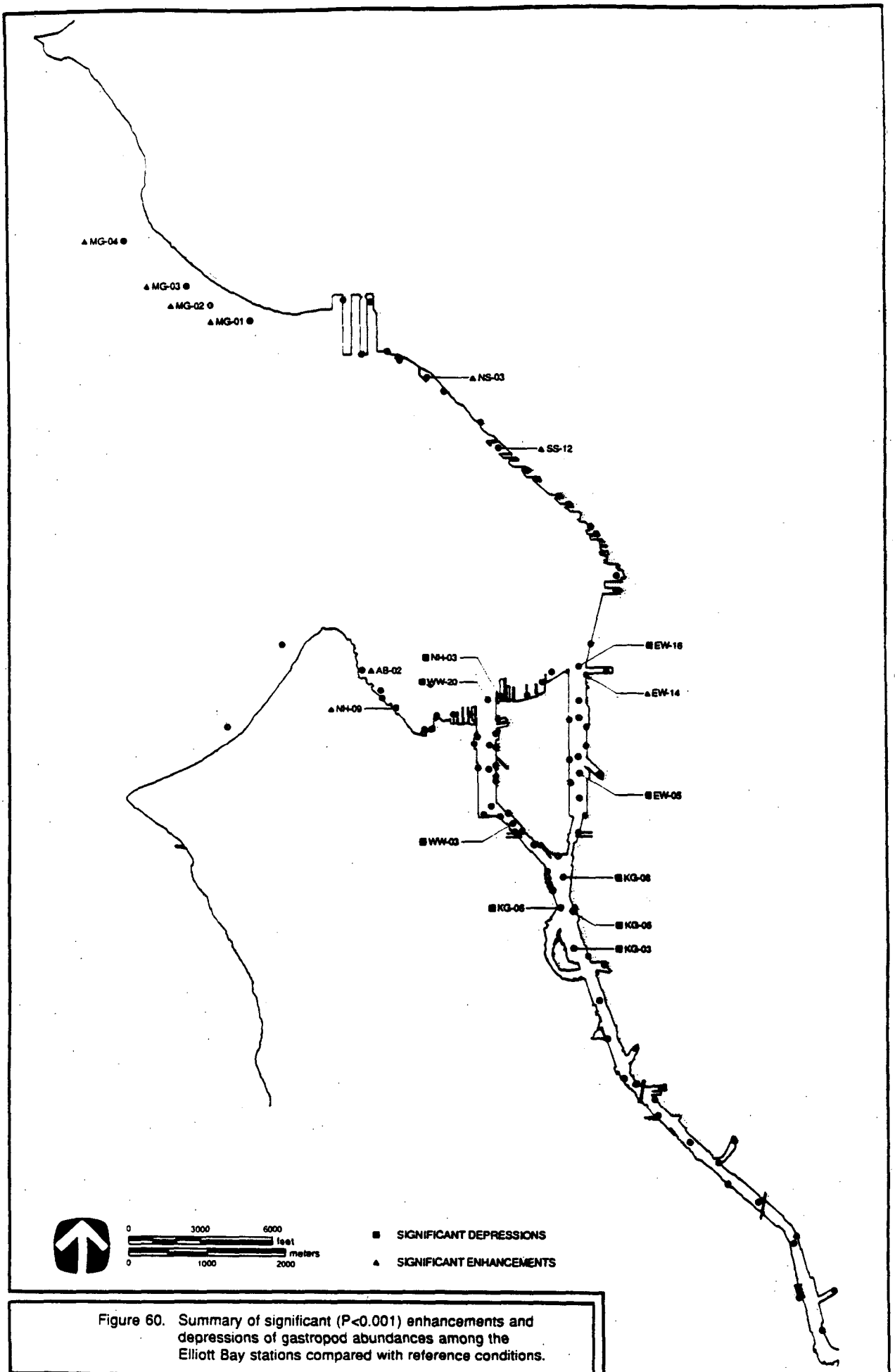


Figure 60. Summary of significant ($P<0.001$) enhancements and depressions of gastropod abundances among the Elliott Bay stations compared with reference conditions.

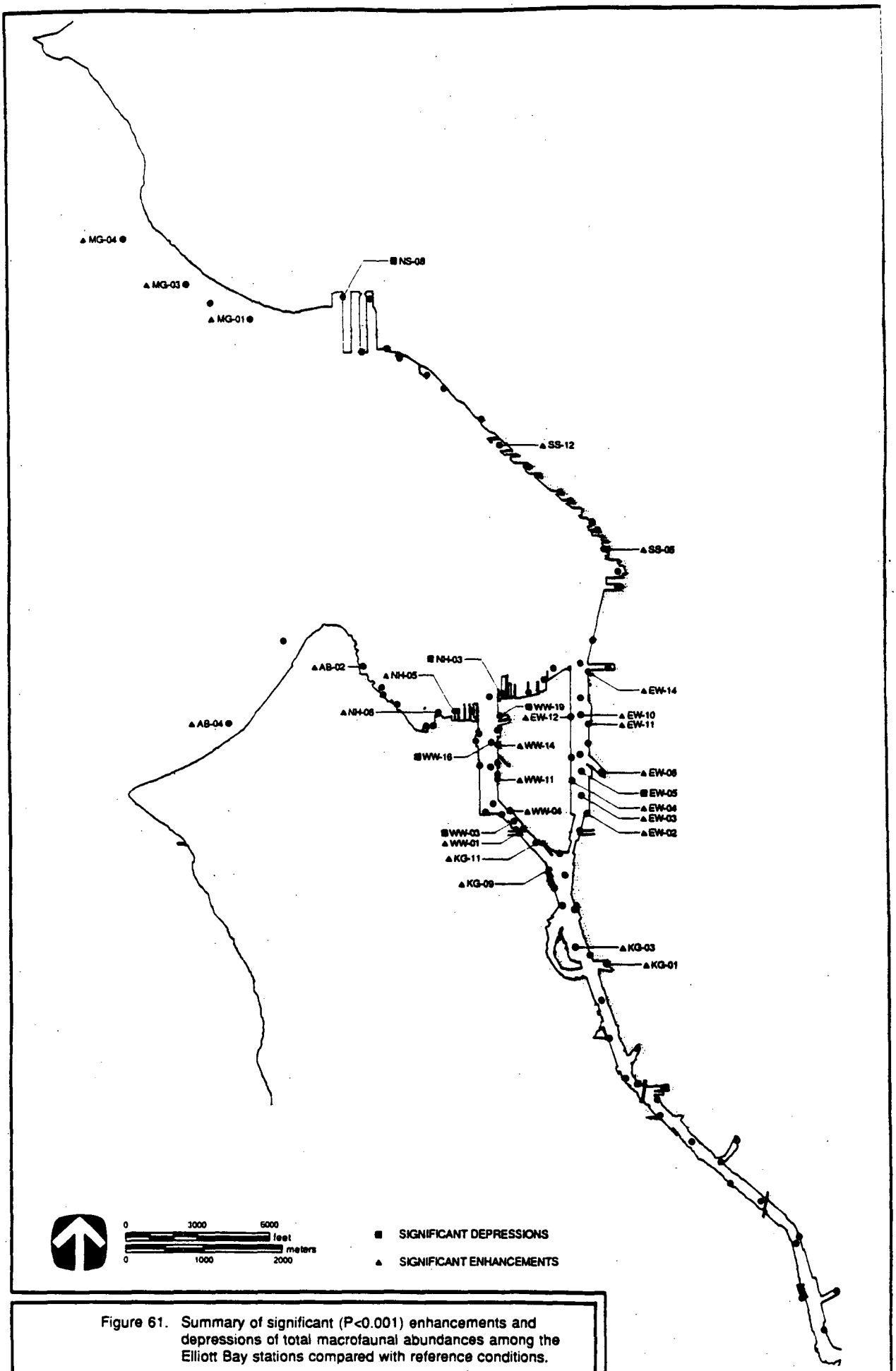


Figure 61. Summary of significant (P<0.001) enhancements and depressions of total macrofaunal abundances among the Elliott Bay stations compared with reference conditions.

Species-Level Comparisons Among Elliott Bay and Port Susan Stations

As discussed above, benthic macroinvertebrates at only 20 of the 78 stations were identified to the lowest possible taxonomic level. Those 20 stations included 4 stations from the Port Susan reference area and 16 stations from Elliott Bay. The 16 Elliott Bay stations were selected based on observed high mortality in the amphipod bioassay tests and by the proximity of stations to known sources of contamination among the nine segments.

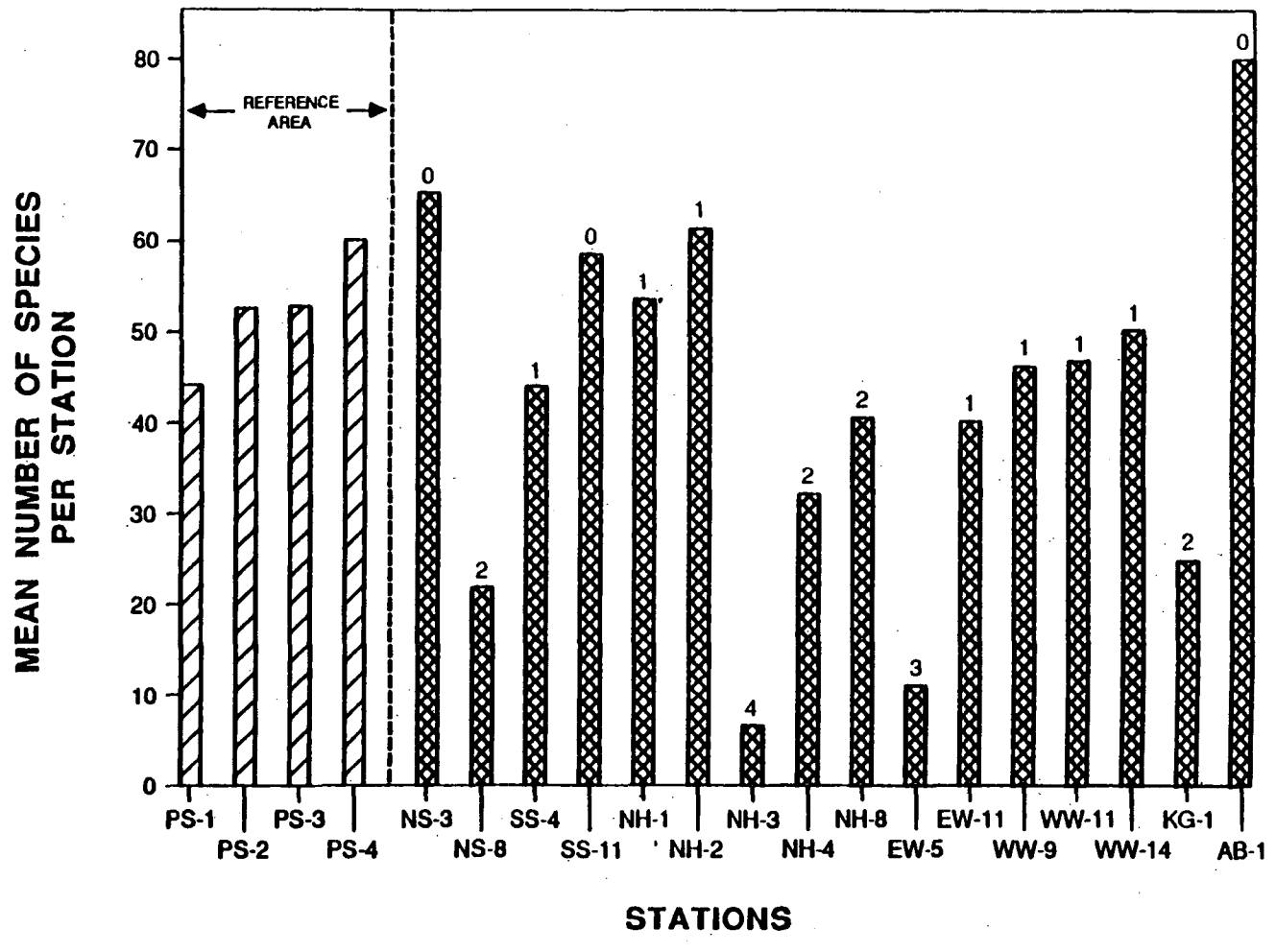
Numbers of Taxa--

Mean numbers of species (in some cases higher taxa) per 0.1-m^2 grab sample varied considerably among the 20 stations (Figure 62). In Port Susan, the mean number of species per grab varied from 44 to 60 and averaged 52.5 species among stations. In Elliott Bay, the mean number of species per station varied from 7 to 80. The highest mean numbers of species occurred at Stations AB-01, NS-03, and NH-02 (80, 65, and 61, respectively), where zero (AB-01 and NS-03) or one (NH-02) significant depression in major taxa abundance (relative to reference conditions) was detected. The lowest mean numbers of species occurred at Stations NH-03, EW-05, NS-08, and KG-01 (7, 11, 22, and 25, respectively), where two or more significant depressions in the abundances of major taxa (relative to reference conditions) were detected. Mean numbers of species at the remaining 13 stations were relatively similar to those in Port Susan, ranging from 32 to 59 species per grab sample (Figure 62). One or no significant depressions ($P<0.05$) in major taxa abundances occurred at these stations, except at Station NH-08 where two significant depressions occurred. In general, the mean numbers of species among these stations varied in a manner similar to total abundances and abundances of the major taxonomic groups (Figure 63; see Appendix E). Mean numbers of species tend to indicate similar potential problem stations as those identified by significant depressions of major taxonomic groups. Station NH-08 is an exception to this trend because two depressions were detected, yet, the mean number of species (41) is only slightly lower than the mean number of species at Port Susan stations.

Numerically Abundant Taxa--

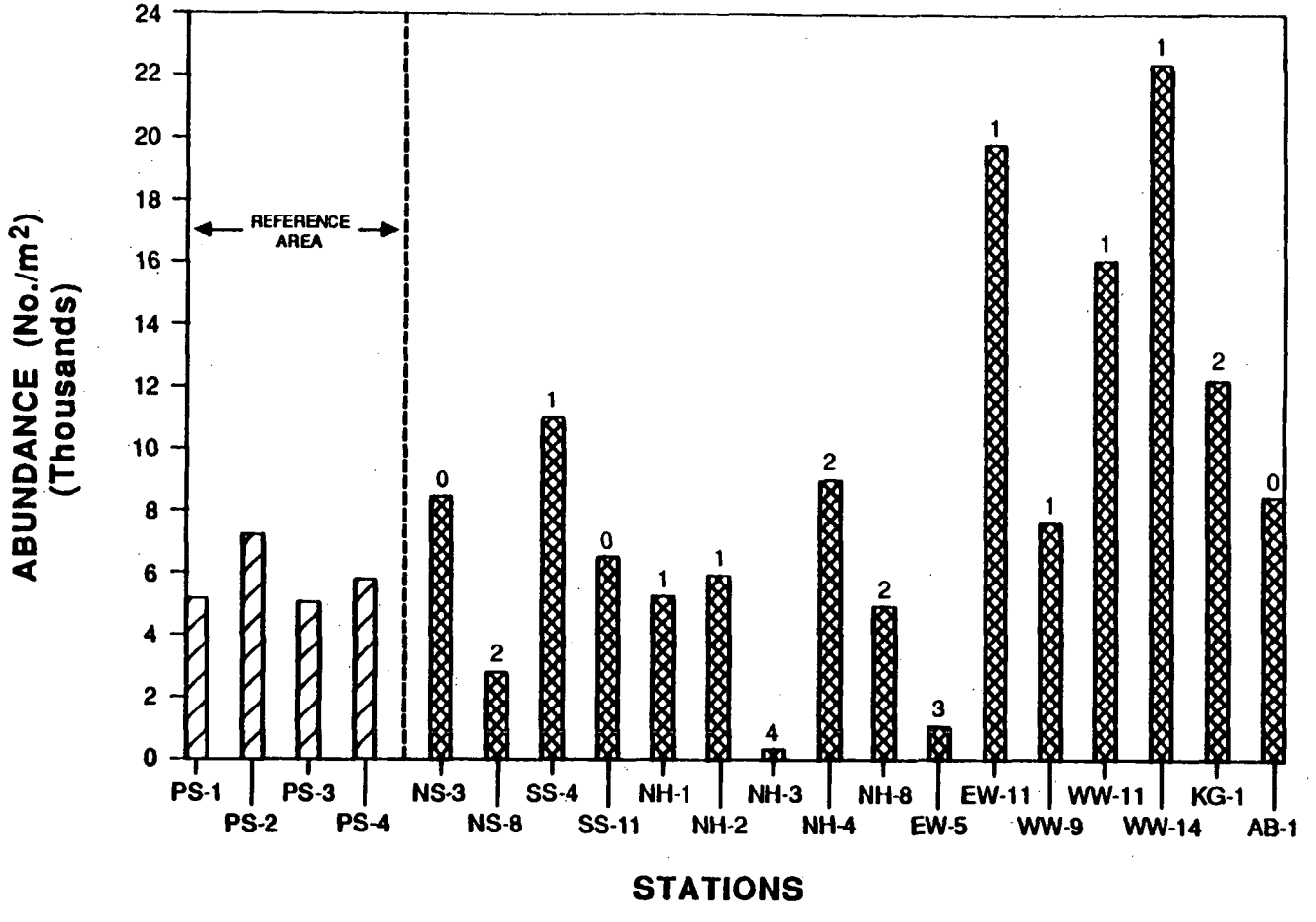
Absolute and relative abundances of the five most abundant taxa (i.e., the numerically dominant taxa) at each station are summarized in Figures 64 and 65 and in Table 29. Among the Port Susan stations, abundances and relative abundances of the dominant taxa were fairly consistent (3,448-4,154/m^2 and 57.5-69.8 percent of the fauna). Species composition of the dominant taxa was also similar among these stations. Each station had at least two, and as many as four taxa in common with each of the other stations. No single taxon dominated the community to the exclusion or near exclusion of other taxa at any of these stations. The highest relative abundance was exhibited by *Psephidia lordi* at Station PS-03 where it represented 39.9 percent of the fauna.

Among the Elliott Bay stations, relative abundances of the dominant taxa ranged from 43 to 94 percent of the total infaunal abundance. At all but Stations NS-03, SS-11, NH-01, NH-02, and AB-01 (where only one or zero significant depressions were detected), the five numerically abundant taxa



NOTE: Numbers at tops of bars indicate numbers of significant depressions detected in major taxa abundances relative to the Port Susan reference area.

Figure 62. Mean number of benthic species per station collected from the 20 Elliott Bay and Port Susan stations where complete identification of benthic samples was performed.



NOTE: Numbers at tops of bars indicate numbers of significant depressions detected in major taxa abundances relative to the Port Susan reference area.

Figure 63. Mean abundance (no./m^2) of total benthic infauna per station collected from the 20 Elliott Bay and Port Susan stations where complete identification of benthic samples was performed.

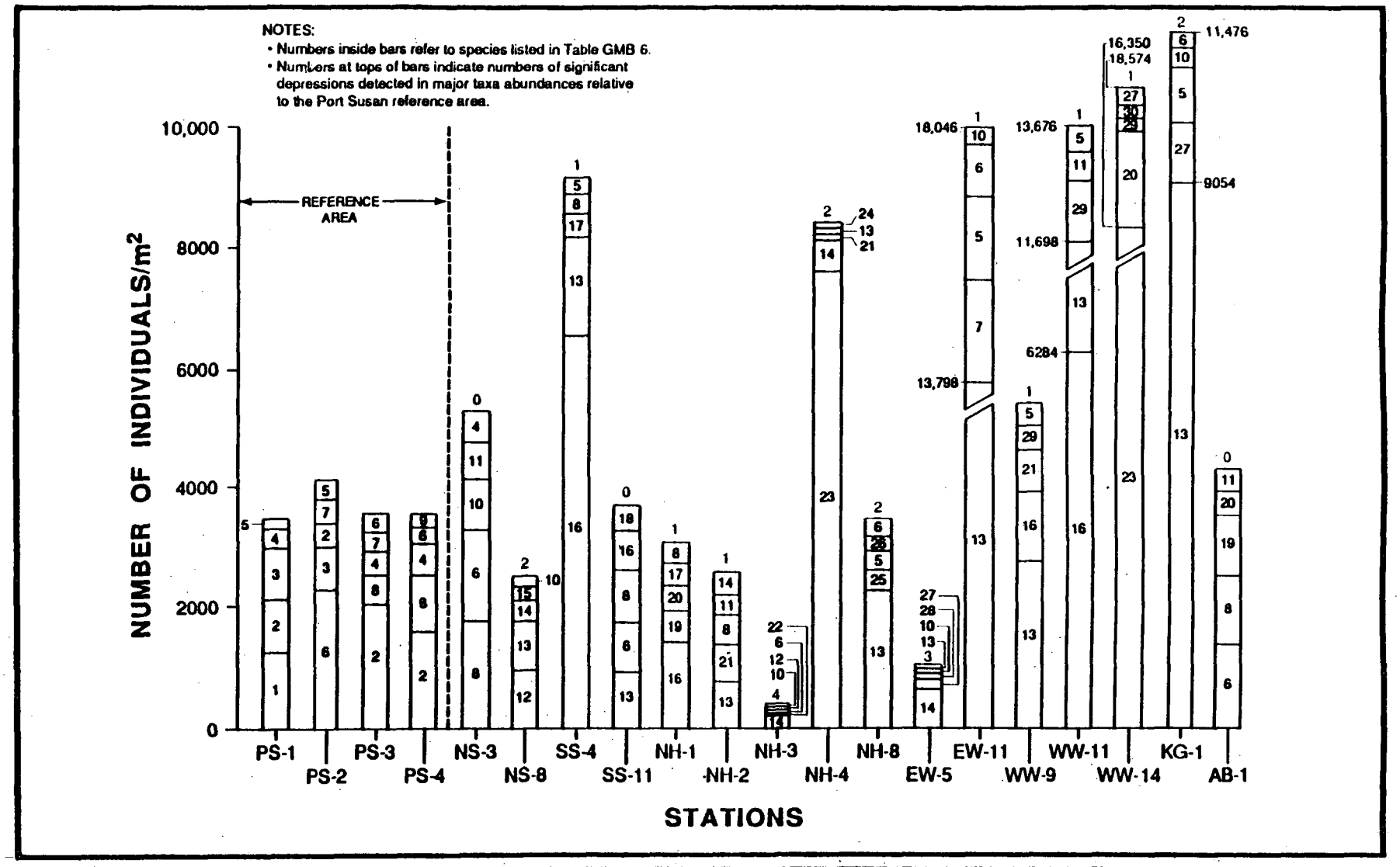


Figure 64. Abundances (no./m^2) of the five most numerically dominant species at completely identified stations in Elliott Bay and Port Susan.

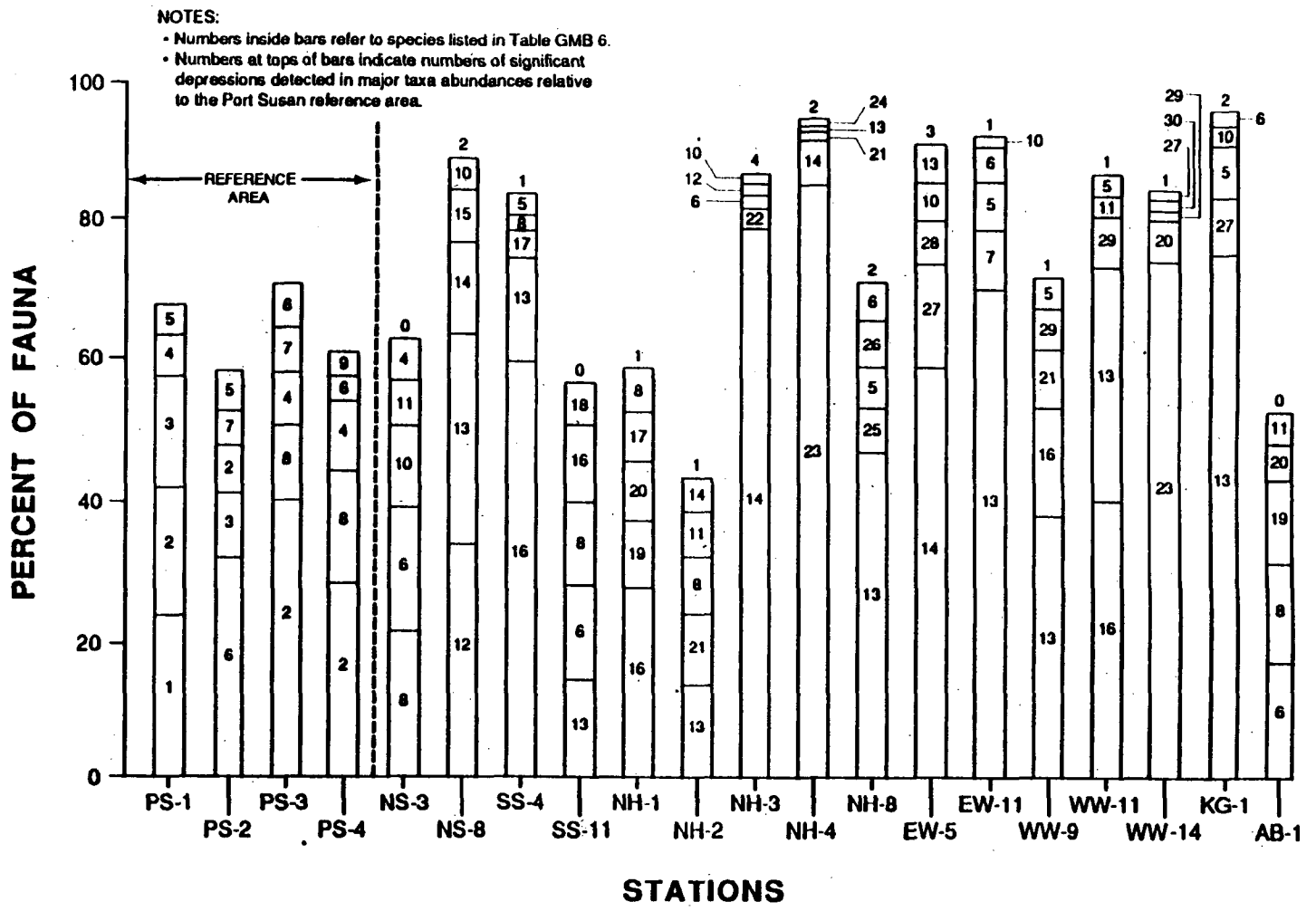


Figure 65. Relative abundances of the numerically dominant species at completely identified stations in Elliott Bay and Port Susan and the proportions of total infaunal abundance for which they account.

