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A REVIEW OF THE WATER QUALITY AND
MARINE RESOURCES OF ELLIOTT BAY,
SEATTLE, WASHINGTON

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and
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Final Report
for Contract Period
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for
URS/METRO Contract CW/F2-82
Renton Effluent Treatment System
for
URS Engineers
and
The Municipality of Metropolitan Seattle
Seattle, Washington

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TABLE OF CONTENTS

	<u>Page No.</u>
LIST OF TABLES	vii
LIST OF FIGURES.	xiii
EXECUTIVE SUMMARY.	xix
ACKNOWLEDGMENTS.	xxiii
PREFACE.	xxiv
1.0 DEFINITION OF STUDY AREA.	1
1.1 Study Area	1
1.2 Water Quality Classification	6
2.0 PHYSICAL DESCRIPTION.	7
2.1 Depth Profile.	7
2.2 Current Patterns	7
2.3 Water Quality.	10
2.4 Suspended Particulate Matter	17
3.0 DISTRIBUTION AND CONCENTRATIONS OF XENOBIOTIC CHEMICALS .	19
3.1 Trace Metals in Water and Sediments.	19
3.2 Trace Organics in Water and Sediments.	42
3.3 Body Concentrations of Chemicals in Biota.	57
4.0 BIOLOGICAL RESOURCES.	65
4.1 Phytoplankton.	65
4.1.1 Phytoplankton Species	65
4.1.2 Distribution of Phytoplankton/Chlorophyll a .	65
4.1.3 Temporal Variability.	65
4.1.4 Spatial Variability	65
4.1.5 Primary Production.	69
4.1.6 Nutrient Distributions and Phytoplankton Interactions.	69
4.1.7 Toxic/Stimulatory Effects on Phytoplankton. .	72

	<u>Page No.</u>
4.2 Zooplankton.	72
4.2.1 Zooplankton Species	72
4.2.2 Spatial Distribution.	72
4.2.3 Toxicant Interactions with Zooplankton.	72
4.3 Nearshore Habitats	74
4.3.1 Nearshore Benthic Assemblages	78
4.3.2 Natural and Anthropogenic Changes in Nearshore Habitats and Biota.	95
4.4 Benthic Ecology.	95
4.4.1 Sediment Characterization	95
4.4.2 Benthic Invertebrates from West Point	102
4.4.3 Benthic Invertebrates from the Denny Way Combined Sewer Overflow	104
4.4.4 U.S. Army Corps of Engineers Dredged Sediment Disposal Site.	104
4.4.5 Distribution Trends	107
4.4.6 Shortcomings of the Existing Benthic Invertebrate Studies.	113
4.4.7 The Geoduck (<u>Panope generosa</u>)	113
4.5 Fishes of Elliott Bay and the Duwamish Estuary	116
4.5.1 Anadromous, Pelagic Fishes.	116
4.5.1.1 Life History of the Salmonids.	116
4.5.1.2 Food Habits of the Salmonids	125
4.5.2 Fishes of the Duwamish Estuary.	125
4.5.3 Demersal Fishes of Elliott Bay.	143
4.5.3.1 Life History of a Typical Flatfish	143
4.5.3.2 Parasitic Infestations of Demersal Fishes	144
4.5.3.3 Reef Fishes.	144
4.5.4 Rocky Intertidal Fishes	144
4.5.5 Abundance and Species Richness.	144
4.5.6 Species Assemblages	156
4.5.7 Food Habits	161

	<u>Page No.</u>
5.0 WATER QUALITY EVALUATION.	185
5.1 Fish Health.	185
5.1.1 Fin Erosion	185
5.1.1.1 Background	185
5.1.1.2 Incidence in Elliott Bay	187
5.1.1.3 Association with Xenobiotics	187
5.1.2 Epidermal Papilloma	189
5.1.2.1 Background	189
5.1.2.2 Incidence in Elliott Bay	189
5.1.2.3 Association with Xenobiotics	190
5.1.3 Liver Neoplasms	190
5.1.3.1 Background	190
5.1.3.2 Incidence in Elliott Bay	191
5.1.3.3 Association with Xenobiotics	191
5.1.4 Other Liver Abnormalities	194
5.1.4.1 Backgrounds.	194
5.1.4.2 Incidence in Elliott Bay	195
5.1.4.3 Association with Xenobiotics	195
5.1.5 Other Abnormalities in Fishes	199
5.1.6 Summary	199
5.2 Invertebrate Health.	199
5.3 Microbiology	200
5.3.1 Microbiology.	200
5.3.1.1 Duwamish River	200
5.3.1.2 Elliott Bay.	209
5.3.1.3 Summary.	217
5.3.2 Human Enteroviruses	220
5.3.3 Relationship of Viruses to Bacteria	221
5.4 Responses to Toxic Chemical Contaminants	221
5.4.1 Acute Bioassays	221
5.4.1.1 Water Column	221

	<u>Page No.</u>
5.4.1.2 Sediments.	224
5.4.1.3 Other Acute Bioassays.	226
5.4.2 Sublethal Bioassays	226
5.4.2.1 Oyster Embryo.	226
5.4.2.2 Worm Respiration	227
5.4.2.3 Genotoxicity Assays.	229
5.4.2.4 Bioaccumulation.	229
5.4.3 Toxicity of Renton Treatment Plant Effluent .	230
6.0 CONCLUSIONS	233
6.1 Rationale.	233
6.2 Water Column	233
6.3 Intertidal Resources	234
6.4 Subtidal Ecology	234
6.5 Fishes	234
6.6 Fish Health.	235
6.7 Microbiology	235
6.8 Marine Toxicology.	235
6.9 Chemistry of Xenobiotic Chemicals.	236
REFERENCES	237
APPENDICES	257

LIST OF TABLES

<u>Number</u>		<u>Page</u>
2.1	Inferred water residence times for inner Elliott Bay.	11
2.2	Summary of water quality data for the east, west, and Duwamish waterways	12
2.3	Physical and chemical parameters for sediment from Elliott Bay and the Duwamish River.	13
3.1	Cumulative emission rates (E_{ATM}^S) of airborne material from point source inputs in Puget Sound . . .	35
3.2	Availability of toxicant loading data for sources discharging into Elliott Bay	37
3.3	Duwamish Estuary annual pollutant mass balances (1970-1980)	38
3.4	Mean trace metal concentrations in the shallow sediment areas of Puget Sound. ^a	44
3.5	Mean trace metal concentrations in deep sediment areas of Puget Sound.	45
3.6	Mean total polychlorinated biphenyl concentrations in various regions of Puget Sound.	46
3.7	Estimated inputs of polychlorinated biphenyls to Puget Sound	50
3.8	Conclusions and summary describing the concentrations of synthetic organic chemicals in sediments from various areas in Puget Sound	51
3.9	Mean trace organic chemical concentrations in shallow sediment areas of Puget Sound. ^a	52
3.10	Mean trace organic chemical concentrations in deep sediment areas of Puget Sound. ^a	53
3.11	Concentrations of DDT and its metabolites in Puget Sound	54
3.12	Concentrations of polycyclic aromatic hydrocarbons associated with suspended matter in the Green River. .	55

<u>Number</u>		<u>Page</u>
3.13	A comparison of the concentrations of combustion polycyclic aromatic hydrocarbons at three locations along the Duwamish River and Elliott Bay . .	56
3.14	Concentrations of polychlorinated biphenyls from sediments and biota from various areas in Puget Sound.	59
3.15	Concentrations of benzo(a)pyrene (ppm; dry weight) in sediment and biota from various areas of Puget Sound.	62
3.16	Concentrations of benzo(a)anthracene (ppm) in sediments and biota from various areas in Puget Sound.	63
4.1	Literature describing the nearshore benthic biota in Elliott Bay and the Duwamish River estuary.	80
4.2	Relative abundance of the 10 most abundant diatom species each season at West Point (W), Alki (A) and Lincoln Park (L)	87
4.3	Five most abundant species in understory (using biomass) within each portion of the bed.	88
4.4	Correlations between biological and physical parameters at the 49 sites	90
4.5	The number of species occurring at the five study beaches by major taxon	91
4.6	The numbers of the most abundant epifaunal species subsampled from two mixed-sediment, zero tide height sites at each beach	92
4.7	The most abundant polychaete species collected with a 1.0 mm mesh screen at various tidal levels. . .	93
4.8	The number and biomass of the numerically dominant species of infaunal bivalves collected with a 6 mm mesh screen at various tide heights.	94
4.9	The most abundant amphipods gathered from the combined 1.0 mm mesh screen and epifaunal samples at various tide heights.	96
4.10	Seasonal summations of the numbers of individuals collected as epifauna and with the 1.0 mm mesh screen at each tidal level	97

<u>Number</u>		<u>Page</u>
4.11	Representative benthic taxa in nearshore habitats at Elliott Bay, Seattle, Washington.	98
4.12	Ranking by abundance of the most common benthic invertebrates occurring in the U.S. Army Corps of Engineers dredged sediment disposal site in Elliott Bay.	108
4.13	Ranking by biomass of the most common benthic invertebrates occurring in the U.S. Army Corps of Engineers dredged sediment disposal site in Elliott Bay.	114
4.14	Fishes that occur in Elliott Bay and the Duwamish River estuary	117
4.15	The freshwater life history of salmon and trout residing in the Duwamish-Green River	122
4.16	Commercial catch by species and year of salmonids from Elliott Bay	123
4.17	The number of steelhead (<u>Salmo gairdneri</u>) caught annually by the Muckleshoot Indian Tribe. . . .	124
4.18	Sport catch of steelhead (<u>Salmo gairdneri</u>) and cutthroat trout (<u>Salmo clarki</u>) in the Duwamish-Green River system.	126
4.19	The number in thousands of juvenile chinook (<u>Oncorhynchus tshawytscha</u>) and coho (<u>O. kisutch</u>) released annually into the Duwamish-Green River system	127
4.20	The number of steelhead (<u>Salmo gairdneri</u>) planted in and migrating out of the Duwamish- Green River system	128
4.21	Two estimates of the importance of three invertebrates in the diet of juvenile chinook (<u>Oncorhynchus tshawytscha</u>)	129
4.22	The importance of various organisms in the diet of juvenile chinook (<u>Oncorhynchus tshawytscha</u>)	130
4.23	Fishes collected in the Duwamish River during 1975-1976.	131
4.24	Sport catches of bottom and near-bottom fishes for 1982 in Elliott Bay.	132

<u>Number</u>		<u>Page</u>
4.25	Fishes collected off West Point during 1975-76	134
4.26	Fishes collected off Alki Point during 1975-76	137
4.27	Seasonal abundance of fish eggs sampled near West Point with a Miller net during 1975-76.	141
4.28	Species and numbers of fish sighted during diving straightline transect series surveys at Pier 91 and 90 (ad = adult, juv = juvenile, UID = unidentified).	146
4.29	Species and numbers of fish sighted during diving zig-zag transect surveys at the end of Pier 91 and off Terminal 37.	147
4.30	Abundance of fish (number fish/100 m ²) in pilings and riprap along sides of Piers 91 and 90.	148
4.31	Abundance of fish (number of fish/100 m ²) associated with pilings and riprap at the end of Pier 91 and Terminal 37.	149
4.32	Species collected at Alki Point with the 9-m beach seine from May 1976 through January 1977	151
4.33	Monthly catch per haul (CPH) of the five most abundant and frequently occurring species taken with the 37-m beach seine at West Point during 1975-76.	157
4.34	Monthly catch per haul (CPH) of the nine most abundant and frequently occurring species taken with the 37-m beach seine at Alki Point during 1975-76.	158
4.35	Seasonal bathymetric distribution of species groups I (ratfish, Dover sole, and rex sole) and II (roughback sculpin and rock sole) at West Point during 1975-1976.	164
4.36	Seasonal bathymetric distribution of species groups I (roughback sculpin, English sole, and rock sole; II (ratfish, slender sole, and Dover sole); and III (northern ronquil and tomcod) at Alki Point during 1975-1976.	165
4.37	Percentage of total IRI contributed by various prey categories to the diets of the dominant nearshore fishes occurring at Alki Point (sand/eelgrass habitat).	166

<u>Number</u>		<u>Page</u>
4.38	Percentage of total IRI contributed to the diets of small-mouthed flatfishes by various prey categories	168
4.39	Percentage of total IRI contributed by various prey categories to the diets of three size classes of English sole from West Point.	170
4.40	Percentage of total IRI contributed by various prey categories to the diets of three size classes of rock sole from West Point	171
4.41	Percentage of total IRI contributed to the diets of large-mouthed flatfishes by various prey categories	172
4.42	Percentage of total IRI contributed to the diets of the roughback sculpin, northern ronquil, sailfin sculpin, spotfin sculpin, and slim sculpin, by various prey categories.	173
4.43	Percentage of total IRI contributed by various prey categories to the diets of the sturgeon poacher, spearnose poacher, bluespotted poacher, and blacktip poacher	175
4.44	Percentage of total IRI contributed by various prey categories to the diets of shiner perch, tomcod, brown rockfish, quillback rockfish, and ratfish.	177
4.45	Percentage of total IRI contributed by various prey categories to the diets of three size classes of ratfish.	178
4.46	Percentage of total IRI contributed by various prey categories to the diets of three size classes of roughback sculpin	179
4.47	Seasonal variation in the percentage of total IRI contributed by various prey categories to the diet of English sole.	181
4.48	Seasonal variation in the percentage of total IRI contributed by various prey categories to the diet of rock sole from West Point	182
4.49	Seasonal variation in the percentage of total IRI contributed by various prey categories to the diet of ratfish	183

<u>Number</u>		<u>Page</u>
4.50	Seasonal variation in the percentage of total IRI contributed by various prey categories to the diet of roughback sculpin	184
5.1	Fin erosion in demersal fishes from various coastal areas.	186
5.2	Reported incidence of fin erosion in Duwamish River flatfish	188
5.3	Sampling locations and number of fish from each location subjected to histopathological examination by Malins et al. (1982)	192
5.4	Histopathological lesions observed in target invertebrate species collected from Puget Sound. . . .	201
5.5	Annual mean bacterial counts from various stations to Elliott Bay and the Duwamish River.	206
5.6	Summary of water quality data collected by the Washington State Department of Ecology during the time-of-travel study of the Green-Duwamish River . . .	207
5.7	Concentrations of various chemicals in urban runoff. .	218
5.8	Mean survival of macrobenthic marine species in sediment toxicity bioassays.	225
5.9	Comparison of the 50 percent effective concentrations (EC50's) for five stages of Renton sewage and equivalent freshwater dilutions.	232

LIST OF FIGURES

<u>Number</u>		<u>Page</u>
ES.1	General overview of the geographic distribution of the more useful benthic data previously collected for Elliott Bay and adjacent marine waters	xx
ES.2	General overview of the geographic distribution of the more useful fish and fish health data previously collected for Elliott Bay and adjacent marine waters.	xxi
ES.3	General overview of the geographic distribution of the more useful toxicity data previously collected for Elliott Bay and adjacent marine waters .	xxii
1.1	Elliott Bay and Duwamish River, Seattle, Washington. .	2
1.2	The Duwamish River, Seattle, Washington.	3
1.3	Changes in the shoreline of Elliott Bay between 1900 and 1973.	4
1.4	Mean monthly and minimum monthly discharges of the Green River near Auburn.	5
2.1	Bathymetry in fathoms of Elliott Bay and adjacent areas	8
2.2	Circulation in Elliott Bay as defined by the direction, speed and energy of the currents.	9
2.3	Annual cycles of temperature, salinity, density, and dissolved oxygen at the surface and 50 m depth in Elliott Bay	15
2.4	Surface salinity distribution in Elliott Bay during 24 - 27 September, 1974	16
3.1	A. Areal distributions of total particulate chromium at the surface and 5 m above the bottom of Elliott Bay.	20
3.2	A. Areal distributions of total particulate manganese at the surface and 5 m above the bottom of Elliott Bay.	22
3.3	A. Areal distribution of total particulate iron at the surface and 5 m above the bottom of Elliott Bay	24

<u>Number</u>		<u>Page</u>
3.4	A. Areal distributions of total particulate nickel at the surface and 5 m above the bottom of Elliott Bay	26
3.5	A. Areal distributions of total particulate copper at the surface and 5 m above the bottom of Elliott Bay	28
3.6	A. Areal distributions of total particulate zinc at the surface and 5 m above the bottom of Elliott Bay	30
3.7	A. Areal distributions of total particulate lead at the surface and 5 m above the bottom of Elliott Bay	32
3.8	Location of dominant atmospheric emission point sources in the Puget Sound basin	34
3.9	Cross sections of total dissolved manganese, copper, nickel, and cadmium in Puget Sound	39
3.10	Concentrations of copper, lead, zinc, and mercury in the sediments of Elliott Bay.	41
3.11	Concentrations of copper, zinc, lead, and mercury in the sediments of the Duwamish River	43
3.12	Concentrations of polychlorinated biphenyls, chlorinated butadienes, and arenes observed in the sediments of Elliott Bay.	47
3.13	Concentrations of polychlorinated biphenyls, chlorinated butadienes, and arenes observed in the sediments of the Duwamish River	49
3.14	Average trace metal concentrations in bay mussels (<u>Mytilus edulis</u>) from Puget Sound.	58
4.1	Variations of salinity, temperature, density, oxygen saturation, phosphate, silicate, nitrate, chlorophyll a and carbon uptake rate in the main basin of Puget Sound in May-June 1966.	66
4.2	Spatial distribution of surface chlorophyll a in Elliott Bay during September, 1972	68
4.3	Spatial distribution of surface nitrate in Elliott Bay during September 1972.	70

<u>Number</u>		<u>Page</u>
4.4	Spatial distribution of ammonia a 3 m depth in Elliott Bay during September 1972.	71
4.5	Variations in zooplankton biomass estimates in 1966, 1967 and 1975 in the main basin of Puget Sound.	73
4.6	The nearshore surface areas in Elliott Bay by depth intervals and shoreline segments (Alki Point to Duwamish Head, Duwamish Head to Pier 89, Pier 89 to Four Mile Rock, and Four Mile Rock to West Point) .	75
4.7	Surface areas of intertidal habitat types by shoreline segments in Elliott Bay to -50 feet.	77
4.8	Nearshore habitats in the Alki Beach-Duwamish Head area.	79
4.9	Average algal cover.	83
4.10	Seasonal change in number of macroalgal species over all beaches	84
4.11	(a), (b) seasonal variation in diatom cover.	85
4.12	Variation in cover and number of taxa on the one month periphyton plates.	86
4.13	Average number of species in the 0.25m ² quadrats over tidal height	89
4.14	Composition and distribution of benthic sediments from Elliott Bay, Washington	99
4.15	Ranking by abundance and biomass of most common subtidal macrofaunal taxa from May 1979 Elliott Bay cruise	103
4.16	Maximum and minimum abundance of benthic invertebrate macrofauna observed at multiple sampling sites in Puget Sound embayments in four seasonal samplings during 1980.	105
4.17	Seasonal changes in abundance and biomass of subtidal benthos in Elliott Bay.	109
4.18	Spatial distribution of the polychaete family Capitellidae	110

<u>Number</u>		<u>Page</u>
4.19	Average infaunal trophic index values (average of 24 sediment samples collected in the winter, spring, summer, and fall of 1979) for each sampling station in the sampling areas	111
4.20	Average number of infaunal trophic index taxa (taxon richness) values (average of 24 sediment samples collected in the winter, spring, summer, and fall of 1979) for each sampling station in the sampling areas	112
4.21	Location of geoduck (<u>Panope generosa</u>) beds with densities of one clam or greater per four square feet	115
4.22	Life cycle of the chinook salmon	119
4.23	Sport fishery for and migration routes of salmonids in Elliott Bay, Seattle, Washington.	120
4.24	Life history of the English sole (<u>Parophrys vetulus</u>)	142
4.25	Proposed spawning grounds for the English sole (<u>Parophrys vetulus</u>).	145
4.26	Relative seasonal abundance of the five most abundant fish species in the Duwamish River during 1975-76	152
4.27	Catch per haul (a) and species richness (b) from sand and eelgrass habitats at Alki Point	153
4.28	Seasonal and bathymetric patterns of catch per haul (a), species richness (b), and Shannon-Wiener diversity (c) at West Point, Alki Point and Point Pully.	155
4.29	Seasonal and bathymetric patterns of catch per haul for English sole, rock sole, and ratfish at West Point (a), Alki Point (b), and Point Pully (c).	159
4.29	Recurrent species groups based on beach seine data from West Point, Alki Point, and Point Pully. . .	162
4.31	Recurrent species groups based on otter trawl data from West Point, Alki Point, and Point Pully. . .	163

<u>Number</u>		<u>Page</u>
5.1	The geographic distribution by geographic subarea of fish species with (a) neoplasms and (b) "preneoplasms" of the liver	193
5.2	The geographic distribution of fish species with nonspecific degenerative/necrotic lesions of the liver	196
5.3	The geographic distribution of fish species with specific degenerative/necrotic lesions of the liver .	197
5.4	The geographic distribution of fish species with intracellular storage disorders of the liver.	198
5.5	The geographic distribution of hepatopancreas necrosis observed in <u>Crangon alaskensis</u> , pandalid shrimp, and <u>Cancer</u> spp.	202
5.6	The geographic distribution of necrotic and nodular lesions observed in shrimp and crab	203
5.7	Water quality monitoring stations in central Puget Sound used by the Municipality of Metropolitan Seattle (METRO)	204
5.8	Coliform concentrations along the shore of Elliott Bay during July through September for the years 1968, 1970 and 1971	205
5.9	Six month geometric mean for total and fecal coliforms for the upper and lower Green River during fall, 1977, and winter, 1978.	210
5.10	Survival times for microorganisms exposed to various concentrations of free chlorine and hypochlorite. . .	211
5.11	Total coliforms in Elliott Bay during April to September 1980.	212
5.12	Fecal coliforms in Elliott Bay during April-September 1980.	213
5.13	Fecal coliform concentrations in Elliott Bay during April-September 1981.	214
5.14	Trends in fecal coliform concentrations at stations located offshore in Elliott Bay	215
5.15	Trends in fecal coliform concentrations at nearshore stations in Puget Sound	216

<u>Number</u>		<u>Page</u>
5.16	Trends in fecal coliform concentrations at near-shore stations in Puget Sound	219
5.17	Historical oyster embryo responses to seawater samples collected annually from surface water of the Duwamish west waterway and assayed by the Washington State Shellfish Laboratory	222
5.18	Historical oyster embryo responses to seawater samples collected annually from surface waters off Pier 91 in Elliott Bay and assayed by the Washington State Shellfish Laboratory.	223
5.19	Hypothetical plot illustrating how positive and negative worm respiration responses could overlap resulting in a net response of zero (= control response) at intermediate toxicant concentrations . .	228

EXECUTIVE SUMMARY

The goals of this review were (1) to assess available data that could be used in the evaluation of potential sites for an outfall in Elliott Bay, and (2) to identify data inadequacies which may prevent future comprehensive assessment of wastewater management activities in Elliott Bay should a new outfall be constructed therein. The management activity addressed is the possible diversion of Renton Treatment Plant secondary effluent from the Duwamish River to an outfall off Duwamish Head. Following diversion of the effluent from the Duwamish River and transfer to either a deep (about 200') or very deep (about 600') site off Duwamish Head, the spatial and temporal effects of the effluent within Elliott Bay may change due to changes in distribution and retention.

Considerable data describe the Duwamish Estuary, Elliott Bay and adjacent marine areas which can be used to meet the first goal; however, if the second goal is to be met, a comprehensive ecological data base remains to be developed from which changes in wastewater management could be adequately assessed. Most research which has been conducted was limited to highly specific goals funded by mission-oriented agencies. These data are usually of limited value due to lack of standardization in sampling techniques and analytical methods or to a weak experimental design. Overall, the data base lacks continuity through time and space which is of critical importance in environmental assessment. A general overview of the geographic distribution of the more useful data is presented in Figures ES.1, ES.2, and ES.3 for benthos, fishes and fish health, and toxicity data, respectively. It is apparent that central Elliott Bay, the area around Duwamish Head to Alki Point and the intertidal area from Smith Cove to West Point lack quantitative assessment. Specific results of this review are presented by study component in the text and summarized in the conclusions.

To develop a comprehensive understanding of the effects of changes in present waste water management strategies and those planned for the future (goal 2), additional baseline studies in Elliott Bay are recommended. If, in March 1984, an effluent diffuser site is selected off Duwamish Head in Elliott Bay for the Renton Treatment Plant outfall, an 18 month (April 1984 - September 1985) period remains to rectify the deficiencies identified if a baseline study were initiated promptly. This study period would exist prior to initiation of underwater construction during which time an adequate seasonal baseline equivalent to that developed for the Seahurst sites could be achieved.

BENTHOS DATA

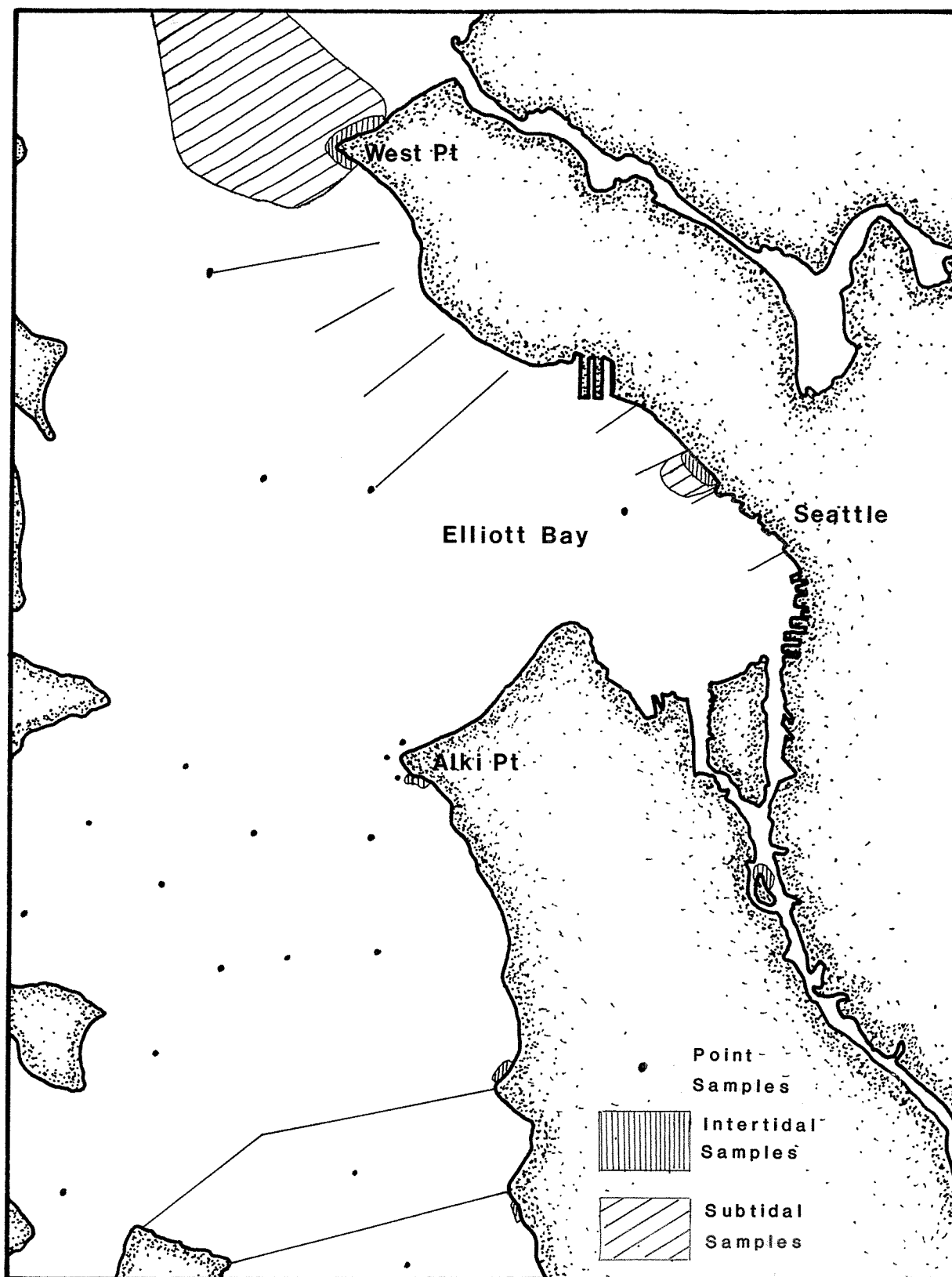


Figure ES.1. General overview of the geographic distribution of the more useful benthic data previously collected for Elliott Bay and adjacent marine waters.

FISH AND FISH HEALTH DATA

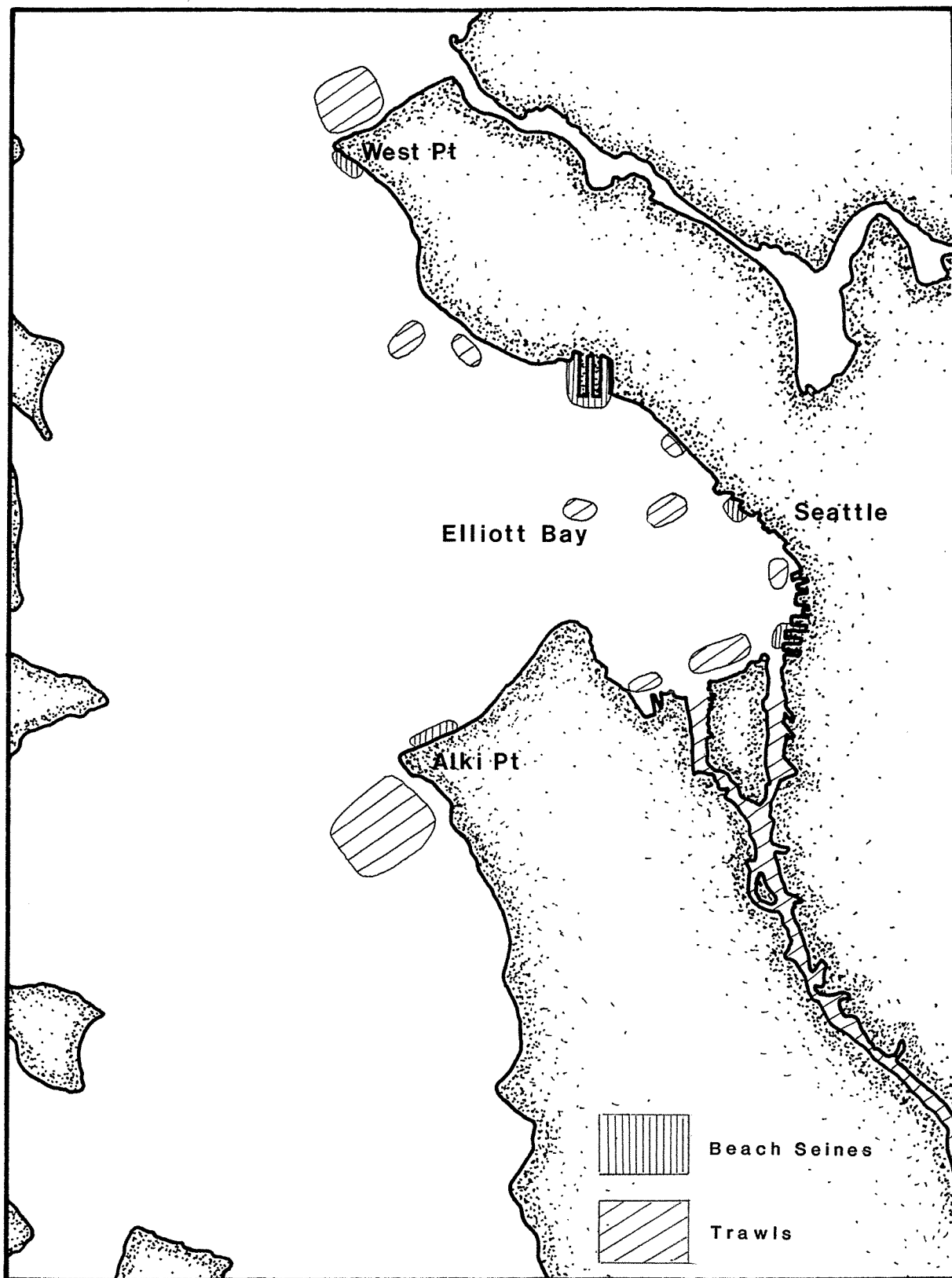


Figure ES.2. General overview of the geographic distribution of the more useful fish and fish health data previously collected for Elliott Bay and adjacent marine waters.

TOXICITY DATA

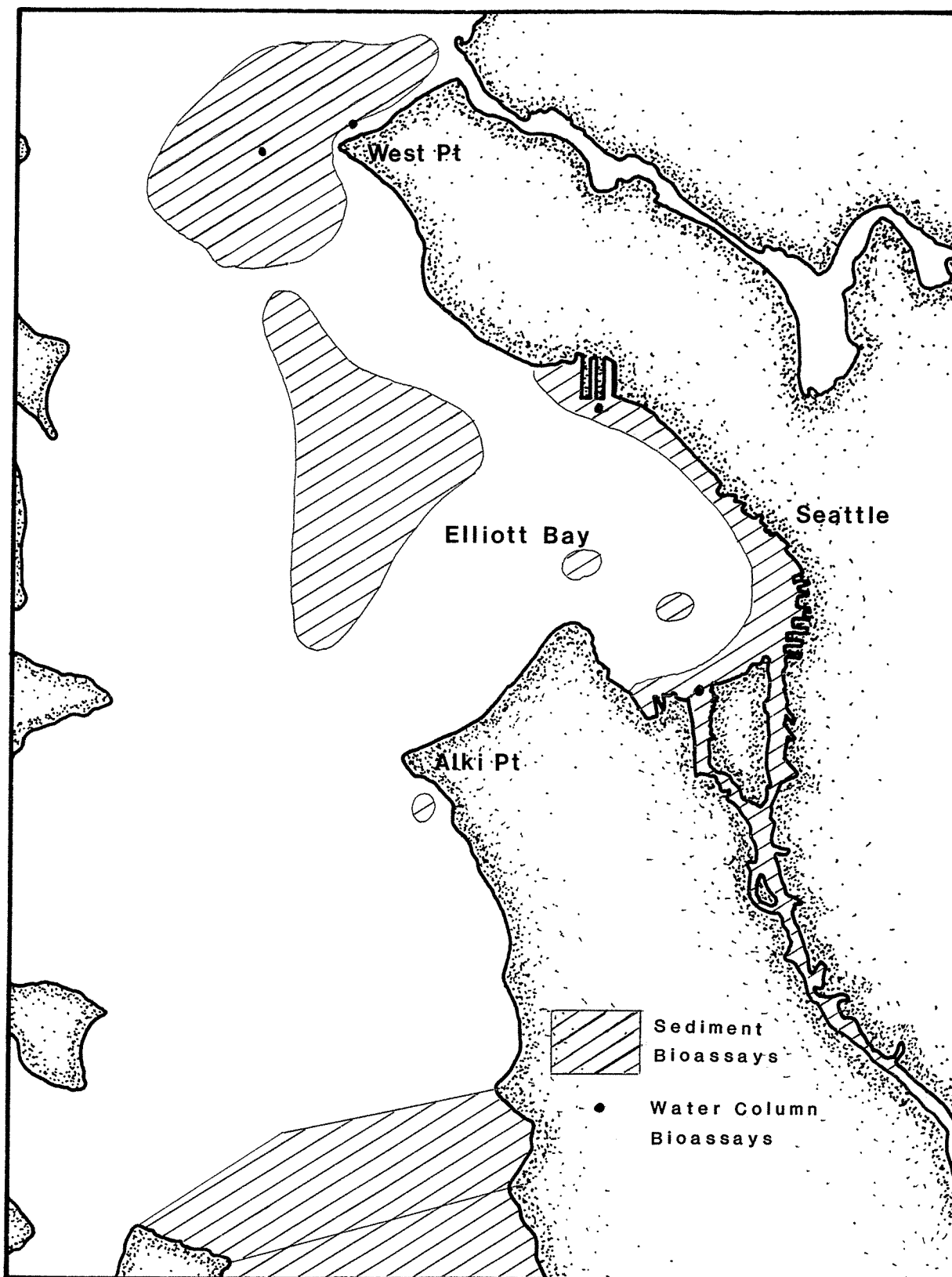


Figure ES.3. General overview of the geographic distribution of the more useful toxicity data previously collected for Elliott Bay and adjacent marine waters.

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PREFACE

The objective of this report is to review the available ecological information for Elliott Bay. An effort has been made to include the subject tasks presently covered in a baseline study of Seahurst Bay to aid in future comparison of the two areas. Additional information from studies specific to the Duwamish estuary-Elliott Bay system relating to the impacts of toxicants and nutrient enrichment has been included. The overall thrust of this report is to identify the present state of knowledge of the biological resources in the area, chemicals in water and sediments and to determine the known biological responses to natural and anthropogenic changes identified in inner and outer Elliott Bay. The process of review of the scientific knowledge base presently existing for the bay will serve to identify the gaps in the ecological understanding which should be addressed to monitor the diversion of secondary effluent from the Duwamish River to an outfall site in Elliott Bay.

1.0 DEFINITION OF STUDY AREA

1.1 Study Area

Elliott Bay is located on Puget Sound adjacent to Seattle, Washington and is the home of the Port of Seattle (Figure 1.1). As it exists today, Elliott Bay includes approximately 21.4 square kilometers (km²; 6 km x 4 km) of water area and can be defined as the body of water east of a line drawn between West Point and Alki Point (Figure 1.1). For the purposes of this review the Duwamish River estuary (Figures 1.1 and 1.2) will be included as part of Elliott Bay.

Since 1900 the shape and area of Elliott Bay have continually changed (Figure 1.3) as man has altered the bay to improve its usefulness as a harbor and shipping facility. These changes were summarized by Bortleson et al. (1980).

The most notable changes since the earliest surveys are the massive landfill of the intertidal reach of Elliott Bay and the channelization of the Duwamish River.

In 1854, the Duwamish River meandered across its valley and entered Elliott Bay through three main distributary channels. A broad intertidal area extended bayward beyond marshlands near the river mouth to near the northern edge of the present-day Harbor Island. Smaller areas of wetland were located in an embayment southwest of the West Waterway, east of the small peninsula of land that was early Seattle, and in Smith Cove. The early mapping of wetland ended about 3 km (1.9 mi) upstream from the former river mouth, but marshland probably continued upstream some additional distance.

In 1895, the filling of the marsh and intertidal area began with the dredging of the East Waterway. Material dredged from the East Waterway was deposited as fill over a wide area of what today is Harbor Island. From 1901 to 1904, several thousand cubic meters of material were removed from Beacon Hill to the intertidal area by hydraulic sluices. By 1917, the East and West Waterways had been formed and more than 5.7 sq km (2.2 sq mi) of intertidal area had been filled largely by deposition of dredge spoil from the two water ways which flanked it. All the former marsh except a small area on the northern tip of Kellogg Island has been filled or converted to urban land use. Dredging to form the Duwamish Waterway has created a channel deeper than the former natural channel and has lengthened the landward incursion of salt water in the channel.

Currently, the inner shoreline of Elliott Bay consists principally of man-made piers and seawalls. The shoreline west of Smith Cove and south of Duwamish Head remain as natural beaches and intertidal areas.

The principal source of freshwater entering Elliott Bay is the Duwamish River which enters the bay at its southwest corner (Figure 1.1). The Duwamish River is formed by the confluence of the Black and Green Rivers at river km 19. Together these three rivers drain approximately 483 square miles. The minimum, maximum, and mean annual discharges of water into Elliott Bay from 1937 - 1965 were 1120, 3024, and 2295 m³/min, respectively (Figure 1.4).

Prior to entering Elliott Bay, the Duwamish River is routed into an east

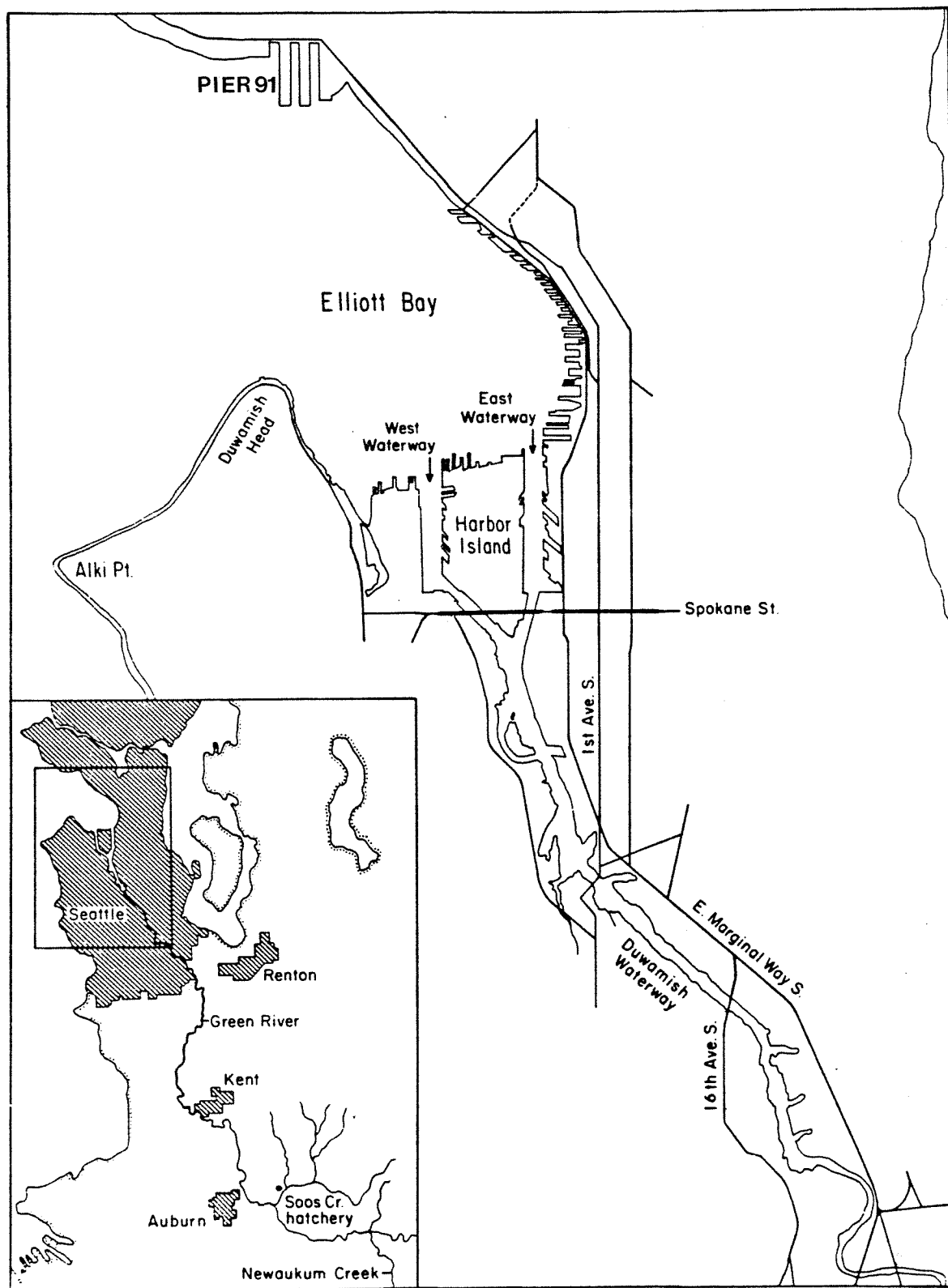


Figure 1.1. Elliott Bay and Duwamish River, Seattle, Washington.
After Salo (1969).

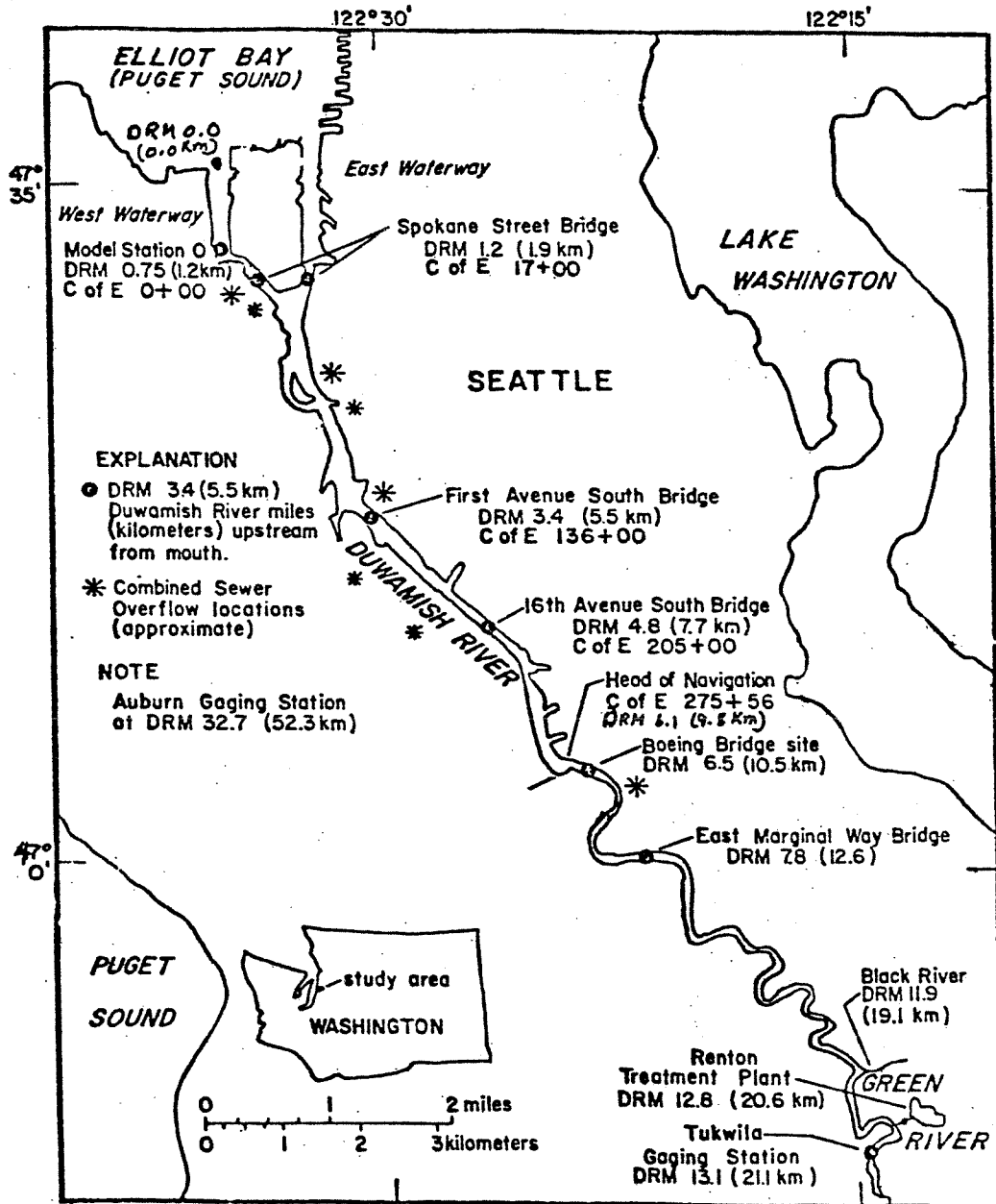


Figure 1.2. The Duwamish River, Seattle, Washington.
After U.S. Corps of Engineers (1982).

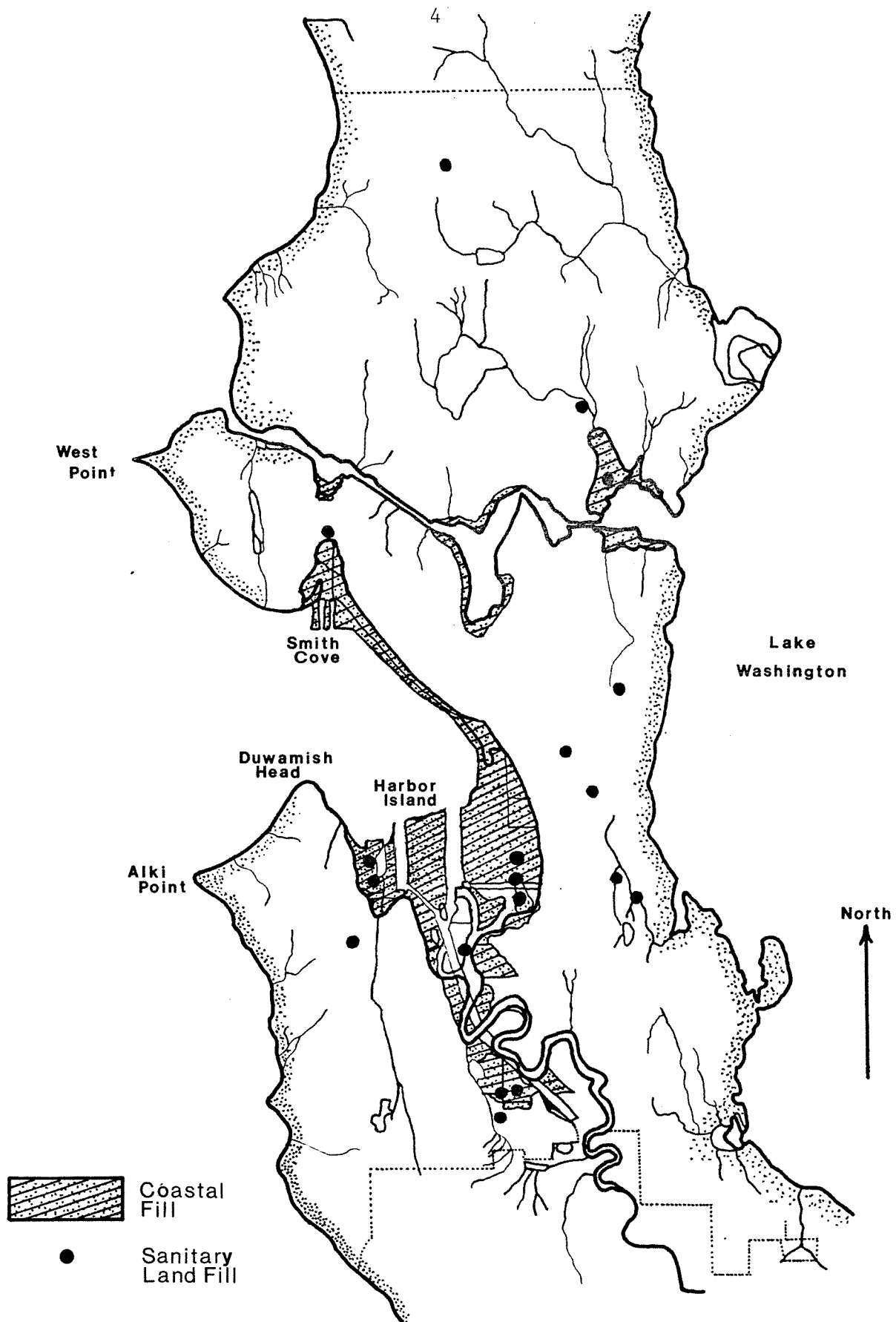


Figure 1.3. Changes in the shoreline of Elliott Bay between 1900 and 1973. After McGreevy (1973).

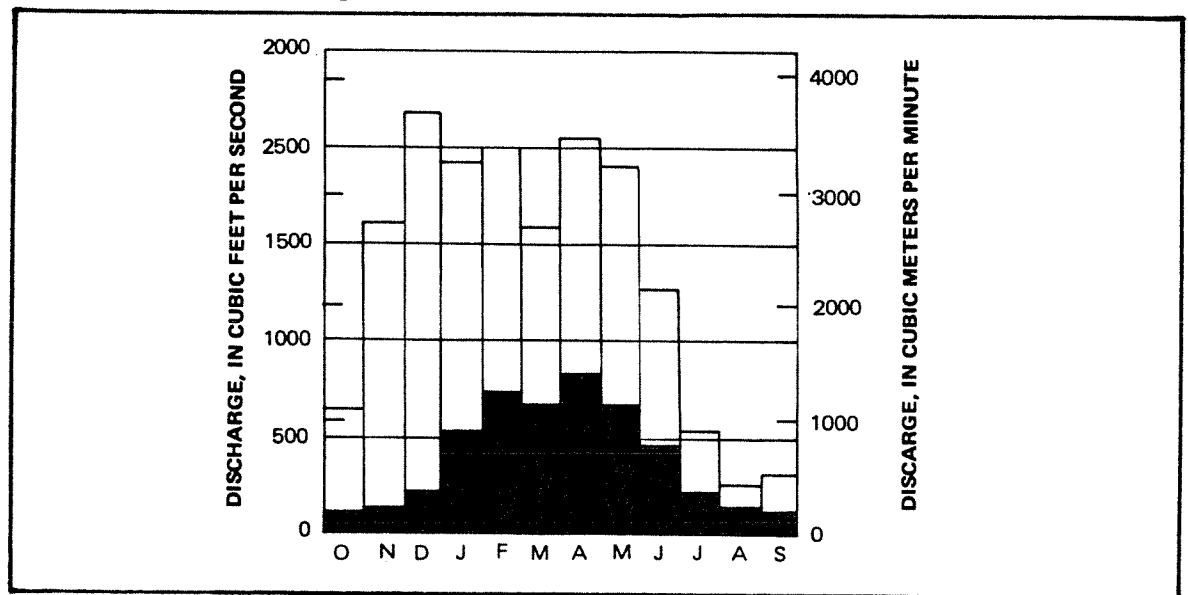


Figure 1.4. Mean monthly and minimum monthly discharges of the Green River near Auburn. Based on the 29-year period, 1937-1965. After Dexter et al. (1981).

and west waterway (Figure 1.1). Most of the water is discharged through the west waterway. These waterways and the lower Duwamish River play significant roles in shipping and hence, have undergone extensive alteration. The river mouth is maintained at a depth of nine meters by periodic dredging as are various stations in the channel.

Entry of the freshwater from the Duwamish River into the marine waters of Elliott Bay results in an estuary of major biological significance. Hydrologic conditions create a salt-wedge estuary with the tip of the wedge usually occurring near river km 12 depending on the flow of water from the river. The volume of runoff depends upon water flow. Water flow depends principally upon rainfall; hence, the highest runoff occurs during the winter months. Stratification of the estuary is greatest during periods of high runoff. The estuary may become partially mixed, however. Above km 5.6 the salt wedge is persistent.

1.2 Water Quality Classification

The outer part of Elliott Bay (west of a line drawn from Duwamish Head to Pier 91, Figure 1.1) is classified by the Washington State Department of Ecology (DOE) as AA (extraordinary) water while the inner part of Elliott Bay is classified as A (excellent) water. Because class AA and A waters mix freely in Elliott Bay, the Washington State water quality standards require that Elliott Bay be considered in the AA category. The water quality standards for class AA and A are presented in Appendix 1.

2.0 PHYSICAL DESCRIPTION

2.1 Depth Profile

The maximum water depths in the inner and outer regions of Elliott Bay reach 200 m (= 660 feet; Figure 2.1). Two canyons exist within the inner bay (Figure 2.1). The northern canyon sits in a northwest-southeast plane while the southern canyon near Duwamish Head sits in a north-south plane. Water depths in both of these inner bay canyons exceed 75 m (= 248 feet). The outer bay is dominated by a single submarine canyon whose depth exceeds 150 m (= 495 feet). At its outer margin this canyon connects with the main basin of Puget Sound. The depth in this region is approximately 200 m (= 660 feet).

2.2 Current Patterns

At least two workers (Winter 1977; McGary and Lincoln 1977) used hydraulic models to predict current patterns in Elliott Bay. Winter (1977) as cited in Sillcox et al. (1981) suggested that water movement was dominated by tides and the salinity distribution. Distinct surface and bottom flows were noted. Clockwise circulation occurred during flood tides whereas counterclockwise flow occurred during ebb tides. Because flood tides were stronger, the net flow out of the bay was directed past Duwamish Head. Water flow out of the bay past Smith Cove occurred only if high-river runoff occurred simultaneously with weak currents.

Few data describe the actual current and circulation patterns in Elliott Bay. Weak tidal and subtidal currents (0-20 cm/sec) were present (typically 5 cm/sec) and did not differ significantly between summer and winter (Sillcox et al. 1981). However, currents in the inner bay were about half the magnitude of those in the outer bay. For example, the mean current speed calculated without regard for direction for shallow depths (about 200 feet) ranged from 2.6 cm/sec in inner Elliott Bay to 8.2 cm/sec in outer Elliott Bay (URS Engineers et al. 1983). At deeper depths (about 600 feet) in inner Elliott Bay the mean current speed averaged 4.0 cm/sec and increased in outer Elliott Bay to 4.6 cm/sec (URS Engineers et al. 1983).

Current meters were used by both Sillcox et al. (1981) to measure net velocity, mean speed, and total variance (Figure 2.2A-D). These combined data suggested a mean counterclockwise flow towards the north in the main basin of Puget Sound and in outer Elliott Bay north of Alki Point (Sillcox et al. 1981). In deeper water the flow was primarily southward. These net movements did not vary with season. Flood and ebb tidal currents moved south and north respectively as predicted by the bathymetry of the basin (Sillcox et al. 1981). Often these tidal currents were directed towards shore (Figure 2.2C).

The tidal energy in inner Elliott Bay was clearly less than that in the outer part of Elliott Bay. Variance (the amount of kinetic energy available by tidal mixing, Figure 2.2D) ranged from 20-100 cm^2/sec^2 in inner Elliott Bay, but was 200 cm^2/sec^2 at midchannel near West Point (URS Engineers et al. 1983). Flow in the inner bay varied with each tide. Subtidal flow was primarily outward at 30 m and inward at greater depths (Sillcox et al. 1981). Hydraulic model predictions and field data generally agreed except for one significant fact. The model and dye studies suggested that the net flow of Duwamish River water from the west waterway would be outward past Duwamish Head whereas field data suggested that the net water flow was to the north

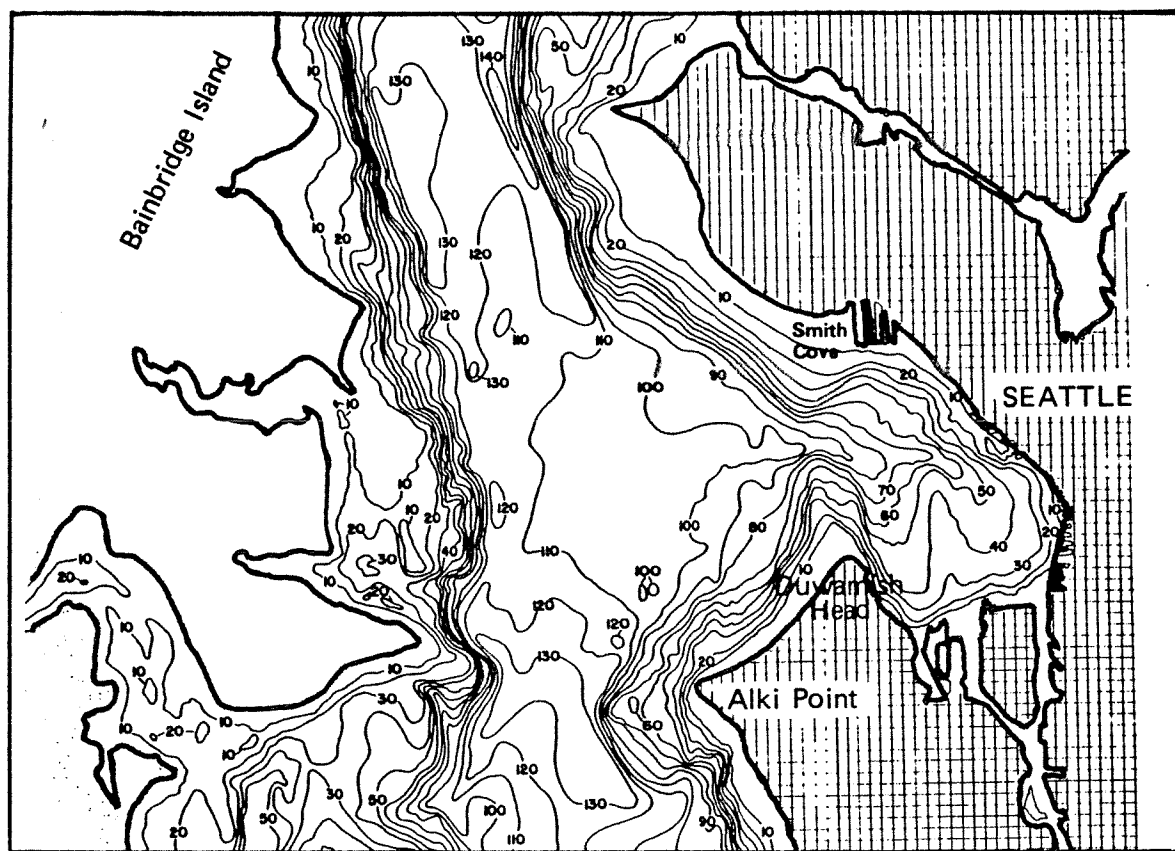


Figure 2.1. Bathymetry in fathoms of Elliott Bay and adjacent areas.
After Dexter et al. (1981).
(1981).

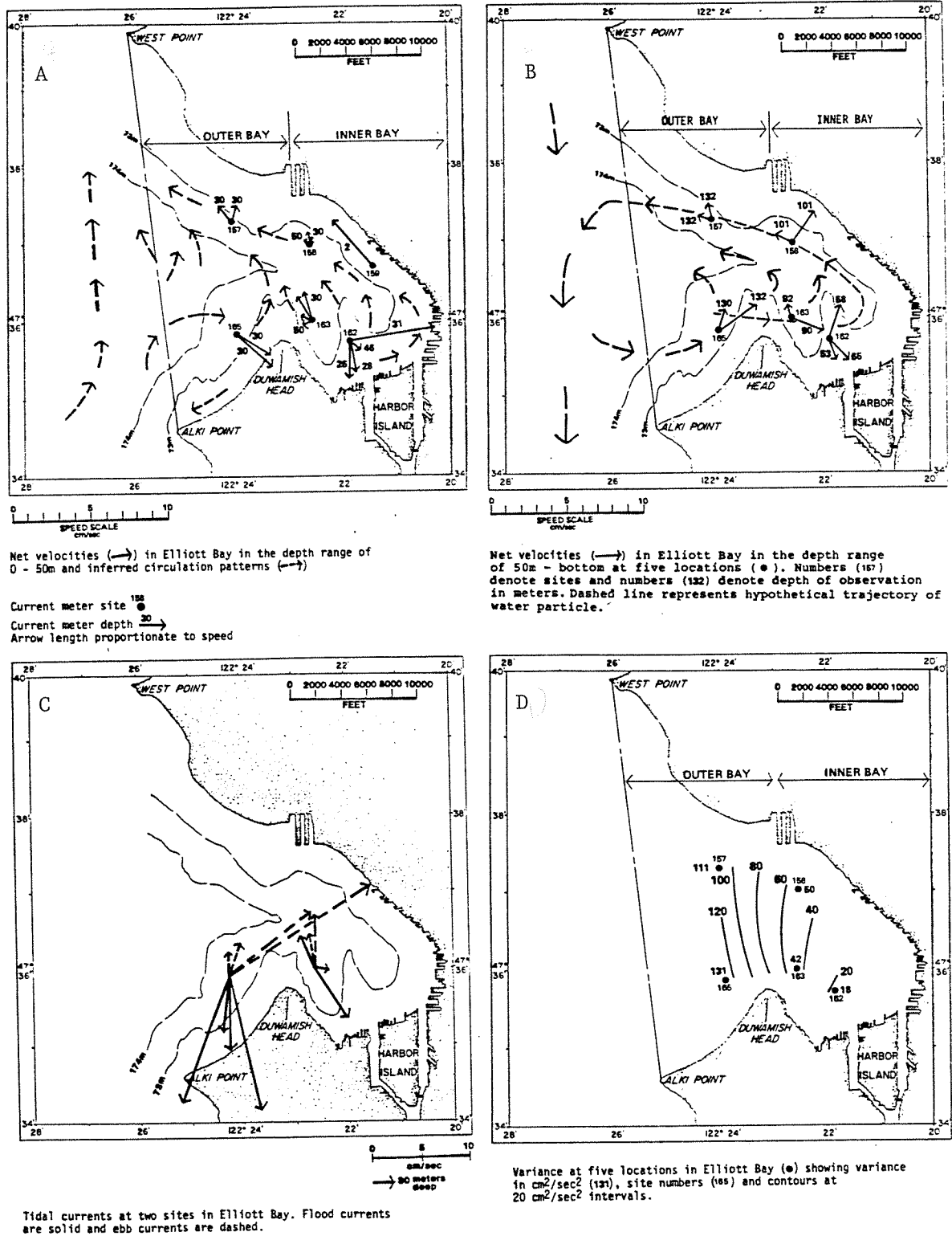


Figure 2.2. Circulation in Elliott Bay as defined by the direction, speed and energy of the currents.
After URS Engineers et al. (1983).

during both ebb and flood tides.

Estimating the residence time of water in Elliott Bay is difficult because of inadequate circulation data. Sillcox et al. (1981) used progressive vector diagrams to calculate transect times across the 4 km bay of 0.98–7.88 days (Table 2.1). URS Engineers et al. (1983) estimated a time scale of 7.5 days by dividing a length scale by a speed scale whose speed was 1.5 cm/sec and assumed that the mean circulation would recycle water throughout the entire bay. Drift cards have only recently been released in Elliott Bay (Ebbesmeyer, personal communication) and recovery data has not yet been reported.

2.3 Water Quality

The first water quality survey of the Duwamish–Green River was conducted in 1948 by the Washington State Department of Fisheries (WSDF 1948). Dissolved oxygen concentrations of less than 5.0 mg/l were measured at South Park. A second series of water quality tests was performed prior to the installation of the Renton Sewage Treatment Plant (Gibbs 1962). The actual effluent was shown to have a low dissolved oxygen concentration and to have high ammonia and nutrient concentrations. In 1964 records of dissolved oxygen concentrations (3–10.5 mg/l), temperature (58–70°F), and chlorinity (1–5 g/l) in the Duwamish estuary were established (Gibbs and Issac 1968; Issac et al. 1964).

The Renton Treatment Plant contributed nearly 80% of the total ammonia present in the Duwamish River during 1970–80 (Healy 1979). Rainfall also was found to influence the water quality of the river. Samples of rainfall runoff had high concentrations of suspended solids, high chemical oxygen demand, high biological oxygen demand, and a significant concentration of oil (Dalseg and Farris 1970). Analyses of storm water runoff over a seven month period showed significant concentrations of suspended solids, high biological oxygen demand, high chemical oxygen demand, and the presence of oil (U.S. Army Corps of Engineers 1974). The concentration of nutrients was relatively low however.

The most complete description of the water quality of the Duwamish River was published by Stevens, Thompson and Runyan, Inc. (1972; Table 2.2) and Chapman et al. (1982c; Table 2.3). Dissolved oxygen concentrations ranged from 8.0–10.2 mg/l at the ten sampling stations. The total phosphorus concentration ranged from 0.08–0.30 mg/l. Chemical oxygen demand ranged from 14–147 mg/l. The concentrations of chlorophyll a ranged from 1.43–17.50 mg/m³.

Recent data showed mean temperatures in the surface waters ranged from approximately 8°C in January and February to approximately 14°C in July (Figure 2.3; Dexter et al. 1981; Pavlou et al. 1973; Kroglund 1975). At 50 m the mean temperatures ranged from approximately 8.5°C in January and February to approximately 12°C in July (Figure 2.3; Dexter et al. 1981; Pavlou et al. 1973; Kroglund 1975).

Mean salinities in the surface waters ranged from approximately 26.4 ‰ in January and February to approximately 29.2 ‰ in September (Figure 2.3; Dexter et al. 1981; Pavlou et al. 1973; Kroglund 1975). A significant decline in salinity (Figure 2.3) occurred between February and mid-June. Mean salinities at 50 m ranged from 29.6 ‰ in January and December to 30.5 ‰ in September (Dexter et al. 1981).

Salinity in the surface water also varied with geographic location within Elliott Bay (Figure 2.4). The freshwater entering Elliott Bay from the

Table 2.1. Inferred water residence times for inner Elliott Bay.
After Sillcox et al. (1981).

Mooring	Duration (days)	Net Flow (cm/s)	Implied Excursions (km)	Direction (°T)	Transit Time of 4-km bay (days)
A. Summer					
ELLBAY 1A					
30m	39.63	0.68	23.18	352	6.84
101m	24.25	4.77	99.48	78	0.98
ELLBAY 2A					
30m	37.21	1.61	51.52	336	2.89
92m	39.50	0.48	16.31	340	9.69
B. Winter					
ELLBAY 1B					
30m	29.54	0.59	14.99	16	7.88
101m	29.54	1.06	26.93	296	4.39
ELLBAY 2B					
30m	29.50	1.63	41.35	347	2.85
90m	29.50	2.41	61.14	110	1.93

Table 2.2. Summary of water quality data for the east, west, and Duwamish waterways.
After U.S. Army Corps of Engineers (1972).

STATION PARAMETER	1A	1B	2A	2B	5A	5B	6A	6B	9A	9B
Dissolved Oxygen	9.9	10.2	9.4	9.6	9.4	9.0	9.0	8.0	10.1	9.4
Turbidity, JTU	13	14	14	12	14	22	30	20	12	20
Temperature, °C	13.0	11.0	13.1	11.0	15.0	11.8	14.5	12.2	14.5	-
Oil/Grease	4.56	-	2.58	-	4.04	-	3.43	-	2.34	-
Total Phosphorus, as P	0.10	0.09	0.11	0.08	0.29	0.18	0.30	0.18	0.13	0.20
Kjeldahl Nitrogen	0.86	-	2.46	-	1.85	-	3.70	-	1.85	-
Ammonia Nitrogen	0.86	-	0.70	-	0.21	-	2.49	-	0.14	-
Chemical Oxygen Demand	134	147	121	135	46	76	14	80	16	23
Salinity	18.0	28	17.1	28.0	3.0	26.8	2.0	26.1	1.0	3.0
pH, Units	7.40	7.51	7.50	7.52	7.30	7.40	7.39	7.41	7.71	7.40
Mercury,	.0015	-	.0005	-	.0005	-	.0005	-	.005	-
Lead,	.50	-	.50	-	.50	-	.50	-	.50	-
Zinc,	.045	-	.040	-	.005	-	.015	-	.005	-
Nickel	.05	-	.05	-	.05	-	.05	-	.05	-
Iron, as Fe	0.12	0.00	0.11	0.07	0.39	0.24	0.35	0.28	0.13	0.39
Chlorophyll a, mg/m ³	5.41	1.43	1.43	1.75	3.04	1.69	4.61	3.04	17.50	4.77

1. Concentrations in mg/L unless otherwise noted
2. "A" refers to 1 meter surface sample
3. "B" in saltwater wedge
4. All data shown for ebb tide condition

Table 2.3. Physical and chemical parameters for sediment from Elliott Bay and the Duwamish River. a. Phi size ranges, sand, -2 to +4; silt, >4 to 8; clay, >8. b. Percent of dry weight sediments. c. Expressed as percent of extractable organic matter (extractables). d. A plus (+) notation after the station number indicates that live organisms were observed in the sediments during sampling. A star (*) indicates that a bad odor, e.g., H_2S , was noted in the sample during collection. e. Fractions in parentheses indicate approximate amount of extract lost during sample preparation. After Chapman et al. (1982c).

<u>Station Number</u>	<u>Sand^a %</u>	<u>Silt^a %</u>	<u>Clay^a %</u>	<u>Water %</u>	<u>DOC^b %</u>	<u>TVS^b %</u>	<u>Extractables^b %</u>	<u>Soluble^c %</u>
<u>Elliott Bay</u>								
1	91.3	5.4	3.3	28.9	1.3	2.2	0.048	46
2	97.4	0.9	1.7	27.2	1.4	2.2	0.025	80
3+ ^d	77.4	15.9	6.7	26.4	1.1	2.4	0.114	47
4+* ^d	8.2	85.7	6.1	41.9	3.2	9.5	0.419	28
5+*	49.0	45.4	5.6	32.3	5.3	3.5	0.224	39
6+*	8.1	67.0	24.9	50.7	11.9	8.9	0.596	81
7 *	5.0	88.7	6.3	47.1	5.2	7.4	0.640	75
8+	60.7	33.4	5.9	37.9	2.2	5.3	0.500	67
9+	34.0	55.5	10.5	46.5	1.5	8.1	0.499	58
10+	55.3	32.3	12.4	43.8	7.8	8.6	0.722	46
11+	34.5	53.7	11.8	56.1	16.0	12.1	1.395	72
12	30.0	61.5	8.5	40.6	5.9	6.4	0.291	25
13	45.7	49.7	4.6	33.5	1.4	9.0	0.061	21
14	64.9	22.9	12.2	40.6	5.1	18.4	0.169	27
15+	56.8	35.2	7.9	31.4	5.1	4.5	0.091	33
16	58.1	26.7	15.2	35.2	1.2	10.0	0.087	50
17+	94.7	1.9	3.4	26.9	1.4	0.9	0.035	68

<u>Duwamish River</u>								
18	49.9	38.2	11.9	42.7	6.1	10.2	0.207	9
19	49.4	30.0	20.6	44.0	4.1	9.1	0.284	40
20+	48.1	46.4	5.5	46.7	3.6	5.4	0.423	23
21+	31.7	54.2	14.1	45.6	3.2	6.5	0.680	65
22	56.6	37.3	6.1	42.7	2.9	5.3	0.163	43
23	25.9	66.2	7.9	45.8	3.6	5.2	0.367	60
24	44.8	49.7	5.5	43.7	3.1	4.9	0.545	24
25	12.8	77.8	7.4	45.7	3.4	5.9	0.501	28
26	15.2	74.1	10.7	47.9	3.9	7.9	0.649	80
27	30.9	51.4	17.7	49.2	2.0	3.9	0.492	27
28	4.7	88.6	6.7	50.8	0.9	8.7	0.622	22
29+	96.2	1.9	1.9	21.9	0.2	2.5	0.033	32
30	22.8	60.1	17.1	45.0	2.7	5.0	0.537	37
31+	21.7	58.9	19.4	45.6	0.8	11.2	0.404	44
32+	12.7	76.9	10.4	49.4	8.5	8.9	0.353	14
33+	14.3	68.1	17.6	45.8	5.6	8.3	0.371	32
34+	10.5	65.1	24.4	46.1	4.1	6.2	0.318	23
35	14.7	67.7	17.6	46.4	4.6	5.9	0.175	27
36	14.4	67.5	18.1	48.0	5.7	7.6	0.471	70
37+	39.8	46.2	14.0	47.3	5.1	6.9	0.098 (1/2) ^e	54

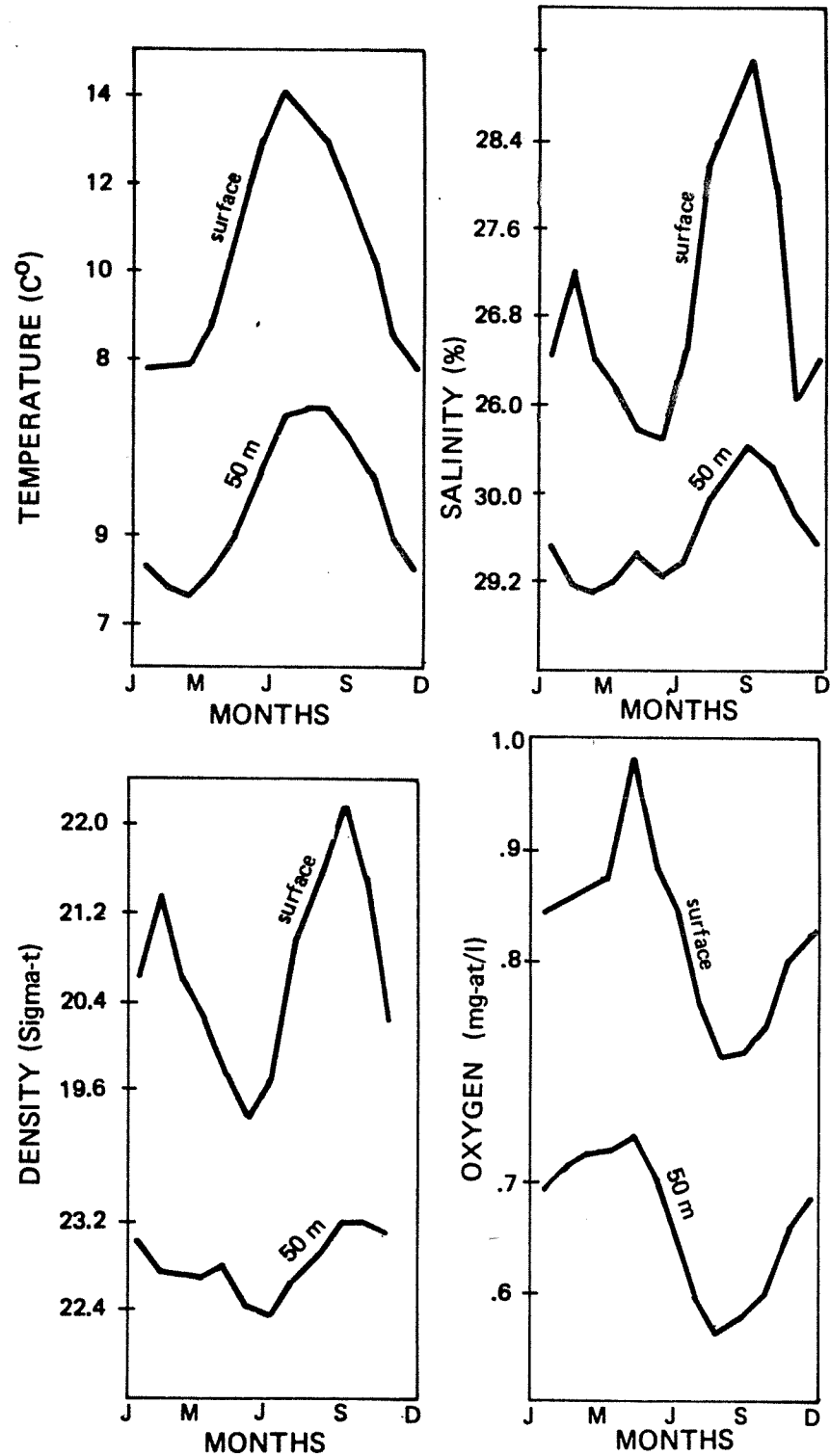


Figure 2.3. Annual cycles of temperature, salinity, density, and dissolved oxygen at the surface and 50 m depth in Elliott Bay. Data collected from 1966 to 1980 were averaged from four METRO Elliott Bay stations. After Dexter et al. (1981).

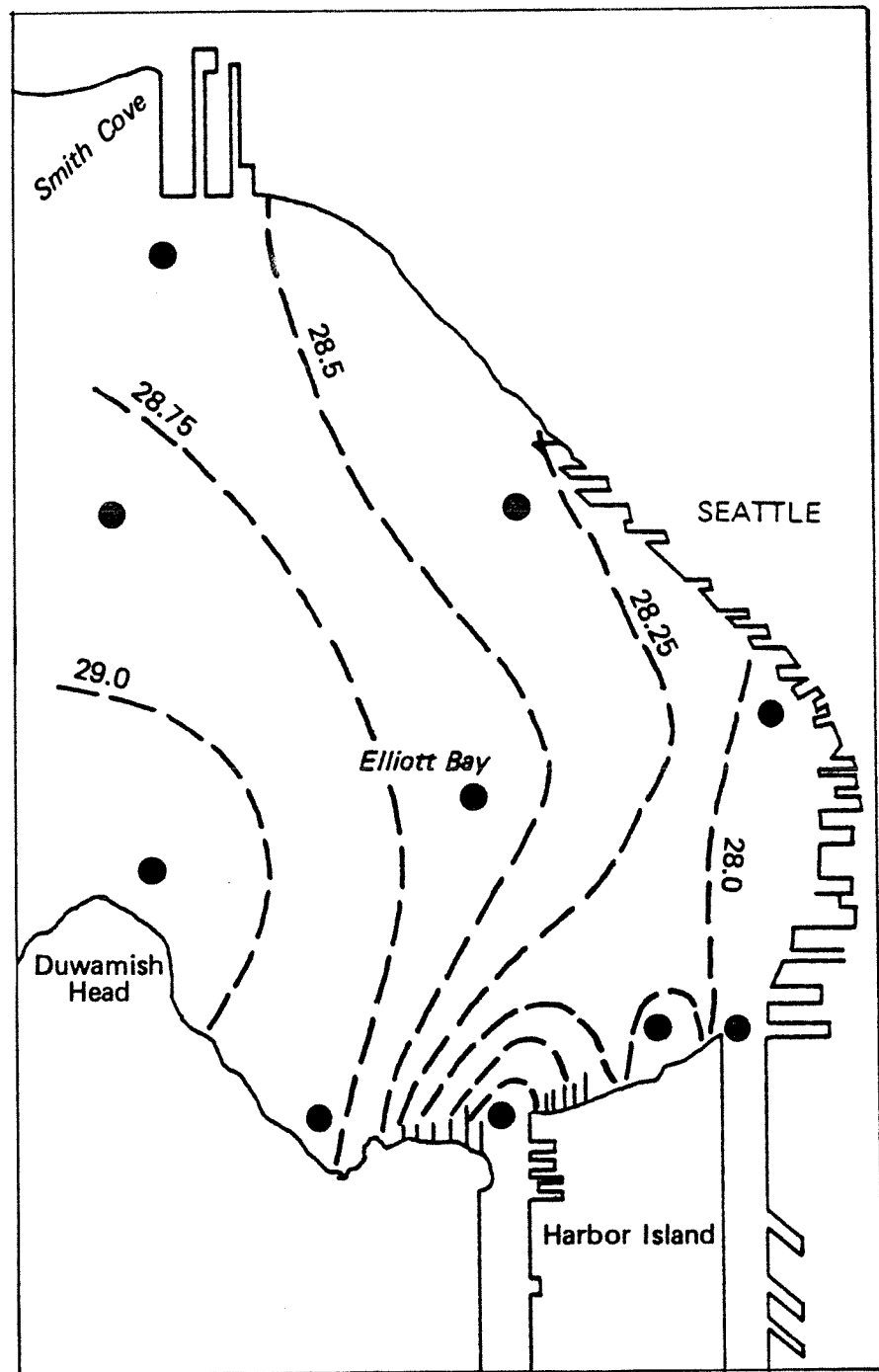


Figure 2.4. Surface salinity distribution in Elliott Bay during 24 - 27 September, 1974. After Dexter et al. (1981).

Duwamish River is less dense than seawater and hence, forms a freshwater lens that floats on the surface. This plume of freshwater occurs predominately along the northwestern shore of the bay and hence, the salinity of those surface waters is correspondingly less than elsewhere in the bay.

Dissolved oxygen concentrations in the surface water ranged from 0.85 mg-at/l in December and January to a maximum of 0.98 mg-at/l in late May (Figure 2.3; Dexter et al. 1981 Pavlou et al. 1973; Kroglund 1975). The dissolved oxygen concentration then declined from June through September and reached a minimum concentration of 0.56 mg-at/l in late August and early September. Oxygen lows in Elliott Bay occurred in the area off Duwamish Head and at the mouth of the Duwamish River (Pavlou et al. 1973). Vertical profiles of dissolved oxygen concentrations in Elliott Bay showed a minimum of >360 ug-at/l at 15 to 20 m depth (Pavlou et al. 1973).

