♻️EPA

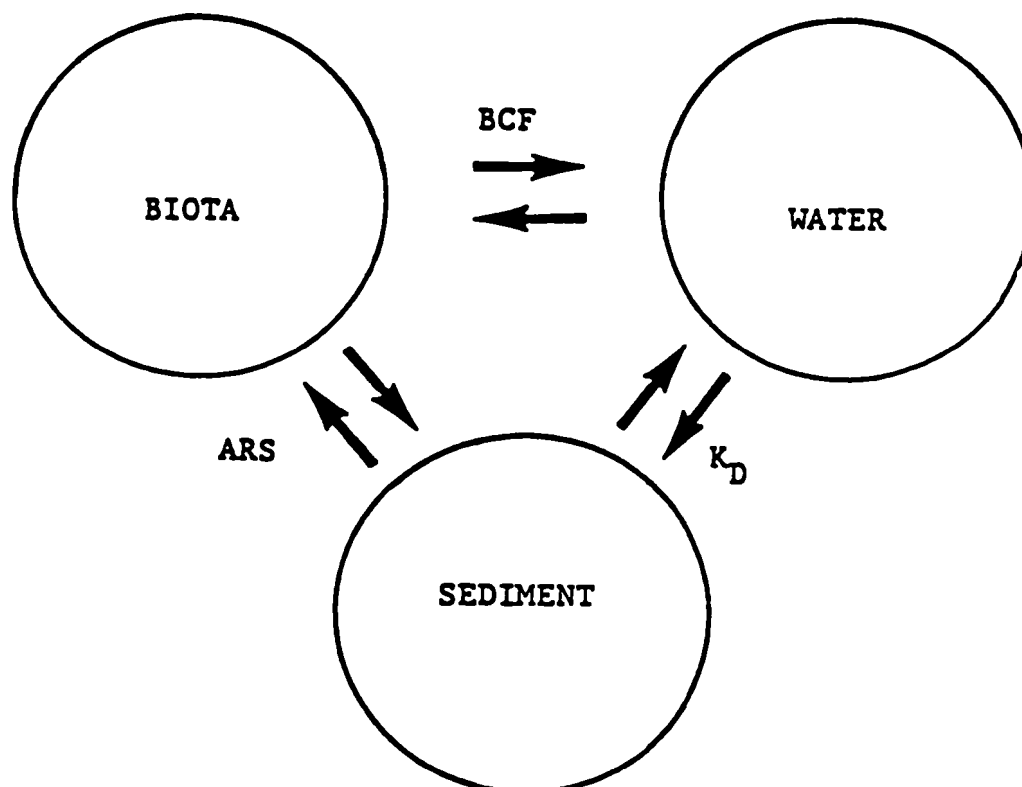# INITIAL EVALUATION OF ALTERNATIVES FOR DEVELOPMENT OF SEDIMENT RELATED CRITERIA FOR TOXIC CONTAMINANTS IN MARINE WATERS (PUGET SOUND)

PHASE I: DEVELOPMENT OF CONCEPTUAL FRAMEWORK

PHASE II. DEVELOPMENT AND TESTING OF THE SEDIMENT-WATER EQUILIBRIUM PARTITIONING APPROACH, 1984

INITIAL EVALUATION OF ALTERNATIVES FOR
DEVELOPMENT OF SEDIMENT RELATED
CRITERIA FOR TOXIC CONTAMINANTS IN
MARINE WATERS (PUGET SOUND)

PHASE I: DEVELOPMENT OF CONCEPTUAL
           FRAMEWORK

FINAL REPORT

October 28, 1983

by:

S.P. Pavlou and D.P. Weston
JRB Associates*
13400-B Northup Way, Suite 38
Bellevue, Washington 98005

PHASE I: DEVELOPMENT OF CONCEPTUAL FRAMEWORK

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 RATIONALE AND OBJECTIVES

The Environmental Protection Agency has focused historically on the development of water quality criteria which are supported by a broad base of toxicological studies. Implementation and enforcement of these criteria provides some degree of assurance that contaminant concentrations will be within acceptable limits for the protection of aquatic life and human health. However, there is disturbing evidence of environmental degradation in many of the heavily urbanized of Puget Sound even though water quality criteria are not exceeded. The majority of adverse biological impacts recently observed are not among organisms living in the water column but those that live in or on the sediments. Macrobenthic communities in the vicinity of point source discharges have demonstrated significant changes in species composition and abundance (Armstrong, et al., 1978; Malins et al., 1982; Comiskey et al., 1983), sediments from urbanized areas have been shown to induce mortality in sensitive benthic species (Swartz et al., 1982) and demersal fishes from heavily polluted areas have been shown to have a higher incidence of histopathological abnormalities than those from reference areas (Malins et al., 1980; 1982). These observations raise some questions as to whether existing water quality criteria alone are adequate to protect the environmental resources of Puget Sound.

It is becoming increasingly evident that some sort of sediment criteria are needed to supplement existing water quality criteria in judging the significance of contaminant concentrations and to provide a basis for remedial action. There are a number of reasons why sediment criteria deserve consideration:

- Most toxic compounds are highly insoluble so the majority of the contaminant is not dissolved in the water but is associated with the organic matrix on sediment particles. For example, sediments in Elliott Bay contain 60,000 times more PCBs than overlying water (Pavlou and Dexter, 1979).

- Sediments serve to integrate contaminant concentrations over time, eliminating the high degree of temporal variability which plagues sampling of toxicants in the water column.

- Sediments serve as a sink for most toxic materials, thus a long-term low level discharge of a contaminant may result in a dangerous build up in the sediment even though water quality criteria are not violated at any given time.

- **Sediments can serve as a reservoir (source) of contaminants which could be reintroduced to unpolluted overlying water.**

- A large number of organisms, including many of commercial importance, spend most of their lives in or on the sediments. For these species, contaminant levels in the sediments may be of greater concern than those in the overlying water and may be the controlling factor with regards to bioaccumulation potential.

The goal of this project is to evaluate selected approaches to developing sediment criteria for Puget Sound. Emphasis will be placed on establishment of methodologies and techniques though tentative criteria may be proposed for selected approaches if the data base is adequate. This report details the results of Phase I, Development of Conceptual Framework. Included are a brief discussion of past efforts to establish sediment criteria, an evaluation of numerous approaches and a discussion of application scenarios. Also presented as an appendix is the results from interviews with a number of investigators and representatives of local agencies currently involved in projects addressing sediment quality in Puget Sound.

1.2 PREVIOUS WORK IN SEDIMENT CRITERIA DEVELOPMENT

Much of the impetus for earlier work in sediment criteria development has come from the need to evaluate the toxicity of dredge spoils in determining the most prudent disposal alternative. Since the late 1950s, several attempts have been made to determine the level of pollutants in sediment which constitute an ecological threat. These previous attempts to establish "safe" levels of contamination have all been adopted to varying degrees though none have met with broad acceptance. A brief summary of these approaches follows with the recommended guidelines presented in Tables 1 and 2.

Table 1

FWPCA CHICAGO GUIDELINES FOR THE DEGREE OF
POLLUTION OF HARBOR SEDIMENTS (AUGUST, 1968)*

	Extent of Pollution		
Parameter	Light	Moderate	Heavy
Ammonia N	0-25	25-75	over 75
COD	0-40,000	40,000-120,000	over 120,000
Total Iron	0-8,000	8,000-13,000	over 13,000
Lead	0-40	40-60	over 60
Oil & Grease	0-1,000	1,000-2,000	over 2,000
Phenol	0-0.26	0.26-0.60	over 0.60
Total Phosphorus	0-100	100-300	over 300
Sulphide	0-20	20-60	over 60
Zinc	0-90	90-200	over 200
Volatile Solids (%)	0-5	5-8	over 8

*Units are in mg/kg dry weight

Table 2

PREVIOUSLY ESTABLISHED SEDIMENT QUALITY GUIDELINES

	Jensen Criteria, EPA, 1971 (mg/kg)	EPA Region V[a] Guidelines for Pollutional Classification of Sediments (mg/kg)	USCS Sediment Alert Levels (mg/kg)	Ontario Ministry of the Environment Dredge Spoil Guidelines (mg/kg)	EPA Region VI Proposed Guidelines for Sediment Disposal (mg/kg)	EPA Region VI Sediment Quality Indicators Interstitial or Elutriate Water (µg/l)
Antimony					500	
Arsenic		3	200	8	5	440
Barium		20	2,000			
Beryllium			200			
Cadmium		6	20	1	2	1.05ln(H) -8.53
Chromium III						1.08ln(H) +3.48
IV						0.29
total		25	200	25	100	
Copper		25	2,000	25	50	5.6
Iron		17,000		10,000		
Lead	50	40	500	50	50	2.35ln(H) -9.48
Manganese		300				
Mercury	1	1	20	0.3	1	0.00057
Nickel		20	2,000	75	50	0.76ln(H) +1.06
Selenium			20			35 (inorganic)
Silver			1,000			1.72ln(H) -6.52
Zinc	50	.90	5,000	100	75	47
Aldrin			0.02			3.0
Chlordane			0.02			0.0043
2,4-D			0.02			
2,4,5-TP			0.02			
DDT			0.02			0.0010
Dieldrin			0.02			0.0019
Dioxin						-0-
Endosulfan						0.056
Endrin			0.02			0.0023
Heptachlor			0.02			0.0053
Heptachlor Epoxide			0.02			0.005
Lindane			0.02			
Malathion			0.02			
Methoxychlor			0.02			
Mirex			0.02			
Parathion			0.02			
Toxaphene			0.02			0.013
PCB		1-10[b]	0.02	0.05		0.014
Phenol	0.26					1.0
Nitrate as N						10,000
Ammonia		75		100		
Phosphorus		420		1,000		25 (lakes)
NO2 + NO3						10,000
NO3 as N						1,000
Cyanide		0.1	100	0.1		3.5
Volatile Solids	60,000	50,000		60,000		
COD	50,000	40,000		50,000		
Kjeldahl Nitrogen	1,000	1,000		2,000		
Oil & Grease	1,500	1,000		1,500		

[a] Levels shown were regarded as the cut-off value between non-polluted and moderately polluted sediments.

[b] Sediments with PCB concentrations between 1 and 10 were considered on a case by case basis. Sediments with greater than 10 ppm PCB were considered grossly polluted.

In 1968 the Chicago office of the Federal Water Pollution Control Administration (FWPCA) released guidelines to be used in establishing the degree of pollution in harbor sediments. The ranking was somewhat arbitrary but was primarily based on correlations between sediment pollutant burden and the benthic community. Sediments were considered heavily polluted in areas where benthic organisms were absent or sharply reduced in number. A predominance of pollution tolerant species was considered indicative of moderate pollution. Sediments were considered lightly polluted in areas in which benthic organisms showed little or no evidence of pollution-induced alteration.

The Cleveland office of the FWPCA performed a similar assessment in 1969 which, together with the Chicago FWPCA guidelines, eventually became the Jensen criteria which were adopted by EPA in 1971. EPA promulgated these criteria for national use in determining the suitability of open water spoils disposal. When one or more parameters exceeded criteria, the sediments were considered unacceptable for open water disposal.

In 1977 EPA Region V released interim guidelines for the classification of polluted sediments in harbors of the Great Lakes. Recognizing that the guidelines were somewhat arbitrary and that a strong scientific basis for criteria were lacking, Region V recommended use of the guidelines only as a tool in making a subjective judgement as to suitability of dredge material for open water disposal. Additional factors such as elutriate test results, source of contamination, particle size distribution, benthic populations, sediment color and odor were also considered. Only in the case of mercury and PCB were violations of guidelines considered irrefutable evidence of severe pollution, thus making sediments unsuitable for open water disposal.

The U. S. Geological Survey employs a system of alert levels for in-house usage in evaluating the extent of sediment pollution. These alert levels were arbitrarily established to flag 15 to 20 percent of the samples analyzed nationwide. Since much of the information available at the time of alert

level establishment was from heavily polluted areas, alert levels established in this manner are artificially inflated (B. Malo, USGS, personal communication). Use of USGS alert levels have been limited to a flagging mechanism to identify potential sites of concern. They were never intended, nor have they been used, as rigid criteria for management decisions.

The Ontario Ministry of the Environment released a document in January, 1976 entitled "Evaluating Construction Activities Impacting on Water Resources" which was amended in 1978. These documents provided guidelines for the evaluation of the suitability of dredge spoil for open water disposal which were based on the Jensen criteria of EPA but modified to reflect data from Canadian harbors on the Great Lakes. For example, guidelines for mercury were made stricter than those originally employed by EPA because of correlations observed between sediment mercury concentrations and tissue burdens of mercury in fish which exceeded guidelines for human consumption. The sediment pollution guidelines proposed by the Ontario Ministry of the Environment have been used subjectively in evaluating dredge spoils but flexibility was allowed in assessing the potential danger of dredge disposal operations.

EPA Region VI has proposed two alternative guidelines for evaluating the degree of pollution in sediments. The region has released guidelines for assessing the extent of metal contamination in dredge material intended for open water disposal. However, of greater significance is a recent attempt by the region to establish sediment criteria for metals, organics and other pollutants of concern based on a modification of existing EPA water quality criteria. The apprdach employed made the assumption that interstitial waters are an extension of the overlying water column and in need of the same level of protection. Existing EPA water quality criteria for the 24 hour average concentration for the protection of freshwater aquatic life were directly applied as sediment quality indicators for both interstitial and elutriate water. In the absence of 24 hour average criteria the maximum permissible concentration in water were used. The sediment quali·y indicators derived in this manner were suggested for use as a screeening tool rather than for use in

regulatory or enforcement actions. They are unique among previous attempts to establish sediment criteria in that they depend upon analysis of interstitial and elutriate water rather than bulk sediments and that they draw upon the broad toxicological data incorporated by existing water quality criteria.

Criteria for PCB concentrations in the sediments of Puget Sound have previously been proposed by Pavlou, et al. (1977). These authors recommended that the total PCB concentration in sediments not exceed 0.5 mg/kg dry weight, and that the individual components not exceed 0.025 mg/kg dry weight. These limits were those necessary to maintain ambient water quality within acceptable standards, based on an estimated sediment-water partition coefficient.

The only sediment criteria currently approved for national usage by EPA is a bioassay to provide an assessment of the toxicity of dredged material intended for ocean dumping (U.S. EPA/COE, 1977). To meet requirements of Section 103 of Public Law 92-532 (Marine Protection, Research and Sanctuaries Act of 1972), any proposed dumping of dredged material into ocean waters must either meet several exclusionary criteria or be evaluated by a solid phase bioassay. Organisms to be employed in the bioassay must include one filter-feeder, one deposit-feeder and one burrowing species. Any statistically significant increase in mortality relative to controls is considered potentially undesirable.

in those sediments corresponding to pre-industrial depositional periods can then be established as the true background concentrations for the region prior to anthropogenic enrichment. Attempts to establish background levels by this method for Puget Sound have already been made (Riley, et al., 1981; Pavlou et al., 1983) and some previously established background levels are presented in Table 3.

An alternative means to establish concentrations representative of unpolluted sediments is to determine the concentration of pollutants in surficial sediments from areas distant from all known pollution point sources. This method has an important advantage over background concentrations derived from deep cores. Since synthetic organics are virtually absent from pre-industrial sediments, except for small amounts incorporated from more recent sediments by bioturbation, background concentrations of synthetic organics established by deep coring' would be essentially zero which may be an unrealistically restrictive criteria.

Establishment of background concentrations should take into consideration the fact that the concentration of most pollutants in the sediments is strongly dependent upon the organic carbon content of that sediment or covariates such as percent fines or total volatile solids. This consideration could be addressed by establishing several criteria for a given pollutant, each of which would be applicable within a specified range of organic carbon content. However, it may be more appropriate to derive a regression equation in which the criteria is a function of the organic carbon content. This approach is directly comparable to EPA water quality criteria for metals in freshwater for which the criteria is a function of water hardness.

Given the above considerations the optimal approach to establishment of sediment criteria on the basis of background concentrations is as follows:

1. Determine the concentration of the pollutant in surficial sediments from relatively pristine areas, ensuring that a wide range of sediment textures are included.

Table 3

PRE-INDUSTRIAL (PRIOR TO 1900) CONCENTRATION
OF TRACE ORGANICS IN PUGET SOUND SEDIMENTS[a]

Compounds	Concentration[b]
Pb	6.0
Hg	0.04
Ag	0.04
Cu	25
As	6.0
Zn	80
PCBs	13
Phthalates	378
CPNAs	337
PNAs	175
DDTs	-0-

[a]Values given are mean of five measure-
ments made at depths greater than 150
cm in sediment cores from Elliott Bay,
Brown's Point, and Meadow Point (from
Pavlou, et al., 1983).

[b]Metal concentrations expressed in µg/g
dry weight, organic concentrations
expressed in ng/g dry weight.

2. Develop a regression equation for the relationship between organic carbon content (or a covariate) and pollutant burden.

3. Determine the extent of departure from this regression line, based on the variability of the data, which would indicate contributions from a local discharge and constitute a criteria violation.

Unlike all other approaches considered in this report, this approach is unique in that it is not necesary to assess the toxicity of a pollutant since any increase in concentration above background is considered undesirable. However, for many compounds this may be unnecessarily restrictive, for the environment may be capable of assimilating additional inputs above background levels with no adverse effects. The optimal approach may eventually involve use of information on toxicity of specific compounds to establish the permissable degree of enrichment above background for these compounds.

Enough data is presently available on levels of pollutants in relatively.clean areas of Puget Sound to establish tentative background levels though additional sampling may be necessary before final criteria can be adopted. It is important to note that criteria established on the basis of background concentrations would probably be valid for only site specific usage since natural variability in background concentrations can be substantial due to geochemical differences.

2.3 ESTABLISHMENT OF CRITERIA BASED ON EPA WATER QUALITY CRITERIA

The attempt by EPA Region VI to develop Sediment Quality Indicators was discussed in Section 1.2. The approach used was simply to employ EPA water quality criteria, without adjustment, to interstitial and elutriate waters. An advantage of this approach, and all others based on EPA water quality criteria, is that they are able to make use of the large toxicological data base incorporated in the establishment of the water quality criteria. These criteria incorporate the results of a great number of bioassays in which a variety of water column organisms were exposed to dissolved pollutants. If

bioassays with water column organisms are equally valid for infaunal biota, then the Region VI approach eliminates the need for a costly and time-consuming redevelopment of a new sediment-oriented toxicological data base.

The applicability of water quality criteria to benthic organisms is a question that will require extensive verification prior to general acceptance. The EPA Region VI approach neglects the potential for direct biota-sediment pollutant transfer without the mediation of interstitial water. The importance of direct biota-sediment transfer processes cannot be adequately evaluated on the basis of existing information, but its potential contribution may be substantial. For example, ingestion of sediment and an associated toxicant by a deposit-feeding organism may result in a greater biological uptake of toxicant than would occur simply by exposure to the comparatively low concentrations of the toxicant in interstitial water.

A second difficulty of the EPA Region VI approach lies in the sampling and analytical difficulties encountered in attempting to quantify pollutant concentration in interstitial water. The concentrations of most pollutants in interstitial water are so low that it is difficult to obtain a sufficient volume of interstitial water to permit accurate quantitation of pollutant levels. The very act of extracting interstitial water from the bulk sediment can substantially alter the chemical content of the water so obtained.

2.4 ESTABLISHMENT OF CRITERIA ON THE BASIS OF EQUILIBRIUM PARTITIONING

2.4.1 Basic Definitions

The concept of equilibrium partitioning has been used extensively in past studies to predict the accumulation of contaminants in the aquatic environment (Pavlou, 1980; Pavlou and Dexter, 1979; Dexter and Pavlou, 1978; Pavlou and Dexter, 1977; Clayton et al., 1977; Neuhold and Ruggerio, 1977; Chiou et al., 1977; Issacs, 1975; Metcalf et al., 1975; Neely et al., 1974; Hamelink, 1971; Grzenda et al., 1970; Gakstatter and Weiss, 1967; Ferguson et al., 1966).

The pathways of contaminant transport among sediment, biota, and water at the sediment water interface can be conceptualized as shown in Figure 1. This mechanism assumes that the system is at equilibrium and that the instantaneous concentration of a conservative contaminant in any one of the three components can be expressed as a function of its concentration in either of the other two and an appropriate constant. These constants have been used extensively to determine accumulation in both abiotic and biotic components. In the former case, they are commonly referred to as partition or sorption coefficients while in the latter case they are being referred to as bioconcentration factors. These quasi-equilibrium constants are defined below:

Sediment-Water Partition Coefficient (K_D):

$$K_D = \frac{\text{Concentration in Sediment}}{\text{Concentration in Interstitial/Interfacial Water}}$$

Bioconcentration Factor (BCF):

$$BCF = \frac{\text{Concentration in Biota}}{\text{Concentration in Water}}$$

Accumulation Relative to Sediment (ARS):

$$ARS = \frac{\text{Concentration in Biota}}{\text{Concentration in Sediment}}$$

Sediment-Water Partition Coefficient (K_D) - These constants can be derived theoretically (Pavlou, 1980) or empirically in both laboratory and field studies. Empirical K_ds have been derived for a number of contaminants measured in Puget Sound based on data obtained in a recent study (Pavlou et al., 1983). The contaminants were 13 trace metals and three classes of organic compounds (PNAs, CPNAs and PCBs). Since there were no interfacial water analyses conducted during this study, sediment/water K_Ds were approximated by calculating the ratio of the contaminant concentration on SPM to the concentration in water at a site in the Central Basin of Puget Sound.
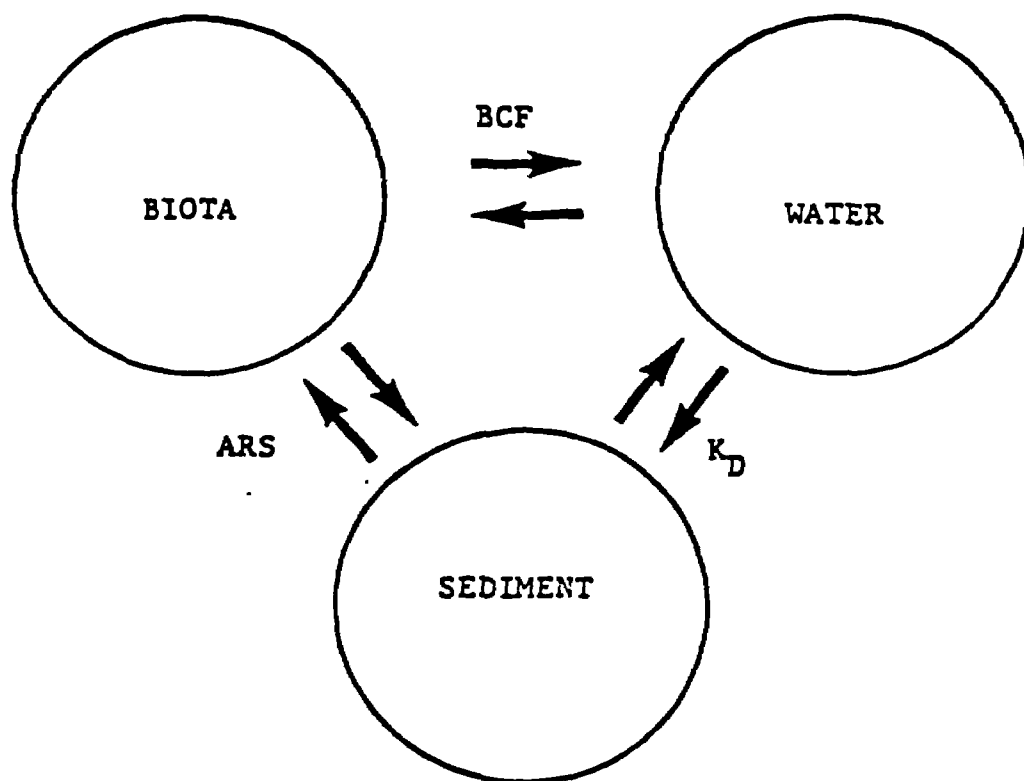
Figure 1

CONCEPTUAL REPRESENTATION OF CONTAMINANT PATHWAYS
AT THE SEDIMENT/WATER INTERFACE

Another independent estimate of K_D for the organic compounds listed above was obtained based on the octanol-water partition coefficient K_{OW}. The relationship between K_D and K_{OW} was established from the regression depicted in Figure 2 as obtained from literature data. K_D values from the literature were expressed on a sediment organic carbon basis. The K_D values for the compounds measured in Puget Sound were then calculated from values of K_{OW}. Table 4 compares the field determined K_D values with those obtained from the K_{OW} relationship. The agreement is good considering the associated uncertainties in both quantities.

Bioconcentration Factor (BCF) - These constants have been determined for many compounds by both field and laboratory studies and are available in the scientific literature. For these chemicals for which BCF values are unavailable, they may be estimated on the basis of K_{OW} (Veith et al., 1980; Gossett et al., 1982). The relationship between these factors was established for 36 compounds reported in Puget Sound for which literature values for both BCF and K_{OW} were available (Figure 3). The regression equation was then used to determine BCF for additional organic compounds for which K_{OW} was known.

Accumulation Relative to Sediments (ARS) - Although the ARS quantity does not reveal the bioaccumulation mechanism, it provides a tool for estimating the potential accumulation in biota from the apparent contaminant burden in the sediment. Typical ARS values are presented in Table 5 for various synthetic organic compounds measured in Puget Sound. It can be seen that the chlorinated hydrocarbons show distinctly higher ratios than the polynuclear aromatics, reflecting the low reactivity of the chlorinated organics vs. the higher reactivity (higher biotransformation potential) demonstrated by the polyaromatic compounds.

If a large data base of biota and sediment concentrations is available, then these constants may provide a gross indicator of bioaccumulation patterns specific to classes of compounds.
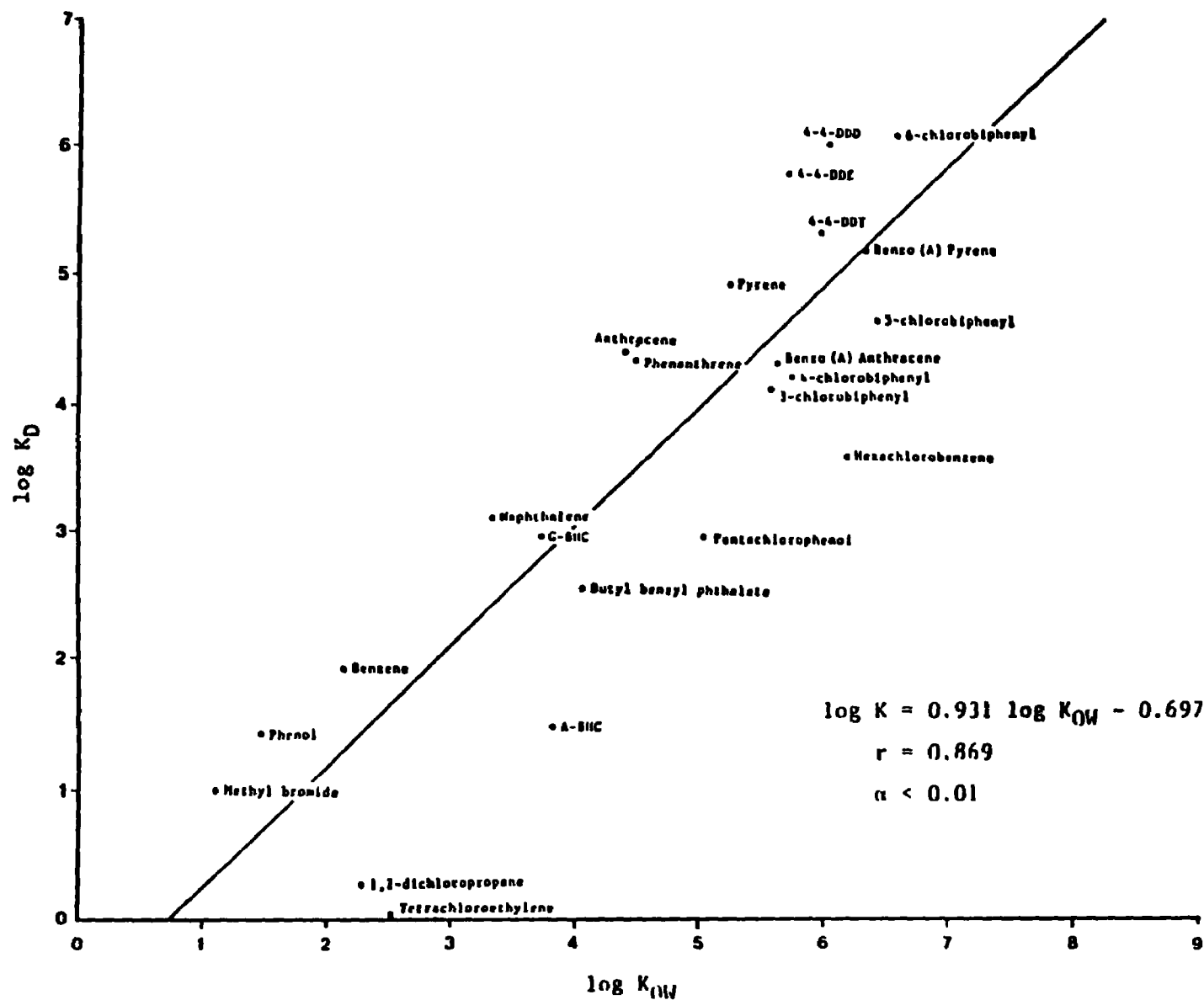
Figure 2

REGRESSION PLOTS OF SEDIMENT SORPTION COEFFICIENT WITH OCTANOL-WATER PARTITION COEFFICIENT

(values taken from Dexter, 1976; Dexter, 1979; Kenaga & Goring, 1980;
Veith et al., 1980; and Versar, Inc., 1979)

Table 4

COMPARISON OF FIELD DETERMINED K_Ds WITH VALUES OBTAINED FROM THE K_D vs. K_{OW} RELATIONSHIP

| | K_D x 10^4 | |
Contaminant	Field (mean $\pm$ sd)	From K_{OW} Regression* (mean $\overset{x}{\div}$ sd)
PNAs	0.8 $\pm$ 2	0.2 $\overset{x}{\div}$ 22
CPNAs	4 $\pm$ 7	20 $\overset{x}{\div}$ 15
PCBs	4 $\pm$ 7	9 $\overset{x}{\div}$ 11
As	2 $\pm$ 0.6	
Be	0.5 $\pm$ 0.3	
Cu	20	
Pb	90	
Hg	300	
Zn	20	

*Standard deviations (sd) are expressed as $\overset{x}{\div}$ rather than $\pm$ since they are antilogs computed from the original log-log regression in Figure 2.
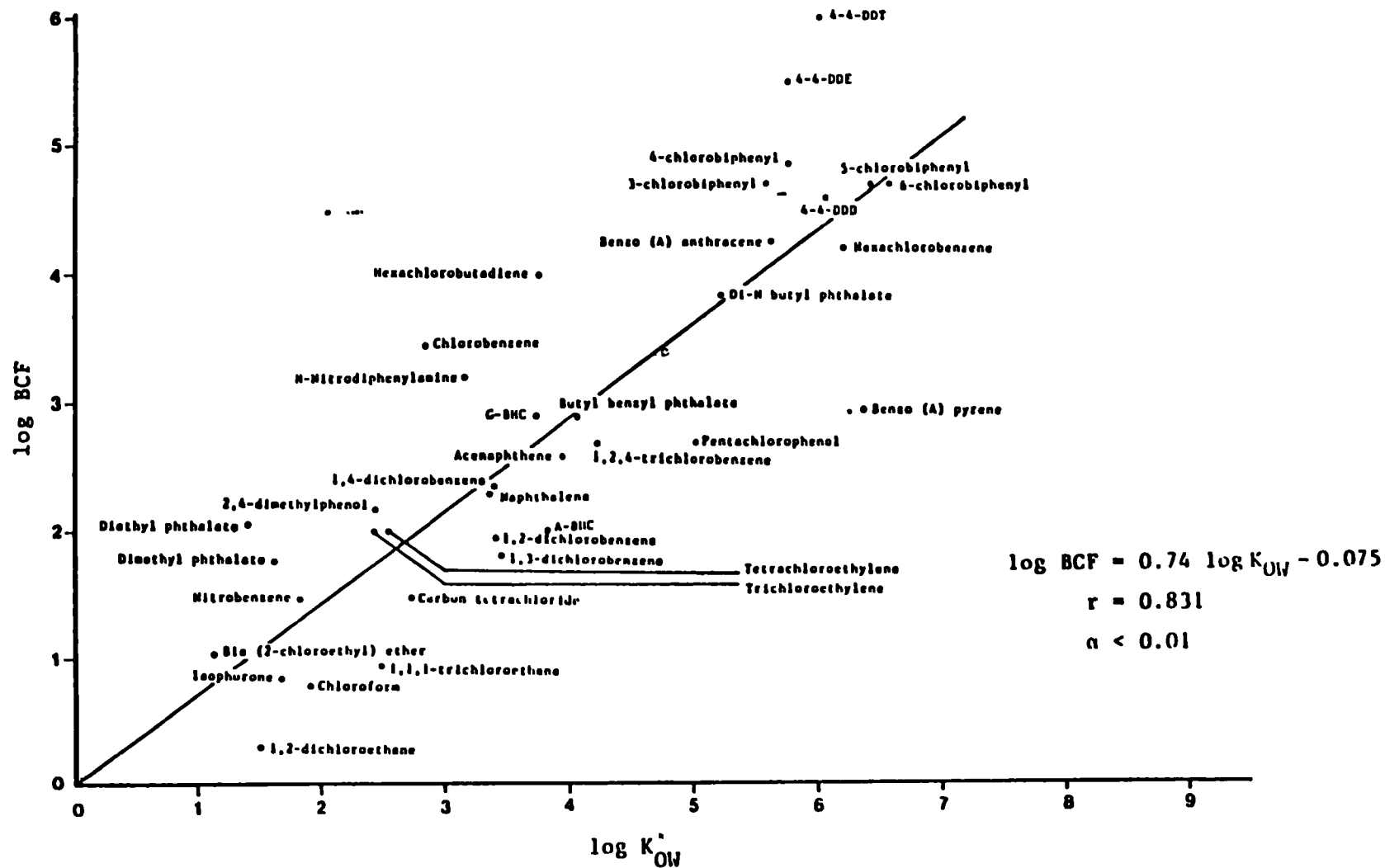
Figure 3

REGRESSION PLOTS OF BIOCONCENTRATION FACTORS WITH
OCTANOL-WATER PARTITION COEFFICIENTS

(values taken from Dexter, 1976; Kenaga &
Goring, 1980; Veith et al., 1980; Versar,
Inc., 1979)

Table 5

ACCUMULATION OF SELECTED TRACE ORGANIC COMPOUNDS IN BENTHIC BIOTA OF PUGET SOUND RELATIVE TO SEDIMENTS[a]

Compound	ARS[b]				
	Worm	Shrimp	Clam	Crab (Hepatop)	Fish Liver
ARENES					
1-2 Ring AHs	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.7 ± 0.6	0.3 ± 0.4
3-5 Ring AHs	0.32 ± 0.22	0.13 ± 0.07	0.36 ± 0.18	0.05 ± 0.01	0.05 ± 0.06
Phenanthrene	<0.7	<0.3	<0.3	0.15 ± 0.1	<0.1
Benz(a)anthracene	0.9 ± 0.6	0.14 ± 0.06	<0.54	<0.06	<0.27
Benz(a)pyrene	0.6 ± 0.5	<0.2	<0.4	0.02 ± 0.01	<0.6
CHLORINATED HYDROCARBONS					
Chlorinated Pesticides	1.7 ± 1.1	1.7 ± 1.4	2.7 ± 2.9	61 ± 32	34 ± 23
Chlorinated Butadienes	1.3 ± 1.7	(3)[c]	(0.22)[c]	(0.2)[c]	1.3 ± 1.7
Polychlorinated Biphenyls	11 ± 12	15 ± 20	5.4 ± 5.4	77 ± 33	111 ± 163
Hexachlorobenzene	17 ± 19	8.1 ± 5.6	4.0 ± 1.0	74 ± 68	93 ± 55

[a]Based on data from Malins et al., 1980.

[b]Accumulation Relative to Sediment (ARS), is defined as the ratio of the concentration of a specific chemical in an organism (or specified tissue) to its ambient concentration in the sediments.

[c]Values in parentheses are from analyses of only one or two samples.

JRB Associates

19

2.4.2 Application of Partitioning Constants to the Development of. Sediment Criteria

Four approaches were considered in establishing sediment criteria based on sediment/water/biota interfacial constants (Figure 4). All of these approaches rely heavily on existing water quality criteria for priority contaminants and the availability of biota threshold values above which a toxic effect may occur.

Approach #1, uses K_D and the existing EPA water quality criteria (applied to interfacial water) to compute a sediment threshold concentration. This calculated value is then compared to the actual measured contaminant concentration in the ambient sediment of a designated site to estimate the extent of violation. Conversely, using the ambient sediment burden and K_D the interfacial water concentration can be computed and compared directly to the apropriate EPA water criteria value.

Approach #2, is based on the application of water quality criteria to interfacial waters and the use of the BCF to compute a biota burden. The sediment threshold value can then be calculated by using the ARS constant. Indirectly, the computed biota burden may be compared to an existing body burden level known to induce a toxic effect.

Approach #3, uses the ARS quantity with either a measured body burden which induces a toxic effect (e.g., pathologic, behavioral or metabolic effect) or a federally established tissue concentration (if public health risks are the prime consideration) to compute a sediment threshold level.

Approach #4, is a combination of the above. It establishes a biological threshold concentration and determines a corresponding sediment threshold value via contaminant transfer through the aqueous phase.
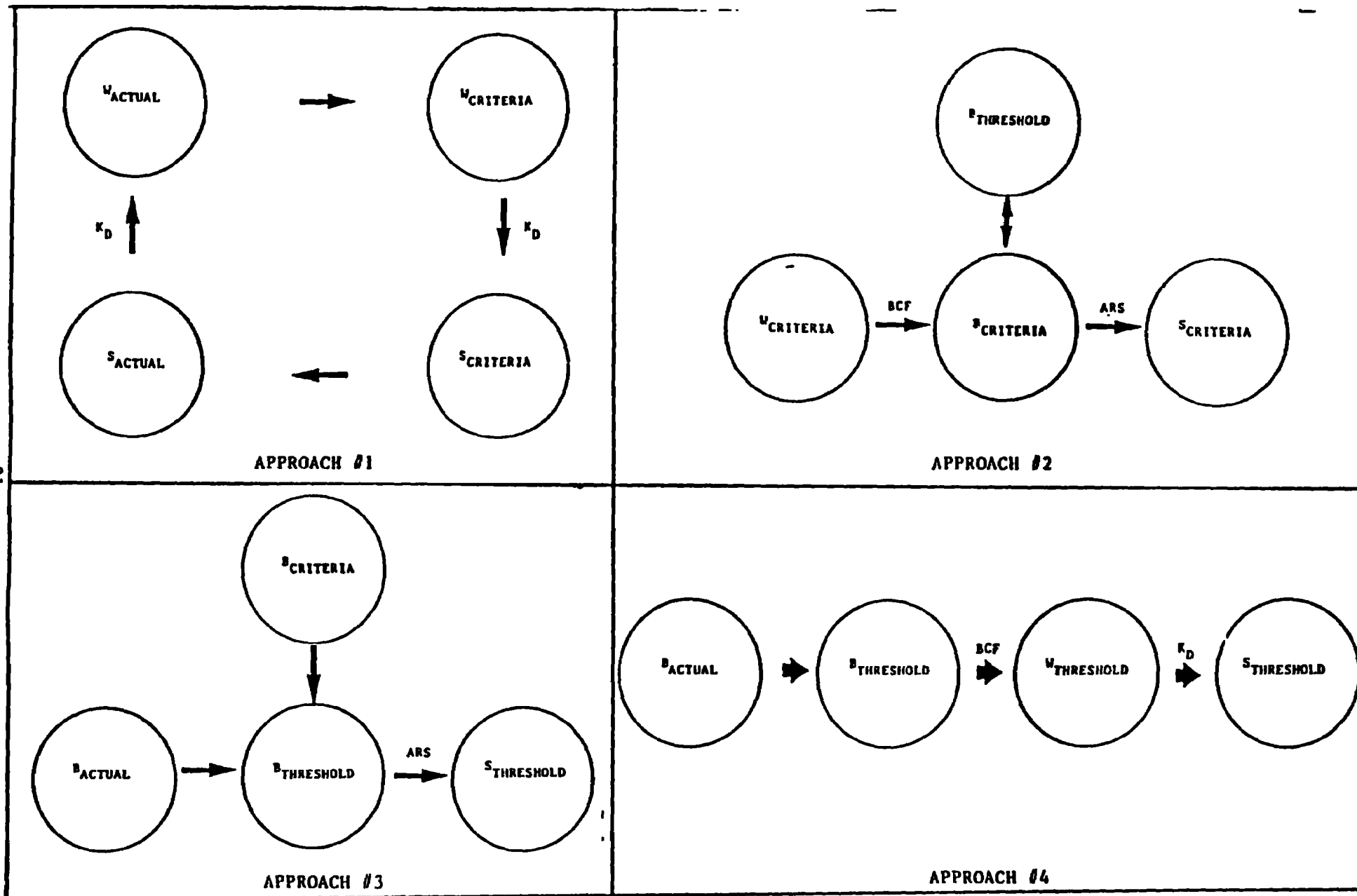
Figure 4

SCHEMATIC REPRESENTATION OF SEDIMENT CRITERIA DEVELOPMENT USING
EQUILIBRIUM PARTITIONING CONSTANTS

The advantage of using partitioning constants to establish sediment criteria is that (1) the approach makes use of the toxicological data base that allowed for the formulation of the EPA water quality criteria and (2) the approach can be implemented immediately to establish a first-order approximation criteria using existing data and some nominal field verification. However, this approach is also limited by a number of factors: (1) the field derived $K_{D}s$ which are based on SPM/water partitioning may not be applicable to sediment/interstitial water partitioning because of the different chemical conditions of the sediments; (2) as discussed in Section 2.3, sediment criteria established on the basis of EPA water quality values (K_D approach) do not address direct sediment-biota contaminant transfer; (3) since Approaches #2 and #4 involve the use of multiple partitioning constants, they have a greater potential for error propagation; and (4) the ARS constant does not address the bioaccumulation mechanism.