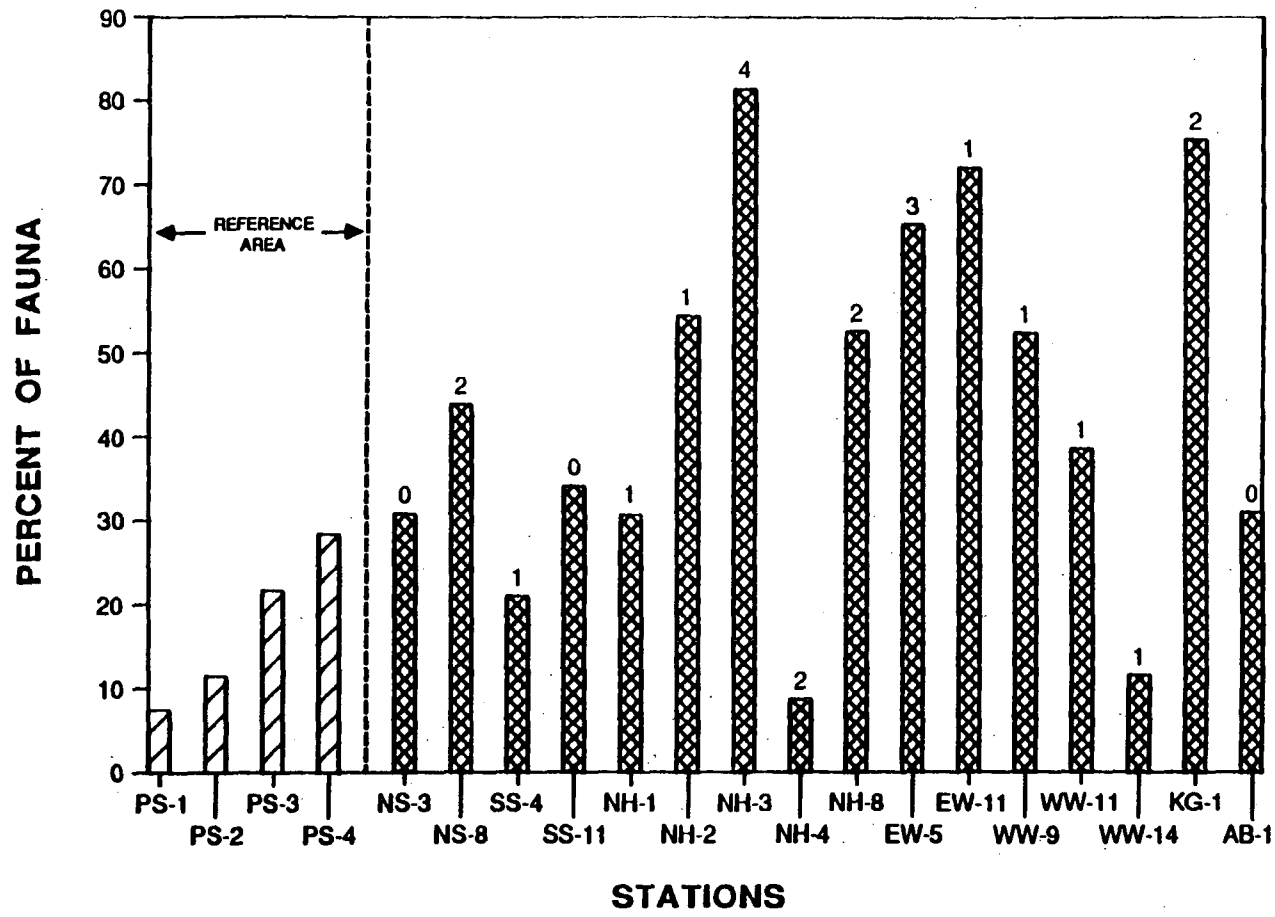
TABLE 29. KEY FOR FIGURES 63 AND 64

1.	*Protomedia prudens*
2.	*Psephidia lordi*
3.	*Terebellides stroemi*
4.	*Euphilomedes producta*
5.	*Lumbrineris* spp.
6.	*Axinopsida serricata*
7.	*Lumbrineris luti*
8.	*Euphilomedes carchardonta*
9.	*Ampharete acutifrons*
10.	*Macoma carlottensis*
11.	*Odostomia* spp.
12.	Nematoda
13.	*Tharyx* spp.
14.	*Capitella capitata*
15.	*Platynereis bicanaculata*
16.	*Leptochelia lourei*
17.	*Exogone dubia*
18.	*Heterophoxus oculatus*
19.	*Notomastus tenuis*
20.	*Mediomastus californiensis*
21.	*Prionospio steenstrupi*
22.	*Cirratulis spectabilis*
23.	*Cirratulis cirratus*
24.	*Caulleriella hamata*
25.	*Lumbrineris cruzensis*
26.	*Polycirrus* spp.
27.	*Euchone limnicola*
28.	*Spiochaetopterus costarum*
29.	*Photis brevipes*
30.	*Corophium acherusicum*

represented over 70 percent of the total fauna per station (Figure 65). High relative abundances of dominant taxa often indicate stressed conditions. As less tolerant species are eliminated from the habitat, opportunistic species fill the vacant niches, often achieving high abundances (Pearson and Rosenberg 1978; Gray 1982). Abundances of the five numerically dominant taxa averaged 3,659 individuals/m^2 among the Port Susan stations. Most abundances of the numerically dominant taxa at Elliott Bay stations were above this average, and Stations EW-11, KG-01, WW-11, and WW-14 greatly exceeded this value (Figure 64; Table 29). Abundances of polychaetes and total infauna at these stations exhibited significant enhancements. In this case, species-specific data indicates that Stations EW-11, WW-11, and WW-14 may be more stressed (in terms of organic enrichment) than indicated by t-tests performed at the major taxa level. Among the major taxa groups tested at these stations only one significant depression was detected. Abundances at Stations EW-05 and NH-03 were greatly depressed below the Port Susan value. Greatly depressed abundances often indicate excessively enriched sediments or the presence of contaminants (Pearson and Rosenberg 1978; Carriker et al. 1982; Wolfe et al. 1982; Dillon 1984). The highest number of significant depressions detected among the stations identified to the species level, occurred at Stations EW-05 and NH-03, where three and four depressions were detected respectively.

Taxonomic composition of the dominant species differed considerably within Elliott Bay and between Elliott Bay and Port Susan (Figure 64; Table 29). For example, Tharyx sp. was among the dominant taxa at 11 of the 16 Elliott Bay stations but was not among the dominant species in Port Susan. This surface deposit-feeding polychaete (Fauchauld and Jumars 1979) dominated many of the benthic communities in contaminated Commencement Bay waterways, and may be indicative of stressed conditions (Tetra Tech 1985a). Other members of the genus have been identified as opportunistic (Dorsey et al. 1983; Raman and Ganapati 1983). Subsurface deposit-feeding nematodes and the polychaetes Capitella capitata and Mediomastus californiensis were among the numerically dominant taxa at two, three, and five stations, respectively, in Elliott Bay. Capitella capitata was the numerically dominant species at Stations EW-05 and NH-03, and nematodes were the dominant taxon at Station NS-08. These stations exhibited the greatest number of depressions in abundances. The molluscs Macoma carlottensis and Axinopsida serricata, the ostracod Euphilomedes carcharodonta, and the tanaid Leptochelia dubia were also abundant at five or more stations in Elliott Bay. Among the foregoing seven taxa, only E. carcharodonta and A. serricata were among the numerically dominant taxa at stations in Port Susan. Nematodes and polychaetes are known to reach very high abundances in organically enriched sediments, often to the exclusion of other taxa (Nichols 1977; Pearson and Rosenberg 1978; Van Es et al. 1980). The dominance of these taxa and the low total abundances observed at Stations EW-05 and NH-03 (Figures 64 and 65; Table 29) suggest that the sediments at these stations are highly organically enriched, contaminated with toxic substances, or both.

Relative abundances of opportunistic and pollution-tolerant taxa (as defined by Word et al. 1977; Pearson and Rosenberg 1978; Word 1980) at the 16 Elliott Bay stations and the 4 Port Susan stations further supports the conclusion that benthic infaunal communities at most Elliott Bay stations are stressed (Figure 66; Table 30). Total relative abundances of opportunistic and pollution-tolerant taxa among Port Susan stations averaged 17.2 percent



NOTE: Numbers at tops of bars indicate numbers of significant depressions detected in major taxa abundances relative to the Port Susan reference area.

Figure 66. Abundances (as percent of fauna) of opportunistic and pollution-tolerant taxa (as defined by Word et al., 1977; Pearson and Rosenburg, 1978; and Word, 1980) at completely identified stations in Elliott Bay and Port Susan.

TABLE 30. ABUNDANCES (AS PERCENT OF FAUNA) OF OPPORTUNISTIC AND POLLUTION-TOLERANT TAXA[a] AT STATIONS IN PORT SUSAN AND ELLIOTT BAY

Taxon	Stations																			
	PS1	PS2	PS3	PS4	NS3	NS8	SS4	SS11	NH1	NH2	NH3	NH4	NH8	EW5	EW11	WW9	WW11	WW14	KG1	AB1
Capitella capitata (Po)[b]	<0.1				<0.1	13.6	0.6	0.1	3.3	5.5	78.3	0.8	1.2	58.5	0.4	1.7	0.7	0.8	0.8	0.4
Corophium asherusicum (Am)						0.1	<0.1		<0.1	0.5	1.2	0.1			<0.1	0.1	0.2	1.3		0.2
Eteone longa (Po)	0.2	0.5	<0.1	0.1	0.1	0.1	0.4	0.1	0.5	0.7		0.1	1.3	0.4	<0.1	0.1	<0.1		0.1	0.2
Euphilomedes carcharodonta (Os)		3.8	9.9	16.1	20.6	0.3	2.5	12.4	6.1	8.8	0.6	0.3	2.0	0.6	1.0	0.4	0.4	0.1	0.3	13.9
Euphilomedes producta (Os)	5.8	3.2	7.6	9.5	6.2	0.1	0.2	0.6	0.4	1.5		0.1	0.1		0.2	<0.1				0.4
Glycinda picta (Po)	0.1	0.2		0.1	0.1		0.2	0.1	0.4	0.6		<0.1	0.1			0.1	<0.1	<0.1		0.3
Leitoscoplos pugettensis (Po)			2.9	1.2	0.4			0.2												0.5
Mediomastus californiensis (Po)	0.1	0.2	0.1	0.2	0.3		0.3	0.6	8.6	5.3		5.7	1.0		0.1	1.6	0.7	6.1	<0.1	5.3
Oligochaeta (Ol)		0.3					<0.1	0.3		4.4								0.2		
Paraprionospio pinnata (Po)	<0.1				<0.1		<0.1	0.1		0.1	1.2			0.2	<0.1	<0.1				<0.1
Prionospio cirrifera (Po)	<0.1	2.0	0.2	<0.1	0.1	0.3	0.7	1.4	4.7	4.0		0.1	<0.1		0.2	2.9	0.9	0.3	<0.1	2.6
Prionospio steenstrupi (Po)	0.2	0.3	0.2	0.4	1.6	0.1	1.1	4.3	5.0	9.6		1.4	0.4	0.2	0.5	8.7	1.8	0.6	<0.1	3.0
Tharyx spp. (Po)	0.7	0.7	0.3	0.3	1.3	30.7	15.0	14.1	1.3	13.1			45.9	5.4	69.5	36.6	33.7	2.0	74.2	3.4
Others	0.3	0.4	0.5	0.8	0.3	0.2	0.1		0.3	0.3		0.1	0.5		0.2	0.3	0.2	0.1	0.1	1.0
(No. of taxa)	(4)	(3)	(4)	(6)	(4)	(2)	(4)		(3)	(6)		(2)	(5)		(4)	(4)	(4)	(2)	(3)	(6)
Total	7.5	11.6	21.7	28.7	31.0	45.5	21.1	34.3	30.6	54.4	81.3	8.7	52.5	65.3	72.1	52.5	38.6	11.5	75.5	31.2

[a] As defined by Word et. al. (1977), Pearson and Rosenberg (1978), and Word (1980).

[b] Po = Polychaeta, Am = Amphipoda, Os = Ostracoda, Ol = Oligorchaeta.

of the total fauna. The ostracods Euphilomedes carcharodonta and E. producta constituted the largest proportion of the opportunistic and pollution-tolerant taxa among these stations. Euphilomedes spp. are known to increase in abundance in areas where only slight organic enrichment of the ecosystem may be occurring. Among the Elliott Bay stations, 13 of the 16 stations had relative abundances of opportunistic and pollution-tolerant taxa higher than any of the Port Susan stations (Figure 66; Table 30), ranging from 30.7 to 81.4 percent of the total fauna. Only at Stations SS-04, NH-04, and WW-14 did relative abundances of opportunistic and pollution-tolerant taxa not exceed the relative abundances of those taxa observed at the Port Susan stations. Stations NH-03, EW-05, EW-11, and KG-01 had the highest relative abundances of opportunistic and pollution-tolerant taxa, ranging from 65.3 to 81.4 percent. At the major taxa level, these four stations exhibited the greatest number of significant depressions. Capitella capitata constituted the largest proportion of opportunistic and pollution-tolerant taxa at Stations NH-03 and EW-05, while Tharyx sp. constituted the largest proportion at Stations EW-11 and KG-01. C. capitata is a known indicator of organically enriched conditions and typically is the only species found in the most stressed areas. Tharyx sp. has also been cited as an indicator of organically enriched conditions. The remaining stations had relative abundances of opportunistic and pollution-tolerant taxa ranging from 30.7 to 54.4 percent; Tharyx sp. also represented a large proportion of the opportunistic and pollution-tolerant taxa at these stations (Figure 66; Table 30).

Classification Analyses

Similarities between station pairs and groups of stations based on the Bray-Curtis Similarity Index and normal classification analysis are shown in Figure 67. Station groups were determined by selecting a 55 percent similarity value. This level of similarity was selected because it separated the stations into three interpretable groups with four outliers. Results of the normal classification analysis indicated a high degree of similarity among the four Port Susan stations (65 percent). Much lower degrees of similarity were apparent between the four stations in Port Susan and the 16 stations in Elliott Bay (25 percent). These results suggest that despite the gradient in sediment grain size composition that exists among the four stations in Port Susan, the benthic macroinvertebrate assemblages were very similar. They also indicate that species composition of the benthic communities in Port Susan differs somewhat from that in Elliott Bay. Reasons for the apparent differences in species composition cannot be confirmed, but likely include habitat and biogeographic differences between the two areas, effects of anthropogenic modifications of Elliott Bay, and stresses resulting from inputs of pollutants from point and nonpoint sources into Elliott Bay.

Included in Group 1 were all four Port Susan stations. Stations PS-03 and PS-04 were very similar to one another, probably due to the similar abundances of Psephidia lordi, Euphilomedes carcharodonta, and E. producta that occurred at each. These taxa were the three most abundant species. They occurred in the same rank order at both stations. P. lordi was common to all four stations, and Axinopsida serricata and E. producta were common to three of the stations. Sediments at the Port Susan stations were primarily fine sands, but spanned a range from medium sands to silt-clays. TOC was low among the Port Susan stations, ranging from 0.39 to 1.49 percent.

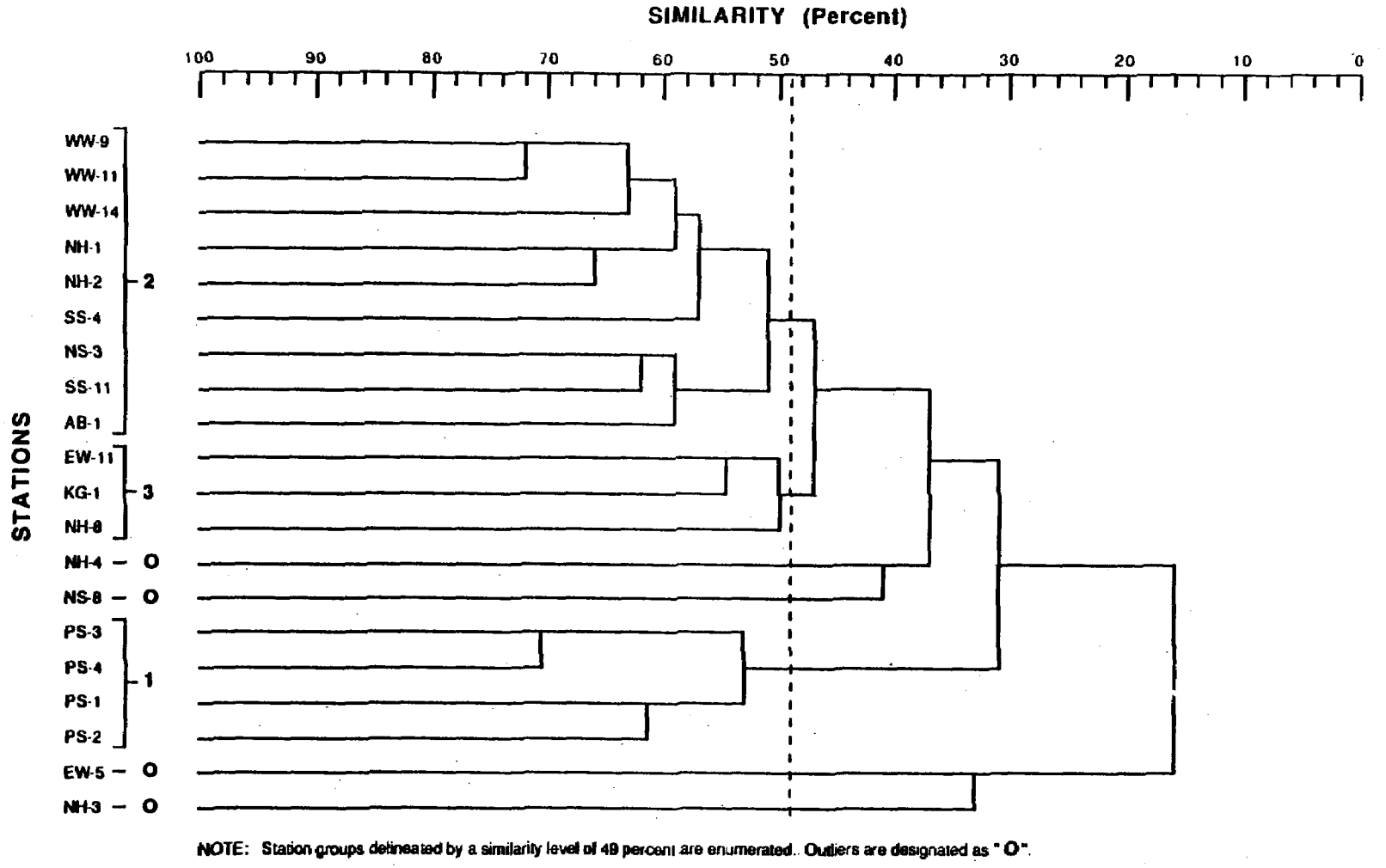


Figure 67. Results of a Q-mode classification analysis (Bray-Curtis similarity index, group average clustering strategy) using log-transformed [$\log_{10}(x+1)$] abundances of the benthic infauna at the completely identified stations in Elliott Bay and Port Susan.

Group 2 comprised nine stations (i.e., Stations AB-01, NS-03, SS-04, SS-11, NH-01, NH-02, WW-09, WW-11, and WW-14) from five of the nine segments. Within this group, the West Waterway stations, the North Harbor Island stations, and Stations AB-01, NS-03, and SS-11 formed groups at higher similarity levels. West Waterway Stations WW-09 and WW-11 were the most similar to each other because of the shared dominance of Tharyx sp. and Leptochelia dubia. In addition to these two species, they also had four of the five most abundant taxa in common. Leptochelia dubia and Tharyx sp. were the two most abundant taxa at Station SS-04.

Within Group 2, Stations AB-01, NS-03, SS-11, NH-01, and NH-02 exhibited a dominance structure similar to that at the Port Susan stations. The most abundant taxa represented 43-63 percent of the fauna, and no individual taxon was highly dominant at any of the stations (see Figures 64 and 65; Table 29). As discussed above, numerically dominant taxa at the Port Susan stations represented 57.5-69.8 percent of the fauna, and were not dominated by a single taxon. The numerically abundant species were also fairly similar among Stations AB-01, NS-03, SS-11, NH-01, and NH-02. E. carcharodonta was among the dominant taxa at all five stations, while A. serricata and Odostomia spp. were common to three of the five stations.

The nine stations in Group 2 had few significant depressions. Among the stations in this group, no significant depressions were detected at Stations AB-01, NS-03, and SS-11 and only one significant depression was detected at the remaining stations when compared to the Port Susan stations. All depressions were attributed to low pelecypod abundances. No consistent trends in sediment characteristics were evident among the stations in Group 2. Grain size varied from medium sands to silty sand, and TOC varied from 0.49 to 6.83 percent.

Group 3 consisted of Stations EW-11, KG-01, and NH-08. All three stations were characterized by extremely high abundances of the polychaete Tharyx sp. Tharyx sp. represented 69.5, 74.2, and 45.9 percent of the total fauna at Stations EW-11, KG-01, and NH-08, respectively. These high abundances were reflected in the t-tests for Stations EW-11 and KG-01, which showed significant enhancements of polychaetes and total infaunal abundances. Crustacean abundances were significantly depressed at all three stations (see Figure 58), and Stations KG-01 and NH-08 exhibited significantly depressed abundances of pelecypods. Sediment characteristics were similar among these stations. Stations EW-11 and KG-01 exhibited similar TOC values (3.43 and 3.13 percent, respectively) and total solids values (47.23 and 43.58 percent, respectively). Sediments at Station NH-08 differed slightly, having 1.96 percent TOC and 57.63 percent total solids. All three stations had relatively high percentages (37.4-79.4 percent) of silt (see Appendix D).

Stations NH-04 and NS-08 were both outliers in the classification analysis. Station NH-04 was an outlier because Cirratulus cirratus was extremely dominant, representing 84.5 percent of the fauna (see Figures 64, 65 and Table 29). Although sediment characteristics (i.e., percent TOC and percent total solids) were similar to most other test stations, polychaete abundances were significantly enhanced and pelecypod abundances were significantly depressed at this station (see Figures 57 and 59). Station NS-08 was located at the north end of the Navy docks, and was co-dominated by

nematodes and Tharyx sp. at relatively low abundances. The sediments at Station NS-08 were characterized as silts, and sulfide concentrations were elevated (i.e., 167 mg/L). High abundances of nematodes are indicative of highly stressed environments (Nichols 1977; Van Es et al. 1980; Bouwman et al. 1984; Lambshead 1986).

Stations EW-05 and NH-03 had the greatest number of significant differences compared with the reference area and were also outliers in the classification analysis. Both exhibited very low total abundances, and had significant depressions in pelecypod, gastropod, and crustacean abundances, and in total infaunal abundances (see Figures 57-61). Both stations were dominated by the polychaete, Capitella capitata, which represented 58.5 percent and 78.3 percent of the fauna at Stations EW-05 and NH-03, respectively. C. capitata is an opportunistic species that is a known indicator of highly stressed conditions (Pearson and Rosenberg 1978).

Comparison of Species and Major Taxa Level Analyses

Species data at the 20 stations in Port Susan and Elliott Bay provide detailed information about benthic communities at particular sites. In general, the species data tend to identify similar patterns of potential problem areas as the significance tests using only major taxa abundances. For example, mean numbers of taxa per station (see Figure 62) were very low at stations where two, three, or four significant depressions were detected (i.e., Stations NS-08, NH-03, NH-04, EW-05, and KG-01). Mean numbers of taxa were slightly lower than reference stations at stations where only one or two depressions were detected, and were equal to or higher than reference conditions at stations where no significant depressions were detected at the major taxa level. Thus, the reductions in the mean number of species generally coincided with depressed abundances of major taxa and were not random occurrences.

Species-level data also provides important information beyond that provided by the major taxa. A major application of species data is for interpreting significant differences in abundances at the major taxa level. For example, polychaete abundances were enhanced at Stations EW-11, WW-09, WW-11, WW-14, NH-04, and KG-01. Only one significant depression was detected at Stations EW-11, WW-09, WW-11, and WW-14. Using the major taxa approach, these stations are not considered to be highly stressed. However, species data (e.g., numerically dominant taxa, dominance structure, opportunistic and pollution-tolerant taxa) at these stations indicate that the high abundances are due to the high abundances of only a few taxa (i.e., Tharyx sp., Leptochelia dubia, Cirratulus cirratus), most of which are known to be indicative of organically enriched conditions. Thus, these stations are potentially more stressed than indicated by the significance test of major taxa abundances.

Abundances of polychaetes and total infauna at stations in the East Waterway (e.g., Stations EW-03 to EW-12) were significantly enhanced. In contrast, Station EW-05, located very near the Hanford CSO, exhibited very low numbers of individuals. The high abundances at nearby stations and the low abundances at Station EW-05 seemed to indicate a perfect example of the organic enrichment model as proposed by Pearson and Rosenberg (1978). Examination of the species data at Station EW-05 indicated that, although the total abundance was low, this station was dominated by Capitella capitata, a

known opportunistic species. Without species data for Stations EW-05 to EW-11, the possible effects of organic enrichment would not be apparent. Thus, it is possible that extreme organic enrichment of the sediments at Station EW-05 is also contributing to depressed abundances of benthic infauna. Species data from nearby stations are needed to confirm this hypothesis.

Among the 16 Elliott Bay stations for which species data are available, one or more significant depressions in abundance at the major taxa level were detected at 13 stations. Of the 13 stations with one or more depressions, abundances at all but two stations (Stations NH-01 and NH-02) were dominated by one or two species (see Figures 64 and 65). At each of these 11 stations, the percentage of the fauna represented by the five numerically dominant taxa exceeded the highest value of the Port Susan stations (i.e., 69.8 percent of the fauna). At Stations NH-03 and EW-05 (where four and three depressions, respectively, were detected) only one species, the opportunistic polychaete Capitella capitata, was dominant. Stations NH-04, NH-08, and KG-01, where two depressions were detected, and Stations SS-04, EW-11, and WW-14, where only one depression was detected, were also dominated by one taxa. Tharyx sp. (Stations NH-08, EW-11, and KG-01), Cirratulus cirratus (Stations NH-04 and WW-14), and Leptochelia dubia (Station SS-04) were the dominant taxa at these stations. Five of the seven stations (71 percent) where only one significant depression was detected were dominated by one or two taxa and had a dominance structure that suggests a stressed condition. Thus, although only one significant depression was detected at the major taxa level, species level indicators suggest a somewhat higher stressed condition. One significant depression was detected at 25 of the 74 stations sampled in Elliott Bay. One depression at stations without species data may or may not be important but cannot be evaluated. Where no significant depressions occur (i.e., Stations NS-03, SS-11, AB-01), species-level indicators provided additional information about the benthic community but did not change the conclusions reached by comparing major taxa abundances.

Relative abundances of opportunistic and pollution-tolerant taxa were more variable than relative abundances of numerically dominant taxa (see Figure 66). In general, relative abundances of opportunistic and pollution-tolerant taxa at stations where two or more significant depressions were detected, represented a higher percentage of the total fauna than any Port Susan station. Of the seven stations where one depression was detected, five had relative abundances of opportunistic and pollution-tolerant taxa that were greater than Port Susan stations. As with the numerically dominant taxa, relative abundances of opportunistic and pollution-tolerant taxa indicate that a more stressed condition may be occurring at stations where only one significant depression was detected.

Indices for Decision Criteria

Concentrations of toxic substances in the sediments may cause reductions in the abundances of sensitive taxa (Wolfe et al. 1982; Rygg 1985, 1986). Similarly, a high degree of organic enrichment may also result in the demise of infaunal species (Pearson and Rosenberg 1978). In this study, the locations and magnitudes of impacts were determined by the results of the statistical tests discussed earlier (see Figures 57-61). Where available,

species level data were used to infer whether the presence of organic materials, toxic substances, or both were causing the observed depressions.

The relative degree of impact at each test station was estimated by ranking stations according to the number of statistically significant depressions in the abundances of the following major taxonomic groups: Polychaeta, Crustacea, Pelecypoda, and Gastropoda. The major taxonomic groups comprised many different species with varying degrees of sensitivities to organic enrichment and toxic chemicals. Most pelecypods and crustaceans appear to be fairly sensitive to organic enrichment and toxic substances and tend to exhibit reduced abundances under these conditions. Because of this sensitivity, they tend to be good indicators of stressed conditions at the major taxonomic level. Some species of polychaetes are sensitive to organic enrichment and toxic chemicals, while some species are tolerant of organic enrichment, or respond positively to low to moderate levels of organic materials. Some species of polychaetes may also be relatively tolerant of low levels of toxic substances. Hence, different species of polychaetes may exhibit either reduced or enhanced abundances in the presence of organic materials and toxic substances. Because of this variability among species, polychaetes do not tend to be very sensitive indicators of toxic substances at the major taxonomic level. Total infaunal abundance was not used in the criteria because the patterns of significance virtually mirrored the polychaetes. Because abundances of polychaetes were often enhanced, and often represented more than 50 percent of the fauna, the depressions in abundances of the other taxa were masked by these abundances at the total infaunal level. Although individual statistical comparisons were performed for amphipods and the other crustaceans, the results of tests on total crustaceans were very similar to both of these taxa.

Using the foregoing statistical criterion, Stations NH-03 and WW-03 appeared to be the most impacted: four depressions were recorded at each (Figure 68). Abundances of all major taxa at these two stations were depressed 33.3-94.5 percent compared with abundances at Port Susan. Polychaetes were depressed the least at both stations (37.3 and 33.3 percent, respectively). The moderately depressed abundances of polychaetes at these stations probably reflect the variable, species-specific responses of polychaetes to pollutant stresses. Many polychaete species are enhanced due to organic enrichment, while other species are reduced in the presence of organic materials and toxic substances. The polychaete Capitella capitata dominated the benthic assemblages at Station NH-03. As discussed above, assemblages dominated by C. capitata are indicative of highly stressed conditions. No species-specific information was available at Station WW-03. Gastropods exhibited the most severely depressed abundances among the major taxa (94.5 and 91.3 percent), although abundances of pelecypods (87.3 and 59.7 percent) and crustaceans (76.6 and 64.8 percent) were also severely depressed at both stations.