2.4 Suspended Particulate Matter

Baker (1982) sampled the suspended particulate matter (SPM) in Elliott Bay during February and August, 1979. A thin (< 5 m) surface layer of SPM derived from the Duwamish River occurred near the river mouth, but decreased along the north shore as the distance from the river mouth increased. Minimum concentrations of SPM (0.4 - 0.6 mg/l) were measured in the middle depths. The concentrations of SPM increased as one approached the bottom. The concentration of the bottom nepheloid layer showed considerable variation in both time and space; however, the greatest concentration of the bottom nepheloid layer always occurred at the deepest stations in the bay.

The organic content of the SPM was greater in August than in February. Samples of SPM from the surface contained more organic matter than did those from greater depths. In both February and August the concentration of organic matter in the SPM decreased with increasing distance from the Duwamish River both in surface and bottom samples. Organic composition of the SPM was not correlated with salinity. An inverse relationship existed between organic content and concentration of the SPM.

During the summer and winter, the distribution of SPM was controlled by the plume of the Duwamish River. The mechanism of this control was not identified. Baker (1982) hypothesized that the river itself could be a source of particulates or could indirectly regulate primary productivity. However, as the water input from the river declines during the summer, an increase in SPM from phytoplankton growth was noted.

In August the upper 5 m of water in inner Elliott Bay contained 573×10^5 g of SPM. Approximately 298×10^5 g of the SPM was derived from both the Duwamish River and phytoplankton. The contribution from phytoplankton was identified as 84×10^5 g. The remainder, 214×10^5 g, was derived from the river. Using the mean flow during August, the river would deposit this quantity of SPM into Elliott Bay in about 12 days.

The situation is different in February. The river could supply the excess surface SPM in 0.32 days, 36 times faster than in summer. Hence, in winter the Duwamish plume clearly controls the SPM concentration in Elliott Bay. Another source of SPM was water entering Elliott Bay via the submarine canyon from the main basin of Puget Sound. However, local resuspension was not a dominant contribution to the bottom nepheloid layer.

3.0 DISTRIBUTION AND CONCENTRATIONS OF XENOBIOTIC CHEMICALS

As early as 1949 Sylvester et al. (1949) recognized the potential for pollution to occur in areas of Puget Sound adjacent to metropolitan Seattle. Subsequent studies were conducted to measure potential sewage toxicity from Seattle effluent and from the discharge of digested sludge off Alki Point (Sylvester 1952; Sylvester et al. 1961).

3.1 Trace Metals in Water and Sediments

Trace metal concentrations were first measured in the Duwamish River in 1971-1972. Surprisingly, the concentration of lead, 5.4 ug/l, in the Duwamish River was the highest concentration recorded in western Washington State waters. Although the exact locations of the sampling stations cannot be identified today, the finding that the lead concentration in the Duwamish River-Elliott Bay waters was 4.5 times higher than in other local waters stimulated much research.

The concentration of mercury dissolved in the water ranged from 0.0005 to 0.005 mg/l, but was undetectable at some stations (Table 2.2). The concentration of lead dissolved in the water was consistently 0.50 mg/l (Stevens, Thompson and Runyan, Inc. 1972). The concentration of zinc ranged from 0.005 to 0.045 mg/l. The concentration of iron dissolved in the water ranged from undetectable to 0.39 mg/l (Stevens, Thompson and Runyan, Inc. 1972).

Contour maps illustrating the concentrations and distributions of particulate-associated chromium, manganese, iron, nickel, copper, zinc, and lead in Elliott Bay were published by Massoth et al. (1982; Figures 3.1 - 3.7).

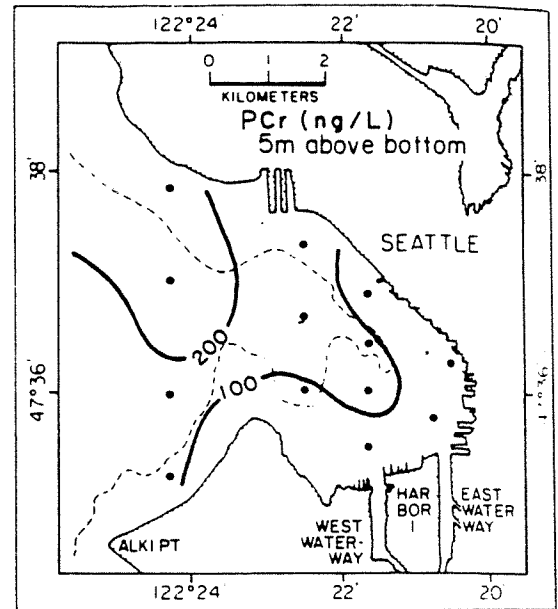
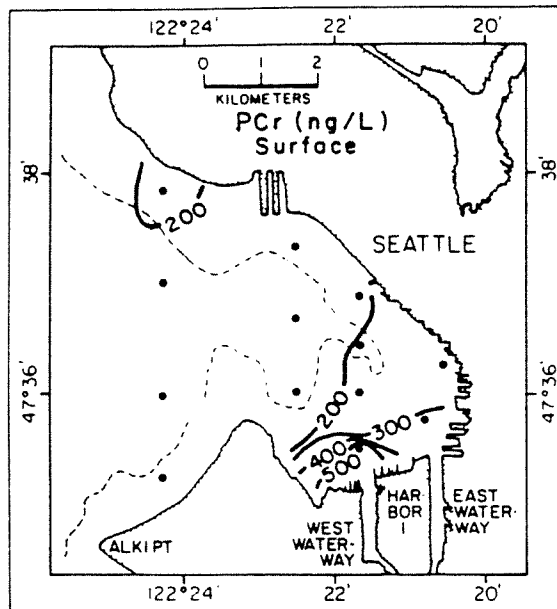
The major sources of metals entering Elliott Bay appear to be the atmosphere and the Duwamish River. Olsen (1973) identified the major sources of metals in the air as traffic dust, fuel combustion, and dust from roads and wind. Harper-Owes (1983) estimated that two thirds of the iron and mercury in the Duwamish Estuary was derived from the Green River.

Dominant point source emission of airborne particulates the in Puget Sound region was compiled by the Washington State Department of Ecology (Figure 3.8). Estimates of the annual mass emission from these sources was compiled (Table 3.1). The total contribution of atmospheric input (equals the sum of the local and global input) into the main basin of Puget Sound has been estimated in terms of total fallout and precipitation. Few, if any, direct measurements of the amount of trace metals and trace organics deposited by precipitation and dry fallout into central Puget Sound are available. Current values used for budget calculations are based on the measurements of radionuclides in surface sediments, deposition velocity of radionuclides at some remote station outside Puget Sound, or computer models.

Early researchers assumed that sewage effluent and/or sewer overflow contributed a significant percentage of the metals present in the Duwamish River. However, Healy (1979) demonstrated that sewage from the Renton Treatment Plant (RTP) did not contain significant metal concentrations and hence, was not the source of the metals present in the river. During periods of low water flow, the RTP did significantly increase the concentrations of copper and cadmium present in river water. However, these copper and cadmium concentrations were inconsequential when compared with the total metal burden present in the water and sediments. Furthermore, the concentration of metals

Figure 3.1. A. Areal distributions of total particulate chromium at the surface and 5 m above the bottom of Elliott Bay. B. East-west and north-south cross sections of particulate chromium in Elliott Bay. After Massoth et al. (1982).

A



B

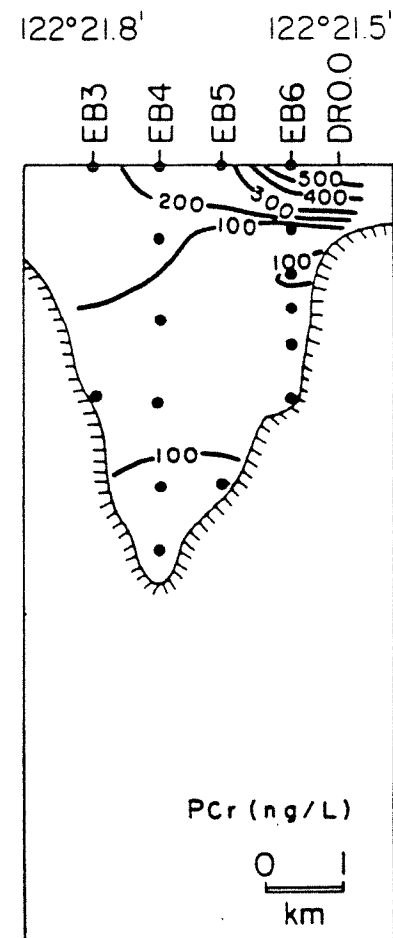
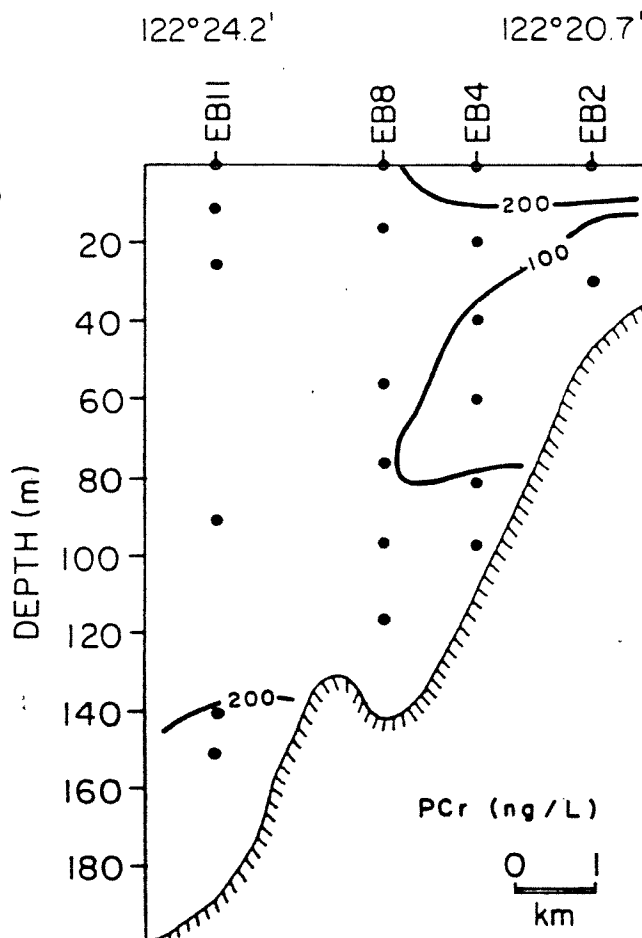


Figure 3.2. A. Areal distributions of total particulate manganese at the surface and 5 m above the bottom of Elliott Bay. B. East-west and north-south cross sections of particulate manganese in Elliott Bay. After Massoth et al. (1982).

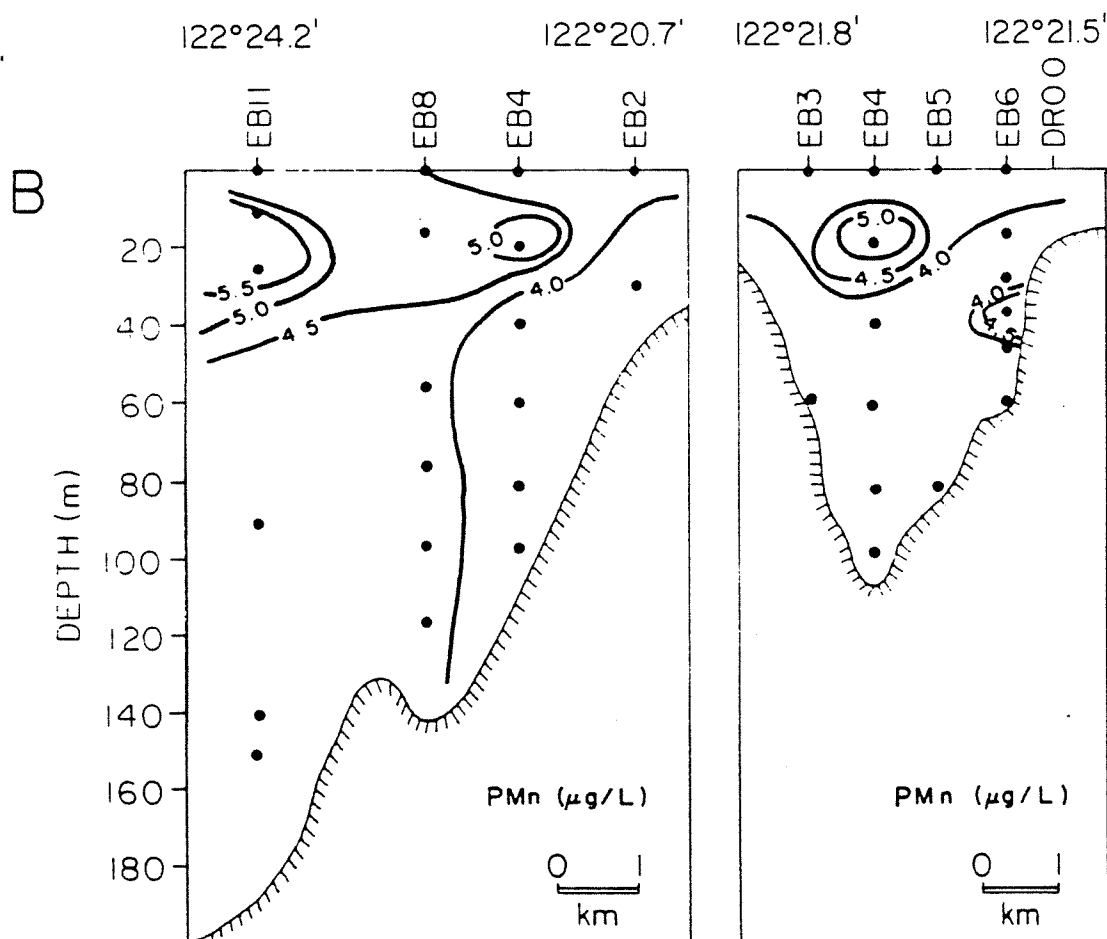
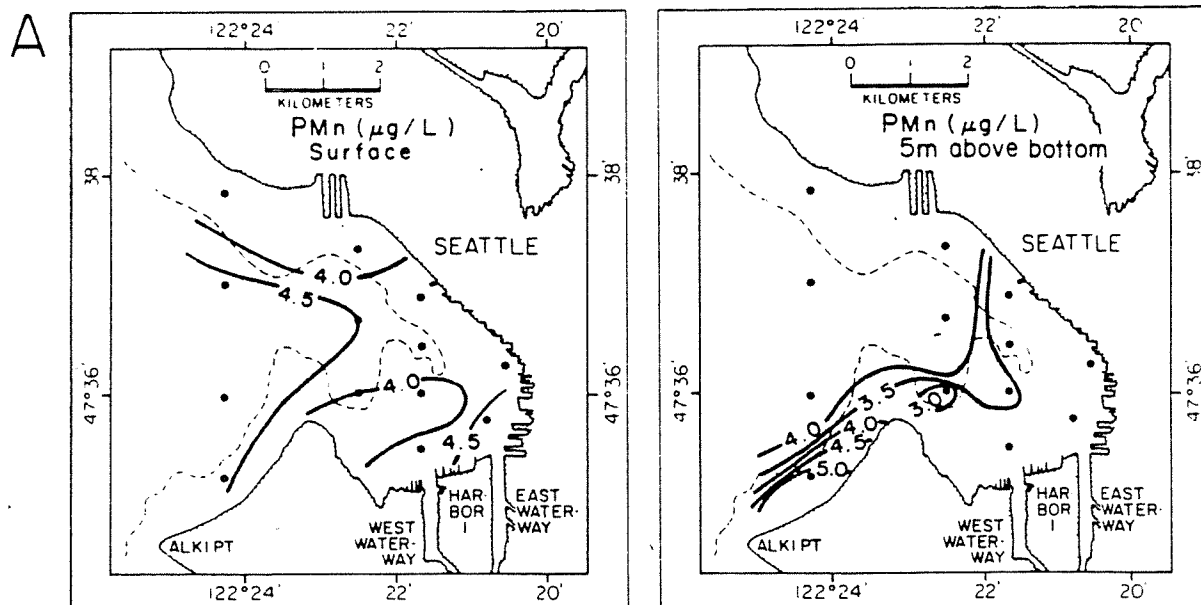


Figure 3.3. A. Areal distribution of total particulate iron at the surface and 5 m above the bottom of Elliott Bay. B. East-west and north-south cross sections of particulate iron in Elliott Bay. After Massoth et al. (1982).

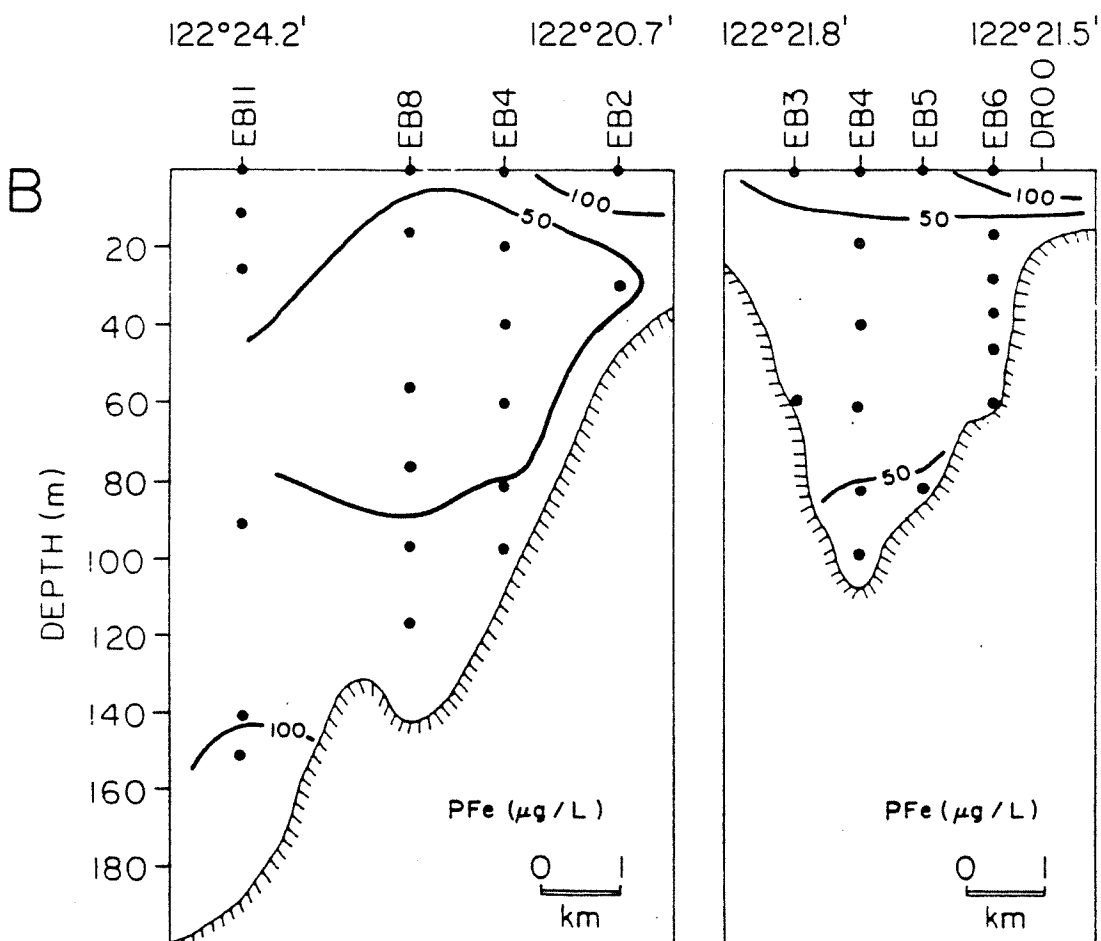
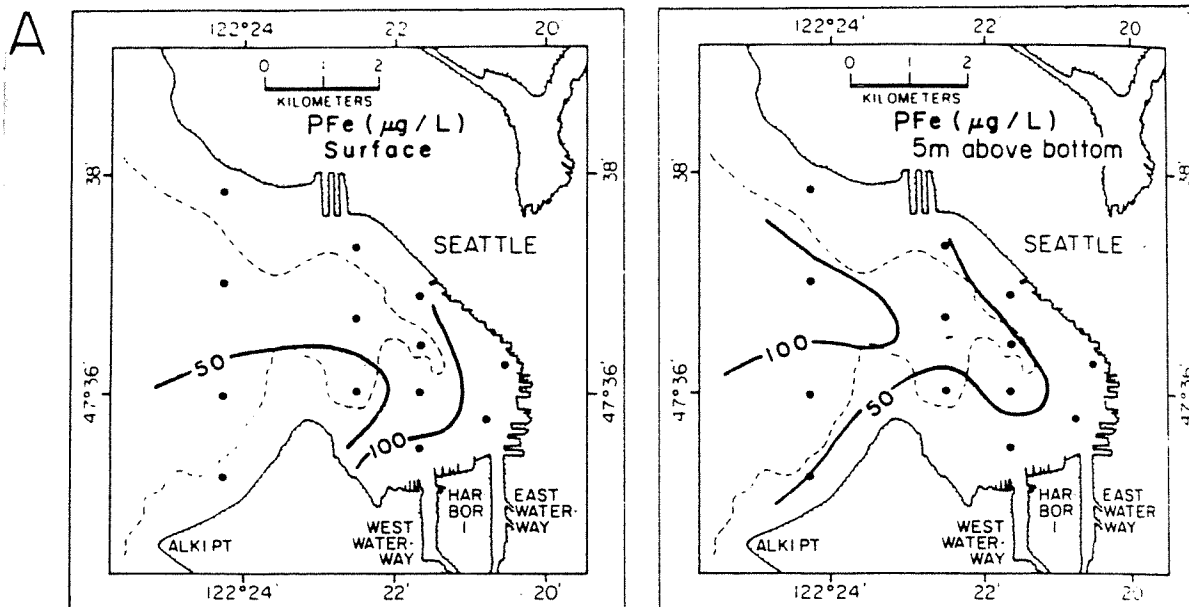
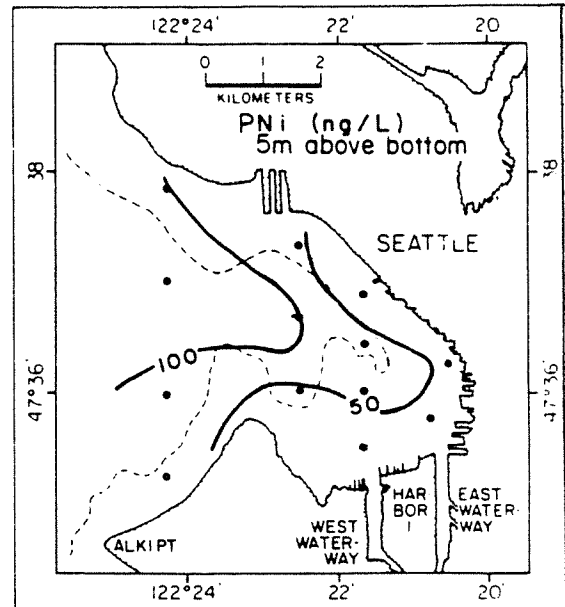
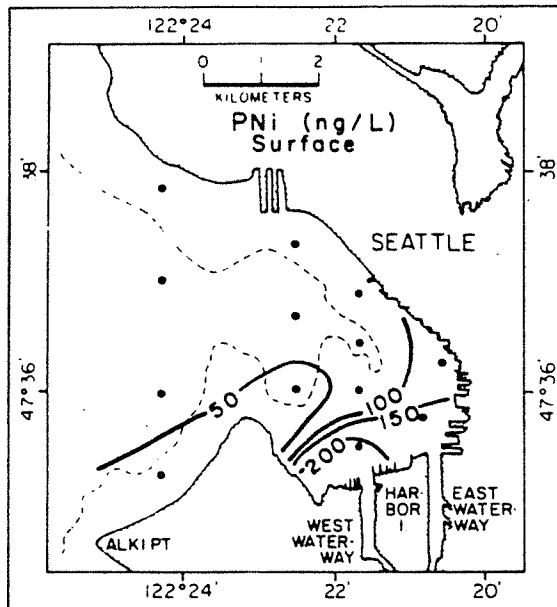


Figure 3.4. A. Areal distributions of total particulate nickel at the surface and 5 m above the bottom of Elliott Bay. B. East-west and north-south cross sections of particulate nickel in Elliott Bay. After Massoth et al. (1982).

A



B

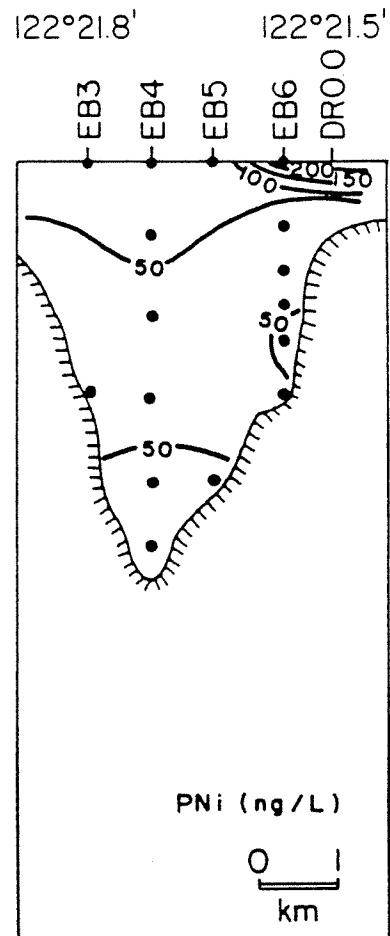
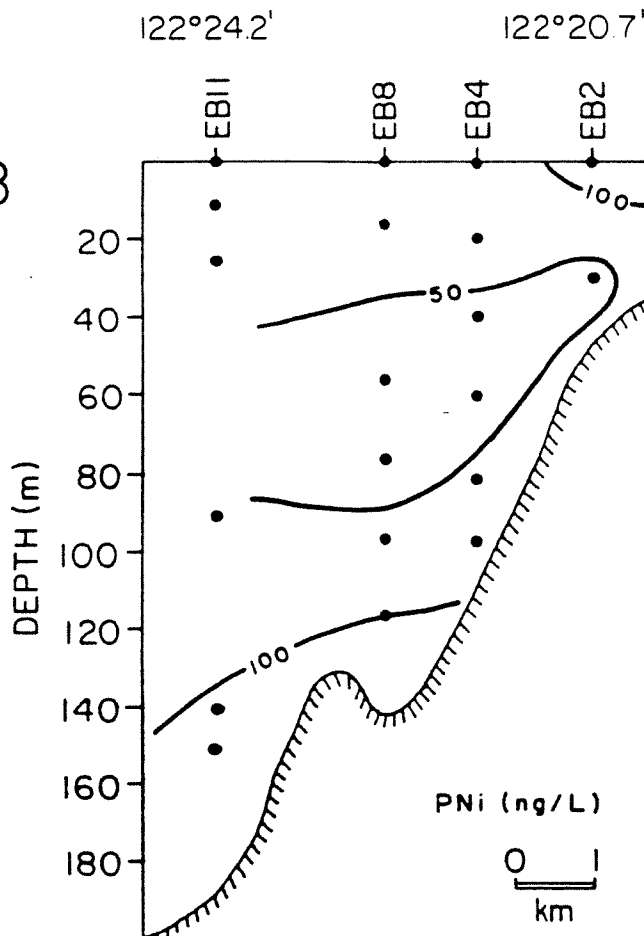


Figure 3.5. A. Areal distributions of total particulate copper at the surface and 5 m above the bottom of Elliott Bay. B. East-west and north-south cross sections of particulate copper in Elliott Bay. After Massoth et al. (1982).

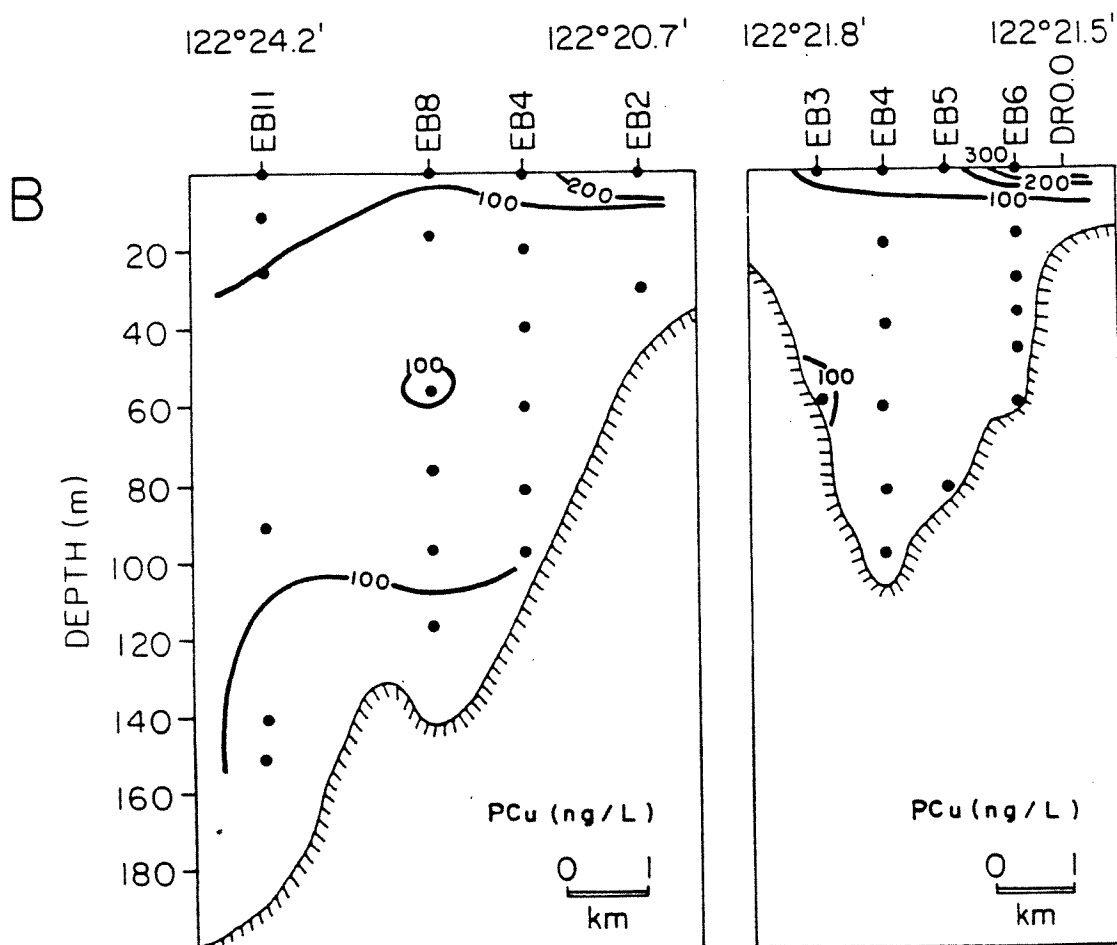
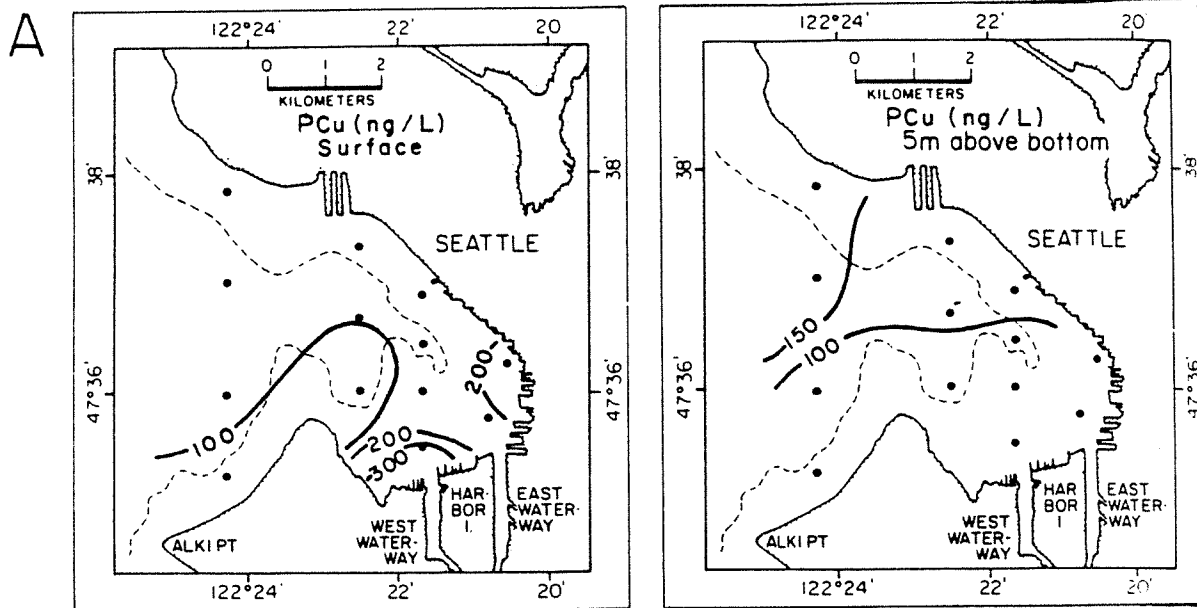


Figure 3.6. A. Areal distributions of total particulate zinc at the surface and 5 m above the bottom of Elliott Bay. B. East-west and north-south cross sections of particulate zinc in Elliott Bay. After Massoth et al. (1982).

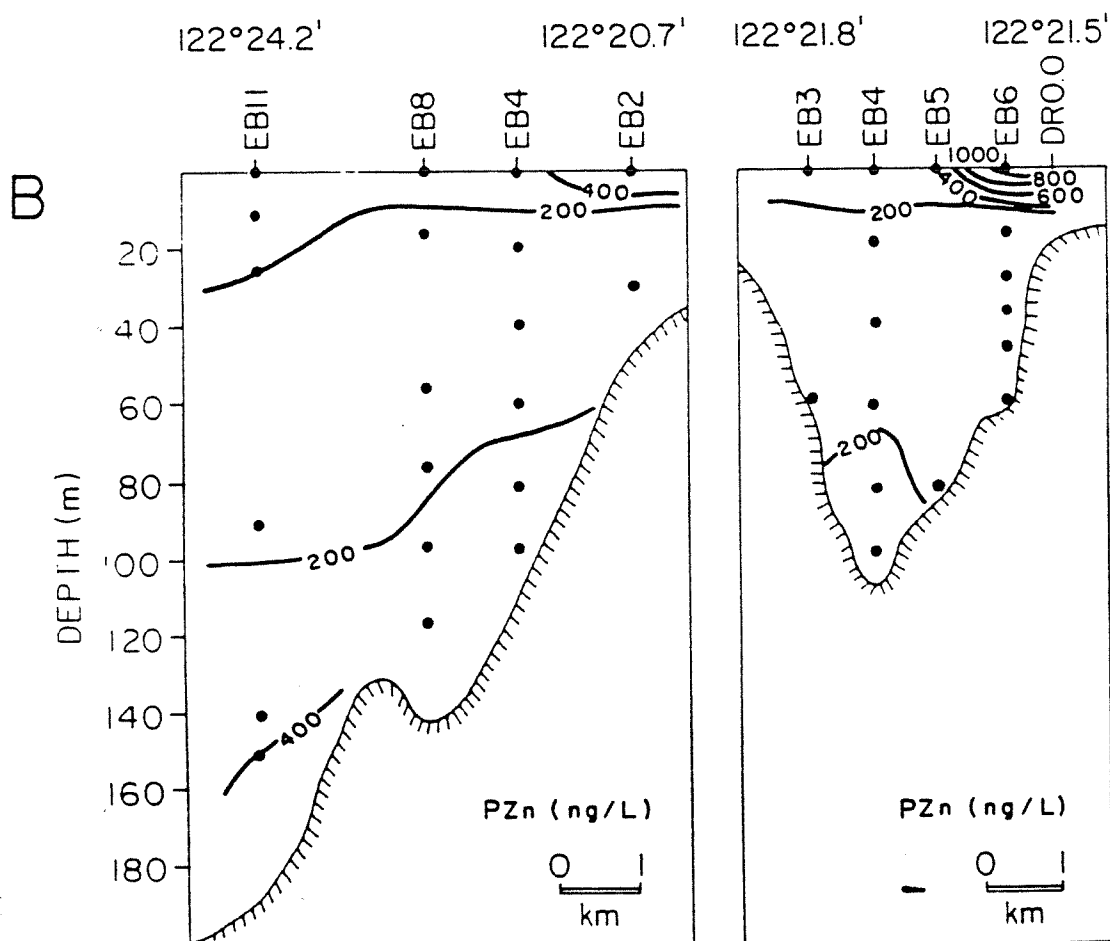
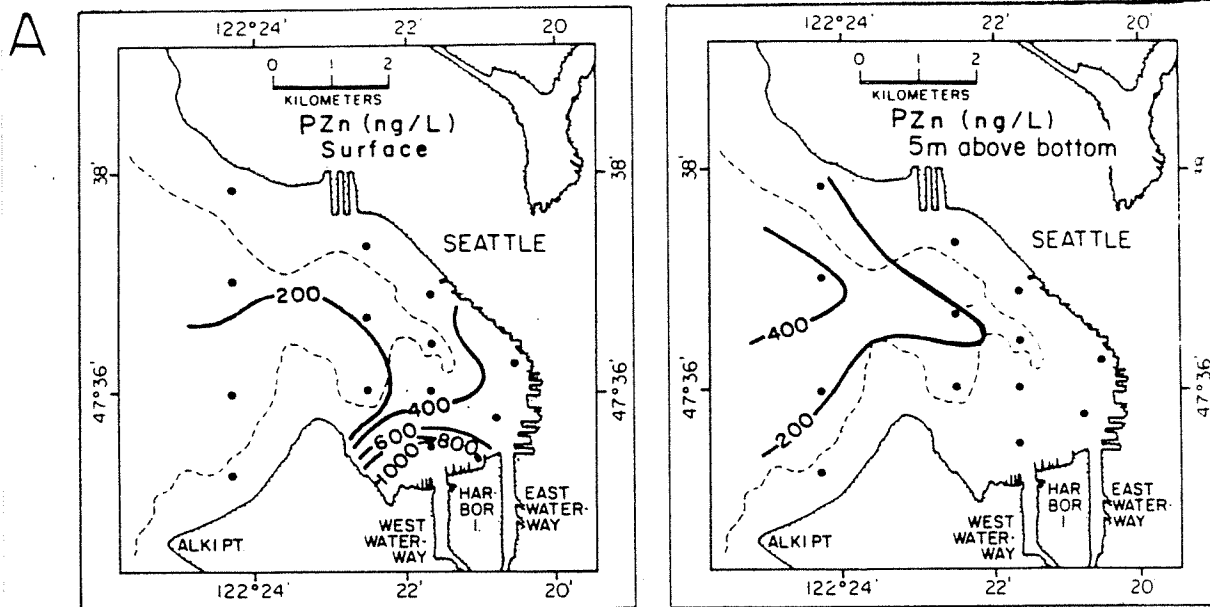
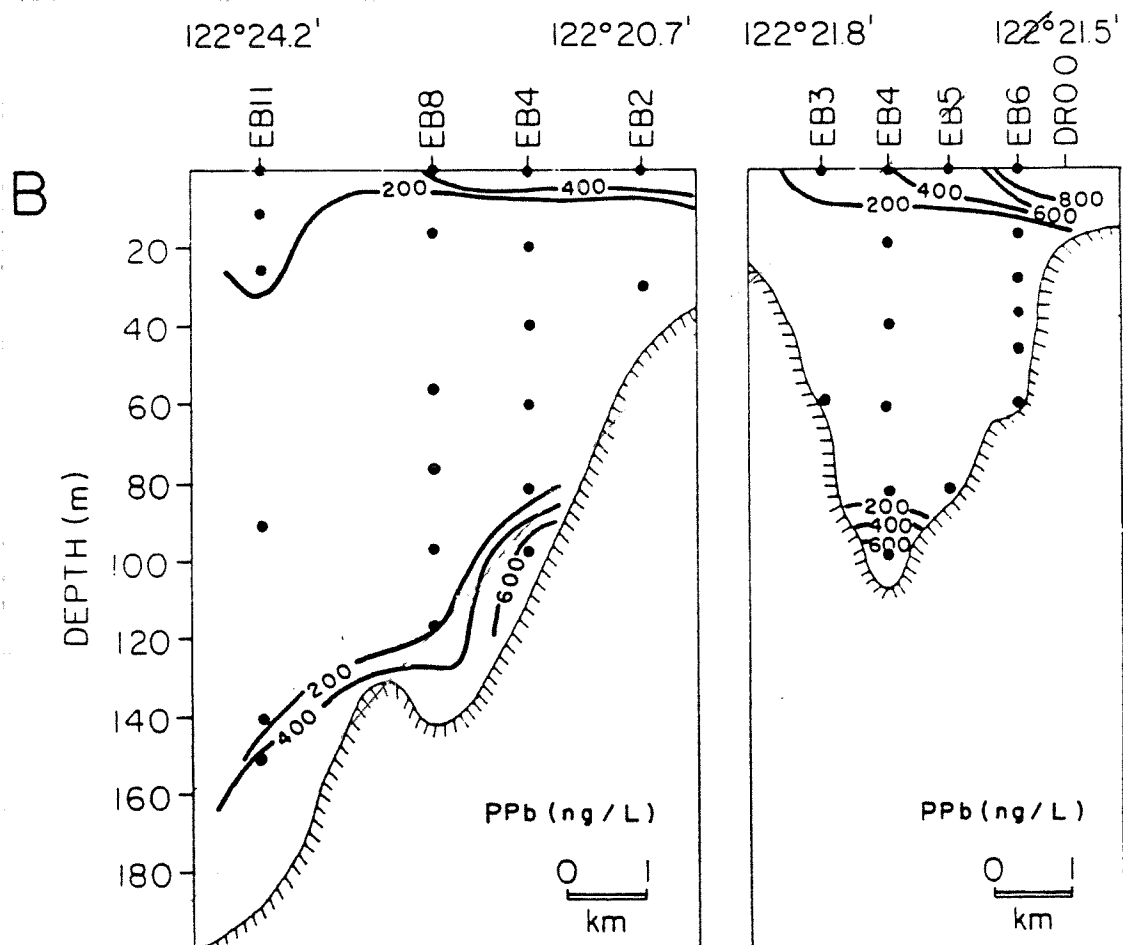
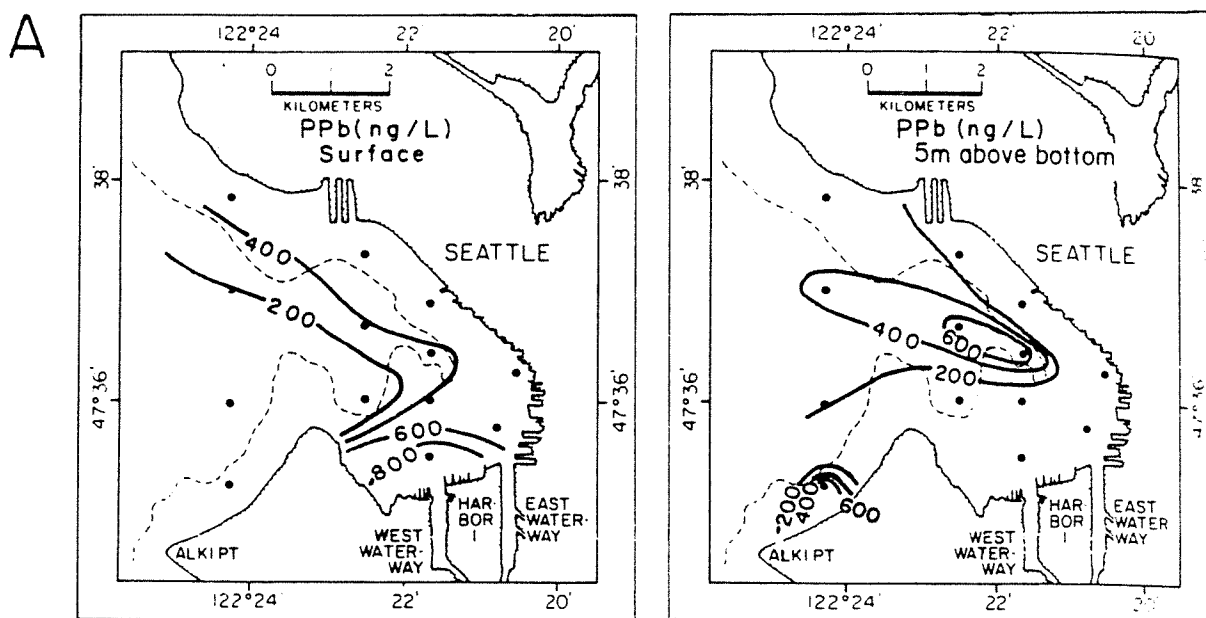


Figure 3.7. A. Areal distributions of total particulate lead at the surface and 5 m above the bottom of Elliott Bay. B. East-west and north-south cross sections of particulate lead in Elliott Bay. After Massoth et al. (1982).



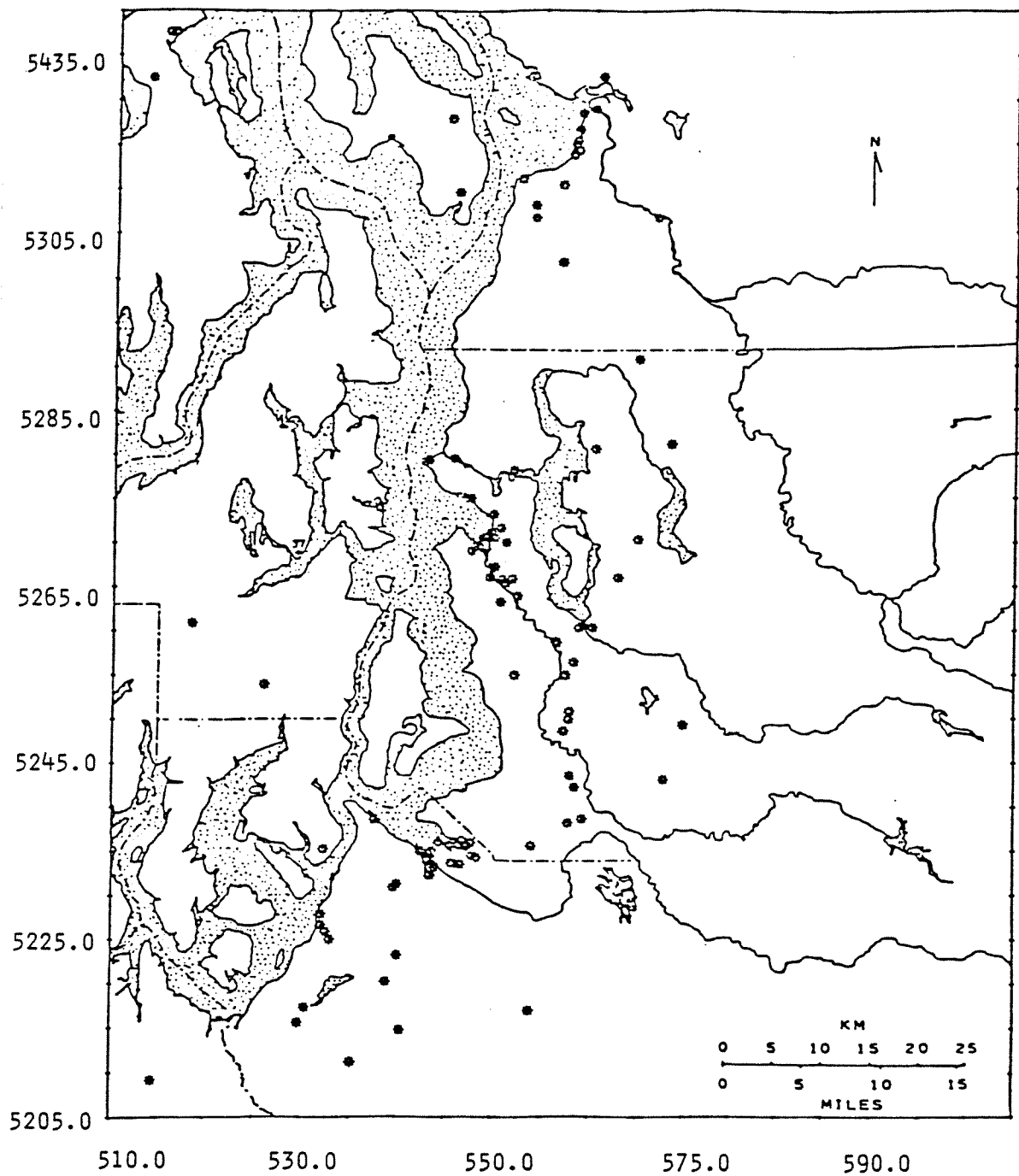


Figure 3.8. Location of dominant atmospheric emission point sources in the Puget Sound basin. After Pavlou et al. (1983).

Table 3.1. Cumulative emission rates (E_{ATM}^S) of airborne material from point source inputs in Puget Sound. After Pavlou et al. (1983).

Material	E_{ATM}^S (tons/yr)
Total Suspended Particulates (TSP)	6,963
Total Fine Particulates (TFP)	594
Sulfur Dioxide (SO ₂)	118,524
Nitrous Oxides (NO _x)	21,018
Hydrocarbons (HC)	6,911
Carbon Monoxide (CO)	32,828

present in storm water runoff was relatively low.

Attempts were then made to correlate the input of metals with the known metal concentrations present in the water and sediments (Tables 3.2 and 3.3). Surprisingly, input from the known sources of metals was substantially less than the existing concentration of metals in the water and sediments. Hence, most metals appear to be derived from natural sources. The primary natural source appears to be the atmosphere. For example, less than 30% of the arsenic entering Puget Sound was associated with sediments (Crecelius et al. 1975).

The concentrations of manganese, copper, nickel and cadmium dissolved in Elliott Bay water were relatively low (Figure 3.9). The majority of the metals present were either associated with sediments or interstitial water. For example, Sugai et al. (1978) showed significant concentrations of manganese in interstitial water.

The mechanisms by which these dissolved metals become bound to sediments are poorly understood. Ions can adsorb to particulates and bind in various manners to organic matrices. Massoth et al. (1982) suggested that the flocculation of iron, chromium, nickel, copper, zinc, and lead provided significant entry of these metals into Elliott Bay sediments. Similarly Paulson et al. (in press) showed that iron and copper were removed from solution in the estuarine mixing zone. In addition, a relationship between metal binding and manganese oxide was noted (Massoth et al. 1982). Particles with newly formed coatings of manganese oxide appeared to scavenge metals such as chromium, nickel, copper, zinc, and lead. However, not all metals behaved in this manner. In the estuarine mixing zone manganese and cadmium desorbed from particulates and went into solution (Paulsen et al. in press). Hence, the ionic form of the metal appears to play a key role in determining the fate of the metal.

The type and concentration of organic matter present in a particle also plays a key role. For example, 85% of the mercury present in Puget Sound sediments was associated with easily oxidizable organic matter (Crecelius et al. 1975). However, the role of organic matter varies from metal to metal. Less than 10% of the arsenic and antimony was bound to easily oxidizable organic matter (Crecelius et al. 1975).

Schell et al. (1977) collected sediment cores from West Point, Duwamish Head and Alki Point. The age of the various sediment layers was estimated by measuring the ^{210}Pb concentration present. The concentrations of zinc, nickel, copper, lead, chromium, manganese, cobalt, and mercury were 1 to 3.6 times greater than the concentrations of the same metals in newly deposited sediments. Concentrations of metals exceeding the ambient concentrations in control sediments were only noted at West Point and Alki Point. Copper concentrations were highest in sediments collected from the northeastern shore of Elliott Bay and from sediments from the north end of Harbor Island (Figure 3.10). Arsenic and antimony were reported from only two stations, one in central Elliott Bay and one on the northwestern edge of Harbor Island. Lead was distributed along the entire shoreline of Elliott Bay, but the highest concentration consistently occurred along the northeastern perimeter of the bay (Figure 3.10). Zinc occurred along the entire shoreline of the bay. Zinc concentrations were uniform along the northeastern shore and off Harbor Island and equivalent concentrations were measured in sediments from two other stations - one in the inner bay and one in the outer bay (Figure 3.10). Mercury concentrations were highest along the northeastern shore of the bay (Figure 3.10).

The concentrations of copper, lead, zinc, and mercury in the Duwamish

Table 3.2. Availability of toxicant loading data for sources discharging into Elliott Bay. After Jones and Stokes Associates, Inc. and Tetra Tech, Inc. (1983).

Source/Pollutant	Municipal*	Industrial	CSO**	Surface Runoff	River**	Atmospheric	Erosion	Water Circulation
<u>PRIORITY POLLUTANTS</u>								
Antimony	-				Good			
Arsenic	-				Good			
Asbestos	-						Poor	
Beryllium	-				Good			
Cadmium	-	Poor			Good			
Chromium	-	Poor			Good			
Copper	-	Poor	Poor	Good	Good		Poor	
Cyanide	-							
Lead	-	Poor	Poor	Good	Good		Poor	
Mercury	-		Poor		Good			
Nickel	-	Poor			Good			
Selenium	-				Good			
Silver	-	Poor			Good			
Thallium	-				Good			
Zinc	-	Poor	Poor	Good	Good		Poor	
Pesticides, PCBs & related compounds	-		Poor		Good			
Halogenated aliphatic hydrocarbons	-				Good			
Halogenated ethers	-				Good			
Monocyclic aromatics	-				Good			
Phthalate esters	-				Good			
Polycyclic aromatic hydrocarbons	-				Good			
Nitrosamines & misc. compounds	-				Good			
<u>EXTENDED CONVENTIONAL POLLUTANTS</u>								
Flow	-	Fair	Poor		Good	-	-	
BOD	-	Poor						
COD	-	Poor						
Total solids	-	Poor						
TNVS	-	Poor						
TSS	-	Poor	Poor		Good	-		
TNVSS	-	Poor				-		
Total nitrogen	-	Poor			Good			
Total phosphorus	-	Poor	Poor		Good			
Oils & grease	-	Poor	Poor			-		
pH	-	Fair			Good			
Fecal coliform	-	Poor			Good	-		

*No municipal discharges to Elliott Bay.

**Several loading studies are in progress; Metro TPPS report may provide some data.

Table 3.3. Duwamish Estuary annual pollutant mass balances (1970-1980).
After Harper-Owes (1983).

Parameter (units)	Surface Advection from Duwamish	OUTPUTS			Percent of Total Retained or Metabolized within Duwamish	Total Documented Inputs (see Table 7)	Residual ^a (% of Total)
		Sedimentation	Estuary Metabolism	Total			
Hydraulic Load ($m \times 10^6/yr$)	1,817.	0	0	1,817.	0	1,817.	0
Sediment ⁶ ($kg \times 10^6/yr$)	33.	212.	0	245.	87%	244.	1. (1%)
Total Organic Carbon ($kg \times 10^3/yr$)	0.74	5.2	0.33 ^b	6.3	88%	1.2	5.1 (91%)
Oil and Grease ($kg \times 10^3/yr$)	290.	580.	?	870.	66%	370.	500. (58%)
Ammonia (as N) ($kg \times 10^3/yr$)	559.	133. ^c	78. ^d	770.	27%	770.	?
Arsenic ³ ($kg \times 10^3/yr$)	4.0	3.7	0	7.7	48%	1.2	6.5 (84%)
Calcium ³ ($kg \times 10^3/yr$)	6.3	0.52	0	6.8	8%	0.83	6.0 (88%)
Chromium ³ ($kg \times 10^3/yr$)	38.	9.6	0	48.	20%	5.2	43. (90%)
Copper ($kg \times 10^3/yr$)	15.	12.	0	27.	44%	5.1	22. (81%)
Iron ($kg \times 10^3/yr$)	1,000.	7,400.	0	8,400.	88%	6,200.	2,200. (26%)
Mercury ³ ($kg \times 10^3/yr$)	0.14	0.80	0	0.94	85%	0.76	0.24 (24%)
Nickel ($kg \times 10^3/yr$)	8.0	6.6	0	14.6	45%	<32.	?
Lead ($kg \times 10^3/yr$)	67.	19.	0	86.	22%	12.	74. (86%)
Zinc ($kg \times 10^3/yr$)	38.	36.	0	74.	49%	35.	39. (51%)
Total PCB (kg/yr)	40.	207.	0	247.	84%	6.2	241. (98%)
Total Pesticides (kg/yr)	0.1	13.	?	13.	>99%	3.5	9.5 (73%)
Total Selected PAH (kg/yr)	110.	710.	?	820.	87%	8.9	810. (99%)
Naphthalene (kg/yr)	3,200.	14.	?	3,200.	41%	13.	3,200. (>99%)
Total Phthalates ($kg \times 10^3/yr$)	290.	580.	?	870.	67%	2.7	870. (>99%)
Polychlorinated Biphenyls (10^3 organisms/yr)	2,450.	?	?	<10,000.	?	10,000.	?

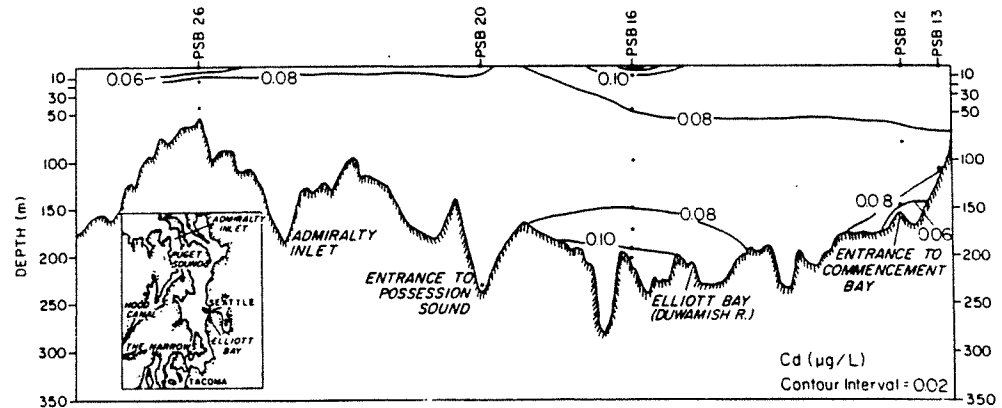
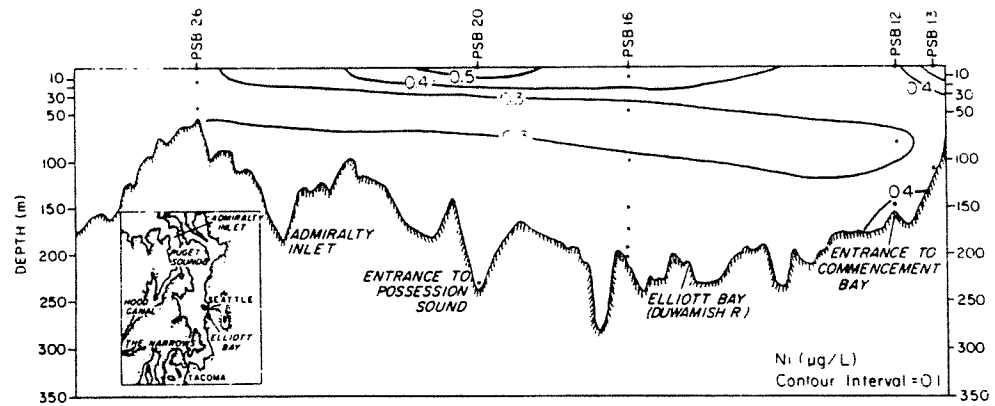
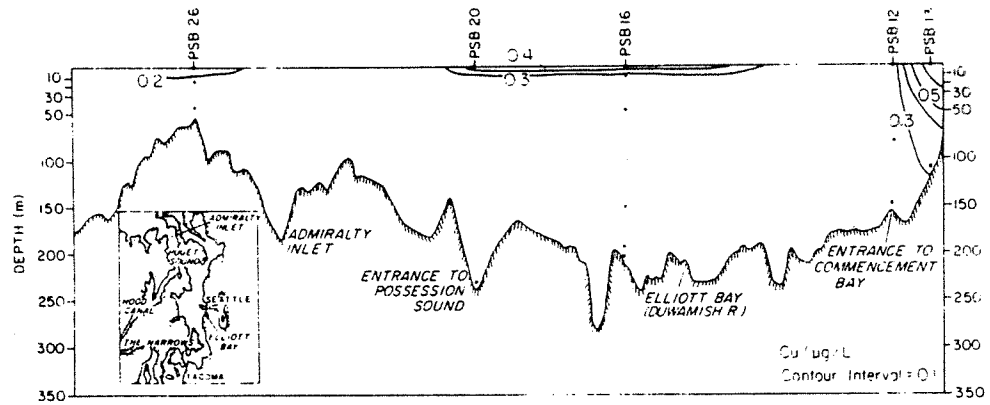
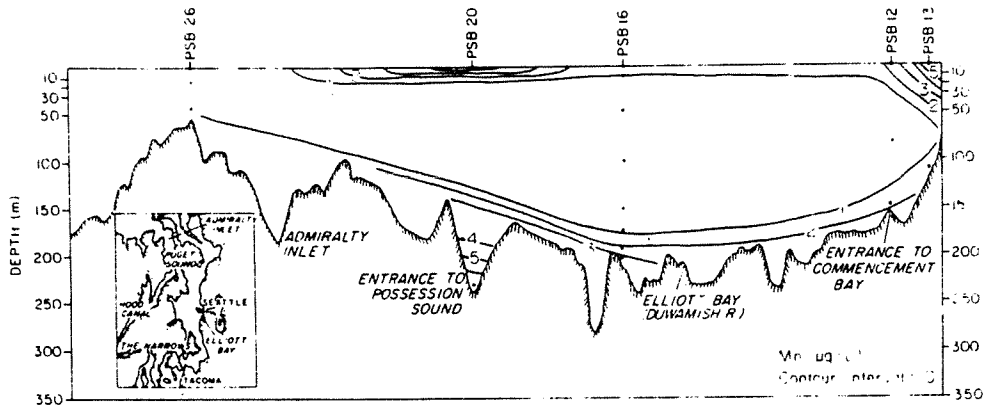
^aResidual term is calculated as Output (=Total) minus documented inputs, and is felt to represent an undocumented source within the Estuary for most parameters (see text).

^bAerobic respiration determined from oxygen balances (60% of O₂ consumption occurred within the salt wedge).

^cEstimated by difference in the mass balance equation (i.e., assuming residual = 0).

^dAmmonia oxidation (i.e., nitrification) determined from increases in nitrate load.

Figure 3.9. Cross sections of total dissolved manganese, copper, nickel, and cadmium in Puget Sound. After Curl (1982).



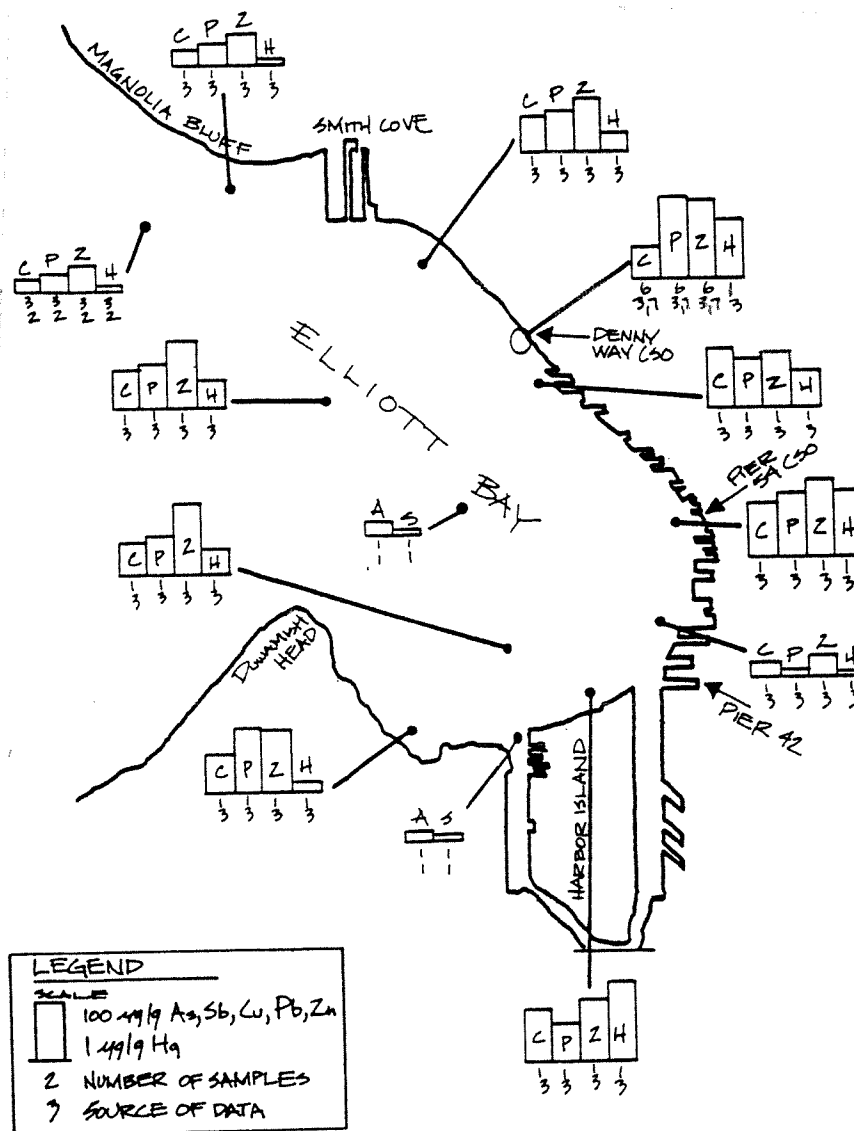


Figure 3.10. Concentrations of copper, lead, zinc, and mercury in the sediments of Elliott Bay. After Dexter et al. (1981).

River were consistently highest in the east and west waterways (Figure 3.11). Concentrations of copper ranged from non-detectable to 815 ug/g sediment (dry weight; Dexter et al. 1981). Lead concentrations ranged from non-detectable to 12,900 ug/g sediment (dry weight; Dexter et al. 1981). Zinc concentrations ranged from non-detectable to 660 ug/g sediment (dry weight; Dexter et al. 1981). Mercury concentrations ranged from non-detectable to 1,200 ug/g sediment (dry weight; Dexter et al. 1981). Concentrations of copper, lead, zinc, and mercury were relatively low in sediments collected directly below the Renton Sewage Treatment Plant (Figure 3.11).

The mean trace metal concentrations in the shallow and deep sediment areas of Puget Sound, including Elliott Bay subregions, as measured in the TPSS studies (Pavlou et al. 1983) are shown in Tables 3.4 and 3.5, respectively. Only five samples were available for comparison in region A. The mean trace metal concentrations in all deep sediments (Table 3.5) compared with the corresponding mean concentrations in shallow sediments (Table 3.4) showed enrichment of the trace metals in the sediments. The ratios for antimony, arsenic, beryllium, chromium, copper, manganese, silver and thallium range from 1.1. to 1.8 for mercury and nickel 1.0; and for cadmium, lead, and xenon 0.9.

3.2 Trace Organics in Water and Sediments

Numerous potentially toxic organic chemicals have been identified in sediments collected from Elliott Bay and the Duwamish estuary. Two principal events have focused the attention of researchers upon these organic chemicals, (1) the hypothesis that liver hepatomas in flatfish collected from Elliott Bay may be caused by exposure to organic chemicals (see section 5.1.3), and (2) a spill of 255 gallons of transformer fluid containing Aroclor 1242 (a PCB) in the Duwamish River on 13 September 1974.

Following this PCB spill extensive chemical analyses were performed to document the occurrence and distribution of PCBs in the sediments. Sediments containing high concentrations of PCBs were dredged and placed in upland disposal sites. About 72% of the spilled PCBs was recovered (Blazevich et al. 1977). Chemical analyses indicated that the dredging operation did not result in significant release or redistribution of the PCBs into the water or nearby sediments (Blazevich et al. 1977).

The mean concentration of PCBs in Elliott Bay water was 11 ± 13 ng/l based on 185 analyses (Konasewich et al. 1982). The mean concentration of PCBs in the Duwamish River was 22 ± 13 ng/l based on 60 analyses (Konasewich et al. 1982). The concentration in Elliott Bay was approximately twice the concentrations reported from other areas of Puget Sound (Table 3.6). The mean concentration of PCB associated with the suspended particulate material from Elliott Bay was 920 ± 200 ng/g based on 87 analyses (Konasewich et al. 1982). The mean concentration of PCB associated with the suspended particulate matter from the Duwamish River was 1770 ± 540 ng/g based on 70 analyses. The mean concentration in Elliott Bay was approximately 4-9 times the concentration reported from other regions of Puget Sound (Table 3.6). The mean concentration of PCBs in sediments from Elliott Bay was $637 \pm$ ng/g (Konasewich et al. 1982). This concentration was about 21 times greater than the PCB concentration in other areas of Puget Sound (Table 3.6).

Although PCBs were distributed throughout Elliott Bay and the Duwamish River (Figure 3.12), the highest concentrations occurred at the Corps of Engineers dredged material disposal site, in the east and west waterways of

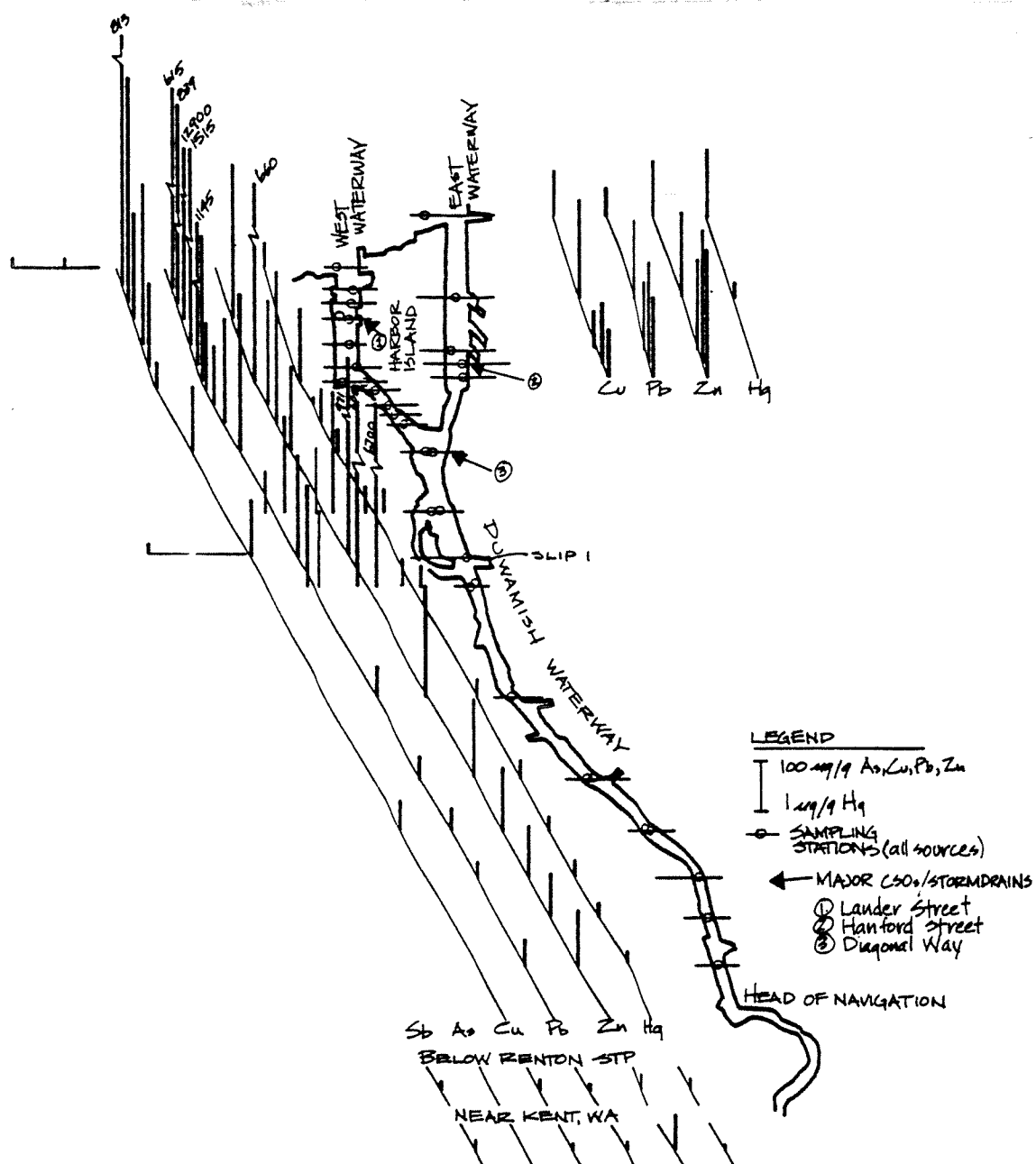


Figure 3.11. Concentrations of copper, zinc, lead, and mercury in the sediments of the Duwamish River. After Dexter et al. (1981).

Table 3.4. Mean trace metal concentrations in the shallow sediment areas of Puget Sound.^a
After Pavlou et al. (1983).

Toxicant:	Area A* Alki Pt. mean ± s.d.	Area B Elliot Bay mean ± s.d.	Area C Elliot Bay mean ± s.d.	Area D Denny Way mean ± s.d.	Area E Magnolia mean ± s.d.	Area F West Pt. mean ± s.d.	Area G Ship Canal mean ± s.d.	Area H Meadow Pt. mean ± s.d.	Area I Carkeek mean ± s.d.	Area K Richmond Beach mean ± s.d.	Area J Port Madison mean ± s.d.	All Shallows mean ± s.d.
Trace Metals												
ANTHONY	0.36 ± .44	2.5 ± 2.0	1.1 ± 1.3	1.5 ± 1.1	5.1 ± 7.5	.64 ± .49	.62 ± .49	.3 ± 0.0	.17 ± .015	.061 ± .042	.33 ± .058	1.23 ± .23
ARSENIC	3.5 ± 2.8	16 ± 9.8	11 ± 5.3	14 ± 8.2	9.2 ± 5.1	3.2 ± 5.2	7.2 ± 6.1	3.3 ± 1.5	2.6 ± 1.5	2.5 ± .90	6.1 ± .34	7.81 ± 7.86
BERYLLIUM	.38 ± .16	.70 ± .34	.35 ± .10	.39 ± .26	.30 ± .11	.22 ± .09	.42 ± .20	.14 ± .046	.16 ± .021	.46 ± .040	.31 ± .18	.34 ± .23
CADMIUM	.42 ± .40	1.3 ± .95	.81 ± .70	.93 ± .75	.17 ± .13	.30 ± .50	.21 ± .15	.14 ± .045	.42 ± .040	.27 ± .085	.39 ± .059	.55 ± .67
CHROMIUM	35 ± 19	44 ± 17	47 ± 13	55 ± 6.5	27 ± 14	29 ± 11	41 ± 4.6	25 ± 8.	23 ± 1.2	13 ± 7.	30 ± 11	36.8 ± 15.9
COPPER	20 ± 12	142 ± 18	48 ± 21	75 ± 32	17 ± 13	17 ± 9.	23 ± 13	16 ± 16	5.5 ± .36	7.9 ± 2.9	14 ± 6.9	43.1 ± 57.4
LEAD	22 ± 11	209 ± 81	94 ± 32	155 ± 151	25 ± 14	33 ± 36	24 ± 5.2	18 ± 9.4	9.5 ± 1.5	13 ± 3.5	22 ± 13	75.2 ± 100.8
MANGANESE	282 ± 145	317 ± 73	282 ± 26	300 ± 90	257 ± 82	400 ± 172	344 ± 96	352 ± 130	227 ± 47	303 ± 116	173 ± 75	328 ± 133
MERCURY	.040 ± .036	.32 ± .38	.22 ± .35	.82 ± .79	.18 ± .094	.17 ± .14	.15 ± .093	.17 ± 12	.0091 ± .0012	.012 ± .001	.3 ± .015	.30 ± .47
NICKEL	32 ± 15	31 ± 13	37 ± 9.	48 ± 7.1	18 ± 11	26 ± 7.5	32 ± 2.6	19 ± 9.1	18 ± 1.7	21 ± 3.	23 ± 6.7	30.8 ± 12.9
SELENIUM	.21 ± .23	.31 ± .20	.49 ± .35	.30 ± .20	.23 ± .054	.22 ± .10	2.0 ± .005	.21 ± .018	.063 ± .015	.068 ± .046	.45 ± .26	.26 ± .18
SILVER	.55 ± .49	1.2 ± .91	1.8 ± .32	2.7 ± 1.7	.26 ± .10	.88 ± .99	.57 ± .41	.23 ± .21	.67 ± .15	.39 ± .078	2.6 ± .17	1.18 ± 1.29
THALLIUM	.072 ± .026	.066 ± .045	.054 ± .051	.086 ± .033	.1 ± 0.0	.1 ± .03	.14 ± .092	.1 ± 0.0	.019 ± 0.0	.0097 ± .0032	.1 ± 0.0	.086 ± .044
ZINC	81 ± 58	326 ± 391	551 ± 454	145 ± 57	50 ± 26	90 ± 105	185 ± 275	43 ± 18	436 ± 50	128 ± 67	50 ± 22	162 ± 230
(# of samples)	(5)	(10)	(6)	(19)	(6)	(31)	(5)	(5)	(3)	(3)	(3)	(96)

^a All concentrations in mg/g dry weight

s.d. = standard deviation

Table 3.5. Mean trace metal concentrations in deep sediment areas of Puget Sound.^a
After Pavlou et al. (1983).

Toxicant:	Area AA South Central Basin mean $\pm$ s.d.	Area BB Urban Central Basin mean $\pm$ s.d.	Area CC West Point mean $\pm$ s.d.	Area DD North Central Basin mean $\pm$ s.d.	Area EE Elliott Bay mean $\pm$ s.d.	Deep Stations mean $\pm$ s.d.	All Areas Grand mean $\pm$ s.d.
Trace Metals:							
ANTHONY	.91 $\pm$.83	7.2 $\pm$ 16.8	.60 $\pm$.75	3.0 $\pm$ 5.1	.72 $\pm$.25	2.87 $\pm$ 9.41	2.25 $\pm$ 6.56
ARSENIC	13 $\pm$ 5.7	13 $\pm$ 5.7	9.2 $\pm$ 2.3	24 $\pm$ 47	11 $\pm$ 2.2	13.2 $\pm$ 17.5	10.0 $\pm$ 13.0
BERYLLIUM	.57 $\pm$.31	.51 $\pm$.18	.43 $\pm$.12	.31 $\pm$.26	.40 $\pm$.20	.46 $\pm$.22	.39 $\pm$.23
CADMIUM	.32 $\pm$.14	.48 $\pm$.15	.27 $\pm$.13	.48 $\pm$.079	.27 $\pm$.12	.37 $\pm$.16	.48 $\pm$.53
CHROMIUM	54 $\pm$ 7.9	56 $\pm$ 11	50 $\pm$ 11	50 $\pm$ 14	46 $\pm$ 15	51.9 $\pm$ 11.7	43.0 $\pm$ 16
COPPER	35 $\pm$ 12	60 $\pm$ 32	38 $\pm$ 14	35 $\pm$ 8.5	49 $\pm$ 15	44.7 $\pm$ 22.4	43.8 $\pm$ 46.2
LEAD	42 $\pm$ 17	69 $\pm$ 52	51 $\pm$ 62	31 $\pm$ 7.2	64 $\pm$ 17	53.4 $\pm$ 44.1	66.2 $\pm$ 82.9
MANGANESE	572 $\pm$ 141	404 $\pm$ 92	435 $\pm$ 93	403 $\pm$ 50	330 $\pm$ 87	434 $\pm$ 122	372 $\pm$ 138
MERCURY	.20 $\pm$.16	.51 $\pm$.54	.22 $\pm$.21	.10 $\pm$.035	.34 $\pm$.21	.30 $\pm$.35	.30 $\pm$.42
NICKEL	35 $\pm$ 6.7	31 $\pm$ 7.5	37 $\pm$ 7.2	34 $\pm$ 4.1	31 $\pm$ 8.4	33.7 $\pm$ 7.3	32. $\pm$ 11.
SELENIUM	.50 $\pm$.36	.79 $\pm$.36	.69 $\pm$.37	.69 $\pm$.34	.38 $\pm$.25	.64 $\pm$.37	.42 $\pm$.33
SILVER	1.8 $\pm$ 1.	.97 $\pm$.93	1.9 $\pm$ 1.6	.64 $\pm$.20	1.7 $\pm$ 1.5	1.42 $\pm$ 1.25	1.28 $\pm$ 1.28
THALLIUM	.084 $\pm$.031	.12 $\pm$.093	.10 $\pm$.11	.092 $\pm$.051	.14 $\pm$.15	.11 $\pm$.009	.096 $\pm$.068
ZINC	99 $\pm$ 34	184 $\pm$ 131	103 $\pm$ 25	92 $\pm$ 16	221 $\pm$ 360	140 $\pm$ 152	153 $\pm$ 201

^a All contrations in mg/g dry weight

s.d. = standard deviation

Table 3.6. Mean total polychlorinated biphenyl concentrations in various regions of Puget Sound.
After Konasewich et al. (1982).

Region	Water ng L ⁻¹	SPM ng g ⁻¹	Zooplankton μg (g-lipid) ⁻¹	Sediment ng g ⁻¹	Surface Film ng L ⁻¹
Duwamish River	22 ± 13 (60) ^a	1770 ± 540 (70)			116 ± 101 (5)
Elliott Bay	11 ± 13 (185)	920 ± 200 (87)	6.8 ± 3.1 (11)	637 ± 830 (4)	98 ± 83 (6)
Main Basin	4.3 (1)	104 ± 31 (3)	5.9 ± 4.4 (4)		12 (1)
Sinclair Inlet		168 ± 21 (4)	16 ± 7.0 (3)		
Whidbey Basin	4.4 ± 2.2 (15)	82 ± 37 (7)	3.7 ± 1.1 (12)	30 ± 14 (5)	
Northern Sound and Strait of Juan de Fuca	3.7 ± 1.7 (9)		1.3 ± 1.2 (3)	16 ± 13 (3)	
Southern Sound				8.0 ± 8.3 (6)	
Commencement Bay				28 ± 17 (8)	
Hood Canal	3.0 ± 2.2 (12)	88 ± 37 (3)		12 ± 3.0 (3)	

*Pavlov and Dexter (1979)

^aValues in parentheses are the number of data points.

SPM = suspended particulate matter.