2.5 ESTABLISHMENT OF CRITERIA ON THE BASIS OF BIOLOGICAL RESPONSE

2.5.1 Bioassays

Bioassays have been employed nationwide and particularly in the northwest region, to evaluate the toxicity of dredged material and sediments of polluted harbors (Swartz et al., 1979; 1982; Chapman et al., 1982; Pierson et al., 1983). Though significant methodological differences among investigators remain unresolved (i.e., selection of test organism, preparation of sediment sample), the approach adopted by EPA/COE for evaluation of dredge spoils involves laboratory exposure of test organisms to bulk sediment for a ten day period after which the number of dead organisms are counted (U.S. EPA/COE, 1977). Survival in the test sediments relative to that in control sediments is taken as the biological response criterion. If sediment criteria for Puget Sound are to be based on a biological response (percent mortality) rather than a chemical burden (concentration) basis, then the sediment bioassay is of immediate utility provided methodological questions can be adequately resolved.

A limitation of evaluating sediment toxicity of chemically-uncharacterized sediment by current bioassay techniques is that the chemical agent or agents responsible for observed mortalities remain unidentified. Therefore, while bioassays are valuable in assessing toxicity of sediments, their regulatory use is limited by the fact that they provide no guidance for the establishment of appropriate control measures. Bioassays, as presently employed, serve as a pass/fail test without identifying the corrective measures required.

Researchers at the EPA-NERC laboratories in Newport, Oregon are currently developing a technique to identify the pollutant or pollutants responsible for observed mortality in sediment bioassays (Swartz, personal communication). The technique involves eight steps:

1. Determine toxicity of a polluted sediment by standard amphipod sediment bioassay

2. Chemically analyze sediment to identify pollutants present and their respective concentrations

3. On the basis of the magnitude of concentrations, bioaccumulation potential, and toxicological information in the literature, rank pollutants according to potential for inducing amphipod mortality

4. Identify the highest ranking compounds and spike the original sediment sample with these compounds

5. Reevaluate toxicity of sediment by same bioassay procedure

6. If toxicity of sediment has not increased, select alternative compounds and repeat procedure

7. If toxicity of sediment has increased, continue spiking sediment at successively higher levels to obtain dose-response relationship

8. Spike clean sediments with same compounds to evaluate toxicity at comparatively low levels of contamination

Spiking of sediment with several contaminants simultaneously provides a mechanism to address synergism. Synergism or antagonism can modify the toxicity of a mixture of pollutants such that the toxicity of the mixture

cannot be predicted simply by knowing the toxicity of each of the components. Given our current state of knowledge, there is no means to predict, on a chemical basis alone, the toxicity of sediment containing a multitude of pollutants, and bioassays remain the only means to account for synergistic effects.

Sediment bioassays can potentially be used to develop sediment quality criteria precisely in the same manner that aqueous bioassays were used to develop existing water quality criteria. The simplest approach to develop sediment criteria in this manner is to spike clean sediment with known concentrations of a pollutant and derive a dose/response relationship. Such an approach has been pursued to evaluate the toxicity of cadmium (Swartz, personal communication) but for the most part, data of this kind are lacking. Development of criteria in this manner would not address synergistic effects but this may be a necessary simplification in the establishment of first-cut criteria.

2.5.2 Biological Field Surveys

Several previous attempts by other investigators to establish sediment quality guidelines (Section 1.2) made use of biological field surveys to establish threshold levels of pollution. The general approach was to correlate sediment pollutant burden in a wide variety of habitats with some measure of benthic community health (e.g. diversity, abundance, species richness) and attempt to establish a threshold value for each chemical below which no biological effects were observed. A similar approach is currently being pursued by NOAA/NMFS by attempting to relate incidence of histopathological abnormalities in fish with levels of contaminants in the sediments of Puget Sound (Malins et al., 1982; McCain, personal communication).

The greatest difficulty encountered in attempting to establish criteria by this approach is in determining the contaminant(s) responsible for an observed impact on the biological community. If only one chemical was substantially

enriched above background levels then an observed biological response could be attributed to that chemical and a threshold value established. However, in most areas a diverse suite of contaminants are simultaneously enriched and it is impossible to identify the causative agents responsible for observed biological impacts. Multivariate techniques have been applied in an attempt to identify contaminants responsible for biological effects (Malins et al., 1982) but the relationships observed by these techniques are correlative rather than causative.

Biological field surveys can also be applied in sediment criteria development by establishing some measure of biological health as a criterion, in much the same way that a certain mortality is considered a criterion in bioassays of dredged material. Criteria can be based upon diversity indices, species evenness, species richness, presence or absence of indicator species, productivity, or some measure of similarity to a reference site. Sediment quality would be considered to be in violation of criteria if indigenous communities demonstrated some level of alteration beyond a threshold value. Benthic organisms are the most appropriate indicator organisms for use in this manner because of their immobility and the high sensitivity of some groups to a wide variety of pollutants.

The use of benthic organisms as indicators of sediment quality has already been incorporated in the 301(h) section of the Federal Water Pollution Control Act. Sediment quality criteria based on an indicator of benthic community health could potentially be used to evaluate the toxicity of dredge spoil or monitor environmental quality in the vicinity of point source discharges. There are two major limitations in use of sediment criteria based on field surveys of benthic communities. First, natural spatial and temporal variability of benthic communities often confounds efforts to ascribe an observed change directly to a pollution impact. Secondly, unacceptable environmental degradation is only detectable after the fact and the success of control or clean-up measures can only be evaluated after adequate time (a few months to several years) is provided to permit the benthic community to reflect a change in environmental quality.

2.6 ENVIRONMENTAL DEGRADATION ASSESSMENT

Three approaches useful in identifying contaminated areas in need of remedial action deserve special mention because of their potential application to sediment criteria development. These approaches are:

- A multidisciplinary approach under development by NOAA (Long, 1983)
- A sediment-oriented ecological risk index (Håkanson, 1980)
- A quality degradation factor under development by JRB

2.6.1 NOAA Approach

In recent years NOAA has been developing an approach to assessing toxicant levels in Puget Sound and identifying sites most urgently in need of clean-up activities (Chapman and Long, 1983; Long, 1983; Long, personal communication). The approach currently involves a three-tiered assessment of the extent of environmental degradation. First, chemical analyses of surficial sediments in the area are performed to establish the type and degree of contamination relative to reference areas. Secondly, bioassays are performed using both impacted and reference sediments to determine if the observed levels of contamination are sufficient to induce an adverse biological response through direct exposure. Finally, a field survey of the benthic communities is performed to establish if the contamination has induced a demonstrable charge in the resident biota.

The approach proposed by NOAA can be considered to be a conglomerate of the individual approaches discussed in Sections 2.2, 2.5.1, and 2.5.2. As a sediment criterion, this approach is too costly and labor-intensive for general use. However, since examination of sediment pollutant burden, bioassay toxicity, and benthic community structure would provide a good measure of the extent of environmental degradation, the approach may be useful for field verification of any tentative criteria established.

JRB Associates

26

2.6.2 Ecological Risk Index

The ecological risk index of Håkanson (1980), and the Quality Degradation Factors which follow in Section 2.6.3, are both indexing methods to assess the relative extent of environmental degradation. It is important to note that as they currently stand, both these techniques are ranking tools rather than enforceable criteria. While they do provide an indication of which sites show the most severe environmental alterations, they do not establish a criteria or threshold value above which remedial measures are required. The key advantage of indexing methods is their ability to synthesize a diverse body of technical information into a non-technical tool to identify sites and contaminants of concern. They are included in this report as a basis for criteria development with the expectation that further refinement of the techniques may eventually provide a tool for environmental policy decisions and a basis for initiating remedial action.

Håkanson (1980) developed an ecological risk index to evaluate the extent of contamination in several Swedish lakes and obtain some estimate of the potential for adverse biological effects. On the basis of sediment contaminant burden the index considered:

- The enrichment of each pollutant relative to pre-industrial levels
- The total enrichment of all pollutants considered
- The relative toxicity of the pollutants present
- The sensitivity of the receiving water body to the pollutants present

All the above factors were considered by inclusion in an equation which yielded an ecological risk index (RI). Specific detailes are presented in Appendix B. RI values less than 150 indicated a low ecological risk for the area, while RI values above 600 indicated a very high ecological risk. The index includes a number of features which make it attractive for use in Puget Sound, though some modifications would be required to include additional pollutants of concern and adopt the index for marine rather than freshwater environments.

$$QDF = (1 - \text{Bray/Curtis similarity relative to control}) \times 100$$

or

$$QDF = \left(1 - \frac{\text{no. of species present at site}}{\text{no. of species present at control}}\right) \times 100$$

The QDF quantities can be expressed in terms of a multiplicative or cumulative contribution of various physical, chemical, biological, or toxicological parameters including contaminant concentrations in sediments, biota and interstitial water, bioassay lethality indicators (e.g., percent mortality), pathologic parameters (percent diseased organisms) and taxonomic indicators of community stress. An overall QDF can be determined as well as QDFs for each of the individual components. Component QDFs can be assigned a weighting factor if degradation of one factor is of more concern than another. The precise equations and weighting factors are still under development but the general approach is illustrated in the sample calculation of Appendix C.

2.6.3 Quality Degradation Factors

JRB is currently developing an index of overall environmental quality based on the expression:

$$QDF = \frac{\text{ACTUAL} - \text{CONTROL}}{\text{MAXIMUM} - \text{CONTROL}}$$

where QDF is the relative quality degradation index applicable to a given site. ACTUAL is the actual value of the parameter determined at the site in question, CONTROL is the same parameter measured at a control or reference site, and MAXIMUM represents the maximum effect (or worst case scenario). The value of QDF may vary between 0 and 100 with the latter indicating maximum degradation.

Obtaining QDF values with regard to contaminants in sediments, interstitial water or biota is straightforward. Background concentrations can be obtained either from an unpolluted control area or, in the case of sediment contaminants, from deeply buried sediments sampled by a coring device (Pavlou, et al., 1983). The maximum concentration would be the highest recorded level of contamination in the sediments, interstitial water or biota of Puget Sound.

QDF factors can also be determined for the bioassay and pathology parameters by considering the percent mortality or percent diseased organisms, respec-.tively, relative to a control and a maximum possible value (100%). If the controls induced no mortality in the bioassays or showed no evidence of histopathological disorders then QDF would reduce to percent mortality or the percent of organisms with histopathological abnormalities.

For the benthic community indicators, the QDF could be defined by possible indices of community health such as:

3.0 APPLICATION SCENARIOS

There are five major environmental quality related regulatory decisions affecting Puget Sound to which sediment criteria are directly applicable:

- The issuance of CWA Section 301 (h) waivers

- The issuance of CWA Section 404 dredge and fill permits

- The designation or redesignation of dredged material disposal sites

- The selection of remedial alternatives at three of the ten designated Superfund sites in the State of Washington (The Nearshore/Tideflats and South Tacoma Channel sites in Commencement Bay and the Harbor Island site in Elliott Bay)

- Issuance of NPDES permits

For the reasons presented in Section 1.0, sediment criteria are considered to be a more effective means of preventing contaminant build up as well as ecological degradation of the marine environment than what can be achieved with the currently available water quality criteria. As part of this study it was therefore deemed appropriate to examine the applicability of sediment criteria to these major regulatory decisions. This section of the report presents a number of possible scenarios where the approaches discussed earlier could be used, under the major regulatory decisions presented above, to facilitate the development of a management action plan involving either remedial action or the formulation of control/enforcement/compliance protocols.

3.1 ISSUANCE OF CWA SECTION 301(h) WAIVERS

Under Section 301(h) conditions upon which modification of the secondary treatment requirement in the NPDES permits may be allowed, include three items to which the establishment of sediment criteria could be directly applicable and beneficial: (1) applicable water quality standards must be in place; (2) no interference with a water quality that assures protection of public water supplies; protection and propagation of a balanced indigenous population of shellfish, fish and wildlife; and that allows recreational activities and (3) an established system for monitoring the impact on representative biota.

Recent studies completed in the central basin of Puget Sound (Pavlou et al., 1983) have revealed that existing water quality criteria levels for toxicants are not exceeded in the water column even within the immediate vicinity of point source discharges including STPs and CSOs. However, in the sediments the concentrations are sufficiently elevated to cause localized biological effects. It is obvious that in Puget Sound the degree of environmental protection achieved by enforcement of water quality standards is questionable. The applicability of optimum sediment criteria to control effluent quality may involve setting up discharge limits commensurate to an acceptable sediment threshold. The optimum criteria may be based on one or a combination of the approaches presented in Section 2.0. Compliance with discharge limits may include statistically allowable deviations during periods where there is a high probability of exceeding a threshold value and the determination of the total variability (field and analytical) associated with measurements of contaminant' concentrations. Enforcement of these limits should take into account these statistical considerations to establish the legal definition of what constitutes a "violation".

The build up and/or reduction of contaminant concentrations in the sediments may be estimated by employing a site specific mass balance model similar to that used by Pavlou et al. (1983).

3.2 ISSUANCE OF CWA SECTION 404 DREDGE AND FILL PERMITS AND DESIGNATION OF DREDGE MATERIAL DISPOSAL SITES

The key element within this decision issue is evaluation of the acceptability of dredged material for open water disposal. Criteria for this evaluation are already established under current federal regulations (U.S. EPA/COE, 1977). These regulations require that the solid phase of all material intended for open water disposal be evaluated by sediment bioassays employing three representative species, unless certain exclusionary guidelines are met. If toxicity of the tese sediment exceeds that of controls, the permit may be denied.

The general utility of bioassays are limited by the fact that the procedure does not identify the contaminant or contaminants responsible for the observed toxicity, providing no information on appropriate remedial action. However, since no corrective measures are addressed in evaluating the acceptability of dredged material, bioassay techniques represent the best available technique to make this evaluation, given our current state of knowledge on chemical toxicity.

3.3 SELECTION OF REMEDIAL ALTERNATIVES AT SUPERFUND SITES

This decision may be based on the application of an integrated indexing method as described in Section 2.6. Sites would be ranked according to the magnitude of a sediment degradation factor and compared to an _a priori_ estimated threshold value. A management action plan could then proceed according to a decision scenario similar to the one shown in Figure 5.

There is a sufficient data base currently available for testing a ranking approach at designated sites in Commencement Bay and Elliott Bay, but further work is needed to establish threshold values.

3.4 ISSUANCE OF NPDES PERMITS

Any of the approaches presented in Section 2.0 could be applicable in establishing criteria based on either control conditions in the vicinity of an existing discharge or current ambient conditions at sites where the proposed facilities would be installed. However, an optimum approach could be to rank the sites based on an indexing method similar to what has been proposed in Section 2.6 and establish an unacceptable level of sediment quality. Effluent requirements necessary to maintain sediment quality below a threshold value could be forecasted. Considerations of effluent physical transport and dispersion as governed by the ambient hydrodynamic and sediment transport processes should also influence the decision on effluent contaminant limits. This can be accomplished by already developed transport and fate models appropriately modified for application to the particular site.
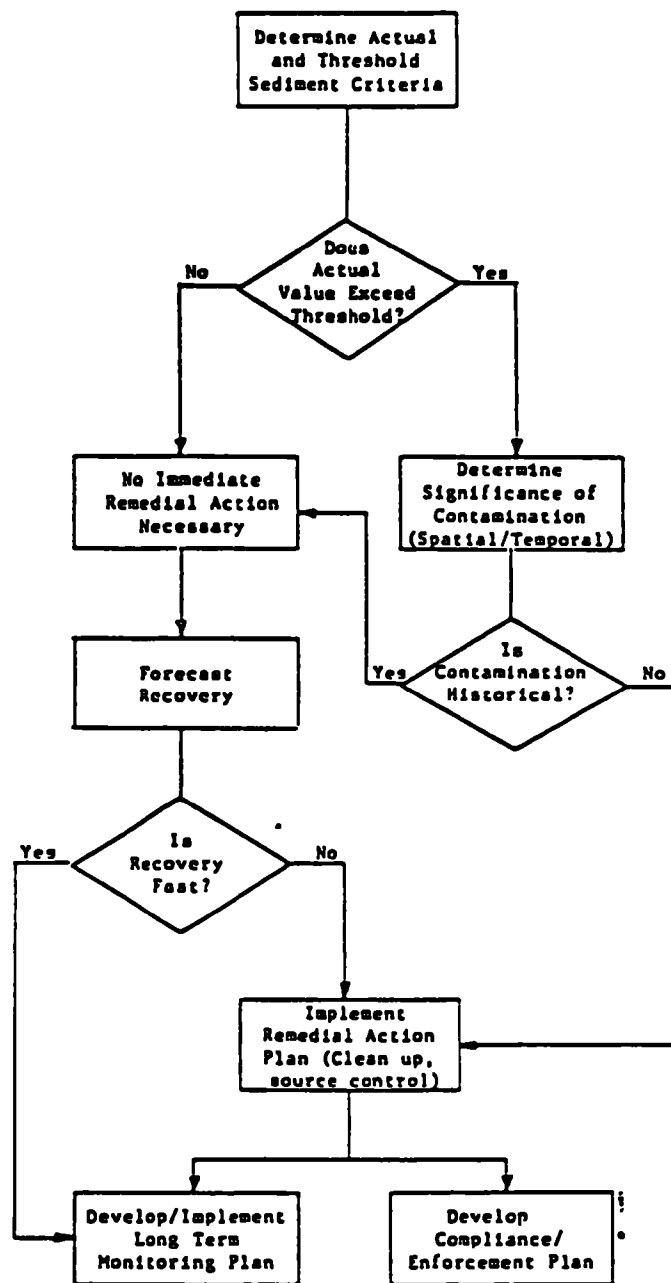
Figure 5

DECISION SCENARIO FOR MANAGEMENT ACTION PLAN
AT SUPERFUND SITES INVOLVING SEDIMENT CRITERIA

4.0 SUMMARY AND CONCLUSIONS

The current state of knowledge regarding sediment criteria was updated and summarized. Five major approaches were identified and then ranked according to nine ranking criteria: adequacy of the existing data base, development costs, application costs, availability of methodology, cost effectiveness, relative completexity, adaptability to new compounds and utility to management division. The results are presented in Table 6.

Among the major categories of approaches listed, approaches based on biological response and the ranking schemes included in these evaluations scored higher than the approaches which involved primarily chemical burden and bioconcentration considerations. This is not surprising, since the inherent utility of establishing sediment criteria is to develop a tool for controlling ecological degradation and minimizing potential human health risks. Both biological approaches and ranking schemes account for these factors with the ranking schemes appearing more favorable in that they address biological effects associated with an observed chemical burden or enrichment in the sediments. As pointed out in Section 2.6 the integrated assessment schemes suffer from one major limitation: they are not as easily enforceable as, for example, a combination of a biological response approach and criteria based on equilibrium partitioning.

In addition to the overall ranking approaches on the basis of development and implementation considerations there are a number of specific concerns which need to be addressed in the establishment of sediment criteria:

- Influence of sediment organic content
- Implications of synergism/antogonism
- Temporal considerations in criteria enforcement

If sediment criter.a are to be expressed in terms of a permissable concentration, the impact of sediment organic content on contaminant burden and

Table 6

SEDIMENT CRITERIA RANKING

(L = Low, M = Medium, H = High, N/A = Not Applicable)

Approach	Adequacy of Existing Data Base	Development Costs	Application Costs	Availability of Methodology	Cost Effectiveness	Relative Complexity	Ability to Address Synergism	Adaptability to New Compounds	Utility to Management Decision
2.2 Background Levels	M	M	M	H	L	L	L	H	L
2.3 EPA Region VI	M	M	M	L	M	L	L	H	M
2.4 Partitioning:									
#1 – K_D	M	M	M	H	M	M	L	H	M
#2 – BCF/ARS	M	M	M	H	L	M	L	H	L
#3 – ARS	M	H	M	H	M	L	L	H	M
#4 – BCF/K_D	M	H	M	H	L	M	L	H	L
2.5 Biological Response:									
2.5.1 Bioassay:									
Unspiked Sediment	N/A	L	L	H	H	L	H	N/A	H
Spiked Sediment	L	H	M	H	M	M	H	H	H
2.5.2 Field Surveys:									
Burden/Effect Relationship	L	H	M	H	M	M	H	H	M
Community Monitoring	N/A	M	M	H	M	M	H	N/A	H
2.6 Environmental Degradation Assessment*									
NOAA/OMPA	M	M	H	H	M	H	H	H	H
Ecological Risk Index	L	H	M	H	M	H	L	H	M
Quality Degradation Factors (QDF)	M	M	H	H	M	H	H	H	H

se approaches are ranking methods designed to evaluate the relative degree of environmental degradation and
uld be considered as aids for decision criteria   her than sediment criteria.

toxicity must be addressed. Not only does the organic content of the sediment effect the concentration of most contaminants, but it is also of major importance in determining bioavailability. For example, addition of small quantities of sewage sludge to sediment can dramatically reduce the toxicity of cadmium relative to sediments containing no sewage sludge (R. Swartz, EPA/NERC, pers. comm.). Given equal contaminant burden, a sediment containing a high proportion of organic carbon would be less toxic than a sediment containing relatively little organic material.

An approach to addressing this issue which deserves further consideration is to establish sediment criteria on the basis of organic content in much the same way as EPA freshwater quality criteria for metals are based on water hardness. The greater the water hardness the higher the permissable metal concentration in the water. A similar approach for sediment quality criteria could be based on organic content or a covariate such as percentage of silt and clay or total volatile solids.

The effects of synergism and antagonism present a major difficulty in the establishment of valid sediment criteria. There is presently no way to predict the toxicity of a mixture of contaminants, given the toxicity of each of the individual components. Often the simultaneous action of several contaminants can have a much greater biological impact than would be predicted by the sum of their individual effects. As applied to sediment criteria, this implies that adherence to criteria established on the basis of individual contaminants will not necessarily provide adequate protection against the biological impacts of a mixture of contaminants.

Biological response criteria (bioassays, community analysis) provide the only means to address synergism given our current state of knowledge. Establishment of chemical criteria on an individual compound basis may be a necessary simplification in the development of first-cut criteria. However, some measure of biological response must be an integral component in application of these initial criteria to adequately protect against synergistic effects.

Sediment criteria could potentially be used in point source control applications. Should sediment contaminant levels in the vicinity of a discharge exceed established criteria, effluent control procedures would be appropriate. An important consideration which must be addressed at this stage is the recovery period necessary for contaminant concentrations in surficial sediments to return to permissable levels. Since sediments serve as a reservoir for most contaminants, their concentration in sediments would not be expected to drop dramatically even if contaminant inputs were eliminated entirely. The success or failure or effluent control measures could not be evaluated on the basis of sediment criteria until sufficient time had elapsed to permit burial of contaminated sediments by deposition of clean sediments. Depending upon local sedimentation rates, natural depositional processes may be considered too slow for burial of heavily contaminated sediments, and dredging or capping may be required.

5.0 REFERENCES

Armstrong, J.W., R.M. Thom, K.K. Chew, B. Arpke, R. Bohn, J. Glock, R. Hieronymus, E. Hurlburt, K. Johnson, B. Mayer, B. Stevens, S. Tettleback, and P. Waterstrat. 1978. The impact of the Denny Way combined sewer overflow on the adjacent flora and fauna in Elliott Bay, Puget Sound, Washington. College of Fisheries, Univ. of Wash., Seattle. 102 pp.

Chapman, P.M. and E.R. Long. 1983. The use of bioassays as part of a comprehensive approach to marine pollution assessment. Mar. Poll. Bull. 14(3):81-84.

Chapman, P.M., G.A. Vigers, M.A. Farrell, R.N. Dexter, E.A. Quinlan, R.M. Kocan, and M. Landolt. 1982. Survey of biological effects of toxicants upon Puget Sound biota. I. Broad-scale toxicity survey. NOAA Tech. Memo. OMPA-25, National Oceanic and Atmospheric Administration, Boulder, CO. 96 pp.

Chiou, C.T., V.H. Freed, S.W. Schmedding, R.L. Kohnert. 1977. Partition coefficients and bioaccumulation of selected organic chemicals. Environmental Science and Technology 11:475-478.

Clayton, J.R., S.P. Pavlou, and N.F. Breitner. 1977. Polychlorinated biphenyls in coastal marine zooplankton: bioaccumulation by equilibrium partitioning. Environmental Science and Technology 11(7):676-682.

Dexter, R.N. 1976. An application of equilibrium adsorption theory to the chemical dynamics of organic compounds in marine ecosystems. Ph.D. dissertation, Univ. of Wash., Seattle. 181 pp.

Dexter, R.N. 1978. Distribution coefficients of organic pesticides in aquatic ecosystems. Report submitted to Battelle Pacific Northwest Laboratories, Richland, WA.

Dexter, R.N., and S.P. Pavlou. 1978. Distribution of stable organic molecules in the marine environment: physical chemical aspects; chlorinated hydrocarbons. Marine Chemistry 7:67-84.

Ferguson, D.E., J.L. Ludke, and G.G. Murphy. 1966. Dynamics of endrine uptake and release by resistant and susceptible strains of mosquito fish. Transactions of the American Fisheries Society 95(4):335-344.

Gakstatter, J.H., and C.M. Weiss. 1967. The elimination of DDT-C14, Dieldrin-C14, and Lindane-C14 from fish following a single sublethal exposure in aquaria. Transactions of the American Fisheries Society 96(3):301-307.

Grzenda, A.R., D.F. Paris, and W.J. Taylor. 1970. The uptake, metabolism, and elimination of chlorinated residues by goldfish (Carassius auratus) fed a DDT-C14 contaminated diet. Transactions of the American Fisheries Society 99(2):385-396.

Håkanson, L. 1980. An ecological risk index for aquatic pollution control. A sedimentological approach. Wat. Res. 14:975-1001.

Hamelink, J.L., R.C. Waybrant, and R.C. Ball. 1971. A proposal: exchange equilibria control the degree chlorinated hydrocarbons are biologically magnified in lentic environments. Transactions of the American Fisheries Society 100(2):207-221.

Issacs, J.D. 1975. Assessment of man's impact on marine biological resources. pp. 329-340 In Marine Pollution and Marine Waste Disposal, E. Pearson and E. DeFraja Frangipane (eds.). Pergamon Press, Ltd. New York.

Kenaga, E.E. and C.A.I. Goring. 1980. Relationship between water solubility, soil sorption, octanol-water partitioning, and concentration of chemicals in biota. pp. 78-115 In Aquatic Toxicology, Proceedings of the Third Annual Symposium on Aquatic Toxicology ASTM Spec. Tech. Publ. 707.

Long, E.R. 1983. A multidisciplinary approach to assessing pollution in coastal waters. pp. 163-178 In Proceedings of the Third Symposium on Coastal and Ocean Management, ASCE/San Diego, CA.

Malins, D.C., B.B. McCain, D.W. Brown, A.K. Sparks, and H.O. Hodgins. 1980. Chemical contaminants and biological abnormalities in central and southern Puget Sound. NOAA Tech. Memo. OMPA-2. National Oceanic and Atmospheric Administration, Boulder, CO. 295 pp.

Malins, D.C., B.B. McCain, D.W. Brown, A.K. Sparks, H.O. Hodgins, and S-L. Chan. 1982. Chemical contaminants and abnormalities in fish and invertebrates from Puget Sound. NOAA Tech. Memo. OMPA-19. National Oceanic and Atmospheric Administration, Boulder, CO. 168 pp.

Metcalf, R.L., J.R. Sanborn, P.Y. Lu, and D. Nye. 1975. Laboratory model ecosystem: studies of the degradations and fate of radiolabelled tri-, tetra-, and pentachlorobiphenyls compared with DDE. Archives of Environmental Contamination Toxicology 3:151-165.

Neely, W.B., D.R. Branson, and G.E. Blau. 1974. Partition coefficients for measuring bioconcentration potential of organic chemicals in fish. Environmental Science and Technology 8:1113-1115.

Neuhold, J.M., and L.F. Ruggerio. 1975. Ecosystem processes and organic contaminants: research needs and interdisciplinary perspective. National Science Foundation, Washington, D.C.

Pavlou, S.P. 1980. Thermodynamic aspects of equilibrium sorption of persistent organic molecules at the sediment-seawater interface: a framework for predicting distributions in the aquatic environment. In Contaminants and Sediments, Volume 2, Robert A. Baker (ed.). Ann Arbor Science Publishers, Inc., Ann Arbor, MI.

Pavlou, S.P. and R.N. Dexter. 1977. Environmental dynamics of polychlorinated biphenyls (PCB) in Puget Sound: interpretations and criteria recommendations. Special Report No. 75, Ref. No. M77-38, Univ. of Wash., Seattle.

Pavlou, S.P., R.N. Dexter, and W. Hom. 1977. Polychlorinated biphenyls (PCB) in Puget Sound: physical/chemical aspects and biological consequences. pp. 100-133 In The Use, Study and Management of Puget Sound: A Symposium. Washington Sea Grant, Univ. of Wash., Seattle.

Pavlou, S.P. and R.N. Dexter. 1979. Distribution of polychlorinated biphenyls (PCB) in estuarine ecosystems; testing the concept of equilibrium partitioning in the marine environment. Environmental Science and Technology 13(1):65-71.

Pavlou, S.P., R.F. Shokes, W. Hom, P. Hamilton, J.T. Gunn, R.D. Muench, J. Vinelli, and E. Crecilius. 1983. Dynamics and biological impacts of toxicants in the main basin of Puget Sound and Lake Washington. Vol. I: evaluation of toxicant distribution, transport and fate. Submitted to the Municipality of Metropolitan Seattle.

Pierson, K.B., B.D. Ross, C.L. Melby, S.D. Brewer, and R.E. Nakatani. 1983. Biological testing of solid phase and suspended phase dredge material from Commencement Bya, Tacoma, Washington. U.S. Army Corps of Engineers. Final Report, Contr. No. DACW67-82-C-0038.

Riley, R.G., E.A. Crecelius, H.L. O'Malley, K.H. Abel, and D.C. Mann. 1981. Organic pollutants in waterways adjacent to Commencement Bay. NOAA Tech. Memo. OMPA-12. National Oceanic and Atmsopheric Administration, Boulder, CO. 90 pp.

Swartz, R.C., W.A. DeBen, and F.A. Cole. 1979. A bioassay for the toxicity of sediment to marine macrobenthos. J. Wat. Polluc. Contr. Fed. 51:944-950.

Swartz, R.C., W.A. DeBen, K.A. Sercu, and J.O. Lamberson. 1982. Sediment toxicity and the distribution of amphipods in Commencement Bay, Washington, USA. Mar. Pollut. Bull. 13:359-364.

U.S. EPA/COE. 1977. Ecological evaluation of proposed discharge of dredged material into ocean waters. U.S. Army Waterways Exper. Sta., Vicksburg, MS.

Veith, G.D., K.J. Macek, S.R. Petrocelli, and J. Carroll. 1980. An
    evaluation of using partition coefficients and water solubility to
    estimate bioconcentration factors for organic chemicals in fish. pp.
    78-115 In Aquatic Toxicology, Proceedings of the Third Annual Symposium
    on Aquatic Toxicology. ASTM Spec. Tech. Publ. 707.

Versar, Inc. 1979. Water-related environmental fate of 129 priority
    pollutants. Submitted to the U.S. Environmental Protection Agency by
    Versar, Inc., Springfield, VA.

APPENDIX A

INTERVIEW RESULTS

APPENDIX A
INTERVIEW RESULTS

One of the tasks under Phase 1 was to interview a number of individual investigators regarding their perceptions on the feasibility of establishing sediment evidence in Puget Sound. In addition, an attempt was made to ellicit suggestions and/or recommendations on approaches that they felt would be worth considering in this study. The list of individuals contacted through formal and/or informal interviews, meetings and telephone discussions are listed in Table A.1. The results of the most significant interviews are also attached to this appendix. These consist of (1) comments received after the basic seven approaches developed by JRB (submitted to EPA on September 19, 1983) were presented to the attendees, and (2) summary of the discussions regarding various approaches. We anticipate to expand this section and incorporate additional 'viewpoints and informational feedback as they are obtained throughout this project. These will be assembled and included in the final report.

Table A-1

INDIVIDUALS CONTACTED DURING THE PHASE I ACTIVITIES

Name	Affiliation	Area of Participation
John Armstrong	EPA-X	Project Reviewer
Richard Bauer	EPA-X	Project Reviewer
Don Baumgartner	EPA/NERC/Newport	Management Considerations
Joe Cummins	EPA-X, Laboratories	Bioassay Testing
Tom Dillon	COE, WES	Dredge Material Management
Ron Garton	EPA/NERC/Corvallis	Freshwater Impacts
Arnold Gayler	EPA-X	Chemical Analyses
Howard Harris,	NOAA/OMPA	Management Considerations
Karl Kassenbaum	EPA-X	Dredge & Fill Permitting
Jim Krull	WDOE	Criteria Applications
Henry Lee, II	EPA/NERC/Newport	Bioaccumulation
Edward Long	NOAA/OMPA	Impact Assessment Techniques
Bernard Malo	USGS	Sediment Alert Levels
Steve Martin	COE, Seattle District	Dredge Material Management
Bruce McCain	NOAA/NMFS	Biological Maladies
Alan Mearns	NOAA/OMPA	Management Considerations
Gary O'Neal	EPA-X	Enforcement Aspects
Rick Parkin	EPA-X	Project COTR
Dan Petke	EPA-X	Dredge Material Management
Keith Phillips	COE, Seattle District	Dredge Material Management
Pat Storm	COE, Seattle District	Dredge Material Management
Rick Swartz	EPA/NERC/Newport	Bioassay Testing
John Underwood	EPA-X	Project Officer
Mike Watson	EPA-X	Project Reviewer
Fred Weinmann	COE, Seattle District	Dredge Material Management
Jack Word	University of Washington	Benthic Ecology

EPA REGION X - SEDIMENT CRITERIA DEVELOPMENT FOR PUGET SOUND

MEETING NOTES: EPA/NERC, NEWPORT, OREGON

September 23, 1983

ATTENDEES:

Spyros Pavlou, JRB
Donald Weston, JRB
Don Baumgartner, EPA
Rich Swartz, EPA
Henry Lee, II, EPA
Ron Garton, EPA

SUMMARY:

The EPA participants commented on JRBs seven basic approaches. A concern was expressed regarding the use of SPM K_{DS} to predict interstitial water K_{DS}. The use of HHRL criteria may not be appropriate since organisms consumed by man are generally not exposed to interstitial or interfacial water.

Don Baumgartner thought that all approaches merit consideration. The use of water quality criteria for interstitial water was worthwhile but there is a need to demonstrate that these levels are not harmful to the interstitial and/or interfacial fauna.

Henry Lee suggested that accumulation through water may not be the only uptake mechanism; the particulate phase may be a contributor to contaminant burden in biota. It was felt that the sediment/biota transport pathways should be investigated more thoroughly.

Rick Swartz suggested that one should develop regression equations for contaminant concentrations vs. sediment communities such as texture and total volatile solids; outliers should show impacted sites. He also noted the importance of synergism in establishing sediment criteria. For example, even though a sublethal effect below LC_{50} values may be shown for a sediment with

JRB Associates

44

one contaminant, elevated effect values above the two LC_{50} threshold may be demonstrated by sediment containing a number of contaminants.

The determination of infaunal recruitment rates is an alternative technique for addressing toxicity of sediments to biota and could be incorporated in the formulation of a sediment criterion.

Don Baumgartner also suggested that sediment criteria may be generated for three or four sediment types dependent upon organic content. Bioassays and benthic field surveys are currently used as criteria for sediment toxicity. For example, benthic surveys are commonly employed to establish compliance of point source dischargers with 301(h) requirements.

EPA REGION X - SEDIMENT CRITERIA DEVELOPMENT FOR PUGET SOUND
NOAA/NMFS MEETING
September 27, 1983

ATTENDEES:

    Donald Weston, JRB
    Bruce McCain, NOAA

SUMMARY:

Much of NMFS work is presented in OMPA-19 (Malins et al., July, 1982).

Factor analysis was used to identify classes of compounds with similar spatial patterns of concentrations. The PAH's were heavily weighted on Axis 1, select metals and organics on Axes 2 and 3, the chlorinated hydrocarbons on Axis 4. Measures of biological health were then correlated against concentrations of these identified contaminants. The number of benthic taxa was linearly related (making it arbitrary to establish a threshold).

Among four chemical groups considered, tumors and PAHs were best correlated, suggesting they may be the causative factor. Chlorinated hydrocarbons were least correlated with biological indices. ITI was not well correlated with any sediment contaminant but number of ITI taxa worked better.

This method does not consider habitat differences other than sediment burden. Covariates of burden (e.g., silt/clay) may be determining number of taxa or incidence of tumors. The next step which they are currently pursuing is sediment bioasssays.

The fish species examined (primarily sole) seem to have a very limited mobility which makes it possible to relate abr malities with specific sites. For example, there is a marked demarcation in r'e incidence of fish lesions at the mouth of the Duwamish.

Evidence is contradictory in Commencement Bay. Sediment burdens of most compounds are high and Swartz has demonstrated toxicity of sediments in Hylebos; yet McCain found no toxicity in bioassays of sediments from Hylebos and crabs maintained in cages in Hylebos showed 100% survival.

EPA REGION X - SEDIMENT CRITERIA DEVELOPMENT FOR PUGET SOUND
MEETING NOTES: NOAA/OMPA OFFICE

ATTENDEES:

Spyros Pavlou, JRB
Donald Weston, JRB
Edward Long, NOAA
Alan Mearns, NOAA
Howard Harris, NOAA

SUMMARY:

Ed Long advocates a three way approach for establishing sediment criteria (1) chemical characterization, (2) sediment bioassay, and (3) infaunal community analysis. The three types of analyses when performed on the same sediment sample may reveal what biota are being impacted and possibly the causative chemical agent (ref. Chapman and Long, 1983). Long also pointed out the importance of establishing contaminant concentrations vs. TOC and/or sediment texture relationships as a method for discriminating sites at which contamination is excesssive (above statistically derived confidence intervals) to allow performance of bioassay and infaunal analysis.

EPA REGION X - SEDIMENT CRITERIA DEVELOPMENT FOR PUGET SOUND

MEETING NOTES: EPA REGION X LABORATORY STAFF, JRB OFFICES

September 28, 1983

ATTENDEES:

Spyros Pavlou, JRB
Donald Weston, JRB
Joe Cummins, EPA

SUMMARY:

Joe Cummins commented on the applicability of various bioassay methods to the sediment criteria development.

He pointed out that elutriate bioassays in general show lesser toxicity to those performed with mixed substrates (water/sediment). Cummins had concerns with the lack of approaches to address the effects of mixtures of chemicals (synergism). He has observed that bioassay procedures may introduce artifacts in results, e.g., when frozen sediments are used, toxicity is reduced by 20 to 30%. He suggested that one should (1) develop methods for applying a weighting factor to contaminant concentrations measured in sediments to reflect level of concern; (2) examine multiple indicators and factor these into an effective threshold level; and (3) develop bioassay methods for addressing mixtures of chemicals.

EPA REGION X - SEDIMENT CRITERIA DEVELOPMENT FOR PUGET SOUND

MEETING NOTES: COE SEATTLE OFFICE

September 29, 1983

ATTENDEES:

Donald Weston, JRB
Fred Weinmann, COE
Steve Martin, COE
Pat Storm, COE
Keith Phillips, COE

SUMMARY:

Bioassays are favored since they provide the most straightforward approach to determining if sediments are an ecological threat. No mathematical manipulations which may or may not be valid are necessary.

There was concern that approaches involving WQC may not adequately guard against direct exchange of contaminants from sediment to biota.