Stations EW-05, WW-20, KG-05, and KG-06 also appeared to be highly impacted; three significant depressions were recorded at each of these stations. Abundances of pelecypods, gastropods, and crustaceans at these stations were depressed by 32.5-94.5 percent when compared with Port Susan. Pelecypods and gastropods were completely absent from the samples at Station KG-05, and were also considered depressed. Abundances of polychaetes were

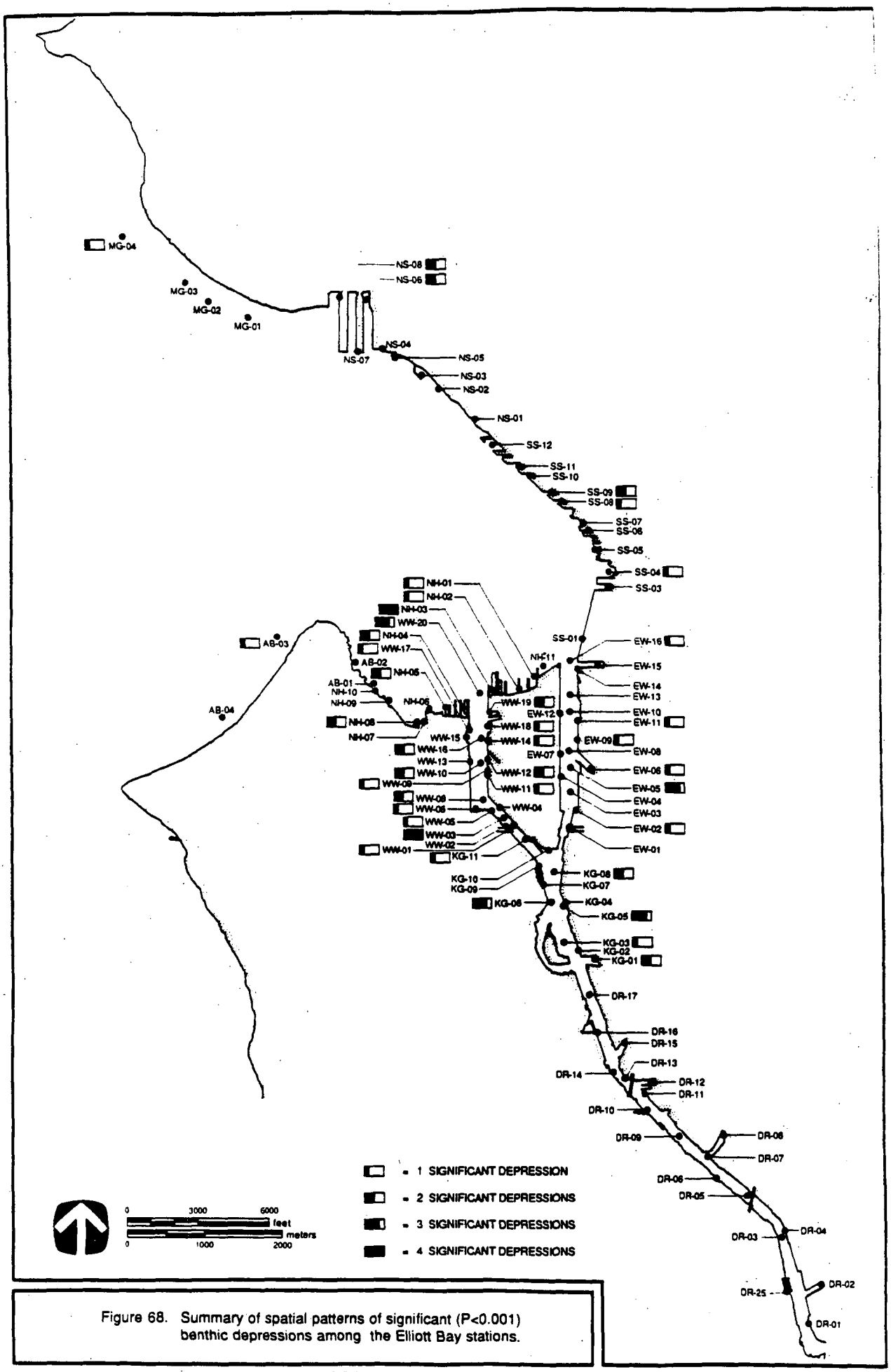


Figure 68. Summary of spatial patterns of significant ($P<0.001$) benthic depressions among the Elliott Bay stations.

not significantly depressed among any of these four stations, but Capitella capitata dominated the assemblage at Station EW-05.

An intermediate level of impact (two depressions detected at each station) was indicated at Stations NS-06, NS-08, SS-09, NH-04, NH-05, NH-08, WW-08, WW-10, WW-12, WW-16, WW-19, KG-01, and KG-08. Four of the five most abundant taxa at Station NS-08 were opportunistic or pollution-tolerant. Nematodes and Tharyx sp. co-dominated the assemblage at this station. Station NH-04 was dominated by Cirratulus cirratus, also an indicator of stressed conditions. Tharyx sp. also was the dominant species at Stations NH-08 and KG-01. No species-specific information was available for the other stations. One significant depression was detected at 21 other stations.

When the number of benthic depressions per station was examined by segment, numbers of depressions were highest in those segments closest to the mouth of the Duwamish River. Stations within the Magnolia and Duwamish Head/Alki Beach segments were virtually unimpacted, only one depression per segment was detected, and these depressions were most likely attributable to low variability among the replicate samples. The benthic communities within both these segments were similar to each other, but the community composition appeared to be different from that of Port Susan. Benthic communities within both these segments tended to have much higher abundances of crustaceans (many of which are typically pollution sensitive) than did the Port Susan stations.

With five exceptions, depressed abundances of benthic infauna were not detected at stations within the Seattle Waterfront North and South segments. Significant depressions were only detected at Seattle Waterfront North. Abundances of pelecypods and crustaceans were depressed at both stations. Pelecypods and crustaceans exhibited depressed abundances at Station SS-09. Depressions were detected at only two other stations (Stations SS-04 and SS-08) and only pelecypods abundances were depressed. No other stations within the Seattle Waterfront South segment had any significant depressions.

Seven significant depressions were detected among 4 of the 15 stations in East Waterway. One depression was detected at Stations EW-02, EW-06, EW-09, and EW-16, and three depressions were detected at Station EW-05. Polychaetes did not account for any of the depressions within this segment, but they did exhibit significantly enhanced abundances at eight of the 15 stations, indicating that this area is probably organically enriched. Polychaete abundances at Station EW-05 were low compared with Port Susan, and very low compared with the other stations in East Waterway. The pollution-tolerant species Capitella capitata dominated this community, and represented 58.8 percent of the total infaunal abundance at this station. The low abundances of polychaete and the domination of this community by C. capitata indicates that this station is highly stressed by organic inputs and may be beyond the "peak of opportunists" defined by Pearson and Rosenberg (1978).

North Harbor Island, West Waterway, and Kellogg Island appeared to be the most severely impacted (see Figure 68). Twelve depressions were detected among 9 stations in North Harbor Island, 25 depressions were detected among 17 stations in West Waterway, and 12 depressions were detected among 8 stations in Kellogg Island. Stations NH-03, WW-03, WW-20,

KG-05, and KG-06 were the stations most severely impacted with three to four depressions each. Two depressions each were detected at 10 of the other stations. Stations within these three segments, all of which were located in the vicinity of the Upper Duwamish Estuary, accounted for 73 percent of the depressions among all Elliott Bay stations.

Comparison with Recent Historical Data

Comparisons of the benthic macroinvertebrate data collected in this study with benthic data collected in previous studies were not conducted. The available historical data were from studies collected in areas that did not correspond to the study area segments in this study, or were collected at locations further from shore and in deeper water (Tetra Tech 1985c). Thus, no direct comparisons were appropriate.

Summary

- Of the 370 paired comparisons conducted among the Elliott Bay stations where benthic infauna were collected, 219 of the comparisons did not detect a significant difference in the abundances of the major taxa. Significantly enhanced abundances ($P<0.001$) were detected in 78 comparisons, and significantly depressed abundances were detected in 73 comparisons (see Figures 57-61).

- Of the 74 stations sampled for benthic infauna, one or more significant depressions ($P<0.001$) of four major taxa selected for problem definition (i.e., Polychaeta, Crustacea, Pelecypoda, and Gastropoda) were detected at 40 of the stations (see Figure 68).

- The most impacted areas in the Elliott Bay study area were North Harbor Island, West Waterway, and Kellogg Island. Stations within these segments accounted for 73 percent of the depressions detected in all Elliott Bay stations. Pelecypods and crustaceans appeared to be the most sensitive indicators among the major taxonomic groups.

- The lowest number of taxa (at stations where organisms were identified to the species level) occurred at Stations NH-03, EW-05, NS-08, and KG-01. Two or more significant depressions ($P<0.001$) in the abundances of major taxa were detected at these stations (see Figure 68).

- Classification analysis of the species-level data (see Figure 67) generated station groups that correspond fairly well to the numbers of significant depressions ($P<0.001$) recorded for abundances of major taxa among the stations.

FISH ECOLOGY

This section provides a description of the general characteristics of the demersal fish assemblages and English sole populations sampled at the

11 transects in Elliott Bay and the single transect at Point Pully (see Figure 6). Demersal fish assemblages are compared between Elliott Bay and Point Pully with respect to species composition, total abundance, total number of species, and diversity. English sole populations are compared between the two areas with respect to abundance and relative abundance.

Demersal Fish Assemblages

Species Composition--

A total of 10,751 fishes, representing 17 families and 37 species, was sampled in this study (Table 31). Elliott Bay yielded 10,399 individuals and 36 species, whereas 352 individuals and 18 species were captured at Point Pully. Much of the observed differences in catches between the two study areas likely resulted from the larger sampling effort expended in Elliott Bay, but may also have been partly the result of increased habitat complexity (e.g., pilings, rocks, debris) in Elliott Bay.

The most abundant family of fishes sampled in both Elliott Bay and Point Pully was Pleuronectidae (35.8 and 61.1 percent, respectively). The most abundant pleuronectids in both areas were rock sole (Lepidopsetta bilineata) (15.6 and 36.4 percent, respectively) and English sole (14.8 and 20.5 percent, respectively).

Assemblage Characteristics--

Demersal fish assemblages at individual transects in Elliott Bay were compared qualitatively with the assemblage at Point Pully on the basis of three major characteristics: total abundance, total number of species, and diversity (Figure 69). The latter variable was estimated using the Shannon-Wiener index (H') (Shannon and Weaver 1949).

Total abundance at 9 of the 11 Elliott Bay transects exceeded the value at Point Pully (i.e., 5.6 individuals/100 m) by a factor of 1.5 or greater. Total abundances at the remaining two Elliott Bay transects (i.e., AB-91, SS-91) were similar to the value at Point Pully.

The total number of species at Elliott Bay transects (i.e., range = 13-25) exceeded the value observed at Point Pully (i.e., 18) in five cases and was lower than that value in six cases. The six transects having fewer species than Point Pully included the four transects within or directly influenced by the Duwamish River (DR-91, KG-91, EW-91, WW-91) and the two transects in outer Elliott Bay (AB-91, MG-91).

The diversity at Elliott Bay transects (i.e., range = 1.38-2.35) exceeded the value observed at Point Pully (i.e., 2.03) in six cases and was lower than that value in five cases. The five transects having lower diversity than that at Point Pully included three of the four transects in or directly influenced by the Duwamish River (DR-91, KG-91, EW-91) and the two transects in outer Elliott Bay (AB-91, MG-91).

In summary, fish assemblages at most Elliott Bay transects were more abundant than those at Point Pully. By contrast, the numbers of species and diversities of assemblages from most transects in or near the Duwamish River

TABLE 31. RELATIVE ABUNDANCES OF FISHES CAPTURED IN ELLIOTT BAY AND AT POINT PULLY

Family	Species	Common Name	Relative Abundance (%) Elliott Bay	Point Pully
Squalidae	Squalus acanthias	spiny dogfish	<0.1	0.6
Rajidae	Raja binoculata	big skate	<0.1	
Chimeridae	Hydrolagus colliei	ratfish	0.1	2.6
Clupeidae	Clupea harengus pallasi	Pacific herring	2.9	
Osmeridae	Hypomesus pretiosus pretiosus	surf smelt	0.8	
Batrachoididae	Porichthys notatus	plainfin midshipman	0.4	1.4
Gadidae	Gadus macrocephalus	Pacific cod	<0.1	
	Merluccius productus	Pacific hake	0.1	
	Microgadus proximus	Pacific tomcod	11.0	
Gasterosteidae	Aulorhynchus flavidus	tube-snout	<0.1	
Embiotocidae	Cymatogaster aggregata	shiner perch	14.6	0.9
	Embiotoca lateralis	striped seaperch	0.8	2.8
	Rhacochilus vacca	pile perch	2.7	6.8
Bathymasteridae	Ronquilus jordan	northern ronquil	0.4	
Stichaeidae	Lumpenus sagitta	snake prickleback	22.2	
Scorpaenidae	Sebastes auriculatus	brown rockfish	0.5	4.0
	Sebastes caurinus	copper rockfish	2.4	11.4
Hexagrammidae	Hexagrammos stelleri	whitespotted greenling	0.2	0.3
	Ophiodon elongatus	lingcod	<0.1	
	Oxylebius pictus	painted greenling	<0.1	
Cottidae	Chitonotus pugetensis	roughback sculpin	0.4	0.3
	Enophrys bison	buffalo sculpin	<0.1	
	Leptocottus armatus	Pacific staghorn sculpin	2.3	
	Rhamphocottus richardsoni	grunt sculpin	<0.1	
	Scorpaenichthys marmoratus	cabezon		0.3
Agonidae	Agonus acipenserinus	sturgeon poacher	<0.1	

TABLE 31. (Continued)

Family	Species	Common Name	Relative Abundance (%) Elliott Bay	Point Pully
Bothidae	Citharichthys sordidus	Pacific sanddab	0.5	2.0
	Citharichthys stigmaeus	speckled sanddab	1.7	5.7
Pleuronectidae	Glyptocephalus zachirus	rex sole	0.7	
	Hippoglossoides elassodon	flathead sole	1.8	
	Lepidopsetta bilineata	rock sole	15.6	36.4
	Lyopsetta exilis	slender sole	1.0	0.3
	Microstomus pacificus	Dover sole	1.6	
	Parophrys vetulus	English sole	14.8	20.5
	Platichthys stellatus	starry flounder	0.1	
	Pleuronichthys coenosus	C-O sole	<0.1	2.8
	Psettichthys melanostictus	sand sole	0.2	1.1
		Total Catch	10,399	352

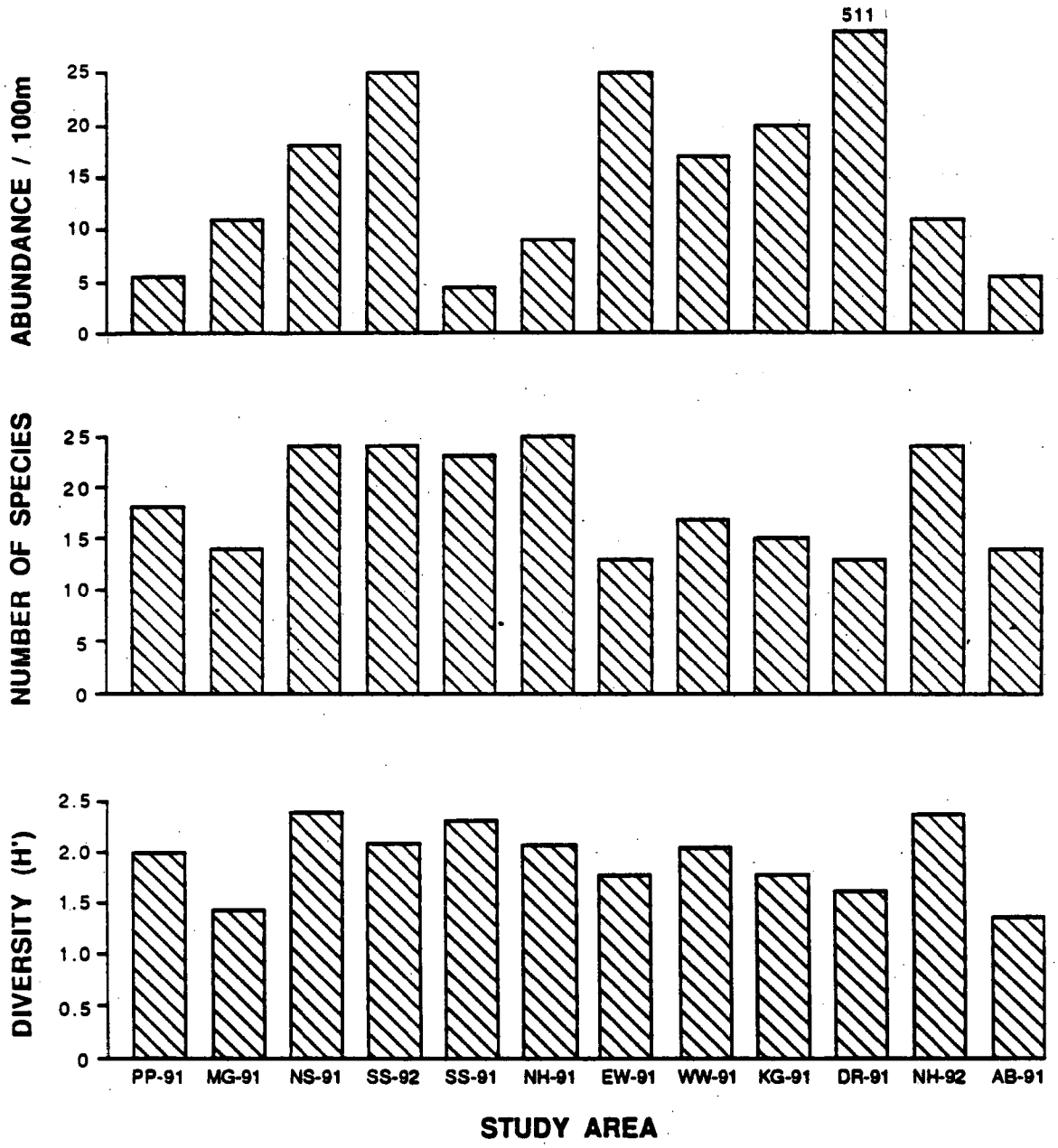


Figure 69. Comparisons of major charactersistics of fish assemblages between Elliott Bay transects and Point Pully (i.e., PP-91).

and in outer Elliott Bay were lower than the respective values observed at Point Pully. Although these comparisons are largely descriptive, they suggest that the gross characteristics of fish assemblages in Elliott Bay differed substantially from those at Point Pully only in the Duwamish River and in outer Elliott Bay. The reasons for these differences are uncertain. They could be related to several environmental factors, including chemical contamination, low salinity in the Duwamish River, or low habitat complexity and reduced benthic food sources in outer Elliott Bay.

English Sole Populations

The abundance of English sole at 9 of the 11 Elliott Bay transects exceeded that at Point Pully (i.e., 1.1 individuals/100 m) by a factor of 2 or greater (Figure 70). Abundances at the remaining two transects (i.e., SS-91, NH-92) were similar to the value at Point Pully. The reason English sole are generally more abundant in Elliott Bay than at Point Pully is unknown, but may be related partly to enhanced abundances of benthic invertebrates (i.e., English sole prey) in the former embayment. The relative abundance of English sole at Elliott Bay transects (i.e., range = 6.2-51.7 percent) exceeded the value observed at Point Pully (i.e., 20.5 percent) in six cases and was lower than that value in five cases (Figure 70). Relative abundances of English sole showed no apparent spatial relationships within Elliott Bay.

Summary

- The most abundant family of fishes in both Elliott Bay and Point Pully was Pleuronectidae
- The most abundant pleuronectids in both study areas were rock sole and English sole, respectively
- The abundances of demersal fishes at all Elliott Bay transects were similar to or greater than the abundance at Point Pully
- The total numbers of species and diversities of fish assemblages at most transects in or near the Duwamish River and in outer Elliott Bay were lower than the respective values at Point Pully
- The abundance of English sole at most Elliott Bay transects exceeded the abundance of that species at Point Pully
- The relative abundances of English sole exhibited no apparent spatial relationships within Elliott Bay.

FISH HISTOPATHOLOGY

This section presents the results of histopathological analyses conducted on the livers of English sole collected at 11 trawl transects in Elliott Bay and at one transect in a reference area off Point Pully (see Figure 6). Three major kinds of lesion were evaluated: neoplasms, foci of cellular alteration, and megalocytic hepatosis (see METHODS section). Before the lesions are considered, the age and sex characteristics of the

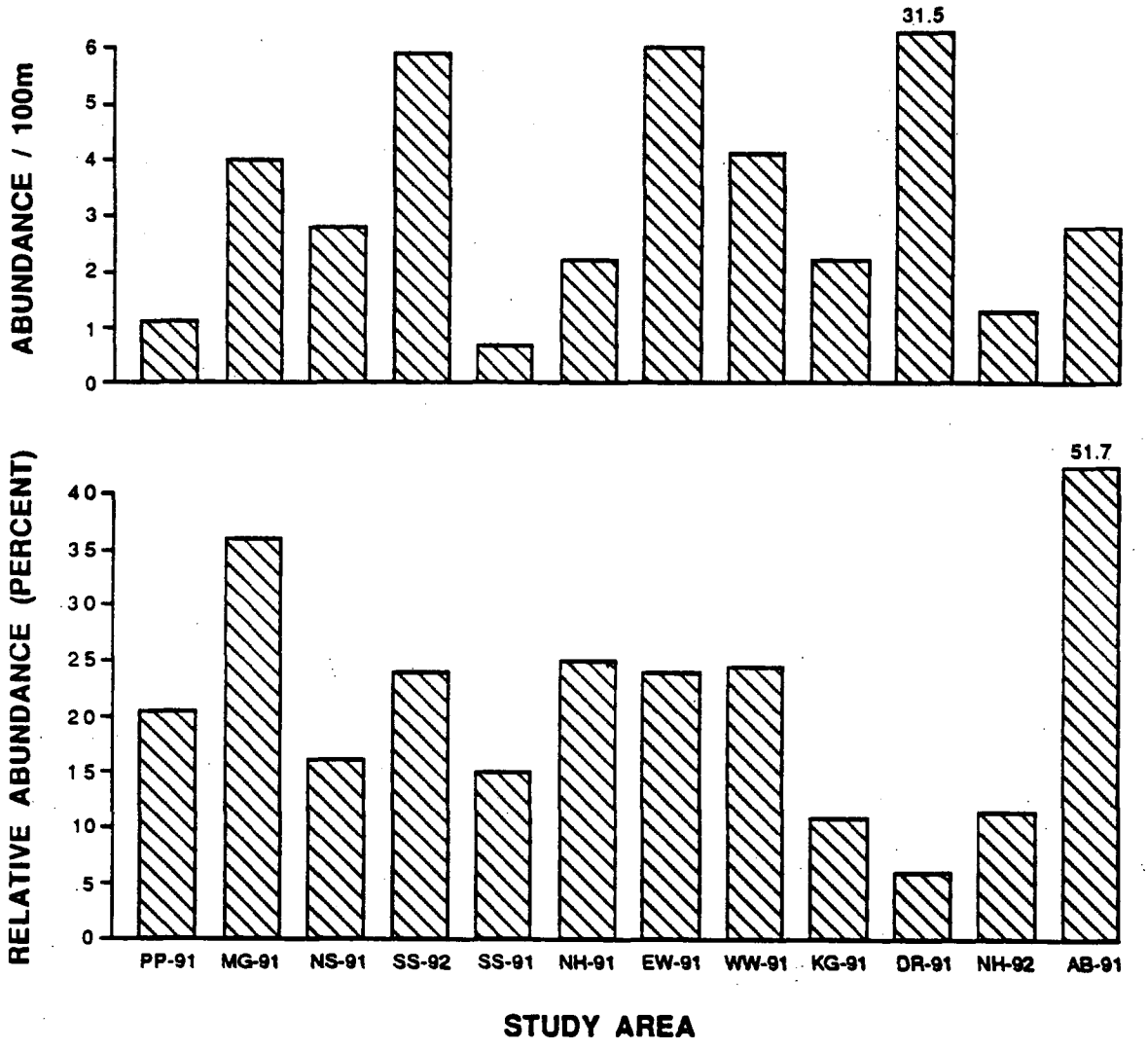


Figure 70. Comparisons of abundances and relative abundances of English sole between Elliott Bay transects and Point Pully (i.e., PP-91).

English sole sample from each Elliott Bay transect is compared with the respective characteristics of the sample from Point Pully. The overall prevalences of the lesions in Elliott Bay and at Point Pully are then presented, and the relationships between the prevalence of each lesion and fish sex and age are determined. Next, comparisons of lesion prevalences between each Elliott Bay transect and Point Pulley are made. Comparisons of length-at-age are then made between fish with and without hepatic lesions in Elliott Bay. Finally, results of the present study are compared with historical information on the prevalence of hepatic lesions in English sole from Elliott Bay.

Evaluation of the Reference Area

The prevalences of major lesions in livers of English sole collected from the Point Pully reference area during the present study were as follows: 3.3 percent megalocytic hepatosis, 6.7 percent foci of cellular alteration, and 0 percent neoplasms. Landolt et al. (1984) previously reported a prevalence of 0 percent for each of these three lesions in English sole at Point Pully. Among eight reference areas reviewed by Tetra Tech (1986e), the range of lesion prevalence was 0-2.6 for megalocytic hepatosis and 0-5.8 percent for foci of cellular alteration. The prevalence of neoplasms in livers of English sole was 0 percent at all eight reference areas. Based on these data, Point Pully appears to be representative of reference area conditions for major liver lesions in English sole of Puget Sound.

Age and Sex Characteristics of Fish Populations

Otoliths were available for age determination for 702 of the 714 (98 percent) English sole sampled in Elliott Bay and at Point Pully. Ages of the 12 fish not having corresponding otoliths were estimated from age-length keys based on the 702 fish of known age, stratified by sex (Ricker 1975). Once age determinations were made, fish younger than 3 years old (n=17) were excluded from subsequent analyses. As noted previously, the goal of this study was to focus on the individuals most likely to be afflicted with serious idiopathic hepatic lesions.

Ages of English sole at four transects from Elliott Bay differed significantly ($P \leq 0.05$) from ages of fish captured at Point Pully (Table 32). In all four cases, median fish age was less than that observed at Point Pully. Male proportion of English sole at nine transects from Elliott Bay differed significantly ($P \leq 0.05$) from the proportion at Point Pully, being greater in all instances (Table 32).

General Patterns of Lesion Prevalences

A total of 291 of the 697 (41.8 percent) English sole (age ≥ 3 years) sampled from Elliott Bay and Point Pully had one or more of the three kinds of hepatic lesion considered in this study (Table 33). Of this total, 185 (63.6 percent) had only a single kind of lesion, 92 (31.6 percent) had two kinds of lesion, and 14 (4.8 percent) had all three kinds of lesion.

Prevalences of every kind of hepatic lesion evaluated in this study were greater in Elliott Bay than at Point Pully (Table 33; Figure 71). In most

TABLE 32. COMPARISONS OF AGE AND MALE PROPORTION BETWEEN ENGLISH SOLE FROM POINT PULLY AND ELLIOTT BAY

Transect	Sample Size[a]	Median Age (yr)[b]	Male Proportion[c]
Point Pully			
PP-91	60	6.2	0.13
Elliott Bay			
MG-91	58	6.2 ns	0.05 ns
NS-91	60	5.0*	0.58***
SS-92	60	4.9*	0.80***
SS-91	48	4.8*	0.63***
NH-91	57	4.6*	0.61***
EW-91	58	5.6 ns	0.81***
WW-91	60	6.1 ns	0.67***
KG-91	59	6.8 ns	0.20 ns
DR-91	59	6.2 ns	0.47***
NH-92	58	6.3 ns	0.47***
AB-91	60	5.1 ns	0.38***

[a] All fish were ≥3 years old.

[b] Comparisons were made using the Mann-Whitney U-test. * = $P \leq 0.05$; ns = $P > 0.05$.

[c] Comparisons were made using the G-test of independence. *** = $P \leq 0.001$; ns = $P > 0.05$.

TABLE 33. PREVALENCES OF HEPATIC LESIONS IN ENGLISH SOLE FROM ELLIOTT BAY AND POINT PULLY

Hepatic Lesion	Prevalence (%) Elliott Bay (n=637[a])	Point Pully (n=60[a])
Neoplasms		
Liver cell adenoma	2.4	0
Hepatocellular carcinoma	3.6	0
Cholangioma	0.3	0
One or more kinds of neoplasm[b]	5.8	0
Foci of celluar alteration		
Eosinophilic foci	14.8	1.7
Basophilic foci	14.9	3.3
Clear cell foci	6.6	1.7
One or more kinds of foci of cellular alteration[b]	25.0	6.7
Megalocytic hepatosis	33.0	3.3
One or more of the three major kinds of hepatic lesion[b]	44.9	8.3

[a] All fish were ≥3 years old.

[b] Some fish had more than one kind of hepatic lesion.