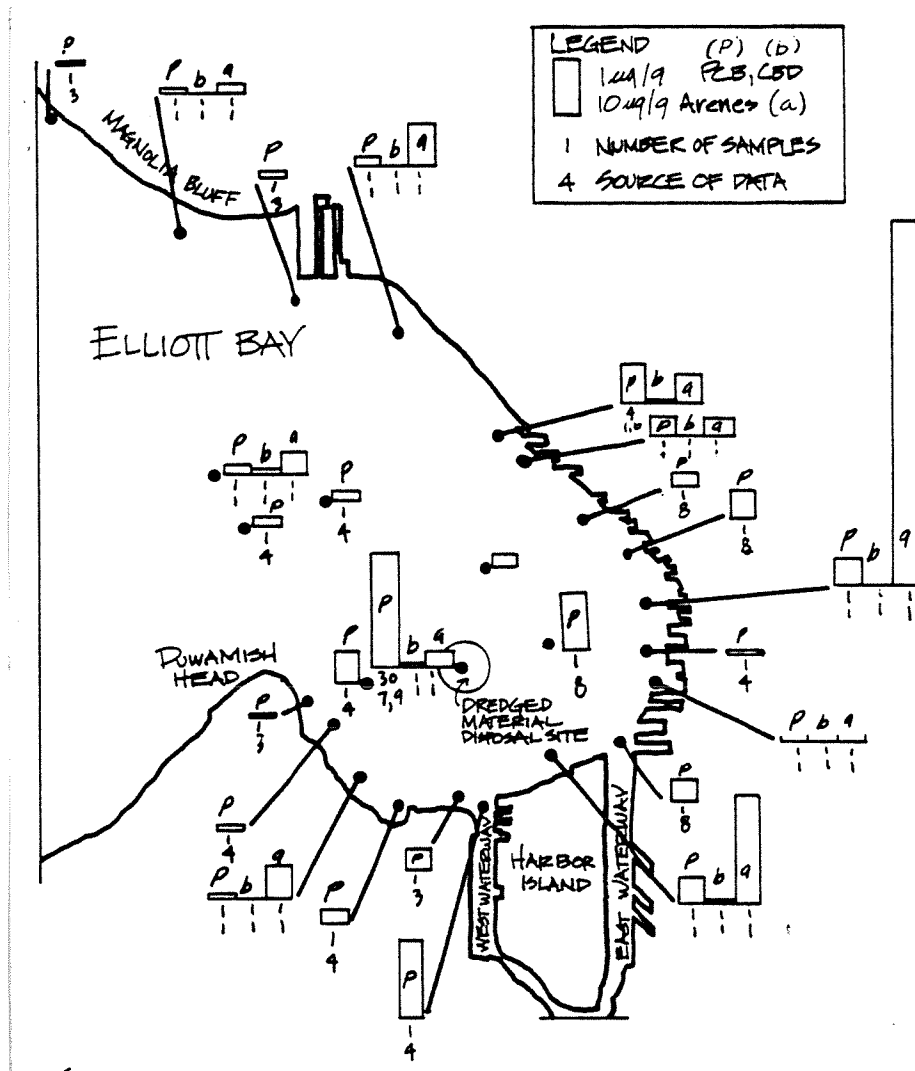


Figure 3.12. Concentrations of polychlorinated biphenyls, chlorinated butadienes, and arenes observed in the sediments of Elliott Bay. After Dexter et al. (1981).

the Duwamish River, and along the northeastern shore of the bay. The concentrations of PCBs in the Duwamish River were highest in the East and West waterways (Figure 3.13), although PCBs were reported from sediments collected from sites along the entire river below the Renton Sewage Treatment Plant.

Konasewich et al. (1982) calculated that the Duwamish River contributed 97 g PCBs/day into Elliott Bay. The sewage effluent from West Point was estimated to contribute 30 g PCBs/day into Elliott Bay (Table 3.7). Hence, approximately 32% of the total input of PCBs into Puget Sound comes from the Duwamish River and the West Point sewage treatment facility.

To date, studies of organic chemicals in Elliott Bay and the Duwamish River have been focused on three classes, polycyclic aromatic hydrocarbons (PAH) such as benzo(a)pyrene, chlorinated hydrocarbons such as DDT and its metabolites DDD and DDE, and the PCBs discussed previously. Interest has focused on these particular organic classes for several reasons. First the PCBs and PAHs have demonstrated mutagenic potential in mammals. The PAHs are also believed to be carcinogenic in mammals and perhaps in aquatic organisms. DDT and its metabolites are bioaccumulated by many organisms. Finally, existing techniques could be used or modified to allow the chemists to conduct quantitative, reproducible analyses of organic chemicals in these classes. Only recently have techniques been developed for other chemicals such as phthalate esters. Numerous unidentified organic chemicals exist in both water and sediments.

A summary describing the synthetic organics in sediments from various areas of Puget Sound appears in Table 3.8. Along the south shore of Elliott Bay, zone A, only four stations were sampled for trace organics. The mean organic concentrations in Elliott Bay and other shallow areas of Puget Sound are presented in Table 3.9. For comparison, the mean concentrations of trace organics in deep sediments of Puget Sound are shown in Table 3.10. Unlike trace metals, the concentrations of trace organics in deep sediments are, in most cases, lower than in the shallow sediments. The ratio of the mean concentrations (deep values/shallow values) are for acids and bases, 0.9; DDT's and PCBs, 0.8; PNAs and CPNs, 0.7; phthalate and di-octyl phthalate, 1.3; CBD 1.6; and volatile solids 1.2.

Trace concentrations of DDT, DDE, and DDD are present in the sediments of Elliott Bay (Table 3.11). Concentrations of DDT ranged from 0.09–50 ppb (dry weight; Konasewich et al. 1982). Concentrations of DDE ranged from 0.23–6 ppb (dry weight; Konasewich et al. 1982). Concentrations of DDD ranged from 0.16–122 ppb (dry weight; Konasewich et al. 1982).

Trace concentrations of PAHs occurred in seawater from Elliott Bay (Riley et al. 1980). These low concentrations were not surprising since most of the higher molecular weight PAHs are of very low solubility in seawater at low temperatures. Five PAHs (anthracene, naphthalene, fluorene, phenanthrene, and pyrene) out of a list of nine hydrocarbons that could be detected (naphthalene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz(a)anthracene, chrysene, and benzo(a)pyrene) were associated with suspended particulate matter from Elliott Bay (Riley et al. 1980). Eleven PAHs (phenanthrene, anthracene, fluoranthene, pyrene, retene, benz(a)anthracene, chrysene, benzo(a)anthracene, benzo(e)pyrene, benzo(a)pyrene, and perylene) at concentrations of 13–730 ng/g sediment (dry weight) were detected in suspended particulate matter from the Duwamish River (Table 3.12; Curl 1982). Concentrations of the combustion PAHs (fluoranthene, pyrene, benz(a)anthracene, chrysene, benzo(a)anthracene, benzo(a)pyrene, and benzo(e)pyrene, were consistently highest at Harbor Island ranging from 1000–4900 ng/g sediment (dry weight; Table 3.13; Curl 1982).

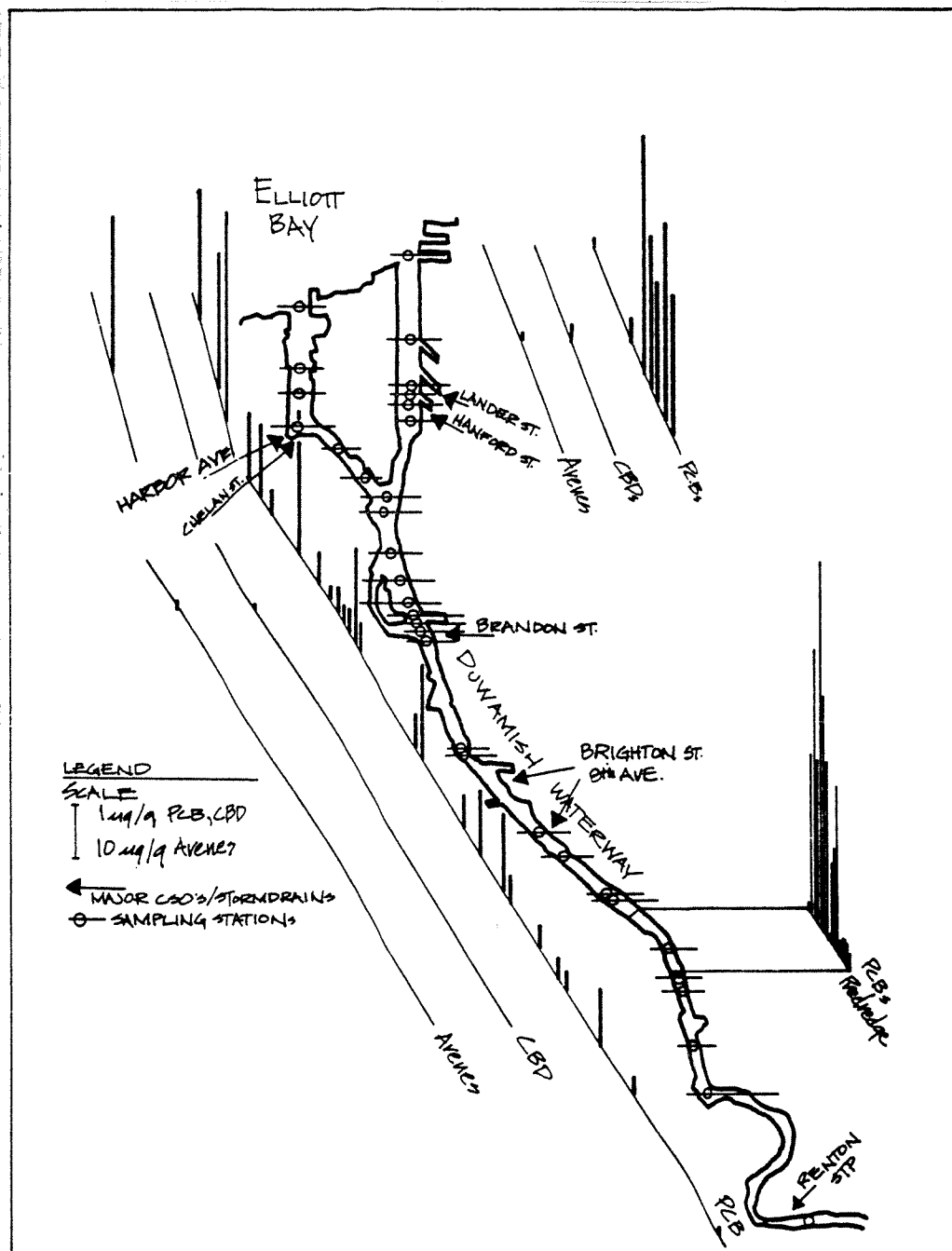


Figure 3.13. Concentrations of polychlorinated biphenyls, chlorinated butadienes, and arenes observed in the sediments of the Duwamish River. After Dexter et al. (1981).

Table 3.7. Estimated inputs of polychlorinated biphenyls to Puget Sound. After Konasewich et al. (1982).

Source	Rate In (g CB day ⁻¹)	
<u>Major River Systems</u>		
Snohomish, Skagit, Stillaguamish Rivers	220	
Lake Washington (Ship Canal)	10	
Duwamish River	97	
Puyallup River	30	
<u>Outfalls</u>		
Westpoint	30	
Renton	3	
Combined Sewage Overflows	10	
TOTAL:	400	(1.44 × 10 ⁵ g/yr)

*Pavlou et al. (1978)

Table 3.8. Conclusions and summary describing the concentrations of synthetic organic chemicals in sediments from various areas in Puget Sound. After Pavlou et al. (1983).

Area - Shallow:	#Stations	# Samples	Notes:
A: Alki Point	4	4	Includes 3 early stations (A160, B160, C160) with very few detections.
B: S. Elliott Bay/ Duwamish Waterway	9	10	Includes one suspect early station (A062).
C: Elliott Waterfront	6	6	No data was collected at S0090 for pesticides.
D: Denny Way	12	19*	Includes 3 early suspect Stations (A060, B060, C060). Numerous large outliers in PNAs and CPNAs, especially from Stations S0031 and S0032.
E: Magnolia	6	6	Suspicious non-detection of pesticides at Station S0087. Almost all non-zero DDT values from Station S0030.
F: West Point Shallow	20	31	Suspiciously few detections at Station S0004, especially of PNAs and CPNAs.
G: Ship Canal	5	5	Few Detections for DDTs.
H: Meadow Point	5	5	Sparse data throughout from early measurements.
I: Carkeek	3	3	
J: Port Madison	3	3	
K: Richmond Beach	3	3	Early stations with few detections.
Area - Deep:			
AA: S. Central Basin	11	16	Data suspiciously sparse for PNAs, CPNAs, and phthalates at Stations S0019 and S0020.
			Suspicious non-detection of PCBs at N618.
BB: Urban Central Basin	17	20	Large outlier for di-n-butyl phthalate at Station S0065.
CC: West Point Deep	12	16*	Suspiciously few data at S0001 and, to a lesser extent, S0001, S0003 and 0127.
DD: N. Central Basin	9	9	Almost no detections at Stations 0111 and 0113.
EE: Elliott Bay	6	9	Stations 0150 and S0062 have relatively few detections.

Table 3.9. Mean trace organic chemical concentrations in shallow sediment areas of Puget Sound.^a
After Pavlou et al. (1983).

Toxicant:	Area A Alki Point mean ± s.d.	Area B South Elliott Bay mean ± s.d.	Area C East Elliott Bay mean ± s.d.	Area D Denny Way mean ± s.d.	Area E Magnolia Point mean ± s.d.	Area F West Point mean ± s.d.	Area G Ship Canal mean ± s.d.	Area H Meadow Point mean ± s.d.	Area I Carkeek mean ± s.d.	Area K Richmond Beach mean ± s.d.	Area J Port Madison Shallow mean ± s.d.
Acids (#/6)	n.d.	2.7 ± 8.6 (1)	258 ± 594 (1)	15 ± 54 (1)	n.d.	8.4 ± 24 (1)	69 ± 24 (1)	152 ± 205 (2)	n.d.	n.d.	34 ± 162
Bases (#/2)	n.d.	9.8 ± 28.6 (1)	160 ± 388 (1)	257 ± 1296 (1)	1.3 ± 3.2 (1)	40 ± 123 (1)	37 ± 82 (1)	.78 ± 1.74 (1)	n.d.	453 ± 784 (1)	92 ± 602
PNAs (#/10)	44 ± 37 (7)	1995 ± 1563 (7)	4661 ± 2054 (9)	4318 ± 4060 (8)	705 ± 883 (5)	4813 ± 7844 (8)	1070 ± 816 (7)	602 ± 739 (6)	461 ± 386 (4)	223 ± 260 (3)	136 ± 85 (5)
CPNAs (#/9)	473 ± 354 (9)	12013 ± 3197 (9)	30754 ± 10895 (9)	24583 ± 14987 (9)	3431 ± 2500 (9)	34906 ± 41001 (9)	9347 ± 2448 (9)	6167 ± 3088 (7)	551 ± 326 (2)	522 ± 370 (4)	834 ± 273 (9)
CLAs (#/5)	n.d.	17 ± 54 (1)	n.d.	886 ± 2718 (2)	n.d.	n.d.	n.d.	12 ± 27 (1)	n.d.	1.6 ± 2.8 (1)	180 ± 1241
CBD	1.1 ± 2.2	.29 ± .62	n.d.	3.7 ± 6.2	1.7 ± 4.1	1.1 ± 2.5	.56 ± 1.25	2.9 ± 2.9	n.d.	n.d.	1.5 ± 3.5
Phthalates (#/4)	56 ± 79 (3)	290 ± 185 (4)	1042 ± 1072 (4)	1267 ± 1262 (4)	636 ± 676 (4)	296 ± 491 (4)	194 ± 113 (4)	1057 ± 1269 (4)	502 ± 211 (2)	620 ± 979 (2)	1750 ± 1897 (2)
Di-octyl Phthalate	691 ± 1212	3853 ± 6816	4800 ± 3274	14294 ± 31852	4263 ± 4543	1110 ± 2354	597 ± 455	865 ± 678	762 ± 470	48 ± 25	2056 ± 1269
DDTs (#/3)	n.d.	28 ± 25 (3)	5.6 ± 4.9 (1)	29 ± 13 (3)	3.2 ± 4.2 (3)	3.0 ± 4.1 (3)	11 ± 11 (2)	1.9 ± 2.6 (1)	n.d.	n.d.	11 ± 16
PCBs (#/4)	19 ± 15 (4)	651 ± 180 (4)	1798 ± 1069 (4)	1368 ± 744 (4)	125 ± 63 (4)	128 ± 128 (11)	65 ± 24 (4)	66 ± 34 (4)	27.2 ± 4.6 (4)	2.5 ± 1.7 (4)	45 ± 19 (4)
Hisc. pesticides (#/4)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Volatiles (#/24)	85 ± 150 (4)	17 ± 26 (4)	2000 ± 3301 (5)	231 ± 859 (3)	n.d.	.43 ± 1.41 (2)	61 ± 121 (4)	n.d.	45 ± 54 (8)	2016 ± 844 (5)	246 ± 1036 (5)
(# of Samples)	(4)	(10)	(6)	(19)	(6)	(31)	(5)	(5)	(3)	(5)	(95)

^a All concentrations in ng/g dry weight
s.d. = standard deviation
(#/n) = number of constituents of chemical class detected out of total number n
nd = not detected

Table 3.10. Mean trace organic chemical concentrations in deep sediment areas of Puget Sound.^a After Pavlou et al. (1983).

Toxicant:	Area AA South Central Basin mean $\pm$ s.d.	Area BB Urban Central Basin mean $\pm$ s.d.	Area CC West Point I mean $\pm$ s.d.	Area DD North Central Basin mean $\pm$ s.d.	Area EE Elliott Bay mean $\pm$ s.d.	Deep Stations mean $\pm$ s.d.	All Areas Grand mean $\pm$ s.d.
Acids (#/6)	59 $\pm$ 159 (1)	18 $\pm$ 55 (1)	2.9 $\pm$ 11.5 (1)	22 $\pm$ 50 (2)	12 $\pm$ 21 (3)	24 $\pm$ 84	30 $\pm$ 134
Bases (#/2)	209 $\pm$ 369 (1)	3.2 $\pm$ 7.9 (1)	111 $\pm$ 262 (2)	5.4 $\pm$ 10.8 (1)	4.2 $\pm$ 10 (1)	75 $\pm$ 228	87 $\pm$ 479
PNAs (#/10)	2197 $\pm$ 3077 (8)	1053 $\pm$ 633 (8)	770 $\pm$ 662 (9)	442 $\pm$ 390 (8)	993 $\pm$ 513 (8)	1164 $\pm$ 1634	2278 $\pm$ 4185
CPNAs (#/9)	1837 $\pm$ 1507 (9)	10209 $\pm$ 6402 (9)	5175 $\pm$ 2278 (9)	1510 $\pm$ 590 (9)	5458 $\pm$ 1921 (9)	5415 $\pm$ 4996	14174 $\pm$ 22441
CLAs (#/5)	ND	9.8 $\pm$ 30. (1)	ND	34 $\pm$ 101 (1)	ND	7.2 $\pm$ 39	107 $\pm$ 944
CBD (#/1)	8.1 $\pm$ 17.1 (1)	3.3 $\pm$ 5.1 (1)	2.1 $\pm$ 3.4 (1)	.64 $\pm$ 1.2 (1)	3.0 $\pm$ 4.9 (1)	3.7 $\pm$ 9.1	2.4 $\pm$ 6.6
PHTs (#/4)	632 $\pm$ 722 (4)	2054 $\pm$ 4879 (4)	645 $\pm$ 1092 (4)	1307 $\pm$ 1672 (4)	375 $\pm$ 308 (4)	1095 $\pm$ 2775	835 $\pm$ 1944
DI-OCTYL	7251 $\pm$ 9660	11494 $\pm$ 16296	6294 $\pm$ 16874	4091 $\pm$ 7707	6239 $\pm$ 11857	7708 $\pm$ 13607	5801 $\pm$ 14553
DDTs (#/3)	1.7 $\pm$ 1.9 (3)	5.2 $\pm$ 7.5 (3)	4.1 $\pm$ 4.9 (3)	1.9 $\pm$ 1.2 (3)	8.6 $\pm$ 7.6 (3)	4.2 $\pm$ 5.8	8.1 $\pm$ 13.1
PCBs (#/4)	146 $\pm$ 70 (4)	474 $\pm$ 315 (4)	165 $\pm$ 88 (4)	157 $\pm$ 72 (4)	748 $\pm$ 519 (4)	323 $\pm$ 330	434 $\pm$ 605
Misc (#/4)	ND	ND	ND	18 $\pm$ 5.3	ND	.23 $\pm$ 330	.1 $\pm$ 1.2
Volatiles (#/24)	749 $\pm$ 1342 (3)	7.0 $\pm$ 2.52 (2)	7.0 $\pm$ 17 (1)	827 $\pm$ 2338 (1)	83 $\pm$ 248 (2)	296 $\pm$ 1097	267 $\pm$ 1059
(# of Samples)	(16)	(20)	(16)	(9)	(9)	(70)	(165)

^a All concentrations in ng/g dry weight

s.d. = standard deviation

(#/n) = number of constituents of chemical class detected out of total number n

ND = not detected

Table 3.11. Concentrations of DDT and its metabolites in Puget Sound.
After Komasevich et al. (1982).

Site	Sample	Dry Weight (ppb)					
		DDT		DDE		DDD	
		o,p'	p,p'	o,p'	p,p'	m,p'	p,p'
Elliott Bay	Sediments						
	Crab hep.	<.04-30	<.05-20	<.2-4	<.03-2	<.07-9	<.04-30
	Worm		120	510	1900	460	510
	Shrimp		<2-3	<2-2	10-15	4-10	10-20
	Clams		<2	<1	10	<2-4	2-10
	Liver - E. Sole		<10	<10	10	5-10	1-4
	Liver - R. Sole		30-90	<10-5700	60-230	<10-90	30-280
	Liver - Sculpin		<40	<20	130	<50	<10
	Liver - Rockfish		20-40	10-20	290-870	<20-140	90-150
	English Sole Liver (Composites)	30-650	10-290	10-30	150-1000	20-240	40-310
	Rock Sole Liver (Composites)	20-90	40-630	1-30	50-700	10-290	30-650
			30-130	<1-3	20-120	9-40	20-90

Table 3.12. Concentrations of polycyclic aromatic hydrocarbons associated with suspended matter in the Green River. The combustion polycyclic aromatic hydrocarbons are indicated by an asterisk (*). After Curl (1982).

Location	Sta 1	Sta 2	Metro	Sta 3
ng/g (dry weight)				
phenanthrene	110	160	730	170
anthracene	23	13	260	33
fluoranthene*	67	160	660	210
pyrene*	53	170	680	270
retene	160	330	---	350
benz(a)anthracene*	14	21	440	130
chrysene*	49	130	330	140
benzofluoranthenes*	71	150	420	140
benz(e)pyrene*	40	93	180	92
benz(a)pyrene*	26	35	180	66
perylene	160	450	60	85

Table 3.13. A comparison of the concentrations of combustion polycyclic aromatic hydrocarbons at three locations along the Duwamish River and Elliott Bay. After Curl (1982).

Compound	Sta 3 ¹	Harbor Is ²	Harbor Is ³	Elliott Bay ⁴
Fluoranthene	210	360	2700	390
Pyrene	270	580	2200	480
Benz(a)anthracene	130	70	1900	220
Chrysene	140	120	1700	200
Benzofluoranthenes	140	-	4900	420
Benz(e)pyrene	92	-	1100	190
Benz(a)pyrene	66	<10	1000	130
Totals	908	>1130	15,500	2,030

-
- 1/ Suspended matter collected at Station 3, October 1980 (PMEL).
 - 2/ Suspended matter collected in West Waterway, July 4-7, 1979. (Riley et al., 1980).
 - 3/ Bottom sediments from Stations 10031 and 10038, West Waterway (Malins et al., 1980).
 - 4/ Bottom sediments from Stations 10038 and 10039, Elliott Bay (Malins et al., 1980).

3.3 Body Concentrations of Chemicals in Biota

The first data to suggest that animals from the Duwamish River and Alki Point contained significant concentrations of xenobiotics were collected in 1971-72. Bay mussels, *Mytilus edulis*, from stations km 4.5 and km 0.96, contained 4.4 ug lead/g tissue wet weight.

Olsen and Schell (1977) subsequently analyzed tissues from 46 species including plankton, molluscs, echinoderms, crustaceans, algae, and fishes to determine the concentrations of mercury, lead, cadmium, cobalt, copper, cesium, selenium, chromium, silver, zinc, arsenic, and antimony present. The highest concentrations of trace metals were found in bay mussels from Alki Point and West Point (Figure 3.14). Approximately 1 ug lead, 0.8 ug copper and 20 ug zinc per g tissue wet weight were present in mussels from Alki Point. Approximately 1 ug lead, 1.2 ug copper, 1.5 ug chromium, and 32 ug zinc per g tissue wet weight were present in mussels from West Point. The concentrations of lead, copper, zinc, cadmium, antimony, chromium, and selenium in plankton samples from Elliott Bay were 1-100 times higher than the concentrations of the same metals in plankton from other areas of Puget Sound (Olsen and Schell 1977).

Most tissue samples had concentrations of organic chemicals which reflected the chemical composition of the sediment to which the animals were exposed. In 1972 the concentration of PCBs in whole bottomfish was 900 times the suggested EPA criterion (Healy 1979). By 1979 the concentration of PCBs in a whole bottomfish had dropped to 220 times the suggested EPA criterion. The EPA criterion was based upon that concentration of PCB which was believed to be capable of causing cancer. The concentration of PCBs in zooplankton from Elliott Bay was 6.8 ± 3.1 ug/g lipid based on 11 analyses (Table 3.6; Konasewich et al. 1982).

Konasewich et al. (1982) summarized available data on the concentrations of PCBs in animal tissues (Table 3.14). To interpret these data, one must understand a few basic facts describing PCB chemistry. Polychlorinated biphenyls are chlorinated hydrocarbons used as lubricating agents. The number of chlorine atoms (1-9) on the two phenyl rings varies with the purpose for which the PCB was manufactured. The various commercial preparations of PCBs (such as Aroclor 1254) are not pure compounds, e.g., they contain several isomers, each of which has a different number of bound chlorine atoms. Hence, when a PCB analysis is performed, several different peaks result. Each peak corresponds to an isomer containing a different number of chlorine atoms. The resulting concentration can be reported in two ways, (1) by individual peak - hence, the data are reported based on the number of chlorine atoms present (Konasewich et al. 1982), and (2) by isomer where a typical isomer peak profile is matched with the peak profile of the unknown.

Concentrations of PCBs from fish livers from Elliott Bay ranged from 2-15,000 ppb dry weight depending upon the number of chlorine atoms present (Table 3.14, Konasewich et al. 1982). These concentrations were comparable with those observed in fish livers from Commencement Bay, but were significantly greater than the concentrations present in fish livers from Sinclair Inlet, Case Inlet, and Port Madison.

The concentrations of PCBs in worms from Elliott Bay ranged from 3-550 ppb dry weight depending upon the number of chlorine atoms present (Table 3.14). Similar concentrations of PCBs were observed in worms from Commencement Bay (2-450 ppb dry weight) and Sinclair Inlet (10-500 ppb dry weight). The concentrations of PCBs in worms from Port Madison were substantially lower than those in worms from Elliott Bay, Commencement Bay,

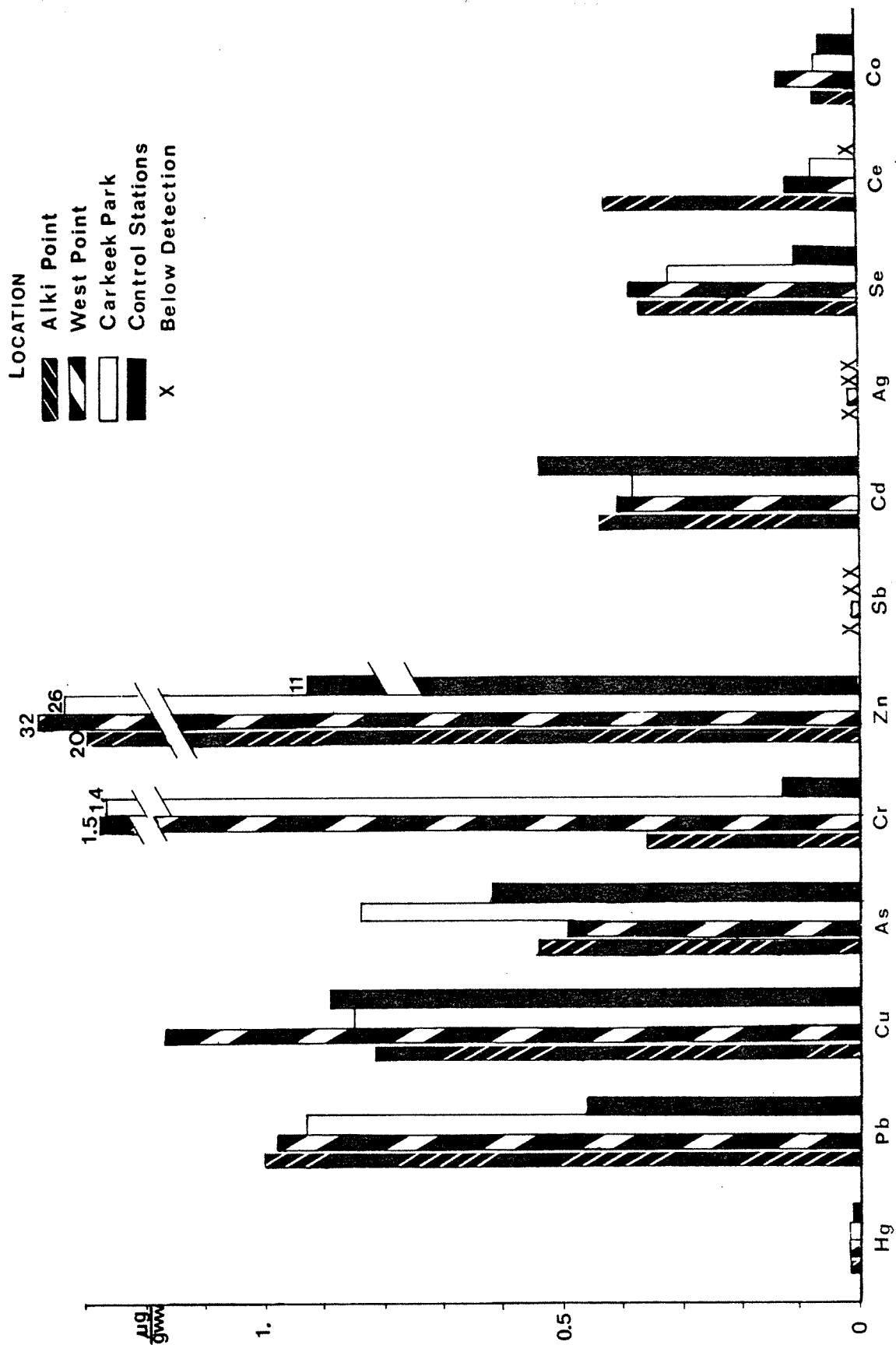


Figure 3.14. Average trace metal concentrations in bay mussels (*Mytilus edulis*) from Puget Sound. After Olsen and Schell (1977).

Table 3.14. Concentrations of polychlorinated biphenyls from sediments and biota from various areas in Puget Sound. After Konasewich et al. (1982).

SAMPLES

Concentration Range - ng/gm (ppb) dry weight; N = Number of Chlorines

Sediments N=	1	2	3	4	5	6	7	8	9
Elliott Bay	<	<.05-20	<.04-70	<.1-180	<.08-540	<.08-790	<.06-420	<.05-160	<.02-20
Commencement Bay	<	<.05-27	<.05-140	<.1-270	<.1-250	<.1-440	<.08-150	<.06-110	<.02-8.7
Sinclair Inlet	<	.01-.6	1-3	3-10	7-40	6-70	7-70	2-40	2-5
Port Madison	<	.1-.2	.4	1-2	1-2	.2-2	<.2-2	<.1-.4	<.04-.08
Case Inlet	<	.02-.2	.1-.5	.04-.9	.2-1.1	.1-.9	.05-<.3	<.04-<.1	<.02-<.1
Budd Inlet	<	.2-.3	.4-.6	2-4	.7-8	.6-5	<.3-3	<.2-.3	<.04-.08
Biota									
Fish liver (all sites)	<	2-310	10-2100	20-5900	50-9800	90-15,000	40-8900	10-2100	2-420
Budd Inlet: sole liver	<	10-30	10-20	80-120	290-450	430-640	310-490	70-160	10-30
crab hep.	<		10	210	480	470	200	30	<1
shrimp	<	10	4	30	80	80	20	2	<1
Elliott Bay: crab hep.	<	70	560	3800	7300	11,000	7800	1100	<3
worms	<	<4-10	10-60	110-350	190-500	280-550	130-250	30-60	<3
shrimp	<	<3-10	10-40	80-210	160-870	300-680	130-220	20	<1
clams	<	<10	<2	70-200	90-500	100-410	40-180	10-20	<5-2
fish liver	<	2-310	<10-1200	110-5900	380-9800	550-15,000	270-8900	20-1200	3-420
Sinclair Inlet:									
fish liver	<	10	30-70	230-490	820-2000	1600-3100	1100-2300	260-510	30-70
crab hep.	<	20	20	310	1200	1500	970	210	10
worms	<	<10	10	110	220	500	320	90	20
shrimp	<	10	N	30	170	280	160	30	<1
Port Madison:									
fish liver	<	10	20	140-190	440-730	700-1100	400-730	90-180	10
worms	<	<4	10	40	60	50	30	2	<2
shrimp	<	10	4	20	90	120	50	10	<1
clam	<	<3	<1	20	60	60	20	3	<1
Commencement Bay:									
crab hep.	<	50-60	190-640	340-1200	3600-11,000	2900-9200	1800-4900	350-1200	40-230
worms	<	<3-10	<1-20	60-120	130-450	110-440	50-160	10-40	2-10
shrimp	<	10	5-50	30-310	100-1400	110-930	40-290	10-40	<1-4
fish liver	<	<1-80	<3-2100	20-3700	50-9000	90-15,000	40-8500	10-2100	<2-410
clams	<	10	<2	30-220	100-310	130-240	50-80	10-20	4
Case Inlet:									
sole liver	<	20-30	10-20	50-140	120-360	200-520	110-400	30-120	5-20
crab hep.	<	N	10	70	160	160	70	10	<.6
shrimp	<	N	3	20	40	60	10	1	<1
clams	<	<2	<1	4	10	10	<1	<1	<1

Water

All Stations: none detected above detection limits of 0.5 - 1.0 ppt.

Suspended Matter

All Stations: none detected above detection limits of 2-4 ppb.

and Sinclair Inlet.

The concentrations of PCBs in shrimp from Elliott Bay ranged from 1-870 ppb dry weight depending upon the number of chlorine atoms (Table 3.14). Shrimp from Commencement Bay had even higher concentrations of PCBs (5-1400 ppb dry weight). Concentrations of PCBs in shrimp from Sinclair Inlet, Port Madison, and Case Inlet had substantially lower concentrations of PCBs (Table 3.14).

The concentrations of DDT and its metabolites varied both by animal species and by tissue within each species (Table 3.11). The highest concentrations of DDT (70-1280 ppb dry weight) occurred in composite livers of English sole, Parophrys vetulus. Hepatopancreas from crab contained 120 ppb dry weight of p p'DDT. The concentrations of DDT in worms, shrimp, and clams were barely detectable (Table 3.11). The concentrations of DDT in the liver of fishes ranged from 20-290 ppb dry weight depending upon the species.

The highest concentrations of DDE (70-5930 ppb dry weight) occurred in the livers of English sole. Significant concentrations also were found in the livers of rockfish (180-1030 ppb dry weight) and sculpins (300-890 ppb dry weight; Table 3.11). The concentrations of DDE in worms, shrimp, and clams were again almost undetectable (Table 3.11). Crab hepatopancreas contained 2410 ppb dry weight DDE.

The highest concentrations of DDD (42-980 ppb dry weight) occurred in composite liver samples from English sole. The concentrations of DDD in worms, shrimp, and clams were again insignificant. Concentrations of DDD were highest in English sole livers, second highest in rockfish, moderate in sculpins, and lowest in rock sole (Lepidopsetta bilineata, Table 3.11).

The most widely studied PAH is benzo(a)pyrene (BaP). Benzo(a)pyrene can be metabolized by most aquatic organisms except bivalves; hence, the reported concentrations of the parent BaP probably do not represent the actual quantities of BaP to which the organisms were truly exposed. Benzo(a)pyrene is considered particularly significant biologically since one of its metabolites binds to the DNA of flatfish and potentially is the cause of the liver hepatomas observed in flatfish.

The concentrations of BaP in livers of English and rock sole from the Duwamish River, Seattle Waterfront, and outer Elliott Bay were < 0.040, < 0.030, and < 0.090 ppm dry weight, respectively (Table 3.15). The concentration of BaP in the livers of English and rock sole from West Point was 0.070 ppm dry weight (Konasewich et al. 1982). These concentrations were representative of those reported for fish livers from most areas of Puget Sound (except Hylebos Waterway). Because these BaP measurements did not include the various metabolites one cannot conclude that BaP was not significantly bioaccumulated by flatfish and rock sole.

Similar measurements of BaP were made using worms, shrimp, and crab hepatopancreas (Table 3.15). Concentrations of BaP comparable to those in English and rock sole were found. The clam data should be given special emphasis, but the sample size reported by Konasewich et al. (1982) was so small, significant trends were not evident.

Konasewich et al. (1982) also summarized the existing data for the bioaccumulation of benzo(a)anthracene (Table 3.16). This PAH can also be metabolized by most marine animals; hence, without data on the various metabolites present in the tissues and with such a small sample size, conclusions cannot be drawn.

Table 3.15. Concentrations of benzo(a)pyrene (ppm; dry weight) in sediment and biota from various areas of Puget Sound. After Konasewich et al. (1982).

Subarea	Sediment avg. (# samples) ^a (range)	Fish Livers ^b	Crab Hepato- pancreus	Worm	Shrimp	Clam
Case Inlet	0.019 (2) (0.030, 0.0070)	< 0.0090 (2)	< 0.010 (1)	- ^c	0.090 (1)	< 0.010 (1)
Port Madison	0.020 (2) (0.030, 0.0090)	< 0.020 (2)	-	< 0.010 (1)	< 0.010 (1)	< 0.010 (1)
Sinclair Inlet	0.30 (4) (0.83, 0.070)	< 0.020 (2)	< 0.0050 (1)	< 0.010 (1)	0.070 (1)	0.12 (1)
Budd Inlet	0.027 (3) (0.040, 0.010)	< 0.0070 (2)	< 0.010 (1)	-	0.030 (1)	
Duwamish Waterway	0.56 (6) (1.5, 0.040)	< 0.040 (6)	0.020 (1)	0.35 (1)	< 0.010 (1)	0.23 (1)
Seattle Waterfront	0.52 (6) (2.2, 0.010)	< 0.030 (2)	-	-	-	0.10 (1)
Outer Elliott Bay	0.077 (4) (0.18, 0.0060)	< 0.090 (4)	-	< 0.030 (2)	< 0.010 (1)	-
West Point	4.0 (1)	0.070 (2)	-	-	-	-
Hylebos Waterway	0.53 (5) (1.7, 0.020)	0.37 (1/11)	< 0.010 (1)	0.73 (1/2)	0.050 (1)	< 0.020 (1)
Commencement Waterways	0.58 (5) (2.6, 0.0020)	-	< 0.0050 (1)	0.25 (1)	-	0.25 (1)
Southwest Corn- mencement Bay	0.12 (3) (0.34, 0.0060)	< 0.080 (3/4)	-	-	-	-
Brown's Point	0.010 (1)	0.21 (1/2)	-	-	< 0.010 (1)	

^aMalins et al. (1980)

^bWhere nondetectable levels of material were observed, a ratio of the number of samples with detectable levels to the total number of samples was substituted.

^cEnglish and rock sole species

- signifies that no sample was taken

Table 3.16. Concentrations of benzo(a)anthracene (ppm) in sediments and biota from various areas in Puget Sound. After Konasewich et al. (1982).

Subarea	Sediment avg. (# samples) ^a (range)	Fish Livers ^b	Crab Hepato- pancreas	Worm	Shrimp	Clam
Case Inlet	0.019 (2) (0.030, 0.0070)	< 0.0090 (2)	< 0.010 (1)	- ^c	0.090 (1)	< 0.010 (1)
Port Madison	0.020 (2) (0.030, 0.0090)	< 0.020 (2)	-	< 0.010 (1)	< 0.010 (1)	< 0.010 (1)
Sinclair Inlet	0.30 (4) (0.83, 0.070)	< 0.020 (2)	< 0.0050 (1)	< 0.010 (1)	0.070 (1)	0.12 (1)
Budd Inlet	0.027 (3) (0.040, 0.010)	< 0.0070 (2)	< 0.010 (1)	-	0.030 (1)	-
Duwamish Waterway	0.56 (6) (1.5, 0.040)	< 0.040 (6)	0.020 (1)	0.35 (1)	< 0.010 (1)	0.23 (1)
Seattle Waterfront	0.52 (6) (2.2, 0.010)	< 0.030 (2)	-	-	-	0.10 (1)
Outer Elliott Bay	0.077 (4) (0.18, 0.0060)	< 0.090 (4)	-	< 0.030 (2)	< 0.010 (1)	-
West Point	4.0 (1)	0.070 (2)	-	-	-	-
Hylebos Waterway	0.53 (5) (1.7, 0.020)	0.37 (1/11)	< 0.010 (1)	0.73 (1/2)	0.050 (1)	< 0.020 (1)
Commencement Waterways	0.58 (5) (2.6, 0.0020)	-	< 0.0050 (1)	0.25 (1)	-	0.25 (1)
Southwest Commencement Bay	0.12 (3) (0.34, 0.0060)	< 0.080 (3/4)	-	-	-	-
Brown's Point	0.010 (1)	0.21 (1/2)	-	-	< 0.010 (1)	-

*Malins et al. (1980)

^aWhere nondetectable levels of material were observed, a ratio of the number of samples with detectable levels to the total number of samples was substituted.

^bEnglish and rock sole species

^c- signifies that no sample was taken

4.0 BIOLOGICAL RESOURCES

4.1 Phytoplankton

4.1.1 Phytoplankton Species

Data describing the species of phytoplankton in Elliott Bay were not found, although Dexter et al. (1981) stated that the composition of species was similar to that found in the main basin of Puget Sound. Welch (1969) noted that phytoplankton blooms in the lower Duwamish River area in 1965 and 1966 were largely diatoms.

4.1.2 Distribution of Phytoplankton/Chlorophyll a

Few studies described the distribution of phytoplankton in Elliott Bay. Distributions and concentrations of chlorophyll a (Figure 4.1) were similar to those in the main basin of Puget Sound (Winter et al. 1975). Chlorophyll levels in Elliott Bay are reported to be lower than those for the main basin of Puget Sound (Ebbesmeyer and Helseth 1977), but the single station sampled (METRO station number 174) was placed off Duwamish Head in the chlorophyll low for Elliott Bay (Pavlou et al. 1973; Figure 4.2), and is probably not representative of Elliott Bay as a whole. Numerous studies have been conducted in the Duwamish waterway (Welch and Isaac 1967; Tilley and Dawson 1971; Brenner 1974; METRO 1980b), but the study areas seldom included Elliott Bay.

4.1.3 Temporal Variability

Phytoplankton blooms in Puget Sound were regulated by water column stability and available light, rather than nutrient availability (Winter et al. 1975; Campbell et al. 1977). Blooms in the Duwamish River occurred at times of minimum river runoff (Welch and Isaac 1967; Welch 1968; Welch et al. 1972; METRO 1980b) which occurred in August–September. Pavlou et al. (1973) saw higher chlorophyll concentrations in Elliott Bay in September 1972 than in June or December 1973, and Kroglund et al. (1975) also found the highest chlorophylls in September.

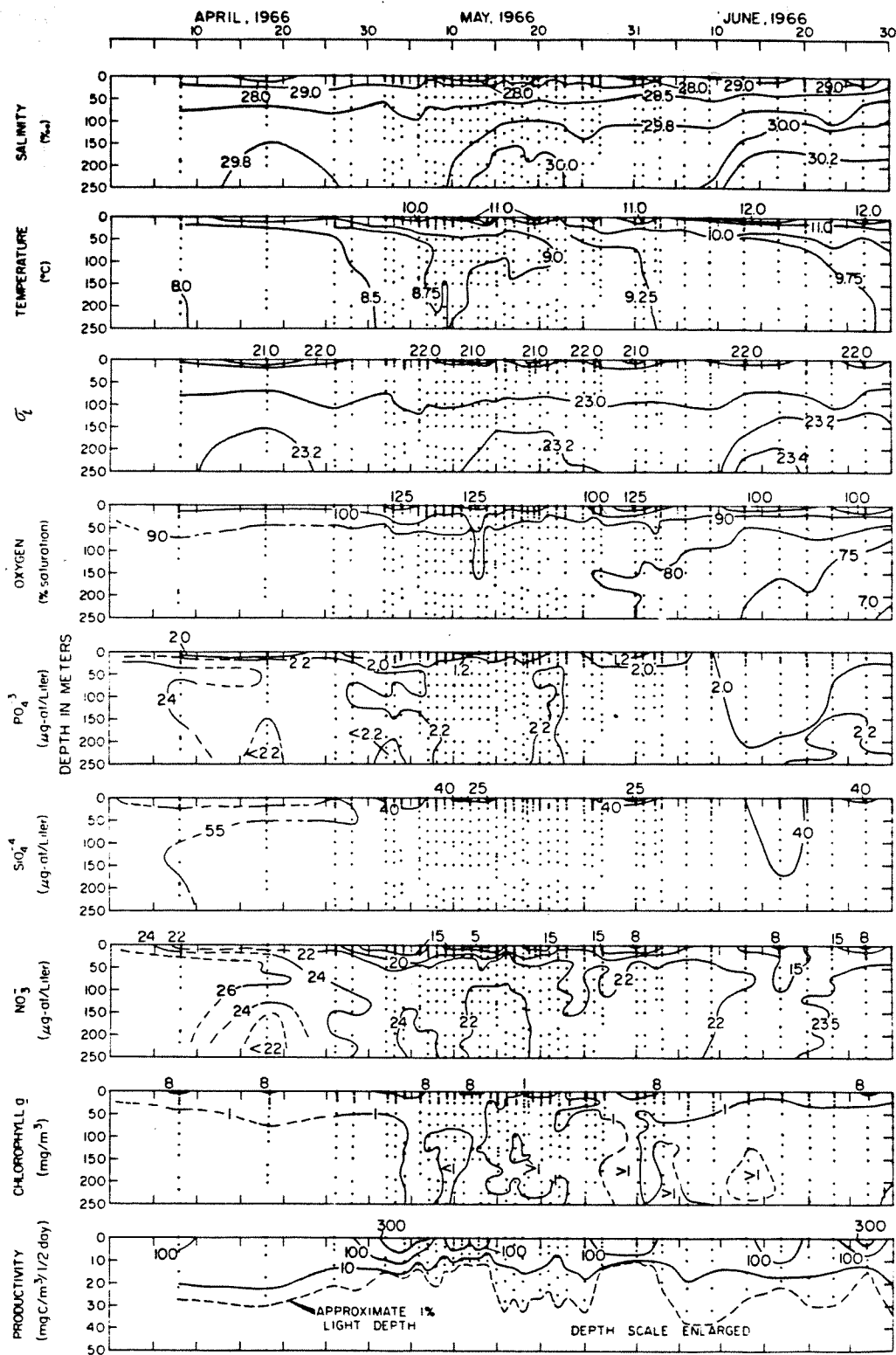
Chlorophyll a concentrations at the mouth of the Duwamish River varied inversely with tidal height (Welch and Isaac 1967). Blooms tended to occur during periods of neap tides, coincident with low river discharge and adequate solar radiation (Santos and Stoner 1972; Welch et al. 1972).

4.1.4 Spatial Variability

The highest surface concentrations of chlorophyll a were found in the center of Elliott Bay and along the shoreline (> 1 ug/l) as shown by direct chlorophyll analysis and by secchi disc readings (Figure 4.2), while the area off Duwamish Head was the center of a surface chlorophyll low (< 0.5 ug/l; Pavlou et al. 1973). During the spring and summer, chlorophyll concentrations reached a maximum at the water surface, except in the vicinity of freshwater sources, where a subsurface maximum was seen (Kroglund et al. 1975). Subsurface chlorophyll concentrations reached a maximum of ≥ 1 ug/l at 5 to 8 meters depth off the mouth of the Duwamish River (Pavlou et al. 1973).

Aerial photographs and water column studies showed that intact patches of

Figure 4.1. Variations of salinity, temperature, density, oxygen saturation, phosphate, silicate, nitrate, chlorophyll a and carbon uptake rate in the main basin of Puget Sound in May-June 1966. Dots indicate sampling depths. After Winter et al. (1975).



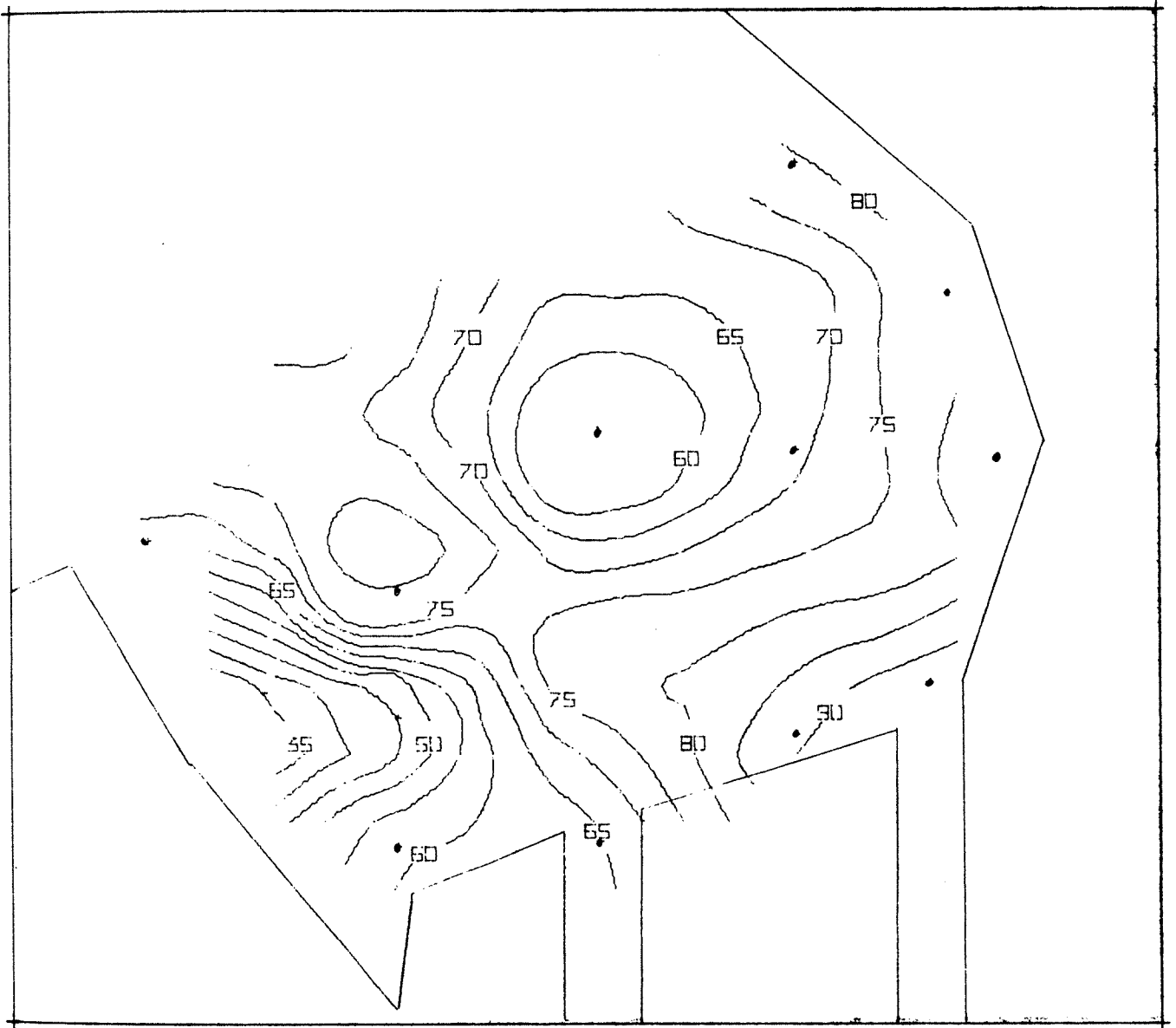


Figure 4.2. Spatial distribution of surface chlorophyll a in Elliott Bay during September, 1972. Chlorophyll is measured in 0.01 mg/l. After Pavlou et al. (1973).

phytoplankton did not travel out of Elliott Bay into the main basin of Puget Sound (Munson 1970). Silt-laden water masses which originate at the Duwamish River were discernible in the main basin (Munson 1970).

4.1.5 Primary Production

Primary production was first measured in January, 1960, in Elliott Bay by Collias and Barnes (1966), but the data were never analyzed. Many productivity experiments have since been performed in the Duwamish River. Welch and Isaac (1967) showed that gross primary production varied inversely with tidal height. Turnover rates for phytoplankton cells have been calculated to be 2.2/day over the 0 to 4 meter interval (Prych et al. 1976) and 0.6/day (0-1 meters), 0.3/day (0-4 meters) (Welch 1968). Harper-Owes (1981) noted that during large phytoplankton blooms carbon dioxide limitation may be approached. Phytoplankton was found to contribute most of the primary productivity occurring in the Duwamish estuary and to control concentrations of dissolved oxygen (Tilley and Haushild 1975). Welch (1969) agreed that phytoplankton controls BOD levels through decomposition and sinking in the Duwamish River. More recently, Harper-Owes (1983) showed that low dissolved oxygen levels in the Duwamish were due to salt wedge water residence time and benthic oxygen demand. Welch (1969) noted a significant correlation between gross production and retention time as determined by freshwater discharge.

Annual primary productivity over the photic zone was significantly lower than that of the main basin of Puget Sound, primarily because of reduced light penetration caused by the silt load in the Duwamish River (Ebbesmeyer and Helseth 1977).

The single station sampled here (METRO station 174) was in the area of lowest phytoplankton standing stock for Elliott Bay (Pavlou et al. 1973) and does not necessarily represent all of Elliott Bay.

Dissolved oxygen concentrations at the surface of Elliott Bay were significantly correlated with integrated primary production (Ebbesmeyer and Helseth 1977).

4.1.6 Nutrient Distributions and Phytoplankton Interactions

Dissolved nutrients occurred at high concentrations throughout the water column in Elliott Bay, with maximum concentrations occurring off the Duwamish River and East Waterway, and decreasing westward out to the main basin of Puget Sound (Pavlou et al. 1973) (Figure 4.3). Typical nutrient concentrations in Elliott Bay are as follows: nitrate: 10-30 ug-at/l, nitrite: 0.01-1.00 ug-at/l, phosphate: 1-2.5 ug-at/l, silicate: 25-60 ug-at/l. The Duwamish River salt-wedge contained up to twice the concentration of dissolved nutrients found in the open bay, due to the settling of particles from river water which bound phosphate and ammonia ions (Tilley and Dawson 1971). Decomposition and settling of phytoplankton cells from the Duwamish River water might have contributed to the accumulation in the salt-wedge (Tilley and Dawson 1971). Duwamish River water had approximately 4 times the nutrient concentrations found in Elliott Bay water (Tilley and Dawson 1971).

Ammonia was the preferred algal nutrient for growth (Dugdale 1976) and was the nutrient in greatest supply in the Duwamish Estuary (Harper-Owes 1981). Ammonia in the surface waters of Elliott Bay reached concentrations of 13 ug-at/l at the mouth of the Duwamish River, decreased to ≥ 1 ug-at/l in the middle of the Bay (Kroglund et al. 1975), and was greatly reduced at 3 meters depth in the vicinity of the river mouth (Pavlou et al. 1973; Figure 4.4).

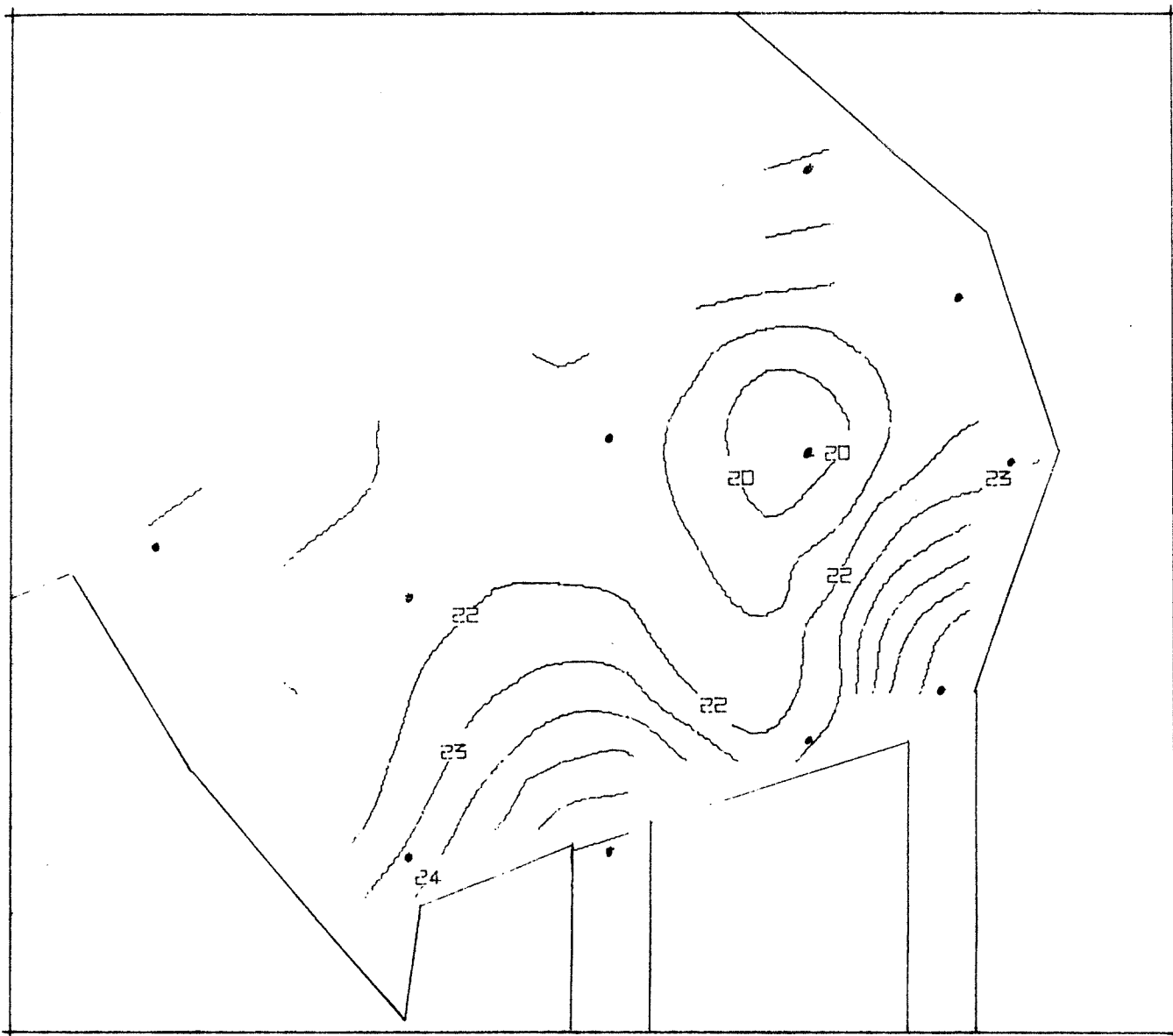


Figure 4.3. Spatial distribution of surface nitrate in Elliott Bay during September 1972. Nitrate is measured in $\mu\text{g-at/l}$. After Pavlou et al. (1973).

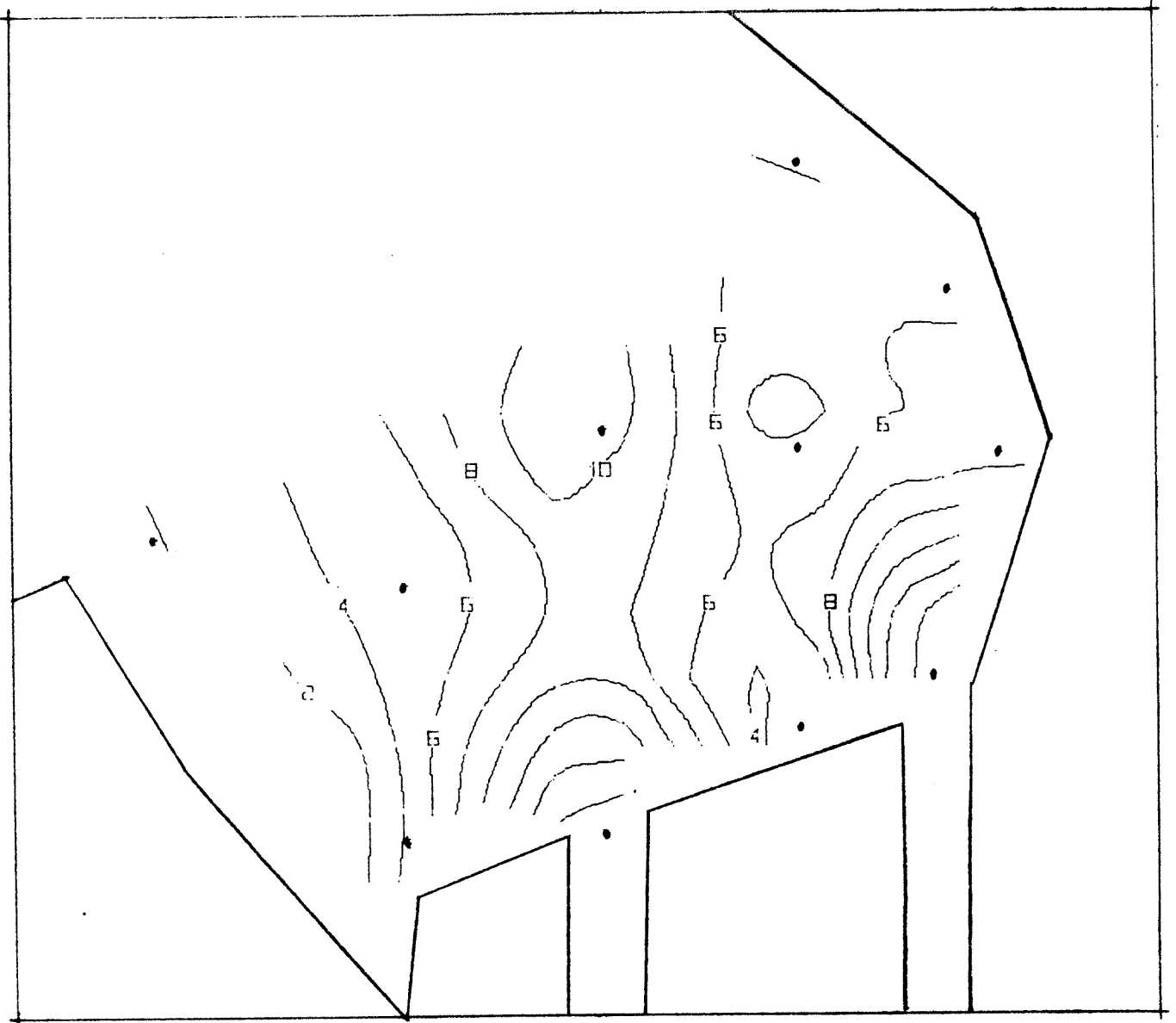


Figure 4.4. Spatial distribution of ammonia at 3 m depth in Elliott Bay during September 1972. Ammonia is measured in $.1 \mu\text{g-at/l}$. After Pavlou et al. (1973).

Total ammonia loading into Elliott Bay from the Duwamish River was calculated to be 5.59×10^8 g nitrogen/yr (Harper-Owes 1983). Highest concentrations of ammonia were found in Elliott Bay in September (Pavlou et al. 1973; Kroglund et al. 1975).

No experiments or observations of nutrient-phytoplankton interactions were found for Elliott Bay. Numerous Duwamish River studies indicated that phytoplankton growth is never nutrient-limited, but rather was controlled by hydrographic conditions and light availability (Welch 1968; Welch 1969; Welch et al. 1972; Brenner 1974; METRO 1980b).

4.1.7 Toxic/Stimulatory Effects on Phytoplankton

There have been no recorded studies of phytoplankton toxicity for Elliott Bay. Welch et al. (1972) noted stimulation of algal growth with water from the mouth of the Duwamish River. Brenner (1974) found similar results with the addition of Renton Treatment Plant effluent, which enters Elliott Bay via the Duwamish River.

4.2 Zooplankton

4.2.1 Zooplankton Species

Aron (1958) reported that 85 - 92% of the macrozooplankton in Elliott Bay, as sampled by pump and nets, were calanoid copepods. Species lists for January resemble closely those of the open main basin of Puget Sound (Aron 1958). An acoustical survey by Cooney (1971) showed a continuous and clearly recorded layer of euphausiids in Elliott Bay. The euphausiid population (made up largely of adult Euphausia pacifica and Thysanoessa raschii) reached peak densities of 800 - 900/m² (E. pacifica) and 10 - 15/m² (T. raschii) in March-April, and were present in Elliott Bay until mid-winter, although the population disappeared from the main basin in October-November (Cooney 1971).

4.2.2 Spatial Distribution

Zooplankton biomass in Elliott Bay was typical of Puget Sound: 0.4 - 0.9 g/m³, wet weight, with higher volumes (>1 g/m³, wet weight) inshore (Pavlou et al. 1973; Figure 4.5). The area around Duwamish Head supported a lower zooplankton biomass than did the rest of Elliott Bay (Pavlou et al. 1973).

4.2.3 Toxicant Interactions with Zooplankton

Elliott Bay zooplankton contained PCB's in concentrations ranging from 10 to 25 ng/g wet weight and DDT concentrations of 1 to 25 ng/g wet weight, with the highest concentrations occurring in animals caught off Duwamish Head (Pavlou et al. 1973).

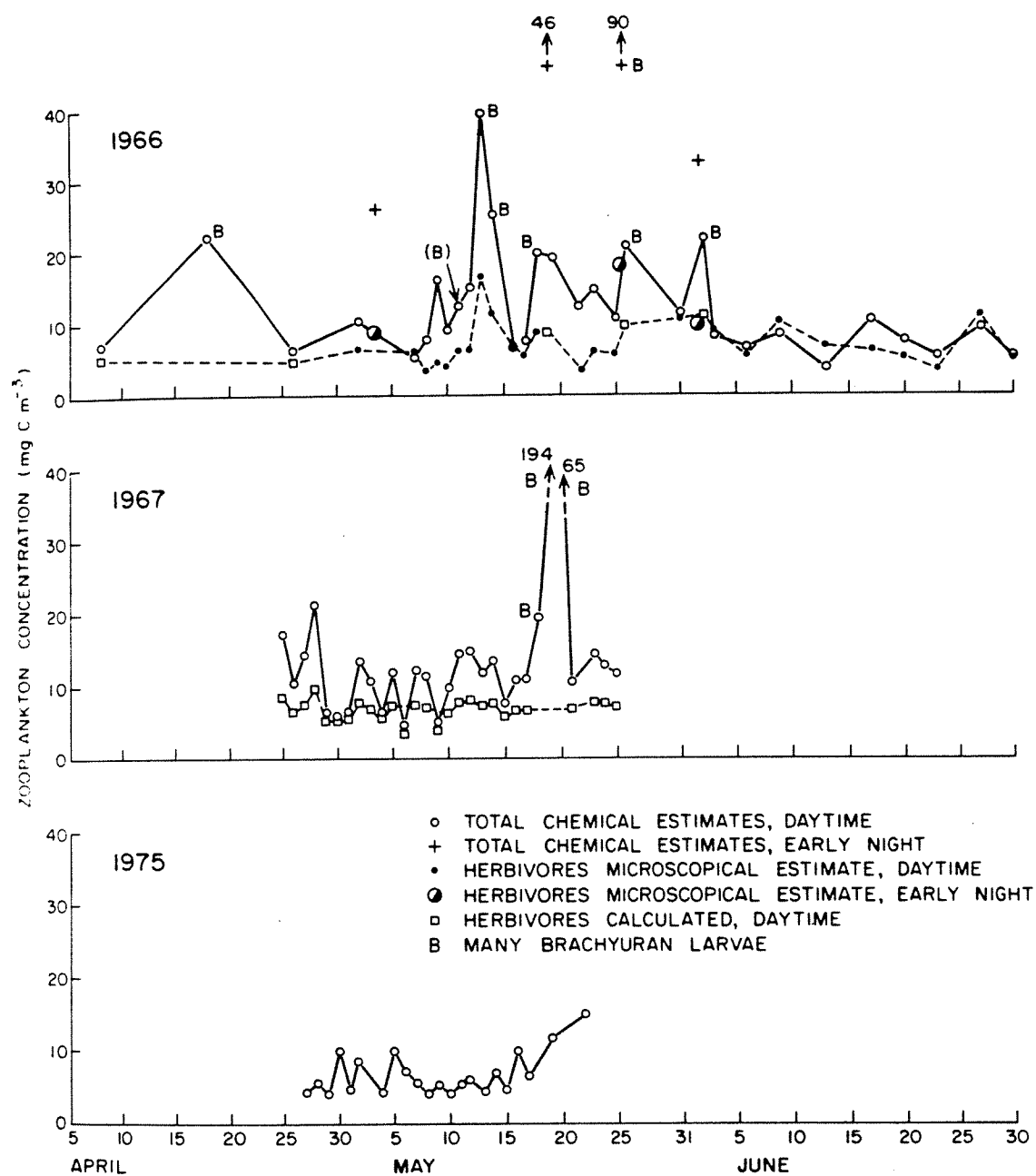


Figure 4.5. Variations in zooplankton biomass estimates in 1966, 1967 and 1975 in the main basin of Puget Sound. Chemical estimates were found by dry weight analysis. After Campbell et al. (1977).

4.3 Nearshore Habitats

The nearshore environment in Elliott Bay consists of the shoreline between West Point and Alki Point (Figure 1.1) and extends vertically from the extreme high water mark down to -50 ft (relative to Mean Lower Low Water, MLLW). Originally this nearshore environment included approximately 850 hectares of eelgrass and marsh habitats. Today these eelgrass and marsh habitats have been reduced to 22 hectares leaving only 2% of these productive habitats present in Elliott Bay. Today this surface area totals approximately 580 hectares, which represents 27% of the total surface area of Elliott Bay. Of this 580 hectares, about 135 hectares (23.2%) are above MLLW, 207 hectares (35.7%) are between MLLW and -20 ft MLLW, and 237.9 hectares (41.0%) are between -20 and -50 ft MLLW. The area in hectares for each depth range for the four geographical areas of Elliott Bay is shown in Figure 4.6. Harbor development (i.e., piers, piling, rip rap) occurs primarily between Duwamish Head and Pier 91, and has the least nearshore surface area. The shoreline between Fourmile Rock and West Point contains the largest proportion of very shallow (i.e., intertidal to -20 ft MLLW) bottom surface area.

The areas occupied by the major nearshore habitats in Elliott Bay was estimated using various data (Armstrong 1977; Thom 1978; Staude 1979; Armstrong et al. 1978; Thom and Chew 1980; Port of Seattle unpubl. data; Phillips 1972; R. Harman and J. Serwold unpubl. data; R. Thom personal observations), and appear in Figure 4.7. The proportions of the total nearshore area representing each habitat are: piling 5.0%; sand and sandy mud 71.7%; cobble and boulder 4.8%; rip rap 5.8%; eelgrass 4.2%; and kelp beds 8.5%. Kelp (*Nereocytis luetkeana*) is common in the northern portion of Elliott Bay, with a dense bed located at the base of Magnolia Bluff. Phillips (1972) described an eelgrass (*Zostera marina*) meadow on the north side of Alki Point. Rip rap walls and piers supported by pilings predominate from Duwamish Head to Magnolia Bluff. Cobble and boulder fields occur at the base of Magnolia Bluff. Medium textured sand comprises the bulk of nearshore surface area in all other regions except the industrialized portion of Elliott Bay. Extensive depositional areas occur from West Point to Pier 91, and from Duwamish Head to Alki Point. Sediments at Duwamish Head are somewhat finer than those further west and north (Harman and Serwold 1974, R. Thom, personal observation).

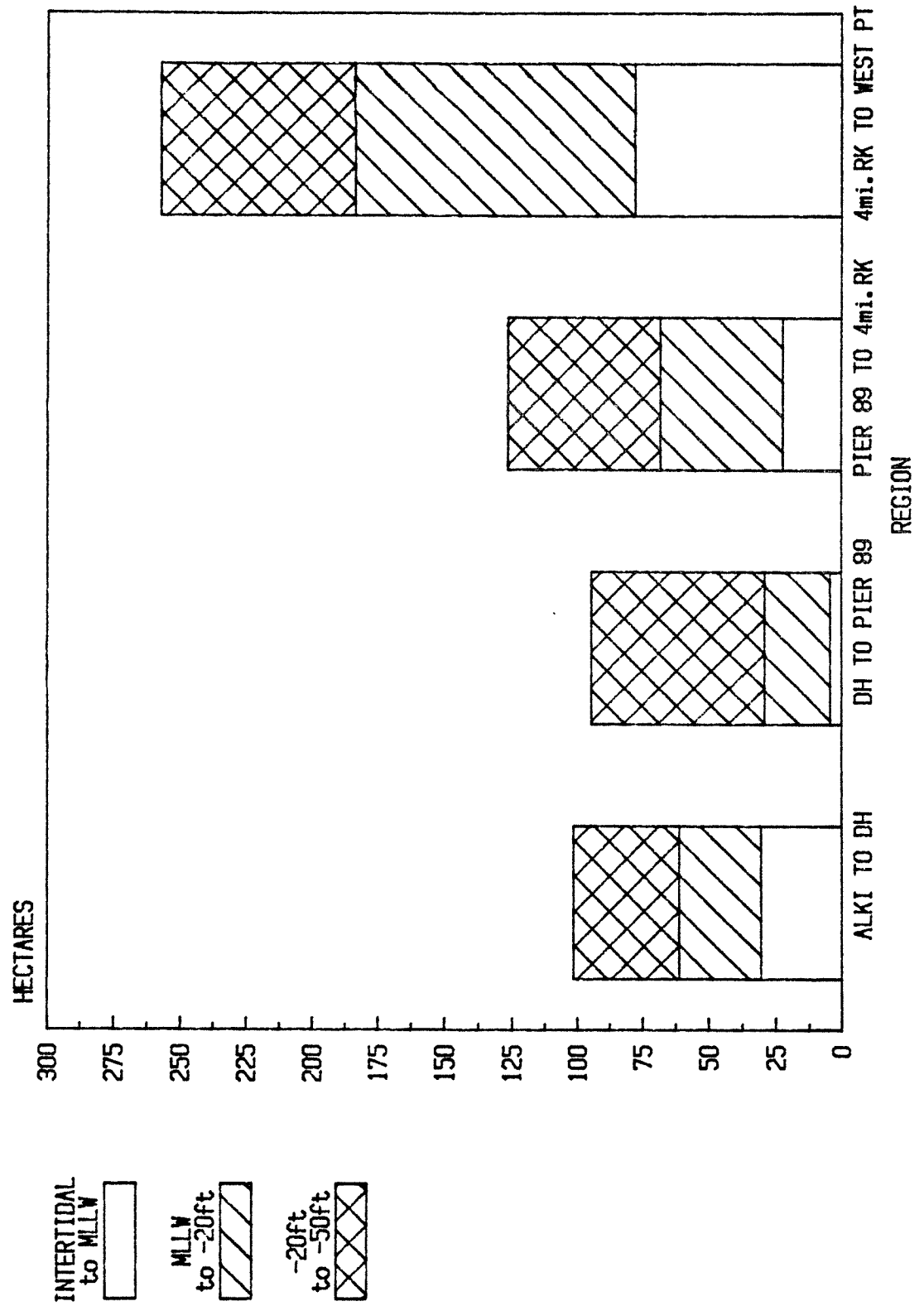
Chew et al. (1971; 1973); Armstrong (1977); Thom (1978); and Staude (1979) described the intertidal substrate and habitat distribution between West Point and a point approximately 600 m south of West Point. The region immediately south of West Point consisted primarily of a gently sloping coarse sand beach with a median grain size of 0.19-0.24 mm (Staude 1979). Qualitative observations (Harman and Serwold, unpubl. data) were made along a number of intertidal transects located in the West Point-Magnolia Bluff region and in the Duwamish Head - Alki Point region. Transect profiles indicated that gently sloping sand beaches near West Point grade to more steeply sloping cobble-boulder fields at Magnolia Bluff. The area between Smith Cove and Pier 70 was largely a steeply sloping rip rap wall with a sessile, rocky intertidal assemblage (Armstrong et al. 1978). Rip rap along with pier piling predominated throughout the remainder of the eastern and southern shoreline. At Duwamish Head, a gently sloping sand beach existed. The beach slope generally increased west of this point. At Alki Point, the beach was moderately sloping (i.e., approximately a 1 ft. vertical rise for a horizontal distance of 20 ft.) and consisted of large cobble.

The benthic biota in the shallow subtidal habitats at Magnolia Bluff

Figure 4.6. The nearshore surface areas in Elliott Bay by depth intervals and shoreline segments (Alki Point to Duwamish Head, Duwamish Head to Pier 89, Pier 89 to Four Mile Rock, and Four Mile Rock to West Point).

NEARSHORE AREAS IN ELLIOTT BAY

FROM NOAA CHART 18449



HABITATS IN ELLIOTT BAY INTERTIDAL TO -50ft

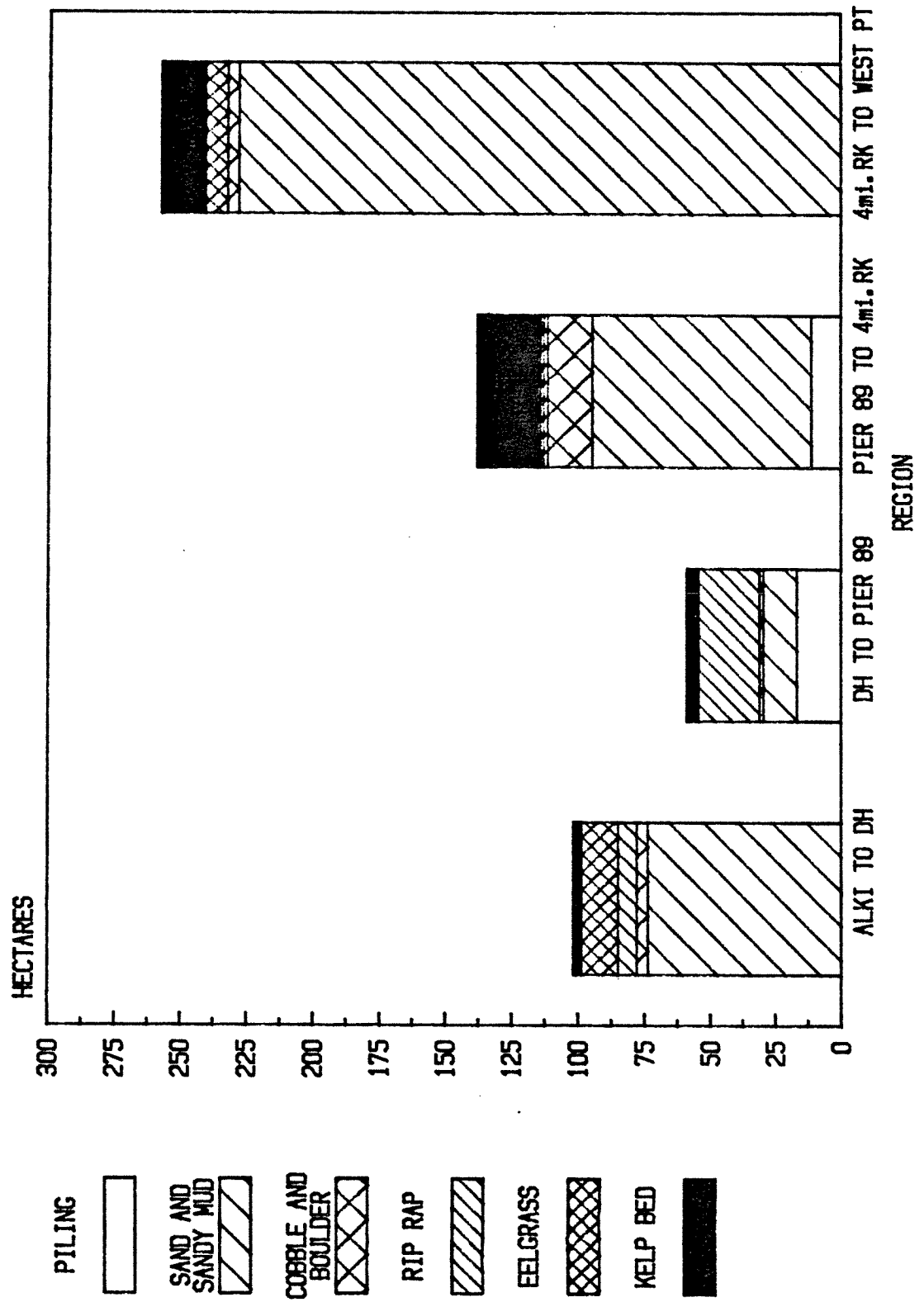


Figure 4.7. Surface areas of intertidal habitat types by shoreline segments in Elliott Bay to -50 feet.

consisted primarily of cobble-boulder and kelp bed assemblages (Shapiro and Associates 1983). Smith Cove is a protected embayment containing two piers supported by pilings that are set in rip rap (J. Dohrman; Port of Seattle; person. commun.). The north and south shores of the cove were gently sloping sand beaches. Some cobble-boulder substrata existed on the southern shoreline (Mauseth and Associates 1980). Few data describe the developed portion of Elliott Bay between Pier 70 and Duwamish Head. The shoreline in this region is dominated by piers supported by wood piling. Bulkheads of rip rap lie underneath and between the piers.

Intertidal habitats between Duwamish Head and the Alki Point Lighthouse appear in Figure 4.8. This region is depositional, and observations on fish catches and those made during diving surveys indicate that the nearshore habitat is highly productive (Pierson, personal communication). The eelgrass meadow studied by Phillips (1972) and the broad sandflats represent major nearshore habitats of biological significance.

4.3.1 Nearshore Benthic Assemblages

All habitats in Figure 4.7 play roles in the Elliott Bay-Duwamish River estuary. Kelp beds and eelgrass meadows contain a rich assemblage of flora and fauna (Thom 1978; Thayer and Phillips 1977). Carbon fixation and detritus production are high in these habitats (Thom 1978, 1981). Sand flats contain associated microflora, and abundant assemblages of meiofauna and macroinfauna (Thom et al., 1983; McIntire et al., 1983). Epibenthic meiofauna, in particular, are important as food for bottom feeding organisms such as juvenile salmonids (Simenstad and Eggers 1981). Cobble habitats in mid-intertidal to subtidal depths provide habitat for bivalves. Rip rap, beams and pilings have an attached assemblage of invertebrates and algae (Mauseth and Associates 1980). The results of the nearshore benthic studies listed in Table 4.1 indicated that the expected assemblages do exist in their respective habitats in Elliott Bay and the Duwamish River estuary.

Quantitative data describing benthic nearshore assemblages were few and limited to the northeastern shoreline of Elliott Bay. Chew et al. (1971, 1973), Armstrong (1977), Thom (1978) and Staude (1979) described the benthic assemblages near West Point. Armstrong (1977) and Thom (1978, 1983) published data describing the benthic intertidal biota of Alki Beach south of Alki Point. Within the Duwamish estuary, Leon (1980) documented the benthic macrofauna species abundances in sand and mud substrata near Kellogg Island. Kellogg Island is an undeveloped intertidal sand-mud flat area and associate marsh.