Currently the COE evaluates dredge material in two ways. For inland disposal a chemical characterization is first performed. If a regulatory official believes levels of any contaminant are high enough to be of concern, he may request a bioassay. For ocean dumping a bioassay must be performed without consideration to the chemical make-up of the dredge spoil. Initially ocean dumping criteria were the same as for inland, but they were challenged in court on the basis that the subjective assessment of hazard may not provide adequate protection. Now a bioassay must be performed in most cases.

Keith Phillips just returned from visiting WES and noted that they are using BCF's and K_D's to estimate exchange among ecosystem components just as we are. There was some question whether organisms which humans ingested, and for which the HHRL criteria were derived, were in fact exposed to our predicted interstitial water concentrations.

· ·

EPA REGION X - SEDIMENT CRITERIA DEVELOPMENT FOR PUGET SOUND
MEETING NOTES: UNIVERSITY OF WASHINGTON, COLLEGE OF FISHERIES
October 5, 1983

ATTENDEES:

    Donald Weston, JRB
    Jack Word, UW

SUMMARY:

The use of partition coefficients derived from exchanges between suspended particulate material and water may be totally inappropriate to predict exchange between sediment and interstitial water. The chemistry of the sediments is profoundly different than that of the overlying water.

Any application of sediment quality criteria in pollution abatement programs should address the aspect of time. Because sediments serve as a sink for most pollutants and integrate pollution levels over time, changes in pollutant input may not be reflected by a change in sediment pollutant burden for a year or more.

O'Connor and Swanson's index of environmental quality has been undergoing extensive development. Jack Word will be testing the index employing data from Puget Sound.

APPENDIX B

COMPUTATION OF ECOLOGICAL RISK INDEX

APPENDIX B

COMPUTATION OF ECOLOGICAL RISK INDEX

The ecological risk index of Håkanson (1980) was developed as a diagnostic tool for water pollution control purposes. It was first used to identify toxic substances and lakes in need of corrective action. The risk index can be expressed as:

$$RI = \sum_{i=1}^{n} E_r^i = \sum_{i=1}^{n} \frac{C_o^i - 1}{C_r^i} \times S_t^i \times K^i \,(BPI)$$

where

RI = the risk index: RI<50 = low ecological risk; 150<RI<300 = moderate ecological risk; 300<RI<600 = considerable ecological risk; RI>600 = very high ecological risk

E_r^i = the ecological risk factor for the contaminant of concern

n = the number of contaminants considered

C_o^i = the observed concentration of the contaminant in surficial sediments

C_r^i = the preindustrial reference level

S_t^i = an estimate of the contaminant's toxicity

K^i = a contaminant specific constant

BPI = the bioproduction index of the area which is a function of the nitrogen and organic content of the sediments

The index takes into account four principal factors (taken directly from Håkanson, 1980):

1. The concentration requirement which emphasizes that RI-value should increase when the sediment contamination increases. This may be revealed by a comparison between preindustrial deposits from deep sediment levels and recent deposits from superficial sediments.

2. The number requirements which states that a lake or a sub-basin polluted by numerous substances should have a higher RI-value than an area contaminated by only a few substances.

3. The toxicity factor requirement which implies that the risk index should account for the fact that various substances have different toxicological effects; some are highly toxic, others slightly toxic. There is a very wide range here—from extremely poisonous substances like PCB and mercury via lead and copper to iron. The requested RI-value should differentiate between mildly, moderately and very toxic substances.

4. The sensitivity requirement which means that the risk index should account for the fact that various lakes and water systems do not have the same sensitivity to toxic substances. In waters of low pH and bioproductivity, for example fish tend to have higher mercury concentrations than in waters of comparable Hg-contamination but with more neutral pH and higher bioproductivity.

APPENDIX C

QUALITY DEGRADATION FACTORS

APPENDIX C

QUALITY DEGRADATION FACTORS ·

The quality degradation factors were calculated from a hypothetical set of data as presented in Table C-1. The chemical measurements consist of contaminant concentrations in biota, sediments and interstitial water for a list of typical contaminants found in Puget Sound.

The biological measurements presented in the table are a benthic community structure index (Bray/Curtis similarity index) the percent amphipod mortality and the percent diseased organisms. These parameters were chosen as representative of the benthic community structure, the toxicity potential of the sediments, and the physiological (pathological) conditions of the type of organisms sampled. Values are entered for the actual site, a control site, and for the maximum observed quantity.

Table C-2 summarizes the calculations for the overall chemical quality degradation factor at the site of interest and Table C-3 presents the calculations performed to determine the overall biological/toxicological factor. For this hypothetical site, it is apparent that the biological score (50) is higher than the chemical score (34) within the defined range of 0-100. Correlations of individual contaminant scores can be performed with this data to estimate contaminants that may be the most significant contributors to the observed biological/toxicological response.

Combinations of these contributions are also useful in obtaining the overall quality degradation of the site of interest. In this example by averaging the chemical and biological factors, a score of 42 was obtained.

JRB Associates

Table C-1

ENVIRONMENTAL PARAMETERS MEASURED AT A
HYPOTHETICAL SITE IN PUGET SOUND

Parameter Designation	Measurement		
	Actual Site	Reference/ Control Site	Maximum Observed
Biota			
CPNAs (ppb)	100	1	800
DDTs (ppb)	23	7	25
PCBs (ppb)	300	90	700
Hg (ppm)	0.5	0.1	1.5
Zn (ppm)	270	270	350
As (ppm)	31	20	70
Sediment			
CPNAs (ppb)	12,000	5,000	28,000
DDTs (ppb)	20	1	30
PCBs (ppb)	1,200	600	1,500
Hg (ppm)	0.5	0.1	2
Zn (ppm)	300	100	475
As (ppm)	10	5	20
Water (interstitial)			
CPNAs (ppb)	0.12	0.08	0.31
DDTs (ppb)	0.0007	0.0003	0.0009
PCBs (ppb)	0.015	0.0081	0.021
Hg (ppb)	0.0009	0.00049	0.008
Zn (ppb)	2.2	2.0	4.1
As (ppb)	1.8	1.7	3.0
Bray/Curtis similarity of benthic community to control/reference site	0.8	1.0	
% Amphipod Mortality	60	5	
% Fish with Histopathological abnormalities	75	10	

Table C-2

CALCULATION OF CHEMICAL QUALITY DEGRADATION
FACTORS FOR A HYPOTHETICAL SITE[a]

Contaminant	Chemical Quality Degradation Factor $(QDF_i^x)_{CHEM}$ [b]		
	$i =$ Sediment (SED)	Tissue (TIS)	Water (WAT)
CPNAs	30	12	17
DDTs	66	89	67
PCBs	66	34	53
Hg	21	29	5
Zn	53	-0-	10
As	33	22	8
Mean	45	31	27
Overall Chemical[c]		34	

---

[a] The data is obtained from Table C-1.

[b] $$(QDF_i^x)_{CHEM} = \frac{c_{i,ACT}^x - c_{i,REF}^x}{c_{i,MAX}^x - c_{i,REF}^x} \times 100$$

where x is the contaminant, c_i^x is the concentration of x in matrix

$i =$ sediments (SED), Tissue (TIS) and Interstitial Water (WAT)

[c] The overall chemical degradation factor is defined as:

$$(QDF_{OVERALL}^x)_{CHEM} = (QDF_{SED}^x + QDF_{TIS}^x + QDF_{WAT}^x)/3$$

Table C-3

**CALCULATION OF BIOLOGICAL/TOXICOLOGICAL QUALITY DEGRADATION
FACTOR FOR A HYPOTHETICAL SITE**

$$QDF_{BENTHOS} = (1 - Bray/Curtis\ similarity\ to\ control) \times 100 = 20$$

$$QDF_{BIOASSAY} = \frac{\%\ mortality\ at\ site - \%\ mortality\ control}{100 - \%\ mortality\ control} \times 100 = 58$$

$$QDF_{PATHOLOGY} = \frac{\%\ disease\ at\ site - \%\ disease\ control}{100 - \%\ disease\ control} \times 100 = 72$$

$$QDF_{BIOL} = (QDF_{BENTHOS} + QDF_{BIOASSAY} + QDF_{PATHOLOGY})/3 \times 100 = 50$$

PHASE II: DEVELOPMENT AND TESTING OF
THE SEDIMENT-WATER EQUILIBRIUM
PARTITIONING APPROACH

INITIAL EVALUATION OF ALTERNATIVES FOR
DEVELOPMENT OF SEDIMENT RELATED
CRITERIA FOR TOXIC CONTAMINANTS IN
MARINE WATERS (PUGET SOUND)

PHASE II: DEVELOPMENT AND TESTING OF
THE SEDIMENT-WATER EQUILIBRIUM
PARTITIONING APPROACH

FINAL REPORT

April 20, 1984

Prepared for:

U.S. Environmental Protection Agency
401 M Street, S.W.
Washington, D.C. 20460

Prepared by:

JRB Associates
A Company of Science Applications, Inc.
13400-B Northup Way, Suite 38
Bellevue, Washington 98005

JRB Associates

ACKNOWLEDGMENTS

JRB Associates

TABLE OF CONTENTS

TABLE OF CONTENTS
(continued)

1.0 EXECUTIVE SUMMARY

With the increased use of our nation's coastal and inland waters, regulatory agencies are frequently confronted with difficult decisions in resolving conflicts between alternate uses of these waters, while at the same time striving to protect overall environmental quality. A significant number of management decisions facing these agencies concern the definition of permissible levels of contaminants in marine sediments. For example, in Commencement Bay the Washington Department of Ecology and EPA are attempting to identify those areas in which sediment contamination poses the greatest environmental threat, with the ultimate intent of initiating remedial action in these areas. At the Four Mile Rock dredge disposal site, regulatory agencies are confronted with an immediate need to establish a permissible level of contamination for sediments which are to be disposed of at the site. In Commencement Bay, at Four Mile Rock, and at countless other areas throughout the country, sediment-related criteria which define environmentally safe levels of contaminants in sediments would be invaluable tools in environmental management decisions. However, given the current state of our technical knowledge, regulatory agencies have been forced to adopt short-term, interim decision criteria until scientifically-sound and legally defensible sediment criteria can ultimately be established.

There are three general approaches currently being pursued to establish sediment-related criteria:

- Background level approach - criteria are established at some permissible level of enrichment above background levels in a reference area.

- Burden-effect relationships - observations of adverse biological impacts are related to contaminant concentrations in order to establish a "safe" level of contamination.

- Equilibrium partitioning approach.

In an effort to develop the equilibrium partitioning approach, JRB Associates was contracted to develop the theoretical framework of the approach. Using this framework, JRB then developed tentative criteria for trace metals and synthetic organics and tested the proposed criteria against measurements of contaminants in the sediments of Puget Sound.

JRB Associates

1

The results of this study suggest that the equilibrium partitioning approach is a method that holds much promise for establishing criteria for marine sediments. The approach provides a relatively simple mechanism whereby the large toxicological data base incorporated in the EPA water quality criteria can be adapted to determine permissible contaminant concentrations in marine sediments which should insure protection of benthic marine organisms. The basic tenet of the equilibrium partitioning approach is that the concentration of each contaminant in sediment should be at or below a level which insures that its concentration in interstitial water does not exceed the EPA water quality criterion.

The key to this approach is the determination of the sediment-water partition coefficient for each compound of interest. This coefficient was determined empirically for trace metals based on measurements of trace metal concentrations in the interstitial water and bulk sediments from a wide variety of substrates. The sediment-water partition coefficients for synthetic organics were estimated from octanol-water partition coefficients. Since the partitioning of a contaminant between sediment and water is strongly dependent upon the organic carbon content of the sediment, the partition coefficient is normalized to organic content.

Sediment criteria were established for six trace metals and 47 synthetic organic compounds of concern in Puget Sound by use of the equilibrium partitioning approach. The derived criteria were tested against existing data on sediment contaminant concentrations in a variety of areas in Puget Sound including Elliott Bay, Commencement Bay, Sinclair Inlet, Budd Inlet, Case Inlet, Port Madison and the West Point area. In most cases the proposed criteria were exceeded only in areas which historically have received high inputs of contaminants from point and nonpoint sources. Among the trace metals, chronic sediment criteria were exceeded most frequently for Hg, Pb, Cu and As in Elliott Bay and Commencement Bay. Among the synthetic organics, only PCBs and DDT consistently exceeded the proposed sediment criteria, primarily in the urban embayments noted above. The polynuclear aromatic hydrocarbons we.e generally well below criteria except for a few isolated sites in the West Point area. Both numerical and graphical procedures are presented to relate the frequency and magnitude of criteria violations to specific sites.

During development of the equilibrium partitioning approach, a number of short-comings in our current state of knowlege on pollutant interactions between sediment, water and biota have been identified. The most significant of these include:

- inability to consider synergistic or antagonistic interactions among contaminants;

- the influence of environmental variables (e.g., organic carbon, pH) on the chemical behavior of contaminants is poorly understood; and

- our inability to differentiate the bioavailable fraction of a contaminant from the total sediment burden of the contaminant.

Until some of the issues identified above are resolved, the sediment criteria proposed in this report are not intended for adoption by regulatory agencies. It is important to recognize that while the numerical values suggested in this report as permissible levels of contaminants in marine sediments are, for simplicity sake, referred to as "criteria", they are not appropriate for immediate use in any regulatory, control or enforcement applications. However, as a first step in a long process, the approach presented herein appears very promising for the eventual adoption of sediment criteria for regulatory application.

The approach developed in this report is noteworthy in that it is capable of providing numerical criteria for a wide diversity of contaminants in marine sediments. This in itself is an elusive goal which has been unachieveable in many past efforts. However it is the approach which has been developed, rather than the criteria per se, which represents the most signficiant contribution of this work. The criteria proposed in this report are presented with the expectation that they will be refined through an iterative process involving input from both the scientific community and environmental management agencies. With continued refinement, the criteria will find application on the short-term basis as guidelines in assisting environmental managers in assessment of the extent of contamination of marine sediments. On a long-term basis, the criteria may ultimately be refined to the point where they find broad regulatory application.

2.0 INTRODUCTION

2.1 RATIONALE AND OBJECTIVES

The Environmental Protection Agency has focused historically on the development of water quality criteria which are supported by a broad base of toxicological studies. Use of these criteria provides some degree of assurance that contaminant concentrations will be within acceptable limits for the protection of aquatic life and human health. However, there is disturbing evidence of environmental degradation in many of the heavily urbanized areas of Puget Sound even though monitoring data does not show that water quality criteria are exceeded in the water column. The majority of adverse biological impacts recently observed are not among organisms living in the water column but those that live in or on the sediments. Macrobenthic communities in the vicinity of point source discharges have demonstrated significant changes in species composition and abundance (Armstrong, et al., 1978; Malins et al., 1982; Comiskey et al., 1983). Sediments from urbanized areas have been shown to induce mortality in sensitive benthic species (Swartz et al., 1982), and demersal fishes from heavily polluted areas have been shown to have a higher incidence of histopathological abnormalities than those from reference areas (Malins et al., 1980; 1982). These observations raise serious questions as to whether existing water quality criteria alone are adequate to protect the environmental resources of Puget Sound.

It is becoming increasingly evident that some sort of sediment criteria are needed to supplement existing water quality criteria in judging the significance of contaminant concentrations and to provide a basis for remedial action. There are a number of reasons why sediment criteria deserve consideration:

- Most toxic compounds are highly insoluble so the majority of the contaminant is not dissolved in the water but is associated with the organic matrix on sediment particles. For example, sediments in Elliott Bay contain 60,000 times more PCBs than overlying water (Pavlou and Dexter, 1979).

- Sediments serve to integrate contaminant concentrations over time, eliminating the high degree of temporal variability which plagues sampling of toxicants in the water column.

- Sediments serve as a sink for most toxic materials, thus a long-term low level discharge of a contaminant may result in a dangerous build up in the sediment even though water quality criteria are not violated at any given time.

- Sediments can serve as a reservoir (source) of contaminants which could be reintroduced to unpolluted overlying water.

- A large number of organisms, including many of commercial importance, spend most of their lives in or on the sediments. For these species, the contaminant level in the sediments may be of greater concern than that in the overlying water and may be the controlling factor with regards to bioaccumulation potential.

In response to the need for sediment-related criteria, the Environmental Protection Agency initiated an effort to identify and evaluate alternative approaches to the establishment of sediment criteria. The current state of knowledge regarding sediment·criteria was updated and summarized in the Phase I report (Pavlou and Weston, 1983) and a number of approaches to the establishment of criteria were identified. Three approaches appeared to be of immediate utility in developing sediment criteria for Puget Sound:

- Background level approach - the concentration of contaminants in the sediments of relatively unpolluted reference areas is determined and the criteria are then established at some permissible level of enrichment above background levels;

- Burden-effect relationships - observations of adverse biological impacts (alterations in benthic community structures, lethal or sublethal effects observed in bioassays, incidence of pathological disorders) are correlated with contaminant concentration in order to determine those concentrations at which no impacts are evident;

- Equilibrium partitioning approach - the sediment criterion is established at a level which will insure that the EPA water quality criterion is not violated in the interstitial water.

The development of sediment criteria by the background level approach and burden-effect relationships is currently underway in connection with other work within Region X. JRB was requested to develop the equilibrium partitioning approach and to examine the suitability of the approach for the establishment of sediment criteria for Puget Sound. The approach is simple, is immediately adaptable to the chemical contaminants measured in Puget Sound, is based primarily on existing data and provides "first cut" numerical criteria values.

2.2 OBJECTIVES

The specific objectives of the Phase II activities in this study were to:

1. Present the theoretical basis of the equilibrium partitioning approach and the derivation of sediment-water partition coefficients. Discuss their application in the marine environment and their dependence on environmental variables.

2. Establish preliminary numerical criteria for selected compounds measured in Puget Sound and estimate the uncertainty in these numerical values.

3. Discuss the assumptions and limitations of the approach and how they may influence the application of the derived criteria.

4. Test the utility of the derived criteria in Puget Sound with representative data sets from contaminated embayments.

5. Identify future research/data needs which may serve to improve the utility of the equilibrium partitioning approach.

2.3 SUMMARY OF APPROACH

Sediment criteria were derived for six priority metals and 47 individual priority organic compounds. These contaminants have been measured historically in the sediments of Puget Sound and have shown elevated concentrations within certain subregions and embayments of the Main Basin.

In this study, a sediment criterion was defined as the concentration of a contaminant in sediment which insures that its concentration in interstitial water does not exceed the established EPA water quality criterion, and therefore a designated water use, such as integrity of indigenous biota, could be attained. The sediment criterion was expressed as the product of the compound-specific sediment-water partition coefficient and its water quality criterion.

For trace metals, the partition coefficients were computed from the literature as an arithmetic mean with an associated standard deviation. For synthetic organic compounds the partition coefficients were computed from existing relationship of experimentally derived sediment-water partition coefficients with octanol-water partitioning ratios. Seven regression equations published in the literature, for a variety of chemical classes, were considered for their applicability to the compounds tested in this study. The optimum equation selected was one derived for 19 priority organic chemicals.

Sediment criteria for each of 53 priority pollutants were derived to correspond to both the acute and chronic values established for water, when available. The applicability of these derived criteria in Puget Sound was tested with two independent data sets. The contaminant concentrations measured in the sediments of various subregions in Puget Sound were compared with the criteria values. Violations were then estimated as excess factors from the derived acute and/or chronic criterion value. A comparison of the frequency of criteria violations values computed among a number of subregions and embayments allowed for a preliminary assessment of the severity of contamination.

The discussion presented in the following sections of this report is a detailed description of the above approach and results obtained.

3.0 TECHNICAL DEVELOPMENT

3.1 BASIC DEFINITIONS

A brief discussion of the concept of equilibrium partitioning was presented in the Phase I report, Section 2.4. As applied to the sediment-water interface, contaminant transport between the solid and aqueous phase occurs via a rapid molecular exchange. This exchange is continuous and therefore maintains the system at chemical equilibrium. The instantaneous concentration of the contaminant in either of the two components can be expressed as a function of its concentration in the other component and an equilibrium constant specific to that contaminant. These chemical specific constants are commonly referred to as partition coefficients and are expressed mathematically as:

$$K_D = \frac{c_S^X}{c_W^X} \qquad (1)$$

where K_D is the partition coefficient and c_S^X and c_W^X are the concentrations of contaminant x in the sediment (s) and surrounding water (w), respectively. Contaminant concentrations are expressed as mass of x/dry mass of sediment and mass of x/mass of water.

A schematic representation of the aqueous-solid components in a marine environment where this mechanism is operable is shown in Figure 1. Partitioning of a contaminant occurs in both the water column and the sediments. In the former case, the exchange is between suspended particulate matter (SPM) and ambient water while in the latter case it is between sediment particles and the interstitial water. In applying the equilibrium partitioning approach to sediments, the zone of interest for developing sediment criteria is the bioturbation layer where most of the biological activity occurs. Sediment criteria using the equilibrium partitioning approach were derived using equation (1) as follows:

- The partition coefficient K_D, was adjusted to account for the dependence on organic carbo·. The modified partition coefficient is defined as:
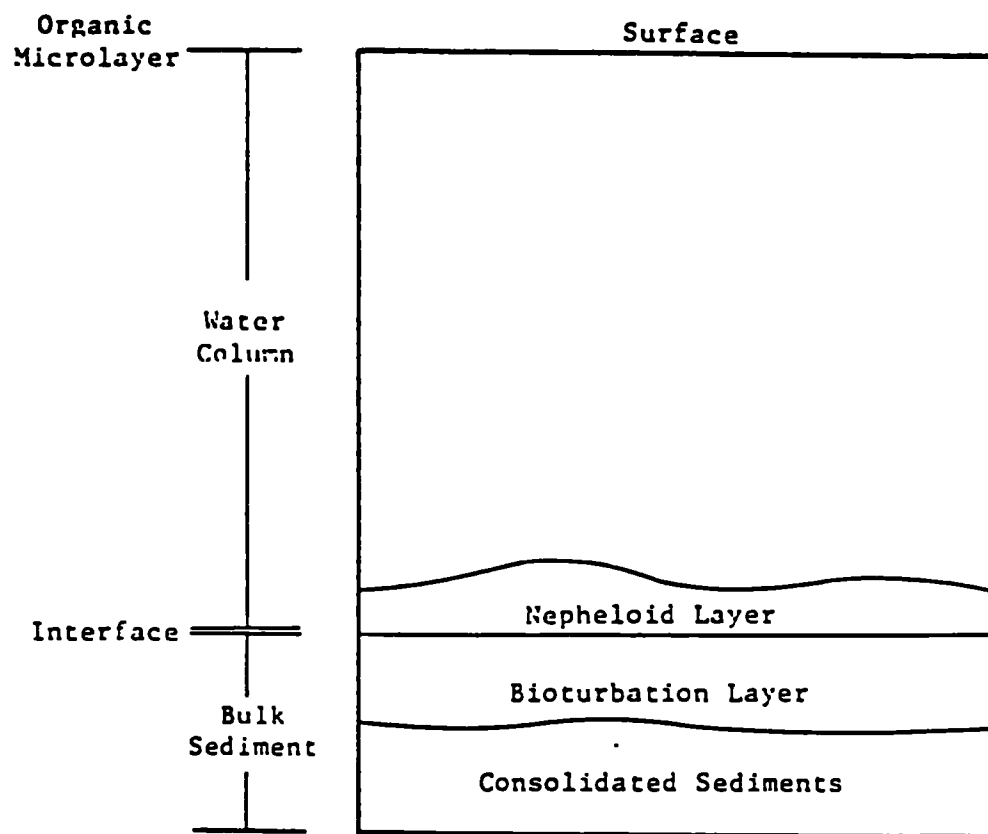
Figure 1

SCHEMATIC REPRESENTATION OF AQUEOUS-SOLID
COMPONENTS IN THE MARINE ENVIRONMENT

$$K_{OC} = \frac{c^X_{S/OC}}{c^X_{IW}} \qquad (2)$$

where K_{OC} is the organic carbon normalized partition coefficient and $c^X_{X/OC}$ is now the concentration of contaminant x in the sediment expressed in units of mass of x/mass of organic carbon. The term c^X_{IW} refers specifically to the concentration of x in interstitial water; the units remain the same as defined in equation (1). Equation (2) can also be expressed as:

$$K_{OC} = \frac{c^X_S}{c^X_{IW}} \times \frac{1}{TOC} = K_D \times \frac{1}{TOC} \qquad (3)$$

where TOC refers to the total organic carbon content in sediment expressed as the fractional mass on a dry weight basis (e.g., 3% organic carbon equals 0.03 g organic carbon per 1 g of sediment dry weight). This adjustment was made to eliminate the variability of K_D on organic carbon. The dependence of K_D on organic carbon has been well documented in the literature. For example, K_D values for nitropyrin were shown to vary about 140-fold in different sediment samples but when expressed on an organic carbon basis (K_{OC}) the variation was reduced to only threefold (Kenaga and Goring, 1980). A similar dependence on sediment-water partitioning on organic carbon content is evident for benzo(a)pyrene as depicted in Figure 2. K_D values for each of three sediment types were found to vary considerably (3.5×10^4 to 15×10^4) though when adjusted to organic carbon content the variability was minimal (3.0×10^6 to 3.8×10^6).

- The sediment criterion is defined as the concentration of contaminant x in the sediment which insures that its concentration in the interstitial water does not exceed the established EPA water quality criterion. Modifying equation (2) by setting c^X_{IW} as the water quality criterion, $c^X_{W/CR}$, then the corresponding sediment criterion for contaminant x, $c^X_{S/CR/OC}$, can be expressed as:
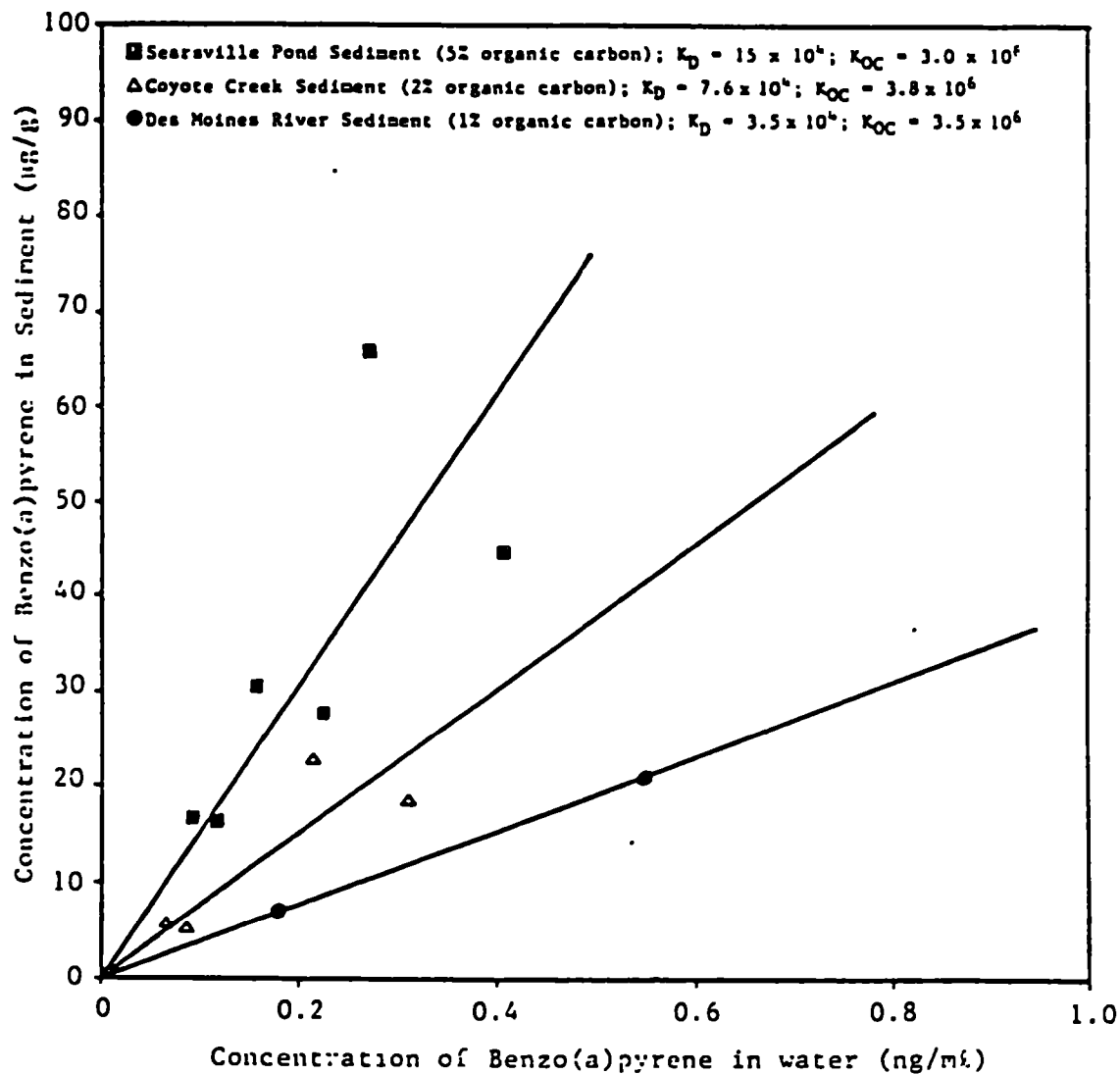
Figure 2

SORPTION ISOTHERMS OF BENZO(A)PYRENE
(From Smith et al., 1978)

$$c^X_{S/CR/OC} = K_{OC} \, c^X_{W/CR} \qquad (4)$$

- In order to apply the sediment criterion to a specific site, the criterion normalized to organic carbon, may be adjusted to the amount of organic carbon in the sediment of concern. This is expressed as:

$$c^X_{S/CR} = c^X_{S/CR/OC} \, TOC \qquad (5)$$

in which T_{OC} is again expressed as the fractional mass on a dry weight basis as in equation (3). The sediment criterion for a given organic carbon content, $c^X_{S/CR}$ can be compared directly to the measured contaminant concentration in the sediment of concern.

The procedures followed in deriving sediment criteria for specific priority pollutants measured in Puget Sound and in testing the application of these numerical values with existing data, are presented in detail in the following sections of the report.

3.2 DETERMINATION OF PARTITION COEFFICIENTS (K_{OC})

Partition coefficients were computed for six priority metals and 47 priority organic compounds which have been measured in Puget Sound sediments. The methods used are presented separately for the two categories of pollutants.

3.2.1 Trace Metals

The distribution of trace metals between interstitial water and sediment is a complex process which depends on a number of factors including chemical speciation, the reduction-oxidation (redox) potential at the solid-aqueous interface, the type of clay minerals present, the nature of the organic matter on both sedimentary particles and in interstitial water, pH, salinity, and particle size. The redox potential and pH, because of their effects on chemical speciation, are probably the most important factors in determining the sediment-water partitioning of trace metals (Jenne and Luoma, 1979). Though the dependence of partitioning on pH and redox conditions is certainly of major importance, the precise nature of this dependence is unpredictable and poorly understood.

The environmental variables and physical/chemical processes responsible for mediating the transport of trace metals in marine sediments are neither well understood nor adequately quantifiable to allow a theoretical computation of sediment-water partition coefficients. Therefore, these coefficients were derived empirically by using measurements of trace metal concentrations in the interstitial water and bulk sediments from a wide variety of substrate types. Empirical K_{OC} values were then calculated for each substrate type and a mean of the individual K_{OC} values was computed to determine a partition coefficient most representative of that particular trace metal.

Upon examination of the recent literature, the most comprehensive data was that of Brannon et al. (1980); the derivation of the K quantities presented in the present report rely solely on this data base. In the study of Brannon et. al, samples were taken from a wide variety of areas throughout the country, primarily from marine sediments but including a few freshwater sites as well. From each site, measurements were made of trace metal concentrations in the bulk sediment and in the interstitial water. K_D values calculated from this data are presented in Table 1. The K_D values were converted to K_{OC} values by dividing by the fractional mass of the sediment organic carbon concentrations.

As discussed in the previous section (Section 3.1) there is clear justification for normalizing the partitioning coefficient of synthetic organics to sediment organic content by use of K_{OC} rather than K_D but for trace metals the issue is more problematic and requires further examination. Of the six metals evaluated, a statistically significant relationship between K_D and organic content was evident for three metals (Cu, Cd, Pb) as shown in Table 2 and Figure 3. For these three metals it is clear that K_{OC} would be a better estimate of the sediment-water partitioning than would K_D. For the remaining three metals (Zn, As, Hg) the apparent independence of partitioning on sediment organic content is not taken as definitive evidence against the use of K_{OC}. It is very probable that the diversity of sites and variations in other environmental parameters among sites (e.g., redox potential) may have masked the relationship of K_D and organic carbon. It is noteworthy that even though normalization of mercury concentrations to organic carbon was not indicated as appropriate by this analysis, Lindberg and Harris (1974) found comparisons of mercury concentrations among sites to be more meaningful after the concentrations were first normalized to sediment organic content.

Table 1

EMPIRICAL SEDIMENT-WATER PARTITION COEFFICIENTS FOR TRACE METALS
(Values calculated from Brannon et al., 1980, as the ratio of total sediment metal concentration to the concentration of the metal in the interstitial water)[a]

Collection Site	Organic Carbon (%)	Cu K_D (×10³)	Cu K_{OC} (×10⁵)	Zn K_D (×10³)	Zn K_{OC} (×10⁵)	As K_D (×10³)	As K_{OC} (×10⁵)	Cd K_D (×10³)	Cd K_{OC} (×10⁵)	Pb K_D (×10³)	Pb K_{OC} (×10⁵)	Hg K_D (×10³)	Hg K_{OC} (×10⁵)
Mobile Bay, AL	0.82	1.8	2.2	2.0	2.6	0.25	0.10	0.06	0.07	3.5	4.3	0.15	0.14
Mobile Bay, AL	2.74	16.9	6.2	2.7	1.0	0.31	0.11	0.11	0.04	1.9	0.7	0.04	0.01
Duwamish Waterway, WA	1.42	8.4	5.9	11.8	8.0	0.44	0.31	0.06	0.03	4.0	2.8	0.47	0.47
Duwamish Waterway, WA	2.84	131.4	46.3	2.7	1.0	0.16	0.13	1.23	0.43	16.3	12.8	0.47	0.17
Duwamish Waterway, WA	1.98	49.7	25.1	11.4	5.7	0.28	0.14	1.02	0.14	4.2	2.1	0.25	0.11
Branford Harbor, CT	4.26	184.9	43.4	4.5	1.1	0.44	0.10	1.32	0.31	16.4	3.8	0.08	0.02
Branford Harbor, CT	5.12	93.7	18.3	0.9	0.2	0.08	0.02	1.11	0.22	13.4	2.6	0.20	0.04
Bridgeport Harbor, CT	6.03	482.0	79.9	10.3	1.7	0.29	0.05	2.80	0.46	74.8	12.4	0.09	0.01
Bridgeport Harbor, CT	6.16	222.5	36.1	37.6	6.1	--	--	17.80	2.89	4.3	2.3	0.16	0.01
Ashtabula Harbor, OH	0.92	2.9	0.8	4.3	4.7	0.26	0.28	1.20	1.30	4.5	4.9	0.01	0.01
Ashtabula Harbor, OH	2.44	10.5	4.3	1.0	0.4	0.23	0.09	1.80	0.74	1.1	0.5	0.11	0.05
Ashtabula Harbor, OH	2.58	7.0	2.7	0.4	0.2	0.47	0.18	1.60	0.62	11.1	4.3	0.06	0.02
James River, VA	3.11	2.2	0.7	1.5	0.5	0.04	0.01	2.50	0.80	0.2	0.1	0.15	0.05
James River, VA	2.01	31.4	15.6	0.2	0.1	0.66	0.32	0.24	0.12	1.8	0.9	0.10	0.05
Oakland Inner Harbor, CA	3.94	16.7	4.2	6.1	1.5	0.05	0.01	1.97	0.50	28.4	7.5	--	--
Oakland Outer Harbor, CA	1.69	4.7	2.8	1.4	0.8	0.14	0.08	1.80	1.07	2.6	1.5	--	--
Hudson River, NY	4.67	8.8	1.9	0.5	0.1	0.36	0.08	15.2	3.25	55.2	11.8	0.13	0.07
Terry Creek, GA	4.87	184.0	37.8	1.1	0.6	0.09	0.02	0.60	0.12	2.0	0.4	0.10	0.02
Brunswick Harbor, GA	3.95	140.0	35.4	6.3	1.6	0.06	0.02	0.60	0.15	1.0	0.3	--	--
Houston Ship Channel, TX	1.68	3.4	2.0	48.6	28.9	0.04	0.02	0.60	0.36	2.3	1.4	0.01	0.02
Houston Ship Channel, TX	3.24	32.7	10.1	10.2	3.1	1.24	0.38	0.30	0.09	1.9	0.6	0.07	0.02
Houston Ship Channel, TX	4.22	14.2	3.4	--	--	0.10	0.02	1.30	0.31	25.1	5.9	--	--
Mean			17.5		3.3		0.13		0.64		3.8		0.08
Standard Deviation			21.0		6.3		0.12		0.56		4.0		0.11

[a] Excludes one aberrant station in Milwaukee Harbor, WI.

Table 2

REGRESSION EQUATIONS ILLUSTRATING THE RELATIONSHIP OF THE
SEDIMENT-WATER PARTITION COEFFICIENT OF TRACE METALS
WITH THE PERCENTAGE OF ORGANIC CARBON IN SEDIMENTS

Metal	Regression	n	r
Cu	$\log K_D = 0.33 \ (TOC) + 3.28$	22	0.74^a
Zn	$\log K_D = 0.074 \ (TOC) + 3.29$	21	0.19
As	$\log K_D = -0.05 \ (TOC) + 2.46$	21	-0.19
Cd	$\log K_D = 0.21 \ (TOC) + 2.34$	21	0.55^a
Pb	$\log K_D = 0.20 \ (TOC) + 3.10$	22	0.47^a
Hg	$\log K_D = 0.05 \ (TOC) + 1.87$	18	0.21

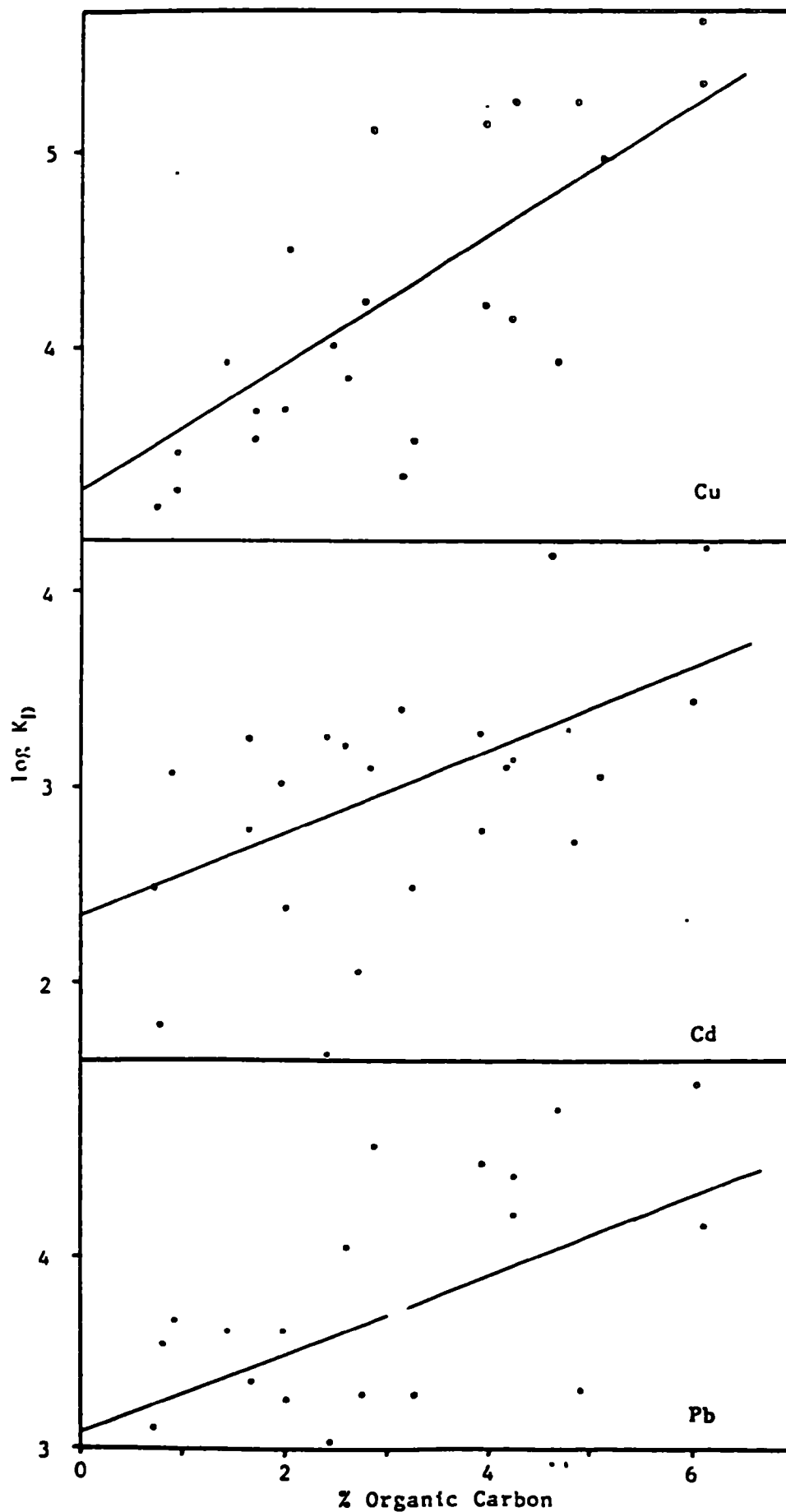[a] r value significant at $\alpha < 0.05$.