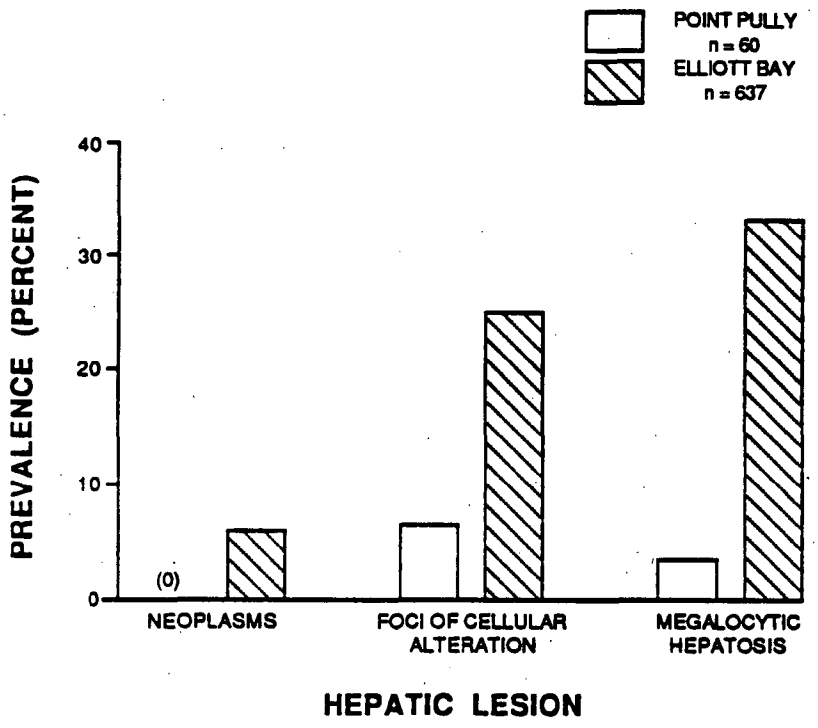


Figure 71. Comparisons of prevalences of hepatic lesions between Elliott Bay and Point Pully.

cases, the differences between these two areas were substantial. Megalocytic hepatosis was the lesion found most frequently in Elliott Bay (33.0 percent), whereas foci of cellular alteration was the lesion observed most commonly at Point Pully (6.7 percent). Neoplasms were not found at Point Pully.

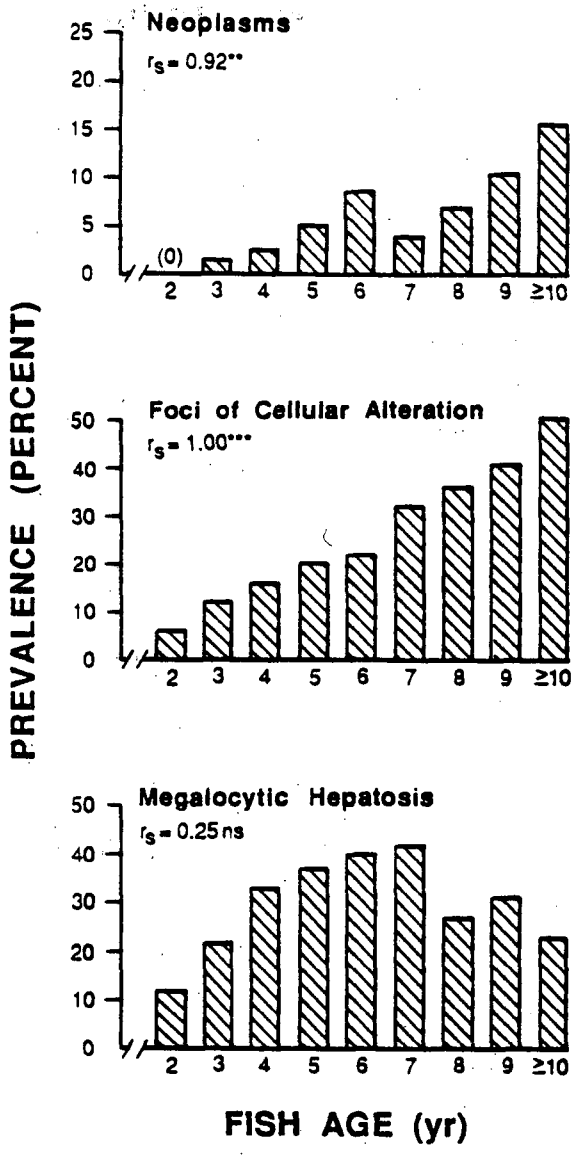
Within Elliott Bay, prevalences of neoplasms and foci of cellular alteration were correlated positively ($P \leq 0.05$) with increasing age of fish (Figure 72). These patterns are consistent with the results of past studies (Malins et al. 1982; McCain et al. 1982; Becker et al. 1987; Rhodes et al. 1987). Prevalence of neoplasms increased from 0 percent in 2-year-old fish to 15.4 percent in fish aged ≥10 years old. Prevalence of foci of cellular alteration increased from 5.9 percent in 2-year-old fish to 50.0 percent in fish aged ≥10 years old. Prevalence of megalocytic hepatosis was not correlated with fish age ($P > 0.05$) (Figure 72), but exhibited a steadily increasing trend between age 2 (11.8 percent) and age 7 (42.1 percent). Prevalences of megalocytic hepatosis at ages 8, 9, and ≥10 (26.8, 30.8, and 23.1 percent, respectively) were considerably lower than the prevalence observed for age 7.

Prevalence of neoplasms exhibited a significant difference ($P \leq 0.05$) between sexes, whereas prevalences of foci of cellular alteration and megalocytic hepatosis did not differ significantly ($P > 0.05$) between sexes. Of the three kinds of neoplasm observed in this study (Table 34), only hepatocellular carcinomas exhibited a substantial difference between sexes (i.e., 26 percent for males, 74 percent for females). No past study has found a relationship between fish sex and prevalence of hepatic neoplasms in English sole (McCain et al. 1977, 1982; Malins et al. 1982; Krahn et al. 1986; Becker et al. 1987; Rhodes et al. 1987). Several of these studies have considered fish collected from Elliott Bay.

Comparisons of Lesion Prevalences Between Study Areas

Because prevalences of neoplasms and foci of cellular alteration in Elliott Bay correlated with fish age (Figure 72), age distributions at those transects that differed from Point Pully with respect to fish age (NS-91, SS-92, SS-91, and NH-91; see Table 32) were adjusted before comparisons with the reference area were made. Adjustments were made by sequentially removing the youngest fish from each of the four Elliott Bay transects until the remaining age distribution did not differ significantly ($P > 0.05$) from the age distribution at Point Pully. In making these adjustments, 7, 7, 3, and 14 fish were removed from Transects NS-91, SS-92, SS-91, and NH-91, respectively. A graphical comparison between the age distribution at each Elliott Bay transect (including the four adjusted distributions) and the age distribution at Point Pully is presented in Figure 73.

Although prevalence of neoplasms differed between sexes (Table 34), the sex distributions at those transects that differed from Point Pully with respect to male proportion were not adjusted before comparisons with the reference area were made. Adjustments were not made primarily because the relationship observed in this study is not consistent with results of past studies of hepatic lesions in English sole. Thus, the relationship observed in this study does not appear to be a general pattern.



AGE GROUP	SAMPLE SIZE
2	17
3	68
4	154
5	100
6	92
7	76
8	56
9	39
≥10	52

Figure 72. Comparisons of prevalences of hepatic lesions with age of English sole from Elliott Bay using Spearman's coefficient of rank correlation (r_S). ** $P \leq 0.01$, *** $P \leq 0.001$, ns = $P > 0.05$.

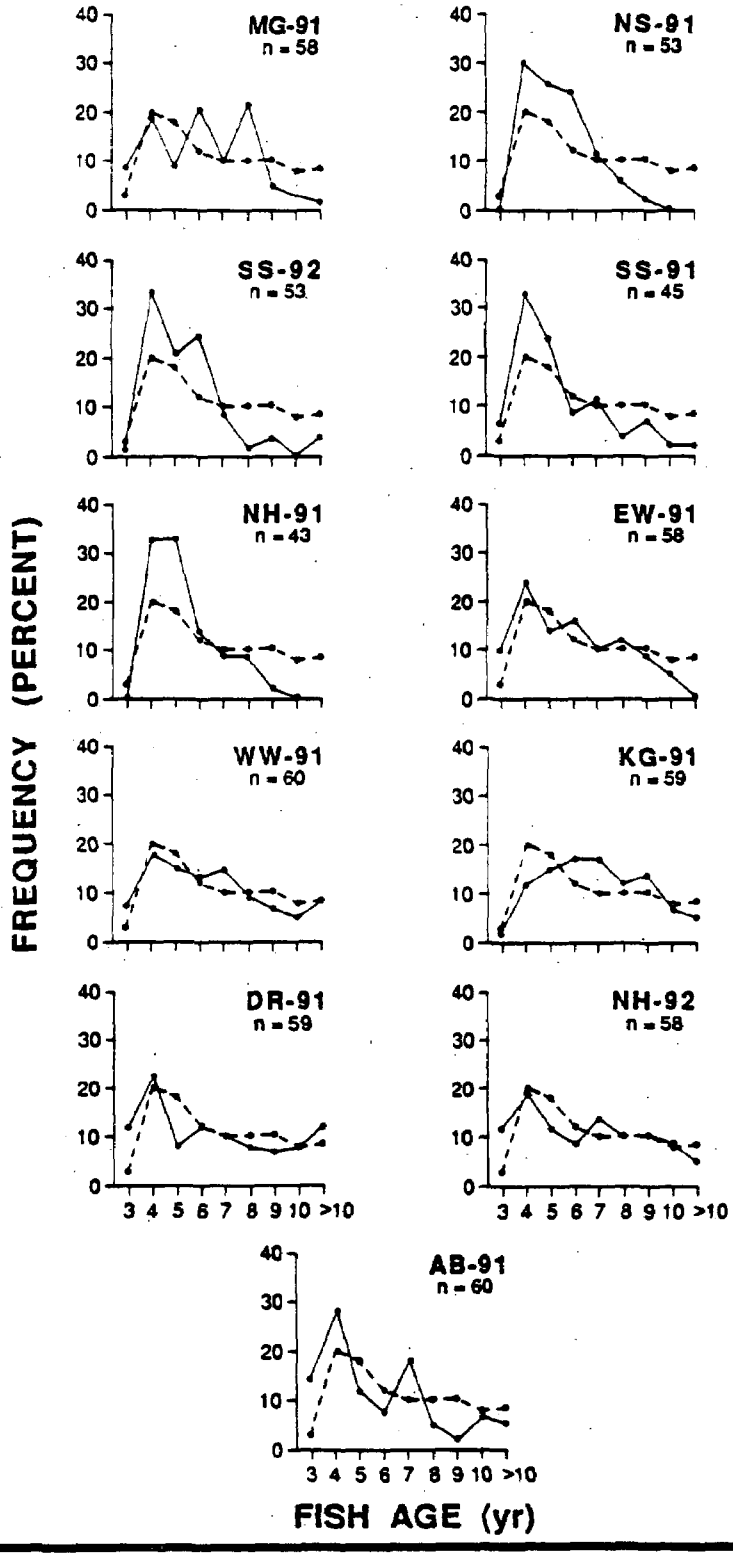


Figure 73. Comparisons of age distributions between Elliott Bay transects (solid lines) and Point Pully (dashed lines).

TABLE 34. COMPARISONS OF LESION PREVALENCES BETWEEN MALE AND FEMALE ENGLISH SOLE FROM ELLIOTT BAY

Hepatic Lesion	Percent having Each Kind of Lesion[a] Males (n=328)	Females (n=309)	Significance[b]
Neoplasms	3.7	8.1	*
Foci of cellular alteration	23.2	26.9	ns
Megalocytic hepatosis	35.4	30.4	ns

[a] All fish were ≥3 years old.

[b] Comparisons were made using the G-test of independence. * = $P \leq 0.05$; ns = $P > 0.05$.

In most cases, age-adjusted prevalences of each kind of hepatic lesion at each transect in Elliott Bay exceeded the corresponding value from Point Pully (Table 35). Concordance among the prevalences of the three kinds of lesions across all 12 transects was significant ($W=0.70$, $P \leq 0.05$).

Prevalence of neoplasms in fish from the 11 Elliott Bay transects ranged from 0 to 12.1 percent, and did not differ significantly ($P>0.001$) from the prevalence of 0 percent observed at Point Pully at any Elliott Bay transect. The highest prevalence of neoplasms in fish from Elliott Bay was found at Transect NH-92.

Prevalence of foci of cellular alteration in fish from Elliott Bay transects ranged from 6.7 to 44.1 percent, and differed significantly ($P \leq 0.001$) from the prevalence of 6.7 percent observed at Point Pully at four transects (NH-91, WW-91, KG-91, and NH-92). The highest prevalence of foci of cellular alteration in fish from Elliott Bay was found at Transect KG-91.

Prevalence of megalocytic hepatosis in fish from Elliott Bay transects ranged from 1.7 to 58.1 percent, and differed significantly ($P \leq 0.001$) from the prevalence of 3.3 percent observed at Point Pully at eight transects (NS-91, SS-92, SS-91, NH-91, EW-91, WW-91, KG-91, and NH-92). The highest prevalence of megalocytic hepatosis in fish from Elliott Bay was found at Transect NH-91.

Prevalence of one or more of the three kinds of hepatic lesion in fish from Elliott Bay transects ranged from 10.3 to 65.0 percent, and differed ($P \leq 0.001$) from the prevalence of 8.3 percent observed at Point Pully at nine transects (NS-91, SS-92, SS-91, NH-91, EW-91, WW-91, KG-91, DR-91, and NH-92). The highest prevalence of one or more of the three lesions in Elliott Bay was found at Transect WW-91.

The spatial distributions of the three kinds of hepatic lesion are presented in Figures 74-76. The highest prevalences of both neoplasms and foci of cellular alteration were found in fish in or near the Duwamish River. Prevalences of both of these lesions were moderate along the Seattle waterfront and low (similar to the prevalences at Point Pully) in outer Elliott Bay. The highest prevalences of megalocytic hepatosis were found in fish from the lower Duwamish River and along the Seattle waterfront. Prevalences of this lesion were moderate in fish from the upper Duwamish River and similar to the prevalences at Point Pully in outer Elliott Bay.

The spatial distributions of the three kinds of hepatic lesion indicate that most abnormalities were confined to inner Elliott Bay. Within inner Elliott Bay, the most serious abnormalities were confined largely to the areas in or near the Duwamish River. These patterns suggest that fish throughout inner Elliott Bay are stressed, and that individuals near the Duwamish River are stressed to the greatest extent.

Length-at-Age Comparisons

Length-at-age of male English sole with hepatic lesions differed significantly ($P \leq 0.05$) from that of fish without lesions only for 10-year-old individuals, being greater for fish without lesions (Figure 77). Median length-at-age for all other age groups was similar between males with and

TABLE 35. COMPARISONS OF PREVALENCES OF HEPATIC LESIONS IN ENGLISH SOLE FROM ELLIOTT BAY AND POINT PULLY

Transect	Sample Size[b]	Prevalence (%)[a] Neoplasms	Foci of Cellular Alteration	Megalocytic Hepatosis	One or More Lesions
Point Pully					
PP-91	60	0	6.7	3.3	8.3
Elliott Bay					
MG-91	58	0 ns	8.6 ns	1.7 ns	10.3 ns
NS-91	53	3.8 ns	15.1 ns	37.7***	41.5***
SS-92	53	0 ns	22.6*	45.3***	54.7***
SS-91	45	4.4 ns	11.1 ns	40.0***	44.4***
NH-91	43	11.6**	41.9***	58.1***	60.5***
EW-91	58	1.7 ns	27.6**	50.0***	53.5***
WW-91	60	10.0**	35.0***	51.7***	65.0***
KG-91	59	10.2**	44.1***	27.1***	62.7***
DR-91	59	11.9**	33.9**	20.3**	49.2***
NH-92	58	12.1**	36.2***	39.7***	53.5***
AB-91	60	1.7 ns	6.7 ns	5.0 ns	11.7 ns

[a] Comparisons were made using the G-test of independence. * = $P \leq 0.05$; ** = $P \leq 0.01$; *** = $P \leq 0.001$; ns = $P > 0.05$.

[b] All fish were >3 years old, and the age distribution at each transect from Elliott Bay does not differ significantly ($P > 0.05$) from the age distribution at Point Pully.

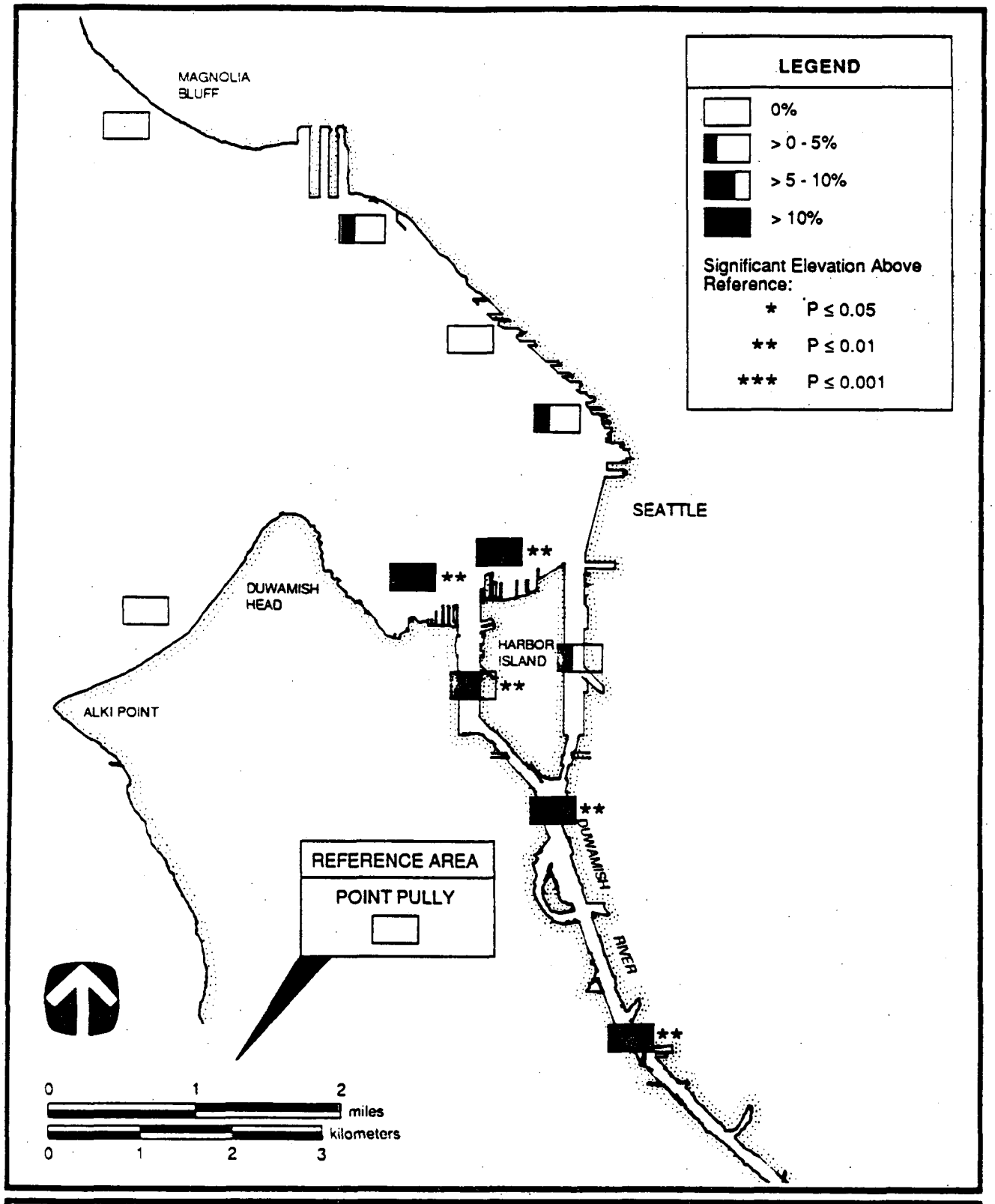


Figure 74. Spatial distribution of prevalences of neoplasms in English sole from Elliott Bay.

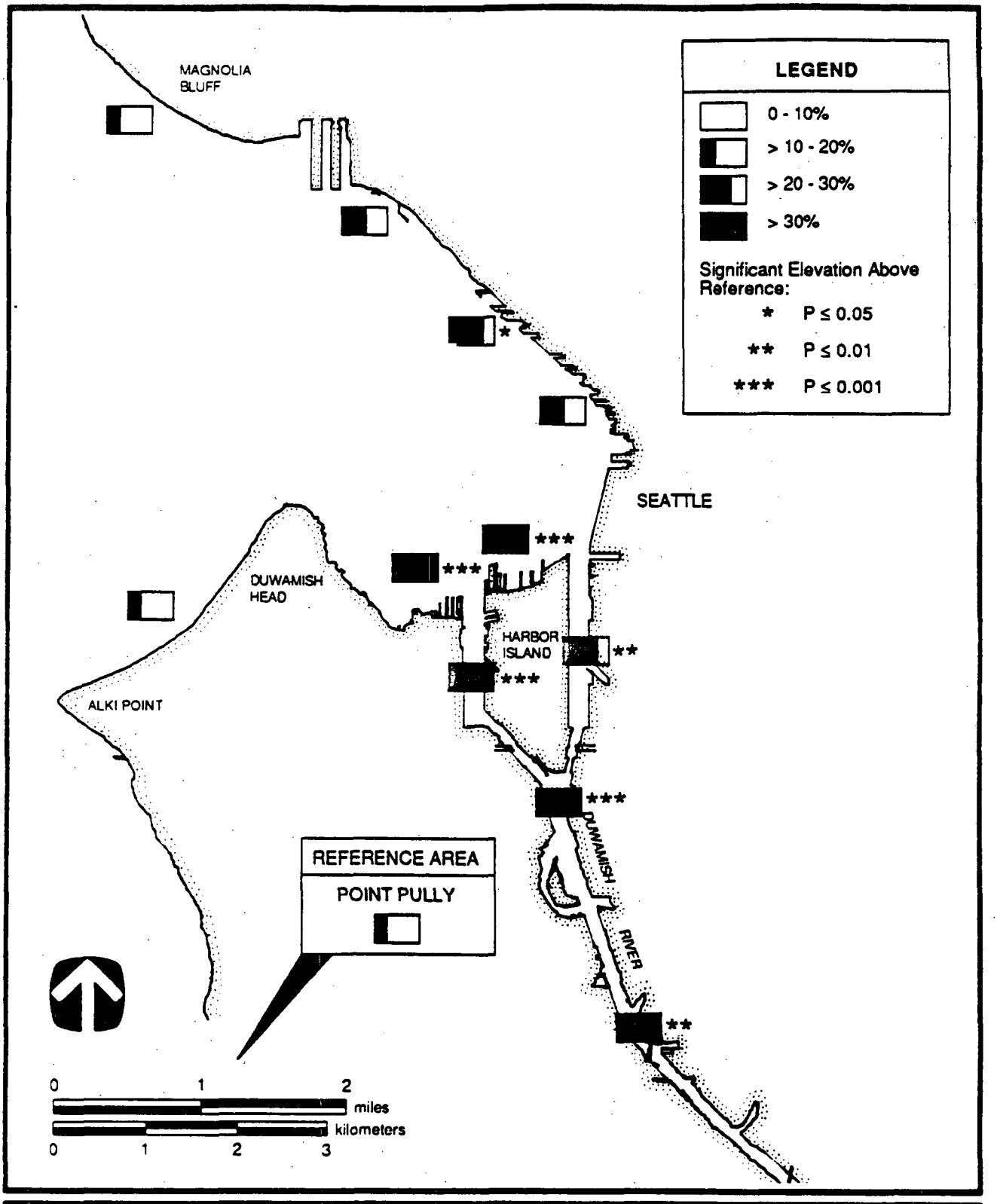


Figure 75. Spatial distribution of prevalences of foci of cellular alteration in English sole from Elliott Bay.

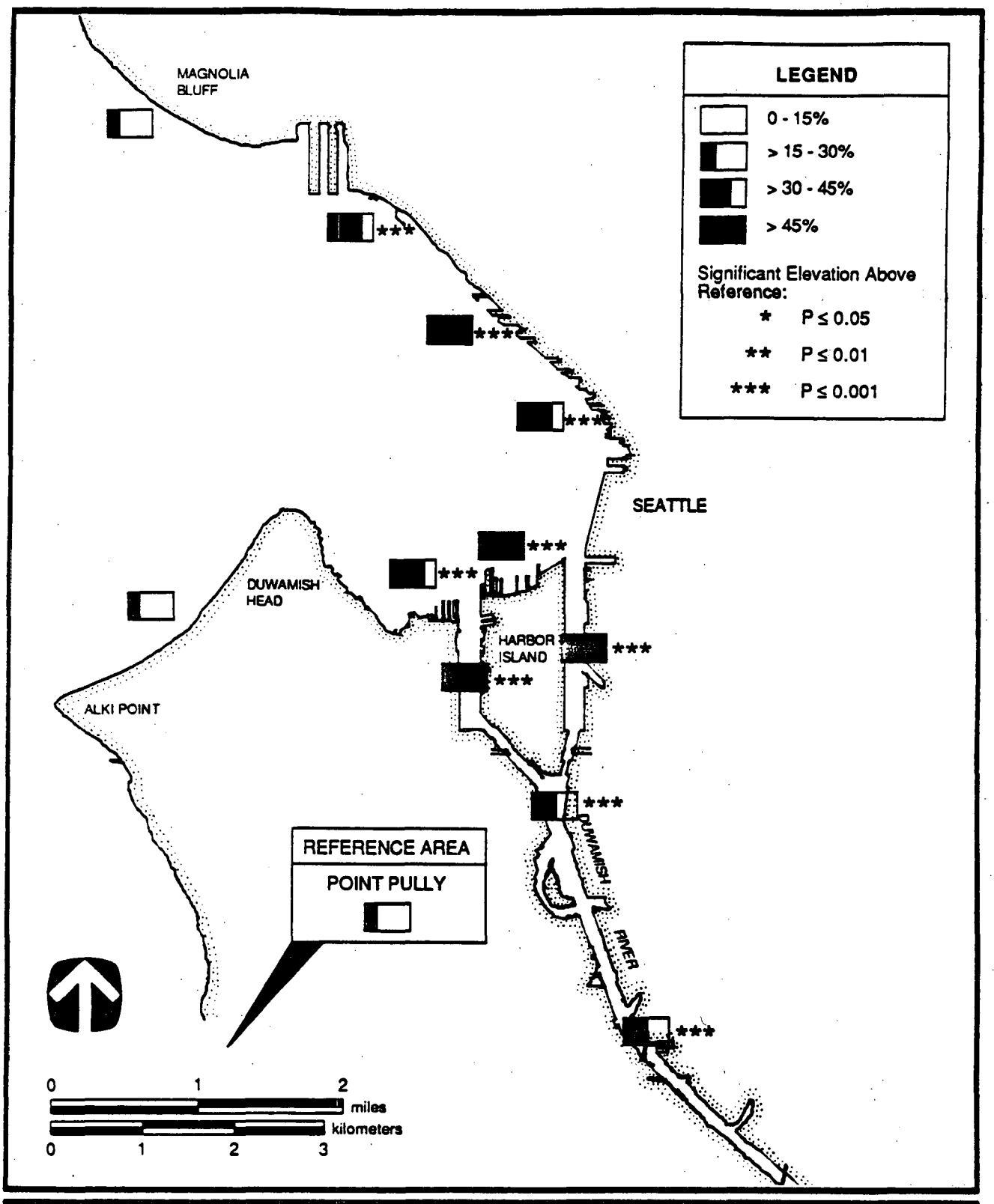


Figure 76. Spatial distribution of prevalences of megalocytic hepatosis in English sole from Elliott Bay.