The most comprehensive works describing the nearshore benthic biota in the region are Armstrong (1977) and Thom (1978). Their studies were conducted at six beaches (i.e., Richmond Beach, Carkeek Park Beach, West Point Beach, the Denny Way CSO, Alki Beach south of Alki Point, and Lincoln Park Beach) on the eastern shore of central Puget Sound, and included extensive quantitative, seasonal sampling of the benthic flora and fauna over a two year period. The data of Armstrong and Thom are used here to indicate the species assemblages and temporal patterns in assemblage structure that may be expected in Elliott Bay.

Approximately 160 taxa of macroscopically evident benthic algae were encountered on the eastern shore of central Puget Sound (Appendix 2). Of these, 40 taxa were green algae, 27 species were brown algae, and 78 species were red algae. The most frequently occurring genera of macroalgae were Enteromorpha, Spongomorpha, Ulva, Ceramium, Polysiphonia, and Porphyra.

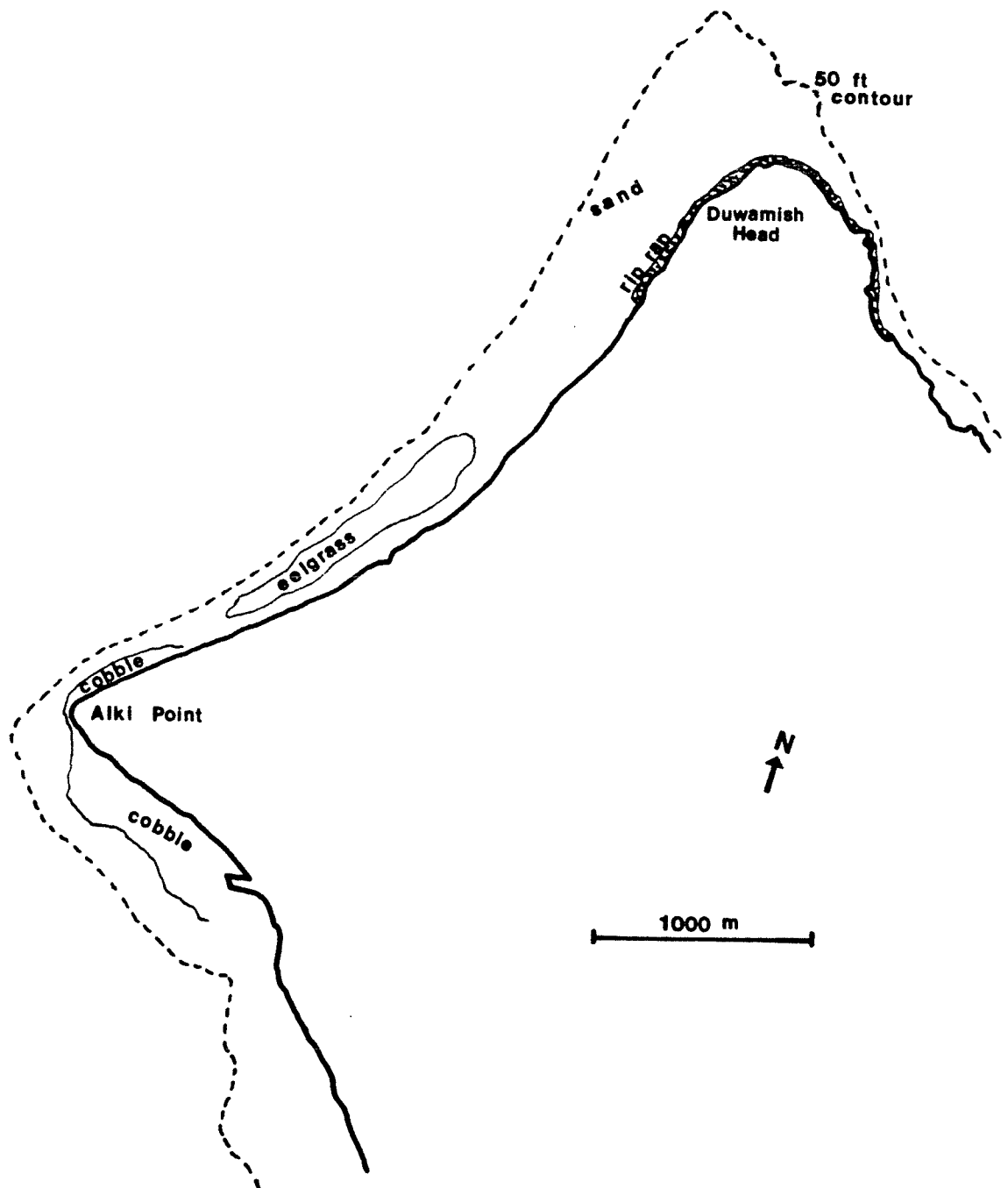


Figure 4.8. Nearshore habitats in the Alki Beach-Duwamish Head area.

Table 4.1. Literature describing the nearshore benthic biota in Elliott Bay and the Duwamish River estuary.

Author(s) and Date	Elliott Bay and Duwamish River study area	Subject of study	Utility as nearshore baseline data
Armstrong (1977)	West Point, Alki Point	Infauna	Moderate
Armstrong et al. (1976)	West Point, Alki Point	Infauna, epifauna	Moderate
Armstrong et al. (1978)	Denny Way CSO	Infauna, epibiota	High
Armstrong et al. (1980-81)	Denny Way CSO	Infauna	High
Chapman et al. (1982)	Elliott Bay, Duwamish River	Oligochaetes, amphipods sediment (toxicity tests)	High
Chew et al. (1971)	West Point	Infauna, epibiota	Moderate
Chew et al. (1973)	West Point	Infauna, epibiota	Moderate
Chia (1969)	Alki Point	Sand dollar	Low
Dexter et al. (1981)	Elliott Bay, Duwamish River	All benthos	Moderate
Harman and Serwold (1974)	Elliott Bay	Infauna, microbiota, sediments	Moderate
Leon (1980)	Kellogg Island, Duwamish River	Infauna	High
Malins et al. (1982)	Elliott Bay, Duwamish River	Infauna, fish	Moderate
Mauseth and Associates (1980)	Smith Cove to East Waterway	Infauna, epibiota	Moderate
Meyer et al. (1981)	Duwamish estuary	Epibenthic zooplankton, fish	Moderate

Table 4.1. (continued).

Author(s) and Date	Elliott Bay and Duwamish River study area	Subject of study	Utility as nearshore baseline data
Phillips (1972)	Alki Beach	Eelgrass	Moderate
Shapiro and Associates (1983)	Magnolia Bluff	Infauna, epibiota	Moderate
Staude (1979)	West Point	Infauna, epibiota	Moderate
Thom (1978)	West Point, Denny Way CSO, Alki Point	epibiota, algae	Moderate
Thom (1983)	Alki Point	<u>Fucus</u>	Moderate
Thom et al. (1976)	West Point, Alki Point	Benthic algae	Moderate
Thom and Chew (1980)	Denny Way CSO	Infauna	High
Tilley and Haushild (1975)	Duwamish estuary	Periphyton	Moderate
Tomlinson et al. (1980)	Denny Way CSO	Benthic animals, plants, sediment, water column	High

Species that were characteristic components of the nearshore environment were Enteromorpha linza, Ulva lactuca, U. fenestrata, Fucus distichus (= F. evanescens), Laminaria saccharina, Nereocystis luetkeana, Petalonia fascia, Sargassum muticum, Scytosiphon lomentaria, Gigartina exasperata, G. papillata, Iridaea cordata, and Pterosiphonia bipinnata.

Seasonal changes in benthic macroalgal assemblages were striking. Mean algal cover was greatest in spring and summer, and least in winter (< 10%) (Figure 4.9). Species richness followed this trend, however, there were seasonal differences in fluctuations in the number of taxa present among algal divisions (Figure 4.10). The typical pattern observed was as follows: there was a winter low in all divisions. Between January and April, species richness increased in all divisions and brown algal richness reached its highest value. Green algal species richness peaked in summer (July), which was followed by a peak in red algal species richness in autumn (October). Diatoms were evident as tufts and filaments on hard substrata, and were abundant during spring (Figure 4.11). Periphyton (primarily diatoms) abundance and species richness seasonality was pronounced (Figure 4.12). One hundred and fifteen taxa of diatoms were encountered in periphyton samples, and were dominated in relative abundance by Cocconeis spp., Synedra tabulata, Achnanthes cocconeoides, Rhabdonema arcuatum, Biddulphia aurita, and Navicula spp. (Table 4.2).

Spatial variations are great in benthic algal assemblages. Thom (1978) identified 10 intertidal species assemblages using cluster analysis. A distinct subtidal kelp bed assemblage was also delineated that consisted of a dense canopy of Nereocystis luetkeana and a rich and abundant understory (Table 4.3). Algal abundance and species richness generally increased with decreasing elevation, and reached a maximum at intertidal to shallow subtidal depths (Figure 4.13). The perennial brown fucoid, Fucus evanescens, formed a dense bed in the upper intertidal zone. The mid-low intertidal zone contained a dense assemblage of bladed green algae (Ulva spp., Monostroma spp.). At lower elevations brown algae, such as Sargassum muticum and Laminaria saccharina, and the red alga Iridaea cordata predominated.

Several factors are probably responsible for spatial patterns in algal assemblages. Based on a correlation analysis, elevation, substrata composition and exposure to sewage effluent exhibited the greatest number of significant correlation coefficient values with assemblage parameters (Table 4.4).

Algal growth rate (Thom 1978) and productivity (Thom 1983, Thom et al. 1983) estimates indicate that the benthic algal assemblages in central Puget Sound rank among the most productive aquatic systems in the world.

Approximately 300 taxa of benthic macrofauna were recorded by Armstrong (1977) at five central Puget Sound beaches (Appendix 3). The number of taxa varied somewhat (195-231) among the beaches and averaged 213 (Table 4.5). The number of taxa unique to a beach was small, and varied from 2-9% of the total number.

The most abundant taxa of epifauna consisted of barnacles (Balanus spp.), flabelliferan isopods, snails (Collisella strigatella, Lacuna variegata) and amphipods (Table 4.6). Infauna were predominated by polychaetes, of which Mediomastus capensis, Owenia fusiformis, and Micropodarke dubia were the most abundant (Table 4.7). Infauna bivalves were also abundant, especially in sediments containing large cobble. Macoma spp. occurred in all sediment types. Protothaca staminea, Saxidomus giganteus, and Tresus capax were abundant in cobble-boulder habitats (Table 4.8). This latter habitat is frequented by recreational clam diggers. The amphipod fauna is rich in

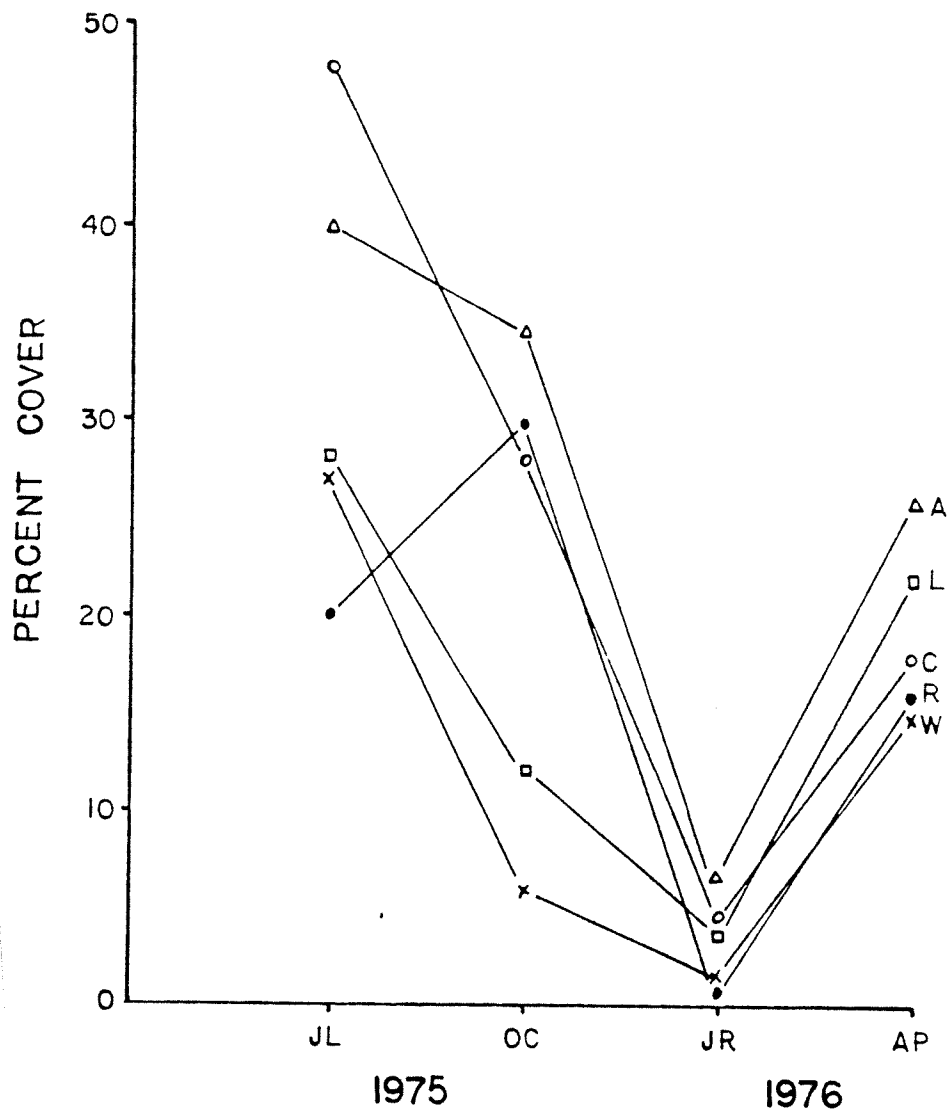


Figure 4.9. Average algal cover. (Beaches: A = Alki Point; L = Lincoln Park; C = Carkeek Park; R = Richmond Beach; W = West Point.) After Thom (1978).

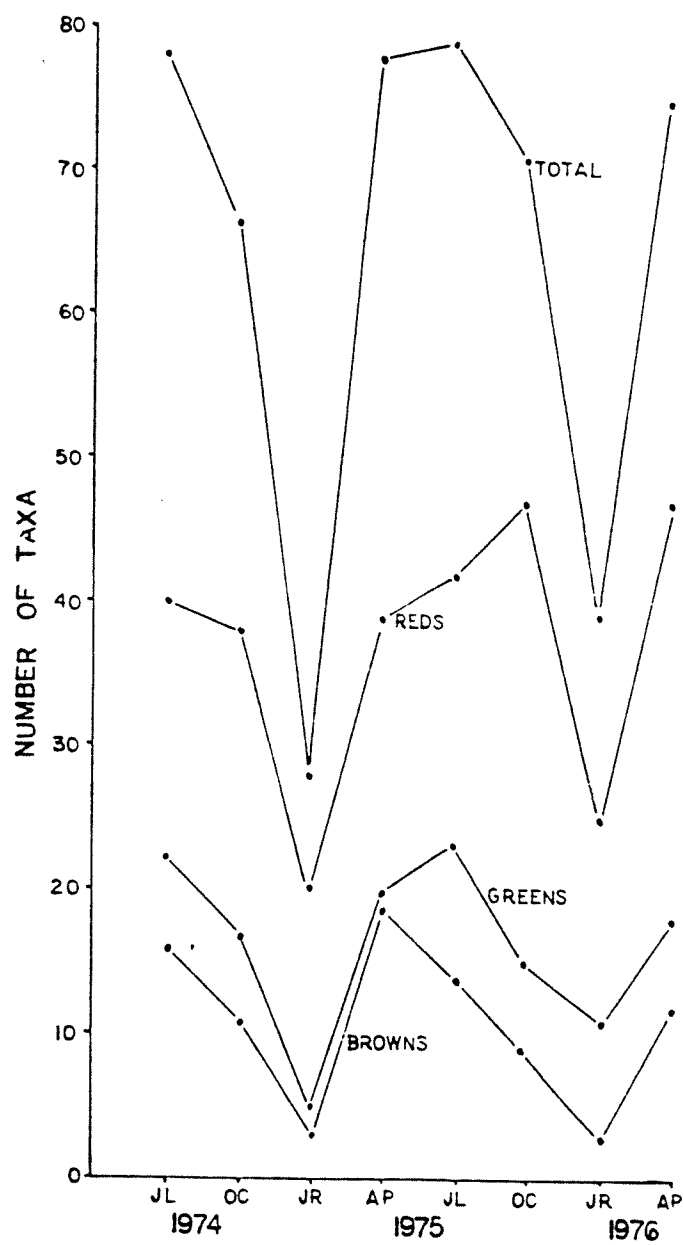


Figure 4.10. Seasonal change in number of macroalgal species over all beaches. After Thom (1978).

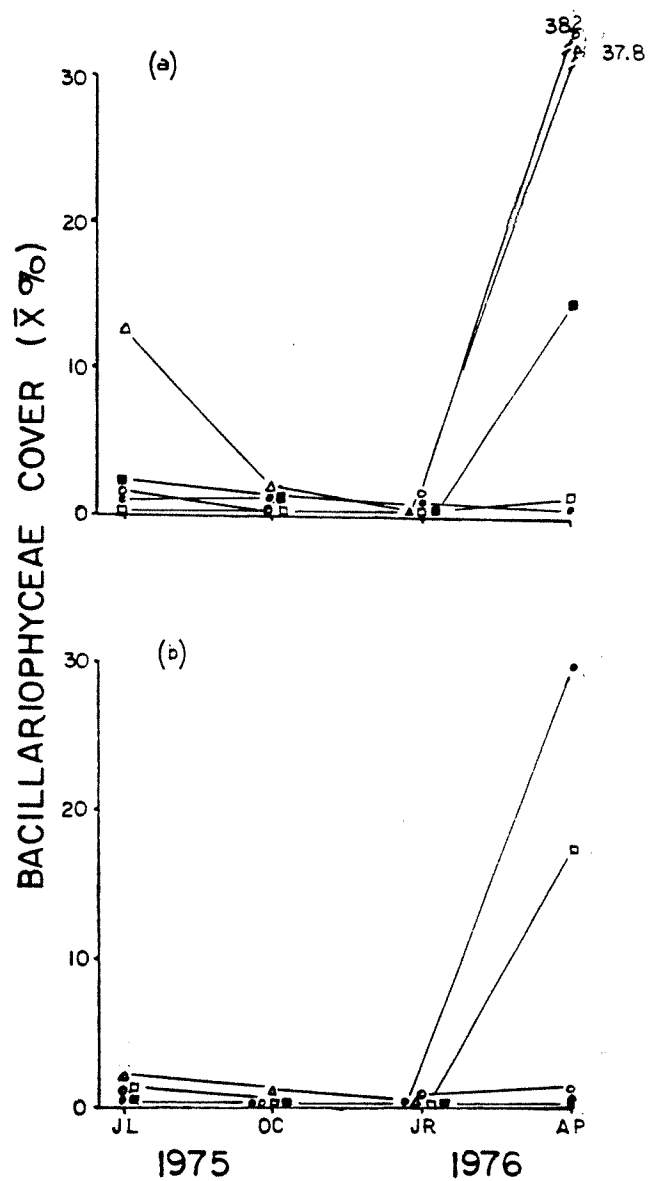


Figure 4.11. (a), (b) seasonal variation in diatom cover. After Thom (1978).

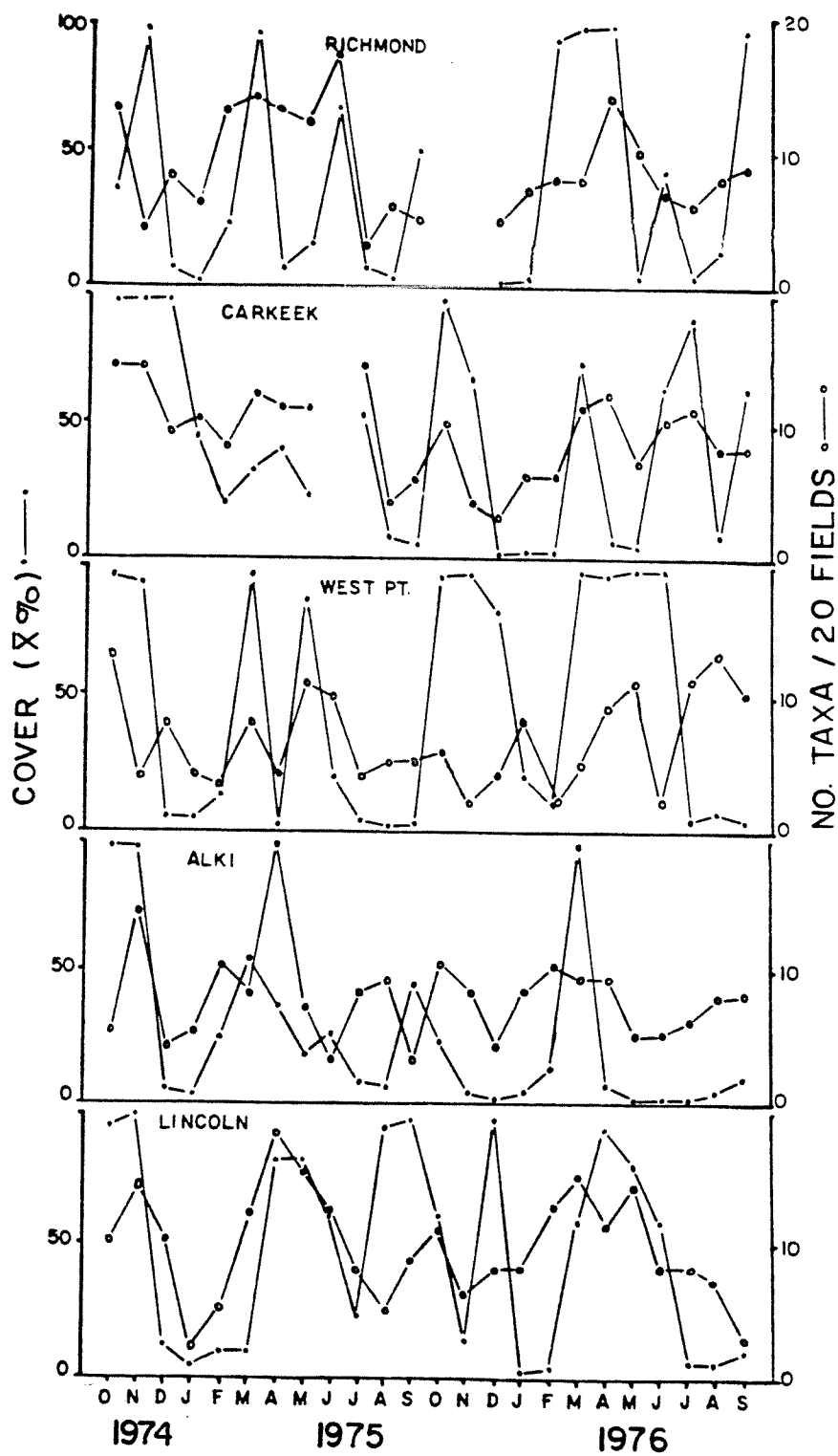


Figure 4.12. Variation in cover and number of taxa on the one month periphyton plates. After Thom (1978).

Table 4.2. Relative abundance of the 10 most abundant diatom species each season at West Point (W), Alki (A) and Lincoln Park (L). After Thom (1978).

[VA = very abundant >41 cells; A = abundant = 21-40 cells; C = common = 11-20 cells; R = rare = 1-10 cells; - = absent.]

Species	1974			1975			1976		
	October	January	April	July	October	January	April	July	
	W A L	W A L	W A L	W A L	W A L	W A L	W A L	W A L	
<u>Cocconeis californica</u>	VA C VA	VA VA A	C R C	VA VA VA	VA VA VA	VA R VA	- R R	VA VA VA	VA
<u>Synedra tabulata</u>	C C VA	- R A	VA VA VA	R R -	- R A	- VA C	R VA VA	- R R	R
<u>Cocconeis costata</u>	R C VA	VA VA VA	- C A	R C C	VA C VA	VA C VA	C A C	R - -	-
<u>Cocconeis scutellum</u>	- R R	- - R	R R -	R VA R	A VA R	VA C A	R C R	R VA R	R
<u>Cocconeis stauroneiformis</u>	- R C	VA C A	- C C	R C R	A R -	R R A	R R C	R R R	VA
<u>Achnanthes cocconeoides</u>	R - -	R - C	R R R	VA R A	C - R	C C A	R R R	C - R	R
<u>Rhabdonema arcuatum</u>	A VA -	- - -	- - -	- - -	- - -	- A -	- - -	- - -	-
<u>Biddulphia aurita</u>	VA R C	- - R	R R R	- - -	- - -	- C R	- - -	- R R	R
<u>Navicula sp. 39</u>	- - -	- - R	R R VA	R R R	R - C	R C R	C R R	R - -	-
<u>Navicula sp. 10</u>	- - -	- - -	- A R	R A R	R - -	- R R	VA C C	R - R	R

Table 4.3. Five most abundant species in understory (using biomass) within each portion of the bed.
After Thom (1978).

POSITION IN BED						
<u>Inner</u>		<u>Mid</u>	<u>Outer</u>			
LINCOLN	WEST PT.	LINCOLN	WEST PT.	LINCOLN	WEST PT.	
1.	<u>Laminaria</u> <u>saccharina</u>	<u>Ulva</u> <u>expansa</u>	<u>Laminaria</u> <u>saccharina</u>	<u>Iridaea</u> <u>cordata</u>	<u>Costaria</u> <u>costata</u>	<u>Ulva</u> <u>expansa</u>
2.	<u>Ulva</u> <u>expansa</u>	<u>Ulva</u> <u>fenestrata</u>	<u>Microcladia</u> <u>borealis</u>	<u>Gigartina</u> <u>californica</u>	<u>Laminaria</u> <u>saccharina</u>	<u>Gigartina</u> <u>papillata</u>
3.	<u>Ulvaria</u> <u>obscura</u>	<u>Iridaea</u> <u>cordata</u>	<u>Enteromorpha</u> <u>linza</u>	<u>Ulva</u> <u>fenestrata</u>	<u>Desmarestia</u> <u>ligulata</u> <u>var. firma</u>	<u>Iridaea</u> <u>cordata</u>
4.	<u>Ulva</u> <u>fenestrata</u>	<u>Gigartina</u> <u>papillata</u>	<u>Ulva</u> <u>lactuca</u>	<u>Laminaria</u> <u>saccharina</u>	<u>Gigartina</u> <u>californica</u>	<u>Gigartina</u> <u>californica</u>
5.	<u>Prionitis</u> <u>lanceolata</u>	<u>Ulva</u> <u>lactuca</u>	<u>Odonthalia</u> <u>floccosa</u>	<u>Ulva</u> <u>expansa</u>	<u>Ulva</u> <u>expansa</u>	<u>Antitham-</u> <u>nionella</u> <u>glandulifera</u>

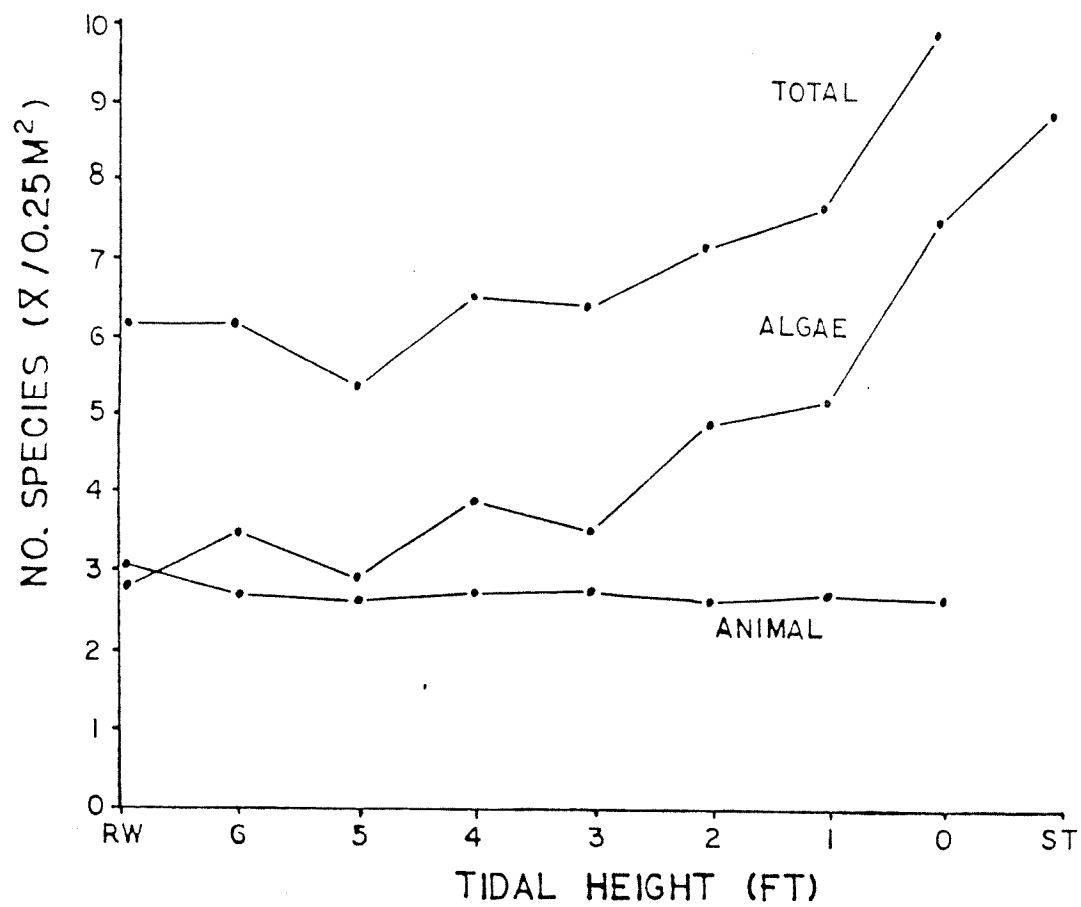


Figure 4.13. Average number of species in the $0.25m^2$ quadrats over tidal height. After Thom (1978).

Table 4.4. Correlations between biological and physical parameters at the 49 sites.
After Thom (1978).

	Tidal Height	Slope	Exposure	Sewage	Rock Shelf	Cobble	Gravel	Sand
Tidal Height	1.00							
Slope	-	1.00						
Exposure	-	-.05	1.00					
Sewage	-	-.66	.30	1.00				
Rock Shelf	-.12	-.18	-.01	.15	1.00			
Cobble	.11	.60	-.06	-.38	-.46	1.00		
Gravel	.11	-.48	.03	.46	-.28	-.31	1.00	
Sand	-.15	-.17	.04	-.01	-.34	-.43	-.09	1.00
Total Species	-.42	.38	-.20	-.52	.48	.10	-.55	-.26
Total Algal Species	-.56	.19	-.12	-.34	.54	-.04	-.48	-.18
Total Animal Species	.22	.63	-.23	-.69	-.02	.42	-.35	-.27
Algal Cover	-.46	-.21	-.08	-.13	.40	-.22	-.12	-.05
Animal Cover	.10	-.09	.08	-.02	.13	-.04	.12	-.24
No. Herbivores	.14	.59	-.37	-.44	-.03	.51	-.14	-.51
Chlorophycophyta Cover	-.44	.06	.05	-.01	.22	-.15	-.11	.07
Phaeophycophyta Cover	-.45	.21	-.19	-.37	.43	-.14	-.37	-.04
Rhodophycophyta Cover	-.41	.13	-.13	-.31	.49	.15	-.46	-.35
Diatom Cover	.07	-.19	-.40	-.13	.29	-.16	-.01	-.14
Algal + Animal Cover	-.40	-.28	.01	-.05	.39	-.26	-.02	-.08

Table 4.5. The number of species occurring at the five study beaches by major taxon. After Armstrong (1977).

Taxon	<u>Number of species per beach</u>				
	Richmond	Carkeek	West Point	Alki	Lincoln
Coelenterates	6	6	5	7	7
Annelids	75	64	73	64	73
Molluscs (total)	44	43	51	51	48
Bivalves	20	20	20	20	18
Gastropods	13	13	15	14	14
Nudibranchs	4	5	9	8	8
Arthropods (total)	59	53	73	65	67
Isopods	9	8	11	10	10
Gammarid Amphipods	19	19	26	24	26
Decapods	19	15	23	19	21
Echinoderms	5	7	8	9	11
Fish	4	5	7	5	8
# species/beach	206	195	230	203	231
# species unique to each beach	8	8	16	5	21

Table 4.6. The numbers of the most abundant epifaunal species subsampled from two mixed-sediment, zero tide height sites at each beach. After Armstrong (1977).

"Species"	Number (rank) collected per beach				
	Alki	Carkeek *	Lincoln	Richmond	West Point
Annelida					
Polychaeta					
<u>Platynereis</u>					
<u>bicanaliculata</u>	40 (9.5)	19 (6)	8 (11)	216 (4)	124 (4)
Arthropoda					
Crustacea					
Amphipoda					
<u>Allorchestes</u>					
<u>angustus</u>	115 (6)	5 (8)	86 (5)	0	32 (8)
<u>Amphithoe simulans</u>	40 (9.5)	3 (9)	46 (7)	6 (9.5)	54 (7)
<u>Caprella</u>					
<u>laeviuscula</u>	53 (7)	72 (4)	6 (12)	159 (6)	23 (11)
<u>Hyale frequens</u>	50 (8)	0	254 (4)	2 (11)	12 (9)
<u>Pontogeneia</u>					
cf. <u>ivanovi</u>	9 (12)	2 (10)	13 (10)	14 (8)	22 (10)
Isopoda					
Flabelliferan					
isopods	324 (2)	77 (3)	52 (6)	82 (7)	183 (3)
Idotea					
<u>wosnesenskii</u>	17 (11)	1 (11)	23 (9)	6 (9.5)	11 (12)
Thoracica					
<u>Balanus crenatus</u> &					
<u>Balanus glandula</u>	614 (1)	209 (1)	2323 (1)	1587 (1)	1010 (1)
Mollusca					
Bivalvia					
<u>Mytilus edulis</u>	191 (5)	50 (5)	25 (8)	318 (3)	117 (5)
Gastropoda					
<u>Collisella</u>					
<u>strigatella</u>	275 (3)	9 (7)	243 (3)	191 (5)	64 (6)
<u>Lacuna ?variegata</u>	216 (4)	152 (2)	815 (2)	1015 (2)	834 (2)
Total	1944	599	3894	3596	2486

* only one site was sampled at Carkeek beach

Table 4.7. The most abundant polychaete species collected with a 1.0 mm mesh screen at various tidal levels. After Armstrong (1977).

Species	Percent of all polychaete species collected at each tide height (m above MLLW)		
	0	+0.9	+1.8
<u>Mediomastus capensis</u>	18.2	30.3	8.0
<u>Platynereis bicanaliculata</u>	11.0		
<u>Owenia fusiformis</u>	9.8	5.7	
<u>Micropodarke dubia</u>	9.6	5.3	
<u>Armandia brevis</u>	8.2	3.7	
<u>Glycinde picta</u>	5.6	5.5	2.2
<u>Hemipodus borealis</u>	5.4	11.7	15.4
<u>Malacoceros glutaesus</u>	5.0	4.1	
<u>Paraonella platybranchia</u>	4.7	3.4	
<u>Scoloplos armiger</u>	3.1		
<u>Notomastus spp.</u>	2.7	2.0	
<u>Saccocirrus eroticus</u>	2.5		
<u>Capitella capitata</u>	2.1		2.7
<u>Polydora natrrix</u>		2.2	28.1
<u>Protodorvillea gracilis</u>		2.7	21.7
<u>Eteone longa</u>		2.1	3.4
<u>Branchiomaldane vincentii</u>			2.4
<u>Syllis alternata</u>		8.2	2.4
<u>Pygospio elegans</u>			2.1
<u>Spio filicornis</u>		2.1	
Total	87.7	89.0	88.4
‡ Miscellaneous (less than 2% each)	12.3	11.0	11.6
Number of individuals collected	4165	3747	2169
Percent of all individuals collected	41.3	37.2	21.5

Table 4.8. The number and biomass of the numerically dominant species of infaunal bivalves collected with a 6 mm mesh screen at various tide heights. After Armstrong (1977).

Species	The number (and biomass in gm) of bivalves collected at each tide height (m above MLLW)		
	0	+0.9	+1.8
<u>Clinocardium nuttalli</u>	174 (168)	122 (203)	19 (7)
<u>Macoma balthica</u>	22 (7)	44 (7)	50 (7)
<u>Macoma inquinata</u> *	993 (1862)	2723 (3773)	349 (532)
<u>Macoma nasuta</u>	18 (84)	8 (28)	6 (35)
<u>Macoma secta</u>	14 (84)	6 (1)	1 (3)
<u>Protothaca staminea</u>	842 (2352)	1061 (1820)	166 (630)
<u>Saxidomus giganteus</u>	551 (3129)	746 (6783)	59 (189)
<u>Tresus capax</u>	250 (749)	67 (315)	33 (70)
<u>Mya arenaria</u>	3 (2)	26 (21)	117 (364)
<u>Tapes japonica</u>	0	0	34 (119)
<u>Tellina buttoni</u>	69 (10)	14 (3)	6 (1)
Total	2936 (8447)	4817 (12,954)	840 (1957)
Percent per tide level	34.1 (36.2)	56.1 (55.4)	9.8 (8.4)

* a small number of individuals of Macoma incongrua are included with Macoma inquinata

central Puget Sound, with the greatest abundance occurring at lower intertidal elevations (Table 4.9).

Seasonal changes were evident in the benthic macrofauna (Table 4.10). Abundance peaked in October (Table 4.10), and species richness peaked in October and January. Seasonality in abundance is probably related to seasonal changes in reproductive effort as well as changes in substrata quality (Armstrong 1977). Data on major biotic components of the nearshore habitats are summarized in Table 4.11.

4.3.2. Natural and Anthropogenic Changes in Nearshore Habitats and Biota

Development has drastically altered the nearshore environment in and surrounding Elliott Bay and the Duwamish River estuary. Prior to 1890, Elliott Bay included approximately 850 hectares of shallow-water and intertidal sand and mudflats (Hershman et al. 1981). This habitat has been reduced to 22 hectares through filling, dredging and bulkheading (Leon 1980). Water and sediment are contaminated by chemicals in several areas of the region (Armstrong et al. 1980; Dexter et al. 1981). Such changes have been hypothesized to explain the decline in biota utilizing the estuary such as salmonids (Meyer et al. 1981). The largest CSO in the METRO system discharges into the intertidal zone approximately 500 m north of Pier 70. The impact of this discharge on benthic life can be shown in the nearshore habitat for at least 600 m north of the CSO (Armstrong et al. 1978; Thom and Chew 1980; Tomlinson et al. 1980). The commercial harvest of shellfish resources in Elliott Bay has been prohibited for a number of years due to high fecal coliform counts in water and shellfish restricting any use of the resource.

4.4 Benthic Ecology

4.4.1 Sediment Characterization

Sediments present in Elliott Bay ranged from fine grained muds to cobble. The finest sediments occurred in the central bay in the deeper water depths (Figure 4.14) and along the northeastern shore. Sand was present primarily in the Alki Beach intertidal area and in the West Point-Magnolia Bluff area (Figure 4.14). The occurrence of gravel was limited mainly to the subtidal areas off Magnolia Bluff with sporadic occurrence elsewhere in the bay (Figure 4.14). The coarsest sediments were found in the shallower areas between Alki Point and the mouth of the Duwamish River and north of Piers 90 and 91 in the northern portions of the bay.

Specific descriptions of sample sites were published by Comiskey et al. (1983) and Dexter et al. (1982). The shallow water stations around West Point were very sandy, contained little gravel, silt, or clay, and were low in biological oxygen demand, volatile solids, and oil and grease content. The 100 m stations around West Point could be divided into two categories based on the gravel content, the percentage of fine sediments, the concentration of volatile solids, biological oxygen demand, and the concentrations of oil and grease.

The stations around the Denny Way CSO contained a high percentage of gravel and the sediments were heavily contaminated with chemicals. The 20-40 m stations in Elliott Bay contained silty-clay sediments which had high volatile solids, biological oxygen demand, and significant concentrations of oil and grease. The 100 m stations in Elliott Bay and at West Point contained

Table 4.9. The most abundant amphipods gathered from the combined 1.0 mm mesh screen and epifaunal samples at various tide heights. After Armstrong (1977).

Species	Percent of all amphipods collected at each tide height (m above MLLW)		
	0	+0.9	+1.8
<u>Allorchestes angustus</u>	20.2	61.3	77.4
<u>Anisogammarus confervicolus</u>		1.9	12.7
<u>Paramoera</u> undescribed sp.		6.0	4.4
<u>Hyale frequens</u>	13.7	8.1	
<u>Ampithoe simulans</u>	5.2	5.8	
<u>Corophium acherusicum</u>	9.4	5.8	
<u>Pontogeneia</u> cf. <u>ivanovi</u>	3.4	3.3	
<u>Eohaustorius washingtonianus</u>		2.4	
<u>Photis brevipes</u>	16.2	1.2	
<u>Caprella laeviuscula</u>	15.2		
<u>Synchelidium shoemakeri</u>	6.2		
<u>Calliopiella pratti</u>	2.1		
<u>Anisogammarus pugettensis</u>	2.0		
<u>Pontogeneia</u> cf. <u>rostrata</u>	1.2		
<u>Aoroides columbiae</u>	1.0		
Total	95.8	95.8	94.5
Miscellaneous (less than 1% each)	4.2	4.2	5.5
Number of individuals collected	3,227	2,487	2,570
Percent of all individuals collected	39.0	30.0	31.0

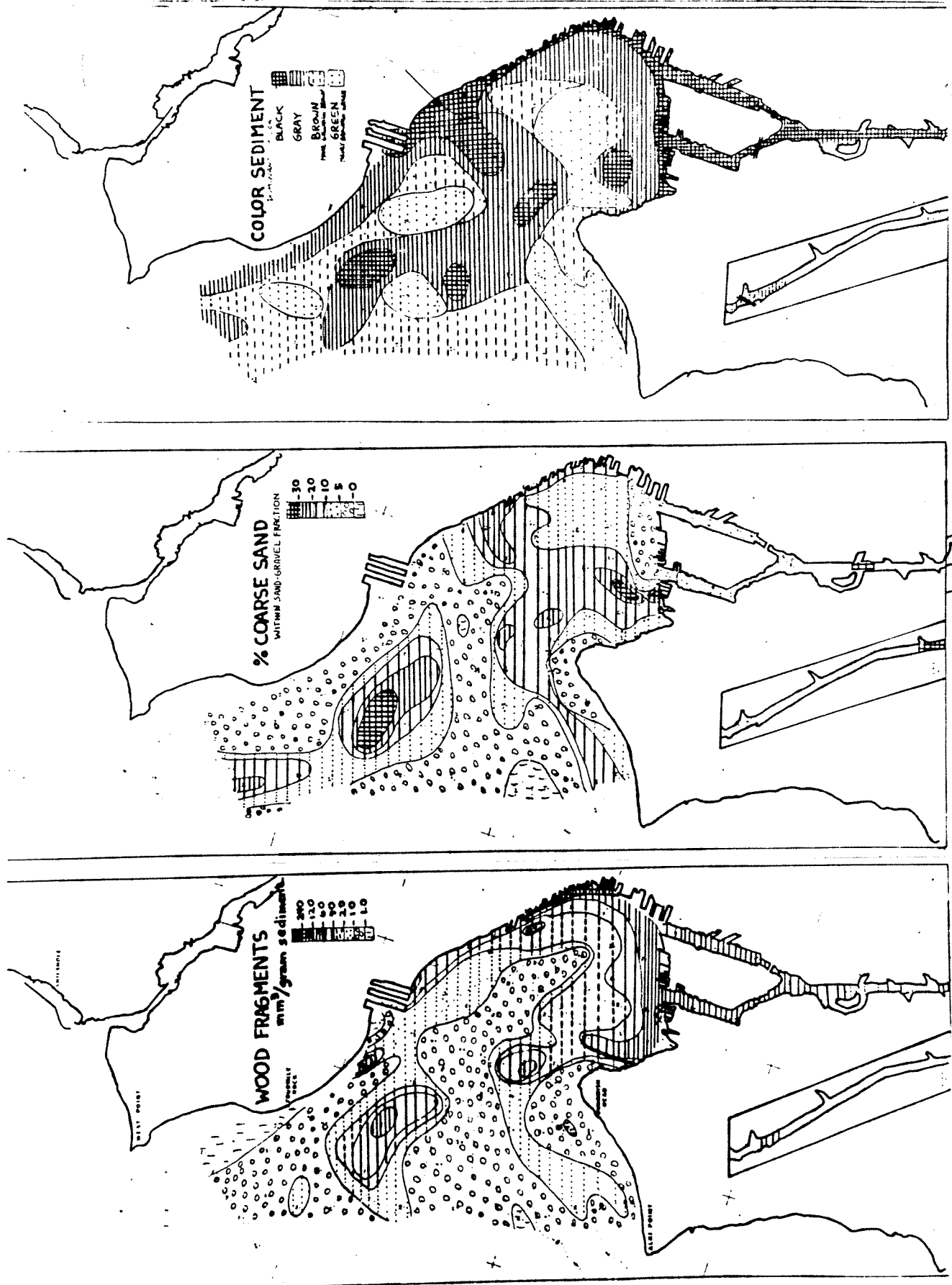
Table 4.10. Seasonal summations of the numbers of individuals collected as epifauna and with the 1.0 mm mesh screen at each tidal level. After Armstrong (1977).

Organisms	Tide height (m above MLLW)	Number collected per month of sampling						Total
		OCT	APR	JUL	OCT	JAN	APR	
Epifauna (excluding amphipods)	0	6,797	1,214	2,428	3,358	2,021	978	16,796
	+0.9	10,749	2,541	4,346	7,532	4,498	2,393	32,059
	+1.8	5,518	810	2,452	3,834	1,611	1,692	15,917
	Total	23,064	4,565	9,226	14,724	8,130	5,063	64,772
Polychaete Infauna (1.0 mm mesh screen)	0	641	427	759	1,196	825	317	4,165
	+0.9	607	393	585	981	669	512	3,747
	+1.8	386	214	297	554	335	383	2,169
	Total	1,634	1,034	1,641	2,731	1,829	1,212	10,081

Table 4.11. Representative benthic taxa in nearshore habitats at Elliott Bay, Seattle, Washington.

HABITAT TYPE					
Piling	Sand and sandy mud	Cobble and boulder	Riprap	Eelgrass	Kelp
<u>Enteromorpha spp.</u>	Diatoms	<u>Ulva spp.</u>	<u>Enteromorpha spp.</u>	Eelgrass, <u>Zostera marina</u>	Kelp, <u>Nereocystis luerkeana</u>
<u>Ulva spp.</u>		<u>Gigartina papillata</u>	<u>Fucus evanescens</u>	<u>Ulva spp.</u>	Kelp, <u>Laminaria-saccharina</u>
Diatoms		<u>Fucus evanescens</u>	<u>Sargassum muticum</u>	Diatoms	<u>Ulva spp.</u>
<u>Fucus evanescens</u>		<u>Enteromorpha spp.</u>	<u>Gigartina papillata</u>		
		Diatoms	<u>Ulva spp.</u>		
Barnacle, <u>Balanus spp.</u>	<u>Capitella capitata</u>	Crab, <u>Hemigrapsis spp.</u>	Barnacle, <u>Balanus spp.</u>	Snail, <u>Lacuna spp.</u>	Kelp crab, <u>Pugettia spp.</u>
Mussel, <u>Mytilus edulis</u>	<u>Oligochaetes</u>	Barnacle, <u>Balanus spp.</u>	Mussel, <u>Mytilus edulis</u>	Isopod, <u>Idothea spp.</u>	Crab, Cancer spp.
Flatworms	Clam, <u>Macoma spp.</u>	Isopod, <u>Ilothea spp.</u>	Flatworms	Chiton, <u>Amphithoe spp.</u>	Tube worms
Polychaetes		Butter clam, <u>Saxidomus giganteus</u>		Crab, Cancer spp.	
				Kelp crab, <u>Pugettia spp.</u>	
				Heartcockle, <u>Clinocardium nuttallii</u>	
				Clam, <u>Macoma spp.</u>	

Figure 4.14. Composition and distribution of benthic sediments from Elliott Bay, Washington. After Harman and Serwold (1974).



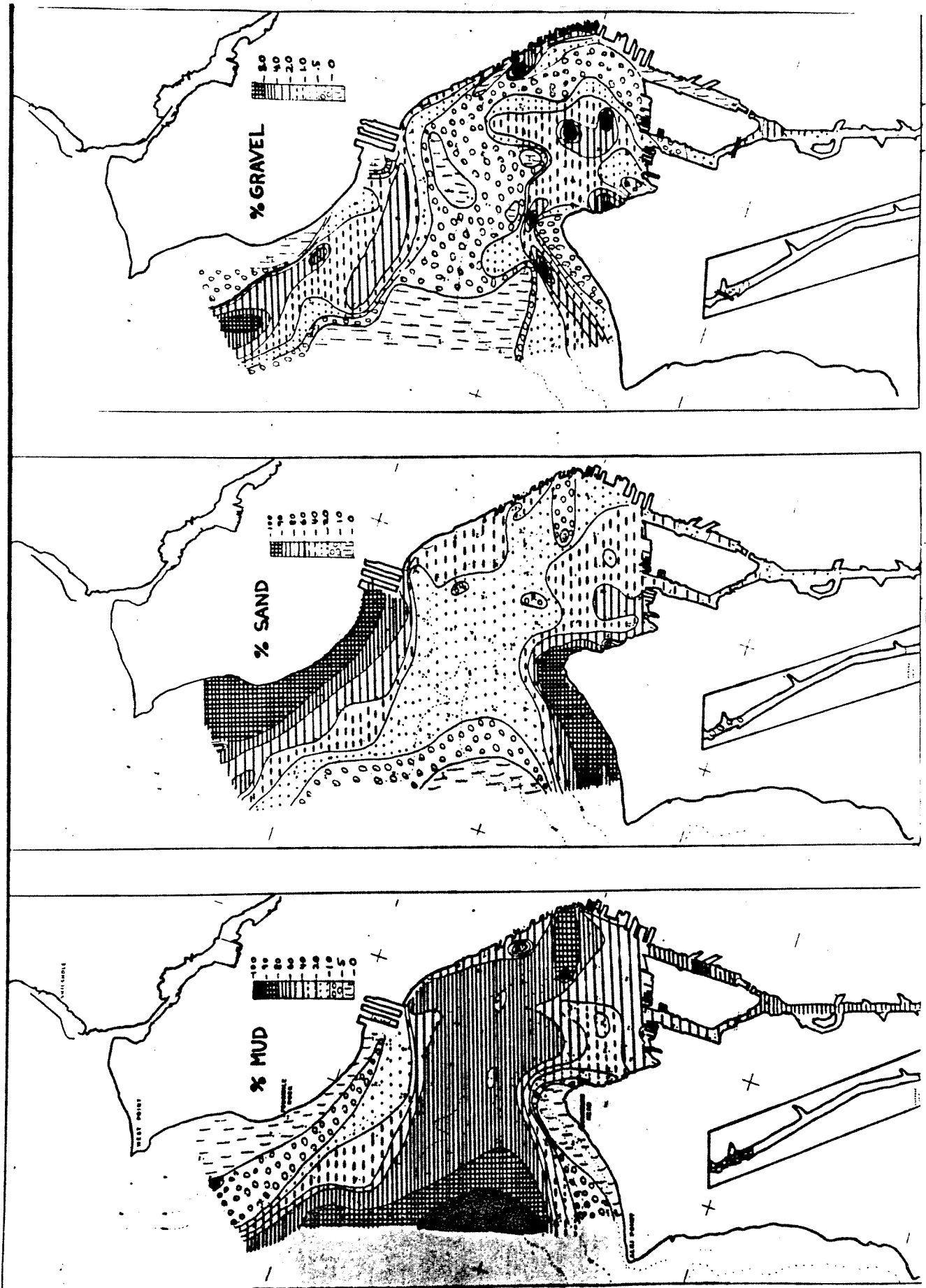


Figure 4.14. (continued).

sediments with the finest particle sizes and the lowest organic indices.

Interestingly, Comiskey et al. (1983) reported that at West Point the highest concentrations of organic chemicals were associated with the small particle sized sediments found at the deepest depths. The lowest concentrations of organic chemicals occurred at the shallow water stations which had the lowest percentage of fine particles. However, within inner Elliott Bay the highest concentration of organic chemicals was associated with the coarser sediments from shallow water and may only be characteristic of the Denny Way site and not the entire Elliott Bay. The organic chemical content of the sediment decreased with depth and increased in the percentage of fine sediments.

Wood chips are associated with the Duwamish River with the greatest concentrations occurring at the bottoms of the two canyons in the inner bay, between Duwamish Head and the eastern shore of the bay including Piers 90 and 91, and at dredge disposal sites (Figure 4.14).

Sediment color ranged from green to black (Figure 4.14). Presumably black sediment indicated anaerobic conditions and/or the presence of hydrogen sulfide partly due to sediments dropped by the river. The presence of black sediment also was correlated with high concentrations of wood chips with the exception of one area between Alki Point and Duwamish Head, the areas containing black and/or gray sediments were associated primarily with the water flow from the Duwamish River. Hence, the gray color of the sediments may stem from the biological oxygen demand created by the decomposition of vascular plants. The excepted area off Alki Point probably derives its black color from the biological oxygen demand created by the decomposition of eelgrass and algae from the Alki beach area.

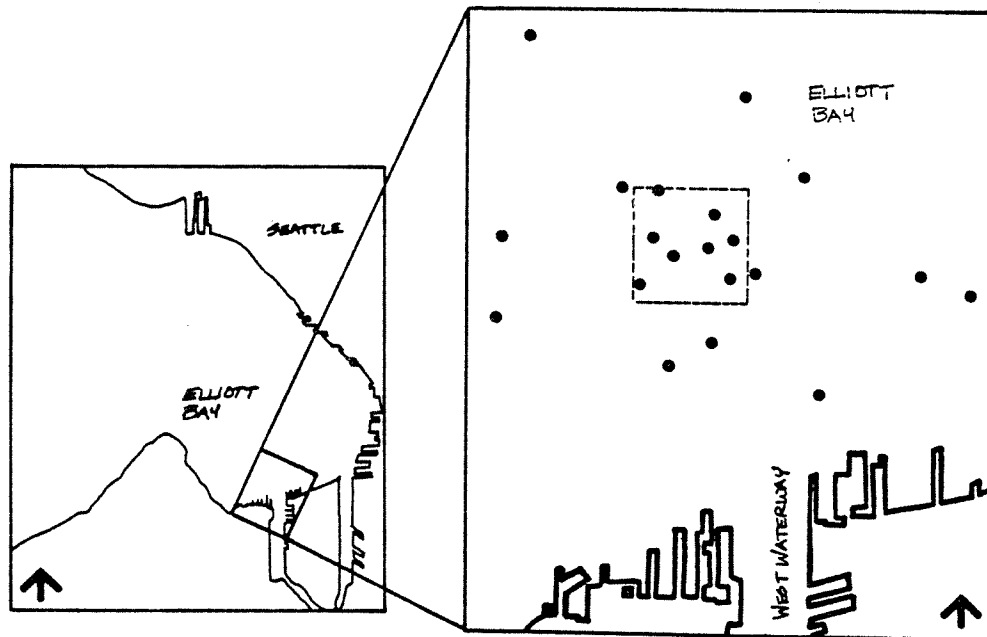
4.4.2 Benthic Invertebrates from West Point

At least 800 species of intertidal and benthic invertebrates (Figure 4.15) have been identified from Elliott Bay (Appendix 4; Comiskey et al. 1983). Three areas, West Point, the Denny Way CSO, and the U.S. Army Corps of Engineers dredged sediment disposal site have been studied most extensively.

At West Point the most numerically dominant group were the polychaetes (40.6% pooled composition). The mean density of polychaetes was 2,004 per m^2 . The second most dominant group were pelecypods (23.7% pooled composition). The mean density was 1,172 per m^2 . Pelecypods and polychaetes occurred in all 31 of the samples which were completely sorted prior to identification of the animals present (Comiskey et al. 1983).

The third most dominant group of invertebrates at West Point were the ostracods (12.9% pooled composition). The mean density of ostracods was 638 per m^2 . Ostracods were widely distributed having been found in 93% of the samples. Amphipods were found in all samples sorted, but represented only 6.8% of the pooled composition. The mean density of the amphipods was 336 per m^2 . The remaining taxa of significance at West Point were sipunculids (3.8% pooled composition), gastropods (3.8% pooled composition), echinoderms (> 1% pooled composition) and cumaceans (> 1% pooled composition).

The most abundant species in the West Point area was the clam, Macoma carlottensis, which had a pooled composition of 10.5%. M. carlottensis was fairly widely distributed having been found in 79% of the samples and occurred at a mean density of 432 per m^2 . The second most abundant organism (7.8% pooled composition) were the sipunculids of the family Golfingiidae. These sipunculids occurred in 54% of the samples and had a mean density of 322 per m^2 . The third most abundant organism (6.9% pooled composition) was the



Depth Range = 50-80 m
 Sample Size = 0.1 m² VanVeen
 Sieve Size = 1 mm
 Sample No. = 20 (3 replicates each)

● = Station location (above)

M = Mollusc
 P = Polychaete
 C = Crustacean
 E = Echinoderm
 E* = Echiura

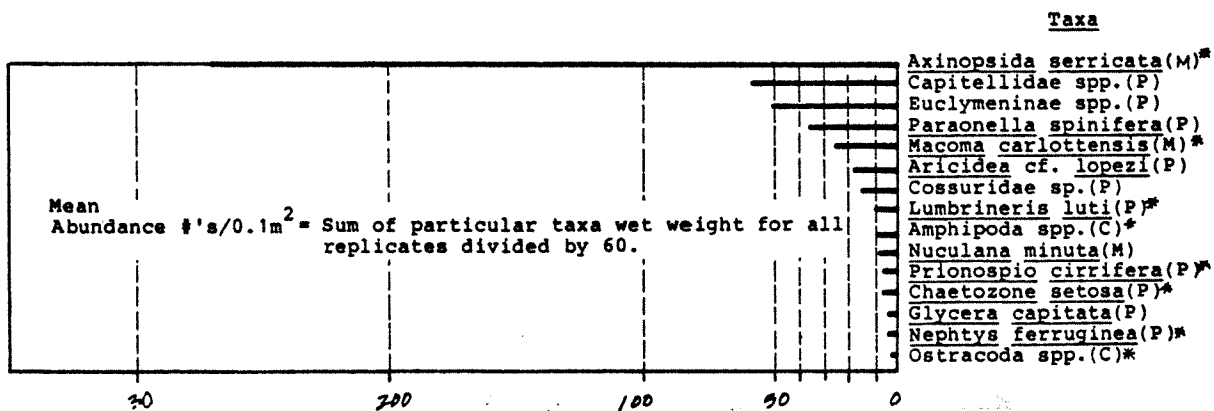
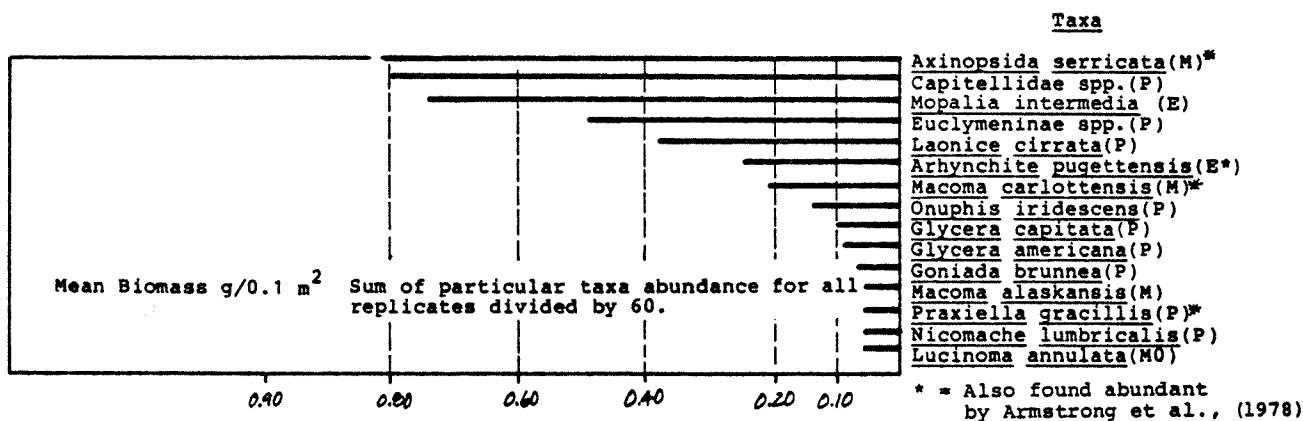


Figure 4.15. Ranking by abundance and biomass of most common subtidal macrofaunal taxa from May 1979 Elliott Bay cruise. After Dexter et al. (1981).

ostracod, Euphilomedes carcharadonata. The fourth most abundant organism (5.7% pooled composition) was another ostracod, E. producta. The polychaete, Phyllochaetopterus, was the fifth most abundant organism with a pooled composition of 5%, but this polychaete had a relatively limited distribution having been found in only 31% of the samples. The sixth most abundant invertebrate was the pelecypod clam, Axinopsida serricata which had a pooled composition of 4.7%. This clam was very widely distributed having been found in 91% of the samples and had a mean density of 201 per m². The remaining abundant species at West Point were the gastropod, Bittium, and three polychaetes, Notomastus tenuis, Polydora, and the family Ampharetidae.

4.4.3 Benthic Invertebrates from the Denny Way Combined Sewer Overflow

Unlike West Point, the benthic fauna from the Denny Way CSO was dominated by only three major taxa. Polychaetes and the pelecypod clams were the dominant invertebrates each with a pooled composition exceeding 40%. Polychaetes had a mean density of 2,113 per m² while the pelecypods had a mean density of 2,016 per m². The distribution of the two taxa diffused sharply however. Pelecypods occurred in all of the 20 samples used for taxonomic analysis whereas the polychaetes had a very clumped distribution. The third dominant taxon was the ostracods which had a pooled composition of 10.6% and a density of 523 per m². Amphipods occurred in 95% of the samples, but had a pooled composition of >1%.

Similarly, three dominant species accounted for 72% of the pooled composition. The pelecypod, Axinopsida serricata, had a mean density of 1,151 per m² and was the most abundant invertebrate (28.7% pooled composition). The second most abundant species was the polychaete, Capitella capitata (22.1% pooled composition) which had a mean density of 887 per m². However, C. capitata had a limited distribution occurring only in a few samples whereas A. serricata was found in 98% of the samples. The pelecypod Macoma carlottensis was the third most abundant species (10.9% pooled composition) and had a mean density of 436 per m². M. carlottensis was widely distributed occurring in 93% of the samples studied. The remaining species of lesser abundance were the ostracod, E. carcharodonta (6.3%), Tauberia gracilies (> 3%), and Tharyx (> 3%).

Comiskey et al.'s (1983) abundance data were based on numbers presented rather than biomass. Clearly the abundance rankings would be significantly different if a unit of weight were used to rank abundance (Figure 4.16).

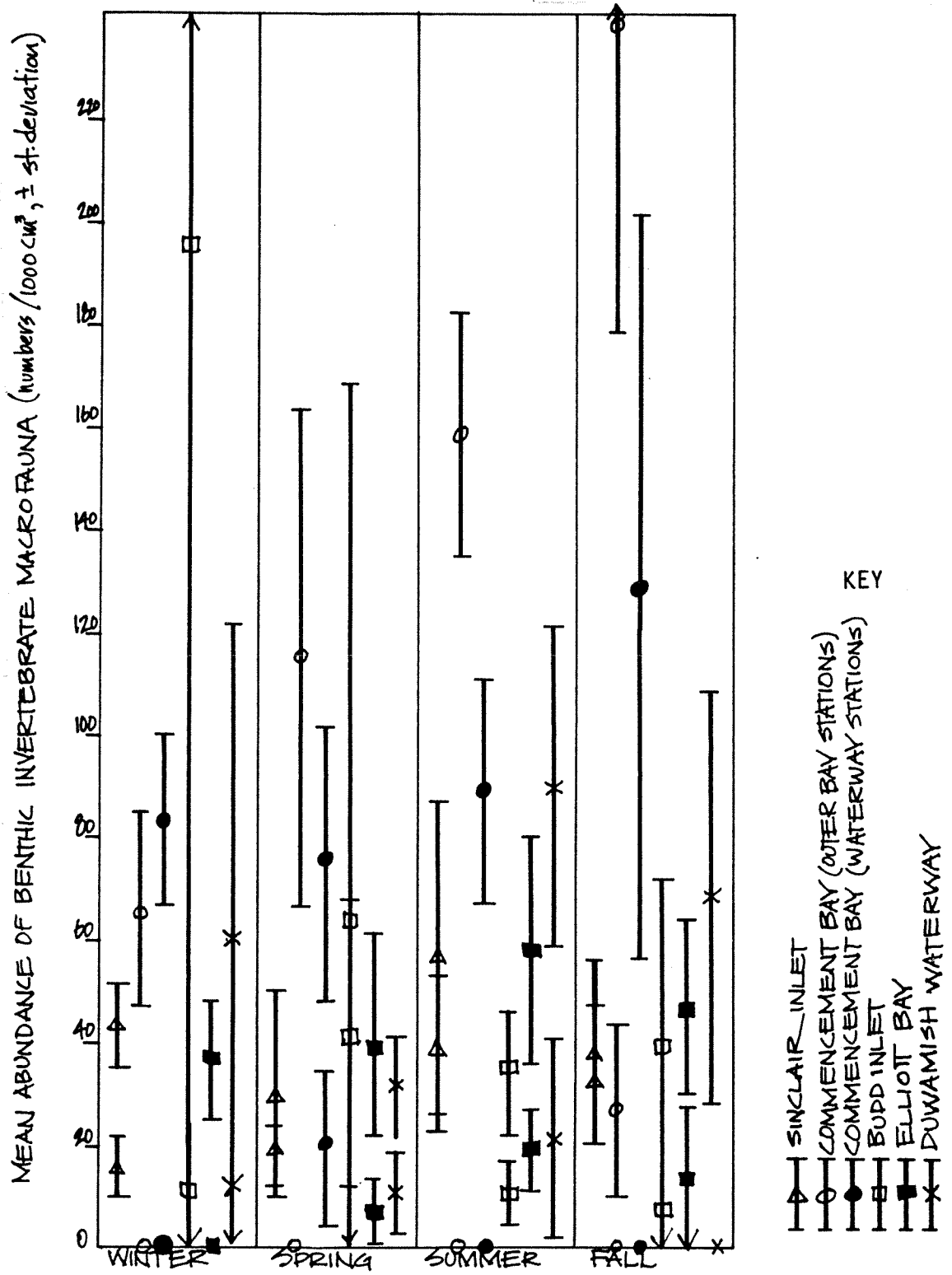
4.4.4 U.S. Army Corps of Engineers Dredged Sediment Disposal Site

In March 1976 114,000 cubic meters of sediment were dredged from the Duwamish River (between 6.28 and 8.16 km) and dumped into Elliott Bay over the 60 m depth isoline due north of the mouth of the west waterway (0.13 square km; 47°37'41"N; 122°21'42"W) by the U.S. Army Corps of Engineers.

In 1979 and 1980 four cruises (February, May, and October, 1979; May, 1980) were made to obtain benthic samples to be used to characterize the fauna occupying the dredged sediments. Preservation of the samples from the February cruise was incomplete; hence, conclusions drawn from these data were considered to be tentative (Dexter et al. 1982). Preservation of the remaining samples was adequate to allow identification, but partial dissolution of some tissues may have created biased estimates of biomass.

The five most abundant animals collected during the two May and October collections were A. serricata, Capitellidae spp., Euclymenianae spp.,

Figure 4.16. Maximum and minimum abundance of benthic invertebrate macrofauna observed at multiple sampling sites in Puget Sound embayments in four seasonal samplings during 1980. a) Data are presented by season for each embayment as the means (symbol) and standard deviations (lines) of the abundance observed at the stations with the maximum and minimum abundances. After Dexter et al. (1981).



Paraonella spinifera, and Macoma carlottensis (Table 4.12). Abundances of these five animals ranged from 29–294/0.1 square meter. The spatial distribution of the Capitellidae appears in Figure 4.18. The total number of taxa collected in February, 1979, was 147; in May, 1979, was 143; in October, 1979, was 155; and in May, 1980, was 140 (Dexter et al. 1982). Mean abundance of A. serricata increased from 145/0.1 square meter in June, 1976, to a high of 294/0.1 square meter in October, 1979. A similar increase in the abundances of M. carlottensis and Euclymeninae was noted (Dexter et al. 1982).

The five animals with the greatest biomass during the latter three collections were A. serricata, Capitellidae spp., Mopaldia intermedia, Euclymeninae spp., and Laonice cirrata (Table 4.13). Mean biomasses (g/0.1 square meter) of these five animals ranged from 0.22 to 1.09 (Dexter et al. 1982).

4.4.5 Distribution Trends

The number of species and abundance of organisms was less at the Denny Way CSO within inner Elliott Bay than at West Point at the outer margin of Elliott Bay. This reduction in number of species and abundance is typical of an estuarine habitat (Comiskey et al. 1983). Within Elliott Bay the western portion of the bay had a significantly greater number of species than did the eastern portion of the bay (Malins et al. 1980).

At least two significant factors, depth and sediment particle size, governed the distribution of these benthic invertebrates. For example, Comiskey et al. (1983) showed that the benthic species occurring at the very deep stations at West Point were different than the species occurring at the 30 and 100 m stations. At the Denny Way CSO the distribution of species typically found at 100 m (Ampharetidae, Photis, Ninoe, Ampelisca, Macrocephala, Axinopsis, Molpadiidae, and Lysianassidae) was significantly correlated with the composition and size of the sediment. As at West Point a different group of species (E. carcharadonta, Parvilvcina tenuisculpta, Polydora, Chaetozone setosa, Lucinoma acutilineata, Prinoospio steenstrupi and Tharynx) occupied the 20 m stations than was found at the deeper stations.

Comiskey et al. (1983) reported a strong change in community structure at all stations at all depths between the rainy and dry season. Unexpectedly, these seasonal changes were greatest at the deepest water depths. For example, Malins et al. (1982) reported that the average abundance of fauna per 1000 cm² sediment (based on 792 samples and 40 species) for winter was 29.2, spring 35.3, summer 45.8, and autumn 46.8 (Figure 4.17).

The infaunal trophic index (ITI) for the main basin of Puget Sound ranged from 59–82. Malins et al. (1982) obtained average ITI values of 71, 72, and 73 during winter 1979, at West Point, Magnolia Bluff, and Alki Point respectively (Figures 4.19 and 4.20). Thom et al. (1979) obtained ITI values of 68, 68, and 75 from the same sites during winter, 1979.

Species richness varied from 2.9 ± 1.4 in the east channel of the Duwamish waterway to 10.6 ± 2.8 on the southeast side of Duwamish Head to 11.1 ± 5 at West Point (Malins et al. 1982). Malins et al. (1982) concluded that six replicate cores was the correct sample size to use in measuring species richness. Six replicate cores provided 90–95% of the ITI species present in 10 replicate cores.

Malins et al. (1982) calculated catch per unit effort for six Elliott Bay invertebrate species. Catch per unit effort was approximately 6 for Crangon alaskensis, 8 for Pandalus danae, 40.4 for P. jordani, 0.6 for the Dungeness crab, Cancer magister, 0.1 for the red rock crab, C. productus, and 0.5 for C.

Table 4.12. Ranking by abundance of the most common benthic invertebrates occurring in the U.S. Army Corps of Engineers dredged sediment disposal site in Elliott Bay. After Dexter et al. (1982).

Taxa ⁽¹⁾ #	Taxa	Rank		Mean Abundance ⁽²⁾		
		May 79	Oct 79	May 79	Oct 79	May 80
175	<u>Axinopsida serricata</u>	1	1	270	294	227
065	<u>Capitellidae spp.</u>	2	4	58	40	69
085	<u>Euclymeninae spp.</u>	3	3	51	52	39
106	<u>Paraonella spinifera</u>	4	5	36	29	44
185	<u>Macoma carlottensis</u>	5	2	25	189	54
108	<u>Aricidea cf. lopezi</u>	6	6	17	16	19
203	<u>Cossuridae sp.</u>	7	8	16	11	8
019	<u>Lumbrineris luti</u>	8	9	10	8	9
151	<u>Amphipoda spp.</u>	9	7	9	14	11
193	<u>Nuculana minuta</u>	10	23	9	2	1
125	<u>Prionospio cirrifera</u>	11	13	8	6	5
074	<u>Chaetozone setosa</u>	12	15	7	5	3
007	<u>Glycera capitata</u>	13	37	4	1	3
025	<u>Nephtys ferruginea</u>	14	11	4	6	16
204	<u>Ostracoda spp.</u>	15	14	3	5	6
126	<u>Polydora hamata</u>	21	10	2	7	8
056	<u>Amphicteis scaphobranchiata</u>	17	12	2	6	1
192	<u>Nucula tenuis</u>	16	16	3	4	2
191	<u>Nemocardium centifilosum</u>	37	17	1	3	1
123	<u>Prionospio steenstrupi</u>	20	18	2	3	1
271	<u>Cumacea spp.</u>	18	19	2	3	3
159	<u>Mitrella gouldi</u>	32	20	1	3	1
176	<u>Cardiomya oldroydi</u>	39	21	1	2	1

(1) Taxa # is the computer code assigned to each individual taxa.

(2) Mean Abundance #'s/0.1m² = Sum of particular taxa abundance for all replicates divided by number of replicates for particular cruise.

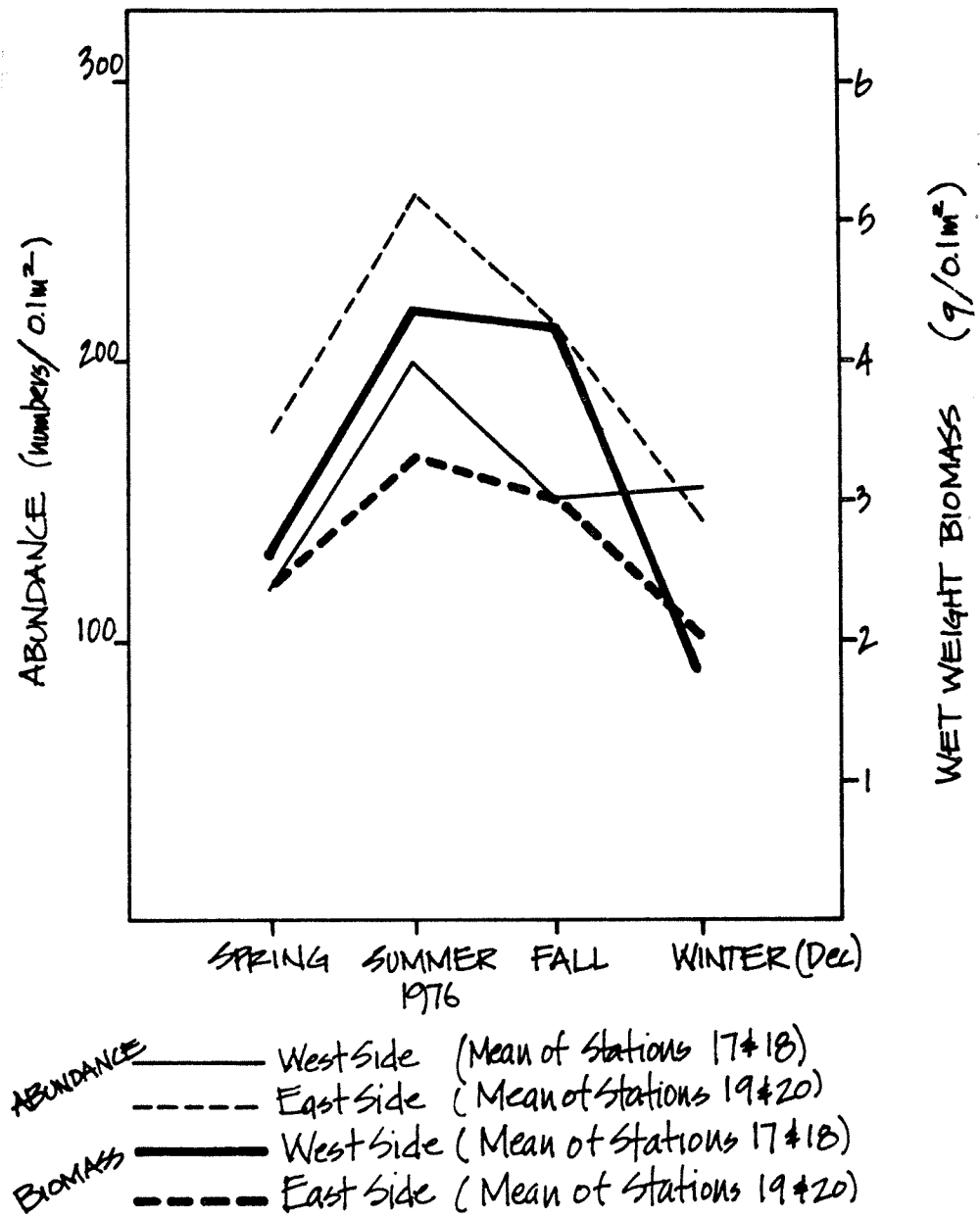


Figure 4.17. Seasonal changes in abundance and biomass of subtidal benthos in Elliott Bay. Reference Stations 17, 18, 19, 20; 3 replicates taken at each station, depths 47-61 m. After Dexter et al. (1981).

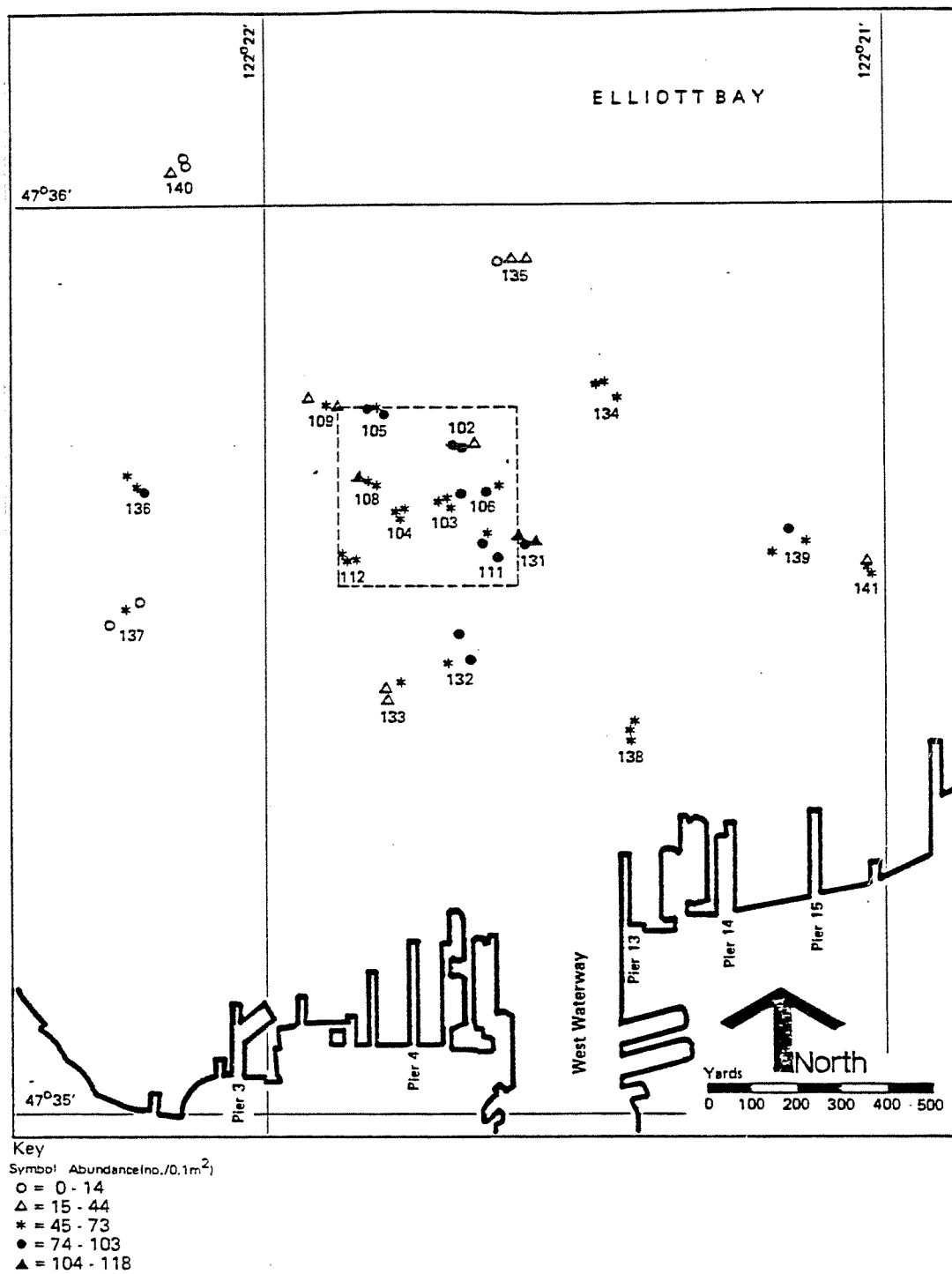


Figure 4.18. Spatial distribution of the polychaete family Capitellidae. After Dexter et al. (1982).

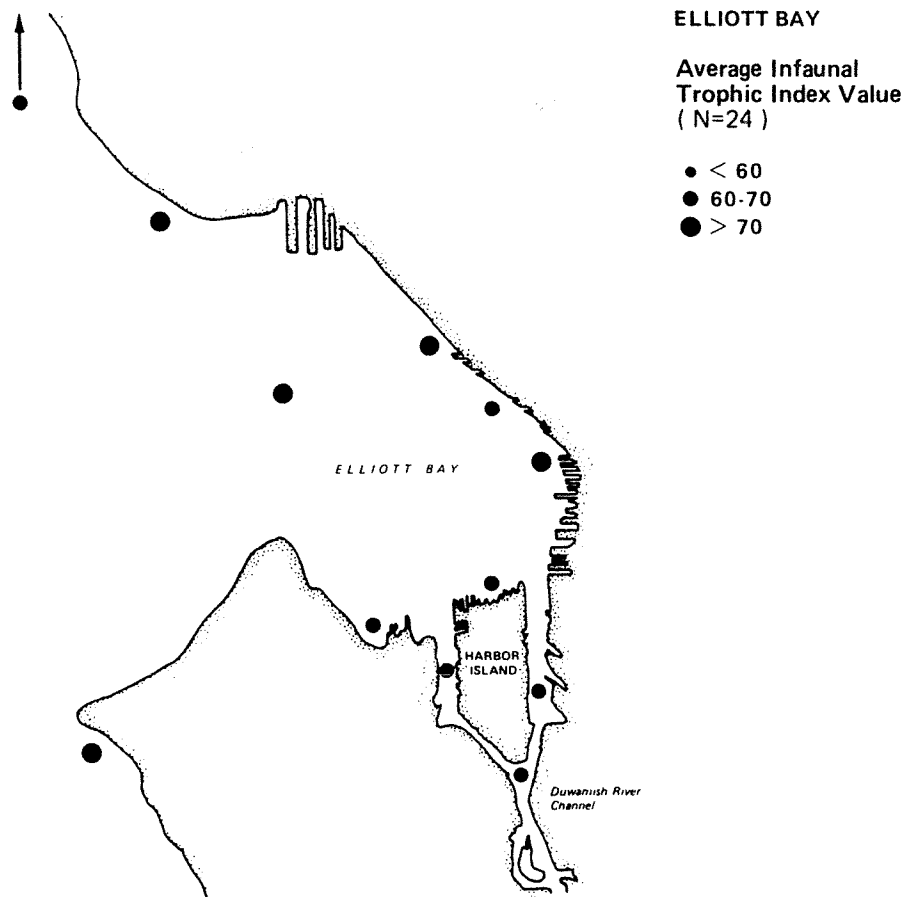


Figure 4.19. Average infaunal trophic index values (average of 24 sediment samples collected in the winter, spring, summer, and fall of 1979) for each sampling station in the sampling areas. After Malins et al. (1982).