Figure 3

RELATIONSHIP BETWEEN THE
SEDIMENT-WATER PARTITION
COEFFICIENT AND THE
SEDIMENT ORGANIC CARBON
CONTENT FOR THREE TRACE
METALS

(All regressions signifi-
cant at $\alpha < 0.05$)

There is widespread evidence in the scientific literature that the trace metal content of marine and freshwater sediments is highly correlated with the concentration of organic carbon in the sediment. Crecilius et al. (1975) demonstrated this relationship for arsenic, antimony and mercury in the sediments of Puget Sound. This correlation is a result of the fact that organic material serves as one of the major trace metal sinks in marine sediments. Organic substances and iron plus manganese oxides dominate the trace metal sorptive properties of sediment (Jenne 1977; Jenne and Luoma, 1975). Thus sediments with a high organic content can generally be expected to exhibit a greater affinity for trace metals, and therefore have a higher K_D, than sediments with a low organic content. Normalization of trace metal concentrations to organic content, by use of K_{OC}, can be expected to provide a better estimate of partitioning, in most cases, than use of K_D alone. There is some limited evidence (Luoma and Jenne, 1975) that such an approach may not be appropriate for zinc and cobalt, but pending a thorough review of the anomalous behavior of these two metals, K_{OC} has been adopted throughout this report for all metals.

There are also biological considerations which support the normalization of K_D for trace metals to organic carbon. These are directly related to the concept of biological availability. Most of the studies addressing uptake of trace metals by sediments and organisms have demonstrated that trace metals in sediments with high concentrations of organic material are less available to deposit-feeding organisms than are those in sediments with little organic matter. For example, the uptake of mercury by both a polychaete and a deposit-feeding shrimp was significantly less when the sediment was rich in organic matter than when the mercury was associated with iron-oxides (Luoma, 1974). Iron-oxide bound cadmium was more available to the clam, Macoma balthica, than was organic-associated cadmium (Luoma and Jenne, 1975). Similar effects have been demonstrated for silver and copper as well (Luoma and Jenne, 1975; Jenne and Luoma, 1975). Consideration of organic content in the derivation of sediment criteria for trace metals makes the criteria more stringent for sediments with lower concentrations of organic matter. This is consistent with observations of increased bioavailability of trace metals in low organic environments. However, there are exceptions to this generality such as zinc and cobalt which demonstrate increased bioavailability in high organic environments (Luoma and

Jenne, 1975). Such exceptions may warrant further examination and may possibly require modifying the approach to sediment criteria for select trace metals.

3.2.2 Synthetic Organic Compounds

Partition coefficients for the synthetic organic priority chemicals were calculated from empirical relationships of K_{OC} versus K_{OW}, the latter quantity denoting the octanol-water partition coefficient for a given organic chemical. K_{OW} is a good indicator of the relative accumulation potential of a chemical in the environment, specifically in biotic components, since it reflects the influence of molecular properties on the affinity of the chemical for an organic matrix. K_{OW} is also useful in estimating a chemical's relative sorption potential on solid surfaces when coated with natural organic matter as is the case with aquatic sediments. As mentioned earlier, there is ample evidence that the affinity of an organic compound for sedimentary particles is determined to a large degree by the concentration of organic carbon in the sediment, hence the use of K_{OC} versus K_{OW} relationships is a highly advantageous technique for estimating sediment water partition coefficients for a variety of organic chemicals.

Estimation of K_{OW}

K_{OW} is usually determined experimentally by adding a small amount of the chemical to an octanol-water mixture, allowing the system to reach equilibrium, and then measuring the concentration of the chemical in each phase. Reliable estimates of K_{OW} have also been obtained by chromatographic techniques (Veith and Morris, 1978), from other solvent-water partition coefficients (Leo and Hansch, 1971), and by the fragment constant method (Hansch and Leo, 1979). K_{OW} values obtained by at least one of the above methods are available for most organic compounds. The K_{OW} values used in this study were obtained primarily from Karickoff (1981) and Kenaga and Goring (1980).

Development of K_{OC}/K_{OW} Relationships

K_{OC} values have been determined experimentally for about 70 organic compounds (Kenaga and Goring, 1980; Karickhoff, 1981). Figure 4 and Table 3 illustrate the various regression equations that have been used to predict K_{OC} from K_{OW}. The variability among the regression equations is a result of the different
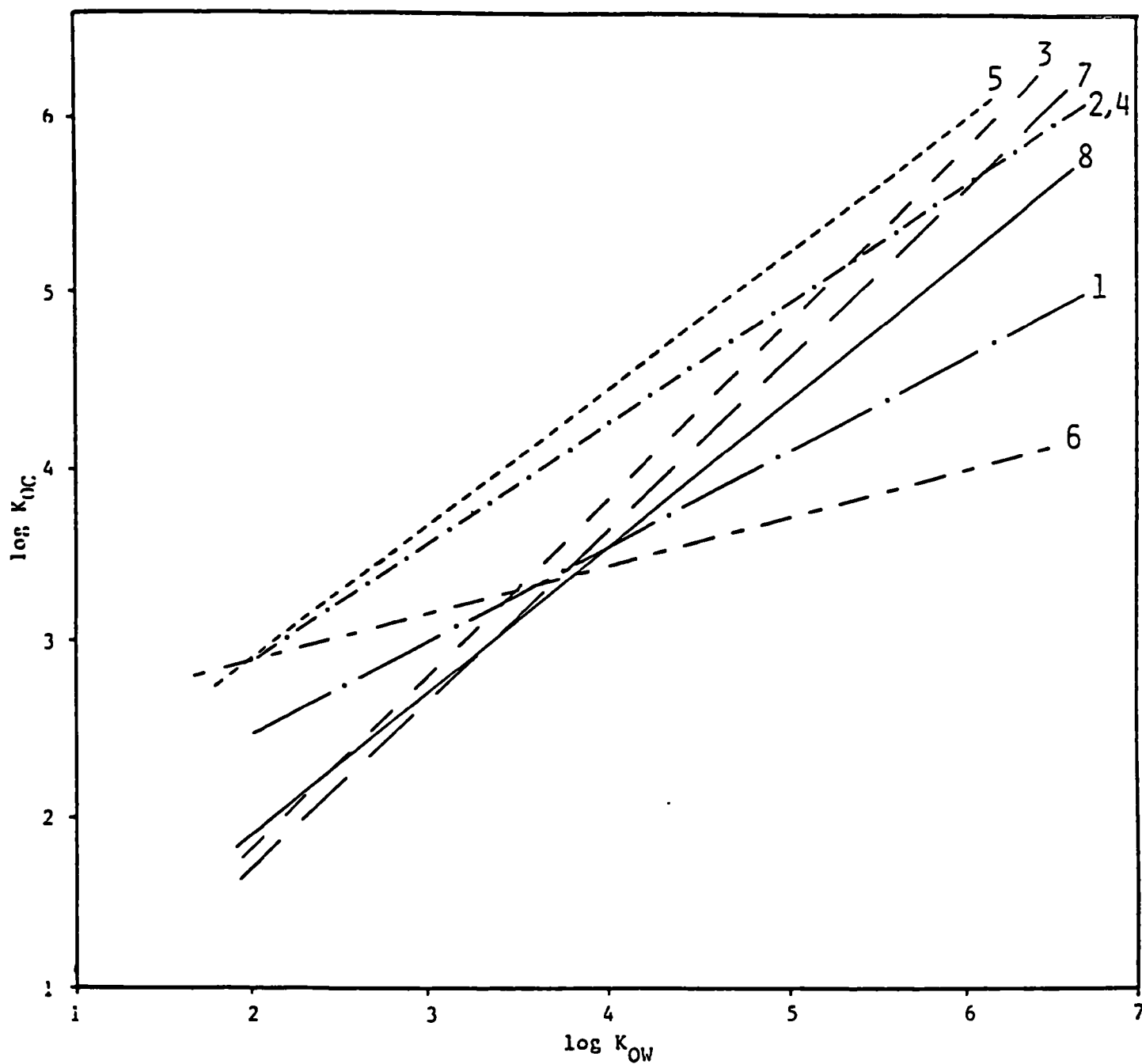
Figure 4

REGRESSION EQUATIONS FROM THE LITERATURE USED TO PREDICT K_{OC} FROM K_{OW}

(Numbers on each regression line refer to the equation numbers in Table 3)

Table 3

REGRESSION EQUATIONS FROM THE LITERATURE FOR THE ESTIMATION OF K_{OC} FROM K_{OW}
(Modified from Lyman et al., 1982)

No.	Regression	Number of Compounds Considered	r	Chemical Class	Reference
1	$\log K_{OC} = 0.544 \log K_{OW} + 1.377$	45	0.86	Pesticides	Kenaga & Goring, 1980
2	$\log K_{OC} = 0.937 \log K_{OW} - 0.006$	19	0.97	Aromatics, polynuclear aromatics, triazines, dinitroaniline herbicides	Brown et al., in prep.
3	$\log K_{OC} = 1.00 \log K_{OW} - 0.21$	10	1.00	Mostly aromatic & polynuclear aromatics	Karickhoff et al., 1979
4	$\log K_{OC} = 0.94 \log K_{OW} + 0.02$	9	--	Triazines and dinitroaniline herbicides	Lyman et al., 1982
5	$\log K_{OC} = 1.029 \log K_{OW} - 0.18$	13	0.95	Variety of herbicides, insecticides, and fungicides.	Rao & Davidson, 1980
6	$\log K_{OC} = 0.524 \log K_{OW} + 0.855$	30	0.92	Substituted phenyl ureas and alkyl N-phenylcarbamates	Briggs, 1973
7	$\log K_{OC} = 0.989 \log K_{OW} - 0.346$	5	1.00	Aromatic & polynuclear aromatic hydrocarbons	Karickhoff, 1981
8	$\log K_{OC} = 0.843 \log K_{OW} + 0.158$	19	0.96	Priority pollutants	Present report

chemical compounds used to derive each regression. For example, regression six was derived for phenylureas and phenylcarbamates, neither of which are relevant to environmental quality of Puget Sound. In order to obtain a K_{OW}-K_{OC} regression most applicable to those compounds measured in Puget Sound sediments, only the chemicals which were among the 129 EPA priority pollutants were considered. Nineteen priority organic compounds consisting primarily of polynuclear aromatic hydrocarbons and chlorinated hydrocarbons were identified for which literature values of K_{OW} and K_{OC} were available. From those compounds a regression equation was derived and the uncertainty in the computed K_{OC} values estimated. The results are shown in Figure 5. Estimates of K_{OC} obtained by this regression were calculated to have a standard error of about $\overset{x}{\div} 3$ (± 0.48 on log scale) though the error is somewhat greater ($\overset{x}{\div} 3.1$) at very high or very low values of K_{OW} and lower ($\overset{x}{\div} 2.8$) for K_{OW} values in the middle of the distribution. A comparison of measured K_{OC} values from the literature with those predicted by the regression is shown in Table 4 for the 19 priority pollutants on which the regression was based. On the average, predicted K_{OC} were within a factor of 2 (0.3 on log scale) of the measured values. The large deviation noted for hexachlorobenzene and pentachlorobiphenyl (nearly by a factor of 10) suggests either that these compounds exhibit anomalous chemical behavior or that the experimentally measured K_{OC} values may be in error.

The predictive capability of the K_{OW} - K_{OC} regression was tested for an additional 45 non-priority pollutants for which literature K_{OC} values were available. These data are superimposed on the regression obtained from the priority pollutants as shown in Figure 6. The predicted K_{OC} values from the regression are compared to the literature values in Table 5. In general the predictive capability of the regression is satisfactory for a wide variety of compounds. The K_{OC} values for polynuclear aromatics and chloro-s-triazines were particularly close to the literature values, generally within a factor of 2 to 2.5 (0.3 - 0.4 on log scale). The K_{OC} values for organophosphates and phenylureas were the least reliable, with an average error of about a factor of 5.

3.3 CALCULATION OF SEDIMENT CRITERIA

Sediment criteria for both the trace metal and priority organic contaminants considered in this study were computed using equation (4), Section 3.1.
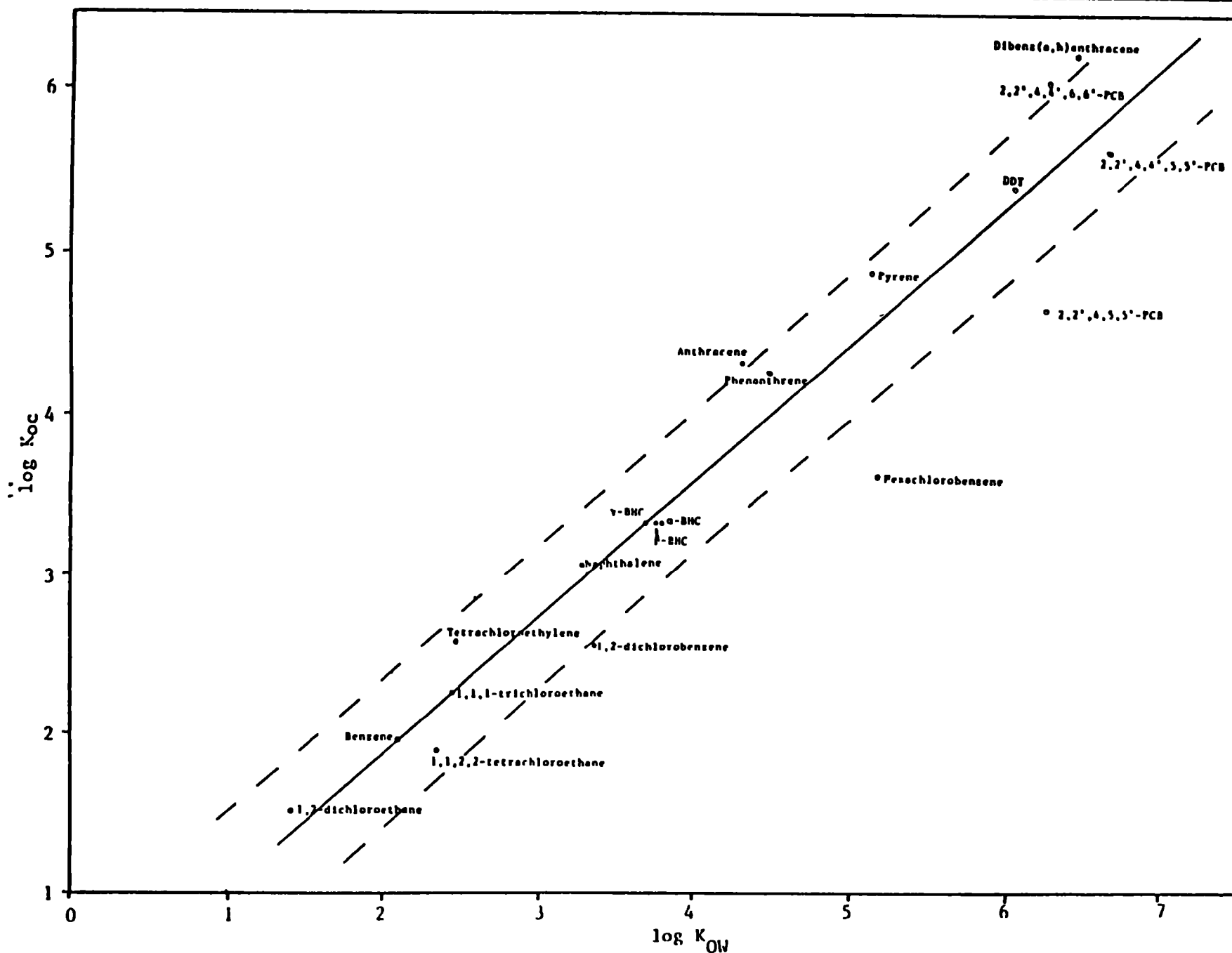
Figure 5

REGESSION OF K_{OC} and K_{OW} AS DEF__ __ FOR THE 19 PRIORITY POLLUTANTS SHOWN
Uncertainty limits on either side __ __ __e regression line are the standard errors

Table 4

COMPARISON OF K_{OC} VALUES PREDICTED BY THE K_{OW}-K_{OC} REGRESSION WITH MEASURED K_{OC} VALUES
FROM THE LITERATURE FOR THE 19 PRIORITY POLLUTANTS ON WHICH THE REGREESION IS BASED
(All literature values from either Karickhoff, 1981 or Kenaga and Goring, 1980)

Compound	log K_{OW} (literature)	log K_{OC} (literature)	log K_{OC} (predicted)	Error
Aromatic hydrocarbons				
Anthracene	4.40	4.32	3.87	-0.45[a]
Py·ei·a	5.18	4.88	4.52	-0.36
Phenanthrene	4.52	4.24	3.97	-0.27
Naphthalene	3.31	3.03	2.94	-0.09
Dibenz(a,h)anthracene	6.50	6.22	5.64	-0.58[a]
Benzene	2.12	1.95	1.95	-0-
			Average	0.29
Halogenated hydrocarbons				
1,2-dichloroethane	1.45	1.51	1.38	-0.13
1,1,1-trichloroethane	2.47	2.25	2.24	-0.01
1,1,2,2-tetrachloroethane	2.39	1.90	2.17	+0.27
Tetrachloroethylene	2.53	2.56	2.29	-0.27
1,2-dichlorobenzene	3.39	2.54	3.02	+0.48[a]
Hexachlorobenzene	5.23	3.59	4.57	+0.98[a]
DDT	5.98	5.38	5.20	-0.18
Y-BHC (Lindane)	3.72	3.30	3.29	-0.01
α-BHC	3.81	3.30	3.37	+0.07
β-BHC	3.80	3.30	3.36	+0.06
			Average	0.25
Halogenated biphenyls				
2,2',4,5,5'-pentachlorobiphenyl	6.30	4.63	5.47	+0.84[a]
2,2',4,4',5,5'-hexachlorobiphenyl	6.72	5.62	5.82	+0.20
2,2',4,4',6,6'-hexachlorobiphenyl	6.34	6.08	5.50	-0.58[a]
			Average	0.54

[a] Error exceeds one standard error.

Figure 6

K_{OC} AND K_{OW} VALUES FOR 45 N(IORITY POLLUTANTS SUPERIMPOSED ON
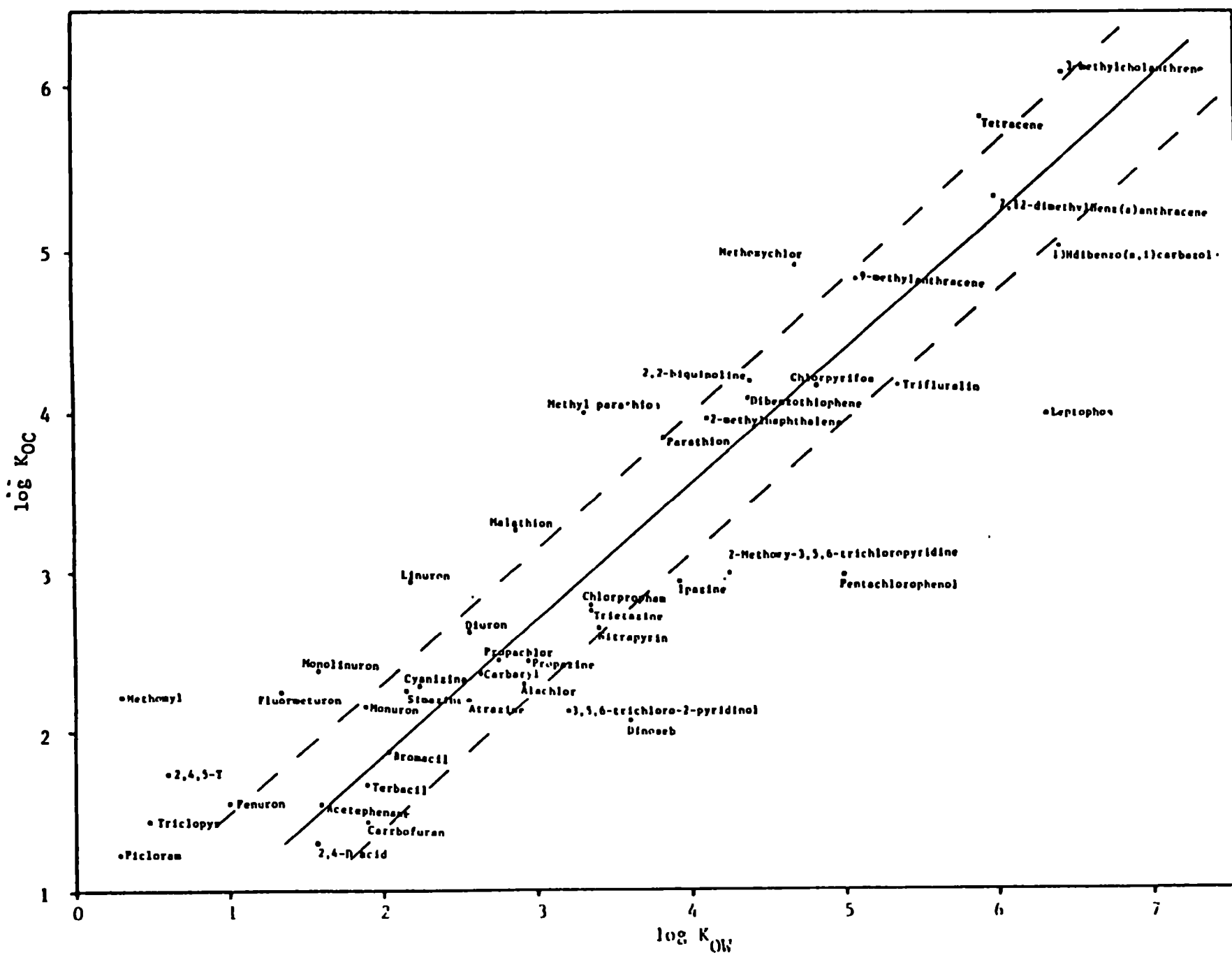THE REGRESSION DE\   , FOR PRIORITY POLLUTANTS

Table 5

COMPARISON OF K_{OC} VALUES PREDICTED BY THE K_{OC}-K_{OW} REGRESSION
WITH MEASURED K_{OC} VALUES FROM THE LITERATURE FOR 45 NON-PRIORITY POLLUTANTS
(All literature values from either Karickhoff, 1981; or Kenaga and Goring, 1980)

	log K_{OW} (Literature)	log K_{OC} (Literature)	log K_{OC} (Predicted)	Error
Aromatic hydrocarbons				
9-methylanthracene	5.07	4.81	4.43	-0.38
2-methylnaphthalene	4.11	3.93	3.62	-0.29
7,12-dimethylbenz(a)anthracene	5.98	5.35	5.20	-0.15
Tetracene	5.90	5.81	5.13	-0.68*
3-methyl cholanthrene	6.42	6.09	5.57	-0.52*
			Average	0.40
Halogenated hydrocarbons				
Methoxychlor	4.68	4.90	4.10	-0.80*
Chloro-s-triazines				
Atrazine	2.56	2.17	2.32	+0.15
Propazine	2.94	2.41	2.64	+0.23
Simazine	2.16	2.25	1.98	-0.27
Trietazine	3.35	2.74	2.98	+0.24
Ipazine	3.94	2.91	3.48	+0.57*
Cyanazine	2.24	2.26	2.05	-0.21
			Average	0.28
Carbamates				
Carbaryl	2.64	2.36	2.38	+0.02
Carbofuran	1.89	1.46	1.75	+0.29
Chlorprophan	3.06	2.77	2.74	-0.03
Methomyl	0.30	2.20	0.41	-1.79*
			Average	0.53
Organophosphates				
Malathion	2.89	3.25	2.59	-0.66*
Parathion	3.81	3.89	3.37	-0.52*
Methylparathion	3.32	3.99	2.96	-1.03*
Chlorpyrifos	4.81	4.13	4.21	+0.08
Leptophos	6.31	3.97	5.47	+1.50*
			Average	0.76
Phenyl ureas				
Diuron	2.57	2.60	2.32	-0.28
Fenuron	1.00	1.55	1.00	-0.55*
Linuron	2.19	2.93	2.00	-0.93*
Monolinuron	1.60	2.38	1.51	-0.87*
Monuron	1.90	2.14	1.76	-0.38
Fluometuron	1.34	2.24	1.29	-0.95*
			Average	0.66
Miscellaneous				
2,4-D acid	1.56	1.30	1.47	+0.17
Picloram	0.30	1.23	0.41	-0.82*
2,4,5-T	0.60	1.72	0.66	-1.06*
Triclopyr	0.48	1.43	0.56	-0.87*
Trifluralin	5.34	4.14	4.66	+0.52*
2-methoxy-3,5,6-trichloropyridine	4.28	2.96	3.77	+0.81*
Nitrapyrin	3.41	2.62	3.03	+0.41
3,5,6-trichloro-2-pyridinol	3.21	2.11	2.86	+0.75*
13Hdibenzo(a,i)carbazole	6.40	6.02	5.55	-0.47*
2,2'biquinoline	4.31	4.02	3.79	-0.23
Dibenzothiophene	4.38	4.05	3.85	-0.20
Acetophenone	1.59	1.54	1.50	-0.04
Terbacil	1.89	1.66	1.75	+0.09
Bromacil	2.02	1.86	1.86	-0-
Dinoseb	3.69	2.09	3.27	+1.18*
Pentachlorophenol	5.01	2.95	4.38	+1.43*
Alachlor	2.92	2.28	2.62	+0.34
Propachlor	2.75	2.42	2.48	+0.06
			Average	0.53

*Error exceeds one standard error.

3.3.1 Trace Metals

Sediment criteria were calculated based on the K_{OC} values derived from Brannon et al. (1980) and the available water quality criteria for protection of saltwater aquatic life. The results are summarized in Table 6 together with the corresponding water quality criteria. The standard deviation reflects the uncertainty in the K_{OC} values. Though many of the trace metal water quality criteria presented are draft criteria, they were chosen as representative of the most current toxicological information available.

3.3.2 Synthetic Organic Compounds

The derived sediment criteria for 47 priority organic compounds measured in sediments of the Central Basin of Puget Sound (Pavlou et al., 1983) are presented in Table 7. These criteria were based on the K_{OC} values estimated from regression equation 8, shown in Table 3. Again the associated standard error reflects the uncertainty in the K_{OC} values as discussed in Section 3.3.1. Though both acute and chronic sediment criteria are presented when available, the chronic value is recommended in order to insure adequate protection of marine life. Specifically, chronic sediment criteria are more appropriate than acute values since: (1) sediment contaminant concentrations reflect long-term conditions and do not demonstrate the extreme temporal variability of water column contaminant concentrations; and (2) benthic organisms often lack the mobility required to escape a contaminated environment and therefore are susceptible to impacts resulting from long-term chronic exposure. However, no chronic criteria are currently available for the majority of organic compounds and in these cases only acute sediment criteria have been presented in Table 7. It may be possible to establish an estimated chronic criteria by one of two methods: (1) for those compounds having a freshwater chronic criterion this may be used as an estimate of the saltwater criterion; and (2) the chronic criterion can be estimated from the acute criterion using the general "rule of thumb" that the acute:chronic ratio is 100:1. Both approaches warrant further consideration but a review of the toxicological literature is necesary to determine if one or both approaches would be suitable for establishment of interim sediment criteria guidelines.

It is important to note that for many compounds EPA has not established a water quality criterion but only identifies the lowest concentration at which

Table 6

SUMMARY OF DATA USED TO DEVELOP SEDIMENT CRITERIA FOR TRACE METALS

Chemical (Trace Metals)	EPA Water Quality[a] Criteria ($\mu g/\ell$)		$(K_{OC} \pm \sigma) \times 10^4$	Sediment Criteria $C_{S/CR/OC} \times 10^{-6} g/g$ o.c.	
	Acute	Chronic		Acute (σ)	Chronic (σ)
Arsenic^{+3}[b]	120	63	1.3 ± 1.2	1,600 ($\pm$1,400)	820 ($\pm$790)
Cadmium[b]	38	12	6.4 ± 8.6	2,400 ($\pm$3,300)	770 ($\pm$1,000)
Copper[b]	3.2	2.0	170 ± 210	5,400 ($\pm$6,700)	3,400 ($\pm$4,200)
Lead[b]	220	8.6	38 ± 40	84,000 ($\pm$88,000)	3,300 ($\pm$3,400)
Mercury[b] (inorganic)	1.9	0.10	0.8 ± 1.1	15 ($\pm$21)	0.8 ($\pm$1.1)
Zinc	170	58	33 ± 63	56,000 ($\pm$110,000)	19,000 ($\pm$38,000)

[a]Acute water quality criteria are the maximum permissible concentrations for protection of saltwater aquatic life as obtained from the Federal Register, Vol. 45, No. 231 (1980) or, in the case of some trace metals from draft criteria documents soon to be released. Chronic criteria are 24-hr average concentrations when obtained from the Federal Register or 30-day average when obtained from draft criteria documents.

[b]Draft criteria documents.

Table 7
SUMMARY OF DATA USED TO DEVELOP SEDIMENT CRITERIA FOR ORGANIC COMPOUNDS

Compound	Water Quality Criteria (μg/l)		log K_{ow}[a]	K_{oc}[b,c]	Sediment Criteria $C_{s/CR/OC} = 10^{-6}$ g/g o.c.	
	Acute	Chronic			Acute[d]	Chronic[d]
Phenol	2,900[e]		1.46	24	70	
Acenaphthene[a]	475[e]	355[e]	4.17	4,700	2,300	
Anthracene[a]	150[e,f]		4.40	7,400	1,100	1,650
Benzo(a)anthracene[a]	150[e,f]		5.61	37,000	5,500	
Benzo(a)pyrene[a]	150[e,f]		6.31	300,000	45,000	
Benzo(b)fluoranthene[a]	150[e,f]		6.57	500,000	75,000	
Benzo(k)fluoranthene[a]	150[e,f]		6.84	840,000	125,000	
Fluoranthene	20[e]	8[e]	5.33	45,000	900	
Fluorene[a]	150[e,f]		4.18	4,800	700	360
Naphthalene[a]	1,175[e]		3.31	890	1,050	
Phenanthrene[a]	150[e,f]		4.52	9,300	1,400	
Acenaphthalene[a]	150[e,f]		4.07	3,900	600	
Dibenz(a,h)anthracene	150[e,f]		6.50	160,000	24,000	
Isophorone	6,450[e]		1.67	37	240	
Nitrobenzene	3,340[e]		1.83	50	165	
1,2-dichlorobenzene	80[e]	65[e]	3.40	1,100	90	70
1,4-dichlorobenzene	80[e]	65[e]	3.37	1,000	80	65
2,6-dinitrotoluene	290[e]		2.05	77	22	
Benzo(g,h,i)perylene	150[e,f]		7.23	1,800,000	270,000	
Chrysene[a]	150[e,f]		5.61	77,000	11,500	
Indenopyrene	150[e,f]		7.66	4,100,000	600,000	
Pyrene[a]	150[e,f]		5.18	33,000	4,950	
Butylbenzyl phthalate	1,472[e,f]		4.05	3,700	5,500	
Di-n-butyl phthalate	1,472[e,f]		5.20	35,000	50,000	
Di-octyl phthalate	1,472[e,f]		9.20	82,000,000	120,000,000	
Diethyl phthalate	1,472[e,f]		1.40	22	32	
Dimethyl phthalate	1,472[e,f]		1.61	33	49	
Hexachlorobutadiene	16[e]		3.74	2,000	32	
a-BHC	0.17[e]		3.81	2,300	0.49	
Lindane[a]	0.16[g]		3.72	1,950	0.31	
DDD[a]	1.8[e]		6.03	180,000	325	
DDE[a]	7[e]		5.74	99,000	700	
DDT[a]	0.13[g]	0.001[g]	5.98	160,000	21	0.16
Aldrin[a]	1.3[g]		--	400[h]	0.52	
2-PCB[a]		0.014[f,g]	4.81	4,600		0.064
3-PCB[a]		0.014[f,g]	5.58	73,000		1.0
4-PCB[a]		0.014[f,g]	5.75	100,000		1.4
5-PCB[a]		0.014[f,g]	6.30	370,000		5.2
6-PCB[a]		0.014[f,g]	6.57	500,000		7
Benzene	2,550[e]	350[e]	2.12	97	245	34
Ethylbenzene	265[e]		3.15	650	140	
Methyl chloride	6,000[e]	3,200[e]	0.91	8	48	
Methylene chloride	6,000[e]	3,200[e]	1.25	16	95	50
Tetrachloroethylene	5,100[e]	225[e]	2.53	200	1,000	45
Toluene	3,150[e]	2,500[e]	2.21	100	315	250
Trichloroethylene	1,000[e]		2.42	160	160	
1,2-Dichloropropane	5,150[e]	1,520[e]	2.28	120	600	100

[a]Criteria for these compounds tested against measured concentrations in Puget Sound (see Section 4.3).

[a]K_{ow} values from Callahan et al. (1979); Dexter (1976); Kenaga and Goring (1980), Veith et al. (1980)

[b]Derived from regression 8 in Table 3.

[c]Standard error of K_{oc} values $\pm$ 3, 95% confidence interval $\pm$ 10.

[d]Standard error of sediment criteria $\pm$ 3, 95% confidence interval $\pm$ 10.

[e]Not nationally adopted water quality criteria, but rather one-half the lowest concentration at which toxic effects have been noted as reported in the Federal Register, Vol. 45, No. 231 (1980). Actual criteria, when established, are likely to be different.

[f]Based on the class criteria for polynuclear aromatic hydrocarbons (300 μg/L), phthalate esters (2,944 μg/L), or polychlorinated biphenyls (0.014 μg/L).

[g]EPA Water Quality Criteria. Acute criteria are the maximum permissible concentrations for protection of saltwater aquatic life as obtained from the Federal Register, Vol.45, No. 231 (1980). Chronic criteria are the 24-hour average concentrations from the same document.

[h]K_{oc} value obtained from Karickoff (1981). No literature value of K_{ow} is available to permit derivation of K_{oc} by the regression equation.

JRB Associates

adverse biological effects have been reported. In these cases, a sediment criterion has been determined on the basis a water quality "criterion" established at one half the lowest concentration causing adverse biological effects. The procedure closely parallels the protocol followed in development of water quality criteria in which a Final Acute Value (FAV) designed to protect 95 percent of a diverse group of species is determined, and the criteria is established at one half of the FAV. This approach has been adopted as an interim attempt to estimate the concentration at which a water quality criterion may eventually be established. However, it is important to recognize that for some compounds the lowest concentration causing adverse effects is based on a very limited toxicological data base. In these cases the estimated water quality "criterion" used in this report could be substantially different from the value eventually established. Therefore, these "criteria" may be inadequate to insure protection of marine life, and therefore any violation of these "criteria" could be of serious consequence.

The EPA water quality criteria for the PCBs, phthalates and polynuclear aromatic hydrocarbons are class criteria based on the cumulative concentration of all members of the class. In the derivation of the sediment quality criteria, it has been necessary to apply the class criterion to each member of the class individually, since each has a unique K_{OC}. In environments where one class member comprises the majority of the sediment burden of the class, this approach should prove adequate. However, if numerous class constituents are significantly enriched, a safe threshold for the class as a whole may be exceeded even though no individual constituent violates the criteria.

3.4 LIMITATIONS

Although the advantages of using the equilibrium partitioning approach were presented earlier in this report, there are a number of limitations inherent in the approach that must be considered as well. These are discussed below together with their implications in the use of the equilibrium partitioning approach.

3.4.1 Lack of Comprehensive Water Quality Criteria

The equilibrium partitioning approach has the advantage of providing a simple mechanism whereby water quality criteria can be adapted to sediment quality

criteria. However, this fact is also a limitation in that sediment criteria can only be established for those compounds for which water quality criteria are available. For the majority of synthetic organic contaminants, EPA has not yet established water quality criteria. This problem was addressed by using one half the lowest concentration causing adverse effects in cases where definitive water criteria were not available. As additional water quality criteria are established by EPA, sediment criteria can be readily determined for the same compounds.

3.4.2 Synergism and Antagonism

Synergistic or antagonistic interactions among contaminants can result in a mixture of contaminants having either a greater or lesser toxicity than would be expected simply on the basis of the toxicities of the individual contaminants. Thus there is some danger that although all individual contaminants may be at concentrations below criteria, synergistic interactions may still induce adverse biological impacts. While sediment criteria should ultimately account for synergistic effects, there is at present no way to do so given our current state of knowledge. The proposed criteria derived by the equilibrium partitioning approach represent an interim solution of immediate applicability. The only means currently available to address synergism is by using bioassay methods. Therefore the optimal approach to insure protection of marine life may be one whereby bioassays and the partitioning method may be used concurrently.

3.4.3 Level of Uncertainty in the Sediment Criteria

Unlike federal water quality criteria, the sediment criteria proposed in this report are presented as a mean with a specified level of uncertainty. This uncertainty is a result of our inability, based upon the current state of knowledge, to accurately predict the degree of partitioning of a contaminant between sediment and water. The water quality criteria is considered as a fixed value, therefore the level of uncertainty associated with the sediment criteria is entirely a consequence of the uncertainty in the K_{OC} value.

A number of options are available to environmental managers in attempting to implement a sediment criterion with a given level of uncertainty. One possible approach is to establish an alert level at the mean sediment criterion

and a maximum permissible sediment contaminant concentration at the upper bound of the uncertainty limit. A sediment in which the concentration of contaminant falls between the mean criterion for that contaminant and the upper bound of the uncertainty level could be identified for further studies such as bioassays in order to demonstrate the absence of any environmental danger. For those sites at which a contaminant concentration exceeds the upper bound of the uncertainty limit, immediate corrective action may be required. This upper uncertainty limit could be established either at one standard deviation from the mean or at the 95% confidence limit depending upon the degree of conservatism desired.

3.5 ASSUMPTIONS

A number of necessary assumptions have been incorporated in developing the equilibrium partitioning approach to sediment criteria. These are listed in Sections 3.5.1 through 3.5.5 below. Section 3.5.6 summarizes these assumptions and provides qualitative estimates of the impact on the criteria should the assumptions be violated.

3.5.1 Validity of The Equilibrium Assumption

The basic premise in the equilibrium assumption is that the distribution of a contaminant at the sediment-water interface is under thermodynamic equilibrium and the ratio of the contaminant concentration in the solid phase to its concentration in the aqueous phase is a constant. This assumption should generally hold except as the concentration of the contaminant approaches saturation at which point the solid phase:aqueous phase ratio may no longer be constant. However, this is not expected to significantly impact the equilibrium approach to sediment criteria since the criterion for a contaminant should be violated long before saturation is reached. It is possible that in the natural environment under certain physical/chemical conditions, kinetically controlled adsorption may be operable, which may violate the equilibrium assumption. These processes are complex and poorly understood (Lyman et al., 1982).

3.5.2 Normalization of K_{OC} to Organic Content

Throughout this report organic carbon content of the sediments has been considered a major environmental variable in determining the sediment-water partitioning for both trace metals and synthetic organic compounds. Justification

for using K_{OC} rather than K_D was provided in Section 3.1 for the organics and Section 3.2.1 for the trace metals. Though this appraoch is considered generally applicable, it may be necessary to modify it for a few select trace metals as discussed earlier (e.g., zinc). Such a determination would require careful review of existing literature and potentially additional experimental work.

3.5.3 Influence of Environmental Variables on K_{OC}

Although as discussed above, organic carbon appears to be an important variable influencing sediment-water partitioning other physical/chemical factors may affect the partitioning process. A brief discussion of the most important variables is presented below.

Reduction/Oxidation Potential and pH

Most of the organic contaminants of greatest environmental concern are the base-neutral compounds. These chemicals are relatively insensitive to changes in the reduction/oxidation (redox) potential or pH. However, for the trace metals, a change in the redox potential or pH can result in a change of oxidation state and/or chemical speciation and thereby dramatically influence the sediment-water partitioning and toxicity of the metal. The approach used in this report to derive K_{OC} values for trace metals was designed to take into account the dependency of partitioning on a variety of environmental variables, while recognizing our inability to predict these dependencies with our current limited of knowledge. Trace metal K_{OC} values were determined for a wide variety of environments (diversity of site locations) and then used to calculate an overall mean and standard deviation. Therefore, the variability in K_{OC} induced by the site specific reduction/oxidation conditions or pH is assumed to be incorporated into the estimate of the uncertainty about the mean.

Temperature

This physical variable may have a small influence on the partitioning of a chemical 'etween sediment and water. For most contaminants, an increase in temperature usually results in a decrease in K_{OC}, though there are exceptions. Lyman et al. (1982) calculated that a 10% decrease in K_{OC} could be typically expected for an increase in temperature from 20°C to 30° C. An 18% increase would be expected for a temperature decrease from 20° C to 5° C. Considering

that the values of K_{OC} used in the derivation of sediment criteria have a standard error of a factor of 3, the uncertainty introduced by variations in temperature is negligible.