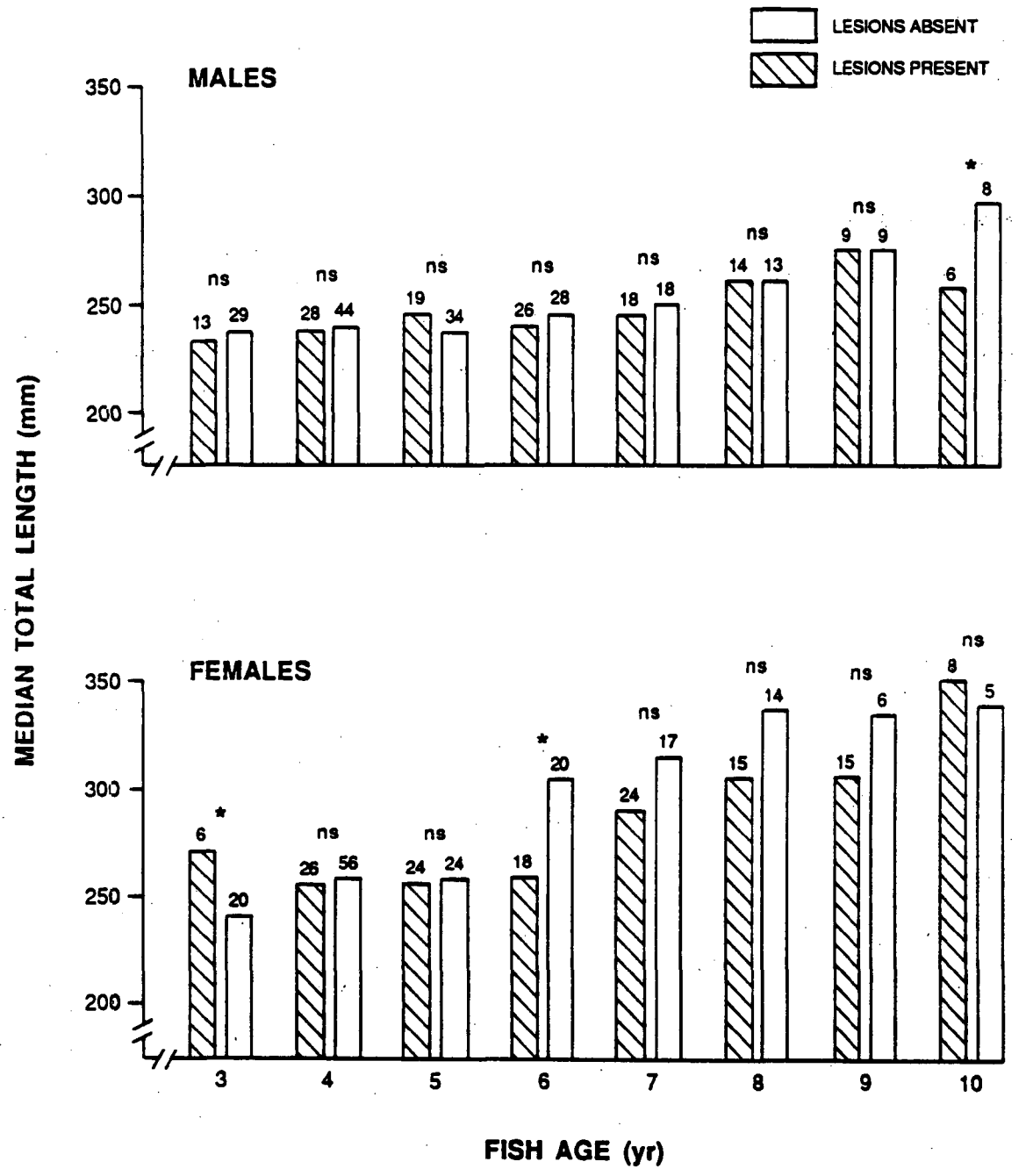


Figure 77. Comparisons of length-at-age between English sole with and without hepatic lesions using the Mann-Whitney U-test. $U \leq 0.05$, ns = $P > 0.05$. Sample size is presented above each bar.

without lesions. Length-at-age of female English sole with hepatic lesions differed significantly ($P \leq 0.05$) from that of fish without lesions only for 3- and 6-year-old individuals, being greater for 3-year-old fish with lesions and 6-year-old fish without lesions. Median length-at-age for 4-, 5-, and 10-year-old females was similar between fish with and without lesions. Although not significant ($P > 0.05$), length-at-age of females aged 7-9 years old was substantially greater for fish without lesions.

The comparisons of length-at-age between fish with and without hepatic lesions suggest that the presence of lesions may be associated with reductions in fish growth only for female English sole. In that case, differences in length-at-age first became evident when fish reached an age of 6 years old. McCain et al. (1982) evaluated English sole from the Duwamish River and found that length-at-age (both sexes pooled) did not differ significantly ($P > 0.05$) between fish with and without hepatic lesions. However, the authors noted that a slight reduction (approximately 2-3 percent) in length-at-age was evident for fish with lesions.

Comparison with Recent Historical Data

Results of the present study were compared with those of a survey conducted throughout Elliott Bay between 1979 and 1982 by Malins et al. (1984). Comparisons were limited to descriptive evaluations because different age distributions of English sole were examined in the two studies and because, in some cases, fish were collected at different locations and during different seasons. In making these comparisons, prevalences were averaged within four areas: the upper Duwamish River (Transects KG-91, and DR-91), the Harbor Island area (Transects NH-91, EW-91, WW-91, and NH-92), the Seattle waterfront (Transects NS-91, SS-92, and SS-91), and outer Elliott Bay (Transects MG-91 and AB-91). Because Malins et al. (1984) did not sample near Point Pully, results from that area in the present study were compared with the averaged results of the four nonurban Puget Sound embayments sampled by Malins et al. (1984): Case Inlet, Discovery Bay, Port Madison, and Port Susan.

The relative spatial patterns of lesion prevalences in the present study and in that of Malins et al. (1984) were nearly identical (Figure 78). The prevalences of both neoplasms and foci of cellular alteration in Elliott Bay steadily declined with increasing distance from the upper Duwamish River. Prevalences were highest in the upper Duwamish River, second in magnitude near Harbor Island, third in magnitude along the Seattle waterfront, and lowest in outer Elliott Bay. Prevalences in outer Elliott Bay were similar to those in the reference areas. By contrast with the above pattern, the prevalences of megalocytic hepatosis did not exhibit a gradient with respect to distance from the upper Duwamish River. Prevalences generally were high throughout the upper Duwamish River, the Harbor Island area, and the Seattle waterfront. Prevalences of all three lesions in outer Elliott Bay were similar to those found in reference areas.

The similarity in the relative spatial patterns of lesion prevalences between the present study and the study conducted 3-6 years earlier by Malins et al. (1984) indicate that these patterns are real (i.e., they are not artifacts of the design of either study), and that they are quite stable over time. The temporal stability of these patterns suggests that the

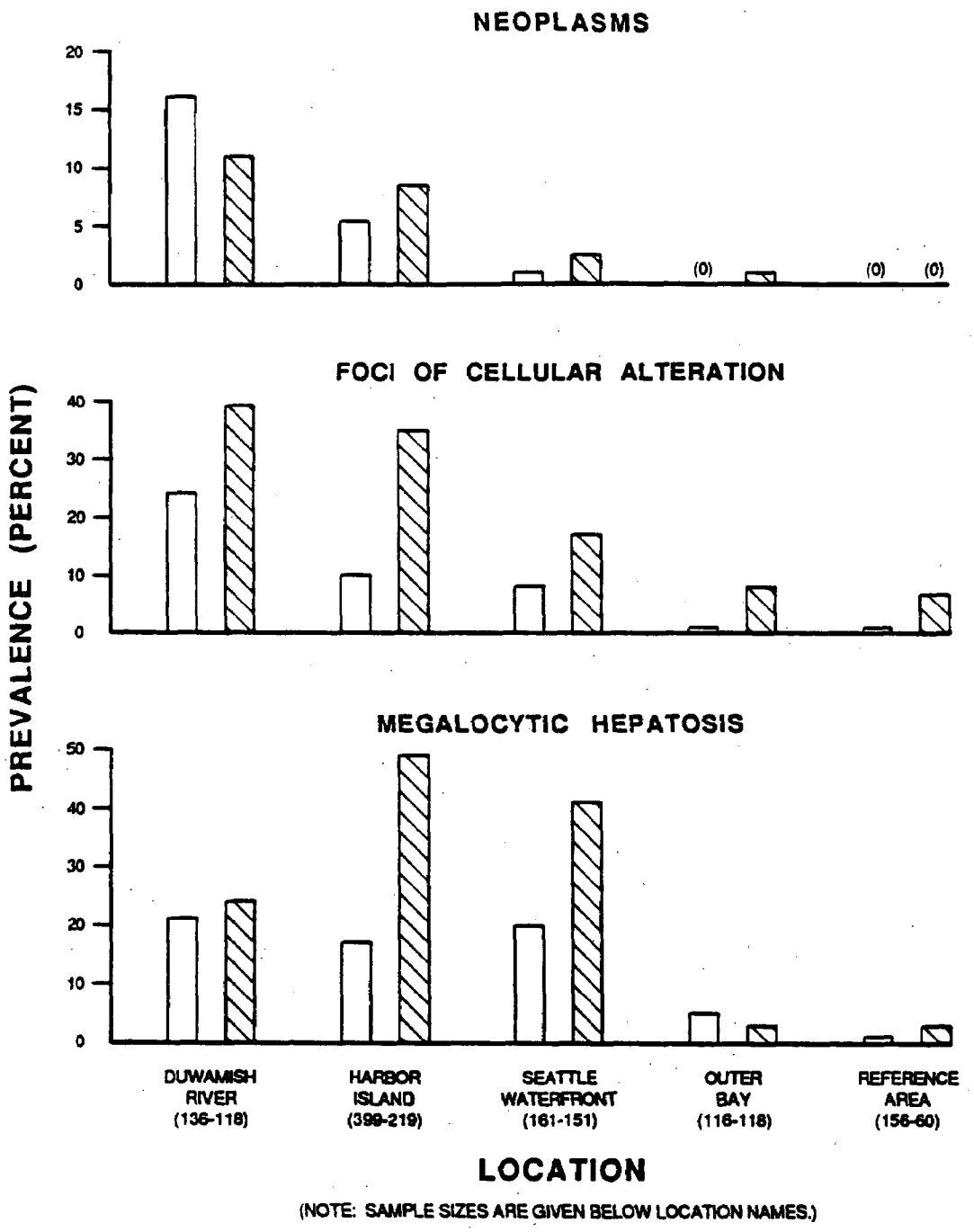


Figure 78. Comparison of prevalences of hepatic lesions in English sole sampled in the present study (stippled bars) and in Malins et al (1984; open bars)

causes of the lesions are localized within Elliott Bay, and that the causes have not been reduced substantially between 1979 and 1985.

Differences between the results of the present study and Malins et al. (1984) were related primarily to the absolute prevalence of each kind of lesion at each location. The prevalences of foci of cellular alteration and megalocytic hepatosis found in the present study were higher than the prevalences observed by Malins et al. (1984) at most locations. By contrast, the prevalences of neoplasms observed by Malins et al. (1984) were higher than the prevalences found during the present study at three of the five locations.

Several other previous studies have documented high prevalences of hepatic lesions in English sole from the Duwamish River. Pierce et al. (1978) examined 62 fish and found hepatic neoplasms in 32 percent of the sample. McCain et al. (1982) examined 551 fish and found prevalences of neoplasms, foci of cellular alteration, and megalocytic hepatosis to be 12.9, 9.0, and 18.5 percent, respectively. Krahn et al. (1986) evaluated the same three lesions in 58 fish and found prevalences of 20.7, 32.8, and 44.8 percent, respectively.

Summary

- Three kinds of hepatic lesion were considered in this study: neoplasms, foci of cellular alteration, and megalocytic hepatosis.
- Prevalences of neoplasms and foci of cellular alteration were correlated positively ($P \leq 0.05$) with fish age.
- Prevalence of neoplasms, primarily hepatocellular carcinomas, was higher ($P \leq 0.05$) in females than in males.
- Prevalence of neoplasms was not elevated significantly ($P > 0.001$) at any of the Elliott Bay transects.
- Prevalence of foci of cellular alteration was elevated significantly ($P \leq 0.001$) at four Elliott Bay transects (NH-91, WW-91, KG-91, and NH-92).
- Prevalence of megalocytic hepatosis was elevated significantly ($P \leq 0.001$) at eight Elliott Bay transects (NS-91, SS-92, SS-91, NH-91, EW-91, WW-91, KG-91, and NH-92).
- The spatial distributions of the three kinds of hepatic lesion indicate that most abnormalities were confined to inner Elliott Bay. Within inner Elliott Bay, most serious abnormalities were confined largely to the areas in or near the Duwamish River.
- Comparisons of length-at-age between fish with and without hepatic lesions suggested that the presence of lesions may be associated with reductions in fish growth only for females at ages greater than 5 years old.

- Results of the present study were compared with historical data collected by Malins et al. (1984). The relative magnitudes of lesion prevalences were similar between studies. The prevalences of both neoplasms and foci of cellular alteration steadily declined with increasing distance from the upper Duwamish River. Prevalences were highest in the upper Duwamish River, second in magnitude near Harbor Island, third in magnitude along the Seattle waterfront, and lowest in outer Elliott Bay. Prevalences of megalocytic hepatosis generally were high throughout the upper Duwamish River, the Harbor Island area, and the Seattle waterfront.

Comparison of Bioassay Responses with Benthic Groupings

Values of amphipod mortality were compared with the groupings of stations determined by classification analysis of benthic invertebrate assemblages (see RESULTS, Benthic Macroinvertebrates). The results of this comparison show that the mean level of amphipod mortality differed among groups of stations that differed in benthic infaunal characteristics (Figure 86). The mean bioassay mortality among Port Susan stations (Group I of benthic infauna in Figure 86) was low relative to other benthic infaunal groups. Amphipod mortalities at stations in benthic infaunal Group II ranged from 10 to 60 percent, with a mean of 30 percent. Generally, the stations in Group II exhibited one or no significant depressions of major taxa. At the six stations where depressions were observed (i.e., Stations NH-01, NH-02, SS-04, WW-09, WW-11, and WW-14), they could all be attributed to reductions of pelecypod abundance. Group III stations (EW-11, KG-01, and NH-08) displayed a wide range of amphipod mortality values, with a mean of 61 percent among stations. All three stations were characterized by extremely high abundances of Tharyx sp. Crustacean abundances were significantly depressed at all three stations in Group III. Pelecypods were also significantly depressed at Stations KG-01 and NH-08. The four stations that were ungrouped in the classification analysis (i.e., Stations EW-05, NH-03, NH-04, and NS-08) showed high amphipod mortalities, ranging from 82 to 100 percent, with a mean of 91 percent. These stations exhibited several characteristics indicative of extremely stressed conditions, including depressions in the abundances of major taxa and dominance by pollution tolerant species (see RESULTS, Benthic Macroinvertebrates).

In conclusion, stations that exhibited the most severe benthic effects also displayed the highest toxicity levels found in the study. These stations were outliers (ungrouped stations) in the classification analysis. A similar finding was reported by Tetra Tech (1985a). The least contaminated stations (i.e., Group I) displayed the lowest toxicity values. At stations with intermediate effects on benthic infauna (e.g., Groups II and III in Figure 86), a wide range of toxicity values was observed, and mean toxicity among stations was generally moderate.

Comparison of Significant Responses

The relationship of significant and nonsignificant amphipod bioassay results to the presence or absence of at least one significant depression of major infaunal taxa is presented in Table 36. Overall, the concordance in the responses of the bioassay and infauna was not substantially better than that expected by chance alone (i.e., the percentage of stations showing consistent responses was not substantially higher than 50 percent). Nevertheless, concordance between the bioassay and benthos was found at highly contaminated sites, especially in the North Harbor Island study area (see RELATIONSHIPS AMONG CONTAMINANTS, TOXICITY, AND BENTHIC EFFECTS, General Correlation of Indicators). The sensitivity of the benthic effects indicators relative to the amphipod bioassay was high in Elliott Bay. In the East Waterway, West Waterway, and Kellogg Island areas, many stations displayed significant benthic effects ($P<0.001$), but were not classified as toxic in the amphipod bioassay ($P>0.001$). There are several reasons why the amphipod bioassay appears insensitive relative to benthic effects indicators.

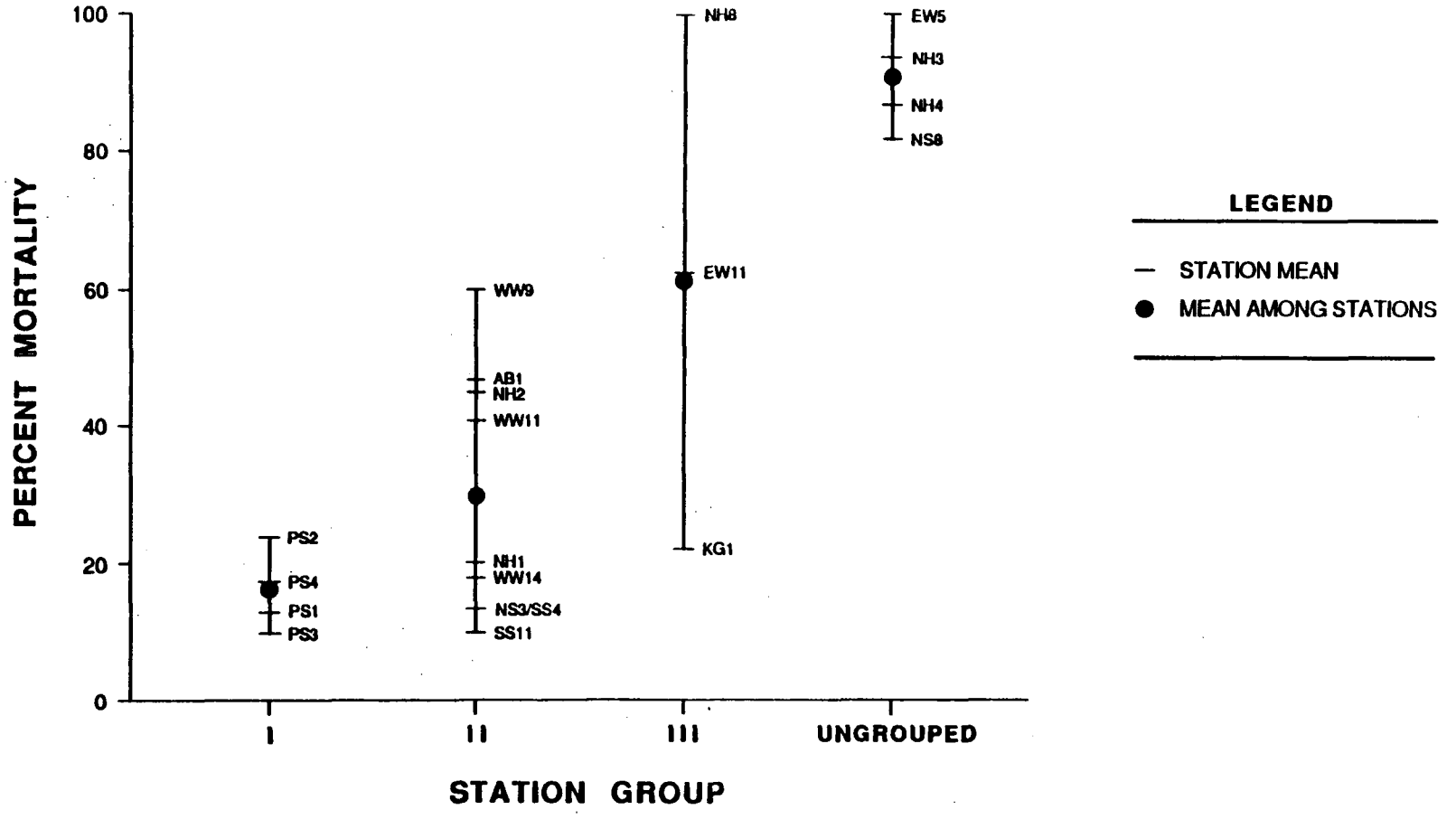


Figure 86. Amphipod bioassay responses in relation to station groupings based on classification analysis of benthic assemblages.

TABLE 36. CORRESPONDENCE BETWEEN STATIONS HAVING SIGNIFICANT (P<0.001) BIOASSAY RESPONSES AND STATIONS HAVING SIGNIFICANT (P<0.001) BENTHIC DEPRESSIONS

Bioassay Response	Benthic Depression	
	Yes	No
Yes	13%	7%
No	40%	40%

NOTE: Total no. stations = 74.

First, the statistical power of the bioassay tests in the Elliott Bay project was low relative to benthic taxa tests because of the relatively high bioassay mortality in Port Susan and because log-transformation of the benthic data greatly increased the power of the test. Second, the benthic effects tests incorporate four indicators (i.e., major taxa), whereas the bioassay is a single variable. Finally, the benthic effects tests are indicators of both chronic and acute effects whereas the bioassay measures only the latter.

RELATIONSHIP BETWEEN BIOACCUMULATION AND SEDIMENT CONTAMINATION

This section addresses the relationship between sediment contamination and bioaccumulation in English sole muscle tissue. Of the chemicals analyzed for bioaccumulation (PCBs, EPA priority pollutant pesticides, and mercury), only PCBs will be examined. Mean concentrations of mercury at study sites were relatively low and in all cases were below the mean concentration at the reference area (Point Pully). Pesticides were detected infrequently and occurred at concentrations well above detection limits in only one fish.

The following approach was used to examine sediment/fish PCB bioaccumulation relationships:

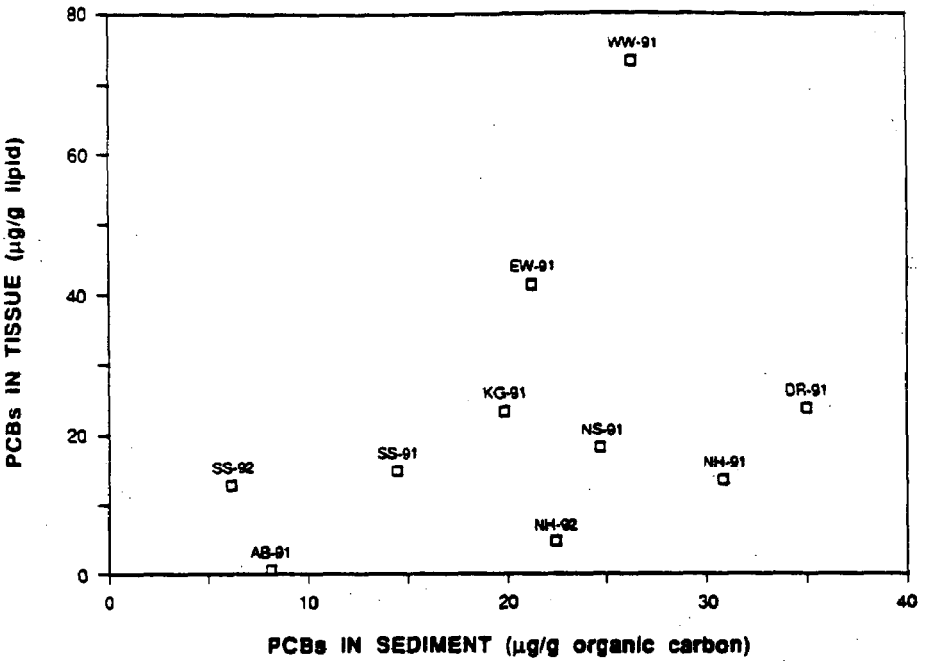
- Sediment PCB concentrations were averaged across regions corresponding to trawl transects (using geometric means). Because detection limits were relatively high for PCBs in sediments (>100 ug/kg DW), detection limits were not used in these analyses. This exclusion resulted in the elimination of Magnolia Beach data (PCBs were undetected at all MG stations at 100-200 ug/kg DW). Sediment PCB data were not collected for Point Pully, so these reference data were not available for inclusion.

- Geometric mean PCB concentrations in muscle tissue were generated for each trawl transect (detection limits were not of concern, as PCBs were detected in all tissue samples).

- Scatterplots were generated and Pearson correlation coefficients were calculated. Scatterplots were generated for wet weight bioaccumulation data vs. dry weight sediment data and for lipid-normalized bioaccumulation data vs. TOC-normalized sediment data.

The use of lipid-normalized bioaccumulation data and TOC-normalized sediment data derives from theoretical models based upon equilibrium partitioning of nonpolar organic compounds, such as PCBs (e.g., McFarland 1984). For sediment/fish systems at equilibrium in the environment, theoretical models predict a linear relationship between lipid- and TOC-normalized data.

Scatterplots of sediment/fish bioaccumulation relationships are presented in Figure 87. The correlations for these scatterplots were not significant ($r=0.33$ to 0.36; $P>0.05$) and did not appear to conform to theoretical predictions. Possible explanations for the lack of significant linear correlations are that: (1) the system is not at equilibrium, (2) fish were not confined to the areas designated for this analysis,



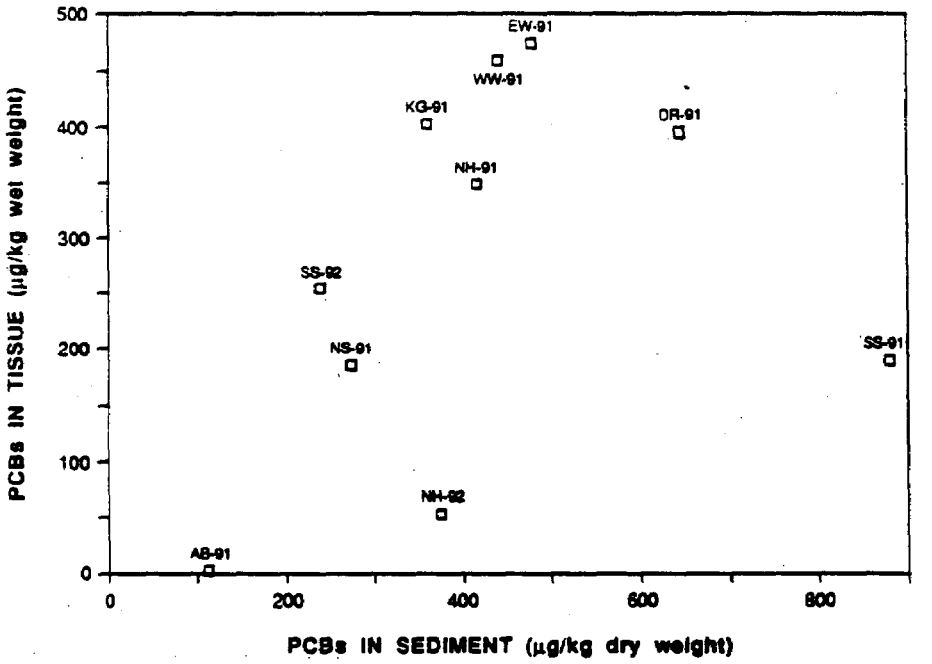


Figure 87. Relationship between PCB bioaccumulation and PCB sediment contamination.

(3) sampling intensity was not sufficient to characterize fish contamination and/or sediment contamination, particularly after detection limits were excluded from sediment data. With regard to the latter explanation, fewer than five stations were used to characterize sediment contamination in 4 of the 10 study areas. All trawl transects were represented by five fish.

SUMMARY

- Biological effects as measured by the amphipod toxicity bioassay and significant reductions in abundances of benthic infauna taxa were generally associated with higher concentrations of contaminants in sediments.

- The relationship between sediment contamination and abundances of several selected benthic taxa was nonlinear. A clear relationship with an apparent threshold in the biological response was found for selected chemicals: PAH, PCBs, copper, arsenic, cadmium, and sulfides. For the other organic compounds evaluated, the number of stations with detected values was too small or the distribution of the data was too skewed to show a strong association with biological variables.

- The abundance of the pollution-tolerant polychaete Capitella capitata displayed a roughly linear increase with sulfide concentration in sediments and no apparent relationship with copper, PCBs, or grain size.

- Amphipod mortality was generally high at higher concentrations of copper and sulfides, but was not clearly related to TOC content, grain size, or the other chemical variables evaluated.

- Both high (>40 percent) amphipod mortality and severe (>80 percent) depression of at least one major taxon of infauna were observed at the following highly contaminated sites: Stations EW-05, NH-03, NH-04, NH-05, NH-08, and NS-08. Severe biological effects were found at only one station (i.e., depressions of all four major taxa at Station WW-03) where chemical contamination was relatively low (i.e., all concentrations were below LAET).

- Biological effects at several stations in Area SS along the Seattle South waterfront were less than expected based on the severity of chemical contamination at these sites (especially Stations SS-03, SS-08, and SS-09). Other highly contaminated sites where severe biological effects were not found included Stations EW-14, AB-01, and intertidal Station KG-10.

- The abundances of most of the benthic taxa evaluated were low at stations with ≥50 percent amphipod mortality in the toxicity bioassay. In contrast, C. capitata displayed low abundances at low levels of amphipod mortality and a wide range of abundances at high amphipod mortality.

- Concordance between statistically significant responses in the toxicity bioassay and depressions of infaunal taxa was not greater than that expected by chance alone. However, this is not surprising given the wide range and levels of contaminants in the Elliott Bay system and the different endpoints measured by these two indicators (i.e., acute mortality of adults of a single species in the bioassay and chronic effects on all life stages of an assemblage of species in the benthic infaunal indices).

- Linear correlations between PCB bioaccumulation and PCB sediment contamination (i.e., wet weight bioaccumulation data vs. dry weight sediment data and lipid-normalized bioaccumulation data vs. TOC-normalized sediment data) were not significant ($P>0.05$).