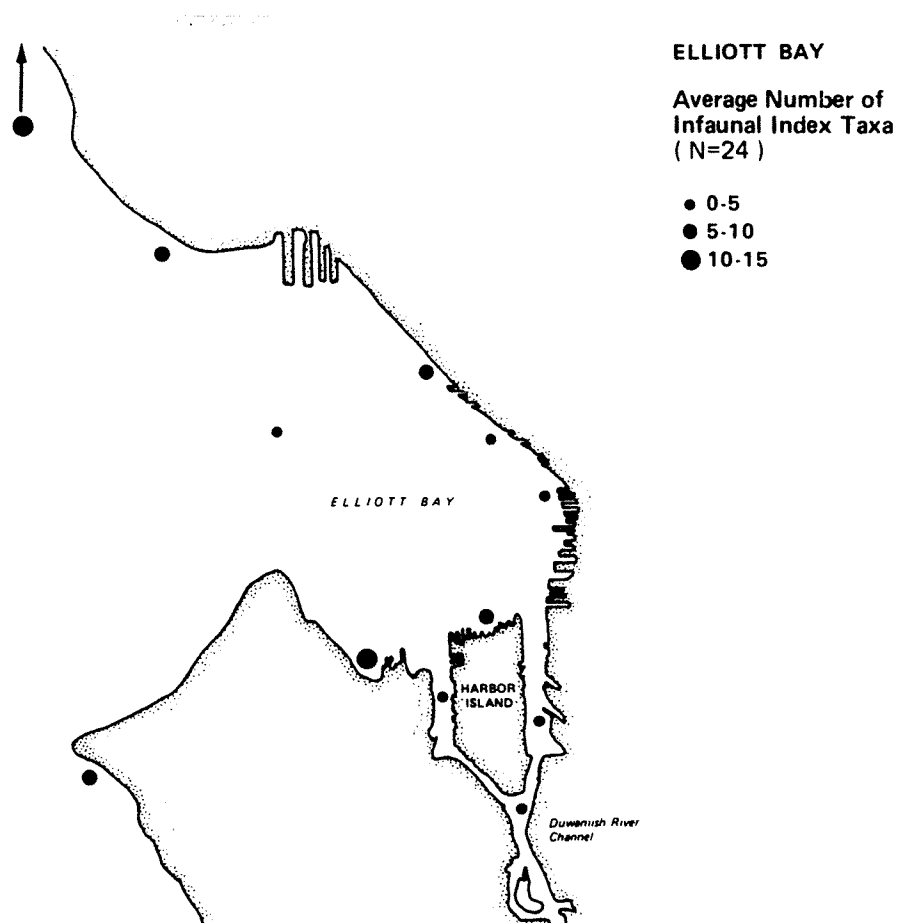


Figure 4.20. Average number of infaunal trophic index taxa (taxon richness) values (average of 24 sediment samples collected in the winter, spring, summer, and fall of 1979) for each sampling station in the sampling areas. After Malins et al. (1982).

gracilis. Catch per unit effort for the total catch was calculated for a five minute tow. Each tow covered approximately 386 m (= 0.2 nautical miles). The otter trawl used had a 7.5 m opening, a 10.8 m total length, 3.8 cm mesh in the body of the net, and a 0.64 cm-mesh liner in the cod end.

The U.S. Army Corps of Engineers dredged sediment disposal site contained an assemblage of macrofauna that differed from the surrounding areas (Dexter et al. 1982). Both abundances and biomasses differed from those at adjoining stations which were outside of the disposal area. Stations north and east of the disposal site exhibited the greatest similarities to stations within the disposal site. Animal abundance and biomass was generally greater near the disposal site. Dexter et al. (1982) therefore concluded that the dominant taxa of the macrofaunal assemblage still exhibited effects from the dredged sediment disposal in early 1976. The chronic effect was an increased abundance and biomass within the dredged material. Species richness was similar both in and away from the disposal site (Dexter et al. 1982). Significant correlations between animal abundance and physical/chemical characteristics of the sediment were not noted.

4.4.6 Shortcomings of the Existing Benthic Invertebrate Studies

Eight invertebrate studies using grab samples or coring tools have been conducted within Elliott Bay. Navigational information that may be used to locate the 203 stations studied was often inadequate. Some studies placed navigational ranges on the shorelines (Thom et al. 1979; Armstrong et al. 1980), others used combinations of LORAN C, and water depth, in conjunction with identifiable shore fixes or ranges as available (Comiskey et al. 1983; Word/EPA unpublished data), others described the navigational techniques but did not describe the fixes for each station (Harmon and Serwold 1974, 1977), while others depended upon compass angles to identify shore locations (Malins et al. 1982). In only two cases could stations be reoccupied with accuracy (Comiskey et al. 1983; Word/EPA, unpublished data).

Replicate samples from each station ranged from one (Thom et al. 1979; Harmon and Serwold 1974; 1977; Comiskey et al. 1983) to five or more (Armstrong et al. 1980; Word/EPA unpublished data). Other workers (Malins et al. 1982) took multiple samples along trawl transects 400-800 meters in length. Samples for seasonal comparisons ranged from one (Harmon and Serwold 1974; 1977; Thom et al. 1979), to two (Armstrong et al. 1980; Comiskey et al. 1983), to six during the year (Word/EPA, unpublished data). Malins et al. (1982) repeatedly sampled at irregular intervals. Long term sampling at fixed stations has not been conducted in the Elliott Bay region.

4.4.7 The Geoduck (*Panope generosa*)

The area south of West Point supports a population of the geoduck clam (Figure 4.21). This bed consists of approximately 190 acres containing approximately 610,000 clams. Using these data Goodwin (1973) calculated that in the 30-60 foot depth range, Elliott Bay had 476 acres suitable for geoduck habitat. If this habitat contains geoducks at the same density as the area south of West Point, these 476 acres would support 768,000 clams. This estimate is probably conservative because geoducks are known to inhabit waters to a depth of 360 feet (Wennekins 1959).

Currently geoducks cannot be commercially harvested from Elliott Bay. Fecal coliforms probably are present in the tissues of the geoducks at sufficient concentrations to prohibit use of the clams as human food. A

Table 4.13. Ranking by biomass of the most common benthic invertebrates occurring in the U.S. Army Corps of Engineers dredged sediment disposal site in Elliott Bay. After Dexter et al. (1982).

Taxa #	Taxa	Rank		Mean Biomass (2)		
		May 79	Oct 79	May 79	Oct 79	May 80
175	<u>Axinopsida serricata</u>	1	1	.81	.97	.85
065	<u>Capitellidae spp.</u>	2	2	.79	.83	.69
226	<u>Mopaldia intermedia</u>	3	6	.74	.28	1.09
085	<u>Euclymeninae spp.</u>	4	3	.49	.45	.30
122	<u>Laonice cirrata</u>	5	5	.38	.31	.22
222	<u>Arhynchite pugettensis</u>	6	14	.25	.08	.07
185	<u>Macoma carlottensis</u>	7	4	.20	.44	.76
031	<u>Onuphis iridescens</u>	8	8	.14	.18	.13
007	<u>Glycera capitata</u>	9	9	.10	.17	.12
006	<u>Glycera americana</u>	10	35	.09	.02	<.01
013	<u>Goniada brunnea</u>	11	13	.07	.09	.16
184	<u>Macoma alaskensis</u>	12	27	.06	.03	.04
089	<u>Praxiella gracilllis</u>	13	21	.06	.04	.02
087	<u>Nicomache lumbricalis</u>	14	(3)	.06	(3)	<.01
181	<u>Lucinoma annulata</u>	15	70	.06	<.01	.04
177	<u>Compsonyx subdaphana</u>	17	7	.05	.24	.03
191	<u>Nemocardium centiflosum</u>	19	10	.04	.15	.12
084	<u>Asychis similis</u>	32	11	.02	.12	.01
145	<u>Cerabratulus sp.</u>	20	12	.04	.10	.16
192	<u>Nucula tenuis</u>	22	15	.04	.07	.04
193	<u>Nuculana minuta</u>	26	16	.03	.07	.03

(1) Taxa # is the computer code assigned to each individual taxa.

(2) Mean Biomass g/0.1 m² = Sum of particular taxa wet weight for all replicates divided by number of replicates for particular cruise.

(3) Not found in this cruise.

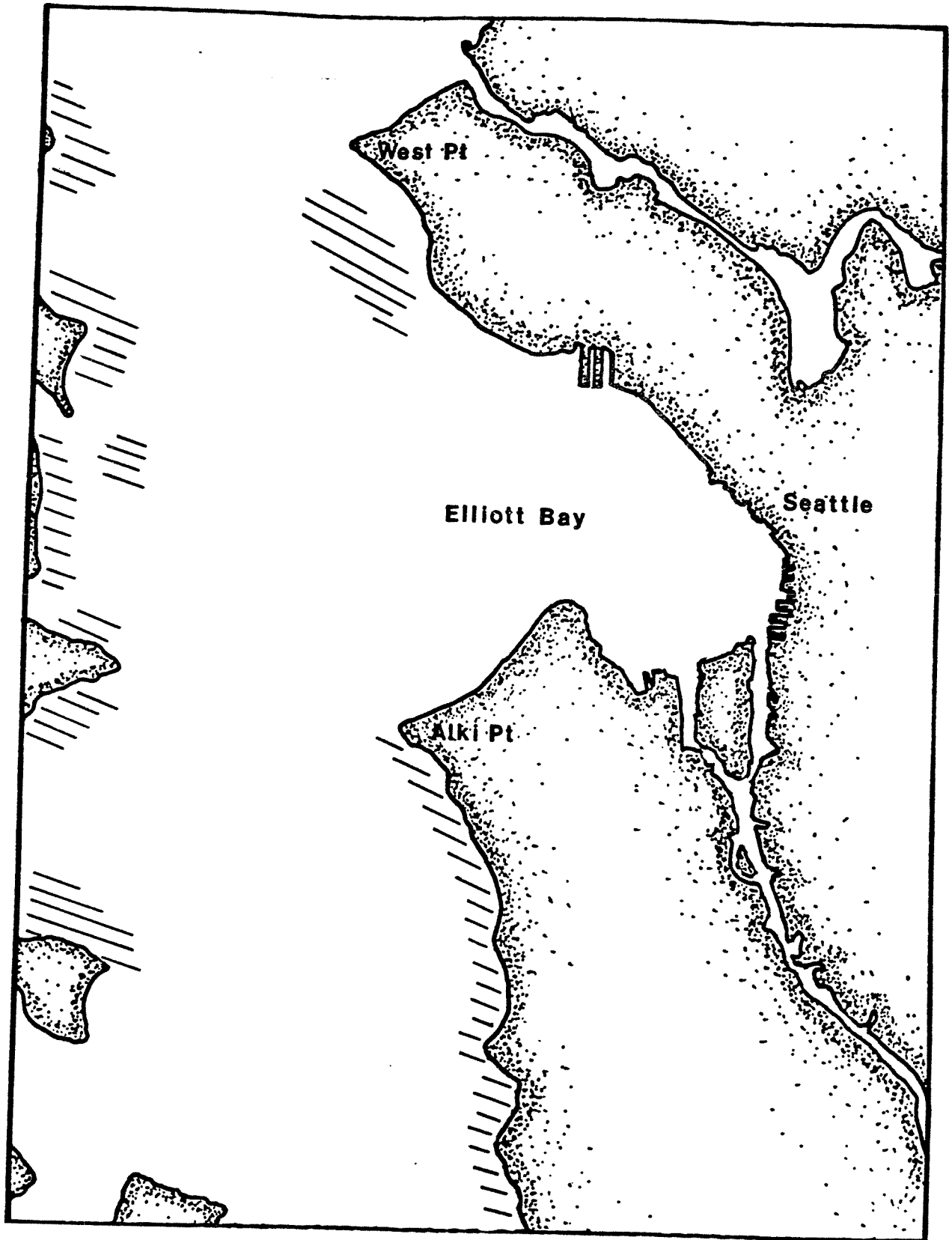


Figure 4.21. Location of geoduck (*Panopea generosa*) beds with densities of one clam or greater per four square feet. After Goodwin (1973).

limited sport fishery for geoducks from Elliott Bay may exist, but specific data were not available (Lynn Goodwin, Washington State Department of Fisheries, person. commun.).

4.5 Fishes of Elliott Bay and the Duwamish Estuary

At least 125 species of fish have been recorded from Elliott Bay and the Duwamish estuary (Table 4.14). Such species as the salmonids occur in large numbers and are economically important. In contrast, other fishes such as the Pacific barracuda (Sphyraena argentea), jack mackerel (Trachurus symmetricus), and ocean sunfish (Mola mola) are infrequent visitors to the area. In this review fishes will be described on the basis of habitat occupied and/or life history type.

4.5.1 Anadromous, Pelagic Fishes

Three salmon species [chinook (Oncorhynchus tshawytscha), coho (O. kisutch), and chum (O. keta)], two trout species [rainbow (Salmo gairdneri) and cutthroat (S. clarki)] and the Dolly Varden char (Salvelinus malma) spawn, reside in, and migrate through the Duwamish-Green River-Elliott Bay complex and thus, might be called residents. Pink and sockeye salmon (O. gorbuscha and nerka) occur in Elliott Bay, but do not utilize the Duwamish-Green River for spawning (Weitkamp and Schadt 1982; Tim Flint, Washington State Department of Fisheries, person. commn.).

Other pelagic species known to occur in Elliott Bay include surf smelt (Hypomesus pretiosus), longfin smelt (Spirinchus thaleichthyes) and Pacific herring (Clupea harengus) (Miller 1980; Weitkamp and Schadt 1982).

4.5.1.1 Life History of the Salmonids

The life histories of the three salmonid genera (Oncorhynchus, Salmo and Salvelinus) living in the Duwamish-Green River, are similar (Hart 1973). Adults spawn in fall or winter in gravel areas in shallow water (Figure 4.22). Following absorption of the yolk sac, the fingerlings emerge from the gravel. In the Green-Duwamish system, the time spent by the fingerlings in freshwater is a species as well as race dependent characteristic and varies from a few days to as much as one or two years. After undergoing smoltification, the juveniles (fry, fingerlings or yearling smolts) move into seawater (Figure 4.23). They remain in seawater from a few months to four or more years (Figure 4.22). The length of time spent in seawater is species and race specific. The juveniles prefer shallow, nearshore waters and follow the shoreline as they begin their northerly migration. As the juveniles grow, they randomly leave the nearshore area and move offshore into somewhat deeper water. During this saltwater residence, the sub-adults (maturing fish) migrate to the North Pacific. After returning as adults to local waters, they move into Elliott Bay and the Duwamish-Green River (Figure 4.23). As maturing adults they migrate into Puget Sound (although many spend their entire saltwater residence in Puget Sound) where they are harvested by both sport and commercial fishermen. The mature salmonids occur throughout Elliott Bay and utilize all entry route (both East and West Waterways) into the Duwamish River. After spawning, salmon die whereas trout and chars may repeat the spawning cycle several times during their lifespan.

Chinook, coho and chum spawn in the fall. The fingerlings emerge from

Table 4.14. Fishes that occur in Elliott Bay and the Duwamish River estuary.

<u>Anarrichthys ocellatus</u> , wolf-eel	<u>Gadus macrocephalus</u> , Pacific cod
<u>Agonus acipenserinus</u> , sturgeon poacher	<u>Gasterosteus aculeatus</u> , three-spine stickleback
<u>Agonopsis emmelane</u> , northern spearnose poacher	<u>Gilbertidia sigalutes</u> , soft sculpin
<u>Anoplarchus purpureus</u> , cockscomb	<u>Glyptocephalus zachirus</u> , Rex sole
<u>Anoplopoma fimbria</u> , sablefish	<u>Gobiesox maeandricus</u> , northern clingfish
<u>Apodichthys flavidus</u> , penpoint gunnel	
<u>Artedius fenestralis</u> , padded sculpin	<u>Hemilepidotus hemilepidotus</u> , red Irish lord
<u>Artedius harringtoni</u> , scalyhead sculpin	<u>Hexagrammos decagrammus</u> , kelp greenling
<u>Artedius lateralis</u> , smoothhead sculpin	<u>Hexagrammos lagocephalus</u> , rock greenling
<u>Asterotheca pentacanthus</u> , bigeye poacher	<u>Hexagrammos stelleri</u> , whitespotted greenling
<u>Atheresthes stomias</u> , arrowtooth flounder	<u>Hexanchus griseus</u> , six-gill shark
<u>Aulorhynchus flavidus</u> , tube-snout	<u>Hippoglossoides elassodon</u> , flathead sole
	<u>Hydrolagus colliei</u> , rat fish
<u>Blepsias cirrhosus</u> , silverspotted sculpin	<u>Hypomesus pretiosus</u> , surf smelt
<u>Brosomphycis marginata</u> , red brotula	
	<u>Icelinus borealis</u> , northern sculpin
<u>Catostomus macrocheilus</u> , largescale sucker	<u>Icelinus filamentosus</u> , threadfin sculpin
<u>Chirolophis nugator</u> , mosshead warbonnet	<u>Icelinus tenuis</u> , spotfin sculpin
<u>Chitonotus pugetensis</u> , roughback sculpin	<u>Isopsetta isolepis</u> , butter sole
<u>Citharichthys sordidus</u> , Pacific sanddab	
<u>Citharichthys stigmaeus</u> , speckled sanddab	<u>Lamna ditropis</u> , salmon shark
<u>Clevelandia ios</u> , arrow goby	<u>Lampetra ayresi</u> , river lamprey
<u>Clinocottus acuticeps</u> , sharpnose sculpin	<u>Lepidogobius lepidus</u> , bay goby
<u>Clupea harengus pallasii</u> , Pacific herring	<u>Lepidosetta bilineata</u> , rock sole
<u>Coryphopterus nicholsi</u> , blackeye goby	<u>Leptocottus armatus</u> , Pacific staghorn sculpin
<u>Cottus asper</u> , prickly sculpin	<u>Liparis cyclopus</u> , ribbon snailfish
<u>Cymatogaster aggregata</u> , shiner perch	<u>Lumpenus sagitta</u> , snake prickleback
	<u>Lycodapus mandibularis</u> , pallid eelpout
<u>Dasycottus setiger</u> , spinyhead sculpin	<u>Lycodes diapterus</u> , black eelpout
<u>Delolepis gigantea</u> , giant wrymouth	<u>Lycodopsis pacifica</u> , blackbelly eelpout
	<u>Lyopsetta exilis</u> , slender sole
<u>Embiotoca lateralis</u> , striped seaperch	
<u>Engraulis mordax</u> , northern anchovy	<u>Merluccius productus</u> , Pacific hake
<u>Enophrys bison</u> , buffalo sculpin	<u>Microgadus proximus</u> , Pacific tomcod
	<u>Microstomus pacificus</u> , Dover sole
	<u>Mola mola</u> , ocean sunfish
	<u>Myoxocephalus polyacanthocephalus</u> , great sculpin
	<u>Nautichthys oculofasciatus</u> , sailfin sculpin

Table 4.14. (continued).

<u>Odontopyxis trispinosa</u> , pygmy poacher	<u>Somniosus pacificus</u> , Pacific sleeper shark
<u>Oligocottus maculosus</u> , tidepool sculpin	<u>Sphyræna argentea</u> , Pacific barracuda
<u>Oncorhynchus gorbuscha</u> , pink salmon	<u>Spirinchus thaleichthys</u> , longfin smelt
<u>Oncorhynchus keta</u> , chum salmon	<u>Squalus acanthias</u> , dog shark
<u>Oncorhynchus kisutch</u> , coho salmon	<u>Squatina californica</u> , Pacific angel shark
<u>Oncorhynchus nerka</u> , sockeye salmon	<u>Syngnathus griseolineatus</u> , bay pipefish
<u>Oncorhynchus tshawytscha</u> , chinook salmon	
<u>Ophiodon elongatus</u> , lingcod	<u>Theragra chalcogramma</u> , walleye pollock
<u>Oxylebius pictus</u> , painted greenling	<u>Trachurus symmetricus</u> , jack mackerel
	<u>Triglops macellus</u> , roughspine sculpin
<u>Parophrys vetulus</u> , English sole	
<u>Pholis laeta</u> , crescent gunnel	<u>Xeneretmus latifrons</u> , blacktip poacher
<u>Pholis ornata</u> , saddleback gunnel	<u>Xeneretmus triacanthus</u> , bluespotted poacher
<u>Platichthys stellatus</u> , starry flounder	<u>Xiphister atropurpureus</u> , black prickleback
<u>Plectobranthus evides</u> , bluebarred prickleback	
<u>Pleuronichthys coenosus</u> , C-0 sole	<u>Zaniolepis latipinnis</u> , longspine combfish
<u>Porichthys notatus</u> , midshipmen	
<u>Poroclinus rothrocki</u> , whitebarred prickleback	
<u>Psettichtys melanostictus</u> , sand sole	
<u>Psychrolutes paradoxus</u> , tadpole sculpin	
<u>Ptychocheilus oregonensis</u> , northern squawfish	
<u>Radulinus asprellus</u> , slim sculpin	
<u>Rhacochilus vacca</u> , pile perch	
<u>Rhamphocottus richardsoni</u> , grunt sculpin	
<u>Ronquilus jordani</u> , northern ronquil	
<u>Salmo clarki</u> , cutthroat trout	
<u>Salmo gairdneri</u> , rainbow trout	
<u>Salvelinus malma</u> , Dolly Varden	
<u>Scorpaenichthys marmoratus</u> , cabezon	
<u>Sebastes auriculatus</u> , brown rockfish	
<u>Sebastes caurinus</u> , copper rockfish	
<u>Sebastes elongatus</u> , greenstripe rockfish	
<u>Sebastes emphaeus</u> , Puget Sound rockfish	
<u>Sebastes flavidus</u> , yellowtail rockfish	
<u>Sebastes maliger</u> , quillback rockfish	
<u>Sebastes melanops</u> , black rockfish	
<u>Sebastes paucispinis</u> , bocaccio	
<u>Sebastes proriger</u> , redstripe rockfish	
<u>Sebastes ruberrimus</u> , yelloweye rockfish	
<u>Sebastes saxicola</u> , stripetail rockfish	
<u>Sebastes zacentrus</u> , sharpchin rockfish	

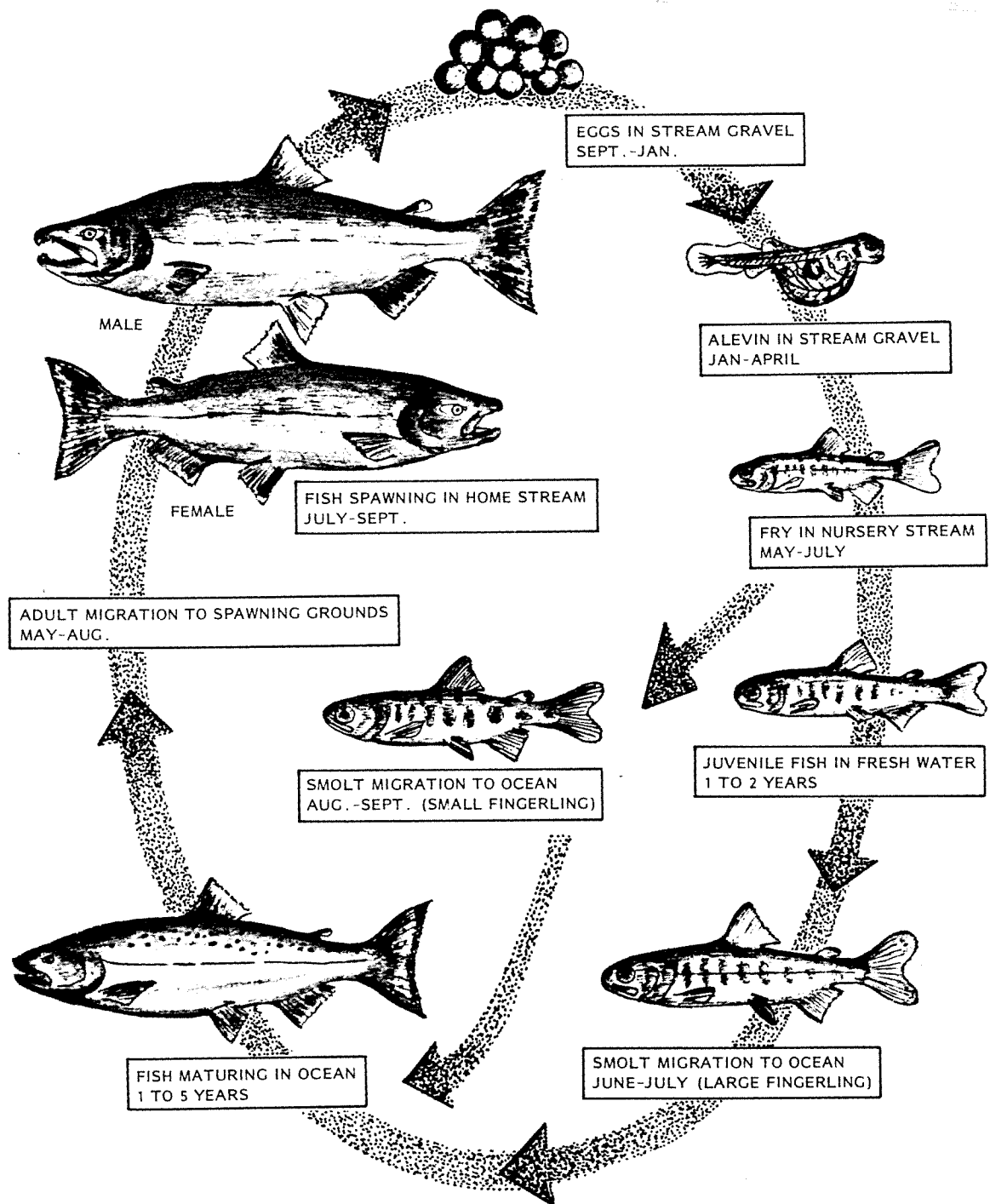


Figure 4.22. Life cycle of the chinook salmon.

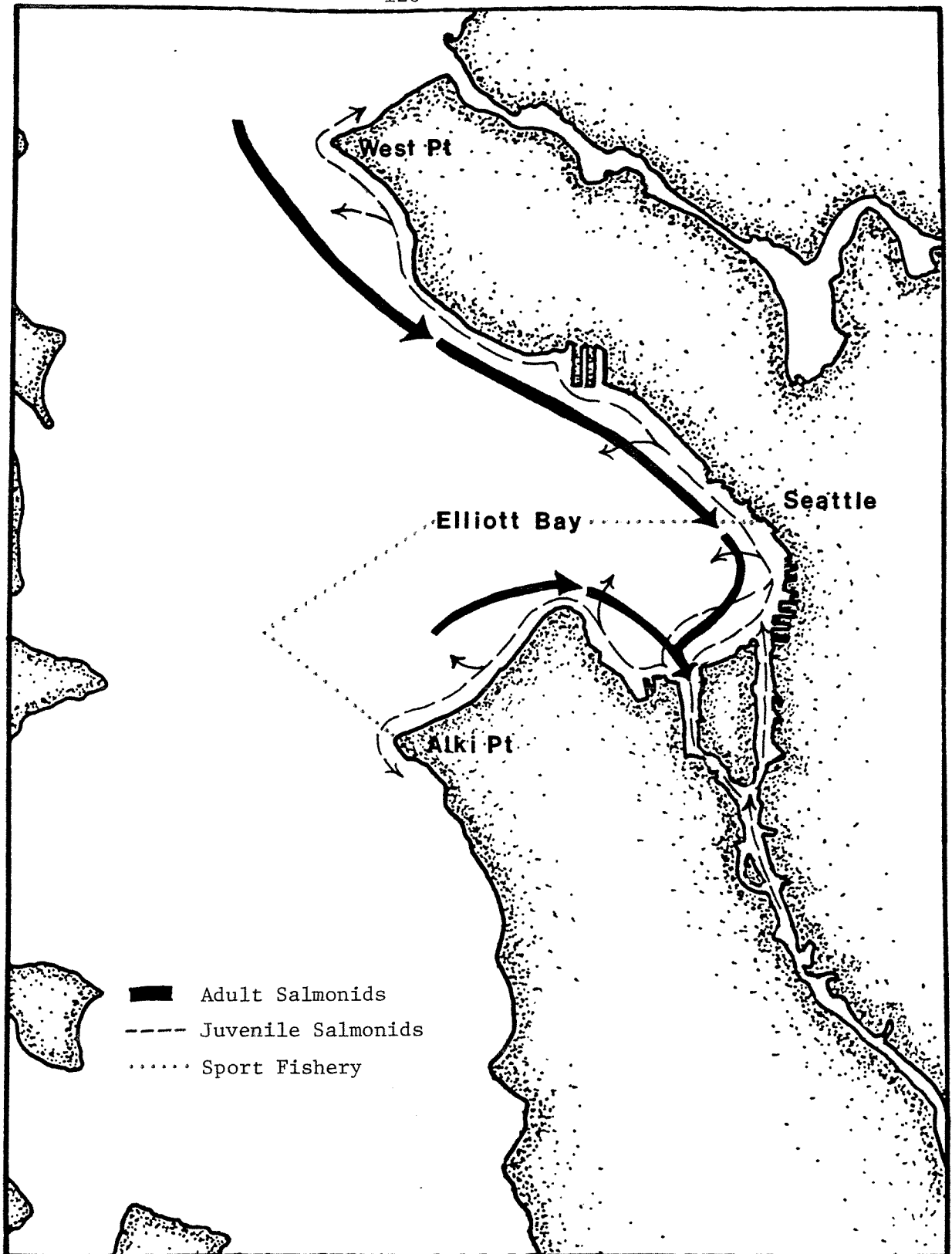


Figure 4.23. Sport fishery for and migration routes of salmonids in Elliott Bay, Seattle, Washington.

late winter to early spring. Chum juveniles move into the estuary in a few days after emergence while fall chinook spend several (3-4) months in freshwater. Coho usually spend one year in freshwater before smoltification. Chum salmon spend from 2 to 4 years, coho 1 to 3 years and chinook 1 to 4 years, respectively, at sea before returning as adults.

The cutthroat trout spawns in the winter, whereas rainbow trout spawn in both fall and winter (Table 4.15). Cutthroat trout juveniles enter seawater at a very small size and remain in the Sound or in the ocean from several months up to 3 years. Rainbow trout juveniles remain in freshwater for 2 or 3 years and then migrate to sea where they remain for 3 to 5 years. The Dolly Varden spawn in the fall. Juveniles remain in freshwater about 3 years and spend 2 to 3 years at sea. Sexual maturity occurs at five years.

Juvenile salmonids occur in the Duwamish estuary either as outmigrants or short-term residents. Juvenile chum salmon spend time in the estuary feeding and growing as they migrate. Coho juveniles move directly into the main basin of Puget Sound and are not as river-shore-estuary dependent as the chinook. Juvenile pink salmon occasionally are found in the nearshore areas of Elliott Bay. Sockeye juveniles are not found within the estuary (Weitkamp and Campbell 1980; Weitkamp and Schadt 1982). A few juvenile trout move rapidly from the estuary into the main basin of Puget Sound (Weitkamp and Campbell 1980).

During the latter half of 1960's studies were conducted to determine the effects of a polluted estuary (the Duwamish) on the behavior and physiology of salmon passing through the estuary (Salo 1969; Smith et al. 1971). Dissolved oxygen (DO) concentrations of 4.0 mg/l or less appeared to stop upstream migrating adult chinook salmon at least during the early part of the migration (Salo 1969; Fujioka 1970). Fujioka (1970) noted that during the later part of the migration the correlation between low DO and migratory delay broke down, suggesting that the urge to spawn overcame the potential deleterious effects of low DO. In addition Fujioka (1970) found the location of the low oxygen water was affected by the tide and riverflow. Migratory delay was correlated (inversely) with temperature (Salo 1969).

Smith et al. (1971) studied both coho and chinook salmon migrating through the Duwamish Estuary. They found the effects of the estuary included decreased swimming stamina and respiratory efficiency, decreased oxygen consumption and increased lactate (Mearns 1971), decreased urine flow and ammonia excretion, especially in the presence of environmental ammonia. Longer form disruptions in hematology and lipid metabolism were seen (Cardwell 1968; Smith et al. 1971). Most of the effects occurred at DO concentrations just below 5.0 mg/l, except for synergistic effects between ammonia and low DO at somewhat higher concentrations.

Wetherall (1971) conducted mark-recapture studies on juvenile chinook salmon in the Duwamish estuary and found survival rates varied from 0.37 in 1966 to 0.99 in 1969; however, he considered the higher survivals to be biased and discounted them. The juveniles appeared to reside in the estuary for two months or more and grew at a rate of 0.37 mm per day (Salo 1969). Salo (1969) cautioned that the growth rate estimate may have been biased by immigration and emmigration.

Adults of all five salmon species support an active sport and commercial fishery within the Duwamish estuary and Elliott Bay (Figure 23). For the last four years the commercial catch of salmon has exceeded 30,000 per year (Table 4.16). Concurrently the Muckleshoot Indian tribe has caught several thousand steelhead annually (Table 4.17). Sport fishermen also catch rainbow trout, cutthroat trout, and Dolly Varden char primarily in the Duwamish estuary

Table 4.15. The freshwater life history of salmon and trout residing in the Duwamish-Green River. After McGreevy (1973).

Species	Fresh-water Life Phase	Month											
		J	F	M	A	M	J	J	A	S	O	N	D
Summer-Fall chinook	Upstream migration												
	Spawning												
	Intragravel develop.												
	Juvenile rearing												
	Juv. out migration												
Coho	Upstream migration												
	Spawning												
	Intragravel develop.												
	Juvenile rearing												
	Juv. out migration												
Chum	Upstream migration												
	Spawning												
	Intragravel develop.												
	Juvenile rearing												
	Juv. out migration												
Summer steelhead	Upstream migration												
	Spawning												
	Intragravel develop.												
	Juvenile rearing ^{1/}												
	Juv. out migration												
Winter steelhead	Upstream migration												
	Spawning												
	Intragravel develop.												
	Juvenile rearing ^{1/}												
	Juv. out migration												
Searun Cutthroat	Upstream migration												
	Spawning												
	Intragravel develop.												
	Juvenile rearing ^{1/}												
	Juv. out migration												

^{1/} Normally extends over a two-year period.

Table 4.16. Commercial catch by species and year of salmonids from Elliott Bay. Numbers represent thousands of fish.¹

Species	Year			
	1979	1980	1981	1982
Chinook, <u>O. tshawytscha</u>	5.1	7.5	5.3	7.1
Coho, <u>O. kisutch</u>	26.4	27.8	19.5	37.4
Chum, <u>O. keta</u>	0.8	6.1	5.2	1.2
Sockeye, <u>O. nerka</u>	0.1	0.0	0.0	0.0
Pink, <u>O. gorbuscha</u>	0.1	0.0	0.1	0.0

¹ Data provided by Tim Flint, Washington State Department of Fisheries.

Table 4.17. The number of steelhead (Salmo gairdneri) caught annually by the Muckleshoot Indian Tribe.

Year	Winter run steelhead	Summer run steelhead
1974-75	7,419	
1975-76	6,190	2
1976-77	3,258	4
1977-78	4,340	3
1978-79	4,670	16
1979-80	4,634	4
1980-81	4,338	23
1981-82	3,656	63
1982-83	2,797	23

¹ These data supplied by Chuck Phillips, regional fisheries biologist, Washington Department of Game (WDG).

(Table 4.18).

The salmonid fishery in Elliott Bay is enhanced by chinook and coho salmon planted by the Washington State Department of Fisheries (WDF) in the Duwamish-Green River (Table 4.19). The steelhead fishery is maintained by both natural spawning and hatchery plants (Table 4.20).

4.5.1.2 Food Habits of the Salmonids

The importance of various food items to each species was estimated by using an Index of Relative Importance (IRI; Pinkas et al. 1971; Simenstad and Kinney 1978). The IRI is defined as:

$$\text{IRI} = (\text{percent frequency of occurrence}) [(\text{percent numerical composition}_i) + (\text{percent gravimetric composition}_i)]$$

where i is the prey category.

Juvenile coho from the Duwamish estuary consumed gammarids (total percent IRI = 51.93), inorganic materials (total percent IRI = 24.37), diptera (total percent IRI = 8.57) and insects (total percent IRI = 5.09). The two most important gammarid amphipods were Corophium salmonis and Eogammarus confervicolus (Meyers et al. 1981). Dipterans, calanoid copepods, gammaridean amphipods and harpacticoid copepods were the most important food items for juvenile chum salmon from the Duwamish estuary (Meyers et al. 1981). Weitkamp and Schadt (1982) found the same food organisms to be important; however the relative number of organisms of each type eaten differed from Meyers et al.'s findings (Table 4.21). Weitkamp and Schadt (1982) sampled larger fish which may partially account for the differences between the findings. The most important food items for pink salmon juveniles were harpacticoids (total percent IRI = 49.41) and calanoid copepods (total percent IRI = 40.87; Weitkamp and Schadt 1982). Meyer et al. (1981) found mysids (total percent IRI = 66.46), juvenile salmonids (total percent IRI = 8.62), gammaridean amphipods (total percent IRI = 5.07) and insects (total percent IRI = 3.01) were the most important foods eaten by juvenile steelhead.

Gammaridean amphipods, calanoid copepods, and dipteran flies were the most important food items in the diet of juvenile chinook salmon from the Duwamish estuary (Meyer et al. 1981). In contrast, Weitkamp and Schadt (1982) found calanoid copepods, brachyurans, and dipterans to be the most important food items for chinook juvenile from both the estuary and Elliott Bay (Table 4.22). The discrepancies may stem from the different areas sampled (e.g., Elliott Bay by Weitkamp and Schadt) or from the different habitats occupied by fishes of slightly different ages. For example, Charles A. Simenstad (Fisheries Research Institute, University of Washington, person. commun.) suggests that salmonids change their feeding habits as they grow and move into different habitats.

4.5.2 Fishes of the Duwamish Estuary

Using a beach seine, Matsuda et al. (1968) found the most abundant species in the Duwamish estuary to be chinook salmon, Pacific herring (Clupea harengus pallasii), shiner perch (Cymatogaster aggregata), and staghorn sculpin (Leptocottus armatus). Chinook salmon occurred seasonally while the other species were resident. Weitkamp and Campbell (1980) used beach seine, purse seine and gillnets to study the fishes near Kellogg Island (Terminal 107) in the Duwamish estuary. They identified 26 species in addition to the 5 species mentioned above. Chum salmon, coho salmon, snake pricklyback (Lumpenus sagitta), and English sole (Parophrys vetulus) were abundant.

Table 4.18. Sport catch of steelhead (Salmo gairdneri) and cutthroat trout (Salmo clarki) in the Duwamish-Green River system.¹

Year	Winter-run steelhead	Summer-run steelhead
1972-73	5,156	
1973-74	6,339	1,069
1974-75	4,326	649
1975-76	1,591	1,014
1976-77	2,400	1,722
1977-78	6,690	1,664
1978-79	7,178	2,477
1979-80	8,962	1,196
1980-81	7,225	1,528
1981-82	3,595	3,398
1982-83	3,413	1,934

Cutthroat trout catches were estimated at 2,000 annually.¹

¹ These data were supplied by Chuck Phillips, regional fisheries biologist, Washington Department of Game (WDG).

Table 4.19. The number in thousands of juvenile chinook (Oncorhynchus tshawytscha) and coho (O. kisutch) released annually into the Duwamish-Green River system. After Weitkamp and Campbell (1980).

Year	Species	Number (thousands)
1978	chinook	5151.5
1978	coho	1254.6

Table 4.20. The number of steelhead (Salmo gairdneri) planted in and migrating out of the Duwamish-Green River system. The data were provided by Chuck Phillips, Washington State Department of Game.

Year	Winter-run steelhead plants	Summer-run steelhead plants	Winter-run steelhead escapement
1973	153,400	68,900	
1974	75,100	58,300	
1975	90,300	94,500	
1976	181,000	63,800	
1977	201,000	93,900	
1978	194,500	90,000	1,077
1979	188,700	140,000	1,385
1980	161,600	118,700	1,586
1981	188,300	114,000	1,083
1982	166,600	75,800	2,121
1983	162,946	76,398	1,526

Table 4.21. Two estimates of the importance of three invertebrates in the diet of juvenile chinook (Oncorhynchus tshawytscha). IRI is the index of relative importance.

Food item	Total percent IRI	Study
Gammaridean amphipods	40.22	Meyer et al. (1981)
Calanoid copepods	25.76	Meyer et al. (1981)
Dipteran flies	16.62	Meyer et al. (1981)
Calanoid copepods	59.75	Weitkamp and Schadt (1982)
Brachyura	11.75	Weitkamp and Schadt (1982)
Diptera	7.91	Weitkamp and Schadt (1982)

Table 4.22. The importance of various organisms in the diet of juvenile chinook (Oncorhynchus tshawytscha). IRI is the index of relative importance.

Food item	Total percent IRI	Study
Diptera	47.84	Meyer et al. (1981)
Calanoida	21.04	Meyer et al. (1981)
Gammaridea	17.30	Meyer et al. (1981)
Harpacticoida	7.03	Meyer et al. (1981)
Calanoida	58.24	Weitkamp and Schadt (1982)
Diptera	17.84	Weitkamp and Schadt (1982)
Harpacticoida	14.65	Weitkamp and Schadt (1982)
Gammaridea	3.64	Weitkamp and Schadt (1982)

Table 4.23. Fishes collected in the Duwamish River during 1975-76. F (frequent) indicates species that occurred in more than 70 percent of the samples; C (common) indicates species that occurred in 30-70 percent of the samples. R (rare) indicates species that occurred in less than 30 percent of the samples. After Miller et al. (1977).

Species	Total number	Frequency of occurrence
Spiny dogfish	1	R
Ratfish	1	R
Pacific herring	73	C
Coho salmon	11	R
Longfin smelt	1555	C
Eulachon	2	R
Pacific cod	1	R
Pacific tomcod	639	C
Tubesnout	1	R
Shiner perch	209	C
Striped seaperch	3	R
Pile perch	11	R
Snake prickleback	1971	C
Saddleback gunnel	1	R
Bay goby	15	R
Padded sculpin	49	C
Roughback sculpin	7	R
Buffalo sculpin	8	R
Pacific staghorn sculpin	964	F
Prickly sculpin	2	R
Sturgeon poacher	1	R
Pygmy poacher	3	R
Rock sole	120	C
Slender sole	8	R
Dover sole	69	R
English sole	1610	F
Starry flounder	1361	C
Sand sole	103	C
English sole x starry flounder hybrid	3	R
Total No. Individuals	8802	
Total No. Species	29	

Table 4.24. Sport catches of bottom and near-bottom fishes for 1982 in Elliott Bay. Numbers represent single fish.¹

Species	Caught from a boat	Caught from a pier	Total
Rock sole, <u>Lepidopsetta</u> <u>bilineata</u>	3,661	330	3,991
English sole, <u>Parophrys vetulus</u>	47	0	47
Sand sole, <u>Psettichthys</u> <u>melanostictus</u>	920	0	920
Starry flounder, <u>Platichthys stellatus</u>	0	132	132
Pacific sanddab, <u>Citharichthys sordidus</u>	9,318	66	9,384
Sablefish, <u>Amoplopoma fimbria</u>	15,259	2,244	17,503
Bocaccio, <u>Sebastes paucispinis</u>	74	0	74
Copper rockfish, <u>Sebastes caurinus</u>	0	83	83
Sculpins, family Cottidae	72	231	303
Surfperches, family Embiotocidae	0	1,089	1,089
Pacific cod, <u>Gadus macrocephalus</u>	13,124	198	13,332
Tomcod, <u>Microgadus proximus</u>	344	0	344
Walleye pollock, <u>Theragra chalcogramma</u>	12,130	100	12,230

Table 4.24. (continued).

Species	Caught from a boat	Caught from a pier	Total
Pacific hake, <u>Merluccius productus</u>	15,435	565	16,000
Spiny dogfish, <u>Squalus acanthias</u>	1,437	264	1,701

¹ Data provided by Mark Pedersen, Washington State Department of Fisheries.

Table 4.25. Fishes collected off West Point during 1975-76.
 F (frequent) indicates species that occurred in more than 70 percent of the samples; C (common) indicates species that occurred in 30-70 percent of the samples; R (rare) indicates species that occurred in less than 30 percent of the samples. After Miller et al. (1977).

Species	Total number	Beach seine			Otter trawl depths				
		9m net	37m ^a net	37m ^b net	5m	25m	45m	70m	95m
Spiny dogfish	9		R	R					
Ratfish	1,420		R		R	C	C	F	F
Pacific herring	481	R	C	C					
Chum salmon	92	R	R	R					
Coho salmon	168		C	R					
Chinook salmon	24		R	C					
Pink salmon	13		R	R					
Dolly Varden	2		R						
Surf smelt	55		R	R					
Longfin smelt	2		R						
Midshipman	1					R			
Pacific tomcod	4,836	C	C	C	R	R	C	C	R
Walleye pollock	18		R				R	R	R
Pacific cod	1					R			
Pacific hake	1								R
Red brotula	1								R
Blackbelly eelpout	56		R			R	R	R	R
Tube-snout	7		R	R	R				
Threespine stickleback	22	R	R	R					
Bay pipefish	1			R					
Shiner perch	4,419	C	C	C	R	R	C	C	R
Striped seaperch	119	R	C	R	R	R	R		
Pile perch	44		C	R		R	R		
Northern ronquil	58		R	R		R	C	R	
Snake prickleback	79		R	R	R	R	R		
Penpoint gunnel	5	R	R	R		R			

^a 37m sinking beach seine.

^b 37m floating beach seine.

Table 4.25. (continued).

Species	Total number	Beach seine			Otter trawl depths				
		9m net	37m ^a net	37m ^b net	5m	25m	45m	70m	95m
Saddleback gunnel	3	R	R						
Pacific sandlance	247	R	R	R					
Brown rockfish	56					C	C		R
Copper rockfish	2					R	R		
Redstripe rockfish	2						R	R	
Quillback rockfish	84					C	C	R	C
Painted greenling	2					R			
Whitespotted greenling	3		R						
Padded sculpin	68	R	C	R		R	R		
Scalyhead sculpin	1					R			
Silverspotted sculpin	9		R	R	R				
Roughback sculpin	61		R		R	C	C	R	R
Sharpnose sculpin	42	R		R					
Buffalo sculpin	96	C	C	C	R				
Pacific staghorn sculpin	296	F	F	C	R	R	R		
Great sculpin	3		R	R					
Manacled sculpin	1					R			
Sailfin sculpin	6		R			R	R		
Tidepool sculpin	27	R	R	R					
Red Irish lord	1					R			
Slim sculpin	13						C	R	R
Tadpole sculpin	1					R			
Grunt sculpin	1					R			
Cabezon	2		R			R			
Northern spearnose poacher	5					R	R		
Sturgeon poacher	92	R	C	R		R	C	R	
Gray starsnout	4						R	R	
Spinycheek starsnout	6					R	R	R	
Pygmy poacher	7					R	R		

^a 37m sinking beach seine.

^b 37m floating beach seine.

Table 4.25. (continued).

Species	Total number	Beach seine			Otter trawl depths				
		9m net	37m ^a net	37m ^b net	5m	25m	45m	70m	95m
Blacktip poacher	7							R	R
Bluespotted poacher	31	R					R	C	R
Tidepool snailfish	1					R			
Pacific sanddab	97		R		R	R	C		
Speckled sanddab	56		C		C	C	R		
Rex sole	60						R	F	C
Butter sole	5		R		R				
Rock sole	1,639	R	F	C	F	F	F	R	R
Slender sole	62	R	C			R	C	C	C
Dover sole	229	R	R			R	C	F	F
English sole	4,114	F	F	F	F	F	F	C	C
Starry flounder	32	R	C	R	R	R			
C-0 sole	92		C	R	C	C	R		
Sand sole	26	R	R	R	R	R	R		
Hybrid sole	1		R						
Flathead sole	1						R		
Arrowtooth flounder	1						R		
Total number of individuals	19,537								
Total number of species	72								

^a 37m sinking beach seine.

^b 37m floating beach seine.

Table 4.26. Fishes collected off Alki Point during 1975-76.
F (frequent) indicates species occurred in greater than 70 percent of the samples; C (common) indicates species occurred in 30-70 percent of the samples; R (rare) indicates species occurred in less than 30 percent of the samples. After Miller et al. (1977).

Species	Total number	Beach seine net		Otter trawl depths		
		9m net	37m* net	5m	45m	70m
Spiny dogfish	1		R			
Ratfish	314				C	F
Pacific herring	13	R	R			
Chum salmon	41		R			
Pink salmon	6		R			
Coho salmon	25		R			
Chinook salmon	34	R	R			
Rainbow trout	1		R			
Surf smelt	1		R			
Midshipman	37				C	R
Northern clingfish	2	R	R			
Pacific cod	17		R		R	
Pacific tomcod	687	C	F	R	C	C
Walleye pollock	47		R	R	R	R
Pacific hake	3					R
Blackbelly eelpout	24				R	R
Tube-snout	1,874	C	F	C		
Threespine stickleback	2	R	R			
Bay pipefish	35	C	C			
Shiner perch	6,509	R	F	R	R	R
Striped seaperch	2,164	R	F	C		R
Pile perch	108	R	F	R		R
Northern ronquil	69				C	R
Wolf eel	1		R			
Snake prickleback	10		R			
Penpoint gunnel	127	F	F	R	R	
Crescent gunnel	21	R	R	R		
Saddleback gunnel	26	C	C			
Brown rockfish	31		R	R	C	R
Sharpchin rockfish	1				R	

*37-m floating beach seine (see Materials and Methods).

Table 4.26. (continued).

Species	Total number	Beach seine net		Otter trawl depths		
		9m net	37m* net	5m	45m	70m
Copper rockfish	3		R			
Quillback rockfish	45		R		C	R
Redstripe rockfish	15				R	
Painted greenling	4			R	R	
Whitespotted greenling	3		R			
Padded sculpin	337	C	F	C	R	
Smoothhead sculpin	5	R	R			
Silverspotted sculpin	71	R	C	R		
Roughback sculpin	162		R	R	F	R
Sharpnose sculpin	76	C	R			
Buffalo sculpin	88	C	C	R		
Northern sculpin	9				R	
Red Irish lord	14		R	R		
Spotfin sculpin	77			R	C	R
Pacific staghorn sculpin	172	C	F		R	
Grunt sculpin	1			R		
Great sculpin	19	R	R			
Sailfin sculpin	40		R		R	R
Tidepool sculpin	19	C	C			
Threadfin sculpin	1					R
Slim sculpin	44			R	R	R
Manacled sculpin	1		R			
Roughspine sculpin	1				R	
Ribbed sculpin	1				R	
Cabezon	6		R	R		
Northern spearnose poacher	14				R	
Spinycheek poacher	1				R	
Sturgeon poacher	55		C	R	R	R
Gray starsnout	5			R		R

*37-m floating beach seine (see Materials and Methods).

Table 4.26. (continued).

Species	Total number	Beach seine net		Otter trawl depths		
		9m net	37m* net	5m	45m	70m
Pygmy poacher	64				C	R
Blacktip poacher	30					R
Bluespotted poacher	69				R	C
Pacific sanddab	32				R	
Speckled sanddab	72	R	C	R		
Rex sole	32				R	C
Rock sole	1,381	C	F	F	F	R
Slender sole	83		R		R	C
Dover sole	178		R		R	F
English sole	1,530	F	F	F	F	C
Starry flounder	8		R			
C-O sole	357		F	F	R	
Sand sole	10			R		
Arrowtooth flounder	1					R
Flathead sole	1					R
Total No. Individuals	17,367					
Total No. Species	75					

*37-m floating beach seine (see Materials and Methods).

Table 4.27. Seasonal abundance of fish eggs sampled near West Point with a Miller net during 1975-76. After English and Thorne (1977).

	<u>JUL</u>	<u>AUG</u>	<u>SEP</u>	<u>OCT</u>	<u>NOV</u>	<u>DEC</u>	<u>JAN</u>	<u>FEB</u>	<u>MAR</u>	<u>APR</u>	<u>MAY</u>	
<u>Less than 1 mm</u>												
<i>Citharichthys</i>		2										
<u>About 1 mm</u>												
<i>Parophrys</i>							2	36	23			
<i>Psettichthys</i>								1	2	3		
<i>Isopsetta(?)</i>									12		1	
dead								69	45	27		
<i>Pleuronichthys</i>		23	47							1	21	
<u>About 2 mm</u>												
<i>Gadus</i>								1	125	102	1	
<i>Merluccius</i>								4	17	9	12	
<i>Lyopsetta</i>									1	2	3	
<i>Glyptocephalus</i>											1	
<i>Scomber(?)</i>											1	
<u>About 3 mm</u>												
<i>Hippoglossoides</i>										1		
<u>Unidentified</u>										5		
TOTAL EGGS		25	47	0	0	0	0	2	111	225	150	40

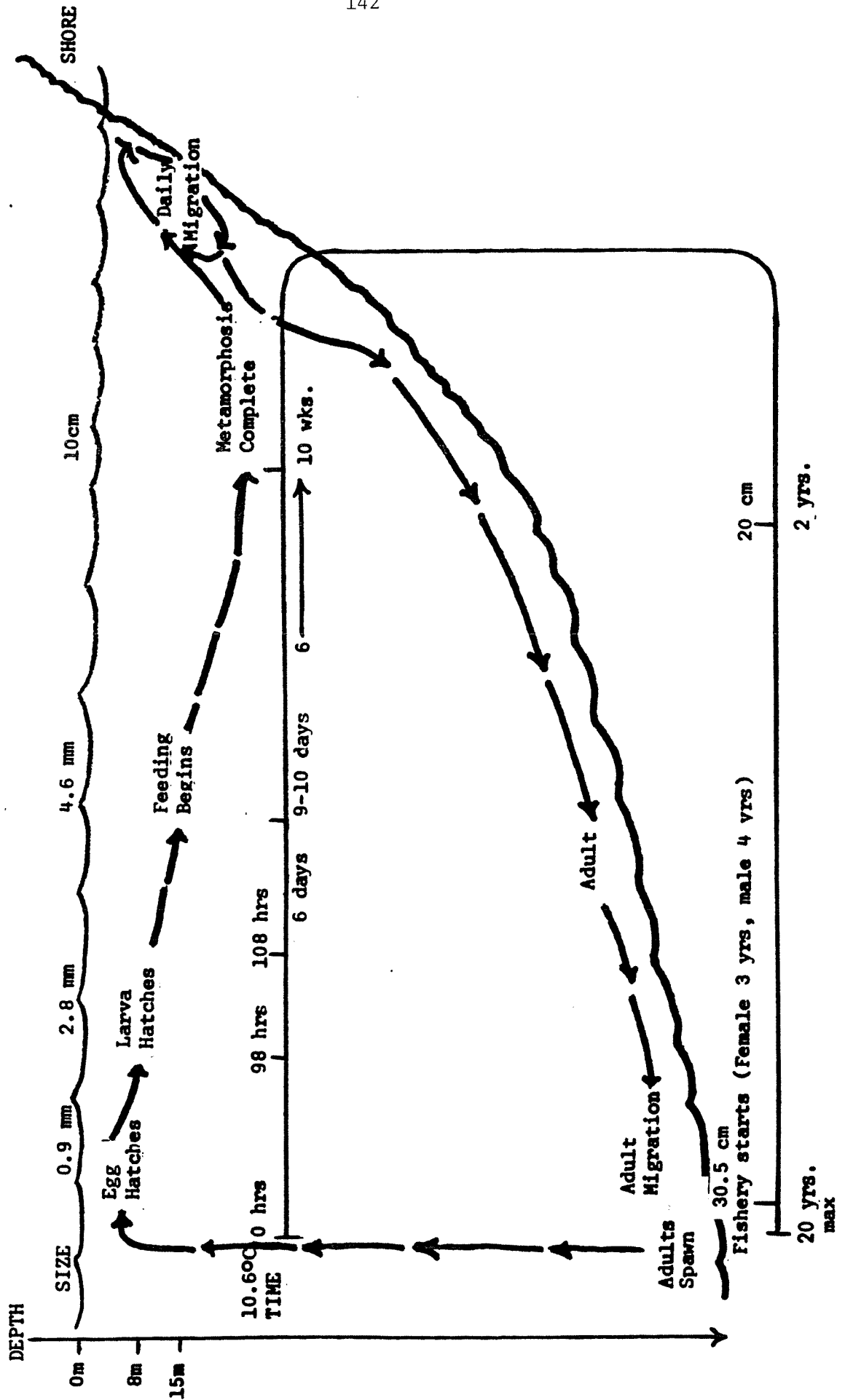


Figure 4.24. Life history of the English sole (*Parophrys vetulus*). Data from Hart (1973).

Salo (1969) used a 3-meter beam trawl to capture demersal fishes from the Duwamish estuary. Twenty species were collected; five species contributed over 92 percent of the total number caught. These five species were staghorn sculpin, starry flounder (Platichthys stellatus), English sole, snake prickleback, and Artedius sp. (primarily the padded sculpin, A. fenestralis). Miller et al. (1977) collected 8,802 fish comprising 29 species from the Duwamish estuary (Table 4.23). English sole and staghorn sculpin occurred most frequently (> 70% of the total samples). Commonly occurring species (30-70%) included: Pacific herring, longfin sculpin, tomcod (Microgadus proximus), shiner perch, snake prickleback, padded sculpin, rock sole (Lepidopsetta bilineata), starry flounder and sand sole (Psettichthys melanostictus). The ten most abundant species represented nearly 98% of the total catch.

4.5.3 Demersal Fishes of Elliott Bay

Demersal fishes of Elliott Bay, although not as economically important as salmon are nevertheless important. For example, in 1982 the Washington Department of Fisheries estimated that over 75,000 pounds of demersal fishes were caught within Elliott Bay (Table 4.24). Little is known about the species assemblages that exist within Elliott Bay; however, extensive studies have been conducted at Alki and West Points.

Miller et al. (1975, 1976, and 1977) and Moulton et al. (1974) found 62 fish species which occurred at both Alki and West Points (Tables 4.25 and 4.26). In addition, twelve species were confined to Alki Point and 10 species to West Point. No abundant species was confined to or absent from either site. At each site the majority of species and individuals were taken with beach seine rather than bottom trawl gear.

Of the 11 species commonly caught with the beach seine, the lowest number (3) occurred at West Point, while 11 species were found at Alki Point. Staghorn sculpin, rock sole, and English sole were abundant at each site. Of the eight species commonly caught by trawl, only ratfish (Hydrolagus colliei), rock sole and English sole were abundant at both sites.

4.5.3.1 Life History of a Typical Flatfish

One of the most abundant demersal fishes is the English sole. Adults are believed to spawn in deep water in January and February. The pelagic eggs rise to the surface where they drift at the mercy of the wind and water currents (Figure 4.24). After hatching, the larvae are bilaterally symmetrical with one eye on each side of their head. At about 3-1/2-4 months of age, the larval flatfish undergo metamorphosis. During metamorphosis the left eye migrates to the right side of the head. The result is a fish with both eyes on the same side of the head. After metamorphosis the juveniles take up bottom residence in the inshore areas. A daily migration occurs within the nearshore region. At about nine months of age (the first autumn) the flatfish move into deeper water. As the juveniles grow and mature, they migrate within and out of Puget Sound. At maturity the adults move offshore into deep water and spawn.

English and Thorne (1977), sampled pelagic fish eggs near West Point on a monthly basis (Table 4.27) and found the greatest concentration of eggs to occur during the winter and early spring months. Some evidence supports the thesis that flatfish may spawn in Elliott Bay. Larval egg surveys in Elliott Bay (English 1961) demonstrated that the least developed eggs were found at

deeper water depths. More highly developed eggs were found in even greater abundance at the surface of the bay (English 1961). The evidence that Elliott Bay may be an important flatfish spawning area remains circumstantial (Figure 4.25).

4.5.3.2 Parasitic Infestations of Demersal Fishes

Miller et al. (1977) and Miller (1980) found that English and rock sole were frequently infested with the parasitic nematode Philometria (blood worm). External parasites were not detected on either English sole or rock sole less than 150 millimeters total length. The incidence of blood worm was higher in the winter and fall and lowest in the spring and summer. Seventy-one percent of the shiner perch collected contained infestations of gill lice (Caligus rapax).

Parasites of the suborders Monopisthocotylea and Polypisthocotylea were found on gill membranes of English sole, rock sole, staghorn sculpin, tomcod and black rockfish (Sebastes maliger; Malins et al. 1980). Copepods and a rickettsium-like organism were also found in the gills of the above species.

4.5.3.3 Reef Fishes

Little is known about reefs and associated fishes in Elliott Bay. Miller (1980), while diving among pier pilings in Elliott Bay, observed several fish species typically associated with reefs (Table 4.28 and 4.29).

Both trawling (5 min, 385 m transects) and SCUBA diving were used by Miller (1980) to sample fishes at Terminals 90-91 and 37 in Elliott Bay. The total number of species, 20, obtained by trawling was similar at both locations. Principal species in the dominant assemblage were English sole, rock sole, flathead sole and shiner perch. Shannon's diversity index was calculated to be 1.5 at both sites. Ninety seven percent of the species sampled were economically important.

The total number of species observed during dives ranged from 10-12. Similar species were noted, but pile perch and rockfish (as opposed to shiner perch and flatfish) were the principal species. The number of fishes per 100 m² ranged from 3.53 to 47.49 depending upon whether the transect was along the landward or seaward side of the terminal (Tables 4.30 and 4.31).

4.5.4 Rocky Intertidal Fishes

Very little rocky intertidal habitat exists within Elliott Bay. Consequently the typical rocky intertidal fish assemblages do not occur within Elliott Bay. However, some tidepool fishes (for example, the tidepool sculpin, Oligocottus maculosus) can occasionally be found in the intertidal regions (Borton 1982).

4.5.5 Abundance and Species Richness

Species richness and total abundance in the Duwamish estuary exhibited considerable annual variation. Catch per haul was generally lowest during late fall and winter, increased markedly through spring and summer (with the exception of a slight decline in July) and peaked in the late summer and early fall. Species richness in the Duwamish estuary showed similar but less dramatic variation. Abundance and species richness through the waterway showed similar seasonal patterns. The relative abundance of the five most

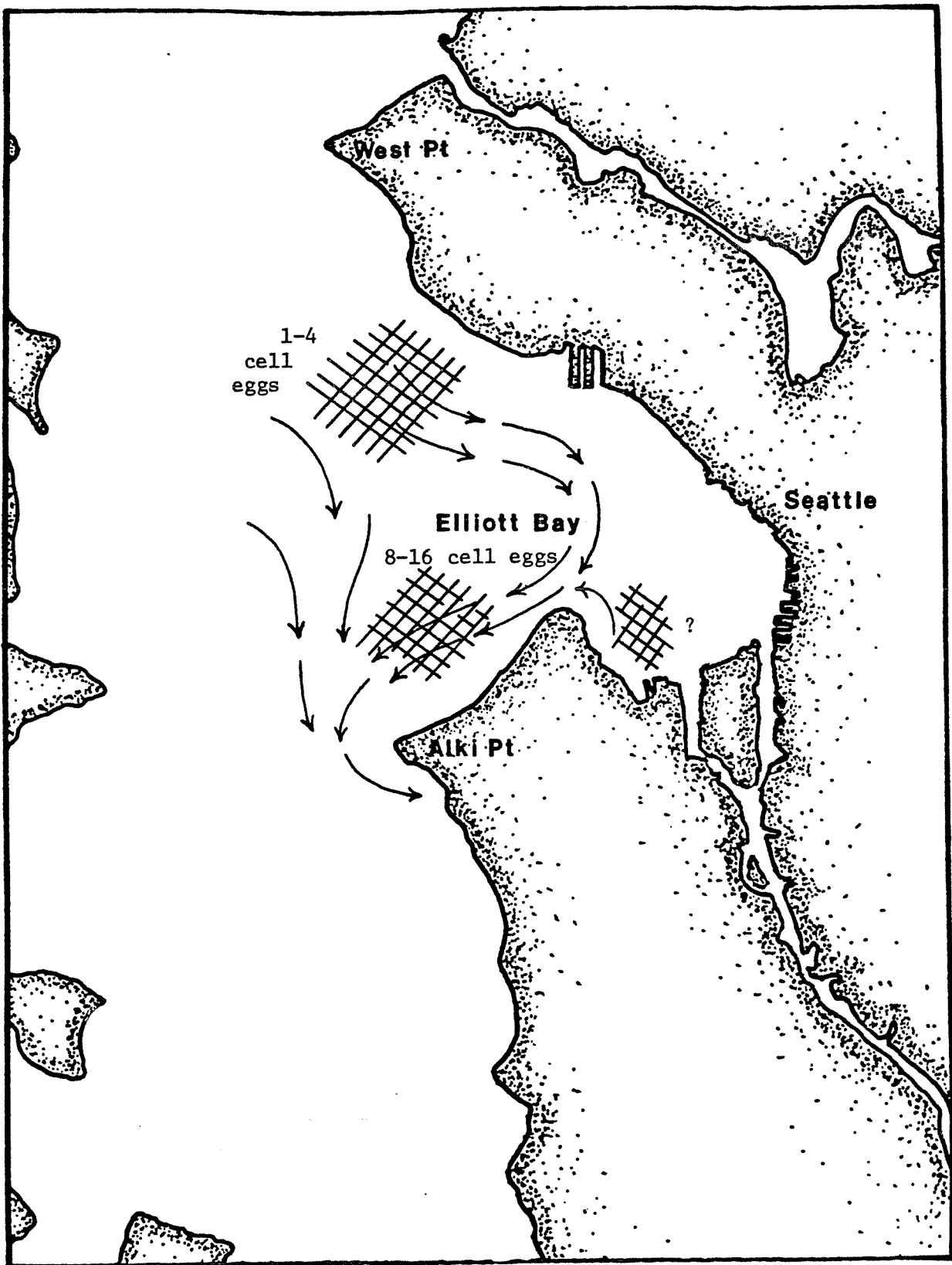


Figure 4.25. Proposed spawning grounds for the English sole (*Parophrys vetulus*). Data provided by Dr. B. S. Miller, Fisheries Research Institute, University of Washington.

Table 4.28. Species and numbers of fish sighted during diving straightline transect series surveys at Pier 91 and 90 (ad = adult, juv = juvenile, UID = unidentified). After Miller (1980).

Species	Slip 91-90						Slip 90 East					
	Landward			Seaward			Landward			Seaward		
	Shallow	Bottom Deep	Surface Deep	Shallow	Bottom Deep	Surface Deep	Shallow	Bottom Deep	Surface Deep	Shallow	Bottom Deep	Surface Deep
Sand lance ad							1					
UID juvs (prob. herring, smelt or sand lance)												(50)
Pacific cod ad	3											
Shiner perch											70	
Pile perch		4	1	2			5	1	25	1	20	4
Striped seaperch					1						20	
Copper rockfish ad	1											
Copper rockfish juv	1											
Brown rockfish ad	1					3				3		
Brown rockfish juv	2									2		
Quillback rockfish ad								1				
UID rockfish ad							1					
UID rockfish juv		3										
English sole ad		1						1		1		
Rock sole ad	1				2						2	
UID flatfish ad	1											
Painted greenling ad				1								
UID sculpins							2					
Sturgeon poacher ad								1				
UID fish								1				

Table 4.29. Species and numbers of fish sighted during diving zig-zag transect surveys at the end of Pier 91 and off Terminal 37. After Miller (1980).

Species	<u>Pier 91</u>			<u>Terminal 37</u>		
	Depth(m)			Depth(m)		
	0-5	6-10	>10(11-14)	0-5	6-10	>10(11-18)
Herring juv				*		
Walleye pollock						2
Pile perch	10	20				6
Copper rockfish ad						1
Brown rockfish ad		1				2
Quillback rockfish ad			1			
Quillback rockfish juv			1			
Black rockfish ad	1					
English sole ad						1
Rock sole ad		1				
UID flatfish		1				
Painted greenling ad		1				1
Sturgeon poacher	1					
UID sculpin (<u>Artedius</u> sp.)					1	

* Several thousand juvenile herring were seen at the surface waters at Terminal 37--some were seen outside the pier and some underneath the pier. These juvenile herring were not seen until after the transect had been completed.

Table 4.30. Abundance of fish (number fish/100 m²) in pilings and riprap along sides of Piers 91 and 90. After Miller (1980).

Species Group	Slip 91-90 Transects		Slip 90 East Transects	
	Landward	Seaward	Landward	Seaward
Pacific cod	1.23	0.0	0.49	0.0
Surfperch	2.46	1.18	15.29	44.40
Rockfish	3.28	1.18	0.99	1.93
Flatfish	1.23	0.79	0.99	1.16
Misc. other	0.0	0.39	1.97	* 0.0
Total Fish	8.20	3.53	19.72	* 47.49

*These values do not include a school of 50 juvenile fish (which were probably herring, smelt, or sand lance) seen in the surface waters under Pier 90.

Table 4.31. Abundance of fish (number of fish/100 m²) associated with pilings and riprap at the end of Pier 91 and Terminal 37. After Miller (1980).

Species Group	Pier 91 Transect	Terminal 37 Transect
Walleye pollock	0.0	0.58
Surfperch	15.23	1.73
Rockfish	2.03	0.87
Flatfish	1.02	0.28
Misc. other	1.02	*0.58
Total Fish	19.29	*4.05

*These values do not include several thousand juvenile herring seen in the surface waters of Terminal 37 after the transect dive was completed.

important species (snake pricklyback, English sole, longfin smelt, starry flounder, and staghorn sculpin) fluctuated throughout the year (Figure 4.26). Snake pricklyback were most abundant in the estuary during the spring, summer and fall. In contrast, starry flounder were most abundant during the fall and winter and least abundant during the summer (Griggs 1979; Miller et al. 1977). Longfin smelt were most abundant in late fall, early winter and summer. The fall-winter peak consisted of longfin smelt 80-115 mm in total length and probably represented a spawning run. The late summer peak of longfin smelt consisted solely of young-of-the-year downstream migrants ranging from 30 to 50 mm in total length. English sole and staghorn sculpin appeared to be waterway residents. Both species were abundant throughout the year with English sole abundance peak in spring and staghorn sculpin most abundant in fall.

At both West Point and Alki Point the lowest values for abundance and species richness occurred during the late winter and early spring. At Alki Point, abundance and species richness increased during the spring and early summer, declined in late summer, then increased again through the fall. West Point had only a single abundance peak in fall. Species richness increased in spring and peaked in summer, but declined throughout the remainder of the year. Diversity as measured by the Shannon-Wiener index exhibited an annual cycle at both sites. Diversity was highest in the late spring, declined during the summer and then increased again in fall and early winter.

Borton (1982) and Miller et al. (1977) found striking differences in abundance and species richness in fishes associated with eelgrass as opposed to fishes associated with sand substrates (Table 4.32). Forty-one species were collected from eelgrass areas, but only 22 species from sandy areas. In addition, the density (fish per unit area of bottom) was substantially higher in eelgrass by a factor of nearly 9:1. The most abundant eelgrass species included sand lance (*Ammodytes hexapterus*), *A. lateralis* and shiner perch while shiner perch, English sole, and tomcod were dominant on sand. Several species were clearly eelgrass - associated and no species was more abundant on sand than in eelgrass. Abundance and species richness were much higher in eelgrass than on sand (Figure 4.27); however, the seasonal patterns of abundance were similar, and were characterized by early summer and fall peaks. In contrast to abundance, species richness increased in early summer and remained high through fall.

Malins et al. 1980 compared the species diversity of several bays in Puget Sound. Elliott Bay had the highest Shannon-Wiener diversity index, 2.7-2.8 during the summer and fall. They further state "deep water stations in Elliott Bay had greater species diversity and [species] richness than those stations in the waterways of these bays...."

Seasonal bathymetric patterns of abundance were similar at both Alki Point and West Point although absolute abundance differed between the two sites (Figure 4.28). Abundance was highest at 45 meters during the fall, but was greatest at 5 meters during the spring and summer. The increase in the shallow water abundance stemmed from the onshore movement of adult English sole and rock sole during spring and summer. Species richness showed a similar but less distinct seasonal pattern. Although several species moved into shallow water in spring and summer, a substantial portion of the increase in species richness, at least at Alki Point, was caused by an increase in the number of nearshore species normally associated with eelgrass or kelp. Alki Point has extensive eelgrass beds whereas eelgrass is generally absent on the north side of West Point (the study location). Diversity showed similar patterns in abundance and species richness.

Table 4.32. Species collected at Alki Point with the 9-m beach seine from May 1976 through January 1977. After Miller et al. (1977).

Species	Total number	Eelgrass		Sand	
		Number	Frequency of occurrence	Number	Frequency of occurrence
Pacific sandlance	1,250	1,250	0.04		
Striped seaperch	992	988	0.76	4	0.08
Shiner perch	846	758	0.84	88	0.21
Tube-snout	655	655	0.64		
Padded sculpin	417	400	0.88	17	0.46
English sole	710	385	1.00	325	0.79
Crescent gunnel	334	328	0.88	6	0.25
Pacific tomcod	390	306	0.36	84	0.33
Rock sole	110	94	0.84	16	0.33
Sharpnose sculpin	122	86	0.52	36	0.42
Buffalo sculpin	88	72	0.88	16	0.50
Saddleback gunnel	73	63	0.76	10	0.29
Bay pipefish	60	60	0.64		
C-O sole	59	59	0.68		
Penpoint gunnel	59	57	0.68	2	0.08
Sturgeon poacher	42	42	0.44		
Pacific staghorn sculpin	55	34	0.60	21	0.38
Silverspotted sculpin	30	28	0.52	2	0.08
Coho salmon	22	22	0.08		
Sailfin sculpin	16	16	0.28		
Pile perch	13	13	0.24		
Smoothhead sculpin	8	8	0.24		
Great sculpin	7	6	0.20	1	0.04
Scalyhead sculpin	4	4	0.12		
Walleye pollock	4	4	0.16		
Threespine stickleback	6	3	0.08	3	0.04
Cabezon	3	3	0.12		
Snake prickleback	5	3	0.12	2	0.08
Tadpole sculpin	3	3	0.08		
Sand sole	5	2	0.08	3	0.13
Speckled sanddab	2	2	0.08		
Pink salmon	2	2	0.04		
Starry flounder	3	2	0.04	1	0.04
Pacific cod	2	2	0.08		
Brown rockfish	2	2	0.08		
Whitespotted greenling	2	2	0.08		
Roughback sculpin	2	2	0.08		
Manacled sculpin	1	1	0.04		
High cockscomb	1	1	0.04		
Quillback rockfish	1	1	0.04		
Surf smelt	5	1	0.04	4	0.13
Tidepool sculpin	6			6	0.17
Pacific herring	15			15	0.21
Slender sole	1			1	0.04
	6,433	5,770		663	

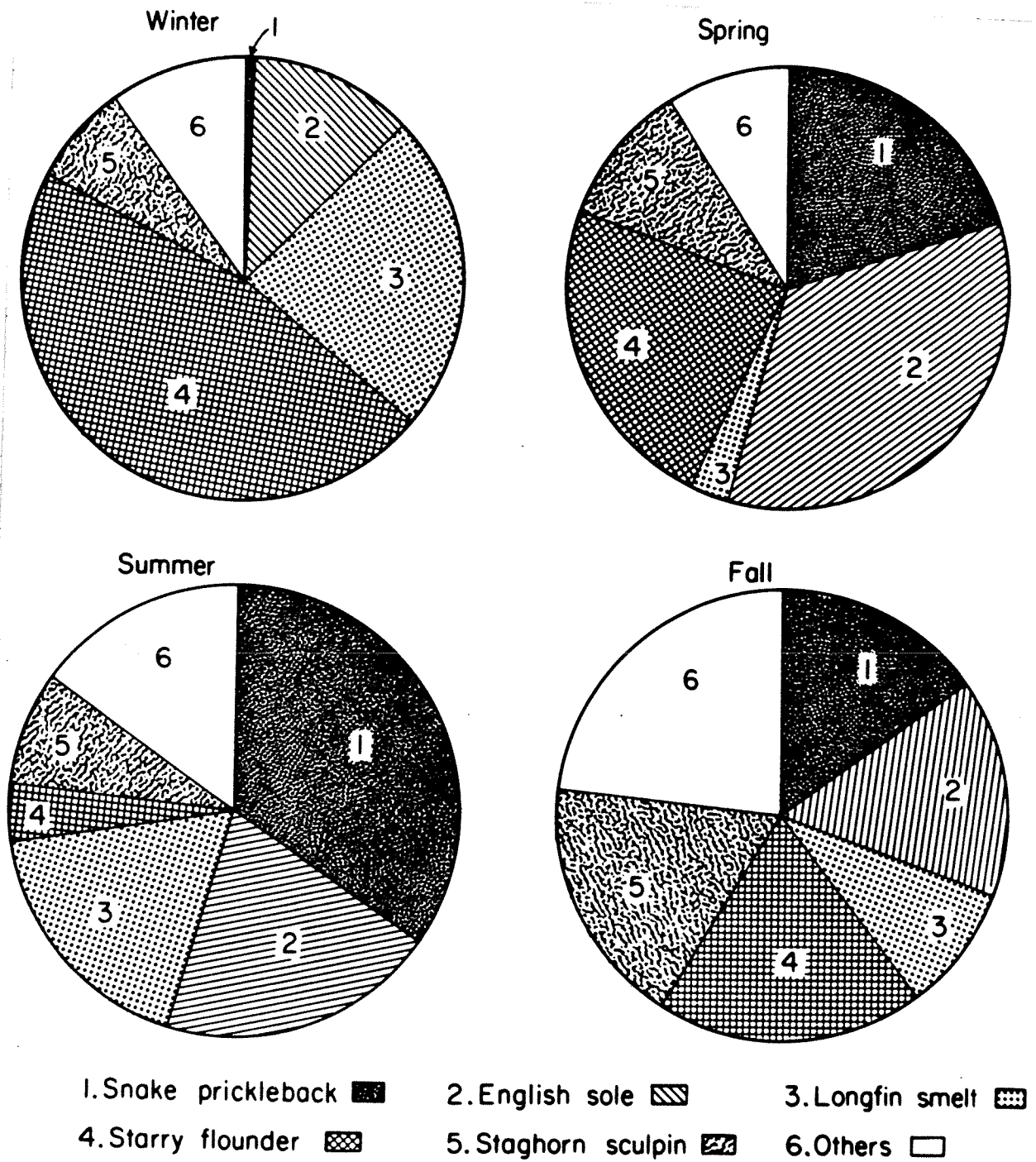
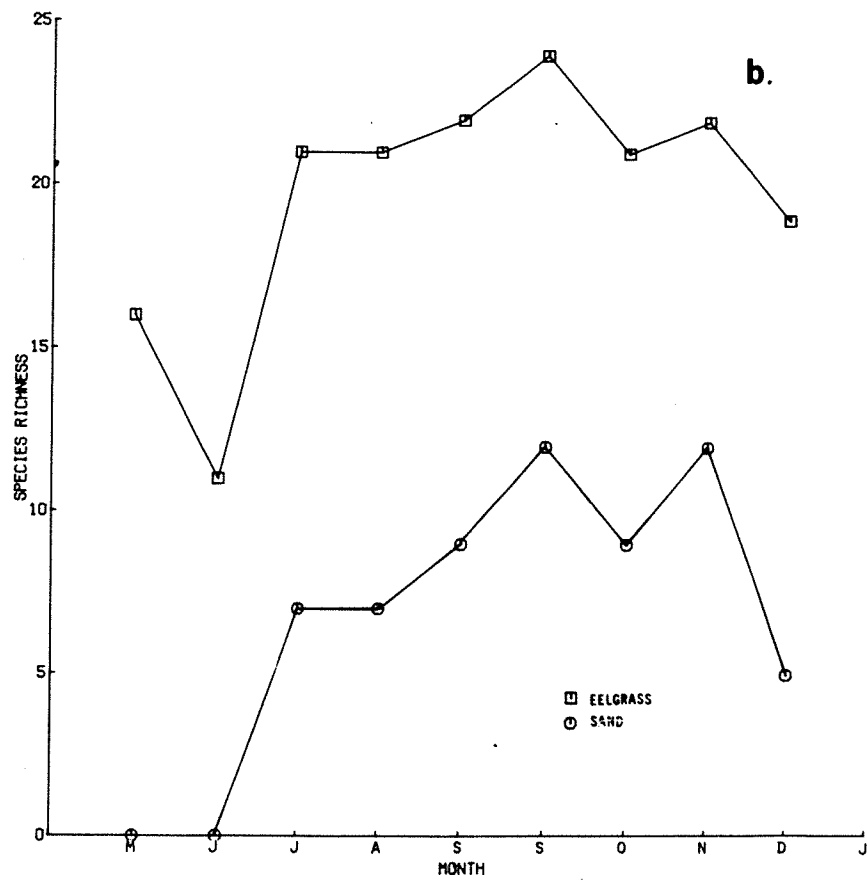
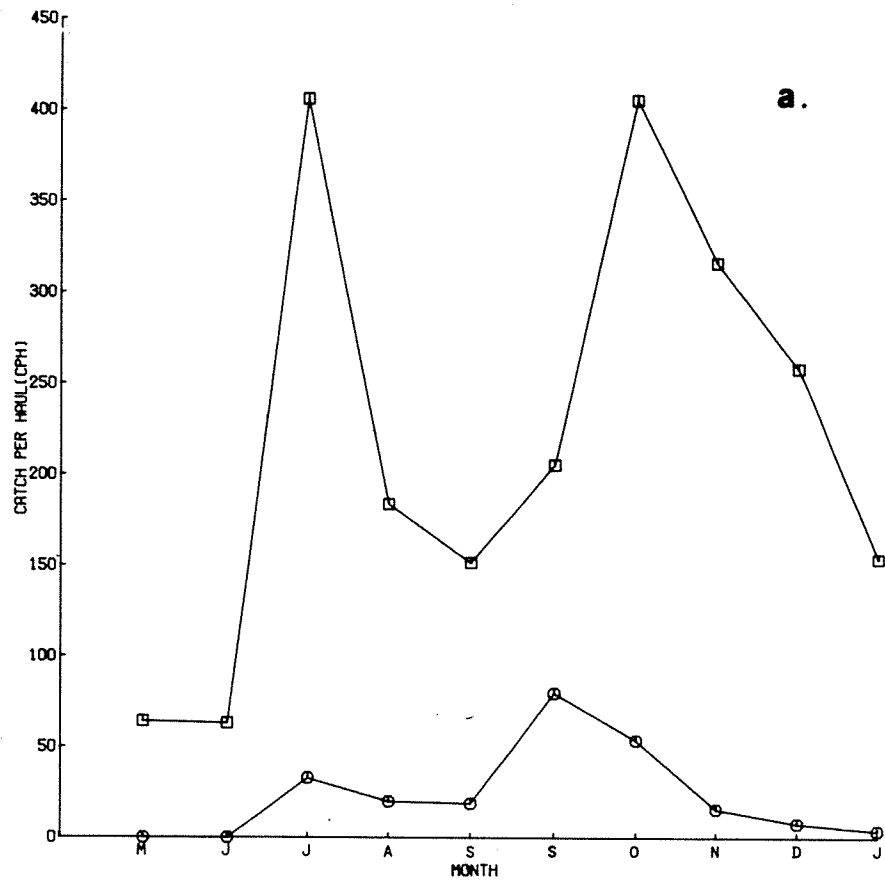


Figure 4,26. Relative seasonal abundance of the five most abundant fish species in the Duwamish River during 1975-76. After Miller et al. (1977).