Salinity

This variable may have some influence on K_{OC}, though as with temperature the impact is minimal. Karickhoff et al. (1979) reported a 15% increase in K_D with a change in salinity from 0 to 20%. Salinity may be of greater importance for the organic acids, though the extent of this importance is dependent upon the relationship of pH to the pK_a of the acid (Pionke and Chesters, 1973).

The salinity of the deep water layer in Puget Sound is fairly uniform and constant, although some variability is expected in the nearshore environments, specifically in the urban embayments. This variability may reflect small-scale circulation phenomena- and tidal mixing. It should be pointed out that the salinity in the water column may not be as important to the equilibrium partitioning approach as variations of ionic strength within the interstitial water.

Dissolved Organic Matter

Natural dissolved organic matter (DOM) consists primarily of refractory polyelectrolytes resulting from the degradation of biological materials (Christman and Minear, 1971). The DOM forms stable solutions which can scavenge trace metals or organic chemicals either through electrostatic interactions (ion-ion, ion-dipole or ligand) or through hydrophobic interactions with non-polar sites of the DOM. At the sediment-water interface these interactions may enhance the contaminant levels in the aqueous phase with the net result being a reduction in the partition coefficient value.

The implication of this phenomenon is twofold (1) under these conditions, the derived criterion should be a lower value, and (2) if direct uptake from interstitial water is the dominant mechanism of bioaccumulation, contaminant bioavailability will be increased. To this date these processes have neither been investigated nor well understood due to their complexity. It should also be noted that any elucidation of the chemical interactions at the sediment-water interface will be further complicated by the effect of pH or ion content

changes which in turn would influence the degree of ionization, the effective charge density and the chemical form of the DOM.

Particle Size

The importance of particle size in determining the magnitude of the sediment-water partition coefficient is largely a function of organic carbon content. Sediments with a high percentage of silts and clays generally have a high organic carbon content and consequently have a higher sediment-water partition coefficient (K_D). Sandy sediments have little organic carbon and have a lower partition coefficient. Grain-size dependent variations of the partition coefficient as a consequence of organic content is accounted for by expressing the partition coefficient as a K_{OC} value rather than K_D.

There is some limited evidence that surface area and other factors related to grain size may affect the partitioning beyond that which could be explained solely on the basis of organic carbon content. Karickhoff et al. (1979) examined the partitioning of pyrene and methoxychlor on a variety of particle size fractions. While K_{OC} remained essentially constant for all size fractions from coarse silt to clay, the sand fraction exhibited a K_{OC} only 20% of that derived from the fines. For sediments with a high percentage of sand (> 95%) some correction of the K_{OC} value may be required to account for particle size effects (Karickhoff, 1981).

As it pertains to sediment criteria, the work of Karickhoff suggests that in very sandy sediments, pollutants would have a lower affinity for sediment particles than predicted on the basis of a generalized K_{OC}. The sediment quality criteria for very sandy sediments would therefore be too high to provide adequate protection. Further laboratory work and field verification is necessary in order to define the dependence of K_{OC} on particle size. In the event such a dependence is established sediment criteria could easily be adjusted on the basis of the percentage of sand as well as on the organic carbon content.

3.5.4 Bioavailability of Contaminants at the Sediment-Water Interface

The soluble fraction of a contaminant is generally readily available for uptake by marine organisms (Jenne and Luoma, 1975; Roesijadi et al., 1978).

Therefore it is a relatively simple matter to establish a permissible concentration of a contaminant in water. However, the development of sediment quality criteria is complicated by the fact that the bioavailability of a contaminant in sediments is strongly dependent upon specific geochemical associations. Although the sediment quality criteria make the assumption that all of the contaminant in the sediment is in a bioavailable form, this is in fact rarely the case, for the total amount of a contaminant does not necessarily reflect its potential for biological effects.

As an example, Luoma and Jenne (1975) exposed clams to a variety of metal-contaminated artificial sediments including iron oxides, manganese oxides, calcium carbonate and an organic detritus. The concentration factors for the trace metals in clam tissue varied over two orders of magnitude depending upon the type of sediment in which they were held. The dependence of bioavailability on geochemical associations between a contaminant and sediments is probably most critical and best documented for trace metals but may be of significance for organics as well.

The question of bioavailability is not adequately treated in the sediment quality criteria proposed, since the criteria are given for the total contaminant in the sediment. It would be advantageous if criteria could be developed only for the bioavailable portion of the contaminant rather than the total contaminant load. Such an approach would require additional research but is not infeasible. A number of investigators have used sequential leaching techniques to extract only select fractions of the total contaminant load in sediments (Brannon et al., 1980; Vangenechten et al., 1983). If an extraction procedure can be found which will reliably identify the bioavailable portion of the total contaminant load, then a sediment criteria can be expressed in terms of the amount of the contaminant extracted by that procedure.

3.5.5 Applicability of Water Quality Criteria to Benthic Organisms

EPA water quality criteria for the protection of saltwater aquatic life are designed to insure that the concentration of contaminants in the aqueous phase do not exceed a level which would induce adverse effects in marine biota. In adapting the water quality criteria to sediment criteria, two assumptions have been made: (1) the permissible concentration of a contaminant in the aqueous

phase, as defined by the water quality criteria, are within safe limits for the protection of benthic organisms; and (2) ingestion of sediment-bound contaminants by benthic deposit-feeders does not result in a greater uptake of contaminants than that predicted by exposure to dissolved contaminants alone.

It is important to consider if benthic organisms would be afforded adequate protection by application of water quality criteria to the interstitial water. EPA water quality criteria are established on the basis of bioassays conducted with representatives of a number of phyla. Though the test organisms are typically free-swimming (e.g., fish, shrimp) a number of benthic invertebrate species have been included. Stephan et al. (1983) provides a list of marine species used in toxicity tests and includes a large number of polychaetes, molluscs and benthic crustaceans. Since benthic organisms have been employed in the derivation of criteria, these criteria should provide adequate protection to these animals. Additionally, there is no evidence to indicate that, as a group, benthic organisms are any more sensitive to dissolved contaminants than organisms in the overlying water column.

The role of uptake of sediment-bound contaminants by ingestion is a critical question in application of any type of sediment criteria. Not only are benthic organisms exposed to contaminants dissolved in the interstitial water, but they may ingest sediment particles during feeding activities and absorb sediment-bound contaminants through the gut wall. The concentration of contaminants on the ingested particle may be several orders of magnitude greater than in the interstitial water, but the amount of particle-associated contaminant available to an organism during passage through the gut depends upon the strength of the contaminant-sediment bond.

The equilibrium partitioning approach to sediment criteria does not discount the potential for uptake of contaminants by ingestion but only assumes that the contaminant body burden of the organism is independent of the route of uptake. If a system containing sediment, water and an organism is allowed to come to equilibrium, the level of a contaminant in each component should reach a constant, predictable concentration. For the purposes of the partitioning approach, it is assumed to be irrelevant whether the organism obtains the contaminant from the interstitial water or ingested sediment since the equilibrium body burden would be the same regardless of the route of uptake.

The experimental evidence available to support this assumption is very limited due to the experimental difficulties involved in assessing the route of pollutant uptake. The limited evidence seems to indicate that for the transuranium elements (plutonium, americium) and some trace metals, ingestion of sediment does not significantly increase the body burden above that attributable to absorption from the interstitial water (Renfro, 1973; Beasley and Fowler, 1976; Miramand et al., 1982; Vangenechten et al., 1983). Uptake of other trace metals and polychlorinated biphenyls on the other hand, may occur largely by ingestion of sediment as shown by a number of laboratory studies (Luoma and Jenne, 1975; Courtney and Langston, 1978; Fowler et al., 1978). The study of Fowler et al. (1978) is especially significant since the animals were allowed to reach equilibrium with the surroundings. In this case, organisms permitted to ingest sediment attained body burdens of PCB two orders of magnitude greater than those exposed to PCB in the dissolved form. It should be pointed out, however, that available experimental evidence is inadequate to either prove or disprove the assumptions of the equilibrium partitioning approach regarding the importance of contaminant uptake by ingestion. For most of the studies, the evidence presented is inconclusive or the experimental artifacts introduced are so great as to bring into question the applicability of the results to natural systems. Additional research is necessary to adequately evaluate the importance of pollutant uptake by ingestion of sediment.

3.5.6 Summary of Assumptions

Since the equilibrium partitioning concept represents a new and unique approach to sediment criteria, the analyses and evaluations presented in this report have focused on the identifications of all assumptions inherent in the approach. None of the assumptions are considered significant enough to invalidate the approach, but it was deemed essential to assess their potential impact. They have been discussed at considerable length both to insure against misuse of the approach and to direct further efforts of refinement.

The assumptions presented above are summarized in Table 8 and cross-referenced with the report section in which they are discussed. For each assumption a potential for violation has been given which represents the likelihood (high, medium or low) that the assumption may prove invalid by further investigation.

JRB Associates

Table 8

ASSUMPTIONS OF THE EQUILIBRIUM APPROACH AND THEIR POTENTIAL FOR VIOLATION

Assumption	Report Section	Potential for Violation of Assumption	Impact of Violation on Proposed Criteria
Sediment-water partitioning of a contaminant is at equilibrium	3.5.1	Medium	Criteria may be too conservative. Violations would be site-specific and source-specific, not compound-specific.
Magnitude of partition coefficient dependent upon sediment organic content	3.5.2	Low (organics) High (metals)	At low organic carbon levels the proposed criteria would be too conservative. At high organic carbon levels the criteria would be liberal.
Variations in the redox potential and pH will not impact criteria	3.5.3	Low (base-neutral organics); High (metals and some organics)	The effect of redox potential on trace metal partitioning has been largely accounted for by empirical derivation of partition coefficients. In some instances, the redox potential may effect partitioning beyond the level already accounted for. Field verification is needed to determine potential impact on criteria.
Independence of partitioning on temperature	3.5.3	Low	Typical environmental variations in temperature will effect criteria by 10% or less.
Independence of partitioning on salinity (ionic strength)	3.5.3	Medium	For most contaminants of environmental concern, variations in salinity typical of marine waters will have a negligible impact on the criteria. Variation in salinity between fresh and salt-water could effect criteria by about 25%. An increase in ionic strength of interstitial water would result in a higher criteria val therefore criteria may be too conservative.
Independence of partitioning on dissolved organic matter (DOM)	3.5.3	Medium	Criteria would be lowered as DOM increases. Criteria may be too liberal.
Particle size is not important in determining partitioning other than as a covariate with organic carbon	3.5.3	Low	Evidence to date is very limited but in very sandy sediments criteria may be too liberal.
Entire contaminant burden of sediments is in a bio-available form	3.5.4	High	If a fraction of the contaminant is not bio-available, the proposed criteria would be too conservative.
Water quality criteria are appropriate for benthic organisms	3.5.5	Low	Criteria would be either too liberal or too conservative depending upon toxicant sensitivity of benthic organisms.
Ingestion of sediment-bound contaminants by deposit-feeders does not increase contaminant body burden above levels attained by exposure to the dissolved contaminant fraction	3.5.5	Medium	Criteria would be too liberal if assumption were violated.

Many of the assumptions are unavoidable because of the inadequacy of our current state of knowledge. In these cases the potential for violation represents a "best guess" by the authors based on the limited information available. Should any of the assumptions be violated, the potential impact on the proposed criteria is also given. The potential impact is quantified in some cases (e.g., temperature and salinity) though for most assumptions it is impossible to go beyond a qualitative statement of potential impact at this time.

4.0 FEASIBILITY TESTING IN PUGET SOUND

4.1 FORMAT OF PRESENTATION

In order to compare a measured contaminant concentration in Puget Sound with the sediment criterion for that compound it is most convenient to use equation (5) Section 3.1 and represent criteria limits as a plot of contaminant concentration $c^X_{S/CR}$ versus percent organic carbon (Figure 7). These plots (diagonal lines) can be produced showing both the acute and chronic criteria as well as the bounds for the uncertainty limits around the criteria. For the purpose of this report, the plots from now on will be referred to as the "criteria-graph" for the contaminant of concern. Specifically, the criteria-graphs are determined by converting the organic carbon normalized criteria ($c^X_{S/CR/OC}$ of Tables 6 and 7) to equivalent dry weight normalized concentrations ($c^X_{S/CR}$) at a given organic carbon content. For example, the chronic $c^X_{S/CR/OC}$ value for Pb is 3,300 ppm. For sediments with 10% organic carbon (0.1 g o.c./g sediment) the permissible concentration of lead in the sediments for protecting the biota from chronic toxicity is 330 ppm. The criteria-graphs present the permissible sediment contaminant concentrations at any specified organic carbon content.

The contaminant concentrations and organic carbon content at sites of concern can be plotted on the graph and readily compared to a criterion. Those stations to the left of a criterion line are below the criterion, while those to the right of the line exceed criterion. In the example of Figure 7, Station A is below the chronic criterion for lead, Station B exceeds the mean criterion but is within one standard deviation and station C exceeds the criterion by more than one standard deviation. The example also illustrates the importance of considering organic carbon content as well as contaminant concentration in assessing the extent of contamination. Station A is the only station below criterion despite the fact that it has a greater contaminant burden on a dry weight basis than Station B.

' couple of points are important to bear in mind in evaluating Figure 7 and similar figures throughout Section 4.3. First, in determining the K_{OC} for trace metals, the standard deviation of the K_{OC} was found to be greater than the mean value (see Table 1). When the uncertainty of the K_{OC} is incorporated
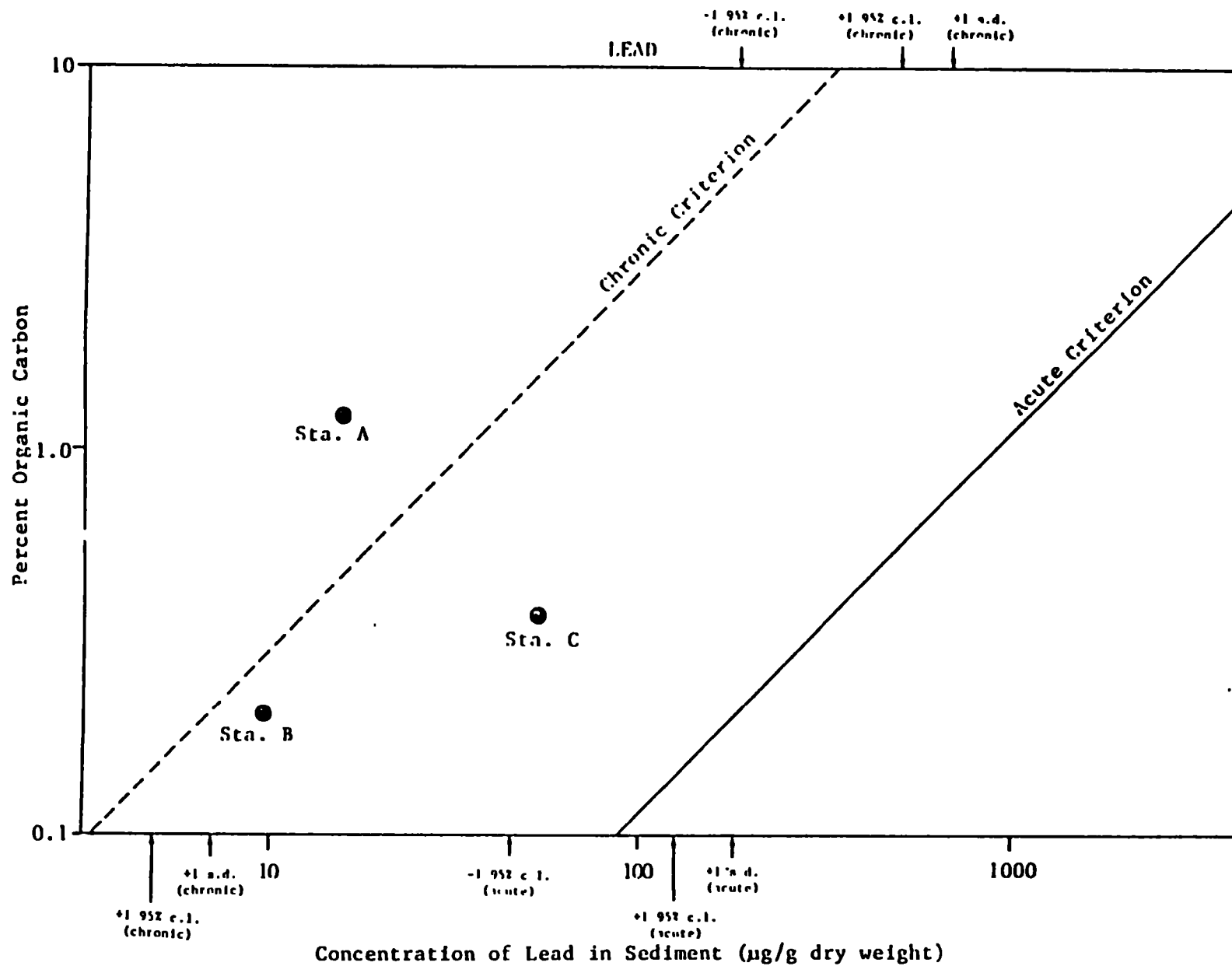
Figure 7

PRESENTATION FORMAT FOR COMPARISON OF SEDIMENT CRITERIA
WITH ACTUAL MEASURED CONTAMINANT CONCENTRATION

in the derivation of sediment criteria for trace metals, the criteria minus one standard deviation lies below a concentration of zero. Therefore it is only possible to show the criteria plus one standard deviation on the criteria-graphs for trace metals. A similar problem is not apparent in the criteria-graphs for synthetic organics since the criteria for organics were derived on the basis of the K_{OW} - K_{OC} regression in which the standard error of K_{OC} was less than the mean. Therefore both an upper and lower standard error can be shown for the organics.

Secondly, the 95% confidence interval is equally as valid as the standard deviation or standard error as a measure of uncertainty around the criteria. Both the 95% confidence interval and the standard deviation are shown in Figure 7 but only the standard deviation or standard error are shown in later figures in Section 4.3 in order to simplify the presentation. It is possible to calculate 95% confidence intervals using the methods shown in Sokal and Rohlf (1981) and numerous other statistics books. For all the trace metals, the 95% confidence intervals would appear on the criteria-graphs at approximately the same position relative to the mean and standard deviation as is shown in Figure 7. For the synthetic organics, the 95% confidence intervals would appear on the criteria-graphs as symmetrical about the mean, located at a distance approximately two standard errors from the criteria value.

4.2   TRIAL DATA SETS

To test the applicability of the derived criteria values to Puget Sound, two independent data sets were selected that had sufficient ancillary information to allow direct comparisons of contaminant sediment concentrations to the numerical criteria values computed by the equilibrium partitioning approach.

1.   The first set of test data used was that published by Malins et al. (1980), encompassing six embayments in Puget Sound (Commencement Bay, Elliott Bay, Sinclair Inlet, Port Madison, Case Inlet, and Budd Inlet). These subregions are known to vary in degree of contamination and therefore provided a wide enough spectrum of contaminant concentrations in sediments to determine the extent of sediment criteria violations. The data used in the analyses are presented in Appendix A of this report and extracted from Appendix D (Results of Chemical Analyses) Tables D-2, D-3, D-4, D-5 and D-7 from Malins et al. (1980).

2. Sediment criteria were also tested by comparison with the concentration of contaminants in sediments measured in Elliott Bay and within the vicinity of the West Point Outfall as published in the Metro/TPPS Draft Report (Pavlou et al., 1983). These measurements constitute the most recent information on toxicant accumulation in sediments in this urban environment. The concentration data of the priority compounds used are presented in Appendix B of this report and were extracted from Appendices 7A.1, 7A.2 and 7B.1 of the Metro/TPPS Report, Volume I. The zone designations for the specific subregions used were: Area EE, Central Elliott Bay; Area B, South Elliott Bay; Area C, Eastern Elliott Bay; and Area D, Northeast Elliott Bay/Denny CSO area. The West Point sampling sites used were those included in Area F.

The Metro/TPPS data did not include measurements of sediment organic carbon content taken concurrently with the samples for chemical analysis. However, since the percentage of silt and clay particles in sediments is highly correlated with the organic carbon content, it is possible to estimate organic carbon content from grain size data. Grain size and organic carbon content data from Malins et al. (1980) was used to develop a regression which defined the relationship between these variables (Figure 8). Metro/TPPS grain size data was then used to estimate the organic carbon content of these sediments (Appendix C). While this approach is the only alternative when organic carbon data is lacking, it should be noted that the procedure adds an additional degree of uncertainty in determination of the appropriate sediment criteria.

4.3 COMPARISON OF MEASURED CONCENTRATIONS WITH DERIVED CRITERIA

The sediment contaminant concentrations in the trial data sets of Malins et al. (1980) and Metro/TPPS were compared to criteria levels using the graphical approach discussed above in Section 4.1. The data from each test station were illustrated as a scatterplot on a graph of sediment contaminant concentration vs. percent organic carbon. The criteria-graphs were superimposed upon these same plots using the solid and dashed lines to represent acute and chronic criteria, respectively, as demonstrated in Figure 7. The results of the comparison of measured concentrations with criteria are illustrated for the trace
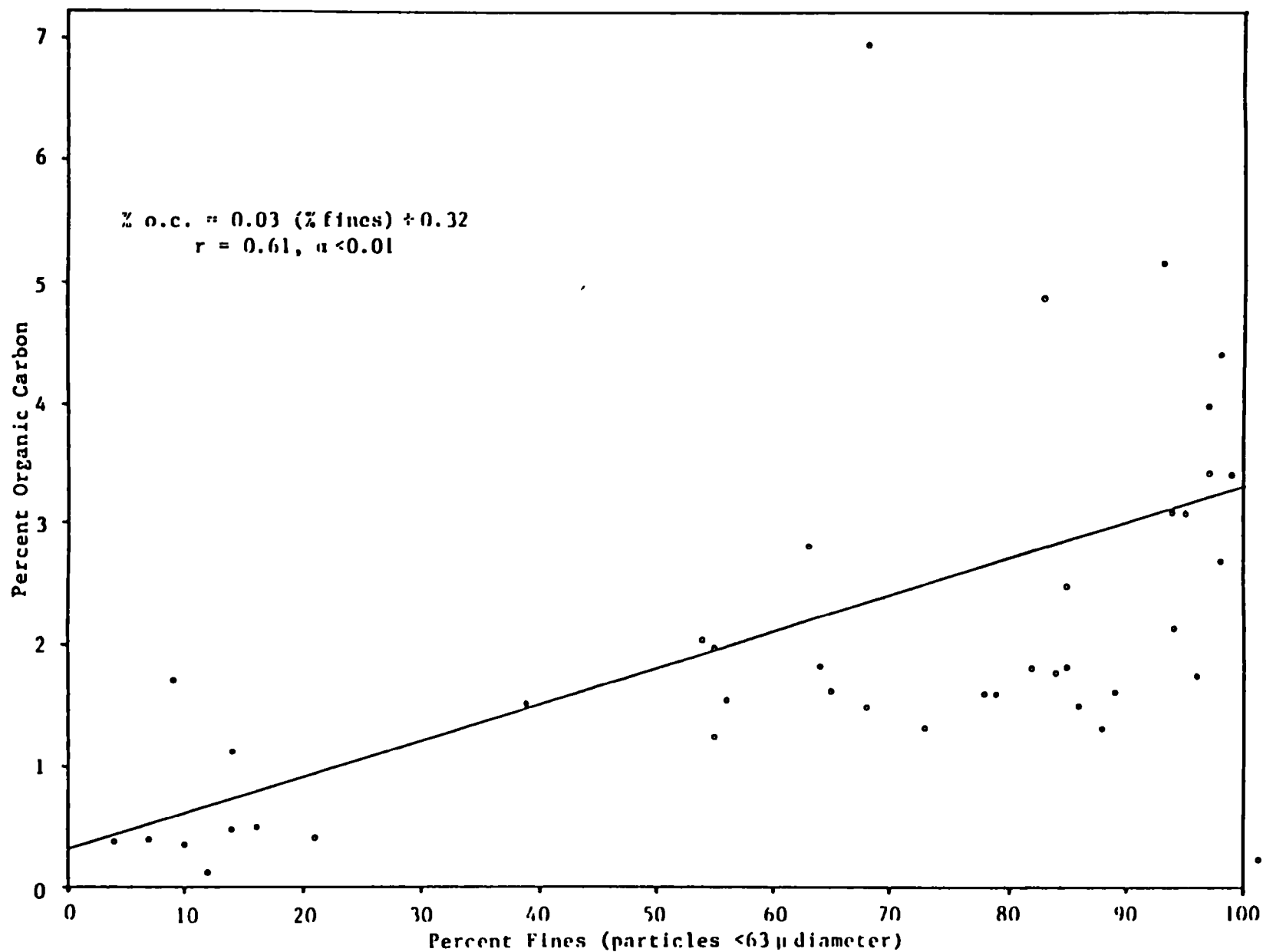
$\%$ o.c. = 0.03 ($\%$ fines) + 0.32
r = 0.61, α <0.01

Figure 8

REGRESSION USED TO ESTIMATE THE ORGANIC CARBON CONTENT OF SEDIMENTS FROM THE PERCENTAGE OF FINES
(Data from Malins et al., 1980)

metals (Figures 9-14) and for the synthetic organics (Figures 15-23). Illustrations are shown only for nine organic compounds. An additional 14 compounds were also examined as designated in Table 7, though observed concentrations were generally well below criteria.

Examination of the graphs reveals the following:

- For the trace metals examined, the chronic criteria is exceeded in the order: Hg>Pb>Cu>As>Zn>Cd. Acute values are exceeded primarily by the metals Hg>Cu>As; no violations are apparent for Cd, Zn and Pb. Among the subregions examined, proposed criteria are exceeded most frequently in Elliott Bay and Commencement Bay. Chronic criteria for Hg are exceeded in all areas suggesting that the criteria for Hg may be unrealistically low.

- For the synthetic organic compounds tested, the absence of chronic criteria for most contaminants prevented an evaluation of the significance of the observed levels. However, for PCBs and DDT chronic values are obviously exceeded within the most contaminated urban embayments. Acute values for the remainder of the chemicals examined were exceeded only by fluoranthene, phenanthrene and pyrene within a fairly localized area north of the West Point Outfall. It should be noted however that for most of the polynuclear aromatic hydrocarbons (PNAs) the criteria values used are both class criteria and one-half the lowest concentrations at which toxic effects have been noted as reported in the Federal Register, Vol. 45, No. 231 (1980). Individual compound criteria may therefore be substantially lower, thus increasing the probability of violations within the regions examined. Similar limitations should also be considered in the use of class chronic criteria for PCBs.

- Most of the measured contaminant concentrations which exceed the derived sediment criteria fall within plus one standard deviation or standard error of the mean criteria values as computed from the uncertainty assigned to the partition coefficient quantities (K_{OC}). This may have some implication on the enforceability of the numerical action levels computed by this approach (see Section 3.4.3).
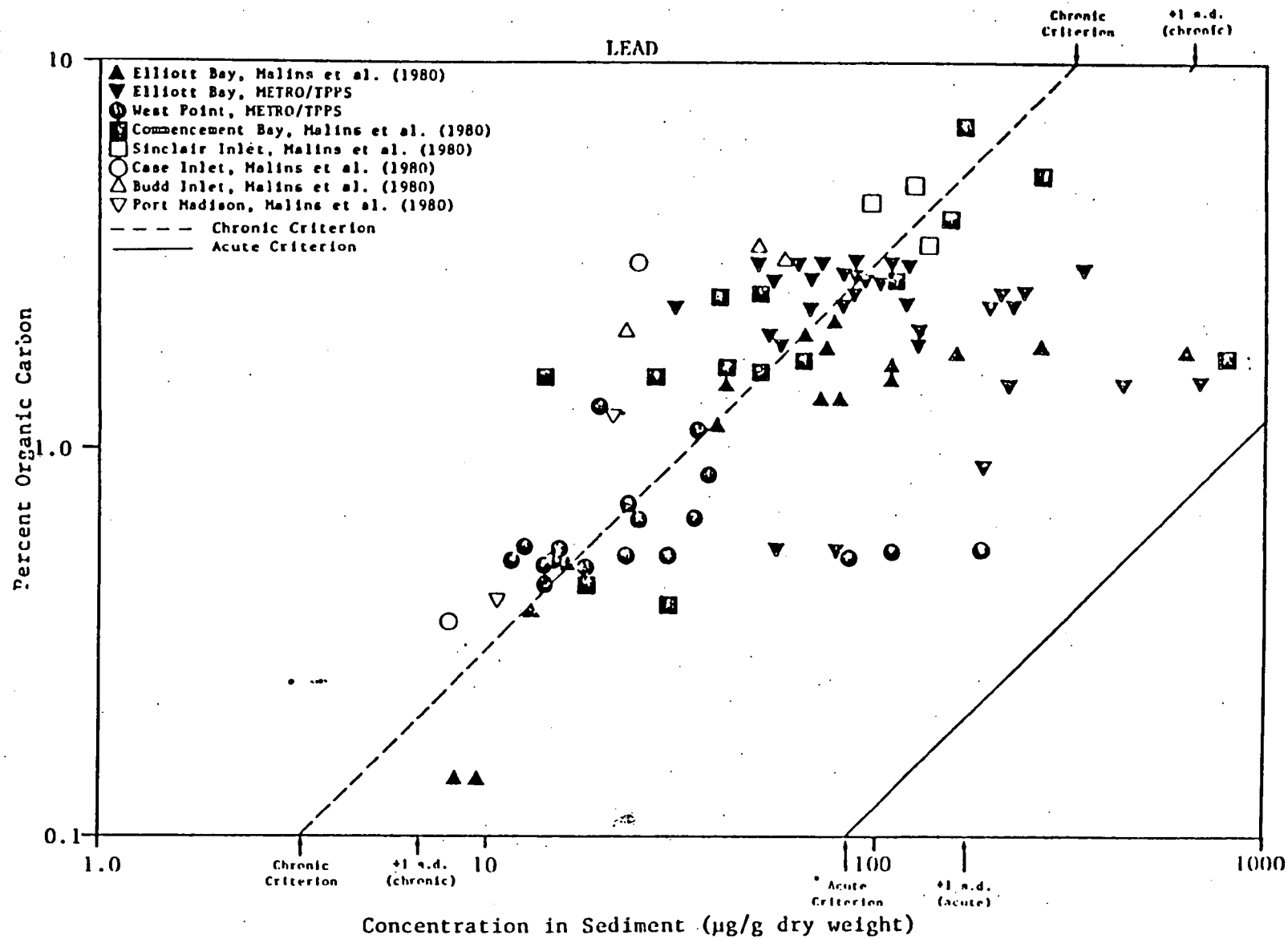
Figure 9

OBSERVED CONCENTRATIONS OF LEAD IN THE SEDIMENTS OF PUGET SOUND
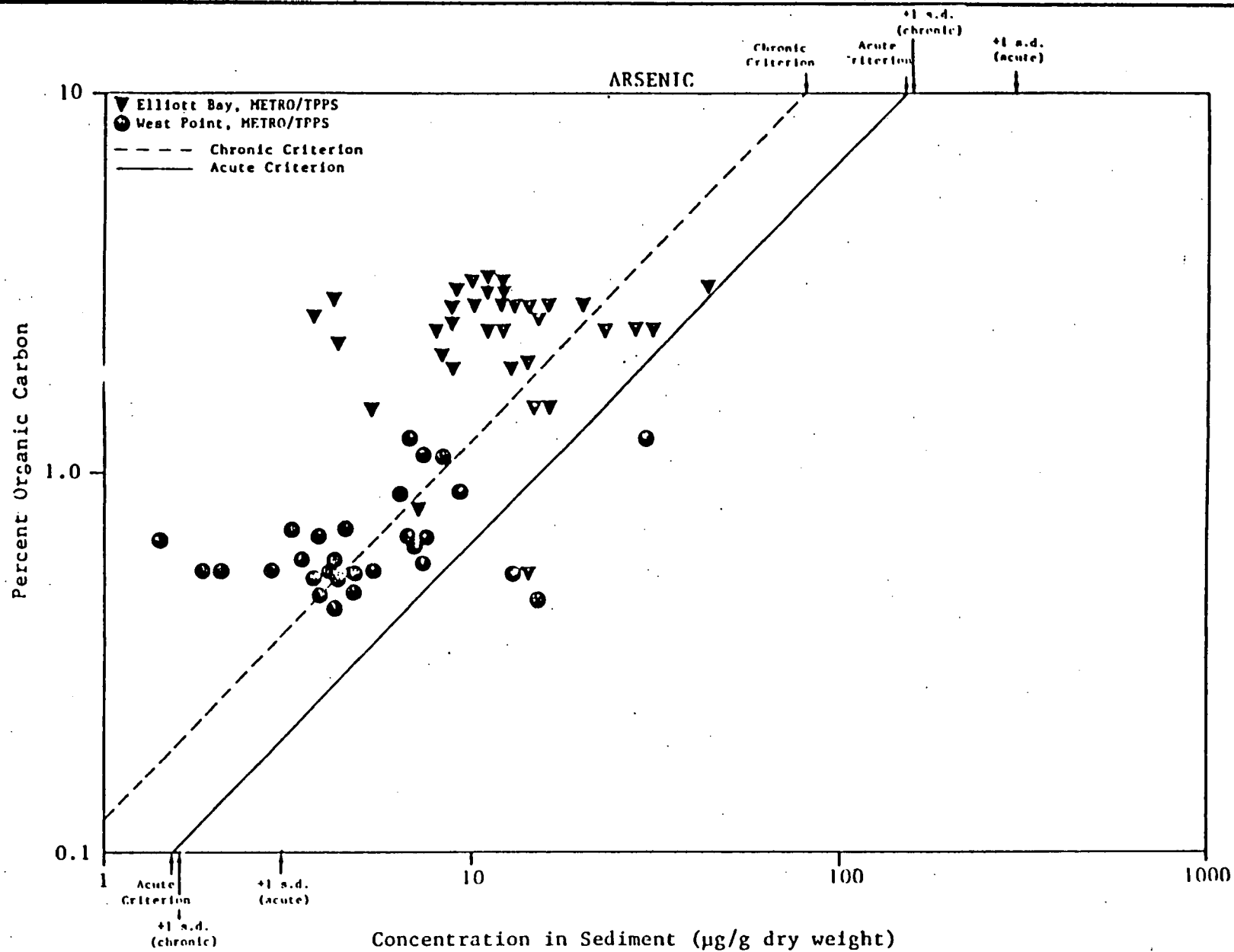IN COMPARISON TO CRITERIA VALUES

Figure 10

OBSERVED CONCENTRATIONS OF ARSENIC IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES
(Arsenic concentrations reported by Malins et al., 1980, are suspiciously high and were not included)
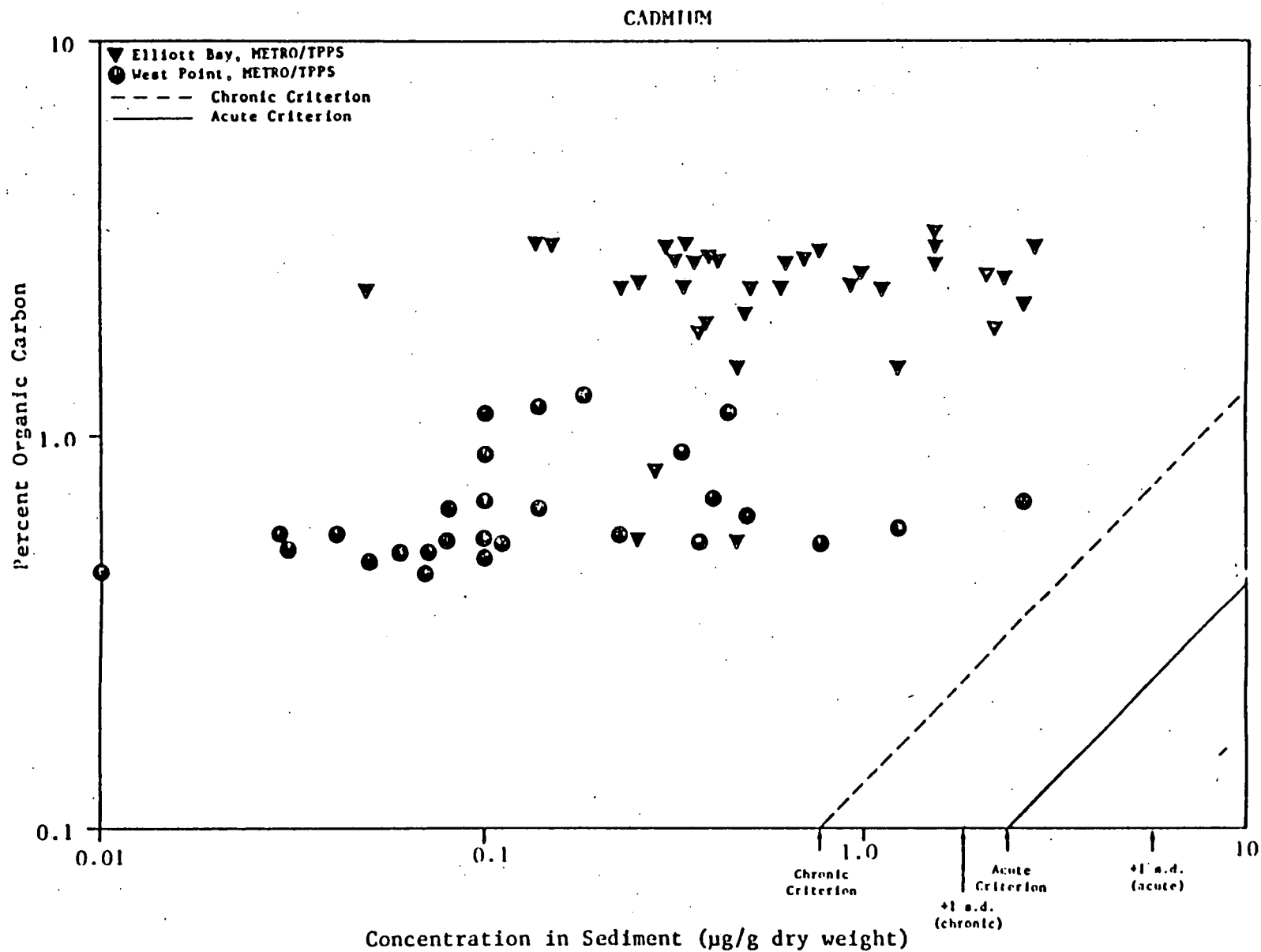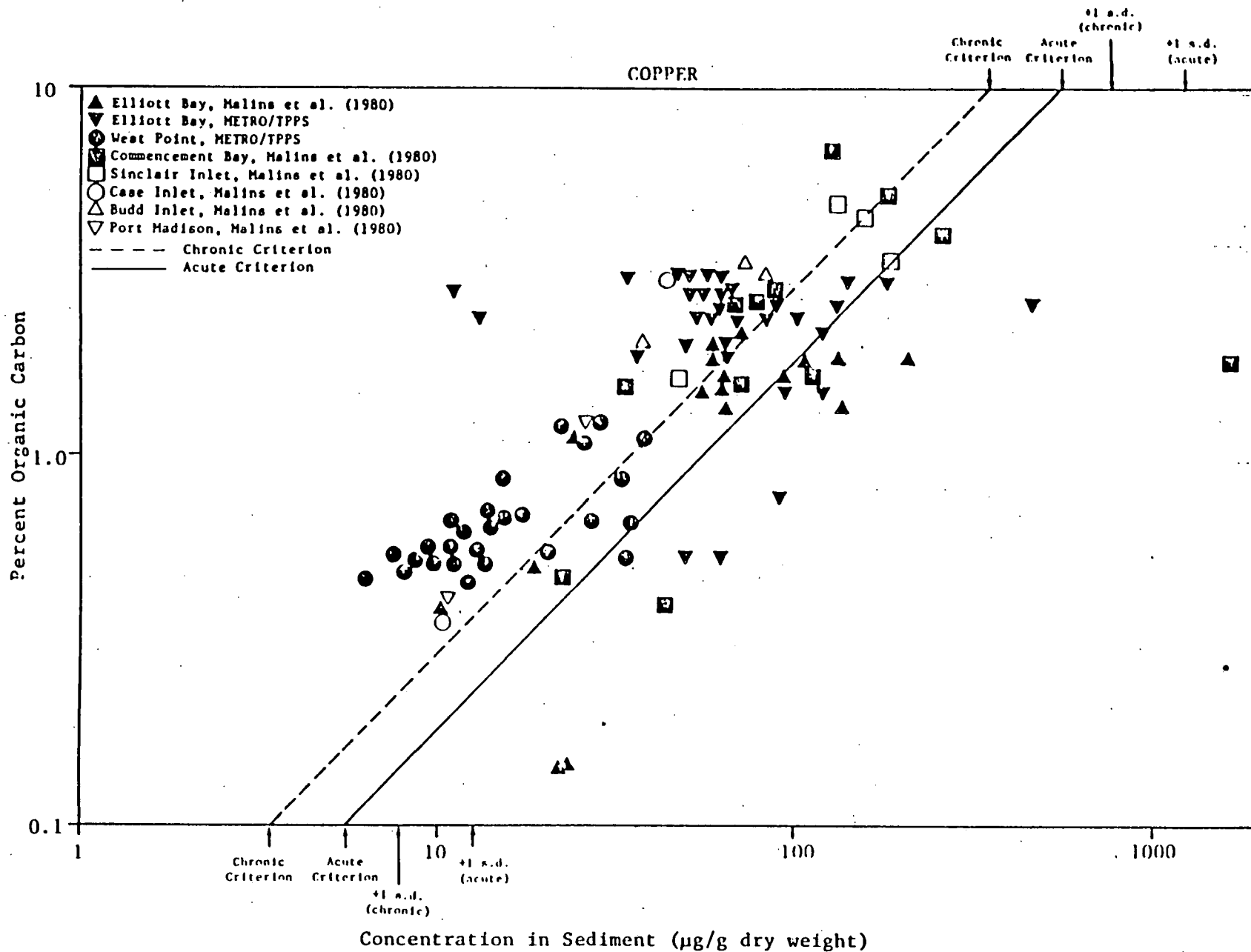
Figure 11