PRIORITIZATION OF PROBLEM AREAS AND CONTAMINANTS

In this section, the selected data for indicators of sediment contamination, toxicity, and biological effects are integrated to evaluate toxic contamination problems in the Elliott Bay system. The approach for the ranking of problem areas was described earlier (see METHODS, Decision-Making Framework) and is summarized in Figure 3. Based on the significance and magnitude of EAR compiled in the Action Assessment Matrix format, analysis of problem areas and their priority ranking was performed in the following phases:

- **Tier I Problem Definition**--Identification of broad areas that exceeded Action-Level Guidelines (see Table 3) for combined significant elevations of sediment chemistry, fish pathology and bioaccumulation

- **Tier II Problem Definition**--Identification of problem stations that triggered Action-Level Guidelines based on significant EAR and exceedance of a) the 90th percentile concentration or HAET of chemicals in sediments, b) 80 percent depression of any one of four major benthic taxa (Polychaeta, Crustacea, Pelecypoda, or Gastropoda), c) 40 percent mortality in the amphipod bioassay, or d) any combination of the preceding.

Grouping of problem stations into problem areas was based on chemical distributions (including data from recent historical studies), the nature and proximity of potential sources, and geographic and hydrographic boundaries.

- **Ranking of Problem Sites**--Scoring of problem stations following the criteria in Table 4, and ranking of each problem area based on the average of the scores for individual stations within the area.

Finally, potential problem chemicals that exceeded AET were identified.

IDENTIFICATION OF PROBLEM AREAS

Broad areas of the nearshore Elliott Bay system displayed significant elevations of PCB concentrations in muscle tissue and of lesion prevalences in liver of English sole. Only the Magnolia and Alki Beach study areas (as delineated in Figure 2) did not exhibit statistically significant elevation of liver lesions. Because every sediment chemistry station in areas other than Magnolia and Alki Beach showed a significant elevation of at least one chemical indicator, all of the Elliott Bay system inside of a line from Pier 90/91 to Duwamish Head exceeded an action level for problem area definition.

Information on the significance of EAR for all indicators at each station was compiled in an Action Assessment matrix. Because of the large number of sediment stations (102) in Elliott Bay, only stations identified as Tier II problem sites were considered for further priority ranking. Stations identified as part of Tier II problem definition are listed in

Appendix G. The indicators that exceeded action levels for severe contamination and effects (i.e., those that potentially cause a single indicator to trigger problem definition) are also shown in Appendix G.

The Tier II problem stations were grouped into problem areas based on consideration of the following factors:

- Chemical distributions (including data from recent historical studies)
- Nature and proximity of potential sources
- Geographic and hydrographic boundaries.

The following problem areas containing multiple stations (including historical stations) were identified (Figure 88):

- DRI (in the upper Duwamish River)
- EW (in the East Waterway)
- KGI and KGII (near Kellogg Island)
- NHI and NHII (in the North Harbor Island area)
- NSI and NSII (along the Seattle North waterfront)
- SS (along the Seattle South waterfront)
- WWI and WWII (in the West Waterway).

In addition, the following single stations were identified as problem areas: AB-01, DR-05, DR-10, DR-12, DR-15, DR-16, DR-25, KG-03, and NH-10 (Figure 88).

RANKING OF PROBLEM AREAS

Ranking of problem areas within the Elliott Bay system was performed using the Action Assessment Matrix. Arithmetic mean EAR values compiled for each data type and each multi-station problem area (Tier II) are shown in Table 37. Reference values are shown on the right-hand side of the table. For each indicator, mean reference values across all stations within the reference area are shown for comparison. The original value for an indicator can be obtained by multiplying the EAR reported in the table by the appropriate reference value. Only the original data for the prevalence of liver neoplasms is shown because the reference area prevalence was zero, resulting in infinite elevations at the study sites. Note that benthic infauna EAR are calculated as the ratio of the reference value to the study site value because a toxic effect is expected to produce a depression in abundance. Refer to Appendix G for information on sample sizes (number of stations) for each indicator.

For perspective in interpreting Table 37, each of the following represent a severe effect that is sufficient for definition of a problem

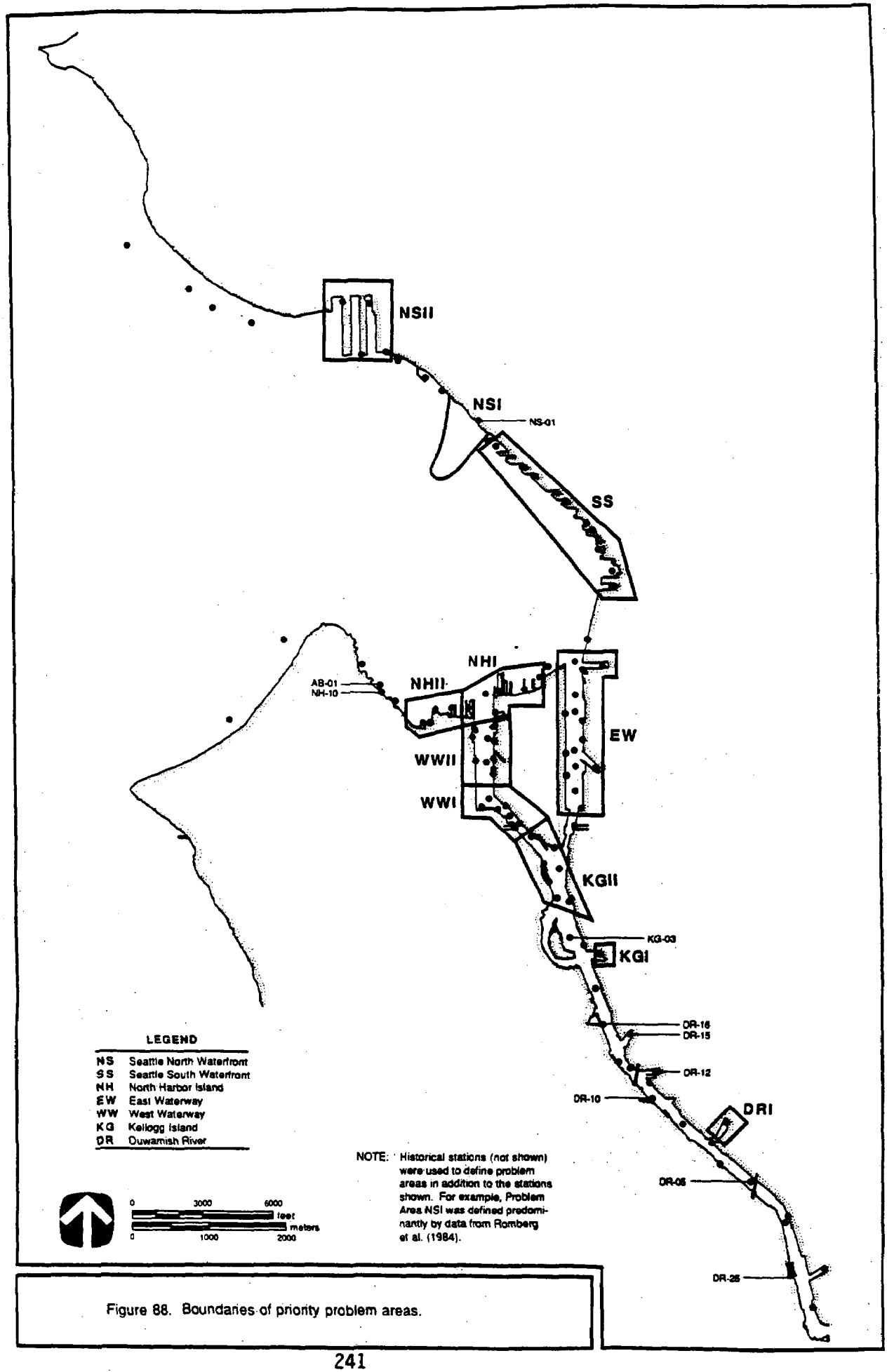


Figure 88. Boundaries of priority problem areas.

TABLE 37. ACTION ASSESSMENT MATRIX OF SEDIMENT CONTAMINATION, TOXICITY, AND BIOLOGICAL EFFECT INDICES FOR ELLIOTT BAY PROBLEM AREAS

Variable	Problem Area Elevations[a] East Waterway	Kellog Island	North Harbor Is. I	North Harbor Is. II	Seattle Water-front-N.	Seattle Water-front-S.	West Waterway I	West Waterway II	Reference Value[b]
Sediment Chemistry									
As	5.6	6.0	21	5.0	1.6	26	3.7	14	3.37 ppm
Cd	2.7	1.4	0.78	2.2	0.48	4.7	0.54	1.1	0.95 ppm
Cu	22	14	140	22	7.7	49	15	41	6.37 ppm
Pb	18	18	26	19	8.9	810	18	140	9.2 ppm
Hg	18	11	57	12	6.0	45	7	20	0.04 ppm
Ag	17	7.9	8.0	6.7	2.9	42	5.0	9.1	<0.09 ppm
Zn	15	13	32	27	6.2	71	11	23	19 ppm
LPAH	120	24	92	840	64	1,800	79	85	<41 ppb
HPAH	230	37	260	940	180	4,500	140	240	<79 ppb
PCBs	110	130	120	130	55	160	100	90	<6 ppb
Phenol		3.5	1.4		1.6	2.5	0.7	2.6	<33 ppb
2-methylphenol			11						U 7 ppb
4-methylphenol		53	47	4.6	34	11	5.4	6.7	<13 ppb
Dimethyl phthalate	0.7	0.96	0.6	0.25		7.0	1.5	7.1	U 40 ppb
Butyl benzyl phthalate	38	8.0	1.5		3.5	8.3	1.8		U 17 ppb
1,4-Dichlorobenzene		14				2,900	18		U 3.5 ppb
p,p'-DDE	1.0					1.4			U 10 ppb
p,p'-DDD			2.7			3.6		2.0	U 10 ppb
p,p'-DDT	1.9	5.2				3.2			U 10 ppb
Benzyl alcohol	46					68	230		U 10 ppb
Benzoic acid		11							<150 ppb
Sediment Toxicity									
Amphipod mortality	2.9	1.6	3.0	5.5	2.6	1.7	1.7	1.5	16%
Infauna									
Polychaetes	0.49	0.54	1.6	0.32	0.87	0.6	1.4	0.8	1,958/m^2
Gastropods	3.1	18	15	0.45	1.0	0.71	7.2	2.0	146/m^2
Pelycypods	4.8	5.2	41	4.4	5.9	3.1	11	4.5	2,307/m^2
Crustaceans	5.6	14	12	4.7	6.4	1.0	5.0	3.2	1,349/m^2
Fish Pathology									
Neoplasms[c]	1.7	10	12	12	3.8	2.2	10	10	0%
Foci	4.1	6.6	6.3	5.4	2.3	2.6	5.2[d]	5.2[d]	6.7%
Meg. hep.	15	8.2	18	12	11	13	16	16	3.3%
Bioaccumulation									
PCBs	95	60	56	17	29	44	81	81	5.4 ppb

[a] Boxed numbers represent elevations of chemical concentrations that exceed all Puget Sound reference area values, and statistically significant toxicity and biological effects at the P<0.001 significance level compared with reference conditions. The "U" qualifier indicates the chemical was undetected and the detection limit is shown. The "<" qualifier indicates the chemical was undetected at one or more stations. The detection limit is used in the calculations. Infauna EAR are based on the elevation in biological effects represented by reductions in infaunal abundances relative to reference conditions. EAR for all other variables reflect an increase in the value of the variable at Elliott Bay compared with reference conditions. Blank spaces in sediment chemistry columns indicate that the chemical was undetected throughout the problem area.

[b] EAR values shown for each area are based on Carr Inlet reference values for sediment chemistry, on Point Pully reference values for fish pathology and bioaccumulation, and on Port Susan (1985) reference values for sediment toxicity and infauna.

[c] Prevalence of neoplasms at each problem area is shown in table instead of EAR because the reference value was 0%.

[d] Data for trawl Station WW-91 were assigned to both problem areas (I and II) in the West Waterway.

area:

- >40 percent amphipod mortality, which corresponds to an EAR of >2.5
- ≥80 percent depression in abundance of one or more benthic taxa, which corresponds to an EAR of ≥5
- Exceedance of the 90th percentile or the high AET for sediment chemistry
- Significant elevation of any three indicators.

At least one of the four primary conditions just listed are met by each area shown in Table 37. Significant EAR for sediment chemistry and fish pathology were found in all of the problem areas shown in Table 37. Nearly all stations within these areas exceeded the 90th percentile for one or more chemicals in sediments (see Appendix G). Chemicals that exceeded AET at each station are discussed in the next section (see CHEMICAL CHARACTERIZATION OF PROBLEM AREAS).

The ranking criteria presented in Table 4 were applied to the Action Assessment Matrix for single stations (see Appendix G). Total scores for sediment chemistry and biological effects were determined separately for each station. The score for each multi-station area was calculated as the average of the scores for individual stations within the area (for details, see METHODS). Normalized scores for the Tier II problem areas and single stations are presented in Figures 89 and 90, respectively. The highest priority problem areas, which were defined as those areas with scores ≥60 percent are:

- SS--South Shore of downtown Seattle
- **NHI and NHII**--Stations immediately north of Harbor Island, at the mouth of the West Waterway, and west to Station NH-08 near the outflow of Longfellow Creek
- **WWI and WWII**--Segments of the West Waterway.

Areas SS, NHII, and WWII ranked as highest-priority areas based on sediment chemistry only. Area WWI ranked above 60 percent based on biology only. Area NHI scored among the highest priority areas for both chemistry and biology.

Twenty-nine stations scored ≥75 percent based on either sediment chemistry or biological effects (Figures 90 and 91). Of the 29 highest priority stations, 5 scored ≥75 percent for both sediment chemistry and biological effects: Stations EW-05, NH-03, NH-04, WW-09, and WW-11. Station NH-03 received high scores for both chemistry and biology. Station SS-09 received the highest possible score for sediment chemistry, but ranked relatively low for biological effects. Stations DR-15, DR-16, and WW-02 received the maximum possible score for biological effects, but displayed only moderate scores for sediment chemistry.

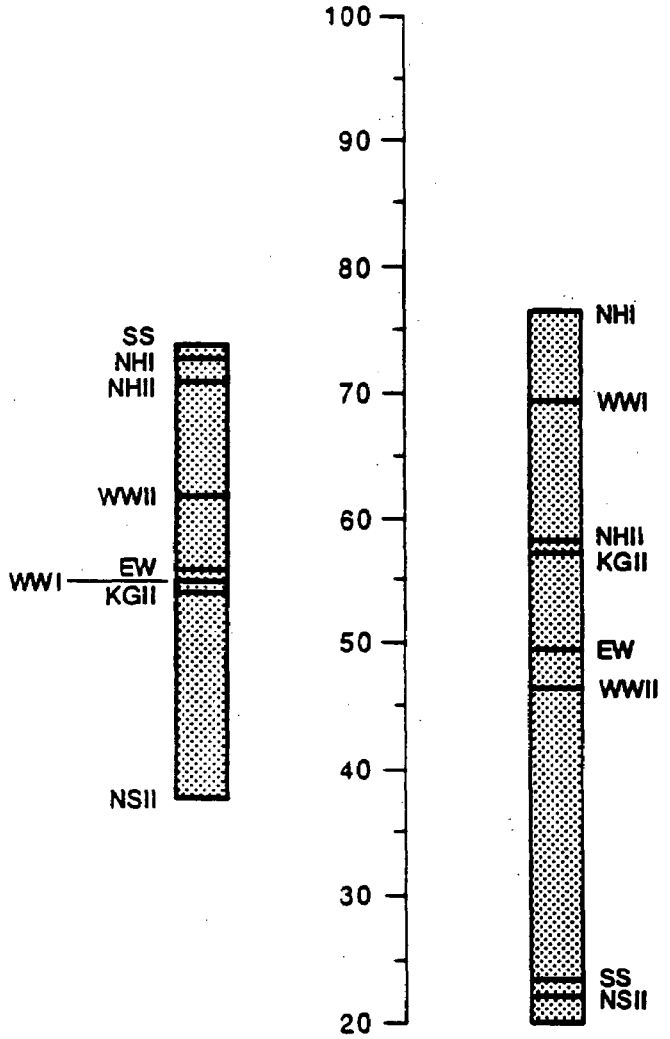
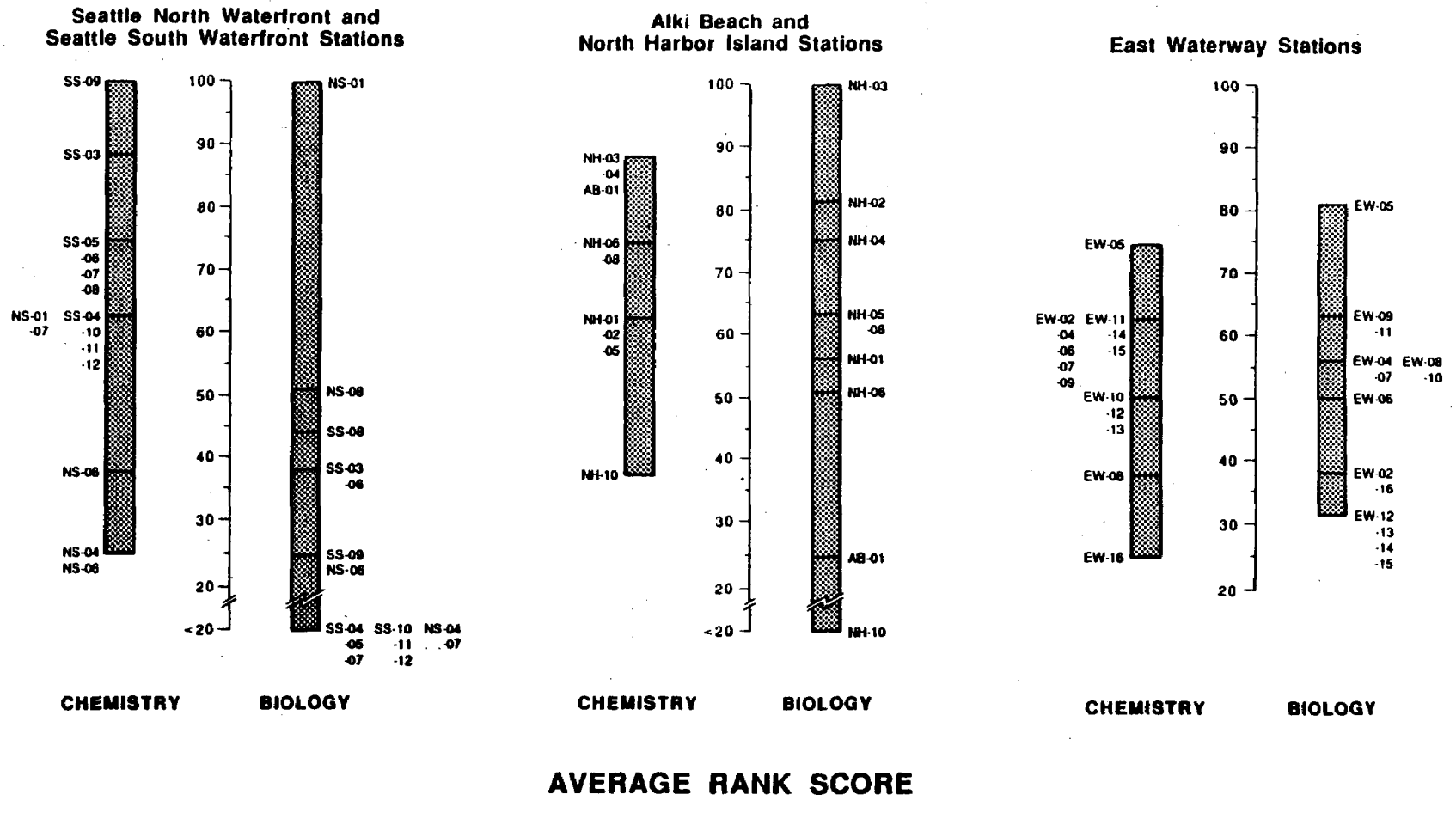
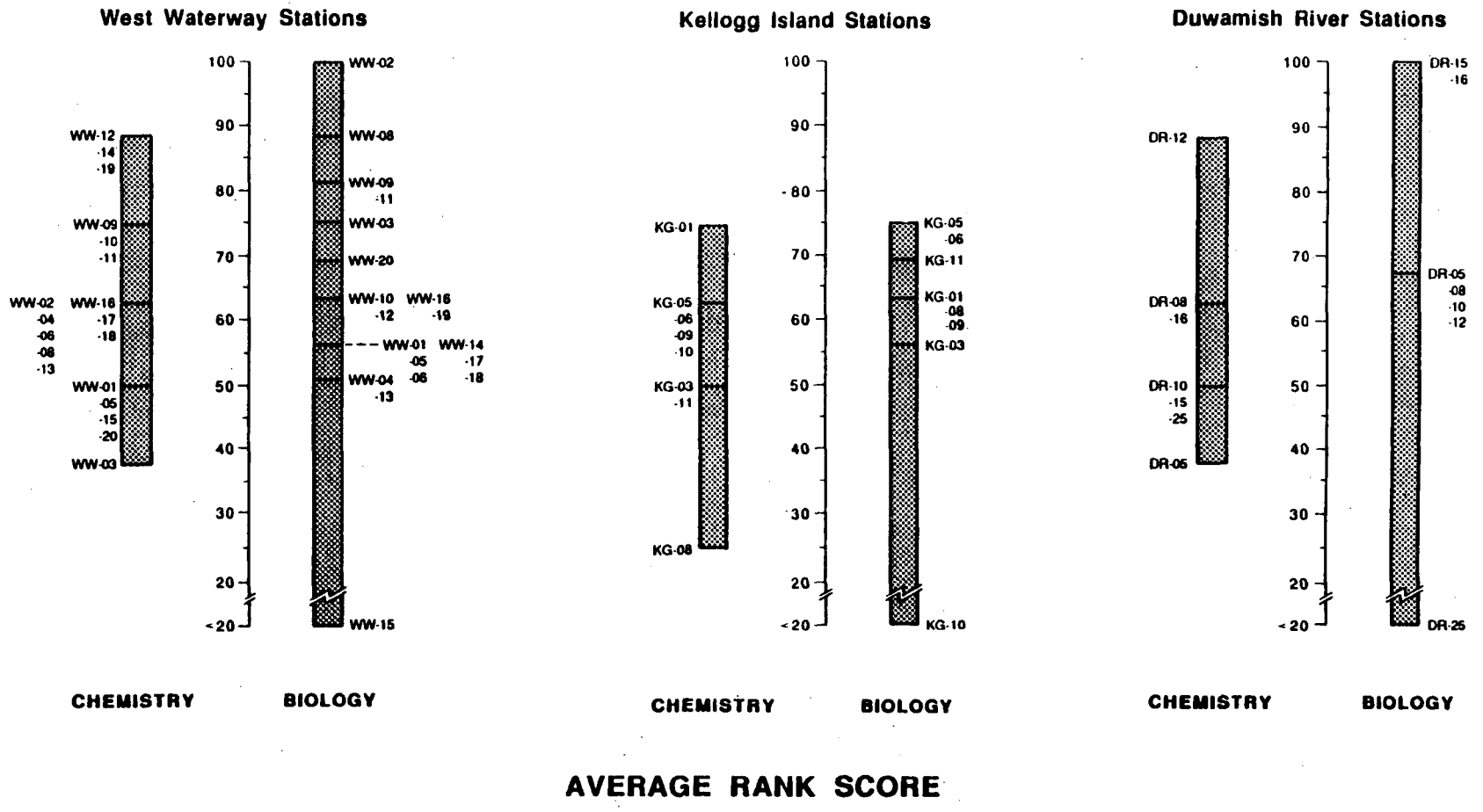


Figure 89. Ranking of priority problem areas based on average conditions within each area.



NOTE: See Figure 5 for station locations. Intertidal sites, which were ranked for biology based on the amphipod bioassay only, included DR-25, KG-10, NH-10, NS-01, NS-04, WW-02, and WW-15.

Figure 90. Ranking of single stations classified as problem sites.



NOTE: See Figure 5 for station locations. Intertidal sites, which were ranked for biology based on the amphipod bioassay only, included DR-25, KG-10, NH-10, NS-01, NS-04, WW-02, and WW-15.

Figure 90. (Continued).

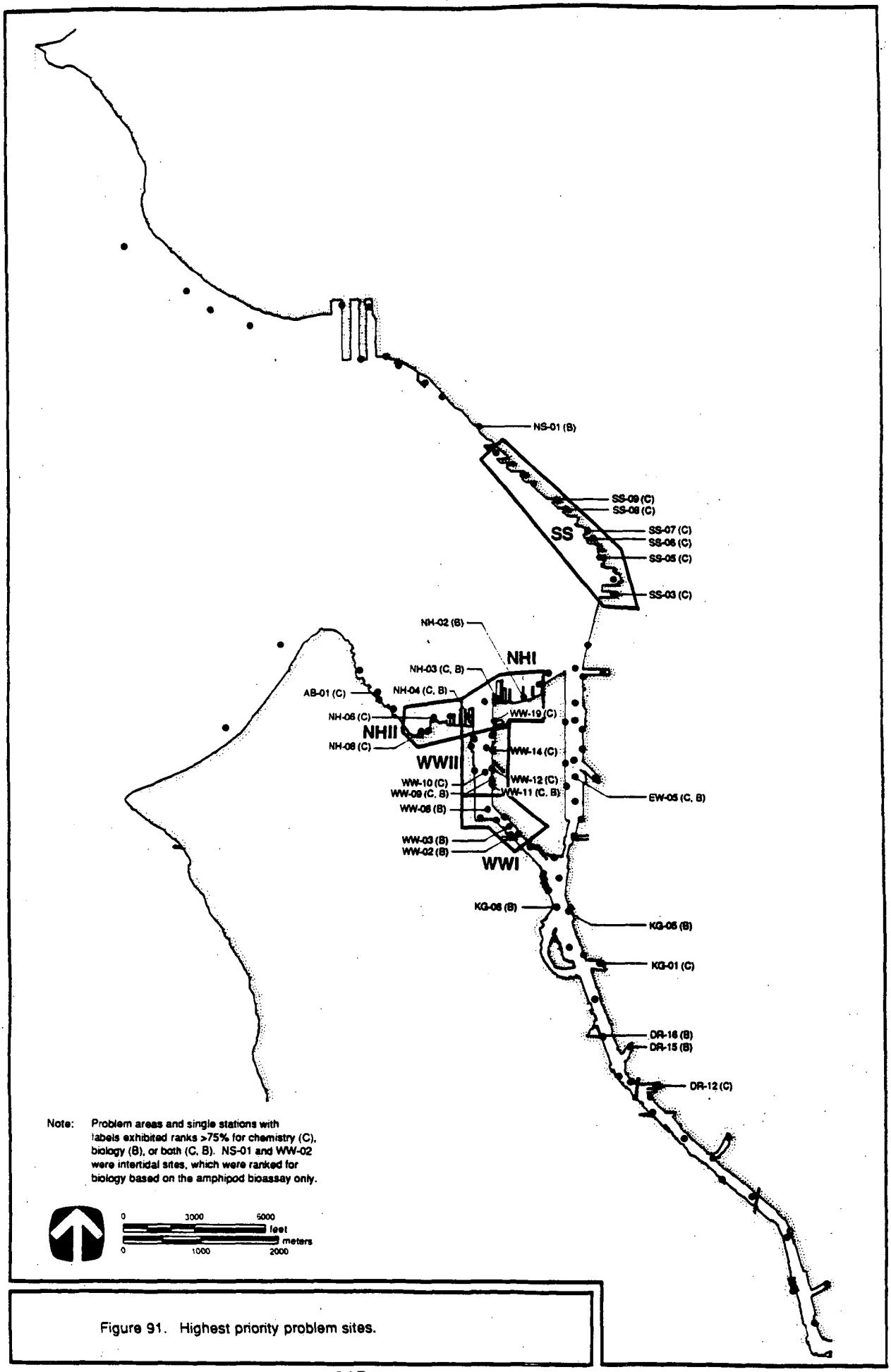


Figure 91. Highest priority problem sites.

CHEMICAL CHARACTERIZATION OF PROBLEM AREAS

In this section, the multiple-station and single-station problem areas listed above are characterized with regard to the distributions of selected problem chemicals (i.e., those chemicals with concentrations that exceed AET). To facilitate analysis by the Elliott Bay Work Group, a description is provided of the chemicals at notable stations within each problem area. Problem chemicals for all Tier II problem stations are summarized in Table 38. Detailed tables of AET exceedances (including the factor by which AET were exceeded) are included in Appendix F. The following points should be considered regarding the application of AET to chemical data in this study:

- AET values have not been established for all chemicals measured in the present study (e.g., pentachlorophenol). However, AET have been developed for the most frequently detected and most elevated chemicals.