Figure 4.27. Catch per haul (a) and species richness (b) from sand and eelgrass habitats at Alki Point. After Miller et al. (1977).



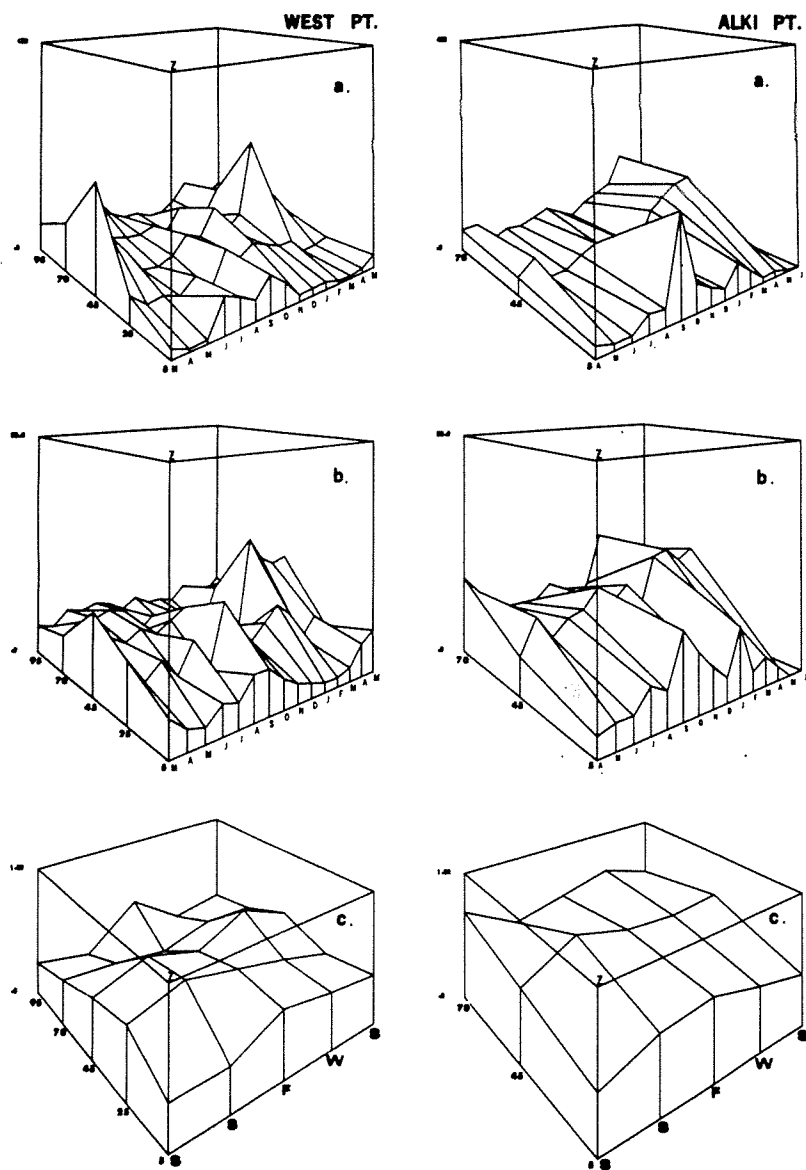


Figure 4.28. Seasonal and bathymetric patterns of catch per haul (a), species richness (b), and Shannon-Wiener diversity (c) at West Point, Alki Point and Point Pully. After Miller et al. (1977).

Abundance was highest during spring, summer and fall, but declined markedly during winter (Tables 4.33 and 4.34). Shiner perch, rock sole, and C-0 sole (*Pleuronichthys coenosus*) were most abundant during the spring and summer at both sites. Striped seaperch *Embiotoca lateralis* were not very abundant at West Point; however, the annual abundance cycles were quite similar at both sites. Shiner perch were abundant at Alki Point during the summer, but not at West Point. During the fall, shiner perch, tomcod, tubesnouts (*Aulorhynchus flavidus*), English sole, padded sculpin, and staghorn sculpin were the most abundant species.

The most abundant and frequently occurring species of trawl caught fish at both sites were ratfish, English sole, and rock sole (Figure 4.29). Both English sole and rock sole were most abundant between 5 and 45 meters water depth; however, each species showed marked onshore-offshore migrations during the year. These movements were characterized by an onshore migration in late spring and summer, followed by an offshore migration in the fall. In contrast, ratfish were most abundant between 70 and 95 meters water depth. At both sites ratfish abundance was highest during spring and summer and declined in fall and winter. Ratfish appeared to migrate to shallower water during the winter at Alki Point; however migration did not occur at West Point.

4.5.6 Species Assemblages

Species assemblages were determined using recurrent group analysis (Moulton et al. 1974; Miller et al. 1975; Miller et al. 1977). Given a set of (N) samples consisting of the occurrences of (P) species, an index of affinity was computed for each species pair using the formula:

$$I.A. = (J/N_a N_b)^{1/2} - 1/2 (N_b)^{1/2}$$

where J = number of joint occurrences, N_a = the total number of occurrences of species A, and N_b = the total number of occurrences of species B. The index of affinity is the geometric mean of the proportion of joint occurrences, corrected for sample size. Once indices of affinity were computed for each pair of species, recurrent groups were constructed according to the following set of requirements:

- a. All group members occurred with one another at some predetermined level of affinity (generally I.A. = 0.5).
- b. Each group formed included the greatest number of possible species.
- c. If several groups with the same number of members were possible, then those groups were selected which gave the greatest number of groups without members in common.
- d. If two or more groups with the same number of species and with members in common were possible, the one which occurred as a unit in the greatest number of samples was chosen.

The requirements were taken in order, such that groups fulfilling requirements a) and b) were determined first, then if several alternatives existed, a choice was made based upon requirements c) and d).

In addition distance measures between groups or species were calculated from meristic data. The actual measure was the Bray-Curtis index (Clifford and Stephenson 1975), where D_{ij} = distance between entities i and j, X_{ki} = values of attribute k in entity i, and X_{kj} = values of attribute k in entity j. The actual process of fusing entities and groups of entities with single entities is termed a clustering or sorting strategy (Wingert and Miller 1979). Group averages were employed in the study.

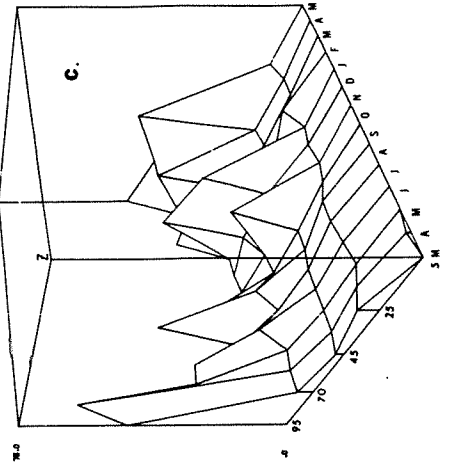
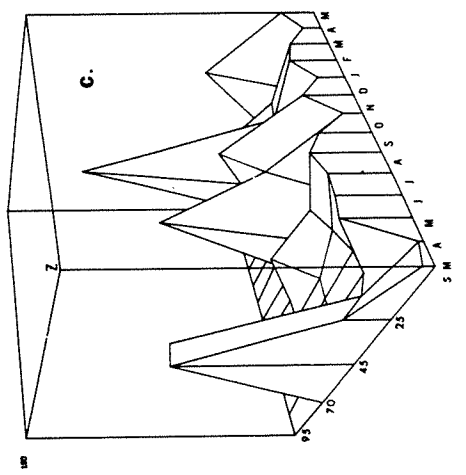
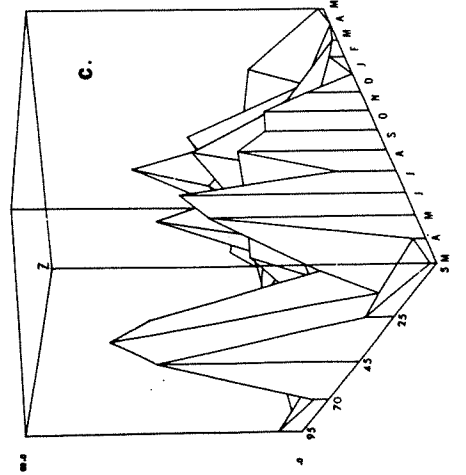
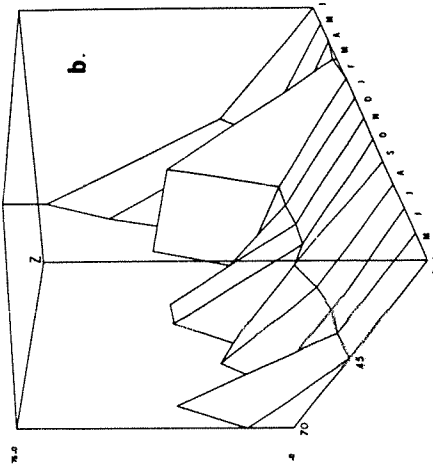
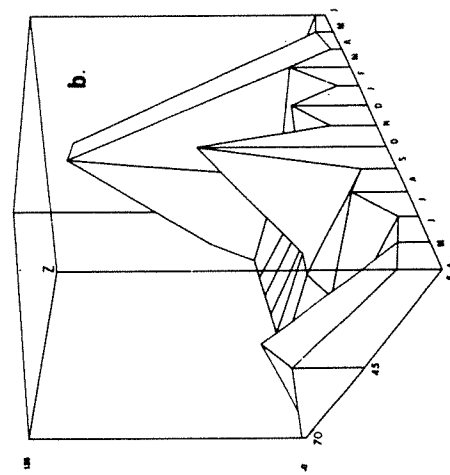
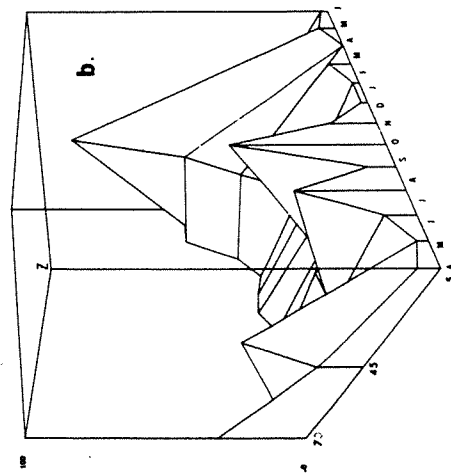
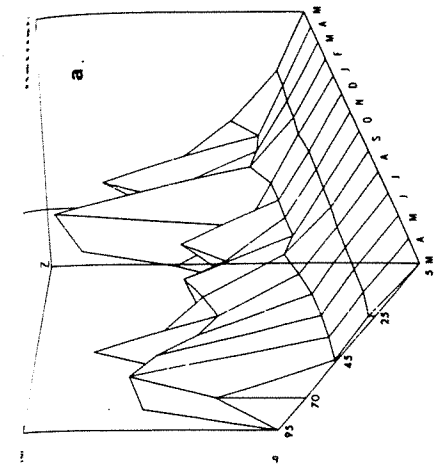
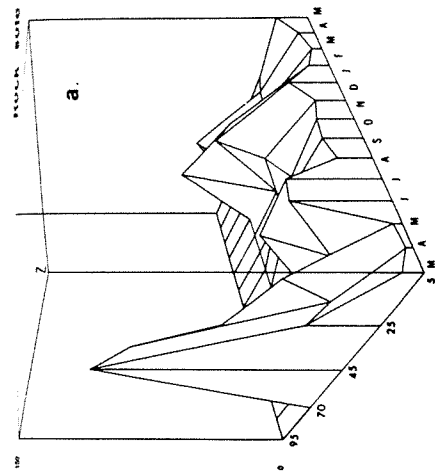
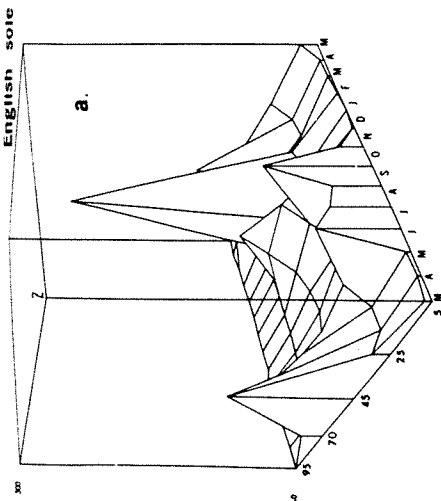
Table 4.33. Monthly catch per haul (CPH) of the five most abundant and frequently occurring species taken with the 37-m beach seine at West Point during 1975-76. Dash indicates no fish collected. After Miller et al. (1977).

Rank	Species	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
1	Tomcod	7.0	--	--	--	--	0.5	0.5	0.5	1412.0	39.0	14.0	33.0	12.5	--	--	--
2	Shiner perch	11.0	--	--	1.0	0.5	25.5	19.0	28.5	929.5	139.5	74.0	36.0	50.5	0.5	--	--
3	English sole	44.0	--	4.0	26.5	71.5	44.0	59.5	67.0	175.5	22.0	103.0	64.5	29.5	15.5	1.0	21.5
4	Rock sole	0.5	--	--	--	35.0	37.0	34.0	29.5	23.5	25.0	27.5	10.5	19.5	2.0	6.0	29.0
5	Staghorn sculpin	13.5	--	0.5	0.5	2.0	6.5	4.0	5.5	10.5	2.5	1.0	16.5	6.0	0.5	--	0.5

Table 4.34. Monthly catch per haul (CPH) of the nine most abundant and frequently occurring species taken with the 37-m beach seine at Alki Point during 1975-76. Dash indicates no fish collected. After Miller et al. (1977).

Rank	Species	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Apr	May	June
1	Shiner perch	0.5	--	130.0	64.0	258.5	189.5	143.0	1542.0	648.0	1307.5	59.0	--	--	26.0
2	Striped perch	1.0	--	83.0	90.0	350.5	301.0	19.0	76.0	99.0	10.5	--	0.5	38.5	24.5
3	Tubesnout	--	--	6.0	5.0	14.5	26.0	90.5	984.0	211.0	136.0	38.0	2.5	9.0	6.5
4	English sole	8.5	--	25.0	79.0	6.0	3.0	20.0	111.0	265.0	41.0	55.0	5.0	15.5	7.0
5	Rock sole	3.0	--	81.5	55.0	41.5	15.5	9.0	24.0	47.0	23.5	11.0	7.0	64.0	33.5
6	Tomcod	--	--	0.5	--	6.5	3.0	25.0	118.0	122.0	37.5	25.0	--	--	--
7	C-O sole	--	--	6.5	14.0	8.0	3.0	6.0	7.0	12.0	7.5	6.0	10.5	21.5	20.0
8	Staghorn sculpin	0.5	--	7.0	6.0	1.0	3.5	6.0	14.0	32.0	19.5	5.0	0.5	4.5	6.5
9	Padded sculpin	1.0	--	4.0	17.0	5.0	7.5	17.5	21.0	13.0	1.5	3.0	--	1.5	7.5

Figure 4.29. Seasonal and bathymetric patterns of catch per haul for English sole, rock sole, and ratfish at West Point (a), Alki Point (b), and Point Pully (c). After Miller et al. (1977).



With the group averaging method, the distance (D) between groups of entities and single entities or between two groups of entities was given by:

$$D_{hk} = \frac{n_i}{n_k} (D_{ni}) + \frac{n_j}{n_k} (D_{nj})$$

where D_{hk} = distance between groups h and k; where group k was a nearly fused group comprising the original groups i and j.

D_{hi} = distance between groups h and i

D_{hj} = distance between groups h and j

n_i , n_j , and n_k = number of entities in groups i, j, and k, respectively.

The fish assemblages at Alki Point were more complex than the fish assemblages at West Point (Figures 4.30 and 4.31). The species groups found at each site were divided into shallow water and mid-depth occurring groups (5, 25 and 45 meters) and deep-water occurring groups (70 and 95 meters). Species group I at West Point and groups I and III at Alki Point usually occurred between 5 and 45 meters (Tables 4.35 and 4.36). In contrast group II was restricted exclusively to 70 and 95 meters at both sites. When the species that composed the primary associations (Group I at West Point and the combined groups I and II at Alki Point) were compared only four species are found in common (shiner perch, staghorn sculpin, English sole, and rock sole). The peripheral species or species pairs with some affiliations with the primary associations generally occurred only at night (usually fall and winter) or were eelgrass associated. For example, the padded sculpin - sturgeon poacher (Agonus acipenserinus) pair at West Point, sailfin sculpin, (Nautichthys oculofasciatus) - giant sculpin (Myoxocephalus polyacanthocephalus) - hake (Merluccius productus) and pile perch (Rhacochilus vacca) - tomcod - sturgeon groups at Alki Point generally occurred at night. Eelgrass associated species included the bay pipefish (Syngnathus griseolineatus) - ornate gunnel (Pholis laeta) pair at Alki Point.

4.5.7 Food Habits

Rock sole (158-269 mm total length) ate primarily bivalves and polychaetes and occasionally crustaceans (Miller 1980). English sole (193-310 mm total length) ate mostly polychaetes and bivalves; English sole, however ate more polychaetes than did rock sole. Pelagic-epibenthic-feeding fishes preferred decapod crustaceans especially caridean shrimp.

The food habits of 17 species of nearshore fishes which occurred either frequently or as members of recurrent species groups in central Puget Sound were considered by Wingert et al. (1979).

Overall, 14 general prey types were found to represent the principal prey (> 1% of total IRI) utilized by the 17 species of nearshore fish (Table 4.37). At Alki Point; however, two prey types, gammarid and caprellid amphipods, tended to dominate the diets of most species. Gammarids occurred in the diets of 16/17 species (Table 4.37), the percentage contributed to the total IRI ranging from 19% for bay pipefish to 55% for penpoint gunnel. The only species which did not exploit gammarids was tubesnout. Caprellid amphipods occurred (> 1% of IRI) in the diets of all species except staghorn sculpin, tubesnout, pile perch, and the three flatfish species, C-0 sole, rock sole,

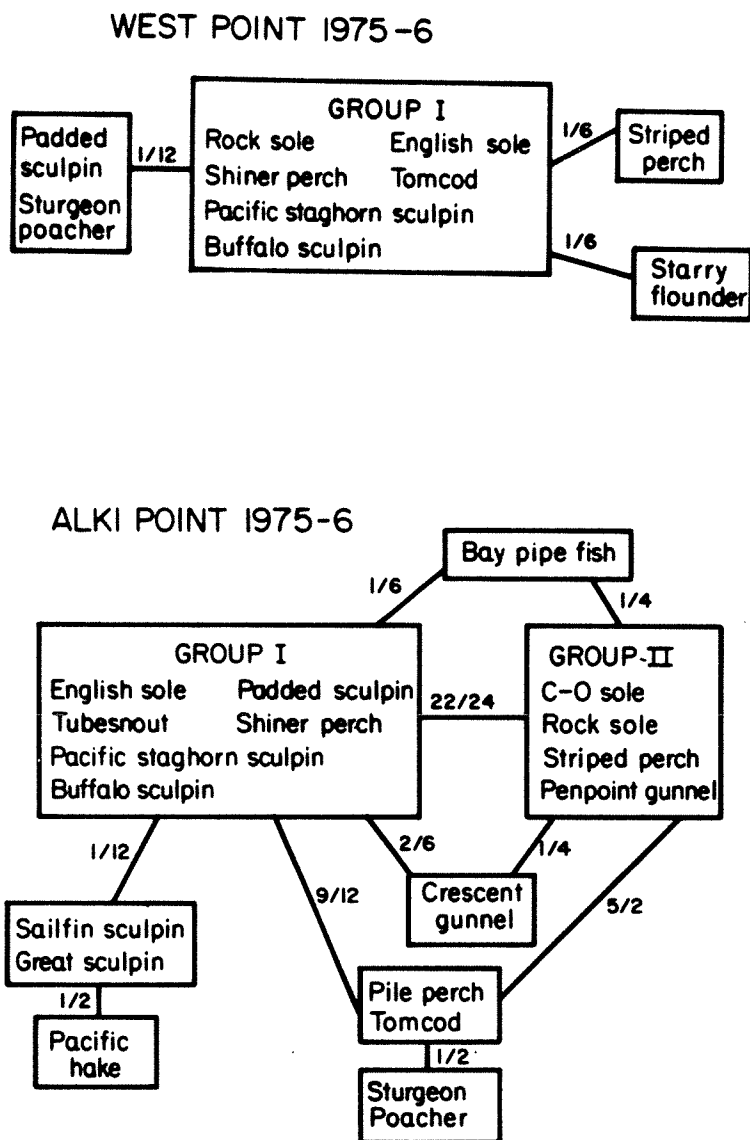
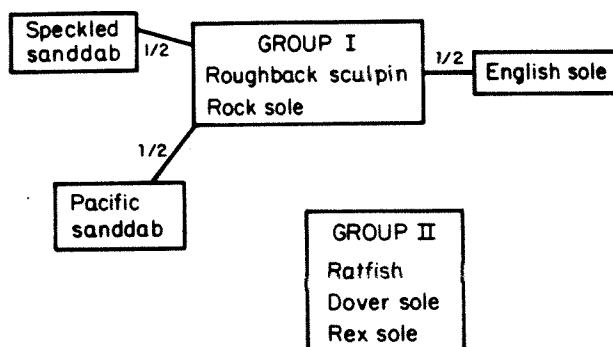


Figure 4.30. Recurrent species groups based on beach seine data from West Point, Alki Point, and Point Pully. After Miller et al. (1977).

WEST POINT 1975-6
(55 species; 137 samples)



ALKI POINT 1975-6
(55 species; 102 samples)

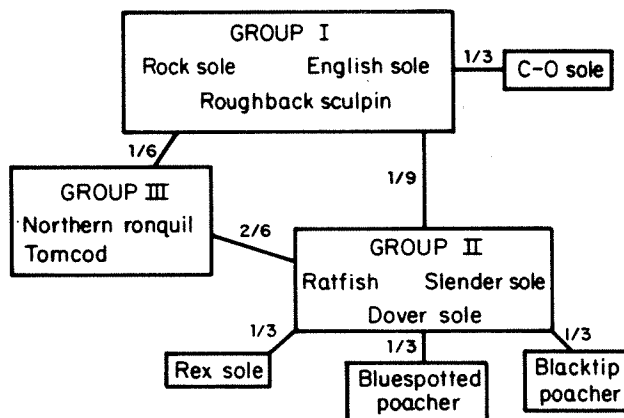


Figure 4.31. Recurrent species groups based on otter trawl data from West Point, Alki Point, and Point Pully. After Miller et al. (1977).

Table 4.37.

Percentage of total IRI contributed by various prey categories to the diets of the dominant nearshore fishes occurring at Alki Point (sand/eelgrass habitat). After Wingert et al. (1979).

Species	Prey categories										
	Gammarids	Caprellids	Bivalves	Gastropods	Calanoids	Tanaids	Polychaetes	Harpacticoids	Decapods	Chlorophyta	Teleostei
<u>Group I</u>											
English sole	23.02		11.35			7.61	48.57	59.37	40.63		2.60
Tubesnout								18.39			
Staghorn sculpin	24.96		6.84								8.09
Buffalo sculpin	34.69	2.61		1.68						58.22	
Padded sculpin	27.58	58.56						1.33			
Shiner perch	38.56	54.05			4.79	1.27					9.26
<u>Group II</u>											
C-O sole	36.72					1.21	54.98				
Rock sole	27.75		10.56			3.29	51.84				
Striped perch	44.25	55.63									
Penpoint gunnel	55.88	17.66					2.17	7.16			14.72
<u>Associated species</u>											
Crescent gunnel	52.27	47.08									
Tomcod	35.16	9.32			22.49				28.46		
Bay pipefish	19.64	46.43							33.83		
Pile perch	22.79			74.99						1.43	
Saddleback gunnel	39.15	51.73						1.52			2.45
Silverspotted sculpin	38.29	39.32							21.40		
Sharpnose sculpin	27.38	72.62									
No. occurrences	16	11	3	2	2	4	4	3	6	1	1
											3

and English sole. Excluding what was probably just an incidental ingestion of caprellids by buffalo sculpin, the percentage contribution of caprellids to the total IRI ranged from 9% in the tomcod diet to more than 72% in the sharpnose sculpin diet.

Decapod crustaceans, which were found in the diets of six species of fish predators, represented the next most frequently taken prey type. Decapods were exploited heavily by tubesnout (40% of IRI), staghorn sculpin (18%), tomcod (28%), bay pipefish (33%), and silverspotted sculpin (21%), but only incidentally by padded sculpin.

Of the remaining 11 prey types (Table 4.37), none were found in the diets of more than four different species of nearshore fish. Both polychaete worms (tube-dwelling and errant forms) and tanaid crustaceans were significantly (> 1% IRI) exploited by four different species; however, in each case three of the four were the flatfish species. Tanaids generally constituted a small portion of the diet (< 7% of total IRI), and were taken principally by juvenile flatfishes. Polychaetes, however, represented a major element of the diet for each of the three flatfishes, the percentage contribution to the total IRI ranging from 48% for English sole to 51% for rock sole.

Harpacticoid copepods, bivalves, and isopods were each preyed upon by three different species of nearshore fish (Table 4.37). Each of these prey resources, however, generally contributed little to the total dietary IRI of these species. Harpacticoids were utilized incidentally by penpoint gunnel and saddleback gunnel (largely juveniles), but were heavily exploited (59% of total IRI) by tubesnout. Bivalve molluscs were taken by two flatfish species (English sole and rock sole) and staghorn sculpin, but the percentage contribution to the total IRI was typically 10% or less. Saddleback gunnel, penpoint gunnel, and padded sculpin each exploited isopods; however, only penpoint gunnel and padded sculpin consumed this prey resource in significant quantities.

Of the remaining prey categories considered (Table 4.37), most were of negligible dietary importance for these 17 species. Exceptions were the consumption of calanoids (22% of IRI) by tomcod, gastropods (74% of IRI) by pile perch, and algae (58% of IRI) by buffalo sculpin.

Dietary composition of twenty-two species of demersal, primarily offshore, fishes were also investigated by Wingert et al. (1979). For convenience, the 22 species were divided into five groups (small-mouthed flatfishes, large-mouthed flatfishes, sculpin and ronquil, poacher, and water-column species), which are discussed separately below.

Small-Mouthed Flatfishes. The small-mouthed flatfishes examined for stomach contents included C-O sole, English sole, rock sole, rex sole and Dover sole. Generally, English sole and rock sole were found together at depths ranging from less than 5 to 60 m. Within this shallow to intermediate depth range, these species were often associated with speckled sanddab (5-25 m), Pacific sanddab (25-45 m), and C-O sole (5-25 m). In contrast, rex sole and Dover sole occurred mostly at depths exceeding 70 m. Often these species were associated with ratfish and slender sole. Both slender sole and Dover sole are known to migrate onshore at night to shallower water.

The diets of all five species were dominated primarily by polychaete worms and gammarid amphipods, and secondarily by bivalve molluscs (Table 4.38). The percentage contributed to the total IRI by polychaetes increased with increasing depth of occurrence for each species of flatfish. In other words, rex sole and Dover sole, the two deepwater species, were found to have a greater percentage contribution to the total dietary IRI by polychaetes than did the three shallow-water species. In addition, the frequency of occurrence

Table 4.38. Percentage of total IRI contributed to the diets of small-mouthed flatfishes by various prey categories. Frequency of occurrence of prey categories is in parentheses. After Wingert et al. (1979).

Prey category	Predator				
	C-O sole (n=50)	English sole (n=99)	Rock sole (n=149)	Rex sole (n=27)	Dover sole (n=40)
Polychaeta	24.81 (0.52)	48.57 (0.80)	51.84 (0.83)	71.77 (0.74)	74.83 (0.93)
Gammaridea	40.19 (0.82)	23.02 (0.79)	27.75 (0.69)	14.56 (0.81)	12.57 (0.72)
Unidentified	1.19 (0.12)	3.16 (0.37)	2.46 (0.30)	8.52 (0.48)	4.25 (0.37)
Ostracoda		2.60 (0.43)		1.45 (0.29)	
Calanoida				1.18 (0.11)	
Bivalvia	2.40 (0.38)	11.35 (0.61)	10.56 (0.49)		1.75 (0.40)
Caprellidea					2.40 (0.33)
Ophiuroidea					1.99 (0.30)
Nereidae	26.75 (0.50)		1.04 (0.14)		
Tanaidacea		7.61 (0.52)	3.29 (0.38)		
"H"--IRI	2.09	2.21	1.96	1.42	1.42
"H"--No.	2.70	3.03	3.01	3.00	2.65
"H"--Biomass	2.59	2.97	3.17	0.80	2.17

addition, the frequency of occurrence of polychaetes in the diet of the deeper-occurring species was also higher. The frequency of occurrence of gammarids in the diet of all species was also consistently high (0.72-0.82); yet the percentage contributed to the total dietary IRI by gammarids decreased markedly with increasing depth of occurrence.

Bivalves occurred in the diets of all species except rex sole; however, English sole and rock sole most heavily utilized this prey resource (> 10-12% of total IRI). Generally, English sole and rock sole, ranging in size from 150 to 250 mm TL, were the primary consumers of bivalves (Tables 4.39 and 4.40).

Nereid polychaetes were found in the diets of C-O sole and rock sole, yet only C-O sole relied heavily (27% of total IRI) on this resource. Tanaids and ostracods occurred exclusively in the diets of English sole and rock sole, although these prey were generally most important in the diets of small (< 250 mm TL) individuals. All remaining prey organisms (caprellids, calanoids, and ophiuroids) which were utilized by the small-mouthed flatfishes occurred in the diet of only a single species and typically constituted less than 10% of a species' composite IRI.

Large-Mouthed Flatfishes. Four species of large-mouthed flatfishes, sand sole, speckled sanddab, Pacific sanddab and slender sole, were examined for stomach contents. Sand sole, speckled sanddab, and Pacific sanddab all occurred primarily at depths ranging from 5 to 45 m, whereas slender sole occurred commonly between 45 and 95 m. Generally, speckled sanddab were most frequent and abundant at depths between 5 and 25 m, and Pacific sanddab more frequent and abundant at 25-45 m.

Sand sole fed exclusively on pelagic prey, and mainly (62% of IRI) on other fishes, notably shiner perch. The only other prey of importance were larvaceans (13.6% of IRI). Only two types of prey were found in the diets of all three large-mouth flatfishes (Table 4.41): Gammarids (13-24% of IRI) and polychaetes (4-16%). With respect to these two prey categories, slender sole and speckled sanddab exhibited a greater similarity in dietary overlap. Caridean shrimp were exploited heavily by both speckled sanddab and slender sole, but were not taken by Pacific sanddab. Similarly, calanoid copepods were exploited only by speckled sanddab and slender sole. Several types of pelagic prey organisms were consumed by Pacific sanddab -- hyperiid amphipods, pteropods, mysids, chaetognaths, fish, and larvaceans. In contrast, epibenthic prey were dominant elements in the diets of slender sole and speckled sanddab. In general, speckled sanddab and slender sole exhibited the highest dietary overlap; however, both Pacific sanddab and slender sole relied more heavily on pelagic prey organisms.

Sculpin-Ronquil Group. Five species from this group of demersal fishes were examined for stomach contents--roughback sculpin, sailfin sculpin, spotfin sculpin, slim sculpin and northern ronquil. Roughback sculpin and sailfin sculpin were typically distributed between 5 and 45 m during much of the year, roughback sculpin being common and abundant and sailfin sculpin being less frequent and less abundant. Sailfin sculpin generally occurred at 25-45 m in the daytime, but moved into shallow water (< 20 m) in the evening. Slim sculpin and spotfin sculpin were normally found between 45 and 70 m, although neither species was particularly abundant. Northern ronquil, unlike the other four species, occurred primarily at 45 m, and underwent little or no onshore or seasonal movement.

The only prey organisms which were exploited by all five species in this group were gammarid amphipods (Table 4.42). Generally, the deeper-occurring species (spotfin sculpin and slim sculpin) utilized gammarids most heavily (26

Table 4.39. Percentage of total IRI contributed by various prey categories to the diets of three size classes of English sole from West Point. After Wingert et al. (1979).

Prey category	Total length (mm)		
	< 150	150-250	> 250
Polychaeta	42.46	33.85	63.63
Gammaridea	29.85	24.93	3.06
Tanaidacea	9.89	17.89	1.06
Bivalvia	7.86	9.06	5.91
Ostracoda	4.36	4.89	
Unidentified	2.49	7.23	24.24
Cumacea	1.11		

Table 4.40. Percentage of total IRI contributed by various prey categories to the diets of three size classes of rock sole from West Point. After Wingert et al. (1979).

Prey category	Total length (mm)		
	< 150	150-250	> 250
Polychaeta	40.88	48.89	59.00
Gammaridea	37.21	20.41	11.36
Tanaidacea	18.21	6.65	
Bivalvia	1.27	6.40	5.51
Ostracoda	1.64		
Unidentified		11.87	18.43
Caridea		2.72	
Nereidae			1.20
Flabelligeridae			1.57

Table 4.41. Percentage of total IRI contributed to the diets of large-mouthed flatfishes by various prey categories. Frequency of occurrence of prey categories is in parentheses. After Wingert et al. (1979).

Prey category	Predator		
	Speckled sanddab (n=25)	Pacific sanddab (n=39)	Slender sole (n=27)
Caridea	45.92 (0.52)		28.93 (0.41)
Gammaridea	23.19 (0.56)	13.24 (0.28)	24.70 (0.59)
Teleostei		18.04 (0.17)	
Cumacea	10.00 (0.24)		
Polychaeta	4.75 (0.36)	16.45 (0.15)	8.04 (0.37)
Caprellidea	3.62 (0.28)		
Larvacea	3.87 (0.12)	6.37 (0.05)	
Paguridae		9.69 (0.11)	
Ostracoda	1.25 (0.24)		
Calanoidea	1.05 (0.12)		15.74 (0.15)
Chaetognatha		3.18 (0.02)	
Mysidacea		1.58 (0.07)	16.70 (0.40)
Isopoda			1.28 (0.18)
Gymnosomata		26.55 (0.23)	
Hyperiid		1.37 (0.08)	
"H"--IRI	2.44	3.10	2.49
"H"--No.	3.12	3.35	2.32
"H"--Biomass	2.87	2.70	2.03

Table 4.42. Percentage of total IRI contributed to the diets of the roughback sculpin, northern ronquil, sailfin sculpin, spotfin sculpin, and slim sculpin, by various prey categories. Frequency of occurrence of prey categories is in parentheses. After Wingert et al. (1979).

Prey category	Predator			
	Roughback sculpin (n=105)	Northern ronquil (n=41)	Sailfin sculpin (n=14)	Spotfin sculpin (n=15)
Caprellidea		1.71 (0.17)	51.22 (0.71)	
Caridea	59.73 (0.45)	36.13 (0.53)	25.84 (0.64)	19.03 (0.26)
Idoteidae			8.27 (0.50)	
Gammaridea	12.36 (0.27)	12.18 (0.36)	8.92 (0.50)	26.98 (0.40)
Nematoda			2.51 (0.35)	
Cumacea				1.31 (0.11)
Unidentified	3.75 (0.18)	4.47 (0.12)	1.15 (0.20)	
Decapoda	17.00 (0.30)	1.11 (0.07)		1.60 (0.07)
Polychaeta	1.80 (0.13)	43.84 (0.53)		33.71 (0.33)
Cancridae	1.29 (0.07)			3.41 (0.07)
Teleostei	1.28 (0.05)			2.25 (0.07)
Calanoida				7.84 (0.20)
Gastropoda				2.95 (0.07)
Ostracoda				
Tanaidacea				
				3.86 (0.22)
				18.60 (0.44)
				2.64 (0.22)

and 42% of IRI, respectively), whereas gammarids contributed less than 13% of the total dietary IRI of the other three species. All species in the group, except slim sculpin which has a small mouth and gape, preyed upon caridean shrimp (19-59% of total IRI), particularly the larger (> 150 mm TL) roughback sculpin. Except for spotfin sculpin, these prey were taken at least 40% of the time. Polychaete worms, which were also taken by four of the five species, were utilized primarily by the three deeper-living species--northern ronquil (43% of IRI), spotfin sculpin (33%), and slim sculpin (30%). Typically, polychaetes were found in 30-50% of the individuals examined for each species. Unidentified decapods were taken by roughback sculpin, spotfin sculpin, and northern ronquil, but only roughback sculpin heavily exploited this resource (17% of IRI).

Caprellid amphipods (51% of IRI) and idoteid isopods (8%) contributed heavily to the diet of sailfin sculpin only (Table 4.42). Both types of prey occur abundantly in shallow-water eelgrass beds, and were probably consumed by sailfin sculpin during their nocturnal onshore migration.

Ostracods, tanaids, and cumaceans, all of which are small epibenthic crustaceans, were taken only by the small-mouthed slim sculpin. Although cumaceans (1.3% of IRI) and tanaids (2.64% of IRI) contributed only slightly to the diet of slim sculpin, ostracods contributed more than 18% of the total dietary IRI. Similarly, spotfin sculpin was the only species in this group to take pelagic prey items (i.e., fish, calanoid copepods). Teleosts and calanoids together contributed approximately 10% of the total IRI; however, both prey types occurred in fewer than 10% of the stomachs examined.

Poacher Group. Four species of poacher--sturgeon poacher, spearnose poacher, bluespotted poacher, and blacktip poacher--were examined for stomach contents. All species except sturgeon poacher occurred exclusively in deep water (> 70 m), generally in association with ratfish and the deepwater flatfishes (Dover sole and rex sole). Sturgeon poacher, however, were typically found at 25-45 m (occasionally deeper) during the daytime and in shallow water (< 5 m) at night.

All four species of poacher heavily exploited gammarid amphipods (Table 4.43), particularly spearnose poacher (> 89% of IRI). Gammarids were also the prey most frequently taken by these four species. Caprellid amphipods were consumed by the three deepwater species, but were primarily utilized by bluespotted poacher (44% of IRI) and blacktip poacher (15% of IRI). Similarly, polychaete worms were consumed primarily by bluespotted poacher (6% of IRI) and blacktip poacher (4% of IRI). Except for caridean shrimp, which was a minor constituent in the diets of sturgeon poacher (6% of IRI) and blacktip poacher (3% of IRI), all of the remaining principal prey categories (> 1% of the total IRI) were consumed by a single species of poacher. Calanoid copepods, for example, were taken frequently (75% of individuals) and contributed substantially to the diet of blacktip poacher (21% of IRI). In addition, harpacticoid copepods and cumaceans occurred only in the diet of sturgeon poacher, yet still constituted nearly 47% of the total dietary IRI.

Water-Column Species Group. The five species included in this group were shiner perch, tomcod, brown rockfish, quillback rockfish, and ratfish. All five species occupy the water column and forage either on the benthos or within the water column. This is in contrast to the bottom-associated, or benthic, species discussed previously.

Both shiner perch and tomcod occurred at all depths sampled (5 m to 95 m), but were most common at 45-70 m. Likewise, the two species of rockfish generally occurred at most sampling depths. Brown rockfish, however, was most common at 25-45 m, whereas quillback rockfish was more common in deep water.

Table 4.43. Percentage of total IRI contributed by various prey categories to the diets of the sturgeon poacher, spearnose poacher, bluespotted poacher, and blacktip poacher. After Wingert et al. (1979).

Prey category	Predator			
	Sturgeon poacher (n=16)	Spearnose poacher (n=11)	Bluespotted poacher (n=38)	Blacktip poacher (n=8)
Gammaridea	45.38 (0.81)	89.65 (0.90)	47.61 (0.84)	40.88 (0.75)
Calanoidea				21.97 (0.75)
Caprellidea		1.48 (0.36)	44.91 (0.84)	16.81 (0.75)
Teleostei				11.39 (0.25)
Polychaeta			6.74 (0.26)	4.08 (0.37)
Caridea	6.67 (0.56)			3.41 (0.37)
Cumacea	41.76 (0.81)			
Harpacticoida	5.05 (0.31)			
Unidentified		6.13 (0.63)		

In contrast, ratfish occurred exclusively in deep water during the daytime and moved into shallower water only at dusk.

Based on percentage IRI contributions, the diets of shiner perch and tomcod exhibited moderate overlap (Table 4.44). Both species relied heavily on gammarid amphipods (35–38% of IRI), and both consumed caprellid amphipods and calanoids as well. Caprellids were a major contributor to the diet of shiner perch (45% of IRI), while calanoids represented a substantial portion of the diet of tomcod.

Similarly, brown rockfish and quillback rockfish exhibited considerable dietary overlap (based on percentage IRI); both species primarily consumed caridean shrimp (47% and 48% of IRI, respectively) and fishes (38% and 27% of IRI, respectively). All other prey organisms taken by these species generally occurred infrequently and contributed only slightly to the total dietary spectrum.

The deepwater-occurring ratfish consumed mainly benthic or epibenthic prey organisms, such as polychaetes (8% of IRI), ostracods (7% of IRI), decapods (13% of IRI), gammarids (5% of IRI), and bivalves (23%; however, a significant contribution to the diet of larger individuals (> 250 mm TL) was made by fish (> 10% of IRI).

Dietary Variation

The composite descriptions of fish food habits from previous sections did not consider the potential dietary variation due to the life history stage (or size) of the predator, the geographic location of capture, or the season of capture. All of these factors may strongly influence the spectrum of prey taken by a particular species of fish. Although there were inadequate sample sizes to investigate these sources of variation for most species, we did have sufficient sample sizes to examine English sole, rock sole, ratfish, and roughback sculpin more carefully.

Effect of Predator Size on Diet Consumption. For English sole and rock sole, both small-mouthed flatfishes, there were very clear dietary changes associated with increasing size (Tables 4.39 and 4.40). For example, the percentage of the total dietary IRI contributed by gammarid amphipods declined markedly for both species as they increased in total length. Concomitant with this decreased utilization of gammarids was a substantial increase in the dietary contribution made by polychaetes. A quite different pattern of exploitation, however, was observed for bivalve molluscs, where the maximum utilization (percentage of IRI) occurred at an intermediate size class (150–250 mm TL) for each species. The only prey to be utilized predominantly by the smaller (< 150 mm TL) English sole and rock sole were small epibenthic cumaceans, tanaids, and ostracods. As predator length increased, these smaller prey items were successively eliminated from the diet.

Ratfish, the dominant fish species in deep water, exhibited several notable changes in dietary composition with increased predator size (Table 4.45). Bivalves and decapod crustaceans were of little importance in individuals less than 200 mm TL, but increased in importance for larger individuals, particularly those greater than 300 mm TL. In contrast, polychaetes and gammarids both decreased in importance (in terms of % IRI) as predator size increased. Teleost fishes were absent from the diet of small (< 200 mm TL) ratfish, but became substantially more important with increased size. The only prey organisms which were utilized primarily by the intermediate-size class of ratfish were ostracods.

The ontogenetic changes in prey exploitation observed for roughback sculpin (Table 4.46) closely resembled those described for ratfish above. Smaller prey such as gammarids, polychaetes, and tanaids were utilized

Table 4.44. Percentage of total IRI contributed by various prey categories to the diets of shiner perch, tomcod, brown rockfish, quillback rockfish, and ratfish. After Wingert et al. (1979).

Prey category	Predator				
	Shiner perch (n=10)	Tomcod (n=37)	Brown rockfish (n=6)	Quillback rockfish (n=5)	Ratfish (n=71)
Bivalvia					23.6
Gammaridea	38.56	35.16	8.41		5.2
Caprellidea	54.06	9.32		2.68	
Calanoida	1.27	22.49			
Tanaidacea	4.79				
Decapoda		28.46			13.0
Natantia			47.06	48.76	
Cancridae			4.25		
Mysidacea				5.48	
Hyperiidea		1.17			
Teleostei			38.05	27.65	10.3
Polychaeta				1.42	8.1
Ostracoda					7.3
Isopoda			1.04		

Table 4.45. Percentage of total IRI contributed by various prey categories to the diets of three size classes of ratfish. After Wingert et al. (1979).

Prey category	Total length (mm)		
	< 200 (13)	200-300 (24)	> 300 (33)
Polychaeta	31.14	4.09	4.17
Gammaridea	7.89	7.13	1.95
Ostracoda	4.77	17.23	
Calanoida	2.89		
Bivalvia	1.04	12.41	22.12
Nematoda	1.59		
Flabelligeridae	1.29		1.86
Natantia	2.24		
Teleostei		16.52	10.96
Hippolytidae		1.27	
Gastropoda			1.10
Decapoda			16.69

Table 4.46. Percentage of total IRI contributed by various prey categories to the diets of three size classes of roughback sculpin. After Wingert et al. (1979).

Prey category	Total length (mm)		
	< 100	100-150	> 150
Gammaridea	37.22	10.06	
Caridea	45.56	68.86	37.12
Polychaeta	8.36	4.63	
Decapoda	3.41	2.50	40.00
Tanaidacea	2.59		
Caprellidea		1.93	
<u>C. oregonensis</u>		1.47	14.50
Teleostei		2.03	2.90

primarily by small individuals, and were generally eliminated from the diet as predator size increased. As these smaller prey items were dropped from the diet, the percentage contribution made by larger prey such as decapods and fish successively increased.

Effect of Season on Diet. Both English sole (Table 4.47) and rock sole (Table 4.48) exhibited similar changes in prey utilization throughout the year. In general, the percentage contribution to the total IRI made by polychaetes decreased in spring and summer for each species, whereas the percentage contributed to the diet by gammarids increased in spring and summer. Bivalves, which were the next most important prey overall, were exploited most heavily during summer by English sole and during winter and spring by rock sole. Tanaids were exploited principally in spring by each species, although English sole also consumed these prey organisms in winter and summer.

Ratfish exploited bivalves and gammarids throughout the year (Table 4.49); however, bivalves were taken primarily in spring and gammarids in fall. Ostracods occurred in the diet of ratfish predominantly in summer (71% IRI) but also occurred in the diet during winter and fall. Teleosts were taken in the diet primarily in winter and contributed more than 36% of the total IRI. Similarly, polychaetes were found in the diet during winter and spring but contributed most heavily to the diet during winter.

The dominant prey organisms of the roughback sculpin, caridean shrimp, unidentified decapods, and gammarids, all exhibited strong seasonal variation in dietary contribution on the basis of percentage IRI (Table 4.50). The peak dietary contribution of each of these prey was found to occur at different times of the year. For instance, caridean shrimp were a significant portion of the diet in spring and summer, gammarids were dominant in fall, and decapods predominated in winter. Polychaete worms were absent from the diet of roughback sculpin in spring and summer, yet contributed significantly to the diet in fall and winter. In contrast, caprellid amphipods and the crab, C. oregonensis were consumed only in spring and summer.

Table 4.47. Seasonal variation in the percentage of total IRI contributed by various prey categories to the diet of English sole. After Wingert et al. (1979).

Prey category	Winter	Spring	Summer	Autumn
Polychaeta	66.72	16.83	19.73	69.64
Tanaidacea	5.65	25.18	2.64	
Gammaridea	10.20	34.65	16.42	4.84
Bivalvia	6.57	9.88	28.28	2.92
Ostracoda		5.66	10.98	
Cumacea		1.43		
Caprellidea			2.98	

Table 4.48. Seasonal variation in the percentage of total IRI contributed by various prey categories to the diet of rock sole from West Point. After Wingert et al. (1979).

Prey category	Winter	Spring	Summer	Autumn
Polychaeta	51.85	7.22	75.02	73.09
Gammaridea	15.82	49.64	7.57	13.24
Bivalvia	12.17	10.97	1.73	
Flabelligeridae	9.96			
Nereidae		10.79		
Tanaidacea		15.44		5.68
Caprellidea		2.94		
Ostracoda				1.39

Table 4.49. Seasonal variation in the percentage of total IRI contributed by various prey categories to the diet of ratfish. After Wingert et al. (1979).

Prey category	Winter	Spring	Summer	Autumn
Polychaeta	13.46	4.74		
Teleostei	36.24			
Ostracoda	7.41		71.18	14.42
Bivalvia	5.99	22.69	1.54	5.92
Gammaridea	1.28	2.67	3.09	23.00
Decapoda		16.41		3.01
Gastropoda		1.42		
Hippolytidae				4.15

Table 4.50. Seasonal variation in the percentage of total IRI contributed by various prey categories to the diet of roughback sculpin. After Wingert et al. (1979).

Prey category	Winter	Spring	Summer	Autumn
Caridea	43.13	67.41	50.2	26.77
Polychaeta	10.40			16.63
Gammaridea	4.03	17.13	3.00	45.03
Decapoda	32.00	1.06	1.00	8.81
Tanaidacea	3.07	1.57	2.30	
<u>C. oregonensis</u>		4.52	3.50	
Caprellidea		1.31	2.10	
Teleostei		1.85		
Crangonidae		1.19		

5.0 Water Quality Evaluation

5.1 Fish Health

Establishing cause and effect relationships between environmental chemicals and observed tissue lesions in free living fish populations is difficult. Variations in genetic history, nutritional status, duration of contaminant exposure, route of exposure, age, and sex cannot be controlled and may not be detectable in wild populations. The difficulty in locating dead or detecting functionally impaired animals (which are quickly scavenged or become easy prey) in a vast body of water further limits the data describing the effects of toxicants on wild populations.

Several researchers have nevertheless attempted to relate prevalence of tissue anomalies to concentrations of xenobiotics in Elliott Bay. In addition to miscellaneous anomalies which might be related to pollution, a few major anomalies in Elliott Bay fishes have been tentatively linked by investigators to environmental factors. These conditions include two lesions of the integument (fin erosion and epidermal papilloma) and several types of neoplastic and non-neoplastic liver lesions.

5.1.1 Fin Erosion

5.1.1.1 Background

Fin erosion in demersal marine fishes is characterized by a loss of fin tissue proceeding from the margin of the fin toward the body. Ulceration, hyperpigmentation, deformation and scarring may occur in both soft tissue and fin rays. Loss of mucous-secreting ability (Sherwood 1978) is frequent and probably reduces the fishes' first line of defense against invading organisms.

Histologically, fin erosion is characterized by a chronic fibrosing condition accompanied by epidermal hyperplasia, proliferation of fibroblasts, and resorption of fin rays.

The etiology of fin erosion is unknown. Numerous bacteria have been isolated from affected fish from a variety of geographic locations, but no single organism or group of organisms has been consistently associated with this disease. Evidence for parasitic, viral or fungal associations has not been found (Miller et al. 1977; Staude 1979; McCain et al. 1982).

Fin erosion has been reported from numerous locations around the world (Sherwood 1978), all of which have some association with toxic waste discharge (Table 5.1). Data from intensively studied areas within the United States suggested to some authors that fin erosion stemmed from exposure to a common component in chemical discharges (Sherwood and McCain 1976). This argument is supported by the following observations: 1) the disease incidence was elevated in waste-receiving areas, 2) no inflammatory response was associated with the condition, 3) no pathogenic organisms were associated with the lesions, and 4) the affected species had extensive association with bottom sediment (Sherwood and McCain 1976). Fins most frequently eroded were those which contact the sediment (Sherwood and Mearns 1977; Sherwood 1978). Although observations and experiments in areas other than Elliott Bay have shown a high correlation between the frequency of occurrence of fin erosion and municipal wastewater discharge (Sherwood and Mearns 1977), a direct cause and effect relationship has not been established.

Table 5.1. Fin erosion in demersal fishes from various coastal areas.
Modified from Sherwood (1978) and Dexter et al. (1981).

Location	Affected species	Reference
Southern California nearshore waters	<u>Microstomus pacificus</u> , dover sole <u>Glyptocephalus zachirus</u> , rex sole <u>Lyopsetta exilis</u> , slender sole <u>Sebastes elongatus</u> , greenstriped rockfish <u>Sebastes miniatus</u> , vermilion rockfish	Mearns and Sherwood (1974) Sherwood and Mearns (1977)
Duwamish River Waterway, Puget Sound	<u>Platichthys stellatus</u> , starry flounder <u>Parophrys vetulus</u> , English sole	Wellings et al. (1976) Miller et al. (1977) McCain et al. (1982) Malins et al. (1982)
Commencement Bay, Puget Sound	<u>Platichthys stellatus</u> , starry flounder <u>Parophrys vetulus</u> , English sole <u>Lepidopsetta bilineata</u> , rock sole	Malins et al. (1982)
Sandy Hook/Raritan Bays; Apex dumping area, New York Bight	<u>Pseudopleuronectes americanus</u> , winter flounder	Murchelano and Ziskowski (1976)
Boston Harbor, Mass.	<u>Pseudopleuronectes americanus</u> , winter flounder	Charles A. Willingham Battelle Columbus Laboratories, Duxbury, Mass., personal communication
Northeast Irish Sea	<u>Pleuronectes platessa</u> , plaice <u>Limanda limanda</u> , dab	Perkins et al. (1972)
Suruga Bay, Japan	<u>Uranoscopus japonicus</u> , Japanese stargazer	Nakai et al. (1973)

5.1.1.2 Incidence in Elliott Bay

The Duwamish River has been studied most extensively because of the high concentrations of xenobiotics in the river sediments. Fin erosion has been found in only two fish species, starry flounder (Platichthys stellatus) and English sole (Parophrys vetulus), in the Duwamish River. Reported incidences for starry flounder ranged from 2.3% (Malins et al. 1982) to 11.4% (Miller et al. 1977) and for English sole from 0.4% (McCain et al. 1982) to 1.3% (Malins et al. 1982, Table 5.2). Sample sizes in these studies were variable. Seasonal fluctuations in fin erosion incidence have been observed for Duwamish River starry flounder (Miller et al. 1977). These variations were attributed to fluctuations in abundance of starry flounder in the river. Miller et al. (1977) also reported that the incidence of fin erosion in starry flounder increased with both size and age; the majority of affected fish were larger than 150 mm total length and were two- and three-year-olds.

Fin erosion has not been found in fishes collected in areas of Elliott Bay other than the Duwamish River. Miller et al. (1977) sampled flatfish near the sewage outfalls at Alki Point and West Point, while Malins et al. (1982) sampled fish from these sites in addition to other sites in outer Elliott Bay and along the Seattle waterfront.

5.1.1.3 Association with Xenobiotics

Several researchers have studied the relationship between fin erosion and tissue concentrations of xenobiotics in wild fish. Sherwood and McCain (1976) compared the concentrations of total polychlorinated biphenyls (PCBs) and p, p'-DDE in muscle, liver, and brain of control and diseased fishes. Dover sole (Microstomus pacificus) with fin erosion were collected off Los Angeles while starry flounder with fin erosion were collected off Seattle. Polychlorinated biphenyl concentrations correlated with the incidence of the disease in both species from both areas, but the correlation was not statistically significant.

In other Puget Sound studies, elevated concentrations of PCBs were found in the livers of affected fish compared with unaffected fish from both the Duwamish River and a control site (Miller et al. 1977). DDE and metals did not correlate with fin erosion at either site. Sherwood (1977) demonstrated that starry flounder from the Duwamish River had elevated concentrations of silver and depressed levels of cadmium, copper, and zinc when compared with control fish. Similar relationships among comparable fish from southern California were not observed.

Attempts to experimentally induce fin erosion in the laboratory by mimicking naturally occurring conditions have shown some promise. Early signs of fin erosion were observed in dover sole exposed to contaminated sediment for 13 months (Sherwood 1976). These lesions resembled those found in wild fish caught in an affected area in southern California. Sherwood (1976 and 1978) suggested that elevated levels of PCBs might be correlated with increased frequency of fin erosion, but the evidence was mostly circumstantial.

Attempts to experimentally reproduce fin erosion by exposing fish to Duwamish River sediment have been inconclusive. In one study, 2 of 30 experimental English sole developed lesions after one month, while none of the controls showed signs of disease (Miller et al. 1977). Starry flounder exposed under identical conditions showed no lesions in the 10 exposed fish. In another study, English sole (100 per group in the first experiment and 32

Table 5.2. Reported incidence of fin erosion in Duwamish River flatfish.

Species sampled	Sampling period	(No. affected/No. sampled)	% affected	Remarks	Reference
<u>Platichthys stellatus</u> (Starry flounder)	Jan.-Dec. 1974	8		29 fish species (6547 fish total) sampled; fin erosion observed only in starry flounder and English sole.	Wellings et al. (1976)
<u>Parophrys vetulus</u> (English sole)		0.5			Wellings et al. (1976)
<u>Platichthys stellatus</u>	Feb. 1975-Jan. 1976	11.4 (155/1357)		Fin erosion confined to fish caught in upper and middle Duwamish River.	Miller et al. (1977)
<u>Platichthys stellatus</u>	Oct. 1978-Oct. 1980	2.9 (8/280)		All reported cases were microscopically confirmed.	McCain et al. (1982)
<u>Parophrys vetulus</u>		0.4 (2/565)			McCain et al. (1982)
<u>Platichthys stellatus</u>	Winter 1978-Spring 1981	2.3 (1/43)		Incidence for starry flounders from upper Duwamish River only.	Malins et al. (1982)
<u>Parophrys vetulus</u>		0.7 (4/567)		Upper Duwamish River incidence for English sole was 1.3% (2/149); lower Duwamish River incidence was 0.5% (2/418).	Malins et al. (1982)

to 35 per group in the second experiment) were maintained for up to 92 days in aquaria containing Duwamish River sediment or control (Snohomish River or Port Madison) sediment. No consistent pathological differences between the test and control fish were observed (McCain et al. 1982).

5.1.2 Epidermal Papilloma

5.1.2.1 Background

Epidermal papillomas occur in several species of flatfish along the Pacific Coast of North America. Three distinctive morphological types - the angioepithelial nodule, the angioepithelial polyp (or transitional angioepithelial nodule), and the epidermal papilloma - were described by Wellings et al. (1965). The angioepithelial nodules are small (1 to 2 mm), circumscribed, sessile nodules that occur over the entire body surface. The angiomatous component shows possible invasive tendencies because of extension into skeletal muscle. These nodules are not observed on fish over one year of age. The angioepithelial polyps are soft, sharply demarcated sessile lesions. The polyps are larger than the nodules and are usually seen in fish over one year of age. The epidermal papillomas are large (1 to 6 cm) cauliflower-like proliferative lesions. The central portion of the tumor is frequently a raised wart-like structure, while the edges often are flat and grade into the surrounding tissue. They do not appear to be invasive.

An unidentified, tumor-specific cell, designated as an "X-cell," has been described in all three types of lesions (Brooks et al. 1969). These hypertrophic cells have a large nucleus and prominent nucleolus. They have numerous dense cytoplasmic granules and lack intercellular bridges. The cells have a thick extracellular coat and are frequently found in groups of two, three and four. The X-cells are seen as small cells in the dermis of angioepithelial polyps and epidermal papillomas (McArn and Wellings 1971). It is not known whether these are fish cells or foreign cells.

The etiology of epidermal papillomas is unknown. Some authors (Cooper and Keller 1969; Miller and Wellings 1971) have reported the distribution of epidermal papillomas in flatfish to be geographically localized, with highest incidences near heavily industrialized areas. A direct causal relationship may exist between xenobiotic exposure and epidermal papilloma formation, or exposure to xenobiotics may increase the susceptibility of flatfish to a tumor-causative agent (Miller and Wellings 1971; Stich et al. 1976). Other researchers, however, have reported high incidences of epidermal papillomas in flatfish from non-industrialized areas such as the Bering Sea (McCain et al. 1978; McCain et al. 1979). Recent evidence suggests that these tumors may be xenomas caused by a parasitic amoeba (Dawe 1980; Myers 1981).

5.1.2.2 Incidence in Elliott Bay

Flatfish with epidermal papillomas have been found at several locations within Elliott Bay. Miller et al. (1977) found tumor incidences in all age classes of 2.2% (37 of 1671 fish) and 2.1% (84 of 3974 fish) in English sole collected near the Alki Point and West Point sewage outfalls, respectively. A tumor incidence of 4.71% (162 of 3436 fish) was found at Point Pully, the Puget Sound reference station. The incidence of tumor-bearing English sole varied with season and age. Tumor-bearing age group 0 (young-of-the-year) fish were generally not seen before September and the incidence of tumors in this age group peaked during September to December. Age group I fish had

generally higher frequencies of tumors which did not show strong seasonal trends. Group II and older fish exhibited few tumors.

Miller et al. (1977) studied the occurrence of epidermal papillomas in Duwamish River starry flounder. Incidence in all age classes for this species was 16.9%. Miller et al. (1977) found that the tumor incidence in starry flounder was highest (44.7%) in young fish (50 to 90 mm total length) and decreased with increasing age of the fish. Papillomas occurred predominately in fish collected from the upper stations of the river. The papillomas in fish collected from the upper stations were primarily late-stage lesions rather than angioepithelial nodules. This finding suggested either that tumor-bearing fish migrated into the area or that they occurred in other parts of the river which were not sampled.

McCain et al. (1982) also investigated papilloma incidence in Duwamish River flatfish and found an incidence in all age classes of 0.5% (3 of 565 fish) in English sole and 6.1% (17 of 280 fish) in starry flounder. All lesion stages were found in these fish, but the majority of lesions in starry flounder were late-stage papillomas.

Miller et al. (1977) and McCain et al. (1982), observed papillomas in reference area fish as well as in Elliott Bay fish. Miller et al. (1977) reported that the overall tumor incidence in age 0 English sole varied from 2.13% (West Point) to 2.39% (Alki Point) to 4.98% (Point Pully). Tumor incidence was statistically higher at Point Pully (reference area) than at either of the other two stations. Apparent differences also were observed in age group I fish (Point Pully, 9.27%; Alki Point, 8.36%; West Point, 4.54%) but differed statistically only at Point Pully and West Point. McCain et al. (1982) found a papilloma incidence in all age classes of 12.8% (6 of 39 fish) in English sole and 3% (1 of 33 fish) in starry flounder in a nonurban embayment, McAllister Creek. The variable occurrence of papilloma-bearing fish in both urban and nonurban areas of Puget Sound makes a relationship between tumor prevalence and chemicals questionable.

5.1.2.3 Association with Xenobiotics

No causal relationship between specific xenobiotics and development of epidermal papillomas has been established.

5.1.3. Liver Neoplasms

5.1.3.1 Background

Liver neoplasms have been described from several fish species, including both wild fish and experimental fish in which neoplasms have been induced by carcinogenic agents. In early literature, liver neoplasms with various histological appearances were lumped under the term "hepatoma." More recent reports categorized these tumors according to standard medical nomenclature, with histological characteristics used to determine the types of cells involved and to assess the degree of malignancy.

Liver neoplasms described from fishes involved hepatocellular, biliary and mesenchymal elements. In a recent report outlining liver neoplasms in Puget Sound demersal fishes, Malins et al. (1982) described three types of neoplasms (minimum deviation basophilic nodules, liver cell adenomas and hepatocellular carcinomas) involving hepatocellular elements, two types of neoplasms (cholangiomas and cholangiocellular carcinomas) involving biliary elements, and two types of neoplasms (hemangiomas and fibromas) involving

mesenchymal elements. The histological characteristics of these neoplasms were described by McCain et al. (1982).

Several reports (Miller et al. 1977; Pierce et al. 1978; Malins et al. 1982; McCain et al. 1982) showed a positive correlation in demersal fishes between liver tumor prevalence and residence in urban waterways, but an inducing agent or agents has not been determined.

5.1.3.2 Incidence in Elliott Bay

In Elliott Bay, liver neoplasms have been recorded principally in flatfish from the Duwamish River (McCain et al. 1977; Miller et al. 1977; Pierce et al. 1978; Malins et al. 1982; McCain et al. 1982). Species affected were English sole, starry flounder and rock sole (Lepidopsetta bilineata) although other fish species were examined in some studies (Table 5.3).

Initially neoplasm incidence in Duwamish River flatfish was estimated at 32% (20 of 62 fish; McCain et al. 1977). More recently workers using larger sample sizes have estimated the neoplasm incidence for starry flounder collected during 1978-80 to be 1.1% (3 of 279 fish; McCain et al. 1982) and for English sole to be 12.9% (71 of 551 fish; McCain et al. 1982). The highest tumor incidence was noted in fishes from the upper Duwamish River (Figure 5.1).

In addition to lesions described as neoplastic, a number of potentially preneoplastic lesions have been reported from Elliott Bay fishes (Malins et al. 1982; McCain et al. 1982). In these studies, lesions were categorized as "preneoplastic" on the basis of histological similarity to "preneoplastic" conditions found in mammals. In mammals, such conditions generally progress to neoplasms and are thought to be irreversible. In general, "preneoplastic" lesions in fish appeared histologically to be proliferative or regenerative or both, in nature, and possessed atypical cellular characteristics (Malins et al. 1982; and McCain et al. 1982). Malins et al. (1982) described four liver lesions - nodular eosinophilic hypertrophy, nodular hepatocellular hyperplasia, hyperbasophilic foci and hyperplastic regenerative islands - as potentially preneoplastic.

"Preneoplastic" lesions have been described from fish collected in several locations in Elliott Bay, including the Duwamish River, Seattle waterfront, outer Elliott Bay, and West Point (Malins et al. 1982; McCain et al. 1982). These lesions were found in both English sole and rock sole, but the highest incidence (21%, 28 of 136 fish) was reported for English sole from the upper Duwamish River (Malins et al. 1982). Although "preneoplastic" lesions were associated principally with urban embayments, some affected fish were collected from nonurban control areas (Malins et al. 1982; Figure 5.1).

5.1.3.3 Association with Xenobiotics

Although the cause(s) of liver neoplasms in Elliott Bay flatfish has not been determined, a variety of carcinogens induced similar neoplasms in other fish species held in the laboratory. The most widely studied liver neoplasm occurred in Shasta strain rainbow trout (Salmo gairdneri) exposed to aflatoxin, a fungal metabolite (Halver and Mitchell 1967). Neoplasms also have been induced experimentally by exposing various fish species to known hepatocarcinogens such as dimethylnitrosamine, acetylaminofluorene, urethane, thiourea and *p*-dimethylaminoazobenzene (Ashley 1969; Halver and Mitchell 1967). In addition, lesions described as preneoplastic have been observed in cutthroat trout (Salmo clarki) exposed to organochlorine pesticides (Eller

Table 5.3. Sampling locations and number of fish from each location subjected to histopathological examination by Malins et al. (1982).

Site No. Geographic area		Number examined				
Site No.	Geographic area	English sole (<u>Parophrys</u> <u>vetulus</u>)	Rock sole (<u>Lepidopsetta</u> <u>bilineata</u>)	Pacific tomcod (<u>Microgadus</u> <u>proximus</u>)	Pacific staghorn sculpin (<u>Leptocottus</u> <u>armatus</u>)	Quillback rockfish (<u>Sebastes</u> <u>maliger</u>)
1	Budd Inlet	103	88	18	40	0
2	Case Inlet	34	28	7	17	0
3	SW Commencement Bay	152	153	35	6	9
4	Old Tacoma	50	42	8	0	0
5	Commencement Bay Waterways	276	125	95	98	2
6	Hylebos Waterway	297	159	120	116	10
7	Brown's Point	37	43	18	16	5
8	Sinclair Inlet	201	82	52	71	3
9	Upper Duwamish River	136	18	0	60	0
10	Lower Duwamish River	399	300	65	37	25
11	Seattle Waterfront	161	138	63	18	53
12	Outer Elliott Bay	116	119	2	2	31
13	West Point	40	38	18	1	21
14	Port Madison	38	22	29	11	14
15	Port Susan	33	1	0	1	0
16	Discovery Bay	51	10	0	17	0

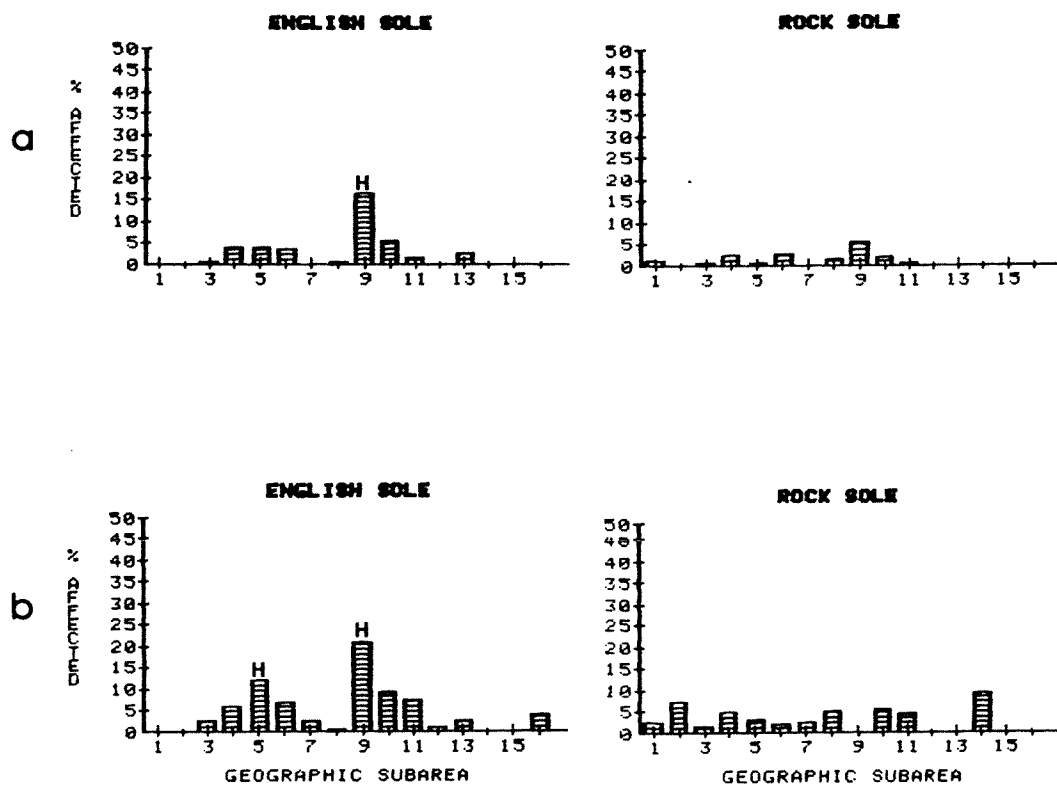


Figure 5.1. The geographic distribution by geographic subarea of fish species with (a) neoplasms and (b) "preneoplasms" of the liver. A significantly ($p < 0.05$) higher (H) or lower (L) prevalence is indicated. (The number of fish examined is given in Table 5.3. After Malins et al. 1982.)

1971).

Attempts have been made to correlate tissue and sediment concentrations of specific contaminants with the occurrence of liver neoplasms in Puget Sound demersal fishes. McCain et al. (1982) measured concentrations of PCBs and naphthalene in livers of English sole with liver neoplasms and preneoplastic lesions, but no consistent pattern was observed. These authors also compared the chemical composition of sediment from two areas (Duwamish River and Lake Washington Ship Canal) with the incidence of English sole liver neoplasms, 12.7% (70 of 551 fish) and 8.2% (4 of 49 fish), respectively. The concentrations of aromatic hydrocarbons and metals were found to be comparable in both locations, but the concentration of PCBs was 3 to 11 times higher in most Duwamish River sampling stations. In addition, PCB concentrations in livers of Duwamish River English sole were approximately 5 to 20 times higher than the concentrations in livers of sole from the Lake Washington Ship Canal. The authors concluded that PCBs could not be directly linked with the liver neoplasms observed in English sole from these locations.

Malins et al. (1982) investigated the relationship between sediment chemical composition and liver neoplasms in Puget Sound English sole by grouping sampling stations with similar sediment chemical profiles. They found a positive correlation ($p < 0.05$) between the prevalence of English sole with liver neoplasms and sediment concentrations of aromatic hydrocarbons and metals, whereas the occurrence of this species with "preneoplastic" lesions was positively correlated only with aromatic hydrocarbons ($p < 0.01$).

5.1.4 Other Liver Abnormalities

5.1.4.1 Backgrounds

Non-neoplastic liver abnormalities have been described from Puget Sound fishes by several researchers (Miller et al. 1977; Pierce et al. 1978; Malins et al. 1980 and 1982; McCain et al. 1982). Some of these abnormalities were associated with parasitic infections and occurred uniformly in both urban and nonurban embayments, but certain idiopathic anomalies were more prevalent in urban embayments. Malins et al. (1982) identified three principal, urban-associated, non-neoplastic liver abnormalities: 1) nonspecific degenerative/necrotic lesions, 2) specific degenerative/necrotic lesions, and 3) intracellular storage disorders.

The first category, nonspecific degenerative/necrotic lesions, included all cases of liver degeneration and necrosis in which no infectious agent was found associated with the liver. This category included lesions ranging from mild cellular or subcellular perturbations such as hydropic degeneration, to increased cytoplasmic eosinophilia or migration of nuclear chromatin, to cell necrosis.

Specific degenerative/necrotic lesions included megalocytic hepatitis (characterized by a massive increase in the diameters of hepatocytes and their nuclei) and nuclear pleomorphism (characterized by hepatocellular nuclear enlargement, nuclear hyperchromasia, and appearance of binucleate cells). Megalocytic hepatitis and nuclear pleomorphism were found in association so frequently that a new name, specific degenerative/necrotic lesions, was assigned by Malins et al. (1982) to encompass both lesions.

Intracellular storage disorders were not considered by Malins et al. (1982) to be lesions per se, but represented variability in the amounts and types of intracellular storage products observed in the fish tissues. Anomalies monitored in this study included excessive accumulations of lipids

and iron-containing storage products such as hemosiderin.

5.1.4.2 Incidence in Elliott Bay

Malins et al. (1982) found demersal fish with nonspecific degenerative/necrotic liver lesions in a variety of urban and nonurban sampling areas (Figure 5.2), but the highest frequencies for English sole and rock sole occurred in the upper and lower Duwamish River, respectively. Highest frequencies for Pacific tomcod (Microgadus proximus) in Elliott Bay were recorded from the Seattle waterfront.

Demersal fish with specific degenerative/necrotic lesions were collected by Malins et al. (1982) almost exclusively from urban embayments (Figure 5.3). In Elliott Bay, English sole with these lesions were most prevalent in the upper and lower Duwamish River and Seattle waterfront, while affected rock sole were most prevalent in the lower Duwamish River and Seattle waterfront. These lesions were also detected in Pacific staghorn sculpin (Leptocottus armatus), Pacific tomcod (1 of 65 fish) and quillback rockfish (Sebastes maliger, 1 of 93 fish) from Elliott Bay.

English sole, rock sole, and Pacific staghorn sculpin with intracellular storage disorders were found by Malins et al. (1982) in many urban and nonurban collection sites. Incidence in English sole was highest in the upper Duwamish River, while incidence in rock sole was highest in the lower Duwamish River (Figure 5.4). Affected Pacific tomcod and quillback rockfish were found primarily in Elliott and Commencement Bays, although affected tomcod also were found in Sinclair Inlet (Figure 5.4).

5.1.4.3 Association with Xenobiotics

Nonspecific hepatocellular necrosis is a common response to poisoning in many vertebrates (Plaa 1975), including teleost fish. Couch (1975) and Walsh and Ribelin (1975) identified hepatocellular necrosis as a general reaction in fishes exposed to a wide variety of compounds, including organophosphate, organochlorine and chlorinated cyclodiene pesticides and PCBs. Lesions characterized by hepatocytomegaly and which resemble specific degenerative/necrotic lesions of Puget Sound demersal fish and have been reported in channel catfish (Ictalurus punctatus) exposed to Aroclor mixtures (Hinton et al. 1978), and in rainbow trout exposed to dietary cyclopropenoids (Malins et al. 1982). Cellular enlargement was a result of accumulation of intracellular products, such as glycogen or lipid, and proliferation of endoplasmic reticulum.

Researchers have attempted to induce liver lesions similar to those observed in wild fish, by exposing English sole to Duwamish River sediments. McCain et al. (1982) reported that intraperitoneal injection of concentrated Duwamish River sediment extracts resulted in significantly higher mortality ($p < 0.05$) than did injection of control (Port Madison) sediment extracts. No attempt was made to identify the toxic component(s) in the Duwamish sediment. Histopathological analysis revealed minor alterations in the appearance of hepatocytes of fish injected with either Duwamish River or Port Madison sediment, but no hepatic lesions resembling those described in wild fish were observed. The authors postulated that the failure to induce lesions similar to those seen in the field may have been caused by several factors; 1) exposure periods (3 weeks maximum) may have been too short, 2) exposure by injection may not readily induce these lesions, and 3) fish used may not have been of a susceptible age.

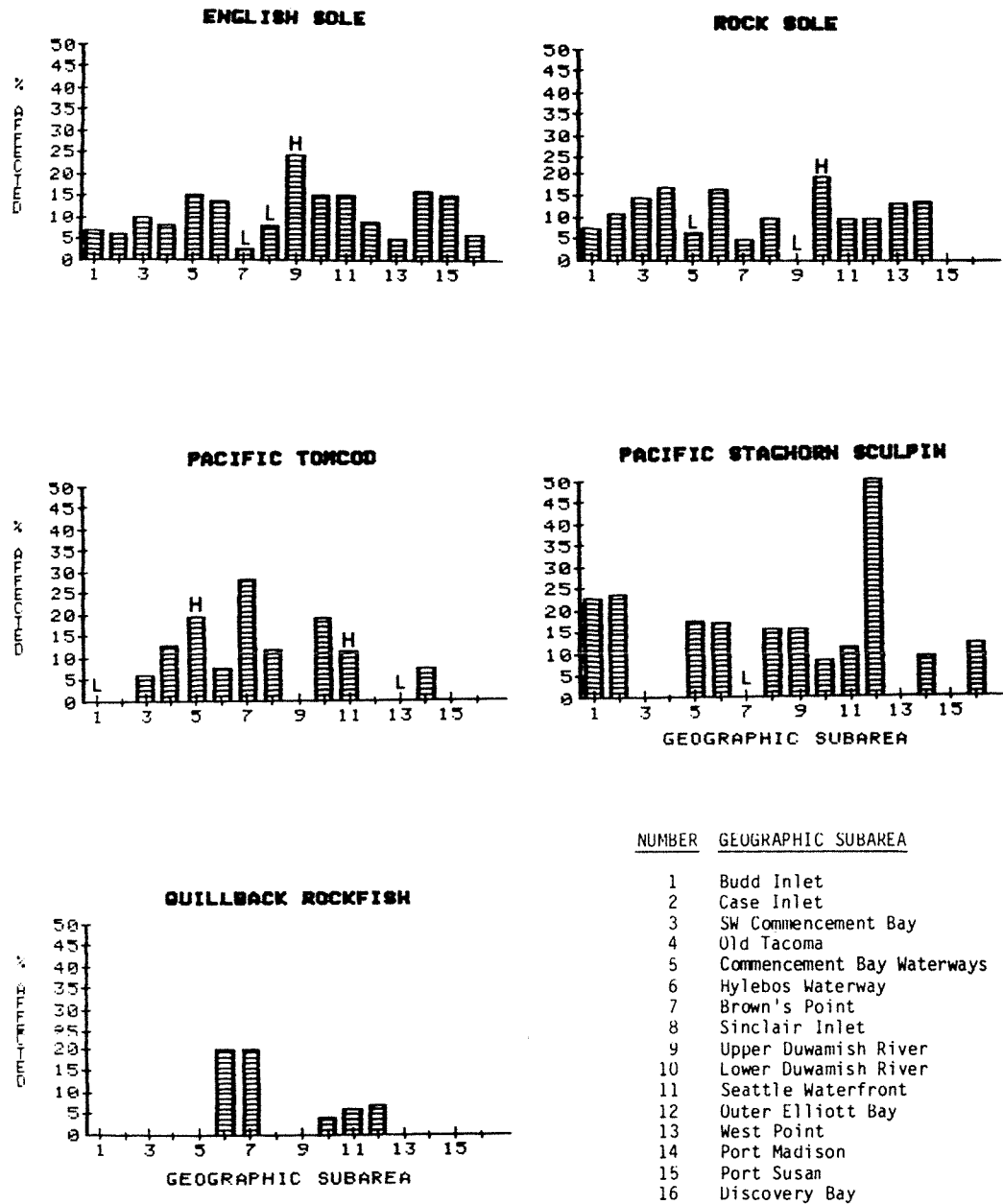


Figure 5.2. The geographic distribution of fish species with nonspecific degenerative/necrotic lesions of the liver. A significantly ($p < 0.05$) higher (H) or lower (L) prevalence is indicated. The number of fish examined is given in Table 5.3. After Malins et al. (1982).

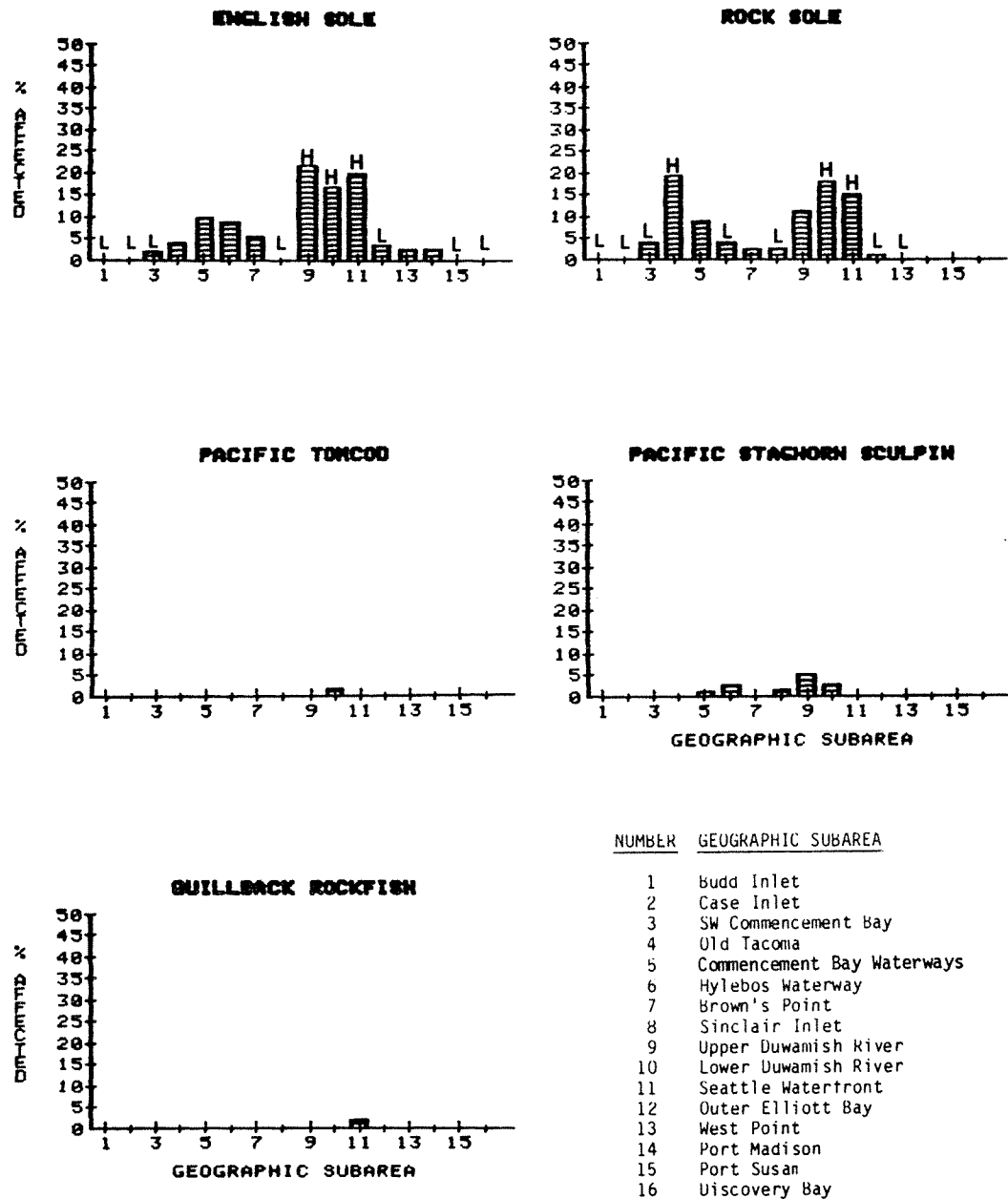


Figure 5.3. The geographic distribution of fish species with specific degenerative/necrotic lesions of the liver. A significantly ($p < 0.05$) higher (H) or lower (L) prevalence is indicated. The number of fish examined is given in Table 5.3. After Malins et al. (1982).