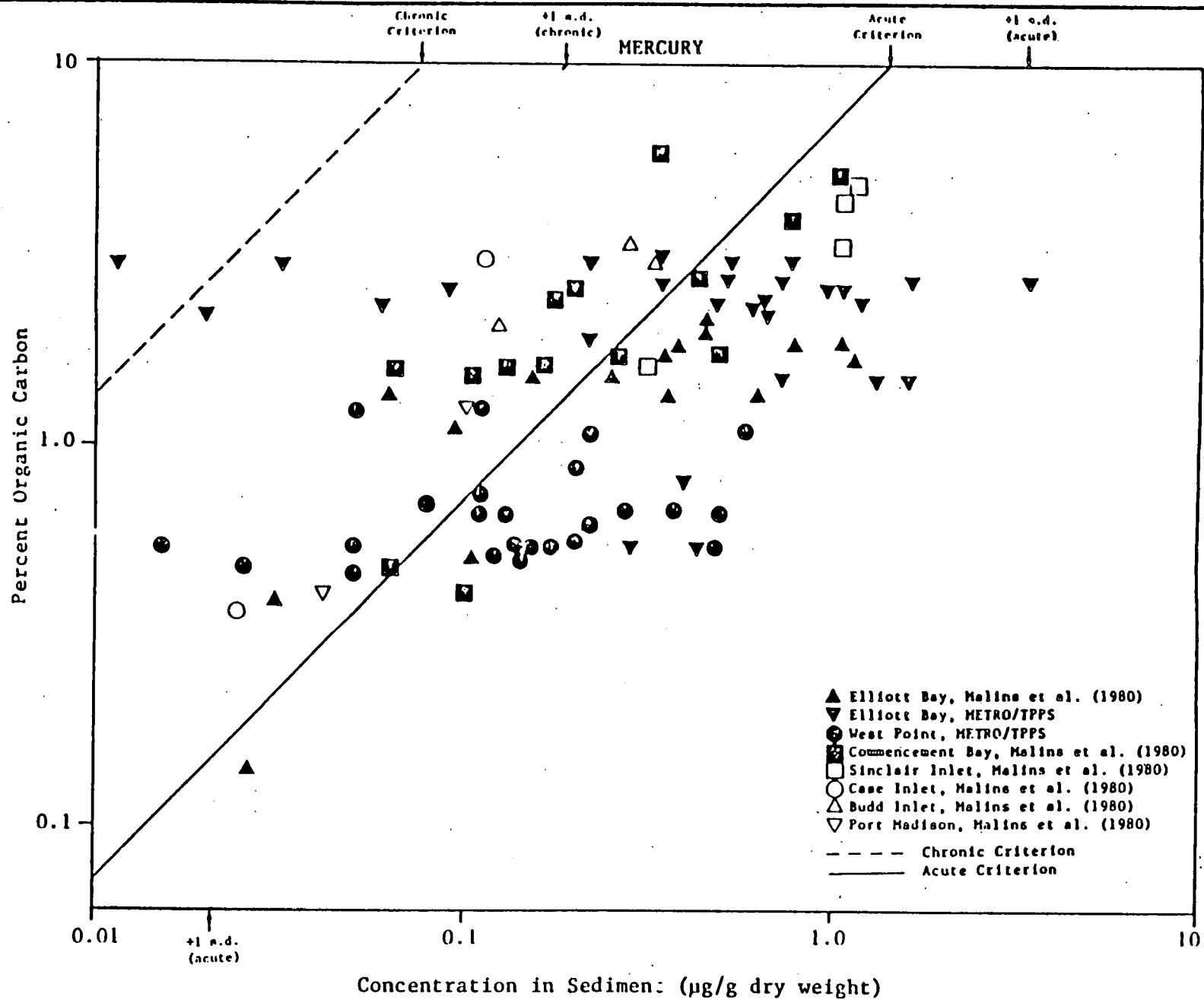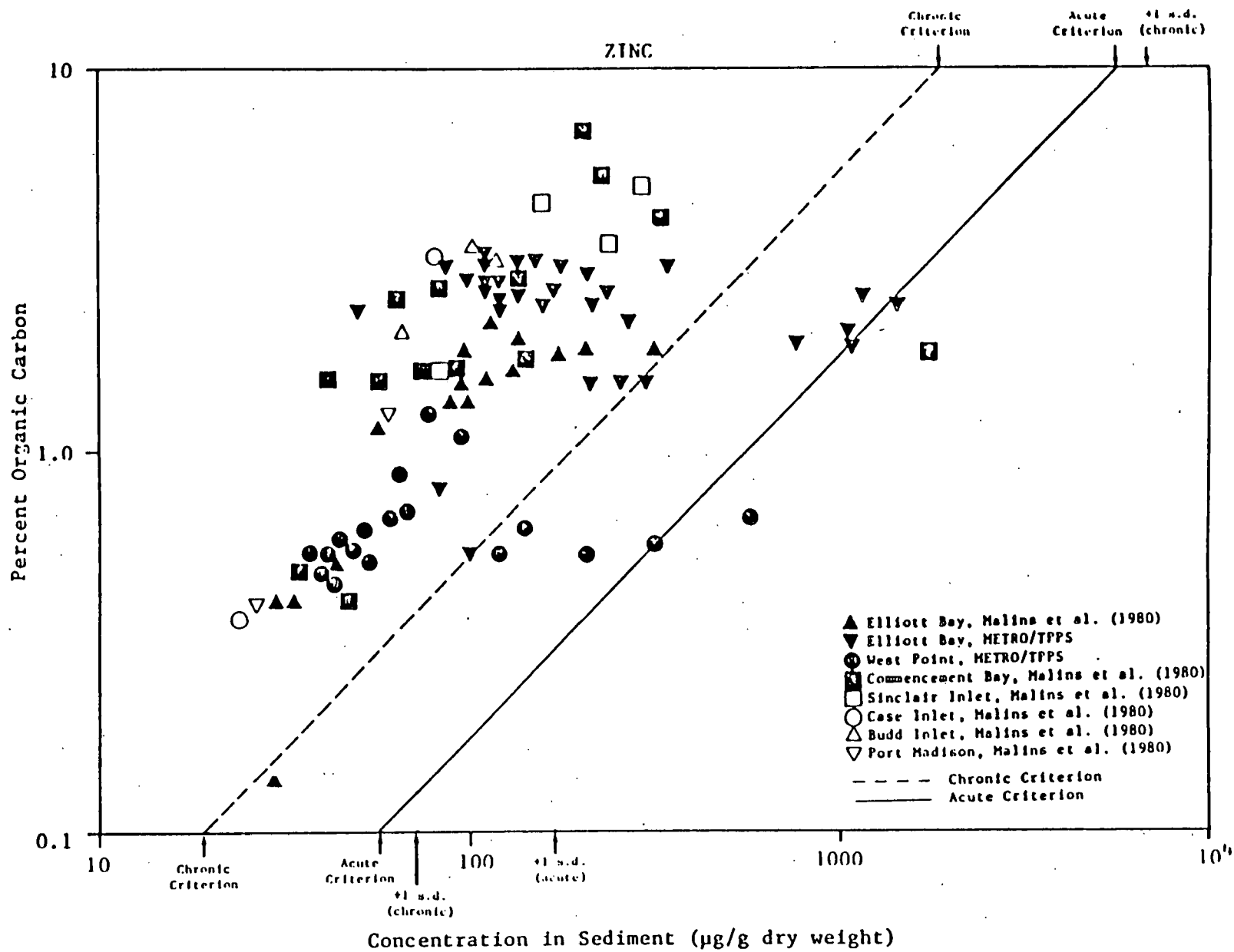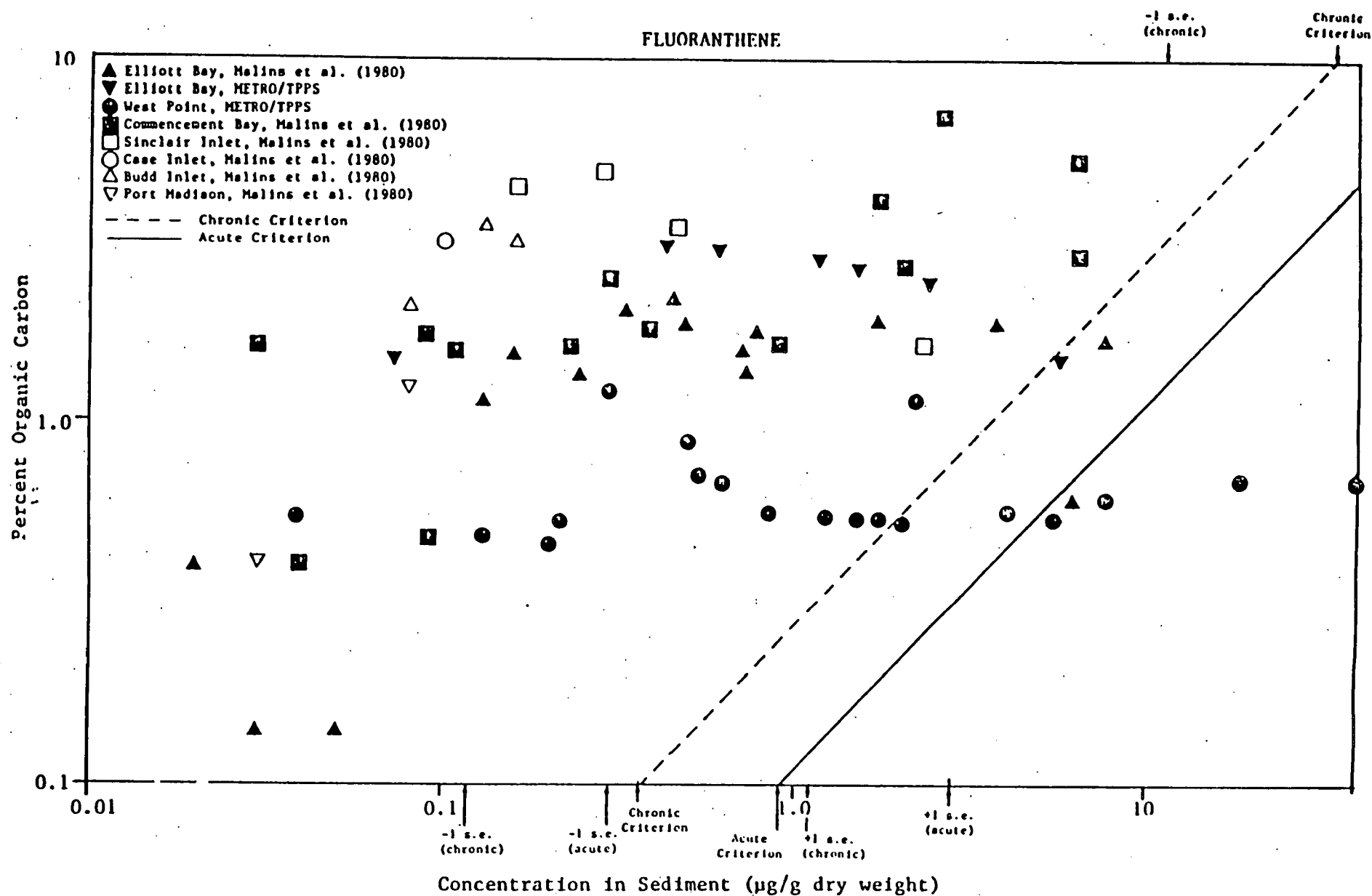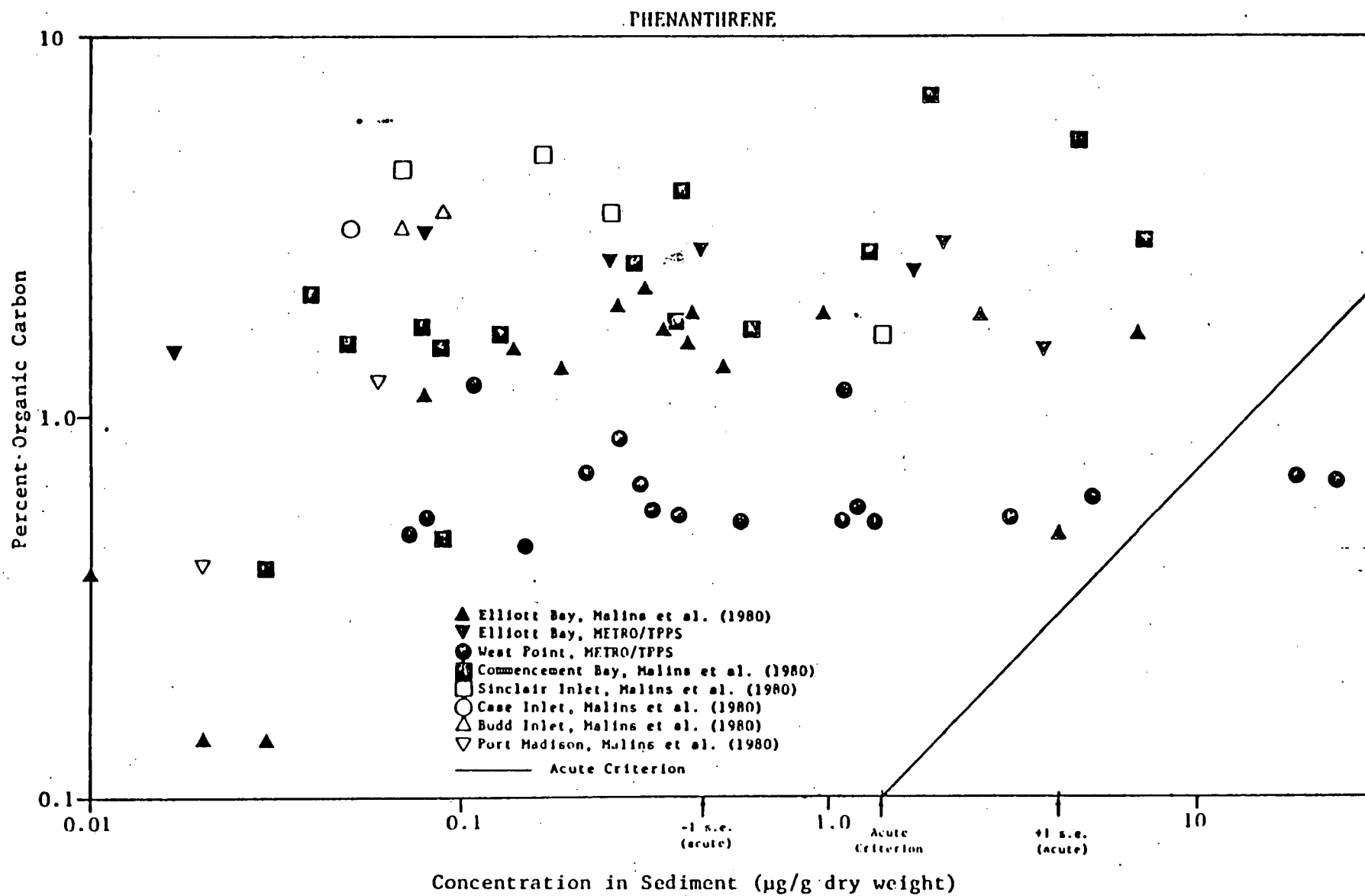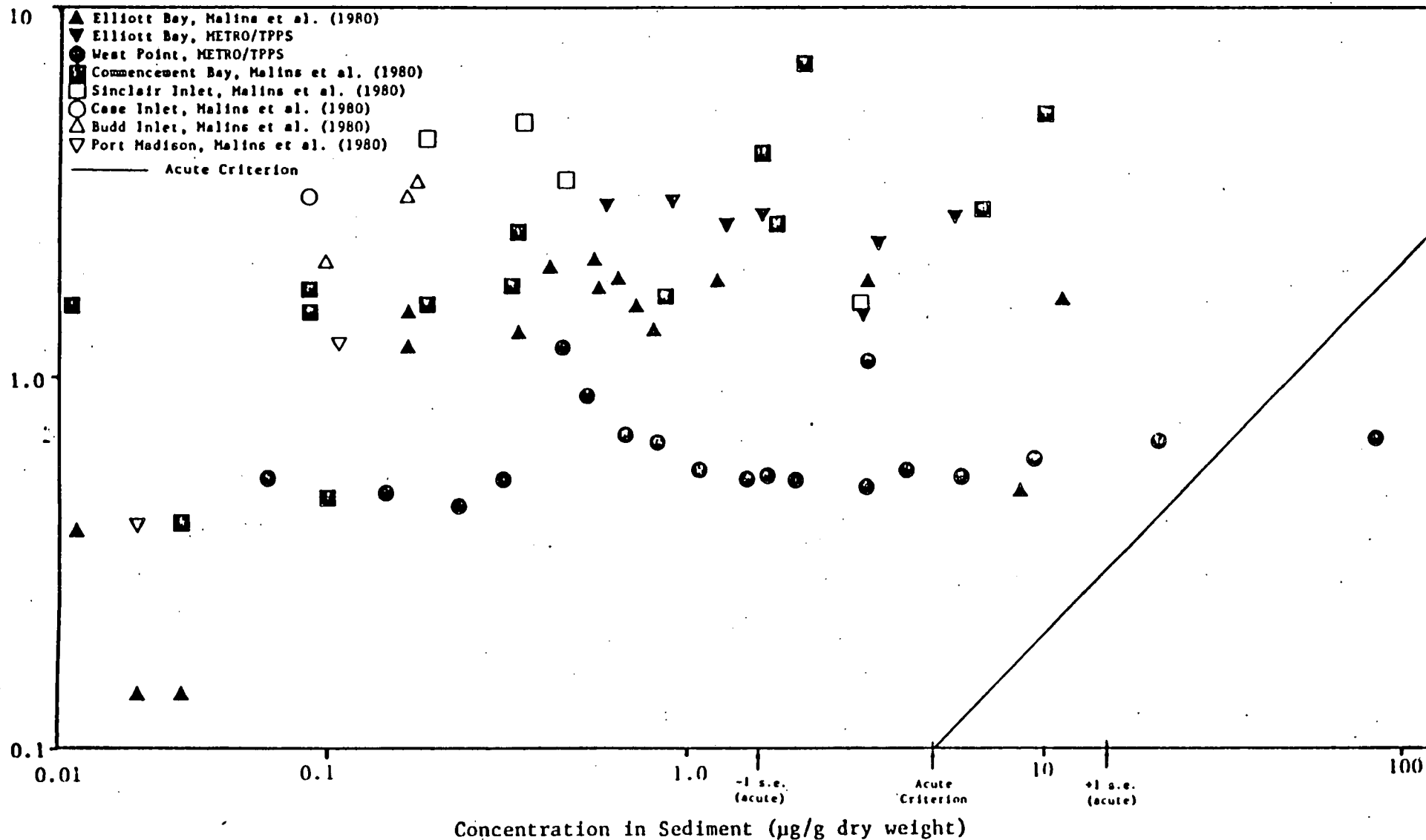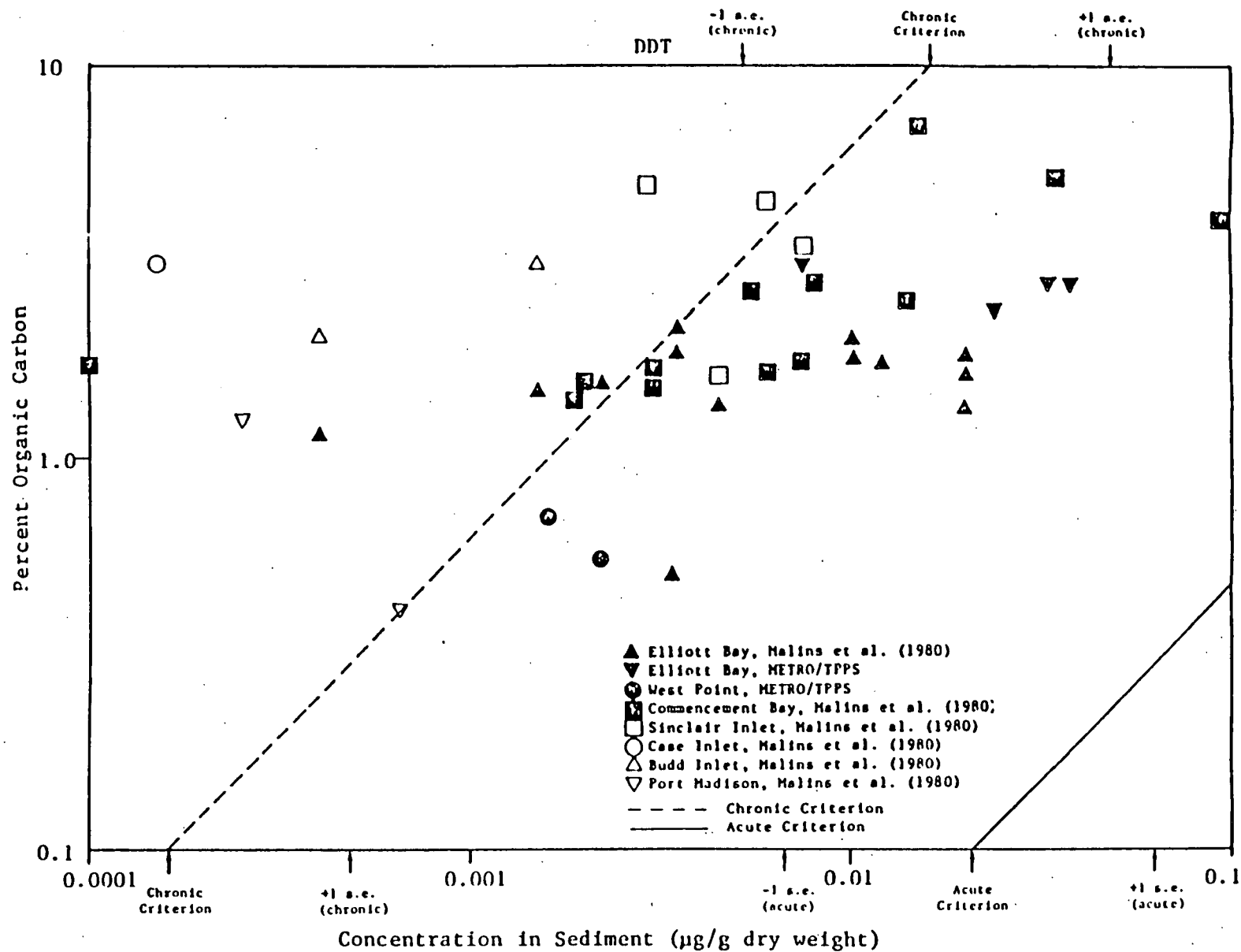OBSERVED CONCENTRATIONS OF CADMIUM IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES
(Cadmium concentrations reported by Malins et a   1980, are suspiciously high and were not includ

48.

COPPER

Legend:
▲ Elliott Bay, Malins et al. (1980)
▼ Elliott Bay, METRO/TPPS
◓ West Point, METRO/TPPS
◪ Commencement Bay, Malins et al. (1980)
☐ Sinclair Inlet, Malins et al. (1980)
◯ Case Inlet, Malins et al. (1980)
△ Budd Inlet, Malins et al. (1980)
▽ Port Madison, Malins et al. (1980)
– – – – Chronic Criterion
――― Acute Criterion

Percent Organic Carbon

Concentration in Sediment (μg/g dry weight)

Figure 12

OBSERVED CONCENTRATIONS OF COPPER IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES

Figure 13

OBSERVED CONCENTRATIONS OF MERCURY IN THE SED⎯⎯NTS OF PUGET SOUND IN COMPARISON TO CRITERIA VAⁱ

Figure 14

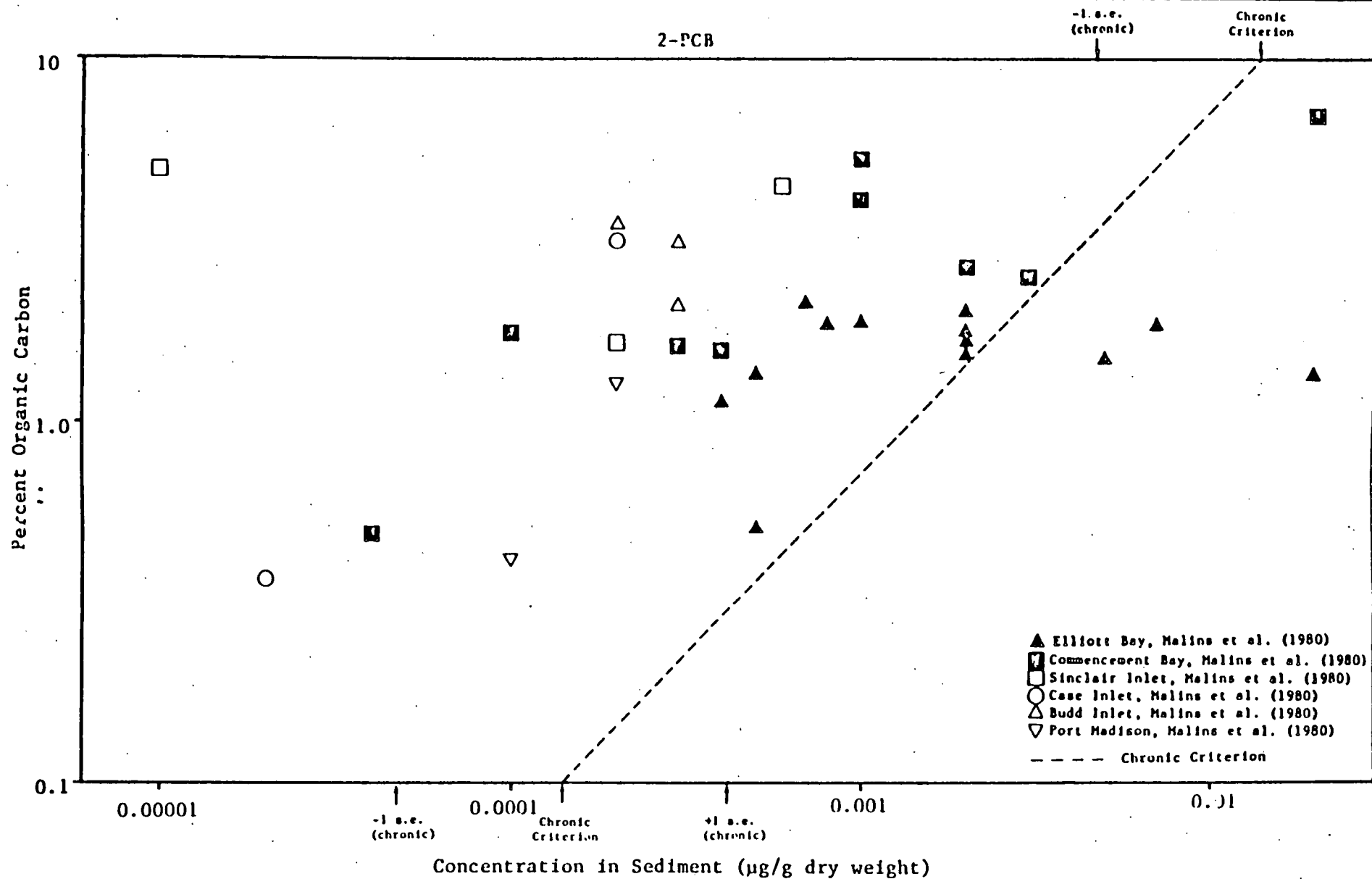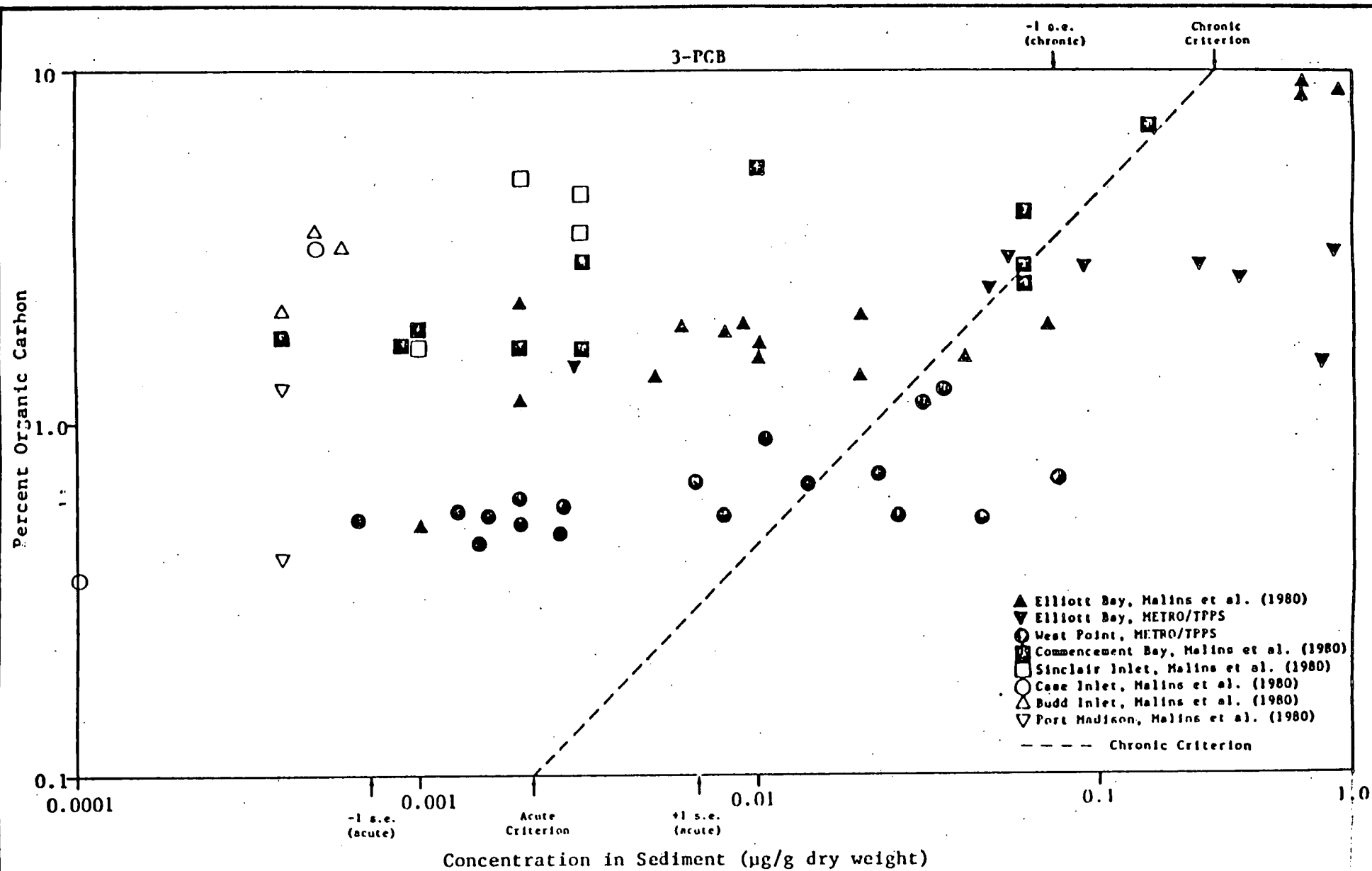OBSERVED CONCENTRATIONS OF ZINC IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES

FLUORANTHENE

Figure 15

OBSERVED CONCENTRATIONS OF FLUORANTHENE IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES

Figure 16

OBSERVED CONCENTRATIONS OF PHENANTHRENE IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES

Figure 17

OBSERVED CONCENTRATIONS OF PYRENE IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES
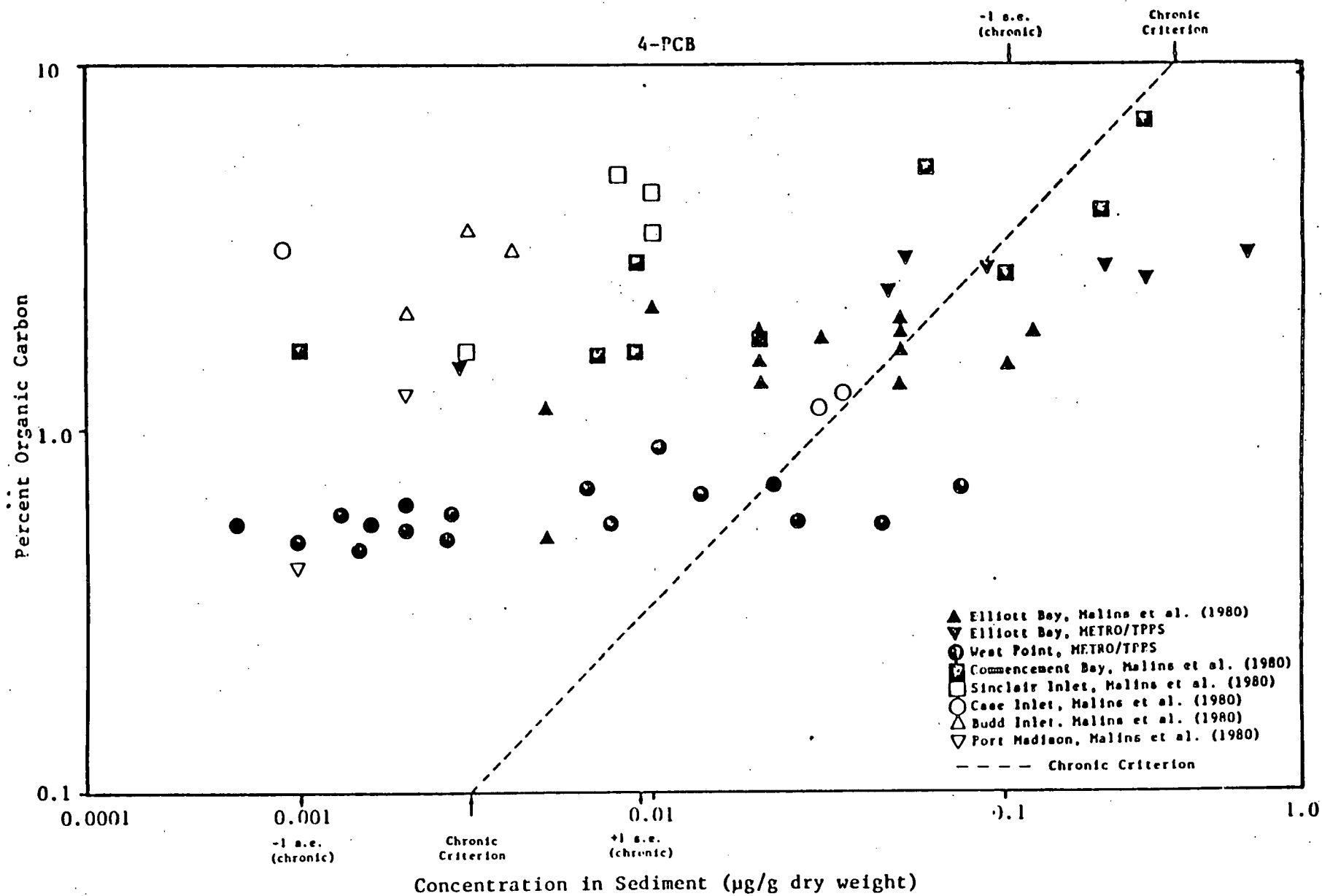
Figure 18

OBSERVED CONCENTRATIONS OF DDT IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES

Figure 19

OBSERVED CONCENTRATIONS OF 2-PCB IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES
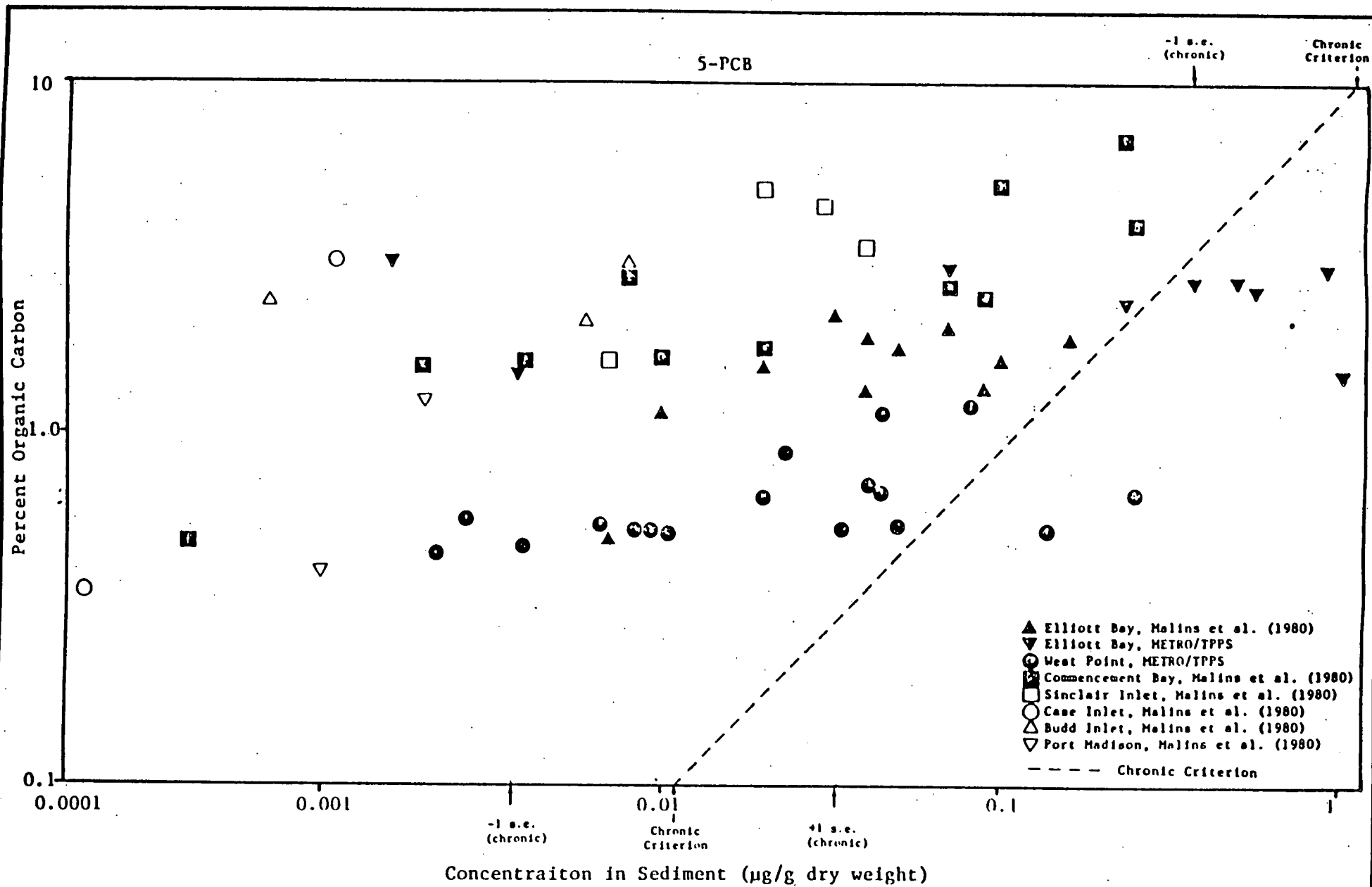
Figure 20

OBSERVED CONCENTRATIONS OF 3-PCB IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES

Figure 21

OBSERVED CONCENTRATIONS OF 4-PCB IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES

Figure 22

OBSERVED CONCENTRATIONS OF 5-PCB IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES
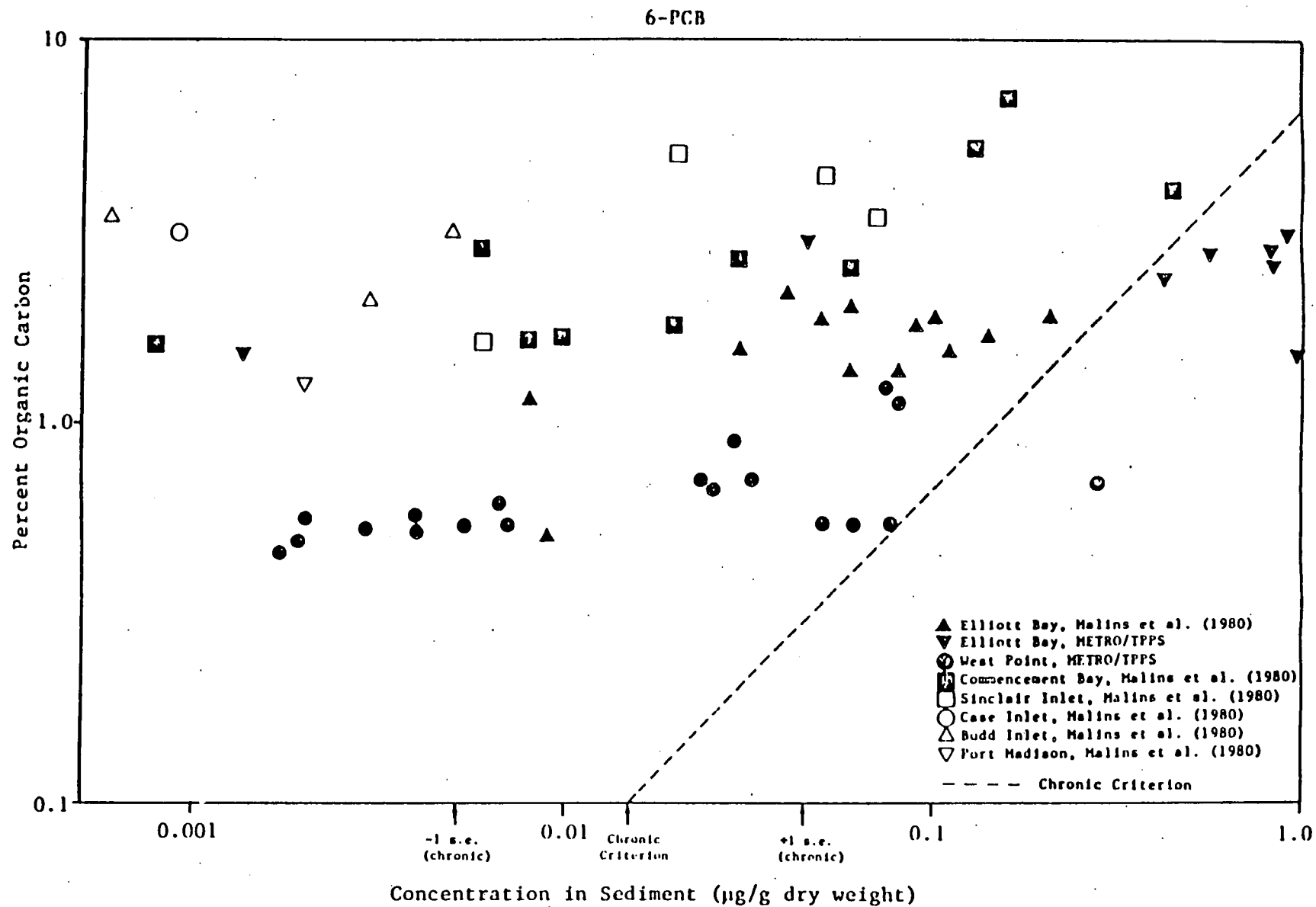
6-PCB

Concentration in Sediment (μg/g dry weight)

Figure 23

OBSERVED CONCENTRATIONS OF 6-PCB IN THE SEDIMENTS OF PUGET SOUND IN COMPARISON TO CRITERIA VALUES

4.4 SPATIAL COMPARISONS

The frequency with which criteria are exceeded and the relative severity of these occurrences can be used to evaluate the extent of degradation within various subregions of Puget Sound. Comparisons between subregions can be made numerically or graphically. The methods presented below are intended as examples of the tools which may be used to establish a priority listing of sites where corrective action may be necessary.