- AET for antimony, chromium, nickel, beryllium, and thallium were not used to determine problem stations in this study. The AET for antimony and chromium were not used because of the likelihood that analytical methods used to generate AET for these chemicals are not directly comparable to the methods used in the present study (see Table 7). The AET for nickel was not used because the range of nickel concentrations in the database used to generate Puget Sound AET is relatively limited. Beryllium and thallium were excluded for similar reasons; the exclusion of these two chemicals applies only to historical data, as they were not measured in the present study.

The 90th percentile concentrations of nickel and chromium and chemicals without AET were used to designate problem stations (if the concentrations were above the range of Puget Sound reference concentrations).

Problem Area SS

The sediments in the problem area along the Seattle South waterfront were highly contaminated throughout, and had more chemicals exceeding HAET than in any other problem area (Table 39). Superimposed upon the high levels of certain problem chemicals throughout this area (e.g., PAH and mercury) were maximum concentrations of different problem chemicals occurring at a number of non-adjacent stations. These patterns suggested that multiple local sources were present, perhaps in conjunction with a more diffuse source for compounds such as PAH.

PAH were the most commonly occurring problem chemicals and exceeded the HAET at 14 of the 15 stations that defined the problem area (Table 39). HAET for other organic compounds (e.g., PCBs, 1,4-dichlorobenzene, and chlorinated pesticides) and a number of metals (including cadmium, copper, lead, zinc, mercury, and silver) were exceeded at least once in the problem area. The highest concentrations of many problem chemicals in the problem area (and in the entire study) occurred at Stations SS-08 and SS-09 (see Tables 8 and 12). Historical TPPS Station S0090 was similar to Station SS-09 in its assemblage of problem chemicals exceeding HAET, but the two

TABLE 38. POTENTIAL PROBLEM CHEMICALS

LPAH[a]	2,4-dimethylphenol
HPAH[b]	1,4-dichlorobenzene
1-methylphenanthrene	dimethyl phthalate
2-methylnaphthalene	butyl benzyl phthalate
biphenyl	benzoic acid
dibenzofuran	benzyl alcohol
PCBs	arsenic[c]
p,p'-DDE	cadmium
p,p'-DDD	copper
p,p'-DDT	lead
phenol[c]	mercury
2-methylphenol	silver
4-methylphenol	zinc

[a] The term LPAH represents the following chemicals: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene.

[b] The term HPAH represents the following chemicals: fluoranthene, pyrene, benzo(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3-c,d)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene.

[c] This chemical exceeded the LAET but never exceeded the HAET. All other chemicals exceeded the HAET at least one time.

TABLE 39. SEATTLE SOUTH WATERFRONT PROBLEM AREAS[a]

Station	HAET Exceedances[b]																	LAET Exceedances[c]
	LPAH	HPAH	PCBs	CU	PB	ZN	HG	CD	AG	DDT/DDE/DDD	PHNL	2,4MEPHN	BNZOH	14DICLBNZ	BUTBNZPH	DMP	TOC	
SS-03		X		X		X							X	X		X		HG, LPAH, AS, PB, CD, PCBs, DDD [AG, DMP]
SS-04	X	X								X					X			HG, PB, PCBs, ZN [AG]
SS-05	X	X							X						X			HG, PB, PCBs, DDD, ZN [RETENE, CARBAZOLE, DINOCT]
m10015[d]	X	X																HG, PCBs
S0090[e]	X	X	X		X	X	X	X		X								
SS-06	X	X																HG, PB, PCBs, ZN [CD, AG]
SS-07	X	X					X		X			X						PB, CU, PCBs, ZN
S0065[e]		X																HG, PCBs
SS-08	X	X															X	HG
SS-09	X	X	X		X	X	X	X		X				X				CU, DMP, PHNL [ALDRIN, RETENE, CARBAZOLE, AS, CR]
SS-10	X	X																HG, ZN [CR, NI]
C061[e]	X	X									X							PCBs, ZN
SS-11		X														X		HG, LPAH, PCBs, ZN [AG]
B061[e]		X	X															PCBs, DDE, ZN
SS-12																		[AG]

[a] LPAH - Signifies AET exceedances for the sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene, or any of these compounds individually. To simplify the presentation of AET exceedances in this table, exceedances of AET for 1-methylphenanthrene, 2-methylnaphthalene, biphenyl, and dibenzofuran are included under LPAH. These compounds covaried with LPAH but are not included in LPAH sums.

HPAH - Signifies AET exceedances for the sum of fluoranthene, pyrene, benzo(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)-anthracene, and benzo(g,h,i)perylene, or of any of these compounds individually.

CU - copper
PB - lead
ZN - zinc
HG - mercury
CD - cadmium
AG - silver
AS - arsenic

BNZOH - benzyl alcohol
BNZACID - benzoic acid
1,4DICLBNZ - 1,4-dichlorobenzene
BUTBNZPH - butyl benzyl phthalate
DMP - dimethyl phthalate
TOC - total organic carbon
DINOCT - di-n-octyl phthalate

PHNL - phenol
4MEPHNL - 4-methylphenol
2MEPHNL - 2-methylphenol
2,4MEPHNL - 2,4-dimethylphenol
TOTXYLENE - total xylenes
CR - chromium
ENDALD - endrin aldehyde
PCP - pentachlorophenol

[b] Chemicals exceeding HAET for Puget Sound. More detailed information on exceedances is presented in Appendix F.

[c] Chemicals exceeding LAET for Puget Sound. More detailed information on exceedances is presented in Appendix F. Chemicals shown in brackets exceeded 90th-percentile concentrations but did not exceed any AET. Chemicals exceeding both AET and 90th-percentile concentrations are not bracketed.

[d] Malins et al. (1982).

[e] Romberg et al. (1984).

stations were not adjacent (Table 39). Although contaminated stations such as SS-08 and SS-09 were not located near obvious potential sources, a number of stations in this problem area are located near CSOs: Station SS-03 (King Street CSO), Station SS-04 [Washington Street CSO (072)], Station SS-05 [Madison Street CSOs (071,164)], Station SS-06 [University CSO (070)], and Station SS-11 [Vine Street CSO (069)]. Sediments throughout the problem area tended to be fine-grained (with the exception of Station SS-07) and rich in organic matter (see Figures 8, 9, 15, and 16). For example, sediments at Stations SS-08 and SS-09 were composed of over 60 percent fine-grained material and had 26.6 and 10 percent TOC, respectively.

Concentrations of PAH, the prevalent organic contaminants in the problem area, decreased in either direction from the extremely high concentrations at Station SS-08 (roughly 0.38 percent DW of the EPA priority pollutant hydrocarbons) (see Figure 32), and tended to correlate well with TOC content (see Table 22). Detection limits for most individual LPAH were very high (>1,000 ug/kg DW) at Station SS-12, which may explain why HAET for PAH were not exceeded at this station.

The most elevated metals in this problem area had similar overall distribution patterns. For the metals of highest concentration in the area, concentrations were relatively constant and elevated throughout the area, with pronounced maxima at non-adjacent stations (typically SS-03, SS-09, and TPPS Station S0090). Examples of these distributions include mercury [with pronounced maxima at Station SS-09 (see Figure 28) and TPPS Station S0090)], zinc [with pronounced maxima at Stations SS-03 and SS-09 (Figure 30) and TPPS Station S0090], lead [with an extreme concentration of roughly 7 percent DW at Station SS-09 (see Figure 26) and a high concentration at TPPS Station S0090], cadmium [with maxima at Station SS-09 (17.2 mg/kg DW), TPPS Station S0090 (27 mg/kg DW), and Station SS-03 (7.16 mg/kg DW)], and arsenic, which had a maximum of 584 mg/kg DW at Station SS-03; other SS stations were typically an order of magnitude lower in arsenic concentrations. Copper distributions were somewhat more variable but maximized at Stations SS-03 and SS-07 (see Figure 24). The high concentration at Station SS-07 is unusual because this station is relatively coarse-grained (roughly 15 percent fine-grained material). Silver concentrations, which were elevated in the problem area near Denny Way CSO, were also elevated above HAET in the SS problem area. Concentrations between 4.3 and 6 mg/kg DW occurred at Stations SS-12, SS-11, and SS-05 to SS-07. Notably, chromium and nickel concentrations maximized at Station SS-10 and were the highest values observed in the study (chromium = 1,080 mg/kg DW; nickel = 366 mg/kg DW). Chromium and nickel were near or below reference levels at other stations in the problem area.

PCB concentrations were generally elevated but patchy in Problem Area SS (see Figure 36), especially considering historical data (e.g., 2,600 ug/kg DW at TPPS Station S0090 in contrast to 600 ug/kg DW at nearby Station SS-05). A high detection limit reported at Station SS-08 (2,400 ug/kg DW) impeded data interpretation in that area. Pesticides exceeded HAET at stations with relatively high PCB concentrations (e.g., Stations SS-04 and SS-09) and may have been overestimated because of GC/ECD interferences. 1,4-Dichlorobenzene concentrations exceeded the HAET at Stations SS-09 (31,000 ug/kg DW) and SS-03 (380 ug/kg DW), but high detection limits preclude detailed evaluation of its distribution in the problem area.

Benzyl alcohol (1,300 ug/kg DW) exceeded the HAET at Station SS-03 (near the King Street CSO), and was undetected at a relatively high detection limit (690 ug/kg DW) at the nearest station.

The Port of Seattle recently provided further characterization of the area by resampling sediments near Stations SS-08 and SS-09 (Aggerholm, D.A., 22 February 1988, personal communication). Analyses for three metals (cadmium, lead, and zinc) and a range of semivolatile organic compounds revealed that contamination in these slips is heterogeneous but highly elevated. PAH concentrations at resampled Station SS-08 and the lead concentrations at resampled Station SS-09 were over 200 times lower than were reported in the present study (but were still at or near the LAET range). Cadmium and zinc concentrations at resampled Station SS-09 were roughly an order of magnitude less than the original concentrations. However, the PAH concentrations at resampled Station SS-09 were similar to but higher than the high concentrations reported in the present study, and the lead concentration at resampled Station SS-08 was 4-5 times the original value. The PAH and lead concentrations at these resampled stations exceeded HAET. Also, PCP was detected at roughly 1,000 ug/kg DW at resampled Station SS-09. These results do not confirm the extreme concentrations originally reported at Stations SS-08 and SS-09. Nevertheless, they do support the characterization of this area as highly contaminated overall (especially by PAH), with localized patches of extreme contamination.

Problem Area NHI

Problem Area NHI, which encompasses two shipyard facilities at the mouth of the West Waterway, is characterized by very high concentrations of PAH, PCBs, and several metals (including copper, mercury, lead, zinc, and arsenic). Chemicals that exceeded HAET in at least one station in this area include LPAH, HPAH, PCBs, copper, lead, zinc, mercury, arsenic, p,p'-DDD, 2-methylphenol, 4-methylphenol, and 2,4-dimethylphenol (Table 40). Although high concentrations were found in this problem area during the present study, data from historical studies contributed significantly to the characterization of this problem area and included the maximum concentrations for most of the problem chemicals.

Stations adjacent to Todd Shipyard [including Station NH-03, Station 4 (U.S. EPA 1982, 1983), and Station 3 (Gamponia et al. 1986)] had the highest concentrations of several high priority chemicals in this problem area. At these three stations, concentrations of mercury ranged from 10.5 to 12 mg/kg DW, concentrations of copper ranged from 1,700 to 2,800 mg/kg DW, concentrations of PAH (as the combined sum of LPAH and HPAH) ranged from 59,000 to over 600,000 ug/kg DW, and concentrations of PCBs ranged from 3,300 to 14,000 ug/kg DW. Concentrations at a historical station seaward of Station NH-03 exceeded HAET values for copper and PAH. Contamination generally decreased moving east from Todd Shipyard, but HAET for PAH were exceeded as far east as Station NH-01. PCB contamination was high but patchy along this area, with a concentration of 7,500 ug/kg DW at Station 1 of Gamponia et al. (1986). The highest lead concentration on the east side of the West Waterway mouth was not adjacent to Todd Shipyard (roughly 1,000 mg/kg DW at EPA Station 37) (see U.S. EPA 1982, 1983). Arsenic concentrations were not highly elevated over most of the problem area, but a

TABLE 40. NORTH HARBOR ISLAND PROBLEM AREAS[a]

Area	Station	HAET Exceedances[b]											LAET Exceedances[c]
		LPAH	HPAH	PCBs	CU	PB	ZN	HG	AS	DDD	4MEPHNL	2MEPHNL/ 2,4MEPHNL	
NHI	NH-01												HPAH, PCBs
	NH-02												HPAH, PCBs, HG
	GAMP1[d]			X								X	HPAH, HG
	E36[e]	X	X										
	GAMP2[d]											X	AS, HPAH, CU, PB, HG, ZN, PCBs
	E37[e]	X	X			X							ZN
	GAMP3[d]	X	X	X	X		X	X				X	AS
	E4[e]	X	X	X	X		X						AS
	NH-03	X	X	X	X			X		X			AS, BUTBNZPH, PB, ZN [TOTXYL]
	E39[e]		X		X								LPAH, PCBs, ZN
	WW-19				X						X		ZN, HG, PCBs, HPAH
----------	E40[e]	X											HPAH, ZN
	GAMP4[d]			X									AS, HG, ZN
(West Waterway Mouth)	WW-20												HPAH, HG, PCBs
	GAMP5[d]											X	LPAH, HPAH, PCBs, HG
	E41[e]												HPAH
	GAMP6[d]			X								X	AS, HPAH, LPAH, PCBs, HG, ZN
----------	E42[e]			X	X	X	X		X				HPAH, LPAH
	NH-04	X	X		X							X	AS, PB, HG, ZN, 4MEPHNL, PCBs [PCP, PHNL]
NHII	NH-05	X											HPAH, HG, PCBs, ZN
	GAMP7[d]	X	X	X									HG
	E43[e]	X	X										ZN
	U120[f]	X											PCBs, ZN
	NH-06	X	X										HG, PCBs, ZN [CARBAZOLE, CD]
	NH-08	X	X										PCBs, ZN
	GAMP8[d]											X	LPAH, HPAH, PCBs
	E44[e]	X	X										ZN
	S00349		X	X									HG, LPAH
NH-10													PCBs [ALDRIN, DIELDRIN]

TABLE 40. (Continued)

[a] LPAH - Signifies AET exceedances for the sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene, or any of these compounds individually. To simplify the presentation of AET exceedances in this table, exceedances of AET for 1-methylphenanthrene, 2-methylnaphthalene, biphenyl, and dibenzofuran are included under LPAH. These compounds covaried with LPAH but are not included in LPAH sums.

HPAH - Signifies AET exceedances for the sum of fluoranthene, pyrene, benzo(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene, or of any of these compounds individually.

CU - copper
PB - lead
ZN - zinc
HG - mercury
CD - cadmium
AG - silver
AS - arsenic
PHNL - phenol
4MEPHNL - 4-methylphenol
2MEPHNL - 2-methylphenol
2,4MEPHNL - 2,4-dimethylphenol
BNZOH - benzyl alcohol
BNZACID - benzoic acid
1,4DICLBNZ - 1,4-dichlorobenzene
BUTBNZPH - butyl benzyl phthalate
DMP - dimethyl phthalate
TOC - total organic carbon
DINOCT - di-n-octyl phthalate
TOTXYLENE - total xylenes
CR - chromium
ENDALD - endrin aldehyde
PCP - pentachlorophenol

[b] Chemicals exceeding HAET for Puget Sound. More detailed information on exceedances is presented in Appendix F.

[c] Chemicals exceeding LAET for Puget Sound. More detailed information on exceedances is presented in Appendix F. Chemicals shown in brackets exceeded 90th-percentile concentrations but did not exceed any AET. Chemicals exceeding both AET and 90th-percentile concentrations are not bracketed.

[d] Gamponia et al. (1986).

[e] U.S. EPA (1982, 1983).

[f] Stober and Chew (1984).

[g] Romberg et al. (1984).

concentration of 560 mg/kg DW was observed at a historical station near Todd Shipyard.

Concentrations of most problem chemicals decreased markedly moving west across the mouth of the West Waterway. A historical station on the west side of the waterway near Lockheed Shipyard (EPA Station 42) (U.S. EPA 1982, 1983) had concentrations of a number of metals that far exceeded HAET, including copper (1,050 mg/kg DW), lead (2,180 mg/kg DW), zinc (4,810 mg/kg DW), and arsenic (1,420 mg/kg DW). Station NH-04, located adjacent to Lockheed Shipyard on the east side of the West Waterway mouth, had LPAH, HPAH, and copper concentrations that exceeded HAET. Notably, this station also had a pentachlorophenol concentration of 6,000 ug/kg DW, which was the highest detected concentration in this study. 4-Methylphenol and 2-methylphenol were also elevated at this station (1,000 ug/kg DW and 240 ug/kg DW).

The southern boundary of the problem area was extended to include Station WW-19, which is located within the West Waterway adjacent to Todd Shipyard. This station was included because it had a copper concentration that was anomalously high relative to other West Waterway stations in the area. The HAET for 4-methylphenol was also exceeded at this station.

Problem Area NHII

Problem Area NHII is predominated by PAH contamination, with less widespread contamination by PCBs and less severe contamination by mercury and zinc (Table 40). The most severe PAH contamination occurred near Stations NH-06 and NH-08, located near the Wyckoff creosote facility and the outflow of Longfellow Slough, respectively. Problem Areas NHI and NHII are contiguous, but are distinguished based upon differences in the nature of contamination (metals contamination is far more severe in Problem Area NHI) and based upon the nature of potential sources.

LPAH concentrations at Stations NH-06 and NH-08 were 57,000 and 37,000 ug/kg DW, respectively, and HPAH concentrations were 130,000 and 79,000 ug/kg DW (among the highest PAH concentrations observed in the present study). Station NH-06 had the highest concentrations of naphthalene, biphenyl, and carbazole in the present study, suggesting creosote as a possible source material (Nestler 1974). Data for historical stations in this area confirmed the high PAH concentrations (U.S. EPA 1982, 1983; Gamponia et al. 1986), although the concentrations reported by Gamponia et al. (1986) were somewhat lower than those reported by other studies at similar locations. PAH concentrations decreased with distance moving east and west from Stations NH-06 and NH-08 but nonetheless exceeded AET at Stations NH-05 and S0034 (Romberg et al. 1984). Notably, contamination was very similar at Stations NH-06 and NH-08 in terms of composition and absolute concentration (based upon consideration of PAH, alkylated PAH, biphenyl, dibenzofuran, and carbazole). The major difference between the two stations was a higher fluoranthene concentration at Station NH-06 (the concentration was higher by a factor of roughly 6). Neglecting fluoranthene, the precision between the concentrations of EPA priority pollutant PAH at these two stations ranged from 4 to 78 RPD (relative percent difference) with a mean RPD of 36 percent. As an indication of the high degree of similarity observed between Stations NH-06 and NH-08, these two samples

would easily pass the precision criterion for analytical replicates specified under the PSEP program.

PCB concentrations (ranging from 3,100 to 6,600 ug/kg DW) exceeded the HAET at two historical stations in the problem area. PCB concentrations in this problem area did not follow readily apparent gradients; however, it was apparent that PCB contamination did not covary with PAH contamination.

Zinc and mercury exceeded LAET at a number of stations in the problem area. Zinc distributions were consistent with PAH distributions (concentrations were nearly identical at Stations NH-06 and NH-08), whereas mercury was more elevated in the region near Stations NH-06 and NH-05 than in the region near Station NH-08. An isolated concentration of 1.2 mg/kg occurred at historical station S0034 (Romberg et al. 1984).

Problem Area WWI

This problem area encompasses several areas of isolated contamination by organic compounds (particularly PAH and PCBs; Table 41) and several stations with severe biological effects but only moderate measured contamination. Isolated but extreme PAH contamination was observed at Station WW-04, located adjacent to the 16th Avenue SW CSO/SD (104). This station was unique not only because of its high PAH concentrations (LPAH = 15,000 ug/kg DW and HPAH = 53,000 ug/kg DW) but also because of its anomalously low HPAH/LPAH ratio (an indication of petroleum-related source material). Concentrations at adjacent stations were over an order of magnitude lower than at Station WW-04 despite comparable grain size and TOC content at these stations. Relatively high PAH concentrations were also observed at Station WW-06 [adjacent to the SW Hinds CSO/SD (099)] and at stations north of this area.

A very high PCB concentration (24,000 ug/kg DW) was observed at historical Station 14 of Gamponia et al. (1986); this was the highest PCB concentration observed among all data reviewed for this study. PCB concentrations decreased sharply at stations on a cross-waterway gradient moving away from Station 14 (mid-waterway concentrations were roughly 1,000 ug/kg DW). Although the SW Hinds CSO/SD (099) is in the vicinity of Gamponia Station 14, the PCB concentration at a station closer to the outfall (Station WW-06, this study) was roughly 40 times lower.

This problem area also contained the highest concentration of benzyl alcohol in the study (8,800 ug/kg; intertidal Station WW-02), but the compound was undetected at detection limits below 200 ug/kg DW at nearby stations and no potential source was apparent. Station WW-08, separated from Station WW-02 by a number of stations without detected benzyl alcohol, had a benzyl alcohol concentration exceeding the HAET (140 ug/kg DW).

Problem Area WWII

Among the variety of chemicals exceeding HAET in this area (Table 41), lead contamination most clearly distinguishes this area from Problem Area WWI. The HAET for lead was exceeded along the east side of the waterway from Stations WW-11 to WW-14. Station WW-14, located adjacent to the SW Lander CSO/SD (105) and the SW Lander SD (21 inches), had an extremely high lead

TABLE 41. WEST WATERWAY PROBLEM AREAS[a]

Area	Station	HAET Exceedances[b]									LAET Exceedances[c]
		LPAH	HPAH	PCBs	CU	PB	DDT/DDD	2,4MEPHNL	BNZOH	DMP	
WWI	WW-01										PCBs
	WW-02								X		PCBs, ZN
	WW-03										
	WW-05										PCBs
	WW-04	X	X								PCBs
	WW-06	X								X	PCBs, PB, HG, ZN, BUTBNZPH, HPAH
	GAMP14[d]			X							HPAH, HG
	S0036[e]	X	X				X				PCBs, PB, HG
	WW-08								X		PCBs, HG, BUTBNZPH [4MEPHNL]
	GAMP12[d]							X			HPAH, LPAH, PCBs
WWII	WW-11					X					HPAH, LPAH, HG, PCBs, ZN [TOTXYLENE]
	WW-09	X	X			X	X			X	CU, HG, PCBs, ZN
	WW-12	X	X			X					AS, CU, HG, ZN, PCBs [CR]
	WW-10										HPAH, PB, HG, ZN, PCBs
	WW-13									X	LPAH, HPAH, HG
	GAMP9[d]	X		X	X	X		X			HPAH, AS, HG, ZN
	GAMP10[d]			X							HPAH, LPAH, HG, ZN
	GAMP11[d]	X									HPAH, PCBs, HG
	WW-14		X			X					PCBs, LPAH, HG, ZN [CD]
	WW-18		X								PB, HG, ZN, PCBs, DDD
	WW-16										LPAH, HPAH, PCBs, HG, ZN
	WW-15										[PHNL]
	WW-17		X								LPAH, PCBs, DMP, HG, ZN

[a] LPAH - Signifies AET exceedances for the sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene, or any of these compounds individually. To simplify the presentation of AET exceedances in this table, exceedances of AET for 1-methylphenanthrene, 2-methylnaphthalene, biphenyl, and dibenzofuran are included under LPAH. These compounds covaried with LPAH but are not included in LPAH sums.

HPAH - Signifies AET exceedances for the sum of fluoranthene, pyrene, benzo(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene, or of any of these compounds individually.

TABLE 41. (Continued)

CU - copper
PB - lead
ZN - zinc
HG - mercury
CD - cadmium
AG - silver
AS - arsenic
PHNL - phenol
4MEPHNL - 4-methylphenol
2MEPHNL - 2-methylphenol
2,4MEPHNL - 2,4-dimethylphenol
BNZOH - benzyl alcohol
BNZACID - benzoic acid
1,4DICLBNZ - 1,4-dichlorobenzene
BUTBNZPH - butyl benzyl phthalate
DMP - dimethyl phthalate
TOC - total organic carbon
DINOCT - di-n-octyl phthalate
TOTXYLENE - total xylenes
CR - chromium
ENDALD - endrin aldehyde
PCP - pentachlorophenol

[b] Chemicals exceeding HAET for Puget Sound. More detailed information on exceedances is presented in Appendix F.

[c] Chemicals exceeding LAET for Puget Sound. More detailed information on exceedances is presented in Appendix F. Chemicals shown in brackets exceeded 90th-percentile concentrations but did not exceed any AET. Chemicals exceeding both AET and 90th-percentile concentrations are not bracketed.

[d] Gamponia et al. (1986).

[e] Romberg et al. (1984).

concentration of 8,730 mg/kg DW. A nearby historical station had a similarly high concentration (10,600 mg/kg DW) (Gamponia et al. 1986), as well as copper and zinc concentrations near or above HAET values. Lead concentrations decreased moving down the east side of the waterway toward Station WW-11 (721 mg/kg DW). Outside of this area, however, concentrations appeared to decrease sharply in all directions. Stations located between WW-11 and WW-14 were predominantly fine-grained (>60 percent fine-grained material in all cases).

PAH contamination was more widespread than lead contamination and had a less evident relationship to potential sources. HPAH concentrations typically ranged from 20,000 to 40,000 ug/kg along the east side of the waterway and remained at a relatively high level in transects of historical stations across the waterway. Potential sources of PAH on the east side of the waterway include the ARCO and Lockheed facilities and the Lander Street discharges discussed previously. The SW Florida CSO/SD (098) near Station WW-17 on the west side of the waterway is a potential source of PAH for that area. Overall, however, PAH distributions are generally elevated in the problem area and do not strongly suggest specific localized sources.

Among the other contaminants exceeding HAET in this problem area, PCBs decreased from 3,700 to 2,300 going from east to west in a cross-waterway transect (Gamponia et al. 1986). However, concentrations at the same stations reported in another study were roughly 5 times lower (U.S. EPA 1982, 1983). Overall, PCB concentrations did not show any strong gradients, although a relatively high concentration was observed at Station WW-09 (1,500 ug/kg DW). Another problem chemical in this area, p,p'-DDD, occurred at 80 ug/kg at Station WW-09, but was undetected at nearby Stations WW-10 and WW-11 at detection limits below 20 ug/kg DW. Although AET were not applied to chromium for reasons discussed earlier, it is notable that the chromium concentration at Station WW-12 (555 mg/kg DW) exceeded the 90th percentile concentration for the study.

East Waterway (EW) Problem Area

The East Waterway problem area appeared to be dominated by contamination with diverse metals and organic chemicals at Station EW-05 and had other relatively isolated areas of local contamination (primarily by PAH). Station EW-05, located in the middle of the waterway near the discharge point of the Hanford CSO (W032), had concentrations exceeding HAET for PCBs, cadmium, mercury, butyl benzyl phthalate, p,p'-DDE, p,p'-DDT, and LPAH (represented by 1-methyl phenanthrene) (Table 42). Sediment at Station EW-05 was also enriched in organic matter (7.39 percent TOC content) and had "oil and grease" and water-soluble sulfide concentrations that were among the highest observed in the study. Station EW-06 was geographically isolated from Station EW-05 but had some similar patterns of chemical contamination (e.g., relatively high concentrations of PCBs, cadmium, and mercury).

Certain chemical evidence suggests that contamination apparently originating near Station EW-05 is dispersed throughout the waterway. Correlation analyses revealed a relatively large number of strong correlations among chemicals in this area (see RESULTS, Spatial Correlations Among Chemicals), suggesting that these contaminants could have derived from the same source and were subject to similar transport processes. For

TABLE 42. EAST WATERWAY PROBLEM AREA[a]

Station	HAET Exceedances[b]								LAET Exceedances[c]
	LPAH	HPAH	PCBs	HG	CD	DDT/DDE/DDD	BNZOH	BUTBNZPH	
EW-02	X								PCBs, HPAH, HG
EW-04		X							PCBs, LPAH, HG
EW-05	X		X	X	X	X		X	HPAH, PB, ZN [CHLORDANE, RETENE, AG, DINOCT]
EW-06	X	X							PCBs, BUTBNZPH, CD, HG, ZN
A062[d]						X			PCBs, CU, BUTBNZPH
C062[d]		X							PCBs, PB, ZN, DDD
EW-07								X	PCBs, HPAH, HG, ZN
EW-08								X	PCBs, HG
m10039[e]					X				PCBs, AS
S0039[d]						X			PCBs, BUTBNZPH, HPAH
EW-09								X	PCBs, HPAH, HG, ZN
EW-11								X	PCBs, LPAH, HPAH, HG, ZN [BUTBNZPH, DINOCT]
EW-10									PCBs, BUTBNZPH, HG [DINOCT]
EW-12							X		PCBs, HPAH
EW-13						X			PCBs, BUTBNZPH
EW-14	X	X							PCBs, BUTBNZPH, HG
S0064[d]		X							PCBs, HG
EW-15									BUTBNZPH, HPAH, HG, ZN [AS]
E1A[f]	X								HPAH
EW-16									BUTBNZPH

[a] LPAH - Signifies AET exceedances for the sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene, or any of these compounds individually. To simplify the presentation of AET exceedances in this table, exceedances of AET for 1-methylphenanthrene, 2-methylnaphthalene, biphenyl, and dibenzofuran are included under LPAH. These compounds covaried with LPAH but are not included in LPAH sums.