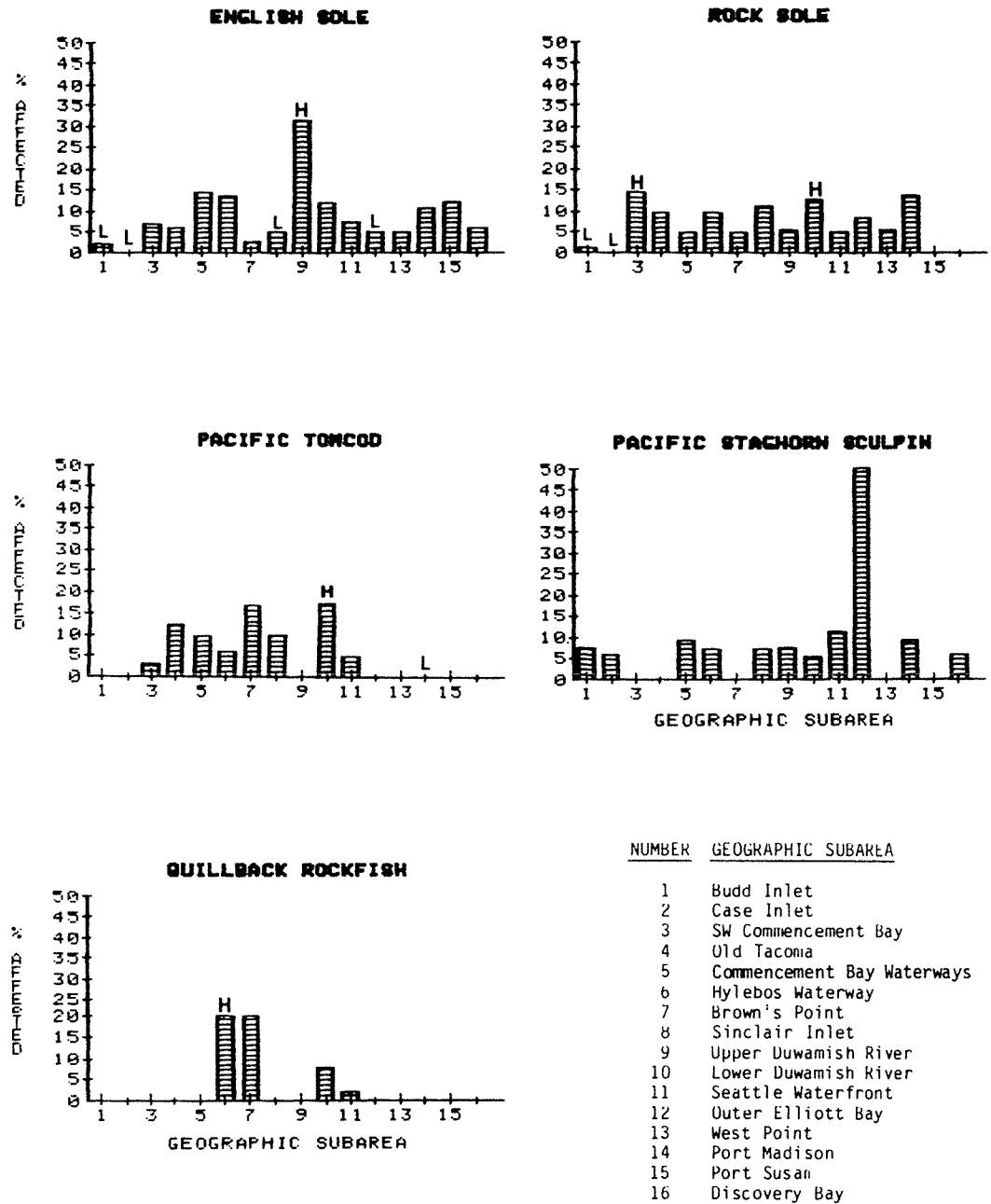


Figure 5.4. The geographic distribution of fish species with intracellular storage disorders of the liver. A significantly ($p < 0.05$) higher (H) or lower (L) prevalence is indicated. The number of fish examined is given in Table 5.3. After Malins et al. (1982).

In another experiment, McCain et al. (1982) exposed English sole for up to three months to Duwamish River sediment or control (Snohomish River or Port Madison) sediment. The sediments were layered on the bottom of aquaria. No significant differences in mortality were observed between the groups, and none of the characteristic liver lesions observed in English sole from the Duwamish waterway were seen in these laboratory experiments.

Other studies have attempted to correlate the prevalence of non-neoplastic liver lesions with sediment chemical composition. Malins et al. (1982) found a positive correlation ($p \leq 0.05$) between the incidence of specific hepatocellular degeneration/necrosis in English sole and sediment concentrations of aromatic hydrocarbons and metals. A direct cause and effect relationship between specific contaminants and the appearance of these lesions in marine fish remains to be demonstrated, however.

5.1.5. Other Abnormalities in Fishes

Recent studies (Malins et al., 1980 and 1982; McCain et al., 1982) also identified lesions in other organs (gills, kidney, gastrointestinal tract, heart, spleen and gall bladder) of fish sampled from Elliott Bay and other areas of Puget Sound. Some lesions, such as kidney necrosis, appeared to be more prevalent in urban embayments in some target species. Generally, the lesions in these organs appeared to be widespread in both urban and nonurban embayments, or incidences were too low for statistical analysis.

5.1.6 Summary

Numerous tissue lesions have been observed in demersal fish in Elliott Bay, but the relationship between these lesions and exposure to xenobiotics is unclear. The incidences of some of these lesions, particularly fin erosion, hepatic neoplasms and "preneoplasms," and certain non-neoplastic liver lesions, appear to be greater in animals caught in areas with high xenobiotic levels and hence, may imply a causal relationship. No specific chemical agent(s) has been identified, however, nor have other non-chemical agents been clearly eliminated, as causes of the lesions.

The possible contributions of many factors (besides chemicals) have not been adequately evaluated. For example, the available data do not elucidate potentially pertinent ecological relationships. Thus, the contributions of such factors as differences in physical environments (salinity, water depth, current patterns, sediment type, etc.) and differences in species interrelationships to the geographical distribution of diseased fish remain unknown. Further, the migratory habits of the populations which have been studied are poorly understood (Dexter et al. 1981). Variability in catch statistics, disease incidences and chemical concentrations in animals from affected areas (Malins et al. 1980) suggest some migration of the test organisms. Determining the history of movement of either healthy or diseased fish is difficult. To date, the contribution of migratory movements to apparent focal distribution of lesions in demersal fish remains unknown.

5.2 Invertebrate Health

Histopathological studies of invertebrates from Elliott Bay and other areas of Puget Sound were reported by Malins et al. (1980 and 1982). These authors collected polychaete worms (Capitella capitata, Glycera capitata and

Prionospio pinnata), clams (Macoma carlottensis, Macoma nasuta and Acila castrensis), shrimp (Pandalus danae, P. jordani and Crangon alaskensis) and crabs (Cancer magister, C. gracilis and C. productus).

No lesions were observed in polychaete worms or mulluscs. Reported sample sizes (Malins et al. 1980) were small, however, and included only 85 polychaetes (8 from Elliott Bay) and 60 clams (2 from Elliott Bay).

Lesions reported by Malins et al. (1980 and 1982) in shrimp and crab most frequently affected the gill, hepatopancreas, midgut and antennal gland, although other organs were occasionally involved (Table 5.4). Some lesions were associated with infectious agents, while others (idiopathic lesions) were caused by unknown factors. Certain idiopathic lesions appeared to be more common in shrimp and crab sampled from Elliott Bay and other urban areas (Figures 5.5 and 5.6). The significance of these observations was not determined, because the low numbers of animals captured and examined precluded meaningful statistical analyses.

5.3 MICROBIOLOGY

5.3.1 Microbiology

The Renton treatment facility was designed for activated sludge secondary treatment and was constructed in 1965 (Matsuda and Farris 1976). The effluent discharges into the Duwamish River 13 miles above Elliott Bay in Puget Sound. This plant chlorinates sewage in the treatment process to kill bacteria and then dechlorinates the effluent with sulfur dioxide prior to discharge into the river.

A water quality monitoring program was initiated in 1961 to assess the impact of wastewater discharge on various receiving waters (Figure 5.7; Matsuda and Farris 1976). The current procedure used to identify and count fecal coliform bacteria began in April 1976. Treatment and chlorination of sewage at the Renton plant was highly effective in reducing the number of bacteria in the effluent (Figure 5.8, Table 5.5). The concentration of total coliforms along the shores of Elliott Bay, decreased from a median of 240,000 per 100 ml in 1968 to a median of less than 200 per 100 ml in 1975. Data from Whitmore et al. (undated) cover the period of 1965 through 1968 for Elliott Bay and 1963 through 1968 for the other areas.

5.3.1.1 Duwamish River

Bernhardt and Yake (1981) studied the effects of wastewater treatment at the Renton plant on the microflora of the Duwamish River. Fecal coliforms were measured in 1979 in the receiving waters 0.5 km above the Renton wastewater treatment plant outfall and 15.6 km below the outfall (Table 5.6). The changes in the concentrations of fecal coliforms at the sampling sites downstream were confounded by tidal action and the resulting flow reversal. During periods of low flow, a partly diluted block of river water was combined with secondary wastewater each time flow reversal occurred. The concentration of fecal coliforms above the Renton wastewater treatment plant was measured at 160 organisms per 100 ml (Bernhardt and Yake 1981). The concentration of fecal coliform in the final effluent was 100 per 100 ml with a chlorine residue of 0.23 mg/l (Table 5.6). The concentration of fecal coliform decreased to 9 per 100 ml after mixing occurred. The number of fecal coliforms remained low for 3.4 km below the outfall and then increased to 190 per 100 ml 7-9 km below the outfall. The concentration of fecal coliforms varied from 1 to 300 per 100 ml (Table 5.6). Other studies done between

Table 5.4. Histopathological lesions observed in target invertebrate species collected from Puget Sound. After Malins et al. (1982).

Organ or tissue type	Condition	Species affected ¹
GILL	A. Necrosis	CA,CC,PS
	B. Melanized nodules and granulomas	CC CA,PS
HEPATOPANCREAS	A. Epithelial necrosis and/or encapsulation	CC,PS CA
	B. Epithelial metaplasia	CC
	C. Phagocytic activation	CC
ANTENNAL GLAND	A. Necrosis	CA,CC,PS
BLADDER	A. Necrosis	CC,CA,PS
MIDGUT	A. Melanized nodules and granulomas	CC
	B. Hemocytic infiltration	CC
MUSCLE	A. Microsporidan infestation	CA
NERVOUS SYSTEM	A. Trematode infestation	CA
SYSTEMIC	A. Yeast infestation	CA

¹ Species affected were Crangon alaskensis (CA); Cancer crabs (CC), C. magister, C. gracilis, and C. productus (CC); and pandalid shrimp (PS), Pandalus danae and P. jordani (PS)

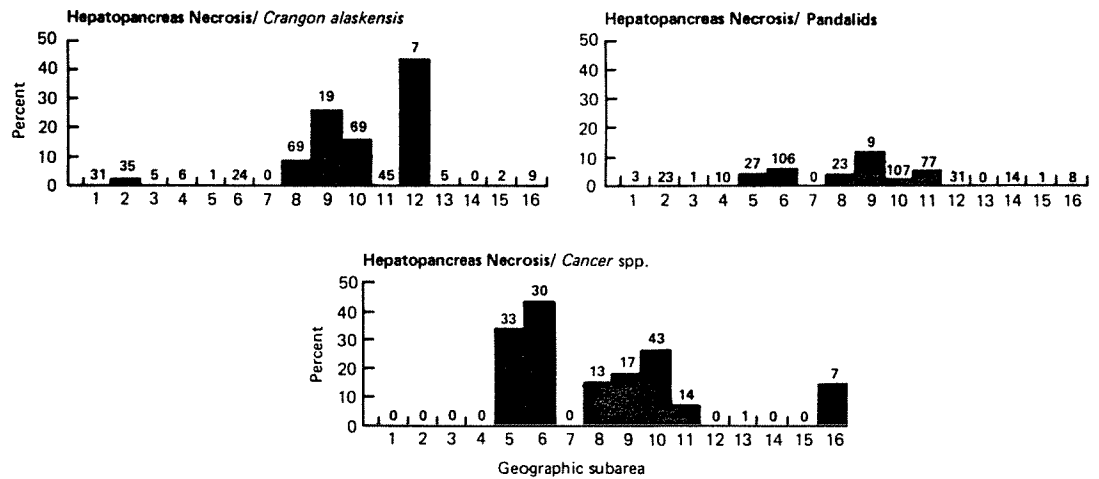


Figure 5.5. The geographic distribution of hepatopancreas necrosis observed in *Crangon alaskensis*, pandalid shrimp, and *Cancer* spp. The number of animals examined for each geographic subarea is given. The subareas are listed in Figure 5.1.4.2.3. After Malins et al. (1982).

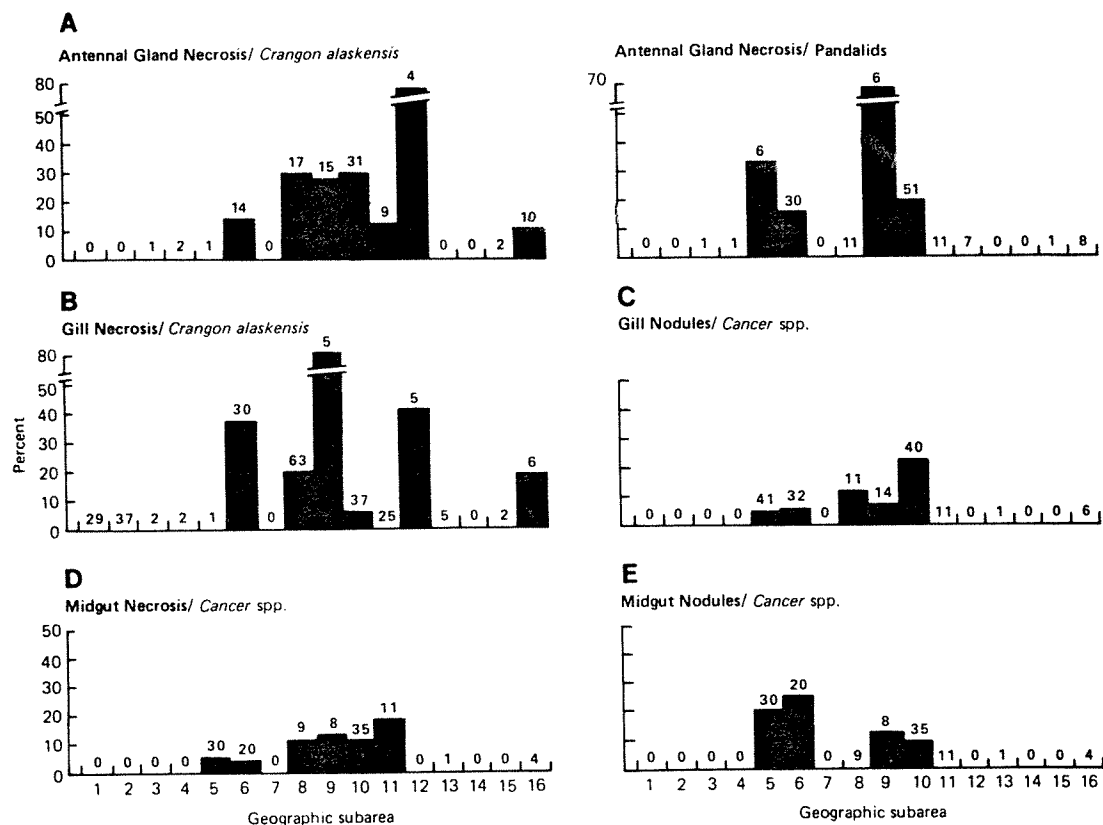


Figure 5.6. The geographic distribution of necrotic and nodular lesions observed in shrimp and crab. (A) Antennal gland necrosis in *C. alaskensis* and pandalid shrimp, (B) gill necrosis in *C. alaskensis*, (C) gill nodules in *Cancer* spp., and (D) midgut necrosis and (E) midgut nodules in *Cancer* spp. The number of animals examined for each geographic subarea is given. The subareas are listed in Figure 5.1.4.2.3. After Malins et al. (1982).

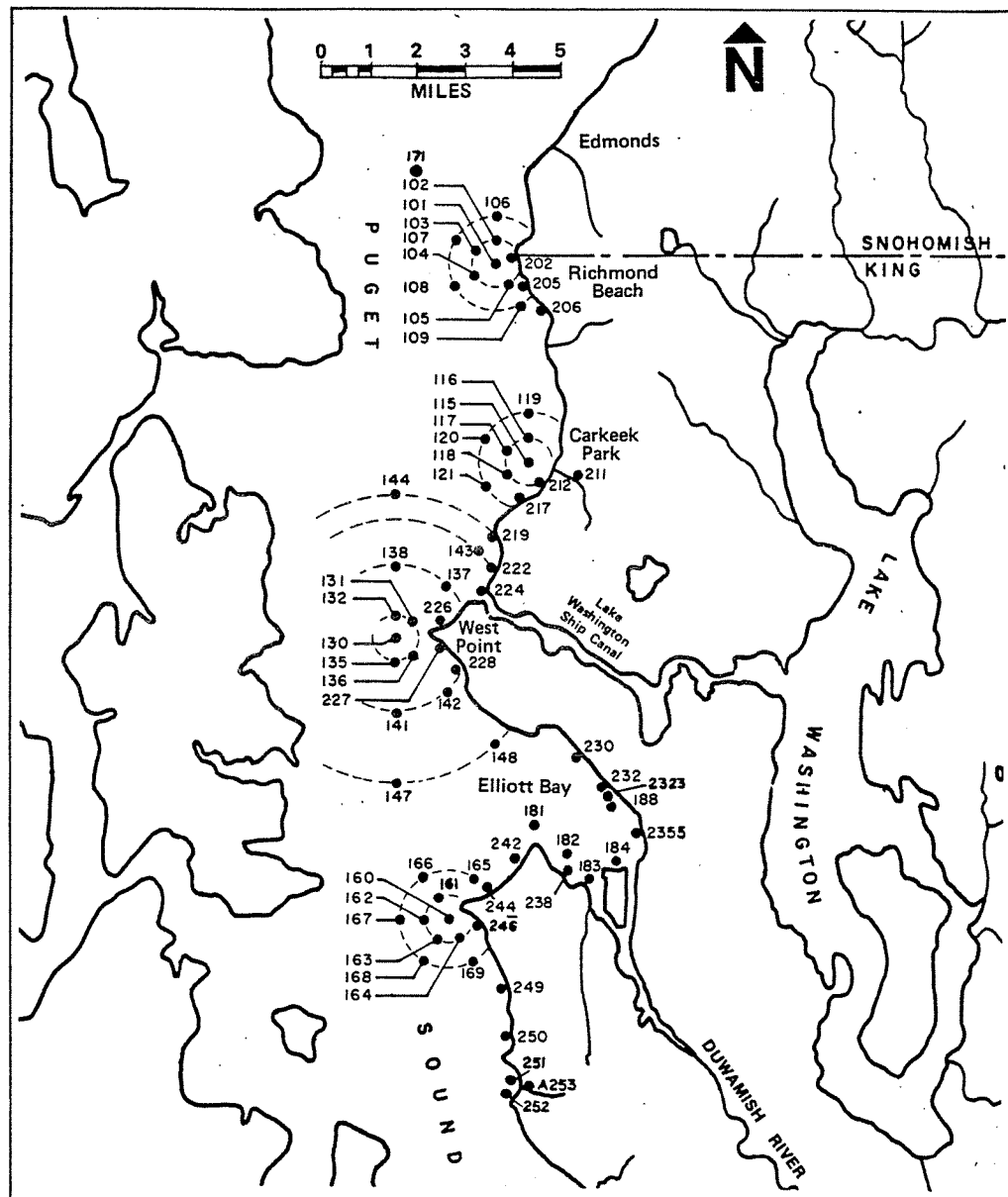


Figure 5.7. Water quality monitoring stations in central Puget Sound used by the Municipality of Metropolitan Seattle (METRO). After Patten and Tomlinson (undated).

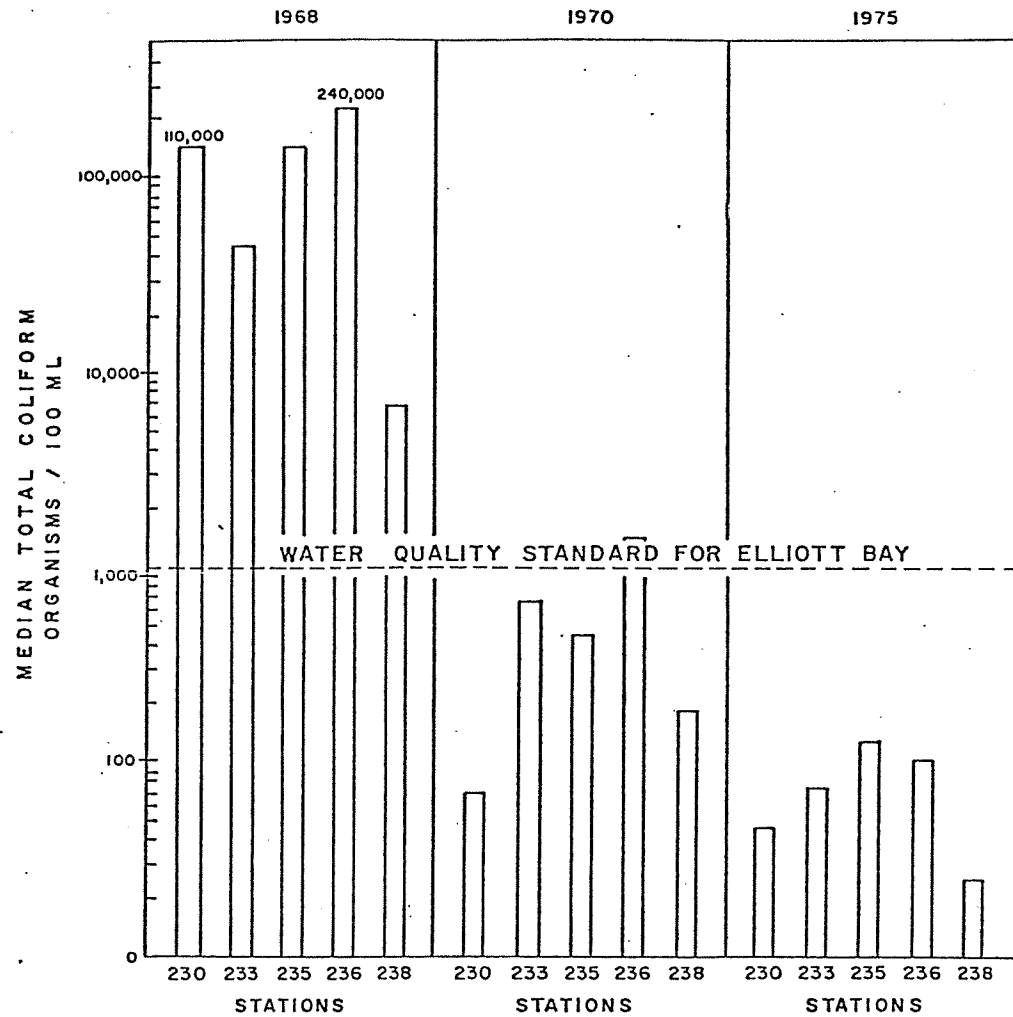


Figure 5.8. Coliform concentrations along the shore of Elliott Bay during July through September for the years 1968, 1970 and 1971. After Matsuda and Farris (1976).

Table 5.5. Annual mean bacterial counts from various stations in Elliott Bay and the Duwamish River. After Whitmore et al. (undated).

Station	1963	1964	1965	1966	1967	1968
			³	³	³	³
230			24x10 ³	40x10 ³	71x10 ³	170x10 ³
			³	³	³	³
233			15x10 ³	12x10 ³	26x10 ³	46x10 ³
			³	³	³	³
235			21x10 ³	73x10 ³	60x10 ³	63x10 ³
			³	³	³	³
236			24x10 ³	71x10 ³	110x10 ³	150x10 ³
			³	³	³	³
238			2.3x10 ³	3.1x10 ³	4.9x10 ³	2.4x10 ³
Duwamish Head						
				³		
241	410	930	1100	1.4x10 ³	800	930
Alki						
242	230	190	190	510	340	--
243	93	180	210	230	160	230
244	150	210	180	430	320	230
245pt	470	480	510	630	800	--
246	93	230	400	380	230	150
247	230	410	360	320	280	230
248	930	380	1400	300	540	430

Table 5.6. Summary of water quality data collected by the Washington State Department of Ecology during the time-of-travel study of the Green-Duwamish River. After Bernhardt and Yake (1981).

Sta- tion	Location	Time of Travel	Flow cfs	Temp. (°C)	S. Cond. (µmhos/cm)	pH	Turb. (NTU)	T. Alk. (as CaCO ₃) (mg/l)	D.O. (mg/l)	D.O. Sat. (%)	Total Chlorine (mg/l)	BOD (mg/l)	Fecal Coli. (Col/100 ml)
19.8	Control 0.5 km abv. Renton Wastewater Treatment Plant (RWTP) Outfall	1530 ---	---	18.5	220	7.6	2	61	9.5	100.6	---	<2	160
19.5	Control 0.2 km above RWTP Outfall	1510 ---	274	18.4	188	7.6	2	57	9.3	98.3	---	2	160
<u>Drogues start upstream movement at 1515</u>													
WTP	RWTP final effluent	1410 ---	68	44	22.8	7.3	5	120	8.4	96.5	0.23 ^{2/}	6	100
19.3	River water from boil at RWTP Outfall	1610 ---	342	22.5	499	7.2	3	110	7.0	80.1	---	4	9
19.5	0.2 km above RWTP Outfall ^{1/}	1640 ---	---	24.2	339	7.3	3	87	7.7	90.8	---	2	6
<u>Drogues stop upstream movement at 1645</u>													
19.3	About 30 m above RWTP Outfall	1720 ---	---	20.0	344	7.3	4	89	7.9	86.2	---	3	10
<u>Drogues pass outfall at 1726 heading downstream</u>													
19.2	At first bend about 250 m below RWTP Outfall	1741 :15	---	23.1	391	7.2	4	93	7.4	85.6	---	--	7
18.6	About 0.7 km below RWTP Out- fall, just below Fort Dent Bridge	1811 :45	---	19.9	365	7.2	3	93	7.5	81.5	---	4	4
17.7	About 1.6 km below RWTP Outfall at mouth of Black River	1850 1:30	---	19.1	320	7.3	3	87	7.6	81.5	---	--	11
15.9	About 3.4 km below RWTP Outfall at North end of Foster Golf Course	2026 3:00	---	18.1	248	7.4	3	71	7.7	80.9	---	4	39
11.4	About 7.9 km below RWTP Outfall, at first bend above Marginal Way Bridge	2226 5:00	---	17.7	319	7.3	4	65	6.6	68.8	---	4	190

Table 5.6. (continued).

Sta- tion	Location	Time of Travel	Flow cfs	Temp. (°C)	S. Cond. (µmhos/cm)	pH	Turb. (NTU)	T. Alk. (as CaCO ₃) (mg/l)	D.O. (mg/l)	D.O. Sat. (%)	Total Chlorine (mg/l)	BOD (mg/l)	Fecal Coll. (Col/100 ml)
<u>Droques stop downstream movement at 2357 and start upstream movement at 0015</u>													
10.5	About 8.9 km below RWTP Outfall, just below Old Highway 99 Bridge	0026 7:00	---	17.5	453	7.3	3	65	6.3	65.5	---	3	650
12.4	About 6.9 km below RWTP Outfall, near S. 122nd St.	0226 9:00	---	17.5	516	7.3	3	67	6.2	64.4	---	---	1,000
<u>Droques stop upstream movement at 0400 and begin downstream movement at 0430</u>													
12.1	About 7.2 km below RWTP Outfall, just above Old Macadam Road Bridge (42nd Avenue South)	0526 12:00	---	17.7	472	7.2	2	71	6.1	63.6	---	4	340
6.6	About 12.7 km below RWTP Outfall, at 1st bend above 16th Avenue South Bridge	0826 15:00	---	16.0	18,000	7.3	2	81	4.9	52.7	---	---	560
3.4	About 15.9 km below RWTP Outfall, near Slip No. 2 just below 1st Ave. So. Br.	1126 18:00	---	16.7	21,300	7.2	2	86	5.5	60.8	---	---	320
<u>Droques begin upstream movement at 1220</u>													
3.7	About 15.6 km below RWTP Outfall, just above 1st Avenue South Bridge	1426 21:00	---	16.6	22,600	7.4	2	93	5.6	62.1	---	---	130
3.9	About 15.5 km below RWTP Outfall, just above 1st Avenue South Bridge	1726 24:00	---	15.7	24,800	7.4	4	86	5.8	63.7	---	---	130

1/ Moved upstream to same location as lower control station.

2/ From Renton WTP self-monitoring data.

"≤" = "less than"

October 1976 and March 1977 and October 1977 and March 1978 showed higher fecal coliform concentrations in the Green-Duwamish River (Figure 5.9). These data, expressed as geometric mean rather than median, probably reflected the high runoff of water. The Duwamish River receives water from several major combined sewer overflows in addition to storm runoff from the residential, commercial and industrial areas in the Duwamish Basin (Harper and Owes 1983). The principal sources of coliform bacteria within the estuary were the combined sewer overflows (CSO) which contributed approximately 80% of the total load. The CSO fecal coliform input originated from excrement while the upstream Green River inputs stemmed from agricultural runoff from dairy and other farming activities.

The median fecal coliform concentrations throughout the Duwamish Estuary exceeded 100 per 100 ml, but stemmed largely from agricultural sources as shown by the coliform/streptococci ratio (Harper and Owes 1983). When water from the CSO entered the Duwamish River, the fecal coliform levels could exceed 68,000 per ml and were principally of human origin.

The decreases in the number of fecal coliforms below the outfall resulted from effects of residual chlorine in the treated effluent as well as dilution effects. The residual chlorine concentration ranged from 0.10 to 0.29 mg/l (Buckley and Matsuda 1973). Scarpino et al. (undated) showed that these chlorine concentrations inactivated *Escherichia coli* (Figure 5.10). Fecal coliform concentrations again increased in the lower river but these bacteria were derived from non-effluent sources. Renton plant effluent did not contribute to the fecal coliform population in the lower stream system. Bacteria from other sources included CSOs, septic tank drainage, and farm land runoff. When the effluent from the Renton plant is diverted, the flow in the river will be decreased. With the improved dechlorination procedure initiated in 1983, the residual concentration in the Renton effluent will decrease.

5.3.1.2 Elliott Bay

Bacteria enter Elliott Bay from direct surface runoff, storm runoff, sewer overflow, septic tank drainage, and the Duwamish River. The concentrations of bacteria, both total and fecal coliforms, varied between stations and some stations had total bacterial concentrations that exceeded fecal coliform concentrations (Figures 5.11, 5.12, and 5.13). Other reports (METRO undated, a-e) showed similar results, October 1975 - March 1976 and October 1980 - March 1981. The reduction in the concentration of total coliforms (Station 184 surface) between 1967 and 1978 illustrated the effects of diverting untreated sewage from Elliott Bay. The total coliform concentrations dropped from 130,000 per 100 ml to 3,000 per 100 ml.

Available data (Patten and Tomlinson, undated, and METRO undated, a-e) indicated that the concentrations of total and fecal coliforms varied with rainfall and overflows. In Patten and Tomlinson (undated) plots of the fecal coliform concentration from Elliott Bay stations were published.

Data from the Elliott Bay offshore stations showed that at station 181-184 and 188 (Figure 5.14) the fecal coliform concentrations usually fell below 43 organisms per 100 ml (METRO undated, a-e). Although the concentrations occasionally dropped below 14 fecal coliforms per 100 ml water, at all stations the concentrations were generally higher than 14 organisms per 100 ml. Puget Sound shore stations (230 and 232 from 1976 to present; Figure 5.15) showed much higher fecal coliform concentrations than did offshore stations. Concentrations varied from 14 fecal coliforms to over 100 organisms per 100 ml during the sampling period. Most stations had high fecal coliform

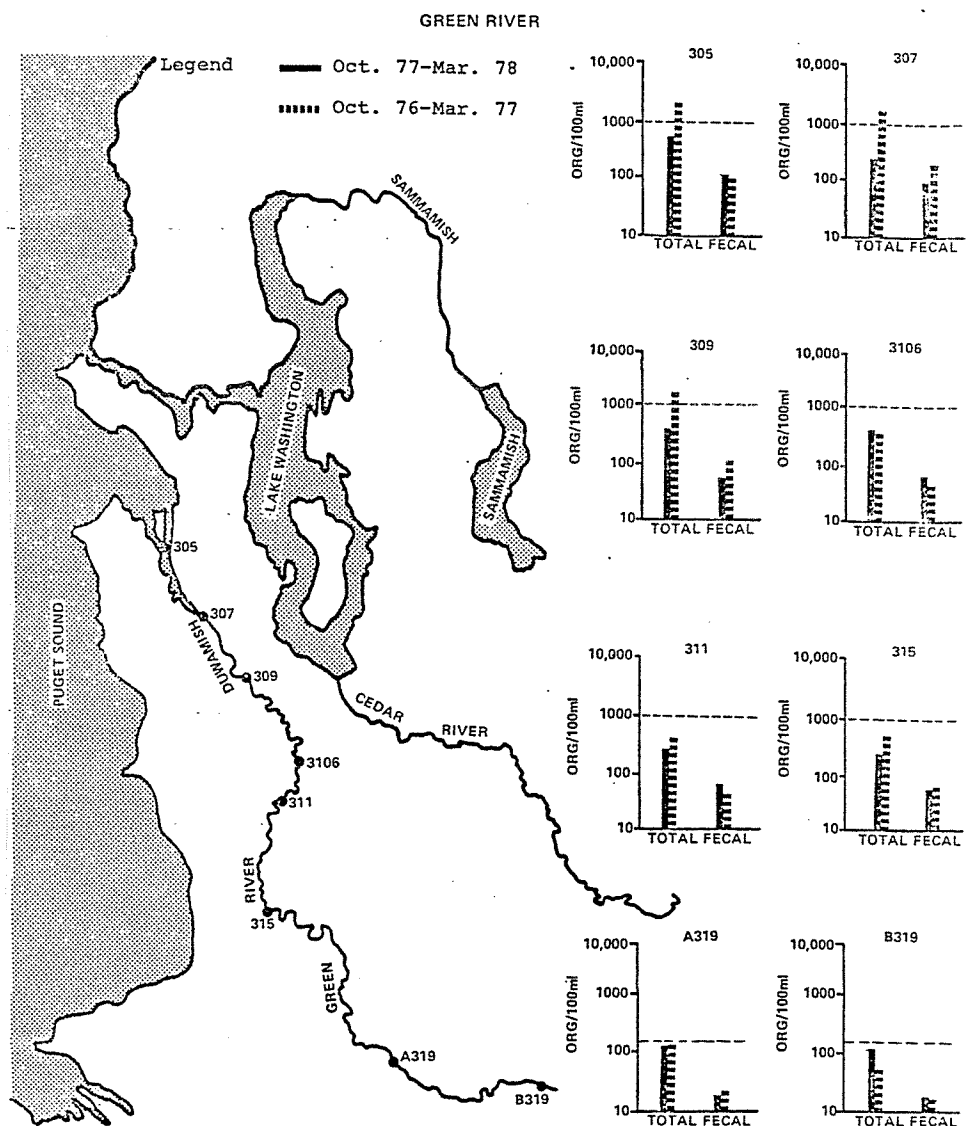


Figure 5.9. Six month geometric mean for total and fecal coliforms for the upper and lower Green River during fall, 1977, and winter, 1978. After METRO (1980b).

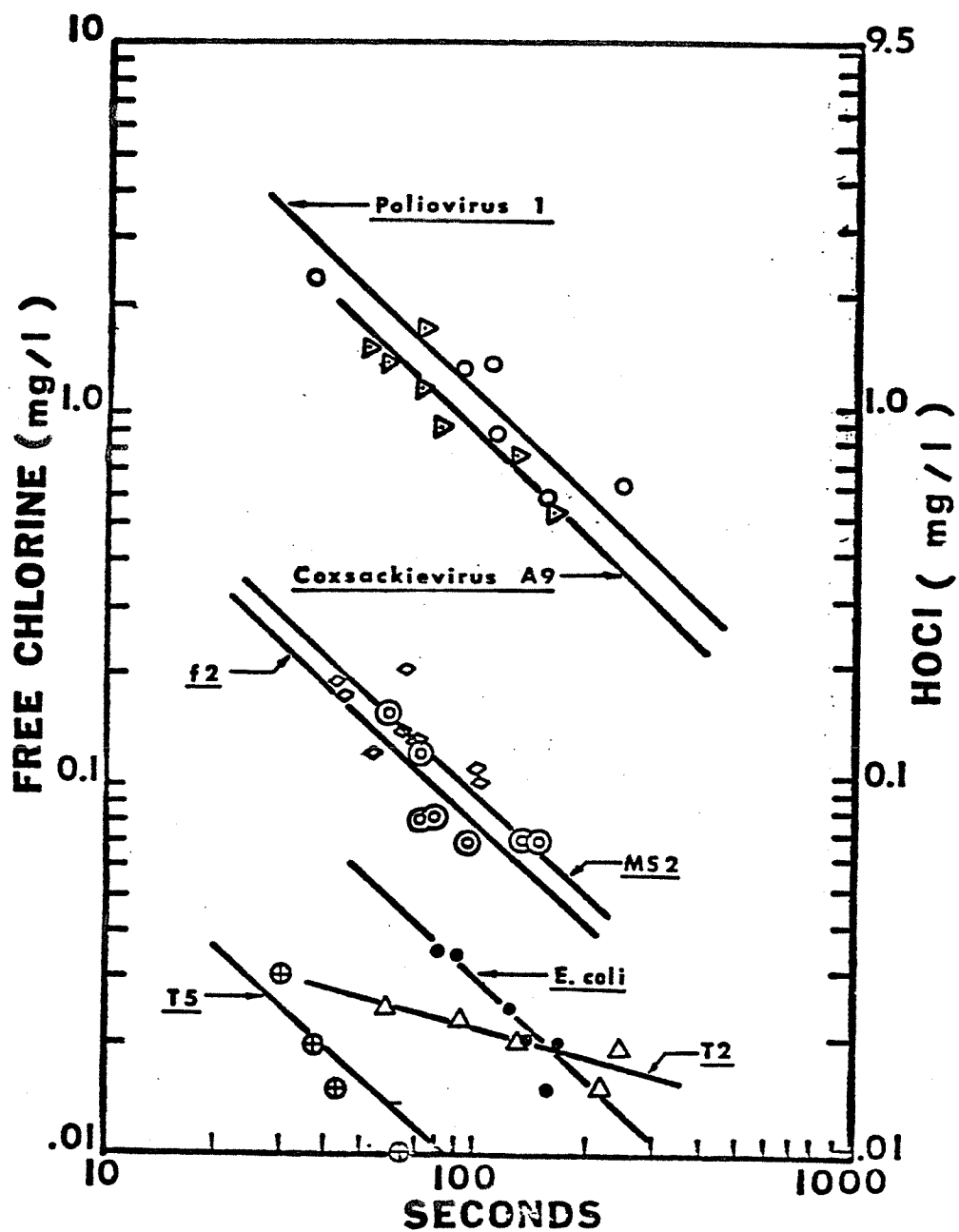


Figure 5.10. Survival times for microorganisms exposed to various concentrations of free chlorine and hypochlorite. After Scarpino et al. (undated).

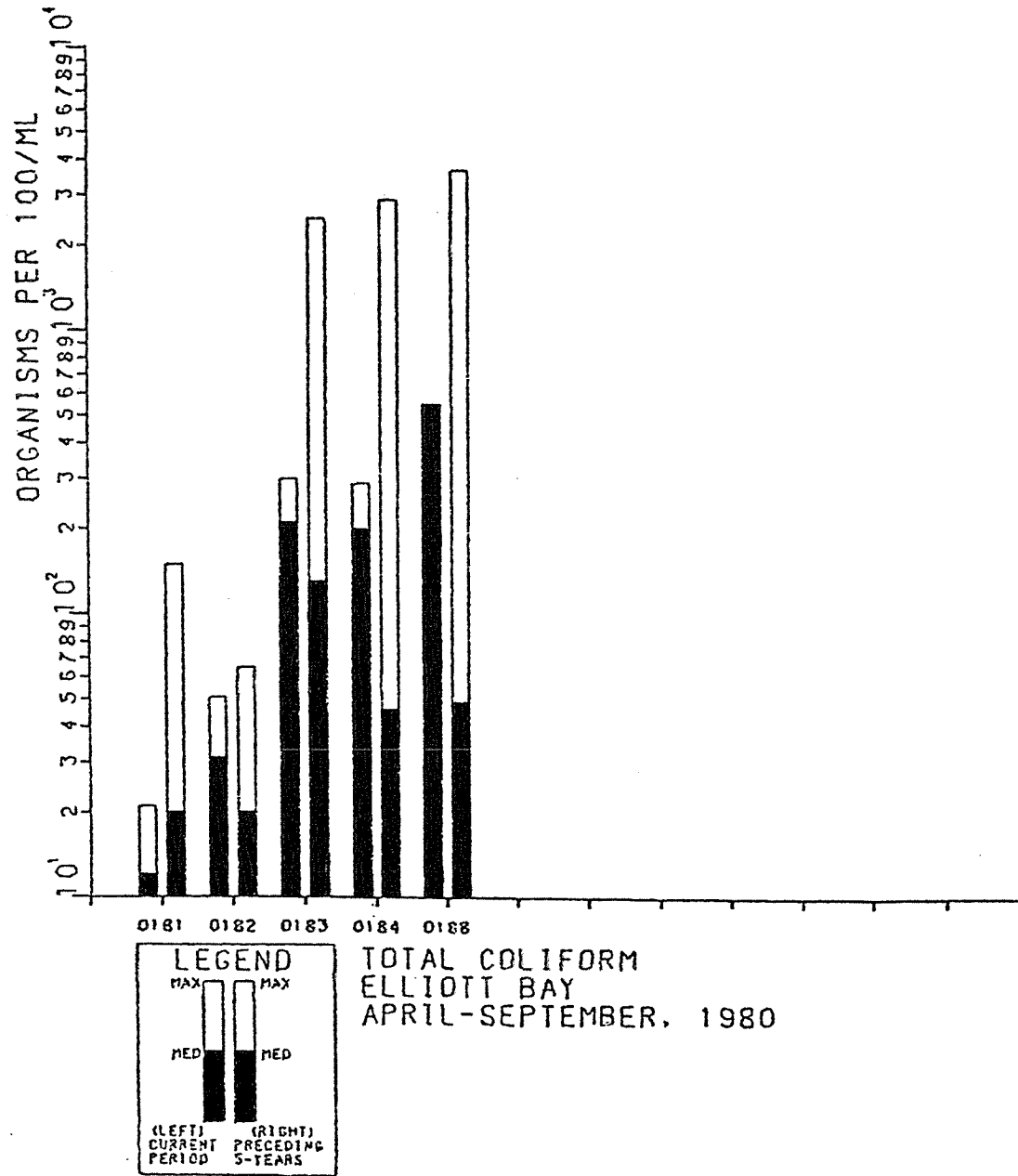


Figure 5.11. Total coliforms in Elliott Bay during April to September 1980. After METRO (1980d).

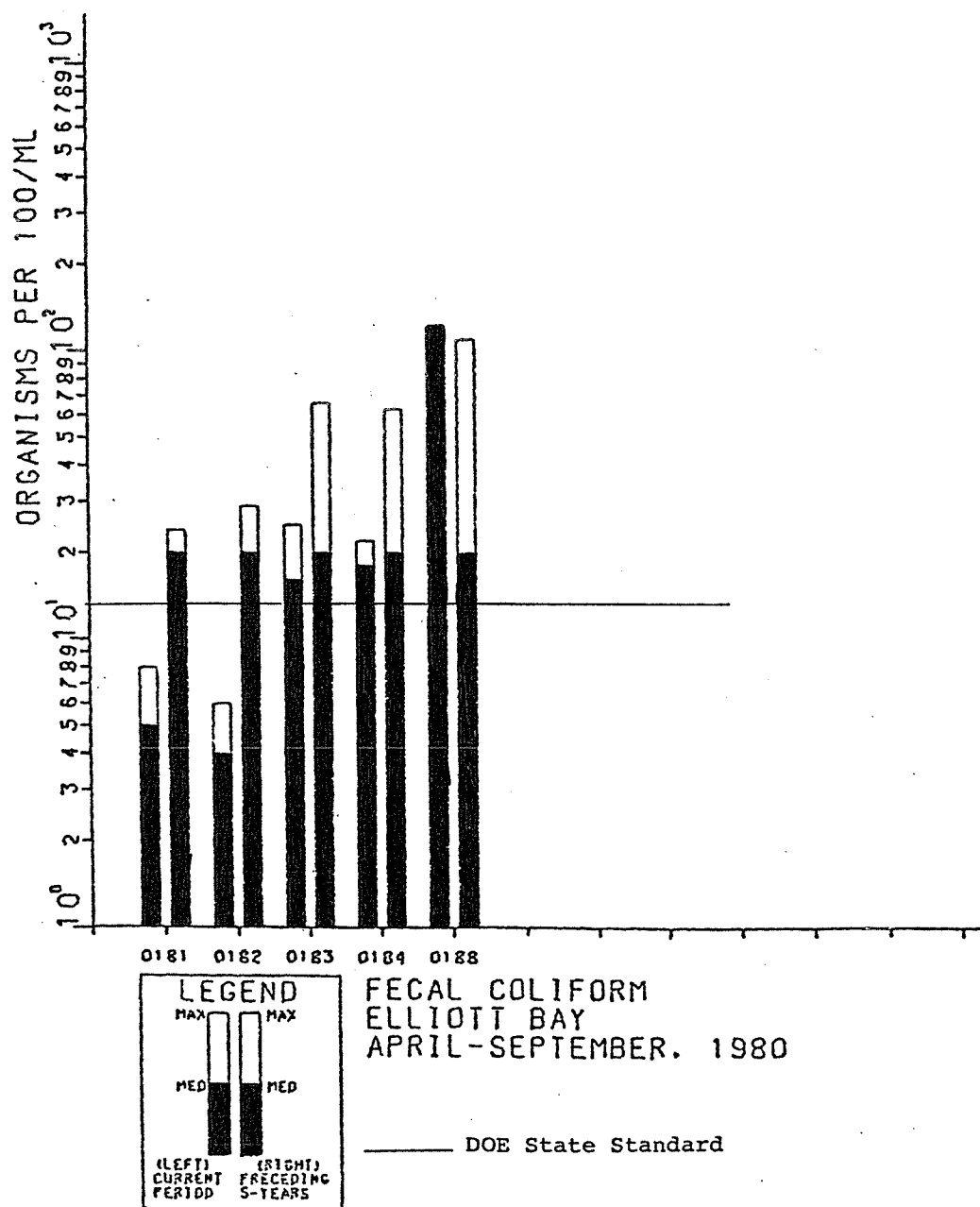


Figure 5.12. Fecal coliforms in Elliott Bay during April-September 1980. After METRO (1980d).

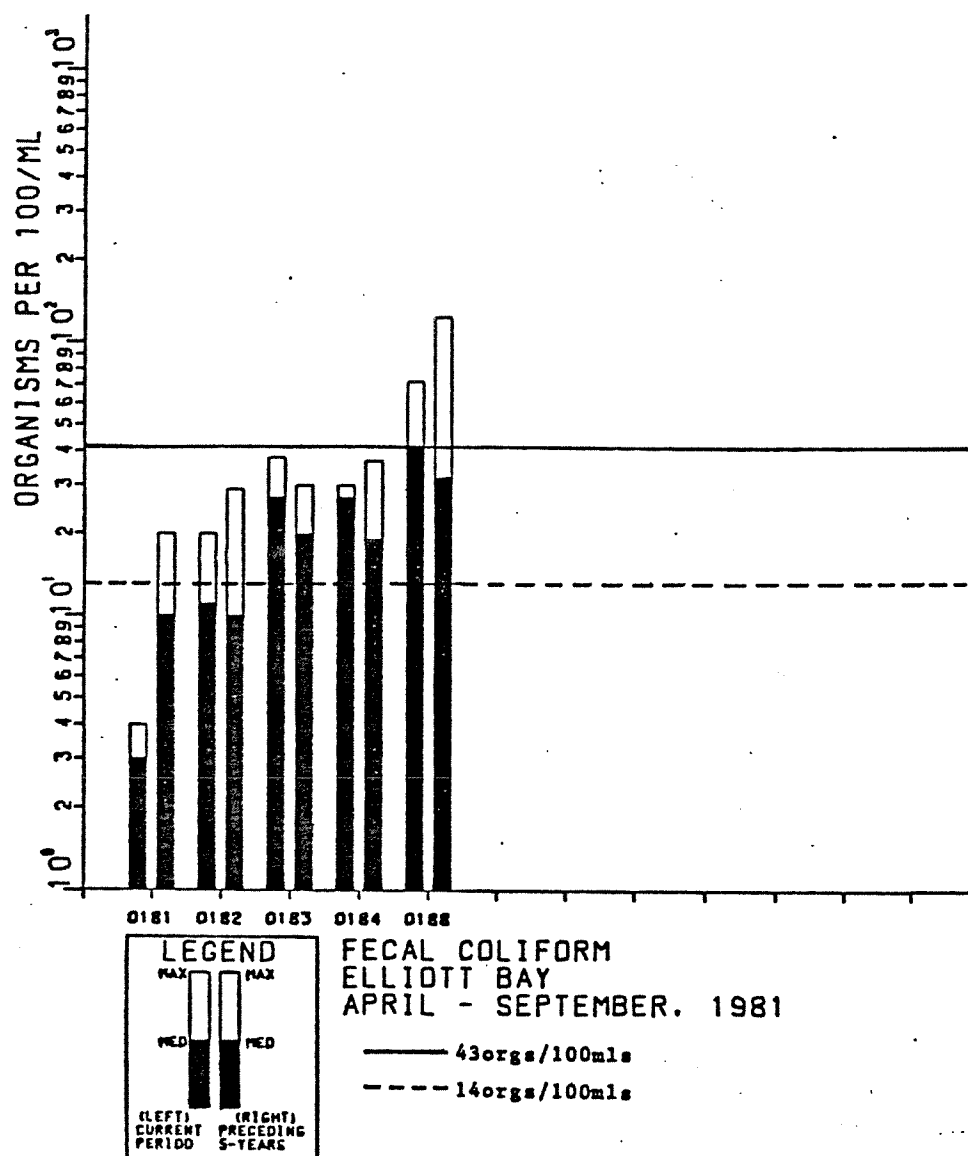


Figure 5.13. Fecal coliform concentrations in Elliott Bay during April-September 1981. After METRO (1980e).

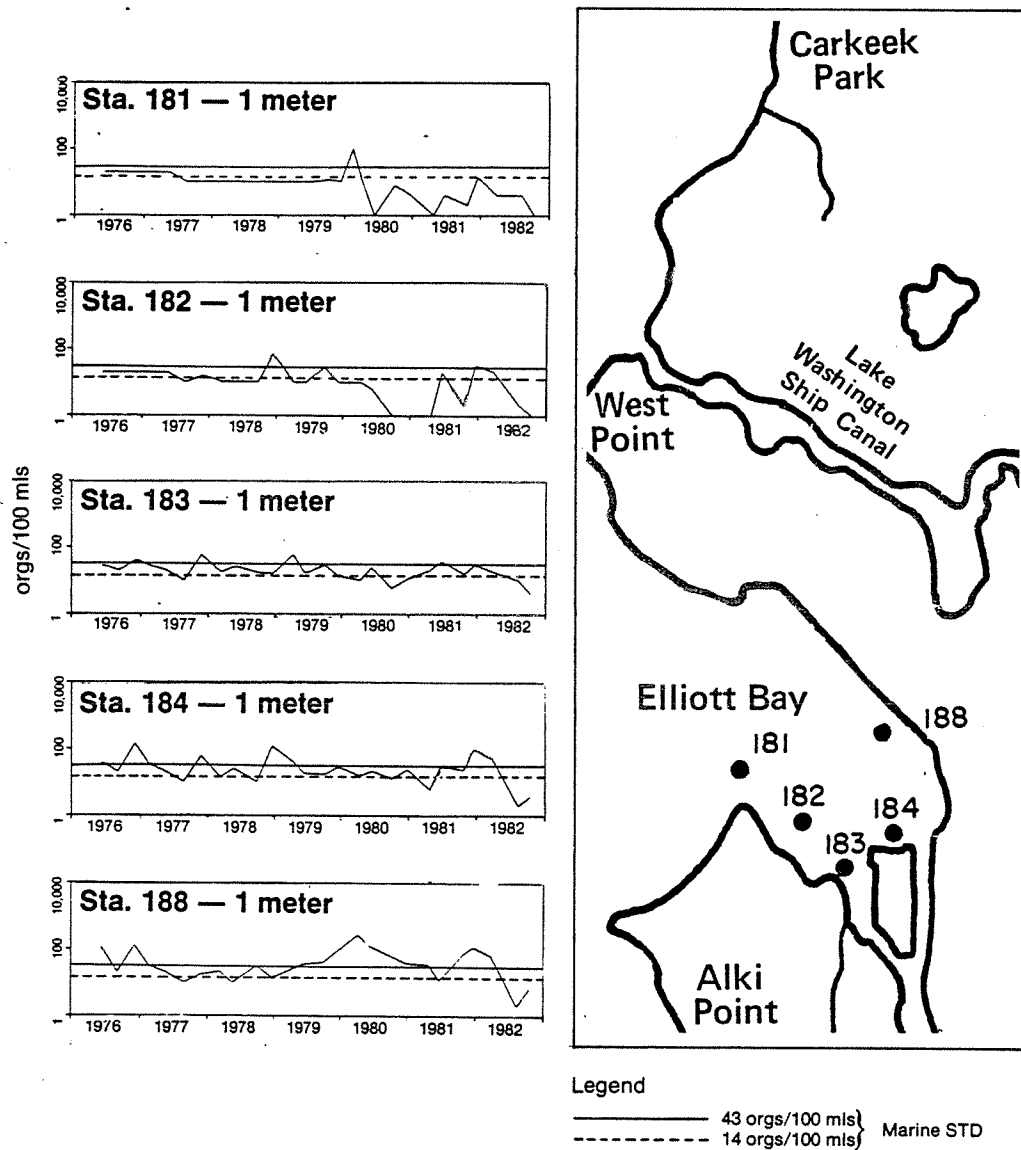


Figure 5.14. Trends in fecal coliform concentrations at stations located offshore in Elliott Bay. After Patten and Tomlinson (undated).

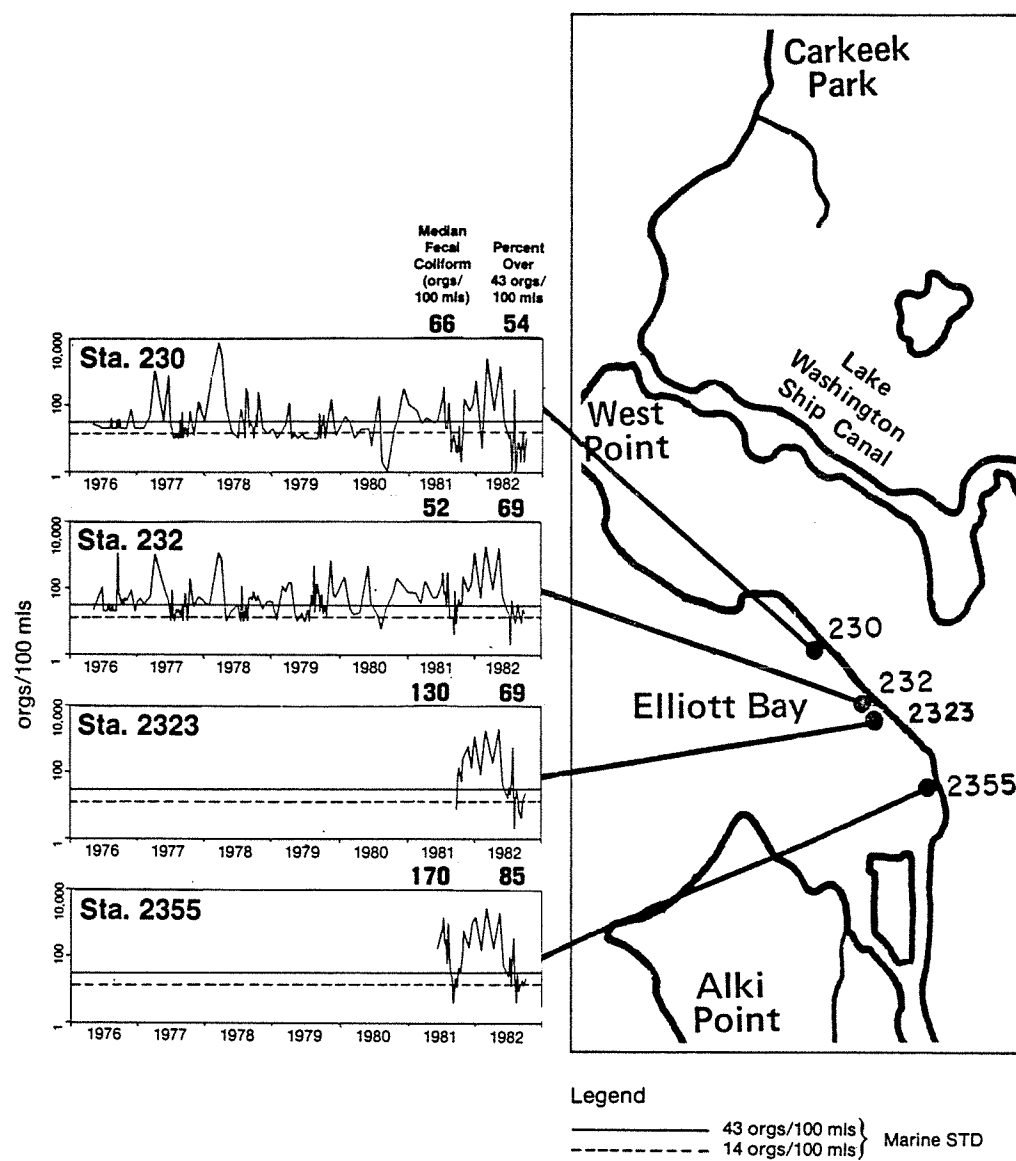


Figure 5.15. Trends in fecal coliform concentrations at nearshore stations in Puget Sound. After Patten and Tomlinson (undated).

concentrations during the wet season. Patten and Tomlinson (undated) concluded that the Duwamish River and the large CSOs were the major causes of these increases in wet season fecal coliform concentrations.

Human and animal excrement from the Duwamish Basin entered sewer overflows and occasionally overflowed directly into Elliott Bay (Figure 5.16 and Table 5.7) adding pathogenic bacteria to the waters. These bacteria may enter humans who eat salmonids, bottomfish, and squid. The presence of Salmonella, Yersinia enterocolitica and fecal streptococci in Elliott Bay has not been adequately documented.

Elliott Bay, east of a line between Pier 91 and Duwamish Head, is Class A water, while all other areas are Class AA water. During the past few years the waters in Elliott Bay, have generally been in compliance with the bacterial standards (Appendix 1). During heavy rains and high runoff, the concentration of fecal and total coliforms have occasionally exceeded the applicable standards.

Alki - Beach Studies

Heyward, Munger and Swartz (1977) concluded that fecal pollution existed in the water and clam samples collected in the intertidal zone near the outfall at Alki Beach. Fecal coliform concentrations ranged from 230-2300 per 100 g of clams, but water samples between June 14-17, 1977 contained less than 30 bacteria per 100 ml. Later in the month (June 28-30, 1977) the concentrations of fecal coliforms ranged from less than 30 to 230 bacteria per 100 g clam and from less than 3 to 9 bacteria per 100 ml water. In August 1979 fecal coliform concentrations from clams collected at Alki beaches ranged from less than 30 to 2300 per 1900 g. Fecal coliform concentrations in low tide water samples ranged from less than 3 to 430 bacteria per 100 ml. Samples collected at high tide contained higher concentrations of fecal coliforms (9 to 23,000 per 100 ml).

Salmonella was only isolated once from Alki Beach water. Vibrio species were isolated both from water and clams with increasing frequency as the water temperature increased. Pseudomonas aeruginosa was isolated from Alki Beach stations; concentrations ranged from none detected to too numerous to count. This organism may have sanitary and public health significance. It was used in the beach studies to indicate recent wastewater or CSO pollution. Pseudomonas concentrations were highest in samples collected at low tide. Concentrations in water samples collected at high tide ranged from 0 to 60 per 100 ml.

Fecal streptococci were isolated from Alki beach waters with concentrations increasing at high tide. The ratio of fecal coliforms to fecal streptococci were used as an indicator of human or animal fecal pollution. From the calculated ratios (FC/FS >4, human origin; FC/FS < 0.7 animal origin) bacteria in sixty percent of the samples were concluded to be of human origin.

The concentrations of fecal coliforms were consistently higher at stations 238 and 246 than at the stations 242 and 244 between Duwamish Head and Alki Point (Figure 5.16).

5.3.1.3 Summary

Data showed that the most comprehensive bacteriological studies were carried out by METRO and were reported in the METRO Water Quality Monitoring Review Board's bi-annual reports (METRO undated, a-e). Other studies by the Washington State Department of Ecology have been done at Harbor Island in the Duwamish River. The data collected included total and fecal coliform concentrations. Prior to 1967 total coliforms were measured on an

Parameter	VR1	VR2	Mean Concentration		LH5	HL6	CBD7**
			SS3	SC4			
Temp. C°	13.1	12.9	14.8	13.3	14.6	10.7	16.6
Cond. umho/cm	125	136	134	99	51	132	210
Turbidity, JTU	30	37	47	18.7	15	22	43
DO, mg/l	8.6	8.9	8.5	9.5	9.6	9.4	7.0
BOD, mg/l	30	30	19	15	8.5	8.0	22
COD, mg/l	95	97	95	70	68	57	66
Hexane Ext., mg/l	12	16	14	11	7.3	8.5	6.8
Chloride, mg/l	7.7	12	12.2	6.6	5.3	7.5	24
Sulfate, mg/l	17	18	26.1	18	7	18	25
Organic N, mg/l	2.6	3.5	1.7	1.4	1.4	1.4	1.1
Ammonia N, mg/l	0.32	0.48	0.32	0.32	0.19	0.09	0.88
Nitrite N, mg/l	0.11	0.12	0.06	0.04	0.03	0.02	0.12
Nitrate N, mg/l	0.67	0.72	0.83	0.64	0.51	0.76	0.72
Hydrolyzable P, mg/l	0.45	0.40	0.24	0.17	0.24	0.35	0.71
Ortho P, mg/l	0.12	0.12	0.08	0.05	0.12	0.10	0.16
Copper, mg/l	0.040	0.056	0.10	0.081	0.076	0.12	0.44
Lead, mg/l	0.44	0.32	0.25	0.40	0.27	0.08	0.37
Iron, mg/l	2.4	2.0	2.1	0.75	0.39	0.44	2.0
Mercury, mg/l	0.0003	0.0004	0.0004	0.0008	0.0003	0.0008	0.0005
Chromium, mg/l	0.025	0.009	0.010	0.074	0.010	0.010	0.28
Cadmium, mg/l	0.005	0.004	0.005	0.004	0.004	0.004	0.013
Zinc, mg/l	0.18	0.12	0.43	0.24	0.082	0.068	0.86
Sett. Solids, mg/l	51	84	60	40	40	68	113
Susp. Solids, mg/l	85	112	80	73	54	98	190
TDS, mg/l	134	125	170	89	72	101	208
Total Coliform* org./100 mls	28000	26000	4200	1600	37000	1600	4600000
Facal Coliform* org./100 mls	3600	1200	30	370	1400	370	440000

*Median

** Due to limited background data from this area, these values are approximate.

Table 5.7. Concentrations of various chemicals in urban runoff. After METRO (1979).

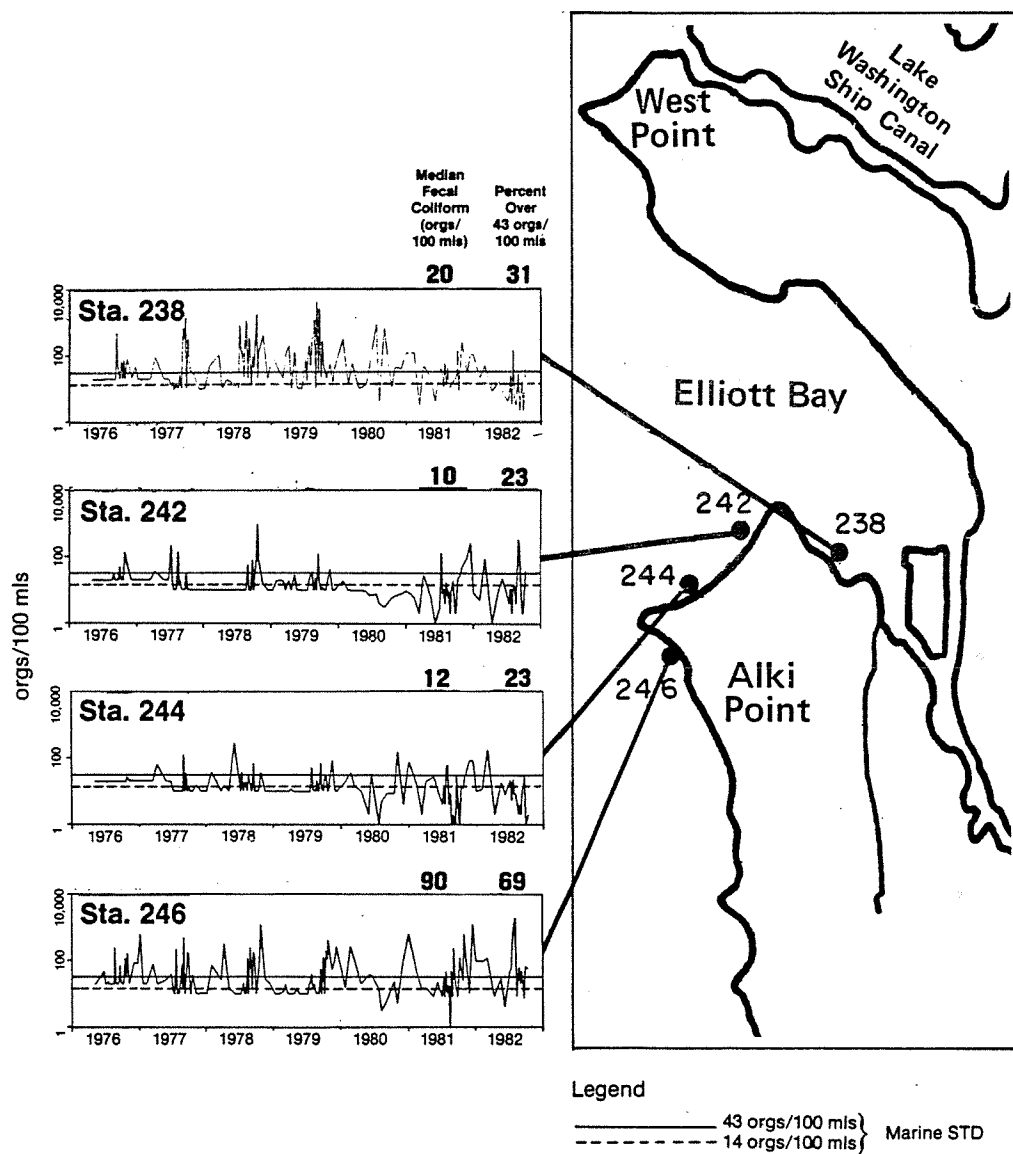


Figure 5.16. Trends in fecal coliform concentrations at nearshore stations in Puget Sound. After Patten and Tomlinson (undated).

intermittent schedule in Elliott Bay offshore waters. Beginning in 1967 fecal coliform concentrations were also measured. Fecal coliform monitoring in samples from the shore or Elliott Bay was conducted April 1965–March 1969 (Patten and Tomlinson, undated). The change from total to fecal coliform concentrations was made because the water quality standard was changed from total to fecal coliform concentrations. Since some bacteria in the total coliform group can grow in the environment, the fecal coliform group is a more meaningful measure of fecal contamination.

Starting in June, 1982, water samples from shore were analyzed for both fecal coliforms and fecal streptococci. The ratio of FC/FS could then be used to estimate the source of pollution, either human or animal. Although contamination from the upper Duwamish River was reported to be of animal origin, the data from other sampling sites indicated human contamination.

Fecal coliform concentrations in water from Elliott Bay sampling stations were variable. This variation correlated with heavy rainfall and contamination of the environment from runoff and CSO.

Although many sources contributed to fecal pollution in Elliott Bay, sewage must be considered the primary source. Little information describing the concentrations of pathogens in Elliott Bay could be found. However, several human pathogens including Salmonella and Shigella serotypes, Yersinia enterocolitica, Aeromonas hydrophilia, Campylobacter jejuni, Clostridium species, Vibrio cholera and enteropathogenic Escherichia coli may be present during an influx of sewage.

The presence of bacteria of sanitary significance entrapped in or on fat and oil particles floating at the surface has recently been noted. These surface particles would not be detected in samples collected at one meter depths.

5.3.2 Human Enteroviruses

To date human enteroviruses have not been shown to occur in Puget Sound. Heyward et al. (1977), for example, reported that shellfish collected in the vicinity of a sewage outfall did not contain enteric human viruses. Similarly, Armstrong et al. (1978) could not isolate human viruses from oysters or mussels held in cages in the vicinity of a combined sewage overflow (CSO) in Elliott Bay. Armstrong et al. (1978) proposed two reasons for their failure to detect viruses. First, storms had not occurred during or immediately prior to the sampling and since oysters can depurate their viral content within 72 hr, human enteric viruses were absent. Second, "toxic substances" present in the oysters appeared to inhibit the viral detection process. Similarly, Tomlinson et al. (1980) attempted unsuccessfully to isolate human viruses from sediment and receiving waters near several CSOs in Puget Sound.

Other workers have reported human enteric viruses to be present in animals and water collected near sewage overflows (Goyal et al. 1979; Vaughn et al. 1980; Gerba et al. 1980; Ellender et al. 1980; Sobsey et al. 1980a and 1980b). Of those viruses isolated, polio type 1 was most prevalent (241/252 and 50/55). Polio type 2 and Echo type 24 were found in 1/55 each. Other viruses identified, but not quantified included polio types 1 and 2 (vaccine strain), Echo types 1, 2, 15, 20, 23, and 24 and Coxsackie type B-3 (Meinhold and Sobsey 1982). The concentration and frequency of virus recovery varied with the depth of water in which the mussels were exposed (Morris et al. 1976) with the number of viruses increasing with depth.

Munger et al. (1976) tracked enteric virus through a sewage treatment

plant. They found that digested sludge yielded less virus than did primary and activated sludges. Hence, human enteric viruses do enter marine waters. However, the low numbers or absence of recovered viruses is not surprising. Viruses require a healthy viable host cell in which to reproduce. Hence, human enteric viruses discharged into the marine environment do not increase in number, rather they are gradually destroyed over time.

5.3.3 Relationship of Viruses to Bacteria

Initially workers assumed that a count of the total or fecal coliform bacteria present in an aquatic animal was a good estimate of the number of enteric virus present. The falsity of this assumption was first recognized by Portnoy et al. (1975). Goyal et al. (1979), Gerba et al. (1980), and Ellender et al. (1980) published similar conclusions. The presence of enteric human viruses in shellfish cannot be statistically correlated with the presence of coliform bacteria in the shellfish or in the surrounding water using current microbiological standards.

5.4 Responses to Toxic Chemical Contaminants

5.4.1 Acute Bioassays

5.4.1.1 Water Column

Most water column toxicity tests have been conducted at the Washington State Department of Fisheries Shellfish Laboratory at Brinnon. From 1962 through 1976 tests were conducted once annually using the 48-hr oyster (*Crassostrea gigas*) embryo bioassay (Woelke 1972). The results are presented in Figures 5.17 and 5.18 for two stations located in the Duwamish west waterway and off Pier 91 in Elliott Bay (Cardwell and Woelke 1979). Water quality was satisfactory at both stations with the exception of the 1972 and 1974 tests for the Duwamish River station. Oyster abnormalities (1972) and mortalities (1972 and 1974) were elevated, but these responses were associated with depressed salinities (11.9 to 12.9 ‰) which were below the acceptable lower salinity limit (20 ‰) for oyster embryos. With the exception of one water sample collected from 60 feet at each station in 1976, all tests were performed using surface waters.

Cummins (1974) conducted oyster embryo bioassays on one Elliott Bay (surface) and six Duwamish estuary (11-21 feet deep) stations. All samples showed slightly reduced survival (4.8 to 30.6% less than survived in Clam Bay control water), but with no increase in the number of abnormal larvae. Salinities were at or above 26 ‰ and, therefore, probably did not cause the reduced survival.

Chapman et al. (1982c) tested one bottom water sample from a Duwamish South Harbor station and a station off Pier 54 in Elliott Bay. Acute toxicity was not noted in sticklebacks (*Gasterosteus aculeatus*), marine oligochaetes (*Monopylephorus cuticulatus*), or amphipods (*Eogammarus confervicolus*) exposed for 96-hr. Significant genotoxicity was not detected using extracts from the water and rainbow trout (*Salmo gairdneri*) gonad cells in the anaphase aberration test, but a significant ($p < 0.001$) reduction in the oligochaete respiration rate (a sublethal toxicity index) was noted for water from the Duwamish South Harbor station.

Adult oysters (*C. gigas*) and mussels (*Mytilus edulis*) held in cages were

SELECTED PARAMETERS FOR C. GIGAS WEST WATERWAY

040113

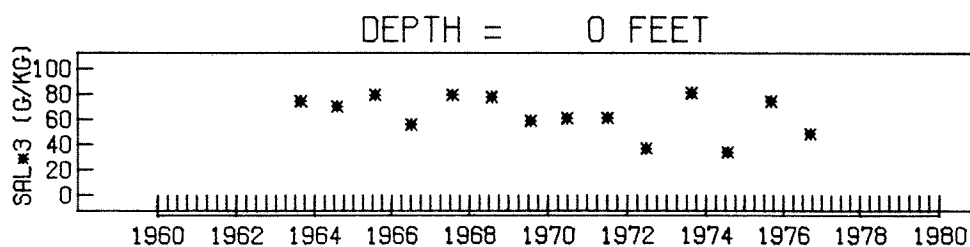
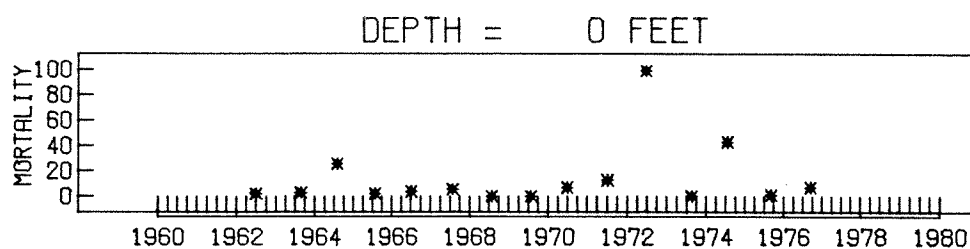
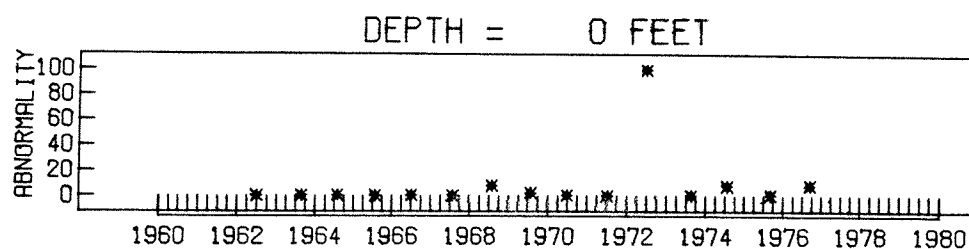


Figure 5.17 Historical oyster embryo responses to seawater samples collected annually from surface waters of the Duwamish west waterway and assayed by the Washington State Shellfish Laboratory. All responses have been corrected for the control responses. After Cardwell and Woelke (1979).

SELECTED PARAMETERS FOR C. GIGAS PIER 91

040114

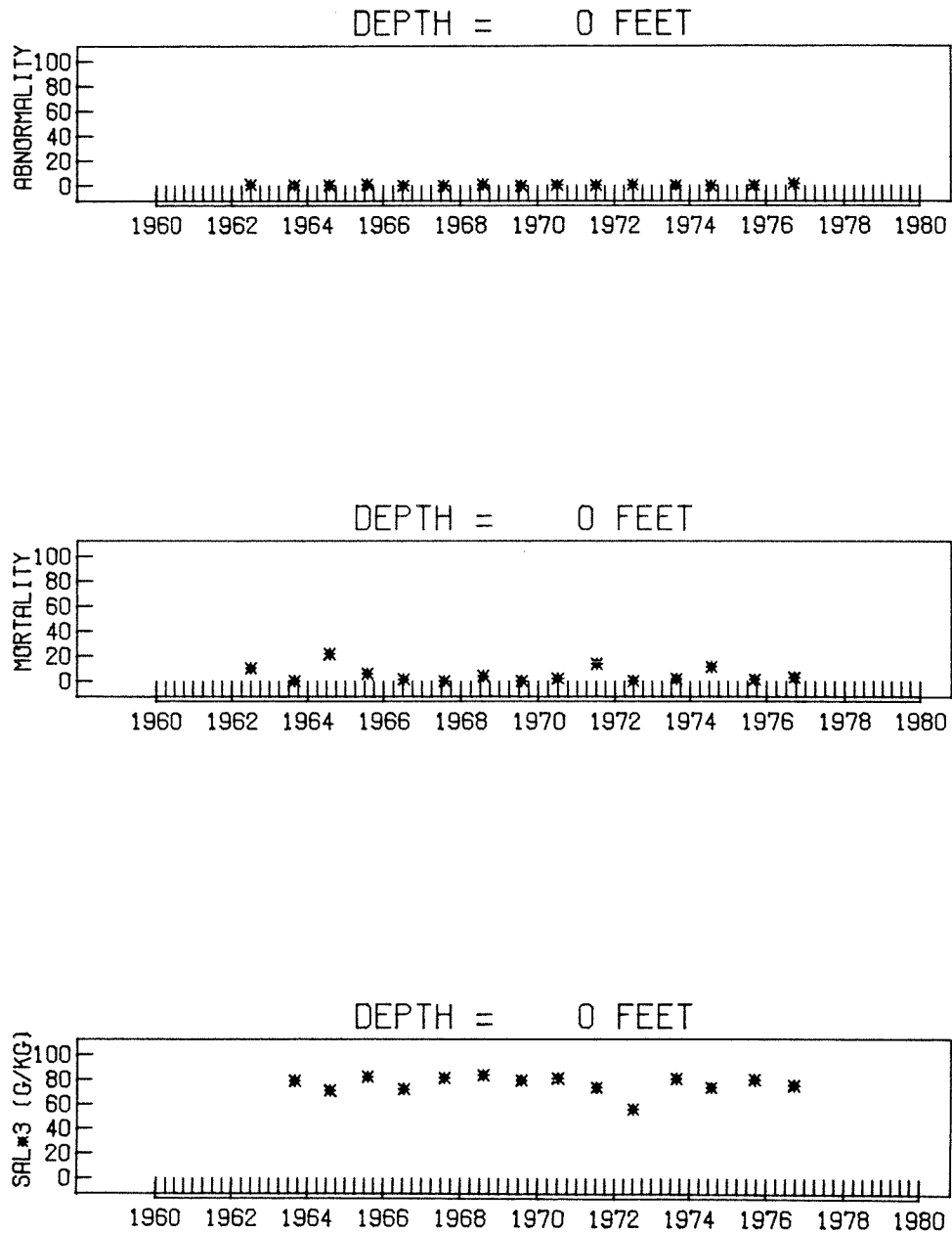


Figure 5.18. Historical oyster embryo responses to seawater samples collected annually from surface waters off Pier 91 in Elliott Bay and assayed by the Washington State Shellfish Laboratory. All responses have been corrected for the control responses. After Cardwell and Woelke (1979).

exposed to Elliott Bay water at six sites adjacent to the Denny Way combined sewer overflow (CSO). The first set of tests were conducted from April 20 to June 2, 1977, during a period when no CSO discharges were observed (Armstrong et al. 1978). During this time no oysters died. However, a few mussels at each site died, probably as a result of predation. A decrease in condition index for both oysters and mussels nearest the outfall was noted. Copper and zinc concentration in the tissues was highest adjacent to and south of the CSO while the concentrations of chromium, lead, pesticides, and PCB's in the tissues increased at all sites. Since no overflow occurred during the test period, Armstrong et al. (1978) speculated that the decreases of condition indexes and uptake of metals and pesticides might be caused by contaminated sediments in the CSO discharge area.

To clarify the studies of Armstrong et al. (1978), an additional set of oyster and mussel exposures was conducted (Tomlinson et al. 1980). No change in either oyster or mussel mortality or condition indexes as a function of distance from the CSO was noted this time. Mussels closest to the CSO did, however, show increases in copper and lead concentration while the zinc concentration in the tissues decreased at all sites.

5.4.1.2 Sediments

Amphipod Bioassays. Amphipods are generally infaunal or epifaunal crustaceans which play an important role in many aquatic food chains. The infaunal amphipod, Paraphoxus epistomus (= Rhepoxynius abronius), was the most sensitive of five macrobenthic animals tested with contaminated sediments from the Duwamish estuary (Table 5.8) and other industrial sites (Swartz et al. 1979). These experiments showed a significant ($p < 0.05$) reduction in amphipod survival in 10-day exposures to sediments from two sites in the Duwamish waterway and from one site in Elliott Bay.