Numerical Approach

The frequency with which criteria are exceeded for individual contaminants can be defined as:

$$f_V^X = \frac{\text{\# measurements exceeding criteria}}{\text{total \# measurements}} \times 100$$

where f_V^X is defined as the frequency of criteria violation and x refers to the specific contaminant measured. Values of f_V^X were calculated for both acute and chronic sediment criteria for six trace metals as shown in Table 8. It is possible to sum the individual f_V^X values to obtain a frequency of criteria violations for a given subregion integrated for a class of priority contaminants. This quantity is defined as:

$$F_V = \frac{\sum_n f_V^X}{n}$$

where F_V is the class integrated frequency of criteria violation in a given region and n is the number of contaminants in the class. Values of F_V are illustrated in the last columns of Table 9. Although the sampling frequency among the subregions is quite variable it is clear that Elliott Bay, Commencement Bay, Sinclair Inlet and the area around the West Point Outfall exhibit the highest frequency of violations. This, of course, is not surprising since these areas have historically been known to receive high contaminant inputs originating from land based point and nonpoint sources.

Graphical Approach

Excess factors, representing the percent enrichment of a contaminant above criteria, can be calculated at each sampling site as:

JRB Associates

Table 9

FREQUENCY OF CRITERIA VIOLATIONS (f_v^X) FOR SIX TRACE METALS IN SEVERAL SUBREGIONS OF PUGET SOUND

(Numbers in parentheses equal the number of stations which exceed criteria/total number of stations tested)

Subregion	As Acute	As Chronic	Cd Acute	Cd Chronic	Cu Acute	Cu Chronic	Pb Acute	Pb Chronic	Hg Acute	Hg Chronic	Zn Acute	Zn Chronic	F_v [a] Acute	F_v [a] Chronic
Elliott Bay	5.5 (2/36)	25 (9/36)	0 (0/36)	0 (0/36)	25 (13/53)	42 (22/53)	0 (0/53)	74 (39/53)	59 (31/53)	100 (53/53)	4 (2/53)	13 (7/53)	22 (46/212)	57 (121/212)
Commencement Bay	--	--	--	--	21 (3/14)	50 (7/14)	0 (0/14)	50 (9/14)	43 (6/14)	100 (14/14)	7 (1/14)	7 (1/14)	18 (10/56)	52 (29/56)
Sinclair Inlet	--	--	--	--	0 (0/4)	50 (2/4)	0 (0/4)	25 (1/4)	100 (4/4)	100 (4/4)	0 (0/4)	0 (0/4)	25 (4/16)	44 (7/16)
Budd Inlet	--	--	--	--	0 (0/3)	0 (0/3)	0 (0/3)	0 (0/3)	0 (0/3)	100 (3/3)	0 (0/3)	0 (0/3)	0 (0/12)	25 (3/12)
Case Inlet	--	--	--	--	0 (0/2)	0 (0/2)	0 (0/2)	0 (0/2)	0 (0/2)	100 (2/2)	0 (0/2)	0 (0/2)	0 (0/8)	25 (2/8)
Port Madison	--	--	--	--	0 (0/2)	0 (0/2)	0 (0/2)	0 (0/2)	0 (0/2)	100 (2/2)	0 (0/2)	0 (0/2)	0 (0/8)	25 (2/8)
West Pt. Outfall Region	10 (3/31)	36 (11/31)	0 (0/31)	0 (0/31)	3 (1/31)	16 (5/31)	0 (0/31)	21 (9/31)	52 (16/31)	100 (31/31)	3 (1/31)	16 (5/31)	15 (18/124)	40 (50/124)
Total	7 (5/67)	30 (20/67)	0 (0/67)	0 (0/67)	16 (17/109)	33 (36/109)	0 (0/109)	51 (56/109)	52 (57/109)	100 (109/109)	4 (4/109)	11 (13/109)		

[a] Excludes As and Cd.

$$EF = \frac{c_{S/ACT/OC}^{X} - c_{S/CR/OC}^{X}}{c_{S/CR/OC}^{X}}$$

where $c_{S/ACT/OC}^{X}$ equals the actual measured contaminant concentration normalized to organic carbon content. Computation of excess factors allows for site specificity and definition of areas where remedial and/or control-enforcement action may be necessary. It is possible to obtain this site specificity by a spatial representation of excess factors. In this manner, a gradient in the degree of violation may be established which could lead to specific source control action. A typical example of this method is depicted in Figure 24. It is apparent that chronic criteria for Cu are exceeded within the immediate proximity of the city's waterfront, the industrialized area around Harbor Island and a very short radius from shore at the Denny Way CSO site. This representation points to the severity of contamination being highly localized and therefore amenable to remedial action. Similar plots could be constructed from the other contaminants to improve site specificity of criteria violations.

4.5 CORRELATIONS WITH OTHER SEDIMENT CRITERIA

The Phase I report discussed the history of sediment criteria development and presented a variety of proposed criteria, many of which had been developed for the Great Lakes. The sediment contaminant concentrations permitted by these earlier criteria were established in a rather subjective manner but were generally based upon correlations of sediment contaminant burden with observations of adverse biological impact. It should also be pointed out here that the effect of the environmental variables discussed in Section 2.4 was not considered in the development of these criteria.

A comparison of these earlier limits with the values proposed in this report are presented in Table 10. The criteria from the literature represent the range of concentrations encompassed by the EPA-Region V, EPA Region VI and Ontario Ministry of the Environment guidelines as reported in the Phase I report. The criteria derived by the equilibrium approach are calculated assuming a 2% organic carbon content. This value is intermediate in the range of organic content typical of sediments and is representative of sediments with 50% sand and 50% silt and clay (Figure 8).
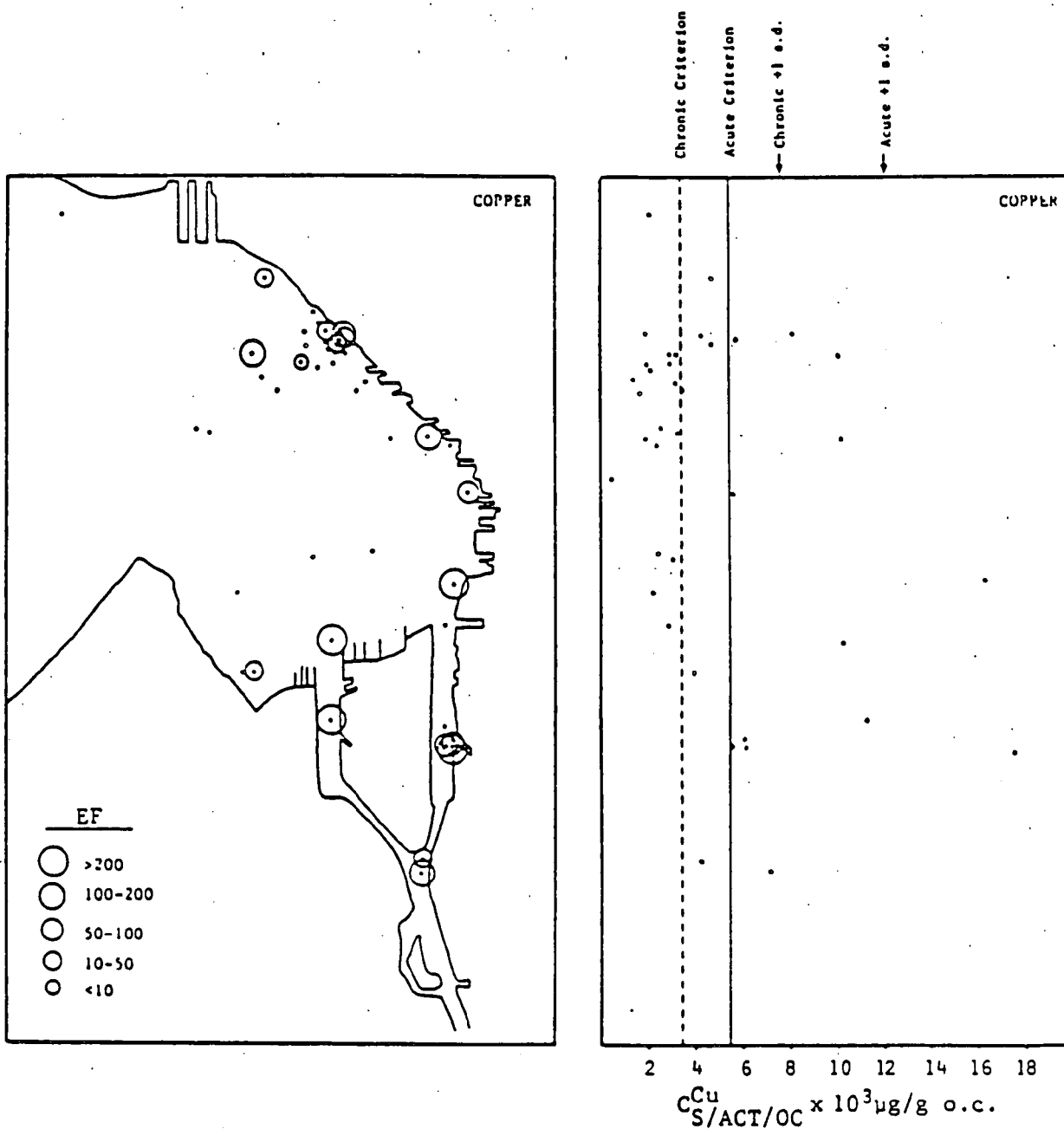
Figure 24

SPATIAL REPRESENTATION OF EXCESS FACTORS (EF) FOR CHRONIC CRITERIA
COMPUTED FOR Cu AND CORRESPONDING SEDIMENT CONCENTRATIONS
MEASURED AT SPECIFIC SITES IN ELLIOTT BAY
Data from Metro/TPPS (Pavlou et al., 1983), and NOAA/NMFS
(Malins et al., 1980)

Table 10

COMPARISON OF SEDIMENT CRITERIA FOR GREAT LAKES SEDIMENTS TAKEN FROM THE LITERATURE AND CRITERIA ESTABLISHED BY THE SEDIMENT-WATER EQUILIBRIUM APPROACH

(concentrations given in mg/kg dry weight)

Contaminant	Sediment Criteria From the Literature	Sediment Criteria Derived by Partitioning Approach[a]
As	3-8	16
Cd	1-6	15
Cu	25-50	68
Pb	40-50	66
Hg	0.3-1	0.006
Zn	75-100	380
PCB	0.05-10	0.06[b]

[a] Based on a sediment containing 2% organic carbon.

[b] Based on an average criterion from 2-6 chlorinated biphenyls.

The criteria derived by the equilibrium approach are in remarkably close agreement with the criteria from the literature developed for Great Lakes sediments. With the exception of Hg, all criteria developed by the partitioning approach are within one order of magnitude of the literature criteria and the difference is generally much less. The fact that the proposed Hg criterion is far below the literature value suggests that our estimate may be too strict as discussed in Section 4.3. Though the proposed PCB criterion agrees well with the literature values, it should be noted that this value represents the mean criterion for 2-6 chlorinated biphenyls. The appropriate criterion can best be determined only after consideration of the relative proportions of all PCB isomers.

5.0 RECOMMENDATIONS

In performing this study a number of immediate information and research needs were identified to validate some of the inherent assumptions and improve the utility of the equilibrium partitioning approach in the development of sediment criteria. The recommendations below are separated into three categories: short-term technical needs, long-term technical needs and management needs. Within each technical category, the needs are presented in approximate order of priority taking into consideration both their contributions to validation of the partitioning approach and their development costs/time. Those recommendations ranked highly are of immediate need for application of the proposed criteria and/or can be accomplished with a relatively low level of effort.

5.1 SHORT-TERM TECHNICAL NEEDS

The following technical needs are those which could potentially be accomplished in a relatively short time frame (less than one year). The needs identified below are recommended primarily to strengthen the equilibrium partitioning approach in two general areas: 1) verify the sediment-water partitioning coefficients developed; and 2) provide additional assurance that the criteria developed are biologically meaningful and adequate to protect marine life. If the short-term technical needs identified are pursued, and the criteria refined in light of new information developed, it should be possible for environmental managers to rely on the numerical values as guidelines in assessing the extent of contamination of marine sediments and to use the values as a tool in decision making.

- Ongoing studies funded by various federal and/or regional agencies should be examined to determine flexibility for sampling contaminant and ancillary sediment parameters to enhance application of the sediment criteria and/or refine the preliminary numerical values derived by this approach. Interagency coordination during field surveys is recommended to attain cost effectiveness. EPA is currently directing an effort to achieve these objectives.

- For sites where violations are predicted by the equilibrium partitioning approach it is necessary to relate the occurrence of violations to the occurrence of biological effects on a site-specific basis. The occurrence of criteria violations should be related to indication of localized biological impact such as sediment bioassays or benthic community structure.

- The partition coefficients calculated in this study were based primarily on empirical relationships. To determine whether these values are applicable in Puget Sound, field studies should be performed to verify the predicted K_{OC} values. These investigations should include measurements of contaminants in both the interstitial water and sediments together with ancillary variables at selected sites spanning a range of contaminant levels. An effort should be made to review existing techniques in sampling interstitial water and if necessary develop the appropriate methodology for obtaining large quantities of water at the sediment water interface and bioturbation layer.

- To test the sensitivity of criteria developed by the equilibrium partitioning approach, it is recommended that sediment bioassays be performed to determine if sediment criteria are indeed below concentrations causing adverse biological effects. These bioassay experiments should employ appropriate sensitive marine species of common occurrence in the Puget Sound environment.

- It is well established that the organic content of the sediments is a dominant factor in controlling the magnitude of the partition coefficient and hence the value of the derived criteria. The development of a relationship between organic content and sediment texture in this study was limited only to one data base (Malins et al., 1980). Since 1980, additional sediment surveys have been performed by various investigators in Puget Sound. It is therefore recommended that all available data on organic carbon/sediment texture measurements be compiled and coherent plots be generated. The existence of subregional variability should also be examined to allow proper normalization of the contaminant residue measurements.

5.2 LONG-TERM TECHNICAL NEEDS

The technical needs identified below are important in the ultimate establishment of sediment criteria but would require a long-term development effort (greater than one year). Several of the needs represent research efforts needed to expand the current state of knowledge on the transfer of contaminants between sediment, water and biota. In this regard they are important not only in development of the equilibrium partitioning approach but in providing the technical basis in support of any sediment criteria eventually adopted. It is recommended that the needs identified below be pursued prior to adoption of legally defensible criteria for regulatory application.

● The bioavailability of contaminants at the sediment-water interface has been identified as a critical factor in deriving realistic sediment criteria using the equilibrium partitioning approach. An effort should be made to determine the factors effecting bioavailability of both trace metal and synthetic organic chemicals of concern in Puget Sound. These studies should include efforts to evaluate the importance of ingestion of particulate-bound contaminants in determining the ultimate contaminant body burden of deposit feeders. There is a need to examine the assumption made that ingestion of contaminated particles will not increase the body burden above that which is attained via the interstitial water.

● As pointed out in the report, the physical/chemical conditions at the sediment-water interface appear to control the chemical form of trace metals and hence their bioavailability. It is therefore recommended that experiments be performed to determine the sediment-water partitioning of trace metals as influenced by environmental conditions (organic carbon, pH, redox, DOM, temperature, salinity). These studies may include: (1) a review of pertinent literature; (2) field measurements; and (3) controlled experiments with natural sediments.

● One of the limitations in establishing sediment criteria in using the equilibrium partitioning approach is the lack of water quality criteria (chronic and acute) for most of the contaminants encountered in Puget Sound. An immediate need is therefore the update of the water quality criteria list to include acute and chronic values for all contaminants of concern measured in

Puget Sound. Though establishment of criteria for a wide diversity of contaminants would involve a major, long-term effort, it may be possible to identify a few select contaminants of greatest concern and derive criteria for these on a short-term basis.

5.3 MANAGEMENT NEEDS

- The historical and ongoing generation of sediment quality related information comprises a substantial bank of numerical values that must be properly handled, processed and documented prior to use in the criteria development program. To facilitate the use of this voluminous information a computerized data management plan must be developed. This system must be flexible and should be updated as more information becomes available. It is recommended that EPA assumes the role of a regional data base coordinator and "clearing house" and take the necessary steps to develop a regional data base management plan for sediment quality information for timely implementation. Coordination with other agencies within the region (e.g., NOAA, Washington State Department of Ecology, Army Corps of Engineers) should be encouraged since these organizations are both users and generators of information and historically have developed project specific data bases for water quality parameters and contaminants.

- The single most important need is for management agencies to continue to encourage and support development of scientifically sound, legally defensible and nationally adoptable sediment criteria. Several steps should be taken to meet this need: (1) continued support of research in the areas of contaminant transport, fate and effects as they pertain to sediment criteria; (2) development of protocols for application of criteria; (3) encourage comparison of criteria developed by alternate approaches; and (4) provide a forum for communication between scientists and agencies involved in development of sediment criteria.

6.0 REFERENCES

Beasley, T.M. and S.W. Fowler. 1976. Plutonium and americium: uptake from contaminated sediments by the polychaete Nereis diversicolor. Mar. Biol. 38:95-100.

Brannon, J.M., R.H. Plumb, Jr. and I. Smith, Jr. 1980. Long-term release of heavy metals from sediments. Chap. 13, p. 221-226. In: R.A. Baker (ed.). Contaminants and Sediments. Vol. 2. Ann Arbor Science Publishers. Ann Arbor, MI.

Briggs, G.C. 1973. A simple relationship between soil adsorption of organic chemicals and their octanol/water partition coefficients. Proc. 7th British Insecticide and Fungicide Conf. Vol. 1. The Boots Company, Ltd., Nottingham, G.B.

Brown, D.S., S.W. Karickhoff and E.W. Flagg. (in prep.) Empirical prediction of organic pollutant sorption in natural sediments.

Callahan, M., M. Slimak, N. Gabel, I. May, C. Fowler, R. Freed, P. Jennings, R. Durfee, F. Whitmore, B. Maestri, W. Mabey, B. Holt and C. Gould. 1979. Water-related environmental fate of 129 priority pollutants. Vol. 1. Prepared by Versar, Inc. for the Environmental Protection Agency under EPA Contract No. 68-01-3852 and 68-01-3867.

Christman, R.F. and R.A. Minear. 1971. Organics in lakes. p. 119-143. In: S.J. Faust and J.V. Hunter (eds.). Organic Compounds in Aquatic Environments. Marcel-Dekker, New York.

Courtney, W.A.M. and W. J. Langston. 1978. Uptake of polychlorinated biphenyl (Aroclor 1254) from sediment and from seawater in two intertidal polychaetes. Environ. Pollut. 15:303-309.

Crecilius, E.A., M.H. Bothner and R. Carpenter. 1975. 1975. Geochemistries of arsenic, antimony, mercury, and related elements in sediments of Puget Sound. Environ. Sci. Technol. 9:325-333.

Dexter, R.N. 1976. An application of equilibrium adsorption theory to the chemical dynamics of organic compounds in marine ecosystems. Ph.D. dissertation, Univ. of Washington. Seattle. 181 pp.

Fowler, S.W., G.G. Polikarpov, D.L. Elder, P. Parsi and J.P. Villeneauve. 1978. Polychlorinated biphenyls: accumulation from contaminated sediments and water by the polychaete Nereis diversicolor. Mar. Biol. 48:303-309.

Hansch, C. and A.J. Leo. 1979. Substituent Constants for Correlation Analysis in Chemistry and Biology. John Wiley, New York.

Jenne, E.A. 1977. Trace element sorption by sediments and soils--sites and processes. pp. 425-553. In: W.R. Chappell and K.K. Petersen (eds.), Molybdenum in the Environment, Vol. 2. Marcel Dekker, New York.

Jenne, E.A. and S.N. Luoma. 1975. Forms of trace metals in soils, sediments, and associated waters: an overview of their determination and biological availability. p. 213-230. In: Biological Implications of Metals in the Environment. Proc. 15th annual Hanford life sciences symposium at Richland, WA. ERDA symposium series, No. 42.

Karickhoff, S.W. 1981. Semi-empirical estimation of sorption of hydrophobic pollutants on natural sediments and soils. Chemosphere 10:833-846.

Karickhoff, S.W., D.S. Brown and T.A. Scott. 1979. Sorption of hydrophobic pollutants on natural sediments. Water Research 13:241-248.

Kenaga, E.E. and C.A.I. Goring. 1980. Relationship between water solubility, soil sorption, octanol-water partitioning and concentration of chemicals in biota. p. 78-115. In: J.G. Eaton, P.R. Parrish and A.C. Hendricks (eds.). Aquatic Toxicology, ASTM STP 707, American Society for Testing and Materials. Philadelphia, Pennsylvania.

Leo, A.J. and C. Hansch. 1971. Linear free-energy relationships between partitioning solvent systems. J. Org. Chem. 36:1539-1544.

Lindberg, S.E. and R.C. Harris. 1974. Mercury-organic matter associations in estuarine sediments and interstitial water. Environ. Sci. Technol. 8:459-462.

Luoma, S.N. 1974. Mercury cycling in a Hawaiian estuary. Water resources research center. Tech. Memo. No. 42. Univ. of Hawaii, Honolulu.

Luoma, S.N. and E.A. Jenne. 1975. The availability of sediment-bound cobalt, silver and zinc to a deposit-feeding clam. p. 213-230. In: Biological Implications of Metals in the Environment. Proc. 15th annual Hanford life sciences symposium at Richland, WA. ERDA symposium series, No. 42.

Lyman, W.J., W.F. Reehl and D.H. Rosenblatt. 1982. Handbook of Chemical Property Estimation Methods. Environmental Behavior of Organic Compounds. McGraw-Hill Book Co. New York.

Malins, D.C., B.B. McCain, D.W. Brown, A.K. Sparks and H.O. Hodgins. 1980. Chemical contaminants and biological abnormalities in central and southern Puget Sound. NOAA Tech. Memo. OMPA-2. National Oceanic and Atmospheric Administration, Boulder, CO. 295 pp.

Miramand, P., P. Germain and H. Camus. 1982. Uptake of americium and plutonium from contaminated sediments by three benthic species: Arenicola marina, Corophium volulator and Scrobicularia plana. Mar. Ecol. Prog. Ser. 7:59-65.

Pavlou, S.P. and R.N. Dexter. 1979. Distribution of polychlorinated biphenyls (PCB) in estuarine ecosystems. Testing the concept of equilibrium partitioning in the marine environment. Environ. Sci. Technol. 13:65-71.

Pavlou, S.P., R.F. Shokes, W. Hom, P. Hamilton, J.T. Gunn, R.D. Muench, J. Vinelli and E. Crecilius. 1983. Dynamics and biological impacts of toxicants in the main basin of Puget Sound and Lake Washington. Vol. I: evaluation of toxicant distribution, transport and fate. Submitted to the Municipality of Metropolitan Seattle.

Pavlou, S.P. and D.P. Weston. 1983. Initial evaluation of alternatives for development of sediment related criteria for toxic contaminants in marine waters (Puget Sound). Phase I: Development of conceptual framework. Prepared by JRB Associates for the Environmental Protection Agency under EPA Contract No. 68-01-6388.

Pionke, H.B. and G. Chesters. 1973. Pesticide-sediment-water interactions. J. Environ. Quality. 2:29-45.

Rao, P.S.C. and J.M. Davidson. 1980. Estimation of pesticide retention and transformation parameters required in nonpoint source pollution models. In: M.R. Overcash and J.M. Davidson (eds.). Environmental Impact of Non-point Source Pollution. Ann Arbor Science Publishers, Inc. Ann Arbor, Michigan.

Renfro, W.C. 1973. Transfer of ^{65}zinc from sediments by marine polychaete worms. Mar. Biol. 21:305-316.

Roesijadi, G., J.W. Anderson and J.W. Blaylock. 1978. Uptake of hydrocarbons from marine sediments contaminated with Prudhoe Bay crude oil: influence of feeding type of test species and availability of polycyclic aromatic hydrocarbons. J. Fish. Res. Board Canada 35:608-614.

Sokal, R.R. and F.J. Rohlf. 1981. Biometry. Second edition. W.H. Freeman and Co., San Francisco, CA 859 pp.

Smith, J.H., W.R. Mabey, N. Bohonos, B.R. Holt, S.S. Lee, T.W. Chou, D.C. Bomberger and T. Mill. 1978. Environmental pathways of selected chemicals in freshwater systems; Part II: Laboratory studies. U.S. Environmental Protection Agency, Athens, GA. EPA-600/7-78-074.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman and W.A. Brungs. 1983. Guidelines for deriving numerical national water quality criteria for the protection of aquatic life and its uses. Draft report.

Vangenechten, J.H.D., S.R. Aston and S.W. Fowler. 1983. Uptake of americium 241 from two experimentally labelled deep-sea sediments by three benthic species: a bivalve mollusc, a polychaete and an isopod. Mar. Ecol. Prog. Ser. 13:219-228.

Veith, G.D., K.J. Macek, S.R. Petrocelli and J. Carroll. 1980. An evaluation of using partition coefficients and water solubility to estimate bioconcentration factors for organic chemicals in fish. p. 78-115. In: J.G. Eaton, P.R. Parrish and A.C. Hendricks (eds.). Aquatic Toxicology, ASTM STP 707, American Society for Testing and Materials. Philadelphia, Pennsylvania.

Veith, G.D. and R.J. Morris. 1978. A rapid method for estimating log P for organic chemicals. U.S. Environmental Protection Agency, Duluth, Minnesota. EPA-600/3-78-049.

APPENDIX A

SEDIMENT CONTAMINANT CONCENTRATIONS
FROM MALINS ET AL., 1980

Table A-1

TOTAL ORGANIC CARBON AND GRAIN SIZE ANALYSES OF SEDIMENTS FROM CENTRAL PUGET SOUND
(From Malins et al., 1980, Appendix Table D-7

Location Description	Station Number	Grain Size (% by weight)					Mean Grain Size φ	Sand/Mud Ratio	% Organic Carbon
		>-2	-2 to 0	0 to +4	+2 to +4	+4 to +8	> +8			
Sinclair Inlet:										
Southwest end	08004		0.48	0.47	0.84	65.03	33.20	---	0.02	4.42
Drydock area	08005		0.21	0.41	2.75	46.80	49.84	---	0.03	3.44
Point Turner, southwest side	08006		0.73	7.55	9.14	46.49	36.11	7.10	0.21	4.90
Point Herron, south side	08007		0.03	2.51	53.69	20.95	22.82	5.24	1.28	1.61
Port Madison:										
Midway from Pt. Monroe to Pt. Jefferson	08106		1.44	9.83	34.23	35.56	18.93	5.12	0.83	1.26
Indianola, southwest	08107		0.06	21.26	57.33	15.12	6.21	2.95	3.68	0.41
Commencement Bay:										
Hylebos Waterway, lower turning basin	09027		0.03	0.42	2.60	77.54	19.41	6.88	0.03	4.00
" " , E. 11th St. Bridge	09028		1.45	16.06	19.21	52.84	10.44	4.76	0.58	2.82
Blair Waterway	09029		0.25	16.08	19.27	46.85	18.14	5.13	0.55	1.64
Sitcum Waterway	09030			1.34	14.88	64.15	19.64	6.08	0.19	1.78
City Waterway	09031			1.41	6.32	66.57	25.70	6.71	0.08	5.17
Puyallup disposal site	09032		0.01	0.67	42.99	49.80	6.54	4.28	0.78	1.56
Between Hylebos and Blair	09033		0.10	3.48	9.98	66.99	19.45	5.99	0.16	1.51
Brown's Point, south side	09034		0.23	2.05	12.08	61.97	23.67	6.15	0.17	2.49
Creek at sewage plant	09035	0.56	3.84	52.54	36.14	2.98	3.95	1.85	13.47	0.40
Tacoma Yacht Club	09036	1.92	7.31	40.03	42.07	3.53	5.15	1.89	10.54	1.72
Brown's Point	09037		6.65	56.81	22.49	7.64	6.41	1.86	6.12	0.48
Hylebos Waterway, outside, to NW	09038			0.22	2.20	70.07	27.51	6.69	0.02	2.64
Old Tacoma	09039		0.37	10.37	21.01	44.34	23.92	5.66	0.47	6.98
Blair Waterway, turning basin	09040		0.02	3.22	17.16	52.48	27.11	6.54	0.26	1.60

Location Description	Station Number	Grain Size (% by weight)						Mean Grain Size φ	Sand/Mud Ratio	% Organic Carbon
		>-2	-2 to 0	0 to .4	.2 to .4	.4 to .8	< .8			
Elliott Bay:										
Magnolia Bluff	10014		0.54	25.18	59.96	6.95	7.38	2.63	5.98	1.13
Pier 54	10015		0.21	3.57	6.70	58.33	31.19	7.02	0.12	1.63
Harbor Island, north end	10016	no data						no data		
Duwamish Waterway, 1st Ave Bridge	10019		0.84	20.02	11.76	52.35	15.04	4.84	0.48	1.50
West Point, north side	10023		0.01	3.59	80.07	11.11	5.22	3.26	5.12	0.50
Alki Point, south side	10028		0.09	38.07	57.52	1.20	3.02	2.23	22.23	0.39
Duwamish Waterway, near lumber mill	10031		0.03	3.13	12.29	46.45	38.09	7.11	0.18	1.33
" " , west channel	10038		0.11	2.99	15.02	40.73	41.15	7.07	0.22	1.82
" " , east channel	10039			0.58	2.82	43.76	52.83	8.52	0.04	1.76
Pier 70	10040		2.38	14.03	10.69	49.11	23.74	5.26	0.37	1.33
North of Pier 71	10041		1.33	9.72	25.36	50.08	13.51	5.03	0.57	1.83
Pier 86	10042		0.07	2.40	9.44	59.33	28.76	6.77	0.14	1.33
Corps dump site	10043		2.84	20.16	22.09	42.90	12.01	4.63	0.42	1.44
Midway from Pier 91 to Duwamish Head	10044		0.01	1.09	4.15	49.13	45.32	7.31	0.06	2.15
Duwamish Head, southeast side	10045	0.91	10.62	26.56	22.79	23.70	15.42	3.77	1.50	1.53
Pier 42	10046		1.98	24.82	60.74	10.45	2.01	2.62	7.02	0.14
Case Inlet:										
Reach Island	12062			1.26	4.67	59.00	35.07	7.39	0.06	3.10
Stretch Island	12063		0.04	24.35	65.36	5.97	4.28	2.56	8.75	0.36
Budd Inlet:										
Entrance channel, south end	12130			0.18	4.73	67.23	27.86	6.95	0.05	3.10
Priest Point	12131		0.02	10.28	35.38	29.00	25.32	5.65	0.84	2.05
Olympia Shoal	12132			0.45	0.93	47.85	50.77	---	0.01	3.41

Table A-2

CONCENTRATION OF METALS IN SEDIMENTS FROM CENTRAL PUGET SOUND IN MAY, 1979, IN μg/g DRY WEIGHT (PPM)

(From Malins, et al. 1980, Appendix Table D-2)

SOURCE OF SEDIMENT SAMPLE		Ag	Al	As	B	Ba	Be	Bi	Ca	Cd	Co
SINCLAIR INLET:	Southwest end	4·76	18811		67·4	54·0	·557		19103	8·14	14·9
	Drydock area	3·42	19650		50·0	65·2	·633		6507	7·73	13·8
	Point Turner, southwest side	2·92	17796		50·8	59·6	·585		13097	7·14	13·2
	Point Herron, south side	2·02	13070		38·5	30·2	·420		7985	5·24	9·66
PORT MADISON:	Midway from Pt. Monroe to Pt. Jefferson	1·97	13712		29·4	34·3	·490		6511	6·25	13·5
	Indianola, southwest	1·48	7309		23·6	16·3	·221		5003	3·08	5·71
COMMENCEMENT BAY:	Hylebos Waterway, lower turning basin	2·93	>20000		99·6	51·2	·703		12340	9·6:	29·6
	Hylebos Waterway, E. 11th St. bridge	2·35	13060		81·4	38·8	·546	90	>20000	6·60	11·9
	Blair Waterway, E. 11th St. bridge	2·14	12857		23·4	25·6	·481		7279	5·45	8·44
	Sitcum Waterway	10·8	12104	472	16·8	34·8	·453		7022	16·2	47·9
	City Waterway	5·02	16471		40·9	79·3	·549		841:	9·09	11·6
	Puyallup disposal site	1·90	12927		17·5	34·9	·484		6209	5·20	10·6
	Between Hylebos & Blair	2·20	15927		20·2	31·8	·530		8044	5·40	:2·6
	Brown's Point, south side	2·37	15671		23·9	35·1	·592		7668	5·99	15·6
	Creek at sewage plant	1·94	8503		14·3	17·4	·327		4915	4·20	12·6
	Tacoma Yacht Club	2·22	9359		25·0	24·4	·426		6144	5·80	29·0
	Brown's Point	1·95	9178		28·8	16·9	·407		4293	4·72	14·1
	Hylebos Waterway, outside, to NW	2·52	16666		30·4	36·5	·613		8467	6·06	15·5
	Old Tacoma	2·46	13009		36·5	58·1	·475		7019	5·57	14·3
	Blair Waterway, turning basin	2·18	14110		20·0	32·7	·544		7741	6·02	19·3
ELLIOTT BAY:	Magnolia Bluff	1·31	9953		26·1	25·8	·494		5063	4·46	8·75
	Pier 54	3·92	>20000		36·6	115	·866		7169	8·55	17·6
	Harbor Island, north end	1·89	14586		18·8	103	·574		6590	5·73	9·45
	Duwamish Waterway, 14th Ave. bridge	2·07	>20000		24·5	74·6	·878		6607	8·29	16·5
	West Point, north side	1·45	10114		15·8	131	·377		5229	4·71	6·86
	Alki Point, south side	1·25	7879		16·6	16·0	·276		4261	3·77	5·33
	Duwamish Waterway, near lumber mill	2·99	>20000	95	28·3	119	·995		8986	11·0	17·3
	Duwamish Waterway, west channel	2·56	>20000	84	25·4	283	·963		9654	11·3	13·5
	Duwamish Waterway, east channel	3·27	>20000	282	45·5	97·0	1·10		8896	18·3	29·7
	Pier 70	3·49	18433		23·3	76·3	·604		6273	7·0:	9·88
	North of Pier 71	3·80	17423		28·5	75·7	·569		6521	6·49	10·5
	Pier 86	3·20	19891		25·9	67·6	·605		6928	7·30	14·2
	Corps dump site	2·22	17152		29·2	63·3	·556		6685	6·46	8·04
	Midway from Pier 91 to Duwamish Head	2·73	>20000		41·8	75·8	·708		7773	8·2:	15·4
	Duwamish Head, southeast side	2·05	14520		23·8	73·7	·487		7109	7·30	12·9
	Pier 42	1·58	10923		15·7	28·4	·354		5733	4·57	7·64
	Pier 42	1·62	10790		12·0	27·5	·349		5507	7·53	10·2
CASE INLET:	Reach Island	2·26	18280		55·6	32·1	·588		8563	7·58	18·6
	Stretch Island	1·83	6430		15·6	11·7	·160		4643	3·16	8·60
BUDD INLET:	Entrance channel, south end	3·67	>20000	140	39·9	31·1	·759		6934	11·2	25·5
	Priest Point	2·66	17415		34·4	20·1	·433		8575	8·19	17·9
	Olympia Shoal	2·97	>20000	57	48·5	29·2	·684	81	7635	9·53	25·8