HPAH - Signifies AET exceedances for the sum of fluoranthene, pyrene, benzo(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene, or of any of these compounds individually.

CU - copper
PB - lead
ZN - zinc
HG - mercury
CD - cadmium
AG - silver
AS - arsenic
PHNL - phenol
4MEPHNL - 4-methylphenol
2MEPHNL - 2-methylphenol
2,4MEPHNL - 2,4-dimethylphenol
BNZOH - benzyl alcohol
BNZACID - benzoic acid
1,4DICLBNZ - 1,4-dichlorobenzene
BUTBNZPH - butyl benzyl phthalate
DMP - dimethyl phthalate
TOC - total organic carbon
DINOCT - di-n-octyl phthalate
TOTXYLENE - total xylenes
CR - chromium
ENDALD - endrin aldehyde
PCP - pentachlorophenol

[b] Chemicals exceeding HAET for Puget Sound. More detailed information on exceedances is presented in Appendix F.

[c] Chemicals exceeding LAET for Puget Sound. More detailed information on exceedances is presented in Appendix F. Chemicals shown in brackets exceeded 90th-percentile concentrations but did not exceed any AET. Chemicals exceeding both AET and 90th-percentile concentrations are not bracketed.

[d] Romberg et al. (1984).

[e] Malins et al. (1982).

[f] U.S. EPA (1982, 1983).

example, PCBs and cadmium correlated well in the waterway (as did PCBs and lead, and PCBs and silver), and may have dispersed from the area of their maximum concentrations (Station EW-05). Also, PCB contamination was relatively constant on an organic carbon normalized basis (see Figure 37), again suggesting a uniform source. The apparent decrease in TOC normalized PCB concentrations toward the mouth of the waterway (see Figure 37) suggests that the most contaminated particles are not reaching the mouth of the waterway or are being diluted considerably there. In addition, metals that were most concentrated at Station EW-05 (e.g., cadmium and mercury) correlated well with TOC content (e.g., $r>0.8$) and were likely transported with the organic material originating in that area. Notably, there metals correlated poorly with percent fine-grained material (e.g., $r<0.4$).

Pesticide contamination by p,p'-DDT and related compounds appeared to be localized in the area between TPPS Stations A062 and S0039. Relatively low detection limits were reported even within this area. Chlordane has no established AET but exceeded its 90th percentile concentration at Station EW-05. Interference from high PCB concentrations may have contributed to the high pesticide concentrations at this station.

Butyl benzyl phthalate concentrations exceeded the HAET in an area encompassing Stations EW-05 to EW-11. Station EW-05 is not strongly indicated as the source region for this compound, as concentrations were higher at Stations EW-07, EW-08, and EW-09.

Unlike most problem chemicals in the East Waterway problem area, PAH did not appear to originate in the area near Station EW-05. Instead, PAH were elevated at various relatively isolated regions throughout the study area, in some cases near storm drain (SD) or CSO discharges. An area-wide gradient in PAH concentrations was not apparent. Station EW-02, located near the SW Hinds CSO/SD (107), had an LPAH concentration (32,000 ug/kg DW) that exceeded the HAET. This station had a distinctly low ratio of HPAH/LPAH (<1; see Figure 33) indicative of a petroleum source. Station EW-04, on the west side of the waterway near the SW Hanford CSO/SD (162) and other storm drains, had a relatively high concentration of HPAH (34,000 ug/kg DW). Station EW-06 had HAET exceedances for both LPAH and HPAH. Station EW-14, near the mouth of the waterway, had very elevated concentrations of LPAH (13,000 ug/kg DW) and HPAH (69,000 ug/kg DW - the highest HPAH sum in the East Waterway). Stations EW-07 and EW-08 had high detection limits for LPAH (particularly naphthalene) that impeded data interpretation in that area.

Benzyl alcohol exceeded the HAET at Station EW-12 (870 ug/kg DW), which is located near the SW Florida SD. However, detection limits at comparable levels at nearby stations did not allow for further characterization.

Problem Area KGII

Distributions of problem chemicals (predominantly polar and nonpolar organic compounds) within this area were heterogeneous. The stations in this area were combined because they are relatively closely spaced together and because the transport of certain compounds throughout the area (PCBs in particular) cannot be discounted. Problem chemical distributions are summarized in Table 43. Three general areas of contamination were observed: Station KG-06, which had the most HAET exceedances of any station in the

TABLE 43. KELLOGG ISLAND PROBLEM AREAS[a]

Area	Station	HAET Exceedances[b]								LAET Exceedances[c]
		LPAH	HPAH	PCBS	DDT	PHNL	4MEPHNL	BNZACID	BUTBNZPH	
KGI	KG-01									ZN, HPAH, PCBs, BUTBNZPH, HG [CD, DINOCT]
	E12[d]	X	X							ZN, PCBs
KGII	KG-05									PB, HG, ZN, PCBs [CD]
	KG-06	X (2METHNAP)[e]		X	X				X	HG, ZN [RETENE, AS]
	KG-08									PCBs
	KG-09						X			PCBs
	S0037[f]				X					PCBs, HPAH
	U133[g]					X				PCBs, HG, ZN
	KG-10	X (2METHNAP)[e]						X		[RETENE]
	KG-11									PCBs [4MEPHNL]
KG-03										BUTBNZPH, PCBs, ZN

[a] LPAH - Signifies AET exceedances for the sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene, or any of these compounds individually. To simplify the presentation of AET exceedances in this table, exceedances of AET for 1-methylphenanthrene, 2-methylnaphthalene, biphenyl, and dibenzofuran are included under LPAH. These compounds covaried with LPAH but are not included in LPAH sums.

HPAH - Signifies AET exceedances for the sum of fluoranthene, pyrene, benzo(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene, or of any of these compounds individually.

CU - copper
PB - lead
ZN - zinc
HG - mercury
CD - cadmium
AG - silver
AS - arsenic
PHNL - phenol
4MEPHNL - 4-methylphenol
2MEPHNL - 2-methylphenol
2,4MEPHNL - 2,4-dimethylphenol
BNZOH - benzyl alcohol
BNZACID - benzoic acid
1,4DICLBNZ - 1,4-dichlorobenzene
BUTBNZPH - butyl benzyl phthalate
DMP - dimethyl phthalate
TOC - total organic carbon
DINOCT - di-n-octyl phthalate
TOTXYLENE - total xylenes
CR - chromium
ENDALD - endrin aldehyde
PCP - pentachlorophenol

[b] Chemicals exceeding HAET for Puget Sound. More detailed information on exceedances is presented in Appendix F.

[c] Chemicals exceeding LAET for Puget Sound. More detailed information on exceedances is presented in Appendix F. Chemicals shown in brackets exceeded 90th-percentile concentrations but did not exceed any AET. Chemicals exceeding both AET and 90th-percentile concentrations are not bracketed.

[d] U.S. EPA (1982, 1983).

[e] 2-Methyl naphthalene (2METHNAP) was the only PAH-related compound to exceed HAET at this station.

[f] Romberg et al. 1984).

[g] Stober and Chew (1984).

area; Station KG-05, which was characterized by LAET exceedances of a number of metals; and six stations between Stations KG-08 and KG-11, which were contaminated with a variety of oxygenated organic compounds including phenol, 4-methylphenol, and benzoic acid.

Station KG-06 had the highest PCB concentration in the problem area (3,100 ug/kg DW). Although no PCB concentration gradient was readily apparent, a number of historical stations in the problem area had concentrations between 500 and 800 ug/kg DW. The p,p'-DDT contamination at Station KG-06 (270 ug/kg DW) appeared relatively isolated, as the pesticide was undetected at most stations within the problem area at detection limits of less than 10 ug/kg DW. It is possible that GC/ECD interferences from PCB contamination at Station KG-06 resulted in an overestimation of p,p'-DDT. Butyl benzyl phthalate at Station KG-06 was over an order of magnitude higher than at any other station in the problem area; however, interpretation is impeded because several samples were blank-corrected down to detection limits. 2-Methylnaphthalene, at 1,900 ug/kg DW, was the only PAH that exceeded a HAET at Station KG-06; this concentration was more than double the sum of LPAH at Station KG-06. High detection limits for 2-methylnaphthalene (e.g., the extreme detection limit of 8,900 ug/kg at Station KG-05) and for LPAH in general impede interpretation of their distribution in the area around Stations KG-04, KG-05, KG-06, and KG-07.

Station KG-05, located adjacent to the Diagonal Way CSO/SD (111), had no HAET exceedances but had 90th percentile exceedances of cadmium (4.1 mg/kg DW) and lead (500 mg/kg DW). Mercury (1.63 mg/kg DW) exceeded the LAET at Station KG-05 and was over 5 times higher than at adjacent intertidal Station KG-04; both sediment samples (i.e., KG-04 and KG-05) were coarse-grained.

The northern portion of the problem area was characterized mostly by contamination by polar organic compounds, although different problem chemicals were observed at different problem stations. Station KG-09, located next to the SW Dakota SD, had a 4-methylphenol concentration exceeding the HAET (1,500 ug/kg DW). This compound was undetected at nearby stations but was detected above the 90th percentile concentration at Station KG-11 (610 ug/kg DW). Historical Station U133 (Stober and Chew 1984), located between Station KG-09 and intertidal Station KG-10, had a phenol concentration exceeding the HAET (2,200 ug/kg DW); phenol was detected at 400 ug/kg DW at Station KG-10.

Station KG-10 was unique in that it had the highest retene concentration in the study (10,000 ug/kg DW), the only detection of benzoic acid (6,300 ug/kg DW), and a very high organic carbon content (10 percent) despite a relatively coarse grain size distribution (17 percent fine-grained material). These attributes suggest that this sample may contain coal particles. Transport of coal particles in the lower Green-Duwamish River system has been suggested by Hamilton et al. (1984); the coal likely derives from exposed coal seams along the river (Barrick et al. 1984). Retene is a useful geochemical marker for sub-bituminous and lignite coal found in the Green River area (Barrick et al. 1984). Retene was reported at 1,700 ug/kg DW at Station KG-06, but was undetected or detected at low concentrations at stations between Station KG-10 and KG-06.

Problem Area NSII

This group of four stations in the vicinity of Piers 90 and 91 was characterized by a relatively small number of problem chemicals, largely consisting of PAH and other organic compounds (Table 44). However, contaminant composition at the four stations was not uniform. The most severe PAH contamination occurred at Station NS-07, which had a HPAH concentration of 40,000 ug/kg DW and an anomalously high HPAH/LPAH ratio (8.7, as compared to ratios typically less than 4 in this area). PAH [specifically 1-methylphenanthrene and indeno(1,2,3-cd)pyrene] also exceeded HAET at Station NS-08, although overall PAH concentrations were considerably lower than at Station NS-07 (e.g., HPAH = 12,000 ug/kg DW). Station NS-06 did not exceed AET for PAH; detection limits for LPAH were very high at this station (e.g., >1,000 ug/kg DW for most individual LPAH) but were acceptable for HPAH. Di-n-octyl phthalate exceeded its 90th percentile concentration at Station NS-06. Intertidal Station NS-04 had a 4-methylphenol concentration that exceeded the HAET (1,300 ug/kg DW), although detected concentrations and detection limits at nearby stations did not exceed 10 ug/kg DW. Pentachlorophenol, which has no established AET, was detected at 330 ug/kg DW at this station.

Problem Area NSI

Only one sample was collected in this area for the present study (intertidal Station NS-01). The problem area boundary is otherwise defined by historical TPPS stations. The sole problem chemical at Station NS-01 was silver (8.27 mg/kg DW), which also exceeded HAET at a number of historical stations (Table 44). Other chemicals exceeding HAET at historical TPPS stations were PAH, PCBs, several chlorinated pesticides, and mercury (Table 44). The area near Denny Way CSO has been characterized previously with these data (Romberg et al. 1984).

A recent study (Romberg et al. 1987) provides results for a more intensive sampling of sediments near the Denny Way CSO outfall. Although these data were not included in the present document, the data presented by Romberg et al. (1987) are generally consistent with the data used for problem area identification. However, silver was not measured by Romberg et al. (1987).

Upper Duwamish River Problem Areas

The upper Duwamish River (defined as Area DR in this study) did not demonstrate gradients for high priority contaminants that were clearly indicative of large-scale transport processes throughout the area; instead, heavy contamination appeared to be localized and, in some cases, in close proximity to potential sources. For this reason, seven separate problem areas containing one or two stations were identified; these areas were separated from one another by less contaminated stations. Most of the problem stations were located in relatively quiescent areas (i.e., three areas were within slips and one area consisted of an intertidal station). Problem chemicals occurring at the seven problem areas are summarized in Table 45. In most cases, the highest priority problem chemicals (i.e., those based on HAET exceedances) differ among problem areas in the upper Duwamish River area, even for the problem areas nearest one another.

TABLE 44. SEATTLE NORTH WATERFRONT PROBLEM AREAS[a]

Area	Station	HAET Exceedances[b]							LAET Exceedances[c]
		LPAH	HPAH	PCBs	HG	AG	DDT/DDE/DDD	4MEPHNL	
NSII	NS-04							X	
	NS-07		X						LPAH, PCBs, HG [PHNL]
	NS-06								[DINOCT]
	NS-08	X	X						BUTBNZPH
NSI	NS-01					X			
	S0031[d]	X	X			X	X		PCBs
	S0032[d]	X	X				X		PCBs
	1406[d]		X				X		PCBs, HG
	1603[d]	X	X	X			X		PB, HG, ZN
	1606[d]	X		X		X	X		HG, HPAH
	1706[d]						X		PCBs, HG, LPAH, HPAH
	1810[d]		X				X		PCBs, HG, LPAH
	1612[d]		X		X		X		PCBs, LPAH
	1512[d]		X				X		PCBs, HG
	1830[d]						X		PCBs, HG

[a] LPAH - Signifies AET exceedances for the sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene, or any of these compounds individually. To simplify the presentation of AET exceedances in this table, exceedances of AET for 1-methylphenanthrene, 2-methylnaphthalene, biphenyl, and dibenzofuran are included under LPAH. These compounds covaried with LPAH but are not included in LPAH sums.

HPAH - Signifies AET exceedances for the sum of fluoranthene, pyrene, benzo(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene, or of any of these compounds individually.

CU - copper
PB - lead
ZN - zinc
HG - mercury
CD - cadmium
AG - silver
AS - arsenic
PHNL - phenol
4MEPHNL - 4-methylphenol
2MEPHNL - 2-methylphenol
2,4MEPHNL - 2,4-dimethylphenol
BNZOH - benzyl alcohol
BNZACID - benzoic acid
1,4DICLBNZ - 1,4-dichlorobenzene
BUTBNZPH - butyl benzyl phthalate
DMP - dimethyl phthalate
TOC - total organic carbon
DINOCT - di-n-octyl phthalate
TOTXYLENE - total xylenes
CR - chromium
ENDALD - endrin aldehyde
PCP - pentachlorophenol

[b] Chemicals exceeding HAET for Puget Sound. More detailed information on exceedances is presented in Appendix F.

[c] Chemicals exceeding LAET for Puget Sound. More detailed information on exceedances is presented in Appendix F. Chemicals shown in brackets exceeded 90th-percentile concentrations but did not exceed any AET. Chemicals exceeding both AET and 90th-percentile concentrations are not bracketed.

[d] Romberg et al. (1984).

TABLE 45. UPPER DUWAMISH RIVER PROBLEM AREAS[a]

Area	Station	HAET Exceedances[b]							LAET Exceedances[c]
		LPAH	HPAH	PCBs	HG	DDT/DDE	2MEPHNL	DMP	
DR-25							X	X	4MEPHNL, BUTBNZPH, PHNL, ZN [DINOCT]
DR-05						X			PCBs
DRI	DR-08		X	X		X			BUTBNZPH, HG, DDD, ZN [CD, ENDALD]
	E19[d]	X		X					HPAH, ZN
DR-10						X			PCBs, DDD
DR-12									AS, CU, PB, ZN, PCBs, HPAH
DR-15									PCBs [DINOCT]
DR-16			X						LPAH, BUTBNZPH, PCBs, ZN [AS]

[a] LPAH - Signifies AET exceedances for the sum of naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, and anthracene, or any of these compounds individually. To simplify the presentation of AET exceedances in this table, exceedances of AET for 1-methylphenanthrene, 2-methylnaphthalene, biphenyl, and dibenzofuran are included under LPAH. These compounds covaried with LPAH but are not included in LPAH sums.

HPAH - Signifies AET exceedances for the sum of fluoranthene, pyrene, benzo(a)anthracene, chrysene, total benzofluoranthenes, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i)perylene, or of any of these compounds individually.

CU - copper
PB - lead
ZN - zinc
HG - mercury
CD - cadmium
AG - silver
AS - arsenic
PHNL - phenol
4MEPHNL - 4-methylphenol
2MEPHNL - 2-methylphenol
2,4MEPHNL - 2,4-dimethylphenol
BNZOH - benzyl alcohol
BNZACID - benzoic acid
1,4DICLBNZ - 1,4-dichlorobenzene
BUTBNZPH - butyl benzyl phthalate
DMP - dimethyl phthalate
TOC - total organic carbon
DINOCT - di-n-octyl phthalate
TOTXYLENE - total xylenes
CR - chromium
ENDALD - endrin aldehyde
PCP - pentachlorophenol

[b] Chemicals exceeding HAET for Puget Sound. More detailed information on exceedances is presented in Appendix F.

[c] Chemicals exceeding LAET for Puget Sound. More detailed information on exceedances is presented in Appendix F. Chemicals shown in brackets exceeded 90th-percentile concentrations but did not exceed any AET. Chemicals exceeding both AET and 90th-percentile concentrations are not bracketed.

[d] U.S. EPA (1982, 1983).

Problem Area DR-25--

Most problem chemicals at this intertidal station were polar organic compounds (phenols). 2-Methylphenol exceeded its HAET, and phenol and 4-methylphenol exceeded their LAET (concentrations for the former two compounds were the highest observed in the study). All three phenols were undetected at low detection limits (<6 ug/kg DW) at the nearest stations upriver and downriver from this station. Station DR-25 is located near the S. 96th Street SD.

Problem Area DR-05--

The only compound to exceed HAET at this station was p,p'-DDT (33 ug/kg DW). This compound was undetected at reasonable detection limits (less than 7 ug/kg DW) at stations downriver (intertidal Station DR-06 and Station DR-07). PCBs were reported at 570 ug/kg DW at this station. Station DR-05 is located adjacent to the 16th Avenue S. SD.

Problem Area DRI (Slip 4)--

A problem area was defined by Station DR-08 and historical EPA Station 19 (U.S. EPA 1982, 1983) based primarily on PCB contamination (5,600 to 5,800 ug/kg DW). PCB concentrations decreased toward the mouth of Slip 4 to 490 ug/kg DW and concentrations at the nearest stations within the river were lower. PAH were also problem chemicals in Slip 4 and appeared highest at the head and lowest at the mouth. Mercury and zinc followed similar patterns. In addition, p,p'-DDE was detected only at Station DR-08. A number of potential sources occur at the head of Slip 4 including the Georgetown Flume, the Slip 4 CSO/SD (117), the Slip 4 SD, the I-5 SD, and the East Marginal PS CSO.

Problem Area DR-10--

Station DR-10, located near the 2nd Avenue S. SD, had p,p'-DDT and p,p'-DDE concentrations exceeding HAET values (both pesticides occurred at roughly 65 ug/kg DW). A related pesticide, p,p'-DDD, exceeded the LAET at this station, as did PCBs (2,100 ug/kg DW). All three pesticides were undetected at detection limits of 10 or less at stations upriver and downriver from DR-10. PCBs were generally elevated in this area of the river (see Figure 35). It is notable that Station DR-10, which had the highest "oil and grease" concentration in the study, had low overall PAH concentrations (LPAH + HPAH = 4,500 ug/kg DW).

Problem Area DR-12--

Station DR-12, at the head of Slip 3, was defined as a problem area because three metals (arsenic, zinc, and copper) exceeded their 90th percentile concentrations at this station. Arsenic was detected at 449 mg/kg DW, zinc at 969 mg/kg DW, and copper at 386 mg/kg DW. Lower concentrations of all three metals were reported at a nearby historical EPA Station E15 (U.S. EPA 1982, 1983). The arsenic concentration, 449 mg/kg DW, was the second highest observed in the present study. Concentrations at the nearest stations in the river were at least several times lower than at

Station DR-12. LAET were exceeded for HPAH and PCBs at this station. There are no known discharges at the head of Slip 3.

Problem Area DR-15--

Station DR-15, located in Slip 2, was included as a problem area because of a 90th percentile exceedance for di-n-octyl phthalate (310 ug/kg DW; this is a blank corrected value). PCBs, which exceeded the LAET at this station, were reported at 230 ug/kg DW.

Problem Area DR-16--

Station DR-16, located near the SW Graham SD, exceeded the HAET for one HPAH compound [indeno(1,2,3-cd)pyrene]. LPAH and HPAH concentrations at this station were higher than concentrations at historical stations upriver and were roughly 4-7 times the concentrations at the nearest station downriver (DR-17).

Problem Area KGI (Slip 1)

High priority problem chemicals in this area were LPAH and HPAH, although several metals were also elevated (see Table 43). The two adjacent samples that established this problem area were not in complete agreement in terms of contaminant concentrations: historical EPA Station 12 (U.S. EPA 1982, 1983) was heavily contaminated with LPAH (42,000 ug/kg DW) and HPAH (94,000 ug/kg DW), whereas concentrations at nearby Station KG-01 were considerably lower (LPAH = 2,400 ug/kg DW; HPAH = 15,000 ug/kg DW). PAH concentrations at Station KG-01 were consistent with concentrations observed at the mouth of the slip. Station KG-01 and EPA Station 12 had comparable concentrations of zinc and cadmium, both of which exceeded their 90th percentile concentrations at Station KG-01 and decreased sharply toward the mouth of the slip. A potential source is not readily apparent in this area.

Problem Area KG-03

Station KG-03 was included among the Tier II problem areas because of exceedance of action level guidelines for biological variables. Contamination at this station was not extreme, although several chemicals exceeded LAET [PCBs (300 ug/kg DW), zinc (275 mg/kg DW), and butyl benzyl phthalate (66 ug/kg DW)]. Because of the lack of a clear association of the contamination at this station with contamination in the other KG problem areas, and because there is a lack of available data for the area between KG-03 and Problem Area KGII, this station has not been combined with Problem Area KGII.

Problem Area AB-01

This problem area is defined by a single station (AB-01) with anomalously high concentrations of mercury and PAH (particularly LPAH) that exceeded HAET. In addition, copper and zinc concentrations exceeded LAET at this station. The mercury concentration at this station, 28.8 mg/kg DW, was the highest observed at any station in the study area (including historical stations). Mercury concentrations at the nearest stations (including intertidal Station NH-10) were over 100 times lower. PAH concentrations were also lower at nearby stations, but the decreases were not as sharp as

those for mercury (LPAH decreased from 10,000 ug/kg at Station AB-01 to 3,400 at Station AB-02). Station AB-01 is located near the discharge point of the Fairmount Avenue SW CSO (078).

Problem Area NH-10

This intertidal station was classified among the Tier II problem areas because of 90th percentile exceedances of two chlorinated pesticides (aldrin, at 90 ug/kg DW, and dieldrin, at 51 ug/kg DW). These pesticides do not have established AET values. The LAET for PCBs was also slightly exceeded at this station (160 ug/kg DW). Station NH-10 was not combined in the problem area for nearby subtidal Station AB-01 because the two stations differed considerably with regard to chemical contamination (e.g., the concentrations of the predominant problem chemicals at Station AB-01 were one to two orders of magnitude lower at Station NH-10).

SUMMARY

Identification of Problem Areas

- The nearshore region of the Elliott Bay system inside a line from Pier 91 to Duwamish Head displayed significant elevations of both sediment contaminants and liver lesions in English sole. This entire area was designated as a Tier I problem area.

- Seventy-two stations were designated as higher priority problem areas (Tier II). Sixty-one of these stations were grouped into the following multi-station problem areas: DRI (Slip 4), EW (East Waterway), KGI and KGII (near Kellogg Island), NHI and NHII (North Harbor Island, the mouth of the West Waterway, and west to just beyond Longfellow Slough outlet), NSI (Denny Way CSO), NSII (Pier 90/91), SS (Seattle South waterfront), WWI (southern segment of West Waterway), and WWII (northern segment of West Waterway).

Ranking of Problem Areas

- Ranking of Tier II problem areas and stations identified five areas (SS, NHI, NHII, WWI, and WWII) and 29 single stations as the highest priority sites. Of the latter, the following stations were outside the five highest priority areas: Stations NS-01, EW-05, AB-01, KG-01, KG-05, KG-06, DR-12, DR-15, and DR-16.

Characterization of Problem Areas

- Problem Area SS--This area is highly contaminated overall (especially by PAH), with localized patches of extreme contamination. Stations SS-08 and SS-09 in this area account for the highest concentrations of several metals (e.g., lead, cadmium, zinc) and organic compounds (e.g., PAH, 1,4-dichlorobenzene) observed in this study; maximum concentrations of other metals occurred at other stations in this problem area

(e.g., arsenic at Station SS-03). Sediments in this area were enriched in organic matter, with TOC concentrations typically greater than 5 percent and as high as 27 percent. Benthic infaunal depressions were found at Stations SS-04, SS-09, and SS-08, with greater than 80 percent depressions of Pelecypoda at the first two sites ($P<0.001$). Significant sediment toxicity to amphipods was found at Station SS-06, where mortality was 45 percent ($P<0.001$). Overall, the SS area did not exhibit the widespread biological effects that might be expected based on consideration of the chemistry data.

- **Problem Area NHI**--Problem Area NHI, which encompasses two shipyard facilities at the mouth of the West Waterway, was heavily contaminated with several metals (most notably copper, but also mercury, lead, zinc, and arsenic), PAH, and PCBs. The most elevated assemblages of organic compounds and metals were observed near Station NH-03 and two historical stations located east of that station. On the west side of the West Waterway mouth, Station NH-04 contained high concentrations of copper, PCP, and PAH, among other chemicals. Problem Area NHI exhibited severe depressions in the abundances of major taxa of benthic infauna (especially Pelecypoda) at all stations. Abundances of all four major taxa evaluated were severely depressed at Station NH-03. Significant amphipod mortality above 85 percent was found at Stations NH-03 and NH-04.

- **Problem Area NHII**--PAH and related compounds (including alkylated PAH, carbazole, and biphenyl) were the predominant contaminants in Problem Area NHII. The most extreme contamination was observed at Stations NH-06 and NH-08, located near the Wyckoff facility and the outflow of Longfellow Slough, respectively. These two stations were very similar in terms of PAH composition and concentration. The high concentrations of carbazole (particularly at Station NH-06) and PAH in this area are consistent with a creosote source. Benthic infaunal effects in Problem Area NHII were less than in most other problem areas, although Station NH-08 exhibited severe depressions of pelecypods and crustaceans. Overall sediment toxicity was highest in this area, with Station NH-08 displaying 100 percent mortality.

- **Problem Area WWI**--Chemical contamination was severe but patchy in this area, and included a relatively isolated but high historical concentration of PCBs in the southwest corner of the waterway, a high benzyl alcohol concentration at Station WW-02, and a high concentration of PAH at Station WW-04. Effects on benthic infauna were moderate overall for this area. However, Station WW-03 was one of two stations in this study where severe (>80 percent) depressions in abundances of all four major taxa were observed. Sediment toxicity in area WWI was generally low, except at Station WW-02, where 82 percent mortality was observed.

- **Problem Area WWII**--The most distinctive chemical feature of this area was extreme lead contamination along the east side of the West Waterway (near the SW Lander Street discharges). PAH concentrations were generally elevated, but gradients or pronounced maxima were not apparent. PCB contamination was moderate and patchy in this area. Severe effects on benthic infauna were restricted to depressions in the abundances of pelecypods and crustaceans at several stations within this area. Sediment toxicity was relatively low in this area overall. Nevertheless, mean amphipod mortality above 40 percent was observed at Stations WW-09 and WW-11.

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