SOURCE OF SEDIMENT SAMPLE		ELEMENT									
		Cr	Cu	Fe	Ga	Ge	Mg	K	Li	Mg	Mn
SINCLAIR INLET:	Southwest end	71.5	151	31817			1.06	190	20.9	10500	301
	Drydock area	65.2	184	32320			1.02	193	20.4	10543	332
	Point Turner, southwest side	57.3	132	30289			1.15	181	19.2	9437	309
	Point Herron, south side	39.4	46.8	27646			.315	128	13.4	6895	336
PORT MADISON:	Midway from Pt. Monroe to Pt. Jefferson	45.6	25.8	28968			.113	136	15.7	8676	345
	Indianola, southwest	22.8	10.4	12687			.042	58.4	7.42	4220	204
COMMENCEMENT BAY:	Hylebos Waterway, lower turning basin	47.6	259	39405			.790	149	15.5	11301	255
	Hylebos Waterway, E. 11th St. bridge	33.5	84.8	23507			.428	87.7	9.91	12961	202
	Blair Waterway.	27.9	59.6	25138			.132	88.1	9.72	5172	166
	Sitcum Waterway	58.7	1602	43354			.492	85.1	8.96	4904	196
	City Waterway	46.5	178	27176			1.03	125	13.4	7381	199
	Puyallup disposal site	25.5	33.7	22625			.065	71.0	7.53	4259	141
	Between Hylebos & Blair	26.9	50.6	25445			.106	98.1	11.0	5639	186
	Brown's Point, south side	28.5	64.8	26758			.173	105	11.5	6405	217
	Creek at sewage plant	31.4	43.0	18233			.100	60.1	8.83	5245	520
	Tacoma Yacht Club	36.3	110	26063			.255	88.6	8.98	5675	577
	Brown's Point	25.6	22.7	22530			.063	141	7.68	4251	213
	Hylebos Waterway, outside, to NW	29.1	77.7	26558			.197	125	12.5	7290	173
	Old Tacoma	28.7	126	22752			.336	98.2	10.7	5993	244
	Blair Waterway, turning basin	29.5	69.9	29914			.157	102	10.6	6110	163
ELLIOTT BAY:	Magnolia Bluff	27.5	23.9	19055			.095	102	8.56	4463	315
	Pier 54	54.4	91.2	33076			1.16	179	19.3	9561	371
	Harbor Island, north end	31.3	90.2	24636			1.38	116	11.9	5435	266
	Duwamish Waterway, 14th Ave. bridge	35.5	54.5	34037			.250	167	15.4	7630	295
	West Point, north side	35.6	18.9	19052			.104	76.2	9.99	7000	243
	Alki Point, south side	27.5	10.2	15856			.031	69.4	8.90	5582	352
	Duwamish Waterway, near lumber mill	44.8	131	45569		119	.383	222	21.4	9391	415
	Duwamish Waterway, west channel	63.9	206	45659		88	.798	226	21.6	9785	430
	Duwamish Waterway, east channel	49.2	109	>50000	86	188	.350	269	25.4	11363	547
	Pier 70	54.0	135	32640			.632	148	16.3	8901	355
	North of Pier 71	53.6	58.8	29460			1.07	154	16.5	9304	323
	Pier 86	54.0	63.7	34013			.355	166	17.4	9735	473
	Corps dump site	38.7	59.6	30767			.423	139	14.0	7163	382
	Midway from Pier 91 to Duwamish Head	51.2	60.1	37278		44	.449	210	21.9	10452	471
	Duwamish Head, southeast side	69.8	60.7	35247			.153	108	13.4	3995	501
	Pier 42	49.4	21.2	20926			.026	63.6	7.46	6830	295
	Pier 42	41.1	22.5	22214			.026	62.6	7.66	6000	335
CASE INLET:	Reach Island	52.7	43.0	25103		43	.118	167	20.5	9963	305
	Stretch Island	20.9	10.2	11120			.024	44.3	7.22	3533	192
BUDD INLET:	Entrance channel, south end	49.4	81.1	36217		101	.329	167	26.8	10407	230
	Priest Point	34.6	36.6	24748		46	.125	105	16.4	7078	154
	Olympia Shoal	50.1	70.3	34800		89	.283	164	24.7	10248	229

SOURCE OF SEDIMENT SAMPLE		ELEMENT									
		Mo	Na	Ni	P	Pb	Sb	Sc	Se	Si	Sn
SINCLAIR INLET:	Southwest end	13·5	>20000	51·4	1227	97·6	43·5	7·13	30	137	37
	Drydock area	14·4	>20000	52·9	985	136	52·0	7·48	30	150	35
	Point Turner, southwest side	12·9	>20000	48·1	893	125	48·6	6·81	27	169	40
	Point Herron, south side	8·02	11728	35·5	697	44·2	31·1	5·02		113	29
PORT MADISON:	Midway from Pt. Monroe to Pt. Jefferson	8·47	12521	42·0	705	20·1	32·4	5·92	22	144	20
	Indianola, southwest		4458	21·5	405	10·3	17·8	3·00		140	22
COMMENCEMENT BAY:	Hylebos Waterway, lower turning basin	17·2	>20000	64·4	1098	154	64·1	6·35	34	189	36
	Hylebos Waterway, E. 11th St. bridge	11·2	12846	41·9	813	111	43·2	4·06	27	149	32
	Blair Waterway, E. 11th St. bridge	8·44	9770	21·1	812	42·5	35·1	4·17		137	22
	Sitcum Waterway	114	10398	36·1	739	793	338	3·77	23	121	65
	City Waterway	13·1	17059	33·3	1017	269	44·0	5·26	23	146	31
	Puyallup disposal site	8·19	7972	18·7	737	14·0	29·2	3·88		207	19
	Between Hylebos & Blair	9·04	10966	22·8	858	27·6	38·7	4·84		135	19
	Brown's Point, south side	10·3	13548	24·0	917	39·9	39·4	5·15	23	137	20
	Creek at sewage plant	7·24	3660	29·4	428	28·8	27·4	3·55		133	15
	Tacoma Yacht Club	10·4	4198	38·5	557	65·1	52·6	3·88		117	20
	Brown's Point	7·23	419A	22·2	491	18·3	25·7	3·81		103	15
	Hylebos Waterway, outside, to NW	12·8	19112	24·8	940	50·1	41·5	5·42	23	121	19
	Old Tacoma	14·1	12254	25·4	800	170	36·1	4·43	22	101	70
	Blair Waterway, turning basin	12·1	14268	22·4	1474	49·0	39·2	4·53		91	18
ELLIOTT BAY:	Magnolia Bluff	6·16	5029	24·6	551	37·1	25·9	3·82		104	20
	Pier 54	13·6	16400	56·4	868	111	48·8	8·40	34	100	36
	Harbor Island, north end	7·94	9584	24·2	680	60·8	34·8	5·47		88	22
	Duwamish Waterway, 14th Ave. bridge	14·8	13084	29·6	878	40·1	48·5	9·89	40	132	30
	West Point, north side	6·24	5799	41·7	473	16·1	21·1	3·75		117	19
	Alki Point, south side		4750	34·8	394	13·0	17·0	2·95		110	14
	Duwamish Waterway, near lumber mill	29·5	15823	36·0	1174	265	73·5	13·1	80	101	52
	Duwamish Waterway, west channel	26·4	19383	38·9	1020	627	80·4	12·4	70	101	52
	Duwamish Waterway, east channel	41·3	19744	47·9	1378	160	81·8	16·1	113	200	65
	Pier 70	10·9	11705	50·4	817	88·6	41·5	7·44	28	156	32
	North of Pier 71	9·98	12377	52·9	686	74·3	39·3	6·92	25	160	31
	Pier 86	11·4	16270	57·5	879	72·8	45·4	7·72	30	150	32
	Corps dump site	10·2	12604	30·0	798	65·1	47·0	6·87	26	153	26
	Midway from Pier 91 to Duwamish Head	14·8	>20000	45·0	968	78·0	51·1	8·60	39	185	37
	Duwamish Head, southeast side	9·93	6640	55·2	649	111	34·9	5·83	23	152	29
	Pier 42	6·71	4244	46·5	371	8·18	25·7	4·28		216	15
	Pier 42	6·00	5286	49·4	398	9·37	24·8	4·32		179	20
CASE INLET:	Reach Island	13·3	>20000	47·0	947	23·9	46·0	7·22	28	117	24
	Stretch Island	5·85	4935	19·4	303	7·93	19·0	2·89		143	9·6
BUDD INLET:	Entrance channel, south end	29·7	>20000	47·6	917	60·1	68·6	9·49	74	105	38
	Priest Point	11·6	14058	34·8	670	22·6	43·7	6·16	28	123	26
	Olympia Shoal	19·7	>20000	44·7	1051	49·3	61·0	8·75	59	142	38

SOURCE OF SEDIMENT SAMPLE		ELEMENT						
		Sr	Ti	V	W	Y	Zn	Zr
SINCLAIR INLET:	Southwest end	183	1058	64·5	21	10·1	156	7·36
	Drydock area	87·3	1117	70·4	26	10·4	238	6·36
	Point Turner, southwest side	99·6	1051	67·0	24	9·99	292	6·29
	Point Herron, south side	64·7	903	50·9	14	7·97	83·2	4·36
PORT MADISON:	Midway from Pt. Monroe to Pt. Jefferson	51·1	1060	60·1	16	8·27	61·9	5·95
	Indianola, southwest	30·4	731	30·3	7·9	4·86	26·8	4·34
COMMENCEMENT BAY:	Hylebos Waterway, lower turning basin	298	1065	80·2	29	9·73	324	12·3
	Hylebos Waterway, E. 11th St. bridge	513	942	66·7	19	7·76	134	11·6
	Blair Waterway, E. 11th St. bridge	91·8	1046	66·9	14	7·34	75·4	9·12
	Sitcum Waterway	85·6	834	59·1	51	6·44	1720	9·56
	City Waterway	109	1009	66·5	22	9·14	224	9·24
	Puyallup disposal site	81·8	1135	68·6	14	6·77	40·5	6·50
	Between Hylebos & Blair	102	1123	69·7	17	8·27	57·0	7·52
	Brown's Point, south side	104	1084	71·3	18	8·68	63·9	7·80
	Creek at sewage plant	32·9	840	43·4	11	5·32	46·5	5·52
	Tacoma Yacht Club	47·4	849	56·4	14	6·18	140	4·78
	Brown's Point	39·4	730	45·5	10	6·97	35·1	5·99
	Hylebos Waterway, outside, to NW	113	1066	71·3	19	9·16	81·8	9·33
	Old Tacoma	103	865	60·5	18	7·93	208	5·83
	Blair Waterway, turning basin	113	900	70·0	17	8·19	92·2	7·34
ELLIOTT BAY:	Magnolia Bluff	43·9	834	47·4	10	6·24	58·3	4·64
	Pier 54	105	1308	81·5	26	11·6	133	8·91
	Harbor Island, north end	73·3	1099	64·1	13	8·19	106	7·01
	Duwamish Waterway, 14th Ave. bridge	94·9	1331	84·1	30	13·8	96·2	9·33
	West Point, north side	37·4	915	45·8	9·4	5·39	44·0	4·76
	Alki Point, south side	26·5	699	34·9	8·2	4·64	30·3	3·90
	Duwamish Waterway, near lumber mill	124	1649	95·9	61	15·7	204	9·07
	Duwamish Waterway, west channel	123	1534	92·2	56	14·8	319	9·30
	Duwamish Waterway, east channel	142	1931	107	81	18·1	175	12·2
	Pier 70	68·7	1239	75·7	20	9·92	97·2	7·73
	North of Pier 71	62·3	1211	67·9	19	9·48	97·8	8·36
	Pier 86	77·8	1284	75·0	22	10·3	91·0	7·96
	Corps dump site	78·4	1203	70·8	19	9·81	177	8·29
	Midway from Pier 91 to Duwamish Head	95·5	1248	81·2	31	11·6	115	7·94
	Duwamish Head, southeast side	62·8	1119	68·8	17	7·96	110	6·94
	Pier 47	33·1	1070	52·0	11	5·99	29·7	7·89
	Pier 42	33·9	1099	56·3	11	6·34	32·1	7·29
CASE INLET:	Reach Island	86·5	1052	60·7	23	9·81	82·5	6·34
	Stretch Island	26·4	679	28·0	8·0	4·26	23·2	4·04
BUDD INLET:	Entrance channel, south end	89·9	1326	71·3	58	10·7	118	10·7
	Priest Point	70·2	1122	49·2	23	7·57	55·1	9·12
	Olympia Shoal	85·3	1233	68·9	45	10·4	101	10·5

Table A-3

CONCENTRATIONS OF TARGET ORGANIC COMPOUNDS IN SEDIMENTS FROM ELLIOTT BAY, IN ng/g DRY WEIGHT (PPB)
(From Malins et al., 1980, Appendix Table D-3)

SAMPLE NUMBER	88	64	60	31	83	86	34	37	38	72	59	87	78	73	81	38	47
STATION NUMBER	10014	10013	10016	10019	10023	10028	10031	10038	10039	10040	10041	10042	10043	10044	10045	10046	10046
1-PROPYLBENZENE	2 0	6 0	2 0	40	10	60	50	7 0	1 0	2 0	4 0	60	20	30	30	1 0	1 0
N-PROPYLBENZENE	80	6 0	2 0	70	10	1 0	60	1 0	2 0	1 0	9 0	3 0	2 0	2 0	2 0	1 0	2 0
INDAN	1 0	30	7 0	6 0	80	30	2 0	20	4 0	90	7 0	20	4 0	4 0	2 0	30	1 0
NAPHTHALENE	50	8 0	610	30	680	8 0	80	310	70	80	270	160	140	210	90	3 0	10
BENZOTHIOPHENE	2 0	80	8 0	90	20	10	90	2 0	3 0	4 0	7 0	6 0	4 0	3 0	90	20	70
2-METHYLNAPHTHALENE	20	1300	250	20	280	3 0	60	150	50	40	90	70	50	80	50	3 0	4 0
1-METHYLNAPHTHALENE	35	340	110	10	130	2 0	30	90	30	20	40	40	30	40	20	1 0	2 0
BIPHENYL	6 0	630	90	6 0	70	2 0	20	40	10	10	30	30	20	30	9 0	70	80
2,6-DIMETHYLNAPHTHALENE	20	600	110	30	210	3 0	50	80	40	70	60	60	40	60	30	1 0	2 0
ACENAPHTHYLENE	4 0	190	10	10	270	10	50	10	1 0	10	20	10	3 0	10	3 0	10	10
ACENAPHTHENE	4 0	1300	210	20	150	1 0	140	350	30	70	50	40	30	30	20	2 0	4 0
FLUORENE	10	970	210	30	270	60	170	350	60	30	60	60	40	30	70	3 0	6 0
DIBENZOTHIOPHENE	1 0	340	30	3 0	690	60	80	140	80	30	80	30	70	40	130	2 0	3 0
PHENANTHRENE	80	6800	1600	140	4200	10	960	2600	370	190	400	320	270	320	410	30	30
ANTHRACENE	30	2400	1200	180	1200	3 0	290	630	160	70	230	190	70	90	580	7 0	3 0
FLUORANTHENE	120	7600	3200	160	8100	20	1700	3700	770	240	490	730	320	450	700	30	30
PYRENE	160	11000	2800	170	8300	20	1200	3200	570	340	640	810	410	340	720	30	40
BENZ(A)ANTHRACENE	80	6800	1400	100	4800	10	1100	2700	310	180	310	660	140	290	670	30	30
CHRYSENE	70	6000	900	70	3900	9 0	930	2400	450	200	360	660	130	260	610	30	30
BENZOFLUORANTHENES	120	4700	2900	110	6800	20	1360	8400	730	480	710	1300	260	570	810	30	40
BENZO(E)PYRENE	60	4000	1100	40	2800	9 0	480	1700	300	250	330	590	120	250	390	10	10
BENZO(A)PYRENE	40	2200	960	40	4000	6 0	440	1900	240	770	260	440	90	180	170	10	10
PERYLENE	60	1700	370	270	1400	8 0	270	930	150	150	170	210	130	200	70	8 0	2 0
INDENO(1,2,3-CD)PYRENE	30	3300	480	30	2400	3 0	240	870	160	120	130	280	90	130	120	8 0	10
2,3,5-TRIMETHYLNAPHTHALENE	140	1000	100	30	370	4 0	50	70	30	30	60	50	60	60	60	70	30
HEXACHLOROBENZENE	070	33	10	10	030	023	20	40	20	30	30	30	10	20	070	010	010
LINDANE	010	10	020	10	020	010	10	040	080	2 0	020	030	040	020	030	010	010
HEPTACHLOR	023	83	50	20	023	010	80	20	3 0	10	40	30	40	10	030	010	010
ALDRIN	023	10	040	023	020	010	20	10	30	020	020	040	080	030	10	010	010
O,P-DDE	40	20	80	1 0	40	050	1 0	20	4 0	50	70	70	20	3 0	20	050	10
A-CHLORDANE	23	2 0	40	40	30	033	20	10	30	60	50	60	50	20	30	010	010
TRANS-NONACHLOR	33	2 0	40	40	10	030	20	10	2 0	60	30	60	30	20	30	010	010
P,P-DDE	40	2 0	83	2 0	20	040	20	10	20	10	10	30	10	10	50	030	040
O,P-DDD	40	40	2 0	3 0	20	050	3 0	40	2 0	10	10	10	20	70	4 0	070	040
M,P-DDD	60	9 0	30	7 0	40	070	3 0	40	9 0	10	20	30	30	10	20	10	070
P,P-DDD/O,P-DDT	83	10	33	10	3 0	040	7 0	20	10	10	2 0	20	20	3 0	3 0	040	040
P,P-DDT	40	20	10	3 0	90	030	7 0	10	7 0	4 0	6 0	10	80	2 0	70	080	040
DICHLOROBIPHENYLS	40	2 0	40	9 0	30	030	7 0	10	2 0	20	80	50	2 0	70	2 0	050	040
TRICHLOROBIPHENYLS	2 0	10	3 0	40	1 0	040	70	9 0	8 0	20	6 0	3 0	20	2 0	10	030	10
TETRACHLOROBIPHENYLS	3 0	50	30	100	9 0	10	120	50	30	50	20	20	50	10	20	10	30
PENTACHLOROBIPHENYLS	10	100	40	140	7 0	090	140	140	50	90	40	40	70	33	20	090	30
HEXACHLOROBIPHENYLS	8 0	140	40	110	9 0	090	100	210	90	80	30	60	60	30	20	080	30
HEPTACHLOROBIPHENYLS	8 0	140	33	33	30	040	70	190	110	30	20	30	30	30	20	040	20
OCTACHLOROBIPHENYLS	2 0	30	10	1 0	8 0	030	4 0	40	40	3 0	10	10	8 0	30	3 0	070	70
NONACHLOROBIPHENYLS	40	20	6 0	33	20	023	2 0	3 0	8 0	1 0	2 0	3 0	80	5 0	4 0	020	030
DICHLOROBENZENE	033	1 0	20	23	90	030	40	40	050	20	20	30	20	10	20	040	040
TRICHLOROBUTADIENE	40	8 0	70	10	40	50	20	1 0	70	3 0	1 0	2 0	1 0	6 0	1 0	040	070
TETRACHLOROBUTADIENE	3 0	40	8 0	10	2 0	2 0	60	5 0	2 0	10	3 0	7 0	5 0	30	5 0	035	040
PENTACHLOROBUTADIENE	23	4 0	1 0	10	080	10	20	60	20	1 0	1 0	10	1 0	3 0	40	030	030
HEXACHLOROBUTADIENE	20	1 0	40	10	40	20	20	60	20	60	40	70	60	3 0	30	010	010
% DRY WT	70	66	61	57	74	77	47	43	42	57	57	51	33	38	63	76	70
SAMPLE WT GRAMS	97.7	98.3	102	100	101	97.1	100	100	101	100	100	100	102	101	98.1	101	103

JRB Associates

Table A-4

CONCENTRATIONS OF TARGET ORGANIC COMPOUNDS IN SEDIMENTS FROM COMMENCEMENT BAY, IN ng/g DRY WEIGHT (PPB)
(From Malins et al., 1980, Appendix Table D-4)

SAMPLE NUMBER STATION NUMBER	45 *027	46 *028	44 *027	43 *030	53 *031	50 *032	49 *033	52 *034	61 *035	55 *036	62 *037	63 *038	44 *039	51 *040
1-PROPYLBENZENE	1 0	9 0	6 0	3 0	3 0	50	2 0	2 0	80	90 <	50	50	640	70
N-PROPYLBENZENE	6 0	70	8 0	1 0	40	1 0	90	2 0	1 0 <	40 <	50	3 0	730	1 0
INDAN	< 80	9 0	6 0	3 0	80	90	50	3 0	60 <	40 <	50	6 0	3 0	3 0
NAPHTHALENE	100	2600	440	170	4000	70	80	310	30	50	80	1300	400	60
BENZOTHIOPHENE	6 0	3 0	20	9 0	230	2 0	2 0	10	60 <	60 <	80	20	50	2 0
2-METHYLNAPHTHALENE	60	880	110	40	1600	20	70	220	10	10	30	710	270	20
1-METHYLNAPHTHALENE	20	330	90	30	720	20	70	90	4 0	8 0	20	240	110	10
BIPHENYL	70	270	70	20	490	8 0	10	40	4 0	2 0	6 0	180	150	10
2,6-DIMETHYLNAPHTHALENE	40	430	130	50	820	40	40	170	6 0	10	30	540	210	30
ACENAPHTHYLENE	< 70	280	30	20	310	10	70	30 <	10	3 0	6 0	110	1 0	10
ACENAPHTHENE	40	210	90	100	710	3 0	7 0	30	4 0	3 0	3 0	90	280	10
FLUORENE	40	820	80	80	810	30	70	40	2 0	4 0	3 0	190	310	7 0
DIBENZOTHIOPHENE	90	370	40	70	270	4 0	3 0	3 0	6 0	8 0	3 0	30	310	30
PHENANTHRENE	400	7300	630	390	4800	50	90	300	30	80	90	1300	1900	130
ANTHRACENE	300	670	170	100	2200	8 0	70	60	9 0	20	70	390	600	40
FLUORANTHENE	1700	6600	900	380	6100	30	110	300	40	90	90	2000	2600	230
PYRENE	1600	6700	870	320	10000	20	100	340	40	90	100	1800	2100	190
BENZ(A)ANTHRACENE	1600	3200	710	220	4700	10	60	110	20	50	40	780	2100	180
CHRYSENE	2400	3000	750	170	3800	10	60	180	20	30	40	1700	1700	260
BENZOFLUORANTHENES	2900	11000	720	200	6600	4 0	70	230	20	70	70	1800	1100	250
BENZO(E)PYRENE	1200	1900	430	120	3100	6 0	40	100	10	30	30	770	790	170
BENZO(A)PYRENE	500	1700	190	70	2400	2 0	20	60	6 0	20	10	330	340	60
PERYLENE	300	470	220	50	630	3 0	20	70	6 0	20	30	160	140	100
INDENO(1,2,3-CD)PYRENE	430	1100	190	60	1300	40	20	30	3 0	10 <	90	150	280	70
2,3,5-TRIMETHYLNAPHTHALENE	40	450	170	40	800	60	30	190	9 0	20	30	420	240	30
HEXACHLOROBENZENE	20	60	3 0	2 0	3 0	1 0	10	60	10	20	1 0	50	250	2 0
LINDANE	< 2 0 < 070 <	10 < 090 <	2 0 <	10	50	2 0 < 010 < 010 < 010			2 0	7 0 < 060				
HEPTACHLOR	< 1 0 < 050 <	20 <	10 / 2 0 <	10 <	10	1 0 < 010 < 020 < 010 <			10	20 < 20				
ALDRIN	< 1 0 < 040 <	20	2 0 < 2 0 <	10	1 0	70 < 030 < 040			70	4 0 < 1 0 < 090				
O.P' - DDE	20	1 0	2 0	2 0	9 0	40 <	20 <	10 < 080	10 < 040 <	60	3 0	60		
A-CHLORDANE	2 0	30	3 0	1 0 < 2 0 <	20	90	10 < 040	10 < 010	90	20	10			
TRANS-NONACHLOR	2 0	30	50	60	4 0 <	20	80	3 0 < 040	10	030	8 0	10	10	
P.P' - DDE	10	20	1 0	60	3 0	20	90	70 < 050	040 < 010	50	7 0	20		
O.P' - DDD	6 0	30	40	50	3 0 <	20 <	90 <	90 < 10 < 030 < 020 <	50	90 < 20				
P.P' - DDD	8 0	1 0	1 0	1 0	10 <	30 <	90 < 1 0 <	20 < 030	40 <	70 < 4 0	50			
P.P' - DDD/O.P' - DDT	50	10	6 0	9 0	30	2 0	2 0	10 <	10	20	50	3 0	10	2 0
P.P' - DDT	70	3 0	3 0	3 0	20	2 0	1 0	9 0 <	20 < 050	1 0	3 0	10	2 0	
DICHLOROBIPHENYLS	< 10	1 0 <	30 <	40	1 0	40 <	30	3 0 < 060	10	040	2 0	20	30	
TRICHLOROBIPHENYLS	60	3 0	90	1 0	10	3 0	N	60 < 050 < 090		40	60	140	2 0	
TETRACHLOROBIPHENYLS	190	9 0	1 0	20	60	9 0	N	130 < 10 <	50	1 0	100	250	7 0	
PENTACHLOROBIPHENYLS	230	8 0	10	20	100	2 0	N	90 < 10 <	40	40	70 ·	230	4 0	
HEXACHLOROBIPHENYLS	440	6 0	10	20	130	80	N	60 < 10 <	40 <	30	30	160	8 0	
HEPTACHLOROBIPHENYLS	100 < 2 0		10 < 3 0	60 <	30 <		N	30 < 090 ·	30 <	40	10	120	1 0	
OCTACHLOROBIPHENYLS	110 < 2 0		2 0 < 2 0	20 <	20		N	10	040 < 20 <	20	4 0	70	90	
NONACHLOROBIPHENYLS	< 20 < 1 0		1 0 <	80 < 2 0 <	10		N	3 0 < 030 · 070 · 040			70	2 0 · 30		
DICHLOROBENZENE	20	2 0 <	30 <	20	20	060	90 ·	70	080 < 040 < 050	40	60	060		
TRICHLOROBUTADIENE	90	20	10	4 0	4 0	1 0	40	270	2 0	5 0	7 0	10	3900	4 0
TETRACHLOROBUTADIENE	270	40	20	10	40	2 0	140	460	10	20	20	120	2800	10
PENTACHLOROBUTADIENE	90	8 0	4 0	7 0	6 0	90	50	140	4 0	3 0	50	90	1200	2 0
HEXACHLOROBUTADIENE	90	2 0	6 0	2 0	2 0	90	30	140	1 0	2 0	4 0	60	1100	2 0
% DRY WT	35	43	59	56	41	62	57	52	70	74	76	42	43	56
SAMPLE WT. GRAMS	100	100	99.6	101	101	100	99.6	102	101	99.6	101	98.7	104	99.3

Table A-5

CONCENTRATIONS OF TARGET ORGANIC COMPOUNDS IN SEDIMENTS FROM OTHER SITES, IN ng/g DRY WEIGHT (PPB)

From Malins et al., 1980, Appendix Table D-5

SAMPLE NUMBER	P MADISON		BUDD INLET			CASA INLET		SINCLAIR INLET			
STATION NUMBER	70	37	35	33	39	36	40	80	36	17	77
	8106	8107	12130	12131	12132	17262	17263	8004	8005	8006	8007
1 PROPYLBENZENE	2 0	1 0	7 0	7 0	30	1 0	20	30	3 0	2 0	70
N PROPYLBENZENE	30	2 0	50	30 <	40	2 0	1 0	40	3 0	3 0	4 0
IMEAN	1 0	30	1 0	4 0	4 0	4 0	40	5 0	4 0	5 0	10
NAPHTHALENE	30	8 0	30	50	80	20	7 0	40	50	100	300
BENZOTHIOPHENE	60 <	20	30	1 0	40	50	20	2 0	7 0	4 0	70
2-METHYLNAPHTHALENE	30	7 0	10	20	20	20	1 0	30	40	70	140
1-METHYLNAPHTHALENE	10	3 0	6 0	6 0	9 0	10	1 0	10	70	20	170
BIPHENYL	6 0	2 0	3 0	6 0	8 0	4 0	10	10	10	70	90
2,6-DIMETHYLNAPHTHALENE	10	3 0	10	9 0	10	20	1 0	20	30	50	280
ACENAPHTHALENE	< 10 <	10	< 20 <	20 <	30	< 40 <	13	20 <	30 <	20	3 0
ACENAPHTHENE	3 0 <	10	10	10	9 0	3 0	20	6 0	70	50	60
FLUORENE	10	40	7 0	9 0	9 0	1 0 <	10	4 0	50	50	90
DIBENZOTHIOPHENE	10	3 0	20	10	10	2 0 <	30	20	50	10	280
PHENANTHRENE	60	20	70	40	90	50	4 3	70	260	170	1400
ANTHRACENE	10	3 0	20	10	20	8 0	30	20	80	60	780
FLUORANTHENE	80	30	160	80	130	100	7 0	160	460	280	2300
PYRENE	110	30	170	100	180	90	8 0	190	460	350	3100
BENZ(A)ANTHRACENE	70	20	110	50	80	40	3 0	140	370	270	2100
CHRYSENE	50	20	90	30	90	40	3 0	120	390	370	1900
BENZOFLUORANTHENES	80	40	110	70	120	60	7 0	290	470	310	1800
BENZO(E)PYRENE	40	10	50	30	60	50	4 0	120	240	170	930
BENZO(A)PYRENE	30	9 0	30	10	40	30	7 0	70	170	140	850
PERYLENE	40	10	120	30	90	40	4 0	70	110	90	510
INDENO(1,2,3-CD)PYRENE	30	10	20	10	40	30	2 0	90	170	130	670
2,3,5 TRIMETHYLNAPHTHALEN	20	4 0	10	10	9 0	20	2 0	30	50	40	320
HEXACHLOROBIPHENE	10	030	10	10	010	040	010	20	40	20	20
LINDANE	< 040 < 010	< 020 < 010 < 020	< 020 < 010	< 040 < 040 < 020 < 040
HEPTACHLOR	< 010 < 010	< 10 < 10 < 030	< 020 < 010	< 020 < 030 < 020 < 030
ALDRIN	< 010 < 010	< 020 < 010 < 040	< 020 < 010	< 040 < 020 < 020 < 030
O.P' - DDE	30 < 040	< 10 < 10 < 070	< 10 < 030	3 0	4 0	2 0	70
A-CHLORDANE	30 < 020	< 30 < 30 < 30	< 10 < 020	60	80	40	20
TRANS-NONACHLOR	30 < 020	< 30 < 30 < 10	< 10 < 020	60	90	40	10
P.P' - DDE	20 < 020	20	70 < 040	< 10 < 030	50	2 0	60	20
O.P' - DDD	083 < 040	< 30 < 30 < 10	< 10 < 020	80	1 0	60	20
M.P' - DDD	10 < 060	20 < 30 < 10	< 30 < 030	< 10 < 20 < 60 < 30
P.P' - DDD/O.P' - DDT	30	10	1 0	60 < 60	30 < 030	8 0	9 0	4 0	1 0
P.P' - DDT	10	60	1 0	10 < 060	< 20 < 020	2 0	3 0	90	4 0
DICHLOROBIPHENYLS	20	10	30	30	30	20	030	60	20	010	20
TRICHLOROBIPHENYLS	40	40	60	40	30	30	10	3 0	3 0	2 0	1 0
TETRACHLOROBIPHENYLS	2 0	1 0	4 0	2 0	3 0	90	040	10	10	8 0	3 0
PENTACHLOROBIPHENYLS	2 0	1 0	8 0	6 0	70	1 1	20	30	40	20	7 0
HEXACHLOROBIPHENYLS	2 0	20	3 0	3 0	60	90	10	30	70	30	6 0
HEPTACHLOROBIPHENYLS	2 0 < 20	60	3 0 < 30	30	030	40	70	20	7 0
OCTACHLOROBIPHENYLS	40 < 10	40	30 < 20	< 10 < 040	40	20	3 0	2 0
NONACHLOROBIPHENYLS	083 < 040	< 20 < 10 < 10	< 10 < 020	2 0	3 0	4 0	2 0
DICHLOROBENZENE	070 < 10	< 10 < 10 < 4 0	< 10 < 060	20 < 20 < 10 < 20
TRICHLOROBUTADIENE	30	50	20	40	30	40 < 030	4 0	10	20	10
TETRACHLOROBUTADIENE	90	2 0	2 0	4 0	2 0	6 0 < 040	10	40	50	30
PENTACHLOROBUTADIENE	40	030	20	70	30	90 < 040	2 0	8 0	10	3 0
HEXACHLOROBUTADIENE	30	20	10	20	050	20 < 030	3 0	10	10	6 0
% DRY WT	33	73	28	37	27	23	71	32	33	38	50
SAMPLE WT (GRAMS)	101	99 1	99 4	101	100	100	100	102	99 2	103	101

APPENDIX B

CONCENTRATION OF TRACE METALS AND
SYNTHETIC ORGANICS IN THE SEDIMENTS OF
ELLIOTT BAY AND IN THE WEST POINT AREA

Concentration of trace metals in μg/g ·.ry weight; organics in ng/g dry weight.
Data from Metro/TPPS report (Pavlou, et al., 1983).

AREA B: ELLIOTT BAY/DUWAMISH WATERWAY

	014g		A062	B062	C602	S0036	S0037	S0039	S0043	S0064	Mean ± S.D.
ANTIMONY	5.9	1.8	1.2	0 027	1.5	4.4	1.3	0 7	3 9	4.3	2.5 ± 2 0
ARSENIC	31	28	3.7	4.3	11	23	16	14	7.1	23	16 ± 9.8
BERYLLIUM	0.61	0.58	1.4	0.94	1.3	0.47	0 5	054	0.2	0.46	0.70 ± 0.34
CADMIUM	0.92	0 6	2 3	2.6	2 8	0.53	0 17	1 6	0 28	1 1	1.3 ± 0.15
CHROMIUM	36	48	4.2	50	50	52	44	56	27	53	44 ± 17
COPPER	100	100	460	120	180	150	56	94	90	69	142 ± 118
LEAD	200	223	240	240	340	310	77	150	190	120	209 ± 81
MANGANESE	390	320	340	270	340	360	390	360	160	240	317 ± 73
MERCURY	0.48	0.004	0 088	0 02	0 032	0.44	0 13	0 38	0.4	1.2	0.32 ± 0.36
NICKEL	21	24	40	38	42	32	49	35	4 9	24	31 ± 13
SELENIUM	0.6	0.14	0 095	0 018	0 33	0 24	0 5	0 42	0.2	0.51	0.31 ± 0 20
SILVER	0 79	2 4	0.15	0 9	1 3	2.2	2 4	0 29	0.16	1 8	1.2 ± 0.91
THALLIUM	0.1	0 01	0 028	0.009	0.009	0.1	0.1	0 1	0 1	0.1	0.066 ± 0 045
ZINC	220	1420	240	270	350	210	120	190	84	160	325 ± 191

AREA C: ELLIOTT BAY

	A061	B061	C061	S0090	S0065	S0064	MEAN $\pm$ S.D.
ANTIMONY	0.41	0.35	0.22	1.3	3.5	0.7	1.1 $\pm$ 1.3
ARSENIC	8.4	13	8.8	4.2	20	9.9	11 $\pm$ 5.3
BERYLLIUM	0.36	0.41	0.31	0.18	0.46	0.35	0.35 $\pm$ 0.10
CADMIUM	0.49	0.37	2.2	0.75	0.62	0.4	0.81 $\pm$ 0.70
CHROMIUM	59	63	45	28	42	45	47 $\pm$. 13
COPPER	64	64	36	11	64	46	48 $\pm$ 21
LEAD	130	130 ·	55	84	100	63	94 $\pm$ 32
MANGANESE	260	290	240	290	300	210	282 $\pm$ 26
MERCURY	0.024	0.072	0.022	0.12	0.92	0.18	0.22 $\pm$ 0.35
NICKEL	45	47	41	25	31	30	37 $\pm$ 9.0
SELENIUM	1.1	0.39	0.35	0.20	0.7	0.2	0.49 $\pm$ 0.35
SILVER	1.9	1.9	1.6	2.1	1.9	1.2	1.8 $\pm$ 0.32
THALLIUM	0.007	0.01	0.006	0.10	0.1	0.1	0.054 $\pm$ 0.051
ZINC	1020	1080	757	210	120	120	551 $\pm$ 454

AREA D: N.E. ELLIOTT BAY/DENNY WAY CSO

	401608		401312		401603		401606		401312		401709		401910		A260	B060	C060	50033	50037	Mean ± S.D.
ANTIMONY	3.2	1.5	2.3	0.87	2.6	3.3	1.3	0.46	3.3	1.0	3.2	0.6	1.0	0.94	0.87	1.3	0.03	0.9	0.45	1.3 ± 1.1
ARSENIC	8.8	13	12	13	15	16	12	9.1	14	14	15	12	12	11	0.53	12	44	11	9.3	14 ± 8.2
BERYLLIUM	0.33	0.33	0.30	0.37	0.31	0.26	0.41	0.16	0.1	0.11	0.4	0.2	0.33	0.18	0.19	1.1	0.49	0.36	0.33	0.39 ± 0.26
CADMIUM	0.99	2.1	0.32	0.39	0.46	2.2	0.13	0.16	0.7	0.36	0.46	0.63	0.47	0.11	1.6	1.3	0.73	0.66	0.39 ± 0.26
CHROMIUM	60	61	46	57	57	63	63	45	60	39	59	53	36	40	39	50	51	50	57	53 ± 6.3
COPPER	130	87	52	53	120	120	52	36	62	56	61	36	67	39	140	41	47	49	75 ± 32
LEAD	89	210	56	96	430	670	62	49	90	98	93	190	42	120	120	110	100	120	153 ± 151
MANGANESE	300	310	300	280	300	320	400	210	330	300	470	310	440	300	220	200	290	230	300 ± 90
MERCURY	0.93	1.0	1.6	0.36	1.3	1.6	0.77	0.22	0.72	3.6	0.62	0.72	0.63	0.61	0.71	0.12	0.93	0.26	0.06	0.62 ± 0.78
NICKEL	44	44	40	51	41	49	36	50	48	50	49	58	39	45	56	50	43	42	48 ± 7.3
SELENIUM	0.48	0.70	0.36	0.70	0.2	0.2	0.4	0.2	0.78	0.2	0.48	0.2	0.2	0.2	0.07	0.63	0.03	0.2	0.2	0.3 ± 0.2
SILVER	4.6	1.1	3.6	2.1	0.9	4.1	3.6	1.3	3.9	1.3	3.2	2.2	2.1	2.4	0.72	1.2	0.49	2.0	1.9	2.2 ± 1.2
THALLIUM	0.10	0.10	0.1	0.10	0.1	0.1	0.1	0.1	0.1	0.1	0.10	0.1	0.1	0.1	0.007	0.013	0.01	0.1	0.1	0.046 ± 0.033
ZINC	140	170	100	110	240	300	150	84	120	110	135	110	120	120	210	140	100	100	100	143 ± 57

AREA F: WEST POINT

	400210		400310		400330		400430		400510		400530		400611		400712		400818		400910		501004		501003	501010		500912		501100		501101		501107		501103		501104		501130		Mean ± S.D.
ANTIMONY																																								

AREA EE: CENTRAL ELLIOTT BAY

	0150	401230		401630		401830		S0015	S0062	MEAN ± S.D.
ANTIMONY	0.31	0.5	0.67	0.8	0.53	1	0.67	1.1	0.86	0.72 ± 0.25
ARSENIC	8.8	13	14	12	8	10	11	14	10	11 ± 2.2
BERYLLIUM	0.45	0.36	0.4	0.45	0.07	0.44	0.24	0.83	0.35	0.40 ± 0.20
CADMIUM	0.25	0.25	0.46	0.23	0.05	0.3	0.14	0.38	0.36	0.27 ± 0.12
CHRONIUM	53	54	47	37	11	47	47	59	56	46 ± 15
COPPER	61	62	50	55	13	50	46	49	61	49 ± 15
LEAD	87	55	81	68	30	62	72	53	68	64 ± 17
MANGANESE	290	420	380	380	130	340	330	400	300	330 ± 87
MERCURY	0.004	0.43	0.29	0.63	0.06	0.53	0.34	0.22	0.52	0.34 ± 0.21
NICKEL	32	32	38	27	13	31	43	36	29	31 ± 8.4
SELENIUM	0.49	0.2	0.3	0.33	0.2	0.2	0.34	0.36	1	0.38 ± 0.25
SILVER	2.9	3.9	0.24	3.6	0.05	2.3	0.74	0.41	0.75	1.7 ± 1.5
THALLIUM	0.01	0.1	0.1	0.1	0.1	0.1	0.1	0.53	0.1	0.14 ± 0.15
ZINC	1180	100	100	120	50	110	100	130	100	221 ± 360

AREA D: NORTHEAST ELLIOTT BAY/DENNY WAY CSO

APPENDIX C

ESTIMATION OF ORGANIC CARBON CONTENT

Table C-1

PERCENTAGE OF SEDIMENT ORGANIC CARBON AT METRO/TPPS STATIONS AS ESTIMATED FROM THE PERCENTAGE OF FINES
(The regression used is shown in Figure 8)

Station Number	% Fines	% Organic Carbon	Station Number	% Fines	% Organic Carbon
Area B			**Area F**		
0149	68.4	2.4	400310	12.3	0.69
A062	74.2	2.6	400330	18.6	0.88
B062	61.1	2.2	400430	26.8	1.12
C062	89.1	3.0	400510	7.8	0.55
S0063	16.4	0.8	400530	13.1	0.71
S0064	69.9	2.4	400621	4.8	0.46
			400712	11.7	0.67
Area C			400730	7.7	0.55
A061	57.9	2.1	400810	7.5	0.54
B061	52.4	1.9	400830	29.8	1.21
C061	52.0	1.9	S0004	5.7	0.49
S0090	84.5	2.9	S0005	8.2	0.57
S0065	81.4	2.8	S0010	7.4	0.54
			S0099	7.4	0.54
Area D			S1100	6.7	0.52
401406	75.6	2.6	S0101	7.4	0.54
401512	81.8	2.8	S0102	9.5	0.61
401603	39.9	1.5	S0103	8.2	0.57
401606	91	3.1	S0104	11.9	0.68
401612	82	2.8			
401810	68.7	2.4	**Area EE**		
A060	40.1	1.5	0150	71.4	2.46
B060	89.2	3.0	401230	7.5	0.55
C060	91.5	3.1	401630	68.7	2.38
			401830	92.4	3.09
			S0015	55.1	1.97
			S0062	83.4	2.82

JRB Associates