Recently, amphipod/sediment bioassays have been used by a variety of investigators to test the toxicity of Elliott Bay/Duwamish estuary sediments. Ott et al. (unpubl. manuscript) found significantly reduced survival and/or sublethal effects in four of the seven test sediments with 10-day amphipod survivals ranging from 37.5 to 91.6%. Chapman et al. (1982b) and Chapman and Fink (1983) reaffirmed the conclusions of Swartz and Ott that Elliott Bay sediments are toxic to amphipods in 4 to 10-day exposures. Earlier tests by Chapman et al. (1982c) using a less sensitive species (Eogammarus confervicolus) showed no lethality (except at a Denny Way CSO station) in 4-day exposures.

Dinnel et al. (1983a) have also reaffirmed the toxicity of some sediments in the Duwamish waterway. Cummins (1983) surveyed the toxicity of sediments in outer Elliott Bay (around the old Duwamish dredge spoils dump site) and found amphipod survivals of 60-90%.

While amphipods are clearly sensitive to toxic chemicals in sediments, a few words of caution must be expressed. First, within and between investigator variability in amphipod test results is evident both in the magnitude of toxicity and in the spatial-temporal distribution of sediment toxicity. Differences related to test methodologies and test species as well as changes in sediment toxicity within the same sample site (both in spatial patchiness of toxicants and changes through time) are evident. Secondly, a variety of interactive stresses (other than toxic chemicals) may potentially influence amphipod mortality. These factors include but are not limited to: sediment grain size, food availability, organic content of the sediments, age and sex of the test animals, and physical test conditions such as temperature,

Table 5.8. Mean survival of macrobenthic marine species in sediment toxicity bioassays. Two replicates, each with 20 individuals/species were used. After Swartz et al. (1979).

Sediment source	Total	Mean Survival				
		<u>Protothaca</u> <u>staminea</u>	<u>Macoma</u> <u>inquinata</u>	<u>Glycinde</u> <u>picta</u>	<u>Paraphoxus</u> <u>epistomus</u>	<u>Cumacea</u>
Yaquina control	87.5	19.5	19.5	14.0	19.5	15.0
Duwamish Turning Basin	69.0*	20.0	17.0	17.5	4.0*	10.5
Duwamish Slip #1	65.0*	20.0	13.0*	16.0	9.0*	7.0
Duwamish mouth	81.5	20.0	16.0	17.0	17.0	11.5
Puget Sound	76.0*	20.0	16.5	14.0	17.5	8.0
Elliott Bay	71.0*	20.0	17.5	15.5	12.0*	6.0

* Reduced survival at $P < 0.05$.

pH, and salinity. Additional research is needed to define these interactive stresses before the full impact of toxic chemicals on amphipods can be understood. Thirdly, amphipod assays provide only a single measure of the effects of chemicals on the highly variable marine system. This test must be used in conjunction with other sensitive acute, sublethal, and bioaccumulation tests which, in turn, must be related to other environmental health indexes such as chemical concentration and benthic community structure.

5.4.1.3 Other Acute Bioassays.

One of the earliest bioassays using Duwamish estuary sediments was by Legore and DesVoigne (1973) who challenged sticklebacks and coho salmon fry (Oncorhynchus kisutch) held in freshwater with up to 5% (wet weight) Duwamish sediments in 96-hour bioassays. Mortality or loss of equilibrium was not observed during the test period. Subsequently, Shuba et al. (1978) bioassayed sediments collected from the Duwamish River channel (site 1) and slip 1 (site 2) near the site of a 1974 PCB spill. The sediment PCB concentrations were 0.38 and 0.66 ppm for sites 1 and 2 and both contained over 300 ppm of total petroleum hydrocarbons plus various metals. The marine copepods Acartia and Tigriopus were each exposed to site 1 liquid phase (LP) and suspended particulate phase (SPP) for 24 hours in four experiments. Tigriopus was unaffected by exposure to 100 percent SPP while Acartia suffered only slight mortality in 100 percent LP or SPP. Estuarine clams Rangia and grass shrimp Palamonetes were exposed to site 1 and 2 sediments (0.1 to 5.0% vol/vol) for 14 days. The clams were unaffected but the shrimp averaged 55 percent survival in the high concentration from site 1 compared to 80 percent survival for the controls. No mortality was evident from the site 2 sediments. Shrimp tissues analyzed for PCB's showed tissue levels of 0.35 (site 1) and 0.68 (site 2) ppm PCB's as compared with 0.06 ppm in control shrimp held in clean sand.

Malins et al. (1982) exposed crabs (Cancer gracilis) and various species of clams to Duwamish sediments in situ in cages for 56-71 days. The results of the first of two such experiments showed no significant clam mortality, but 6 out of 8 crabs died in the Duwamish River vs. 3 out of 10 dead in the controls at Port Susan (significant difference at $p < 0.01$). However, post-exposure histological examination suggested that the crabs were probably underfed. A second set of tests showed no significant differences in crab mortality between Duwamish and control sediments.

Chapman et al. (1982c) exposed sticklebacks and marine oligochaetes to sediment-water slurries for 4 days. They found no acute toxicity from sediments from 97 stations around Puget Sound. Acute responses were not to be expected using these test species; however, since Legore and DesVoigne (1973) clearly showed the insensitivity of sticklebacks to contaminated sediment slurries a decade ago. Similarly, Chapman et al. (1982a) pointed out the great tolerance of oligochaetes to sewage sludge and organic-enriched sediments.

5.4.2 Sublethal Bioassays

5.4.2.1 Oyster Embryo

Schink et al. (1974) conducted the prototype oyster embryo bioassays using sediment during a 1971-1973 dredging effects survey in several urban waterways. They exposed 19-hour old larvae to sediment slurries rotated at 4

RPM for 29 hr. Grays Harbor industrial area and Duwamish Harbor sediments were the most toxic. A significant percentage of abnormal development occurred in slurries as low as 0.2 g/liter (dry wt.) and 100 percent abnormalities in 1.0 g/liter Duwamish sediments. However, the highest correlations for percent abnormal development were with total sulfides, biological oxygen demand and chemical oxygen demand, indicating that sediment organic content significantly influenced the test results.

Concurrently Cummins (1973, 1974) conducted oyster embryo assays on a different set of sediment samples from the Duwamish estuary and Elliott Bay. Cummings found that the oyster mortality and abnormal responses were very similar to responses of the oyster embryos to the control (Clam Bay) sediments.

Chapman and Morgan (1983) retested sediments from 22 Puget Sound stations originally assayed with other acute and sublethal tests. Oyster embryo tests using sediment (20 g/liter) in static beakers showed higher percentages of abnormal larvae in 1 out of 5 stations in Elliott Bay and from all four stations in the Duwamish waterway. Percent relative survival followed this same trend. Chapman and Morgan claimed that this oyster embryo assay "provides comparable data to other toxicity tests," but failed to present any analyses or comparisons which support this claim. Considering Schink et al.'s (1974) correlation of toxicity with total sulfides and not toxic chemicals, simple interpretations such as Chapman and Morgan's must be viewed with caution. Nevertheless, oyster embryo assays (and similar short-term sensitive assays) hold promise when the methodology has been fully worked out and validated specifically for sediments.

5.4.2.2 Worm Respiration

Another sublethal test currently used to test potential sediment toxicity measures changes in the respiration rate of a marine oligochaete (M. cuticulatus) (Chapman et al. 1982b, 1982c; Chapman and Fink 1983). Worms were incubated 4-8 hours in sediment elutriates. Changes in oxygen uptake (either positive or negative) were measured and compared with the oxygen uptake of control worms. Generally, toxicity (= deviation from control respiration rate) occurred in known areas of chemical contamination, but control elutriates also caused occasional significant toxicity. Chapman and Fink (1983) compared the data from worm respiration tests from nine stations tested during three consecutive studies and found general agreement for only 4 out of 9 of the stations. However, patchiness in the occurrence of toxic chemicals cannot be ruled out as a contributing factor for the lack of agreement.

Data from the worm respiration tests were difficult to interpret. Either positive or negative deviation from the control respiration rate can be interpreted as toxicity. The potential also exists for equal stress in both a positive or negative direction resulting in no change thus yielding an insignificant response. The specific causes of these positive and negative deviations are unknown. The different responses may be caused by different factors or low concentrations of toxicants may yield a stimulatory (i.e., positive) response while higher concentrations may depress respiration (i.e., negative response) with possibly intermediate concentrations "crossing over" to produce no response (Figure 5.19). Indeed, respiration data may differ each time tests are run with new sediment samples from one area. Comiskey et al. (1983) noted that respiration testing of sediments from the Denny Way CSO yielded all negative respiration rates during one study (Chapman et al. 1982c) and almost all positive rates during a second test (Chapman et al. 1982b).

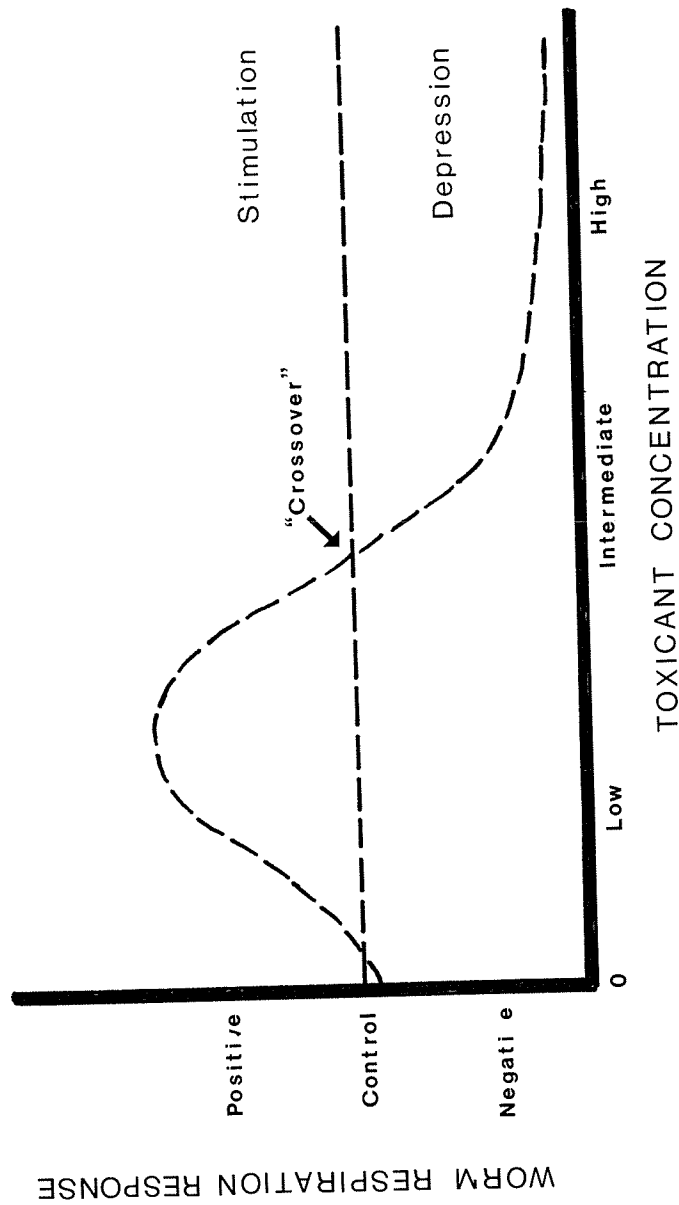


Figure 5.19. Hypothetical plot illustrating how positive and negative worm respiration responses could overlap resulting in a net response of zero (= control response) at intermediate toxicant concentrations.

Agreement of the respiration data with data from other tests is also elusive. Presently, few comparative data exist for amphipod or other acute bioassay tests and agreement with an index of genotoxicity (discussed below) is at best 50% (extrapolated from results of Chapman et al. 1982b).

5.4.2.3 Genotoxicity Assays

Many chemicals being discharged into Elliott Bay in sublethal concentrations interact with the genetic components of cells and may cause DNA mutations. These alterations may then be passed on to subsequent generations. While effects of this nature are often noticable in human or terrestrial populations, less fit aquatic organisms usually suffer silent mortality - genetically deficient individuals simply fall prey to other organisms and mortalities are never seen. Therefore, the need for genetic effects data has prompted several researchers to develop short-term genotoxicity laboratory tests that are currently being used to study genetic effects of chemicals on aquatic organisms.

Dexter et al. (1979) used the Ames mutagenicity assay to test organic chemical extracts from sediments from 20 stations in Elliott Bay and the Duwamish waterway. The results were inconclusive because of the high acute toxicity of the extracts and the lack of agreement with known concentrations of chemicals in the sediments. The authors suggested, however, that fractionation of extracts might partition out the acute toxicity and still allow successful mutagenicity testing.

A second genotoxicity assay measured the frequency of sister chromatid exchanges (SCE) in cells of English sole collected from the Duwamish estuary. Stromberg et al. (1981) determined a SCE rate of 3.25/cell from Duwamish fish vs. 2.16/cell in control fish from Agate Pass. This statistically ($p < 0.05$) elevated SCE rate from Duwamish fish was similar to the rate induced by injection of 0.05 ug/g of the known carcinogen, benzo(a)pyrene.

A third genotoxicity test has recently been used in conjunction with sediment assays by Chapman (1982b, 1982c). The anaphase aberration assay using cultured rainbow trout gonad cells assesses the ability of organic chemical sediment extracts to cause a variety of chromosomal defects during cell division. While significant toxicity (= chromosomal damage) has been recorded using this system, the data are not consistent with other toxicity indexes (for example, worm respiration tests). However, good correlations were not necessarily expected since many chemicals which cause genotoxic effects may not be acutely or sublethally toxic to aquatic animals. This test is supported by a substantial amount of basic laboratory testing (see Kocan et al. 1979, 1981, 1982), a factor missing with many of the bioassay systems discussed previously. Although this system currently uses a freshwater fish cell line, recent work by Hose and Puffer (1983) suggested that the anaphase aberration assay could be performed using cultured cells from embryos of marine invertebrates.

5.4.2.4 Bioaccumulation

A third factor to be considered in the evaluation of biological health of aquatic systems is the accumulation (or the potential for accumulation) of toxic chemicals. Accumulated chemicals may eventually induce lethal or sublethal effects or be concentrated in animals in the higher trophic levels. History has shown that certain chemicals (e.g., DDT in Brown Pelicans and methylmercury in humans from Minimata Bay, Japan) increase in concentration as

the chemical is passed from prey to predator through ingestion.

Many field studies around Puget Sound (see chapter 3.3) documented increases in the concentrations of metals and organic chemicals in marine life associated with urban areas. However, relatively few studies have dealt with bioaccumulation from an experimental bioassay approach.

Several bioaccumulation studies relative to Elliott Bay have already been discussed above in conjunction with acute or sublethal bioassays. These include Armstrong et al. (1978) and Tomlinson et al. (1980) who noted increases in the concentration of metals, pesticides, and PCB's by oysters and mussels held in live cages near the Denny Way CSO and Shuba et al. (1978) who found accumulations of PCB's in shrimp exposed to Duwamish sediments.

The only other bioaccumulation assays conducted in Elliott Bay address chemicals associated with dredging activities and the water quality of the Duwamish estuary. Teeny and Hall (1977) exposed spot shrimp, Alaska spot shrimp, mussels, sea cucumbers, and English sole held in cages at the disposal area to chemically contaminated Duwamish dredge spoils in outer Elliott Bay. No significant uptake of either mercury or chromium occurred during a 39-week exposure period. Similarly, Stout and Lewis (1977) did not find significant increases in PCB concentration in a similar set of test animals held in the disposal area. However, variability was high between test animals and some animals had high body burdens of PCB's (up to 0.17 ppm) at the test initiation.

Calambokidis et al. (1979) transplanted mussels from the Duwamish River estuary to a relatively clean site on south Puget Sound and monitored the depuration of PCB's. Initial body burdens of PCB's averaged 487 ng/g and fell to 46 ng/g over an 89-day period. The authors found that PCBs decreased in concentration logarithmically and that higher chlorinated biphenyls were retained, probably because of their lower water solubility.

5.4.3 Toxicity of Renton Treatment Plant Effluent

While technically outside the present study area (i.e., Duwamish estuary/Elliott Bay), METRO's Renton sewage treatment plant effluent has been the focus of a variety of toxicological studies relative to its discharge of approximately 30-40 million gallons per day (MGD) of partially dechlorinated secondary treated sewage approximately 20 km above Elliott Bay. Studies have shown that the Renton treatment plant contributes nearly 80 percent of the total ammonia, most of the residual chlorine, and measurable amounts of various metals and organics to the Duwamish River (Harper-Owes 1983). Because of this, METRO biologists have conducted a variety of bioassays of Renton effluents in an attempt to determine effects on resident and anadromous fishes (especially salmonids). Specifically, Buckley and Matsuda (1973) conducted whole effluent bioassays of Renton effluent using 96-hr exposures to coho salmon in a static test system. They determined 24 and 96-hr fifty percent lethal concentrations (LC50's) to be 33 and 29 percent effluent, respectively. The principal toxicant was determined to be residual chlorine, the LC50 effluent concentrations corresponding to 0.20 to 0.23 mg/liter for 24 and 96-hr exposures. Since a lethality index provides insufficient data for long term maintenance of fish health, Buckley (1976) followed up with studies to define the sublethal toxicity of Renton effluent to coho salmon. This study showed that salmon exposed to chlorinated secondary effluent for up to 12 weeks suffered symptoms of hemolytic anemia, increased numbers of circulating immature erythrocytes, pathological changes in erythrocytes, and a reduction in packed cell volume and hemoglobin levels. These changes were attributed to

the oxidative nature of the chlorine used for disinfection at concentrations as low as 0.003 mg/liter. These studies eventually led to partial dechlorination (to about 0.25 mg/liter) of the effluent during the late 1970's and early 1980's with essentially complete dechlorination starting in 1983 (R. Finger, personal communication).

A second major component of Renton effluent is ammonia. Buckley (1978) conducted studies of ammonia toxicity to coho salmon and found that the 96-hr LC50's were associated with 0.45 mg/liter un-ionized ammonia in Duwamish River water. Subsequent toxicity studies investigated the sublethal intoxication and modes of action of chlorine and/or chlorine in conjunction with ammonia (monochloramine) on rainbow trout erythrocytes (Buckley 1981a, 1981b, 1982).

A third area of concern surrounding any sewage or industrial discharge is toxic metals and organics. Only one study has been conducted with Renton effluent which directly addresses these groups. This study by Buckley (1984) looked at the toxicity of copper to coho salmon relative to its degree of complexation with Renton effluent organics. Buckley determined that the LC50 of the Cu^{2+} ion was 0.017 to 0.022 mg/liter while the toxicity of total copper varied from 0.164 (in river water) to 0.286 (in 40% sewage effluent) mg/liter and that mean survival times in diluted effluent with added copper were inversely proportional to the Cu^{2+} concentration.

All of the Renton effluent toxicity studies described above were conducted using non-saline Duwamish River water in order to assess any real or potential impacts on the freshwater/anadromous biota. Presently, however, METRO plans to discharge the Renton effluent directly to Puget Sound estuarine waters via a pipeline which will bypass the Duwamish River. Because major physical, chemical, and biological differences exist between fresh and marine waters, METRO commissioned additional bioassay studies to determine the toxicity of Renton effluent to sensitive marine life stages (Dinnel et al. 1983a and 1983b). The marine bioassays conducted to date have utilized 60-min sand dollar (Dendraster excentricus) and green sea urchin (Strongylocentrotus droebachiensis) sperm exposures, 48-hr oyster embryo tests, 96-hr green sea urchin embryo tests, and 48-hr Dungeness crab (Cancer magister) zoea tests. The average 50 percent effective concentrations (EC50's) of Renton influent, primary, secondary, chlorinated secondary, and de-chlorinated secondary sewage to each of these life stages is summarized in Table 5.9. Generally, the relative toxicities of Renton sewage were: chlorinated secondary > influent > primary > dechlorinated secondary > secondary sewage. The 60-min sperm assays generally proved to be most sensitive to Renton sewage while the crab zoea were the least sensitive.

Table 5.9. Comparison of the 50 percent effective concentrations (EC50's) for five stages of Renton sewage and equivalent freshwater dilutions. The EC50's are based on the average responses from 7 to 10 separate bioassays.

Renton Sewage Type	EC50 (% sewage in seawater vol./vol.)						
	Sand dollar ¹ sperm assay	Oyster embryo ¹ abnormal	Oyster embryo ¹ mortality	Grab ² zoaea mortality	Green ² urchin sperm assay	Green ² urchin embryo abnormal	Green ² urchin embryo mortality
Influent	1.9	4.2	5.7	NT	NT	NT	NT
Primary	2.9	5.9	7.3	>20.0	10.5	15.8	>20.0
Secondary	17.6	>20.0	>20.0	>20.0	>20.0	18.1	>20.0
Chlorinated secondary	1.0	2.3	3.2	>20.0*	0.4	11.9	>20.0
De-chlorinated secondary	7.1	>20.0	>20.0	>20.0	>20.0	17.4	>20.0
Freshwater dilutions	>20.0	>20.0	>20.0	>20.0	>20.0	>20.0	>20.0

¹Tests conducted summer 1982.

²Tests conducted winter 1983. These results are not directly comparable to the summer 1982 tests since sewage characteristics vary by season.

*Moribund zoaea commonly noted in 13.0 and 20.% chlorinated secondary sewage.
NT = not tested.

6.0 CONCLUSIONS

6.1 Rationale

The goals of this review were (1) to assess available data that could be used in the evaluation of potential sites for an outfall in Elliott Bay, and (2) to identify data inadequacies which may prevent future comprehensive assessment of wastewater management activities in Elliott Bay should a new outfall be constructed therein. The management activity addressed is the proposed diversion of Renton Treatment Plant secondary effluent from the Duwamish River to an outfall off Duwamish Head. A more detailed understanding of Elliott Bay circulation is being developed, but this understanding should not alter assessment of the existing data base. This review considered the potential recovery of the Duwamish River following effluent diversion, but only when needed to achieve understanding of the effects of effluent diversion on the bay. Following diversion of the effluent from the Duwamish River and transfer to either a deep (about 200') or very deep (about 600') site off Duwamish Head, the spatial and temporal effects of the effluent within Elliott Bay may change due to changes in distribution and retention. NOAA sampling programs in the Duwamish River for xenobiotic chemicals are expected to continue and to avoid duplication, industrial pollution in the Duwamish River was given limited attention.

This evaluation was based on the following questions:

1. What are the deficiencies in the data base which are likely to compromise post-operational assessment of a Duwamish Head outfall?
2. What is the quality and utility of the existing data in the assessment of pre-versus post-discharge assessment?
3. If the data are inadequate to meet either or both of the goals, what are the reasons?

6.2 Water Column

Understanding of the responses of phyto- and zooplankton to water quality changes in Elliott Bay was found to be very limited. Seasonal plankton cycles and comparisons of the plankton in the inner and outer bay do not exist. Seasonal chlorophyll distribution studies have not been conducted. Primary productivity is slightly lower in Elliott Bay than in the main basin of Puget Sound. However, these existing results may be biased by the position of the Elliott Bay station in the chlorophyll low for the bay. Some nutrient data exists, but most was limited to the Duwamish estuary. Phytoplankton species have not been identified nor have responses to blooms in the bay. Data on zooplankton biomass or species composition were not found hence, relationships in the lower food chain are uncertain. The inhibitory/stimulatory responses of phytoplankton to ammonia in the Duwamish River and Elliott Bay may be the parameter which will show the greatest single change following effluent diversion. Water column biota require further characterization if responses to natural physical parameters, distributions in time and space, and responses to changes in the dispersion of nutrients are to be modeled and used for management purposes.

6.3 Intertidal Resources

The only undeveloped intertidal areas remaining extend from Alki Point to Duwamish Head and from Smith Cove to West Point and represent 2% of the original shallow water habitat existing in 1890. The remainder of the shoreline has been extensively modified and the shallow water habitat destroyed. The beach from Alki Point to Duwamish Head is one of the most heavily utilized public beach areas in Seattle. Use of the Smith Cove to West Point segment is limited by more difficult access. The intertidal communities of plants and animals have been extensively sampled along the east shore of Puget Sound including West and Alki Points and a good historical data base exists. However, the remainder of Elliott Bay has received limited attention except near the Denny Way CSO. Assessments of the accumulated floatables (oil, grease, bacteria, priority pollutants) in the intertidal sediments and organisms were not reported. Few data describe the existence and use of commercially or recreationally important invertebrates; such data are needed to assess the impact of the marine resources upon human health.

6.4 Subtidal Ecology

Subtidal infaunal studies have partially characterized the benthic environments in Elliott Bay but the following deficiencies exist. Synoptic sediment examinations at relocatable stations exist on northern and eastern areas of the bay but not near Duwamish Head. However, long-term data were absent. Comparisons of existing data sets may be possible in certain cases but not in others because of the different levels (species vs. family) to which organisms were identified, inclusion of dead with live animals in counts and differences in sampling procedures. Evaluation of existing data with statistical tests having greater resolving power is possible and would be useful for certain data sets. Effects of the Duwamish River on Elliott Bay microfaunal benthos were significant and well documented. Those same riverine materials probably influence macrofaunal benthic communities (generally the primary emphasis of benthic studies). However, these effects were not well documented in Elliott Bay, especially near Alki Point and Duwamish Head. Synoptic sampling and long-term studies would aid the assessment of the benthic environment. Reanalysis of existing data (where feasible) would further strengthen the data base to allow quantitative assessment of waste water related changes in the bay.

6.5 Fishes

Considerable information on the life histories, community ecology, specific habitat requirements and food habits of Puget Sound fishes exists. Most of these data were collected near Alki and West Points as well as in the Duwamish River. Circumstantial evidence suggests that English sole spawn in areas around Duwamish Head and near Smith Cove. Many species including flatfish and salmonids in large numbers dwell as juveniles in the eelgrass beds along the beach near Smith Cove and from Duwamish Head to Alki Point. A large reef fish community which has never been sampled probably exists among the debris on the bottom of Elliott Bay. The fish community associated with the numerous pilings along the east shore of the bay has received very limited assessment. Fish communities in the bay have not been characterized by

habitat type so that these data may be compared with the more extensive fish data available from outside Elliott Bay. Specific marine fish spawning areas, residence times and development rates of ichthyoplankton in the bay require further definition. The importance of eelgrass habitats for rearing and breeding of juvenile salmonids and flatfishes in the bay has not been defined.

6.6 Fish Health

Research by NOAA that attempts to relate occurrence of xenobiotic chemicals with the occurrence of liver tumors in fishes has been focused upon the Duwamish estuary. Fish health has not been examined in other areas of the bay. However, many fish species migrate freely from the bay to the estuary and back. Documentation of the health of fishes in the bay may further elucidate these interactions as well as establish a health baseline prior to effluent discharge off Duwamish Head.

6.7 Microbiology

Monitoring of fecal coliform bacteria in the Duwamish estuary and parts of Elliott Bay is a routine procedure which has been utilized for many years. In the past only fecal coliform counts have been made. Detection and counts of selected pathogenic (enterococci, Yersinia and Salmonella) organisms would provide a better index of water quality condition. Bacterial counts in the estuary may be one of the parameters that will show a significant response once the effluent is diverted from the river. The possible concentration of bacterial pathogens in floatable particulates (oil and grease) in the surface microlayer has not been examined in the estuary or in Elliott Bay. These floatable particulates represent a potential mechanism to reconcentrate and transport bacteria to beaches.

The presence of human viruses in shellfish in the marine environment cannot be statistically correlated with the presence of coliform bacteria in shellfish or in the surrounding water. Areas declared to be free of contamination by human enteric bacteria are not necessarily free of contamination by human enteroviruses.

Although no shellfish have been found to be contaminated with human enteric viruses in Elliott Bay, shellfish have been shown to be contaminated with viruses in other parts of the country demonstrating that such a potential exists. Most enteric human viruses found in marine shellfish occurred near known sewage outfalls or in areas known to be contaminated by human sewage. Most human enteric viruses found in contaminated marine shellfish were the polio type 1 (vaccine) strain. The best method to detect the presence of human viruses in the marine environment is the use of sentinel (indicator) organisms suspended in the study area.

6.8 Marine Toxicology

Limited intermittent toxicity testing has been conducted on the waters off Alki and West Points, in the Duwamish estuary, near the Denny Way CSO, and along the Seattle waterfront. The test methodology has varied over time. Much of the prior testing was limited to surface water samples. A variety of rapid and sensitive toxicity tests now available could define background responses of water from Elliott Bay that will be needed to interpret future wastewater toxicological data. The toxicity of xenobiotic chemicals in the sediments has been intermittently tested in the Duwamish River and near the

Denny Way CSO, however, no significant testing has been conducted near Duwamish Head and Alki Point. Seahurst baseline data define significant amphipod mortalities in sediments from the northern part of the East Passage of Puget Sound.

6.9 Chemistry of Xenobiotic Chemicals

A recent review describing the properties, fates, sources, and distribution of the 126 EPA "priority pollutants" (petroleum hydrocarbons, polychlorinated dibenzofurans, and particulates) in Puget Sound revealed numerous data gaps. Relationships between contaminated sediment, benthic uptake, and organism/ecosystem impact are unclear. Concentrations of pollutants in biota (with possible exception of metals, PCB's, and benzo(a)pyrene) are not well known. Elliott Bay and the lower Duwamish River show some of the highest levels of As, Cu, Pb, Hg, Zn, DDT/DDE, PCB, and PAHs found in Puget Sound. While there have been numerous investigations of the concentrations of metals in the tissues of various fish species from Puget Sound, few studies conclusively demonstrate the accumulation of metals in tissues in excess of "normal" or "background" concentrations. None of the studies to date has included sufficient numbers of replicate samples to allow statistical analysis of the data. Available data on the concentrations of PCBs in fishes of Puget Sound (and similarly for most other organic contaminants) suffer from lack of adequate replication, differences in fish species analyzed, and lack of appropriate controls.

The discharge rates and water quality characteristics of the Duwamish River and the identification of toxicant loading for sources discharging into Elliott Bay indicate that reasonable toxicant loading data exist for the Duwamish River. Data from other sources are poor. In Elliott Bay most data on trace metals and trace organics in sediments and biota are from the West Waterway, Harbor Island, East Waterway and the Seattle Waterfront. Few data exist between the West Waterway and Duwamish Head along Alki Way in the area between Duwamish Head and Alki Point.

Most trace metal data in the water column describe suspended particulate matter. Few data describe the concentrations of soluble trace metals and trace organics. Biological data for both trace metals and trace organics are mainly on benthic fishes; few data describe chemical concentrations in pelagic and semi-pelagic fish, and data are almost nonexistent for migratory fish such as salmon, cod, and herring. A need exists to establish the input and flux of (a) water-borne nutrients, (b) metals, (c) hydrocarbons, (d) microbial constituents, (e) chlorinated hydrocarbons, and (f) other organics. The bioaccumulation patterns of organisms should be used to investigate the process of contaminant transfer through the food web.

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APPENDIX 1

Class AA and A water quality standards defined in Chapter 173-201-045 of the Washington State Administration Code are as follows:

1. Class AA (extraordinary)

a. General characteristic. Water quality of this class shall markedly and uniformly exceed the requirements for all or substantially all uses.

b. Characteristic uses. Characteristic uses shall include, but not be limited to, the following:

1. Water supply (domestic, industrial, agricultural)

2. Stock watering

3. Fish and wildlife:

Salmonid migration, rearing, spawning, and harvesting.

Other fish migration, rearing, spawning, and harvesting.

Clam, oyster, and mussel rearing, spawning, and harvesting.

Crustaceans and other shellfish (crabs, shrimp, crayfish, scallops, etc.) rearing, spawning, and harvesting.

4. Wildlife habitat

5. Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).

6. Commerce and navigation

c. Water quality criteria.

1. Fecal coliform organisms

(A) Freshwater - fecal coliform organisms shall not

exceed a geometric mean value of 50 organisms/100 ml,

with not more than 10 percent of samples exceeding 100 organisms/100 ml.

- (B) Marine water - fecal coliform organisms shall not exceed a geometric mean value of 14 organisms/100 ml, with not more than 10% of samples exceeding 43 organisms/100 ml.

2. Dissolved oxygen

- (A) Freshwater - dissolved oxygen shall exceed 9.5 mg/l.

- (B) Marine water - dissolved oxygen shall exceed 7.0 mg/l. When natural conditions, such as upwelling, occur, causing the dissolved oxygen to be depressed near or below 7.0 mg/l, natural dissolved oxygen levels can be degraded by up to 0.2 mg/l by man-caused activities.

3. Total dissolved gas shall not exceed 110% of saturation at any point of sample collection.

4. Temperature shall not exceed 13.0°C (marine water) due to human activities. Temperature increases shall not, at any time, exceed $t = 8/(T-4)$ (marine water).

When natural conditions exceed 13.0°C (marine water), no temperature increase will be allowed which will raise the receiving water temperature by greater than 0.3°C.

For purposes hereof, "t" represents the permissive temperature change across the dilution zone; and "T" represents the highest existing temperature in this water classification outside of any dilution zone.

Provided that temperature increase resulting from nonpoint

source activities shall not exceed 2.8°C.

5. pH shall be within the range of 7.0 to 8.5 (marine water) with a man-caused variation within a range of less than 0.2 units.
6. Turbidity shall not exceed 5 NTU over background turbidity when the background turbidity is 50 NTU or less, or have more than a 10 percent increase in turbidity when the background turbidity is more than 50 NTU.
7. Toxic, radioactive, or deleterious material concentrations shall be less than those which may affect public health, the natural aquatic environment, or the desirability of the water for any use.
8. Aesthetic values shall not be impaired by the presence of materials or their effects, excluding those of natural origin, which offend the senses of sight, smell, touch or taste.

2. Class A (excellent)

- a. General characteristic. Water quality of this class shall meet or exceed the requirements for all or substantially all uses.
- b. Characteristic uses. Characteristic uses shall include, but not be limited to , the following:
 1. Water supply (domestic, industrial, agricultural).
 2. Stock watering.
 3. Fish and shellfish:

Salmonid migration, rearing, spawning, and harvesting.

Other fish migration, rearing, spawning, and harvesting.

Crustaceans and other shellfish (crabs, shrimp, crayfish,

scallops, etc.) rearing, spawning and harvesting.

4. Wildlife habitat.
 5. Recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment).
 6. Commerce and navigation.
- c. Water quality criteria.
1. Fecal coliform organisms.
 - (A) Freshwater - fecal coliform organisms shall not exceed a geometric mean value of 100 organisms/100 ml, with not more than 10 percent of samples exceeding 200 organisms/100 ml.
 - (B) Marine water - fecal coliform organisms shall not exceed a geometric mean value of 14 organisms/100 ml, with not more than 10 percent of samples exceeding 43 organisms/100 ml.
 2. Dissolved oxygen.
 - (A) Freshwater - dissolved oxygen shall exceed 8.0 mg/l.
 - (B) Marine water - dissolved oxygen shall exceed 6.0 mg/l. When natural conditions, such as upwelling, occur, causing the dissolved oxygen to be depressed near or below 6.0 mg/l, natural dissolved oxygen levels can be degraded by up to 0.2 mg/l by man-caused activities.
 3. Total dissolved gas shall not exceed 110 percent of saturation at any point of sample collection.
 4. Temperature shall not exceed 18.0°C (freshwater) or 16.0°C (marine water) due to human activities. Temperature

increases shall not, at any time, exceed $t=28/(T+7)$ (freshwater) or $t=12/(T-2)$ (marine water).

When natural conditions exceed 18.0°C (freshwater) and 16.0°C (marine water), no temperature increase will be allowed which will raise the receiving water temperature by greater than 0.3°C.

For purposes hereof, "t" represents the permissive temperature change across the dilution zone; and "T" represent the highest existing temperature in this water classification outside of any dilution zone.

Provided that temperature increase resulting from nonpoint source activities shall not exceed 2.8°C, and the maximum water temperature shall not exceed 18.3°C (freshwater).

5. pH shall be within the range of 6.5 to 8.5 (freshwater) or 7.0 to 8.5 (marine water) with a man-caused variation within a range of less than 0.5 units.
6. Turbidity shall not exceed 5 NTU over background turbidity when the background turbidity is 50 NTU or less, or have more than a 10 percent increase in turbidity when the background turbidity is more than 50 NTU.
7. Toxic, radioactive, or deleterious material concentrations shall be below those of public health significance, or which may cause acute or chronic toxic conditions to the aquatic biota, or which may adversely affect any water use.
8. Aesthetic values shall not be impaired by the presence of materials or their effects, excluding those of natural

origin, which offend the senses of sight, smell, touch, or taste.

	WINTER	SPRING	SUMMER	AUTUMN	HABITAT
	R C WP A L	R C WP A L	R C WP A L	R C WP A L	
SEAGRASS					
Zostera marina Lamouroux	C ¹ R R R K	R R R R R	C R R C R	R R R R R	L
CYANOPHYCOPHYTA					
Arthrospira brevistriata Satchell & Gardner		R R - R R	R R - R R	R R - R R	H M L, epiphyte
Dermocarpa sp.	- - - - R	- - - R R R	- - - R R R		M, epiphyte
Lyngbya ? confervoides Agardh		R R - R -	R R R R R	- R - R -	M L, epiphyte
L. sp.		R R R R R	R R R R R	R - - -	M L, epiphyte
Oscillatoria sp.		- - - R R -	- - - R -		H, epiphyte
Pleurocapsa sp.					
Xenococcus sp.					
BACILLARIOPHYCOPHYTA					
Ampilepsis rutilans (Trentepohl) Cleve				R R - R -	H M L
Melosira sp.				- - - R	M L
Nannula ramosissima (Agardh) Cleve var. ramosissima				- - - R	H M L
Odontella aurita (Lyngbye) C. A. Agardh	R R R - R	- - - - C	R R R - R	- R - - R	H M L
CHLOROPHYCOPHYTA					
Biddingia minima (Naegeli) Kylin var. minima	- R R - -		- R R - -		H
Byrsope corticulans Setchell			- - - R -		S
Chaetomorpha californica Collins	R R R R R	R R R R R	R R R R R	R R R R R	H L
C. canabina (Areschoug) Kjellman	R R R R R	R R R R R	R R R R R	R R R R R	H S
Chlorochytrium inclusum Kjellman			- - - R -		L S, endophyte
Cladophora albida (Hudson) Kuetzing var. albida					
C. gracilis (Griffiths) Kuetzing		- R - - -	R - R R R	R - R R R	L
C. microcladioides Collins var. microcladioides		- - - R R -	R R - R R	R R - R R	M
C. stimpsonii Harvey					H M
C. sp.			- R - - -		L
Codium fragile (Suringer) Hariot	- R R R -		- R R - -		M
Derbesia marina (Lyngbye) Solier			- R - - -		H
Enteromorpha compressa (Linnaeus) Greville			- - - R -		M
E. clathrata (Roth) Greville					
E. intestinalis (Linnaeus) Link var. clavata J. Agardh		R R - - -	R - R R -		H
E. intestinalis (Linnaeus) Link var. cylindracea J. Agardh	- - R R -	R R R R R	F F F C F	C C R R R	H M L
E. intestinalis (Linnaeus) Link var. intestinalis	R R R R R	R R R R R	C C C C C	R C R R R	M L
E. linza (Linnaeus) J. Agardh			- R - - -		L
E. tubulosa Kuetzing			R R - R -		M L, epizoic
Gomontia polyrhiza (Lagerheim) Bornet & Flahault	R R - R -		R R - R -		L, epiphyte
Kornmannia zostericola (Filiden) Biding	- R R R -	R R R R -	- R R - -		H
Lola lubrica (Setchell & Gardner) A. & G. Hamel	- - - R -	- - - R -	- R R R -		M
Monostroma arcticum Wittrock	- - - R -	R - R R -	- R R - -		L S
M. fractum Jao					

	WINTER			SPRING			SUMMER			AUTUMN			HABITAT
	R	C	W	R	C	W	R	C	W	R	C	W	A
<u>Phaeophila polymorpha</u> Jao													S, endophyte
<u>Rhizoclonium riparium</u> (Roth) Harvey var. <u>riparium</u>													H
<u>Spongomorpha arcta</u> (Dillwyn) Kuetzing													M
<u>S. conalta</u> (Ruprecht) Collins													M
<u>S. saxifolia</u> (Ruprecht) Collins var. <u>saxifolia</u>													M
<u>S. spinescens</u> Kuetzing													M
<u>Ulothrix flacca</u> (Dillwyn) Thuret													H
<u>U. subflaccida</u> Wille													H
<u>Ulva expansa</u> (Setchell) Setchell & Gardner													L
<u>U. fenestrata</u> Postels & Ruprecht													M
<u>U. lactuca</u> Linnaeus var. <u>lactuca</u>													M
<u>U. rigida</u> C. Agardh													L
<u>U. vexata</u> Setchell & Gardner													M
<u>Ulvaria obcura</u> (Kuetzing) Gayral													L
<u>Urospora mirabilis</u> Areschoug var. <u>mirabilis</u>													L
<u>U. wormskjoldii</u> (Mertens) Rosenvinge													L
PHAEOPHYCOPHYTA													
<u>Alaria tenuifolia</u> Setchell in Collins, Holden & Setchell													L
<u>Colpomenia bulbosus</u> (Saunders) Yamada													M
<u>C. peregrina</u> (Sauvageau) Hamel													M
<u>Costaria costata</u> (Turner) Saunders													L
<u>Desmarestia aculeata</u> (L.) Lamouroux													M
<u>D. ligulata</u> var. <u>firma</u> (C. Agardh) J. Agardh													L
<u>D. ligulata</u> var. <u>ligulata</u> (lightfoot) Lamouroux													L
<u>D. viridis</u> (O. F. Mueller) Lamouroux													L
<u>Ectocarpus similans</u> Setchell & Gardner													L
<u>Elachistus fucicola</u> (Velley) Areschoug													L
<u>Fucus distichus</u> subsp. <u>evanescens</u> (C. Agardh) Powell													L
<u>Haploglossa anderssonii</u> (Farlow) Levring													L
<u>Laminaria ephemera</u> Setchell													L
<u>L. farlowii</u> Setchell													L
<u>L. saccharina</u> (L.) Lamouroux													L
<u>L. sinclairii</u> (Harvey ex Hooker f. & Harvey) Farlow, Anderson & Eaton													L
<u>Leathesia difformis</u> (Linnaeus) Areschoug													L
<u>Neorecystis luetkeana</u> (Mertens) Postels & Ruprecht													L
<u>Petalonia fascia</u> (O. F. Mueller) Kunzke													L
<u>Pyralella littoralis</u> f. <u>littoralis</u> (Lyngbye) Kjellman													L
<u>P. littoralis</u> f. <u>rupicola</u> (J. E. Areschoug) Kjellman													L
<u>P. tenella</u> Setchell & Gardner													L
<u>Ralfia pacifica</u> Hollenberg in Smith													L
<u>Sargassum muticum</u> (Yendo) Fensholt													L
<u>Scytosiphon lomentaria</u> (Lyngbye) J. Agardh													L
<u>Sphaelaria subfusca</u> Setchell & Gardner													L
<u>Streblomena</u> sp.													L

[illegible]

Appendix 2 (continued).

	WINTER			SPRING			SUMMER			AUTUMN			HABITAT			
	R	C	WP	A	L	R	C	WP	A	L	R	C	WP	A	L	
<i>Odonthalia floccosa</i> (Esper) Falkenberg	-	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H M L
<i>O. washingtoniensis</i> Kylin	-	-	R	R	C	-	-	R	R	C	-	-	R	R	R	L S
<i>Palmeria palmata</i> (Linnaeus) Stackhouse	-	-	R	R	C	-	-	R	R	C	-	-	R	R	R	M
<i>Petrocellis middendorffii</i> (Ruprecht) Kjellman	-	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Pilea californica</i> Harvey	-	-	R	R	C	-	-	R	R	C	-	-	R	R	R	L
<i>Pleonosporium vancouverianum</i> J. Agardh	-	-	R	R	C	-	-	R	R	C	-	-	R	R	R	M L S
<i>Polysiphonia latissima</i> (Harvey) Kylin	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	L
<i>Polysiphonia hendryi</i> var. <i>deliquescens</i> (H.) Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	M
<i>P. hendryi</i> var. <i>gardneri</i> (Kylin) Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	M L
<i>P. hendryi</i> var. <i>luxurians</i> (H.) Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	M L
<i>P. pacifica</i> var. <i>determinata</i> Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. pacifica</i> var. <i>distans</i> Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	M
<i>P. pacifica</i> var. <i>disticha</i> Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. pacifica</i> var. <i>gracilis</i> Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. pacifica</i> var. <i>pacifica</i> Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. paniculata</i> Montagne	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Porphyra abbottiae</i> Krishnamurthy	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. kanakaensis</i> Mumford	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. miniata</i> (C. Ag.) C. Agardh	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. nereocystis</i> Anderson	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. perforata</i> J. Agardh f. <i>perforata</i>	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. torta</i> Krishnamurthy	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Prionitis anderssoniana</i> Eaton & J. Agardh	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. lanceolata</i> Harvey	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Pterosiphonia bipinnata</i> var. <i>bipinnata</i> (Postels & Ruprecht) Falkenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. bipinnata</i> var. <i>robusta</i> (Gardner) Doty	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>P. dendroidea</i> (Montagne) Falkenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Rhodochorton purpureum</i> (Lightfoot) Rosenvinge	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Rhodoglossum californicum</i> (J. Agardh) Abbott	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Rhodomeia larix</i> (Turner) C. Agardh	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Rhodoptilum plumosum</i> (Harvey & Bailey) Kylin	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Rhodomyenia pertusa</i> (Postels & Ruprecht) J. Agardh	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Scagellia occidentalis</i> (Kylin) Wollaston	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Schizymenia borealis</i> Abbott	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H
<i>Smithoria nalladum</i> (Anderson) Hollenberg	R	-	R	R	C	-	-	R	R	C	-	-	R	R	R	H

1p = frequent: found in >20 per cent of the samples at a beach within a season.

C = common: found in 6-20 per cent of the samples at a beach within a season.

R = rare: found in <6 per cent of the samples at a beach within a season, or incidentally collected.

H = high intertidal: found at > +5 ft (1.5 m) above MLW.

M = mid intertidal: found from +2 ft (0.7 m) to +4 ft (1.2 m) above MLW.

L = low intertidal: found from -1 ft (0.3 m) below MLW to +1 ft (0.3 m) above MLW.

S = subtidal: found -2 ft (0.7 m) below MLW and deeper.

D = drift.

Appendix 3. Habitats and relative abundances of macrofauna at five central Puget Sound beaches.
After Armstrong (1977).

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
PHYLUM PORIFERA						
<u>Haliclona permollis</u> (Bowerbank)	A	A	A	A	A	0; Bo, Co
<u>Halichondria panicea</u> (Pallas)	A	A	A	A	A	0; Bo, Co
PHYLUM CNIDARIA						
<u>Anthopleura artemisia</u> (Pickering)	C	C	C	C	C	0,+3; Bo, Co
<u>Anthopleura elegantissima</u> (Brandt)	A	A	A	A	A	0,+3; MSi, Si
<u>Halcampa decententaculata</u> (Hand)					R	0; MSi
<u>Haliplanella luciae</u> (Verrill)	C	C		R	C	0,+3,+6; Co
<u>Metridium senile</u> (Linnaeus)	C	C	C	A	C	0; Bo
<u>Ptilosarcus gurneyi</u> (Gray)	C	C	C	C	C	-2; Si
<u>Tealia coriacea</u> (Cuvier)				R		0; Bo
<u>Tealia crassicornis</u> (Müller)	R	R	R	R	R	0; Bo
PHYLUM PLATYHELMINTHES						
Order POLYCLADIDA						
	A	A	A	A	A	0,+3; Co, Cu
PHYLUM NEMERTEA						
<u>Amphiporus ?formidabilis</u> Griffin	C	C	C	C	C	0; Bo
<u>Cerebratulus californiensis</u> Coe	R	R	R	R	R	0,+3; MSi, Si
<u>Cerebratulus marginatus</u> Renier	R					0,+3; MSi, Si
<u>Emplectonema gracile</u> (Johnston)	C	C	C	C	C	0,+3; MSo, Bo, Co
<u>Paranemertes peregrina</u> Coe	C	C	C	C	C	0,+3; MSo, Bo, Co
<u>Tubulanus sexlineatus</u> (Griffin)		R			R	0; Bo
PHYLUM NEMATODA						
	A	A	A	A	A	0,+3,+6; MSi, Si

Relative abundance at each beach ¹							Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln		
PHYLUM MOLLUSCA							
Class AMPHINEURA							
<u>Cryptochiton stelleri</u> (Middendorff)					R	-2; Bo	
<u>Cyanoplax dentiens</u> (Gould)	C	C	C	C		0,+3,+6; Bo,Co	
<u>Katharina tunicata</u> (Wood)	R	R	C	R	C	0; Bo,Co	
<u>Mopalia ciliata</u> (Sowerby)	C	C	C	C	C	0,+3; Bo,Co	
<u>Mopalia lignosa</u> (Gould)	C	C	C	C	C	0,+3; Bo,Co	
<u>Mopalia muscosa</u> (Gould)	C	C	C	C	C	0,+3; Bo,Co	
<u>Tonicella lineata</u> (Wood)				C	C	0; Bo,Co	
Class BIVALVIA							
? <u>Bornia</u> sp.						+6; MSi	
<u>Clinocardium nuttallii</u> (Conrad)	C	R	C	C	C	0,+3; MSi, Si	
<u>Crassostrea gigas</u> (Thunberg)		R				+3; MSo	
<u>Macoma balthica</u> (Linnaeus)	C	C	C	C	C	0,+3,+6; MSi, Si	
<u>Macoma inquinata</u> (Deshayes)	A	A	A	C	A	0,+3,+6; MSi	
<u>Macoma incongrua</u> Martens	C	C	C	C	C	0,+3; MSi	
<u>Macoma nasuta</u> (Conrad)		C	R	R		0,+3; MSi, Si	
<u>Macoma secta</u> (Conrad)	R	R	R	R		0; Si	
<u>Tellina modesta</u> (Carpenter)	C	C	C	C	C	0; Si	
<u>Tellina nukuloides</u> (Reeve)	R				R	0; MSi	
<u>Modiolus rectus</u> (Conrad)			R			0; Bo	
<u>Mytilus edulis</u> Linnaeus	A	A	A	A	A	0,+3,+6; Bo,Co	
<u>Cryptomya californica</u> (Conrad)	R	R	R	R		0,+3; MSi	
<u>Mya arenaria</u> Linnaeus	C	C	C	C	C	0,+3,+6; MSi	
<u>Mya truncata</u> Linnaeus					R	0; MSi	
<u>Hiatella arctica</u> (Linnaeus)	C		C		C	0; Bo,Co	
<u>Solen sicarius</u> Gould	R					0; Si	
<u>Spisula ?falcata</u> (Gould)			R			0; Si	

Appendix 3 (continued).

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
<u>Tresus capax</u> (Gould)	C	C	C	C	C	0,+3; MSI
<u>Protothaca staminea</u> (Conrad)	C	C	C	A	A	0,+3; MSI
<u>Saxidomus giganteus</u> Deshayes	C	C	C	C	C	0,+3; MSI
<u>Transennella tantilla</u> (Gould)	A	A	A	A	A	0,+3; MSI
<u>Tapes japonica</u> Deshayes	R			C	R	+6; MSI
<u>Mysella ?tumida</u> Carpenter	A	A	A	A	A	0,+3; MSI
<u>Pododesmus cepio</u> (Gray)	C	C	C	C	C	0; Bo
<u>Zirfaea pilsbryi</u> Lowe				C		0,+3; RI
<u>Bankia setacea</u> Tyron	C	C	C	C	C	+3; in wood
Class GASTROPODA						
Subclass PROSOBRANCHIA						
<u>Collisella digitalis</u> (Rathke)	C	A	C	C	C	+6; Bo
<u>Collisella pelta</u> (Rathke)	C	C	C	C	C	+3,+6; Bo,Co
<u>Collisella strigatella</u> (Carpenter)	A	A	A	A	A	0,+3,+6; Bo,Co
<u>Crepidatella lingulata</u> (Gould)			R	R	R	0; Bo
<u>Notoacmea persona</u> (Rathke)	C	C	C	C	C	+3,+6; Bo,Co
<u>Notoacmea scutum</u> (Rathke)	C	C	C	C	C	0,+3; Bo,Co
<u>Alvinia</u> sp. 1	R	R				0; Co
<u>Lacuna ?variegata</u> Carpenter	A	A	A	A	A	0,+3; Ao,Co
<u>Littorina scutulata</u> Gould	A	A	A	A	A	+3,+6; Co
<u>Littorina sitkana</u> Philippi	C	C	C	R	C	+3,+6; Co
<u>Nassarius mendicus</u> (Gould)			R	C		0; Ao,Co,MSO
<u>Polinices lewisii</u> (Gould)	R	R	R	R	R	0; MSI,SI
<u>Thais emarginata</u> (Deshayes)	C	R	C	R	C	0,+3; Bo,Co
<u>Thais lamellosa</u> (Gmelin)	C	A	A	A	A	0,+3; Bo,Co
<u>Margarites</u> sp. 1			R		R	-1; Bu

Appendix 3 (continued).

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
Subclass OPISTHOBRANCHIA						
<u>Aglaja diomedea</u> (Bergh)	R	R	R	R	R	0; So
<u>Onchidella borealis</u> Dall	C	C	C	C	C	+3,+6; Bo,Co
<u>Tritonia diomedea</u> Bergh			R			-1; Bo
<u>Acanthodoris nanaimoensis</u> O'Donoghue			R	R		0; Bo,Co
<u>Aeolidia papillosa</u> (Linnaeus)	R			R	R	0; Bo,Co
<u>Archidoris montereyensis</u> (Cooper)		R	R	R	R	0; Bo,Co
<u>Archidoris odhneri</u> (MacFarland)		R	R	R	R	0; Bo,Co
<u>Diaulula sandiegensis</u> (Cooper)					R	0; Bo
<u>Hermisenda crassicornis</u> (Eschscholtz)			R	R	R	0; Bo,Co
<u>Odostomia ?quadrae</u> Dall	R	R	R	R	R	0; Ao,Co
<u>Onchidoris bilamellata</u> (Linnaeus)	C	C	C	C	C	0; Co,Cu
<u>Precuthona ?divae</u> (Marcus)			R			+3; Co
<u>?Hermatea vancouverensis</u> (O'Donoghue)	C	C	C	C	A	0; Ao
<u>Stiliger fuscovittata</u> Lance	C	C	C	C	C	(<u>Spongomorpha</u> sp.)
Class CEPHALOPODA						
<u>Octopus</u> sp.						0; Ao
PHYLUM SIPUNCULA						(<u>Pterosiphonia</u> <u>bipinnata</u>)
<u>Golfingia pugettensis</u> Fisher						
PHYLUM ANNELIDA						
Class POLYCHAETA						
Ampharetidae						
? <u>Amphisamytha bioculata</u> (Moore)					R	+3; MSI
Arenicolidae						
<u>Abarenicola pacifica</u> Healy and Wells		R	R	R		+3,+6; MSI

	Relative abundance at each beach ¹						Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln		
<u>Branchiomaldane vincentii</u> Langerhans							
<u>Capitellidae</u>							
<u>Capitella capitata</u> (Fabricius)	C	A	C	C	R	+3,+6; MS1	
<u>Barantolla americana</u> Hartman	R						0,+3; MS1
<u>Mediomastus capensis</u> Day	C	C	C	A	C	0; MS1	
<u>Notomastus lineatus</u> Claparede	C	C	C	C	C	0,+3,+6; MS1	
<u>Notomastus tenuis</u> Moore	A	A	C	A	C	0,+3,+6; MS1	
<u>Chaetopteridae</u>							
<u>Spiochaetopterus costarum</u> (Claparede)	C	R	C	R	C	0; S1,T1	
<u>Chrysopetalidae</u>							
<u>Palaenotus bellis</u> (Johnson)	C	C	C			0; MS1	
<u>Cirratulidae</u>							
<u>Chaetozone setosa</u> Malmgren							0; S1
<u>Cirriformia</u> sp.			R		R	+3; MS1	
<u>Cirratulus cirratus</u> Müller	R	R	C		C	0,+3; MS1,S1	
<u>Caulieriella</u> sp. 1	R			R	R	0; MS1	
<u>Caulieriella</u> sp. 2					R	+6; MS1	
<u>Tharyx ?multifilis</u> Moore		R			R	0,+3,+6; MS1	
<u>Dorvilleidae</u>							
Undescribed dorvilleid	C	C	R	C	C	0,+3,+6; MS1	
<u>Protodorvillea gracilis</u> (Hartman)	A	C	A	C	C	0,+3,+6; MS1	
<u>Schistomeringos longicornis</u> (Ehlers)	R	R		R		0,+3; MS1	
<u>Glyceridae</u>							
<u>Glycera americana</u> Leidy	R	C	C	C	C	0,+3; MS1	
<u>Glycera capitata</u> Oersted	C	C	C	R	C	0,+3; MS1	
<u>Hemipodus borealis</u> Johnson	C	A	C	A	C	0,+3,+6; MS1	
<u>Goniadidae</u>							
<u>Glycinde picta</u> Berkeley	C	C	C	C	C	0,+3; MS1	
<u>Hesionidae</u>							
<u>Gyptis brevipalpa</u> (Hartmann-Schröder)	R		R		R	0; S1	
<u>Micropodarke dubia</u> (Hessle)	A	C	C	C	C	0,+3; MS1	

	Relative abundance at each beach ¹						Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln		
<u>Lumbrineridae</u>							
<u>Lumbrineris zonata</u> (Johnson)	A	R	C	C			0,+3,+6; MS1
<u>Magelonidae</u>							
<u>Magelona longicornis</u> Ojuda	R		R				0; S1
<u>Magelona hobsoni</u> Jones	R	R	R				0; S1,T1
<u>Magelona sacculata</u> Hartman			R				0; S1
<u>Maldanidae</u>							
<u>Euclymene zonalis</u> Verrill			R				0; S1,T1
<u>Nephtyidae</u>							
<u>Nephtys caeca</u> (Fabricius)	C	C	C				0,+3; MS1,S1
<u>Nephtys caecoides</u> Hartman	C		C			C	0,+3; MS1,S1
<u>Nephtys ?californiensis</u> Hartman		R					0,+3; MS1, S1
<u>Nephtys ?ferruginea</u> Hartman		R					0; S1
<u>Nephtys ?longosetosa</u> Oersted			R			R	0,+3; MS1,S1
<u>Nereidae</u>							
<u>Nereis brandti</u> (Malmgren)	R	R	R				0,+3; MS1
<u>Nereis limnicola</u> Johnson	R	R					+3; MS1
<u>Nereis ?pelagica</u> Linnaeus		R	R				0,+3; MS1
<u>Nereis procera</u> Ehlers	C	C	C		C		0,+3; MS1
<u>Nereis vexillosa</u> Grube	C	C	C		C		+3,+6; MS1
<u>Nereis ?zonata</u> Malmgren	C	C	C		C		0,+3,+6; MS1
<u>Platynereis bicanaliculata</u> (Baird)	A	C	C		C		0,+3; Co,T1
<u>Opheliidae</u>							
<u>Armandia brevis</u> (Moore)	A	A	A		A		0,+3; MS1, S1
<u>Ophelia limacina</u> (Rathke)	C		C		R		0,+3; S1
<u>Onuphidae</u>							
<u>Diopatra ornata</u> Moore	R	R	R		R		0,+3,+6; S1,T1
<u>Onuphis elegans</u> (Johnson)	C		C				0; S1,T1
<u>Orbinidae</u>							
<u>Naineris dendritica</u> (Kinberg)	R				R		0,+3; MS1
<u>Scoloplos acmeiceps</u> Chamberlin						R	+3; S1
<u>Scoloplos armiger</u> (Müller)	C	C	C			C	0,+3; S1

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
<u>Scoloplos pugettensis</u> Pettibone		C	C			0,+3; Si
Owenidae						
<u>Owenia fusiformis</u> delle Chiaje	A	A	A	A	A	0,+3; MSI,TI
Paraonidae						
<u>Paraonella platybranchia</u> (Hartman)	C	C	C		C	+3,+6; Si
Parergodrilidae						
<u>Stygocapitella subterranea</u> Knöllner	R				R	0,+3; Si
Pectinariidae						
<u>Pectinaria granulata</u> Linnaeus	C	C	C	C	C	0; MSI,TI
Phyllodocidae						
<u>Eteone longa</u> (Fabricius)	C	C	C	C	C	0,+3; MSI
<u>Eteone pacifica</u> Hartman					R	0; MSI
<u>Eulalia quadrioculata</u> Moore	C	C	C	R	R	0,+3; MSI
<u>Phyllodoce maculata</u> Linnaeus	C	C	C	C	C	0,+3; MSI,SI
Pilargidae						
<u>Sigambra tentaculata</u> (Treadwell)	C				C	0,+3; MSI
? <u>Synelmis</u> sp. 1		R				+6; MSI
Undescribed pilargid					R	0; Si
Pisionidae						
<u>Pisone cf. remota</u> (Southern)	R		R		R	0,+3,+6; Si
Polynoidae						
<u>Arctonoe fragilis</u> (Baird)	C	R	C	C	C	0; COM
						<u>Evasterias troschellii</u>
<u>Arctonoe vittata</u> (Grube)				R		0; COM
						<u>Mediaster aequalis</u>
						0; MSI, COM
<u>Halosydna brevisetosa</u> Kinberg	R	R		R	R	<u>Neoamphitrite robusta</u>
						0; MSI, COM
<u>Harmothoe imbricata</u> Linnaeus	R		R	R	R	<u>Neoamphitrite robusta</u>

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
<u>Harmothoe lunulata</u> (delle Chiaje)		R		R	R	0; MS1
<u>Hesperonoe complanata</u> (Johnson)	R		R		R	0; COM <u>Callianassa</u> <u>gigas</u>
<u>Polyeunoa tuta</u> (Grube)			C		C	0; COM <u>Neoamphitrite</u> <u>robusta</u>
Serpulidae						
<u>Serpula vermicularis</u> Linnaeus	C	A	C	A	A	0; Bo
Sabellidae						
<u>Chone duneri</u> Malmgren						+3; MS1, T1
<u>Eudistylia ?polymorpha</u> (Johnson)	C	C	C	C	R	0; Bo
<u>Eudistylia vancouveri</u> (Kinberg)	C	C	C	C	C	0; Bo
<u>Pseudopotamilla ocellata</u> (Moore)	C	C	C	C	C	0; Bo
<u>Schizobranchia insignis</u> Bush	C	C	C	C	C	0; Bo
Sigalionidae						
<u>Pholoe minuta</u> (Fabricius)	C	C	C	C	C	0, +3; MS1
Spionidae						
<u>Malacoceros glutaeus</u> (Ehlers)	C	C	C	C	C	0, +3, +6; MS1
<u>Polydora caulleryi</u> Mesnil	R	R		R	R	+3, +6; MS1
<u>Polydora columbiana</u> (Berkeley)	C	C	C	C	C	0, +3, +6; MS1
<u>Polydora natrrix</u> (Soderström)	C	A	C	A	C	0, +3, +6; MS1
<u>Polydora ?socialis</u> (Schmarda)	R	R	R		R	0, +3; MS1
<u>Prionospio cirrifera</u> Würen	C	C	C	C	C	0, +3; MS1
<u>Prionospio steenstrupi</u> Malmgren	C		C		C	0, +3; MS1
<u>Pygospio elegans</u> Claparede	C	C	C	C	C	0, +3, +6; MS1
<u>Scolecopsis ?foliosa</u> (Audouin and Milne-Edwards)	C	C	C	C	C	0, +3; MS1
<u>Spio filicornis</u> (Müller)	C	C	C	C	C	0, +3; MS1
<u>Spiophanes bombyx</u> (Claparede)	C	C	C	C		0, +3; Si, T1
Syllidae						
<u>Exogone gemmifera</u> (Pagenstecher)		R			R	0; MS1

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
<u>Syllis longocirrata</u> Oersted		C	A			0,+3; S1
Undescribed Syllid sp. 1	R		R			0; S1
<u>Syllis adamantea adamantea</u> (Treadwell)	C	C	C	C	C	+3,+6; MS1
<u>Syllis alternata</u> Moore	A			C	A	0,+3,+6; MS1
<u>Syllis heterochaeta</u> Moore	C			C	C	0,+3; MS1
<u>Syllis pulchra</u> Berkeley & Berkeley	C	C	C	C	C	0,+3; MS1
<u>Terebellidae</u>						
<u>Eupolyornia heterobranchia</u> (Johnson)					R	0; Bo,Co,Ti
<u>Neomphitrite robusta</u> (Johnson)	C	C	C	C	C	0; Bo,Co,Ti
"Archannelida"						
<u>Protodrilidae</u>						
<u>Protodrilus flabelliger</u> Wieser	A		C		R	+3,+6; S1
<u>Saccocirridae</u>						
<u>Saccocirrus eroticus</u> Gray	C		C	C	C	0,+3,+6; S1
<u>Class OLIGOCHAETA</u>	A	A	A	A	A	0,+3,+6; MS1,S1
<u>Class HIRUDINEA</u>					R	+6; Ao
PHYLUM ARTHROPODA						
<u>Class ARACHNIDA</u>						
<u>?Lohmannella</u> sp.	C	C	C	C	C	+6; Ao,Bo,Co
<u>Class INSECTA</u>						
<u>Order DIPTERA</u>	C	C	C	C	C	+3,+6; Ao,Bo,Co
<u>Order COLEOPTERA</u>	C	C	C	C	C	+3,+6; Ao,Bo,Co

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
Class CRUSTACEA						
Subclass CIRRIPIEDIA						
<u>Balanus glandula</u> Darwin	A	A	A	A	A	0,+3,+6; Bo,Co
<u>Balanus cariosus</u> (Pallas)	A	A	A	A	A	0,+3; Bo,Co
<u>Balanus crenatus</u> Bruguiere	A	A	A	A	A	0,+3; Bo,Co
<u>Chthamalus dalli</u> Pilsbry	A	A	A	A	A	+6; Bo,Co
Order TANAIDACEA						
<u>Leptochelia dubia</u> (Krøyer)	C	C	C	C	C	0,+3; Si,MSi,Ti
Order ISOPODA						
<u>Excrolana kincaidii</u> (Hatch)	C		C		R	+6; Si
<u>Dynamenella shearerii</u> (Hatch)	A	A	C	A	A	0,+3; Bo
<u>Exosphaeroma amplicauda</u> (Stimpson)	R	R	R	R	R	0,+3; Co,MSo,So
<u>Exosphaeroma ?media</u> George & Strömberg	A	A	A	A	A	0,+3,+6; Ao,Bo,Co, MSi,MSo,Si,So
<u>Exosphaeroma octoncum</u> Richardson	C	C	C	C	C	0,+3; Ao,Co,MSo
<u>Gnorimosphaeroma oregonensis</u> (Dana)	A	A	A	A	A	0,+3,+6; Ao,Bo,Co, MSi,MSo,Si,So
<u>Hemiarthrus abdominalis</u> (Krøyer)	R		R	R	R	0; PAR <u>Heptacarpus</u>
<u>Phyllodurus abdominalis</u> (Stimpson)			R	R	R	+3; PAR <u>Upogebia</u>
<u>Idotea wosnesenskii</u> (Brandt)	C	C	C	C	C	0,+3; Bo,Co,MSo
<u>Ligia pallasii</u> Brandt	R	C	C	C	C	+10; Bo
<u>Munna chromatoccephala</u> Menzies		R	R	R		0,+3,+6; Ao,Bo,Co, MSo
Order LEPTOSTRACA						
<u>Nebalia pugettensis</u> (Clark)				R		+6; MSi

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
Order AMPHIPODA						
Suborder GAMMARIDEA						
Ampithoidae						
<u>Ampithoe lacertosa</u> Bate	R		R	R	R	0; Ao, Co, MSo
<u>Ampithoe lindbergi</u> Gurjanova			R			0; MSo
<u>Ampithoe simulans</u> Alderman	C	C	C	C	C	0, +3; Ao, Co, MSo
Aoridae						
<u>Aoroides columbiae</u> Walker		R	R	C	C	0; Ao, MSo
Atylidae						
<u>Atylus collingi</u> (Gurjanova)			R			0; So
Calliopidae						
<u>Calliopella pratti</u> Barnard	R	C	R	R	C	0, +3; Ao, MSo
<u>Calliopius undescribed</u> sp. 1	C	R				0, +3; Ao, So
Corophiidae						
<u>Corophium acherusicum</u> Costa	R	A	A	C	C	0, +3, +6; Ao, S1, MS1, T1
		R	C	C	R	0, +3; MS1, T1
		R		R		+3; MSo
Corophium brevis Shoemaker						
Calliopieidae						
<u>Oligochinus lighti</u> Barnard	C	R		R		
Eusiridae						
<u>Paramoera undescribed</u> sp. 1	C	C	R	R	A	+3, +6; MSo
<u>Paramoera columbiana</u> Bousfield		R				+6; MSo
<u>Pontogeneia cf. rostrata</u> Gurjanova			R		R	0; MSo
<u>Pontogeneia cf. ivanovi</u> Gurjanova	C	C	C	C	A	0, +3; Ao, MSo
Gammaridae						
<u>Anisogammarus confervicolus</u> (Stimpson)	R	C	C	C	C	+3, +6; Ao, MSo, So
<u>Anisogammarus pugettensis</u> (Dana)	C	C	R	C	C	0, +3; Ao, MSo
<u>Melita dentata</u> (Krøyer)			R	R	R	0; Co, MSo

Appendix 3 (continued).

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
Haustoriidae						
<u>Eohaustorius washingtonianus</u> (Thorsteinson)			C			0; S1
Isaeidae						
<u>Photis brevipes</u> Shoemaker		C	A	A	A	0,+3; Ao,MS1,S1,T1
cf. " <u>Podoceroipsis inaequistylis</u> " of Shoemaker	C			R	R	0; Ao,MSO
Ischyroceridae						
<u>Ischyrocerus</u> cf. <u>anguipe</u> Kroyer	R		R			+6; So
<u>Ischyrocerus</u> cf. sp. B of Barnard				R	R	0; Ao,MSO
Lysianassidae						
<u>Orchomene</u> cf. <u>pinguis</u> (Boeck)	R		R		R	0,+3,+6; MSO
Oedicerotidae						
<u>Synchelidium shoemakeri</u> Mills	C	C	C	C	C	0,+3; Ao,MS1
<u>Synchelidium rectipalium</u> Mills	R					0; S1
<u>Westwoodilla caecula</u> (Bate)		R				0; So
Phoxocephalidae						
<u>Paraphoxus</u> cf. <u>epistomus</u> Shoemaker	R				R	0,+3,+6; S1,MS1
<u>Paraphoxus milleri</u> (Thorsteinson)	R	R				0; S1
<u>Paraphoxus spinosus</u> Holmes			R	R	R	0; S1
Pleustidae						
<u>Parapleustes pugettensis</u> (Dana)		R	R		R	0,+3; MSO
Superfamily Talitroidea						
<u>Allorchestes angustus</u> Dana	A	A	A	A	A	0,+3,+6; Ao,Co,MS1,MSO
Hyale frequens (Stout)						
<u>Hyale plumulosa</u> (Stimpson)	C	C	C	C	A	0,+3; Ao,Co,MSO
<u>Hyale grandicornis californica</u> Barnard		C	C	R		+6; MSO
<u>Orchestia georgiana</u> Bousfield			C	R	R	+8; Bo
<u>Orchestia traskiana</u> Stimpson				R		0; MS1,MSO
<u>Orchestoidea pugettensis</u> (Dana)			R	R	C	+8; MSO
						+6; MS1,MSO,S1,So

Appendix 3 (continued).

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
Suborder CAPRELLIDEA						
<u>Caprella laeviuscula</u> Mayer	A	C	C	C	C	0,+3,+6; Ao,MSo
<u>Tritella pilimana</u> Mayer			R			0; MS1
<u>Metacaprella anomala</u> (Mayer)	R		R			0,+3; Ao,MSo
Order CUMACEA						
<u>Cumella vulgaris</u> Hart	R	C	C	C	C	0,+3,+6; Ao,MS1, MSo,Si,So
<u>Diastylopsis dawsoni</u> Smith	R	C	R			0; MS1,Si
<u>Lamprops quadriplicata</u> Smith	R	C	C	R	C	0,+3; MS1,Si
Order DECAPODA						
Suborder NATANTIA						
Section CARIDEA						
<u>Crangon alaskensis</u> Lockington			R			0; MS1
<u>Crangon nigricauda</u> Stimpson	C	C	C	C	C	0; MS1,Si
<u>Crangon franciscorum</u> Stimpson	R		R			0; MS1,Si
<u>Heptacarpus brevistriatus</u> (Stimpson)	R	R	R	R	R	0,+3; TP1
<u>Heptacarpus sitchensis</u> (Brandt)	C	R	R	R	R	+6; TP1
<u>Pandalus danae</u> Stimpson					C	0; TP1
Suborder REPTANTIA						
Section BRACHYURA						
<u>Hemigrapsus nudus</u> (Dana)	R	R	R	R	R	0,+3,+6; Bu,Cu
<u>Hemigrapsus oregonensis</u> (Dana)	C	C	C	C	C	0,+3,+6; Cu
<u>Cancer magister</u> Dana	R	R	R	R	R	0; Si,So

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
<u>Cancer oregonensis</u> (Dana)	C	C	C	C	C	0,+3; Bo
<u>Cancer productus</u> Randall	R	R	C	C	R	0,+3; Cu,MS1
<u>Lophopanopeus bellus</u> (Stimpson)	R		R	R	C	0; Cu
<u>Pugettia gracilis</u> Dana	C	R	R	C	C	0; Co,Cu
<u>Pugettia producta</u> (Randall)	C	R	C	C	C	0; Co,Cu
<u>Scyra acutifrons</u> Dana			R			-1; Cu
<u>Fabia subquadrata</u> Dana	R		R			0,+3; COM in bivalve molluscs
<u>Pinnixa faba</u> (Dana)	C	C	C	C	C	0,+3; COM in bivalve molluscs
<u>Pinnixa schmitti</u> Rathbun	C	C	C	C	C	0,+3; COM in bivalve molluscs
<u>Telmessus cheiragonus</u> (Tilesius)				R	R	-2; MSo
Section ASTACURA						
<u>Callianassa ?gigas</u> Dana			C	R	R	0; MS1
<u>Upogebia pugettensis</u> (Dana)	R	R	C	R	R	0,+3; MS1
Section ANOMURA						
<u>Elassochirus tenuimanus</u> (Dana)			R	R	R	0; Co,MSo
<u>Pagurus beringanus</u> (Benedict)	R		R	R	R	0; Co,MSo
<u>Pagurus granosimanus</u> (Stimpson)	R	R	R	R	R	0; Co,MSo
<u>Pagurus hirsutiusculus</u> (Dana)	C	C	C	C	C	0,+3,+6; Co,MSo
<u>Pachycheles rudis</u> Stimpson					R	-2; Cu
<u>Petrolisthes eriomerus</u> Stimpson			R	C	C	0; Cu

	Relative abundance at each beach ¹					Habitat ²
	Richmond	Carkeek	West Pt.	Alki	Lincoln	
PHYLUM BRYOZOA	C	C	C	C	C	0; Ao,Bo,Co
PHYLUM PHORONIDEA						
<u>Phoronopsis harmeri</u> Pixell	C	C	C	C	C	0,+3; MSI
PHYLUM ECHINODERMATA						
Class ASTEROIDEA						
<u>Evasterias troschelii</u> (Stimpson)	C	R	C	C	C	0; Co
<u>Henricia leviuscula</u> (Stimpson)					R	0; Co
<u>Hippasteria spinosa</u> Verrill			R			0; So
<u>Mediaster aequalis</u> Stimpson		R	R	R	R	0; So
<u>Pisaster ochraceus</u> (Brandt)			R	R		0; Co
<u>Pycnopodia helianthoides</u> (Brandt)	R		R	R	R	0; Co
<u>Solaster stimpsoni</u> Verrill					R	0; Co
Class ECHINOIDEA						
<u>Dendraster excentricus</u> (Eschscholtz)			R	R		0,+3; So
<u>Strongylocentrotus droebachiensis</u> (Müller)	R	R	R	R	R	0,+3,+6; Bu,Cu
Class HOLOTHUROIDEA						
<u>Cucumaria miniata</u> (Brandt)		C		C	C	0; Bu
<u>Eupentacta quinquevittata</u> (Selenka)	R	C	R	C	C	0; Bu
<u>Leptosynapta clarki</u> Hedding	R	C		C	C	0,+3; MSI
<u>Parastichopus californicus</u> (Stimpson)					R	0; MSO
Class OPHIUROIDEA						
<u>Amphiodia occidentalis</u> (Lyman)	R	C			C	0; Cu

Appendix 3 (continued).

Relative abundance at each beach ¹						
	Richmond	Carkeek	West Pt.	Alki	Lincoln	Habitat ²
PHYLUM CHORDATA						
Class ASCIDIACEA						
<i>Boltenia villosa</i> (Stimpson)		R			R	0; Bo
cf. <i>Chelyosoma productum</i> Stimpson			C			-1; Bu
<i>Pyura haustor</i> (Stimpson)	C	C	C	C	C	0; Bo
<i>Styela gibbsii</i> (Stimpson)		R				0; Bo
Class OSTEICHTHYES						
<i>Artedius lateralis</i> (Girard)						0; TP1
<i>Clinocottus acuticeps</i> (Gilbert)	R		R	R	C	0,+3; TP1
<i>Clinocottus embryum</i> (Jordon & Starks)			R	R		0; Cu
<i>Oligocottus maculosus</i> Girard	C	C	C	C	C	0,+3,+6; TP1
<i>Anoplarchus purpureus</i> Gill	C	C	C	C	C	0; Cu
<i>Apodichthys flavidus</i> Girard			R	R	R	0; Cu
<i>Pholis laeta</i> (Cope)	R	R	R	R	R	0; Cu
<i>Pholis ornata</i> (Girard)		R				0; Cu
<i>Gobiesox maeandricus</i> (Girard)		C	C	C	C	0; Cu
<i>Parichthys notatus</i> Girard					R	0; So

¹A = very abundant; describes species with a density of greater than 100/m².
 C = common; corresponds to a density of between 2 and 100/m².
 R = rare; corresponds to a density of 1/m² or less.

²Tide heights are given in feet above or below the mean lower low water level. Mixed-sediments are a mixture of sands and gravel up to about 60 mm in diameter. Cobble are large rocks from approximately 60 mm to 250 mm in diameter. Boulders are rocks larger than cobble.
 Ao = on algae, Bo = on boulders, Bu = under boulders, Co = on cobble, Cu = under cobble, MSo = on mixed-sediments, MSi = in mixed-sediments, Ri = in rock, So = on sand, Si = in sand, Ti = in tubes, TP1 = in tide pools, COM = commensal with, PAR = parasitic on.

Appendix 4. Benthic invertebrates known to occur in Elliott Bay and the Duwamish Estuary. Data supplied by Jack Word, Fisheries Research Institute, University of Washington. Numbers on right represent computerized code for each taxon.

* Annelida	50
* Oligochaeta	5004
* Polychaeta	5001
* Ampharetidae	500167
* Amage	50016701
* Amage anops	5001670101
* Ampharete	50016702
* Ampharete acutifrons	5001670208
* Ampharete finmarchica	50016702??
* Amphicteis mucronata	50016703??
* Anobothrus gracilis	5001670701
* Asabellides	50016708
* Asabellides lineata	5001670804
* Asabellides sibirica	5001670801
* Schistocomus hiltoni	500167????
* Aphroditidae	500101
* Aphrodita parva	5001010103
* Apistobanchidae	500142
* Apistobanchus ornatus	50014201??
* Arabellidae	500133
* Arabella	50013302
* Drilonereis falcata minor	5001330104??
* Notocirrus californiensis	50013303??
* Capitellidae	500160
* Barantolla americana	5001600601
* Capitella	50016001
* Capitella capitata	5001600101
* Decamastus	50016005
* Decamastus gracilis	5001600501
* Heteromastus	50016002
* Heteromastus filiformis	5001600201
* Heteromastus filobanchus	50016002??
* Mediomastus	50016004
* Mediomastus californiensis	5001600402
* Neomediomastus	500160??
* Neonotomastus	500160??
* Notomastus	50016003
* Notomastus californiensis	50016003??
* Notomastus lineatus	5001600303
* Notomastus pacificus	50016003
* Notomastus tenuis	5001600302
* Chaetopteridae	500149
* Phyllochaetopterus	50014902
* Phyllochaetopterus claparedii	5001490201
* Phyllochaetopterus prolifica	5001490202
* Spiochaetopterus costarum	5001490302
* Cirratulidae	500150
* Caulleriella alata	5001500202
* Caulleriella hamata	5001500201
* Chaetozone	50015004
* Chaetozone acuta	50015004??
* Chaetozone setosa	5001500401
* Chaetozone spinosa	50015004??

Appendix 4 (continued).

*	<i>Cirratulus</i>	50015001
*	<i>Cirratulus cirratus</i>	5001500101
*	<i>Cirratulus spectabilis</i>	5001500103
*	<i>Tharyx</i>	50015003
*	<i>Tharyx tessellata</i>	50015003??
	Cossuridae	500152
*	<i>Cossura</i>	50015201
*	<i>Cossura brunnea</i>	50015201??
*	<i>Cossura soyeri</i>	5001520104
*	Dorvilleidae	500136
*	<i>Dorvillea caeca</i>	5001360102
*	<i>Dorvillea pseudorubrovittata</i>	5001360101
*	<i>Protodorvillea gracilis</i>	5001360201
*	<i>Schistomeringos</i>	50013605
*	<i>Schistomeringos caeca</i>	50013605??
*	<i>Schistomeringos cf. caeca</i>	50013605????
*	<i>Schistomeringos japonicus</i>	50013605??
*	<i>Schistomeringos longicornis</i>	5001360501
*	<i>Schistomeringos rudolphi</i>	5001360504
	Flabelligeridae	500154
*	<i>Brada sachalina</i>	50015401??
*	Glyceridae	500127
*	<i>Glycera</i>	50012701
*	<i>Glycera americana</i>	5001270104
*	<i>Glycera capitata</i>	5001270101
*	<i>Glycera robusta</i>	5001270106
*	<i>Glycera tenuis</i>	5001270102
*	<i>Hemipodus borealis</i>	5001270201
*	Goniadidae	500128
*	<i>Glycinde armigera</i>	5001280103
*	<i>Glycinde brunnea</i>	50012801??
*	<i>Glycinde picta</i>	5001280101
*	<i>Glycinde polygnatha</i>	5001280105
*	<i>Goniada</i>	50012802
*	<i>Goniada brunnea</i>	5001280203
*	<i>Goniada maculata</i>	5001280202
*	Hesionidae	500121
*	<i>Gyptis brevipalpa</i>	5001210102
*	<i>Kefersteinia cirrata</i>	5001210501
*	Lumbrineridae	500131
*	<i>Lumbrineris</i>	50013101
*	<i>Lumbrineris bicirrata</i>	5001310101
*	<i>Lumbrineris californiensis</i>	50013103??
*	<i>Lumbrineris cruzensis</i>	5001310118
*	<i>Lumbrineris gp. 1</i>	50013103??
*	<i>Lumbrineris gp. 2</i>	50013103??
*	<i>Lumbrineris gp. 3</i>	50013103??
*	<i>Lumbrineris gp. 4</i>	50013103??
*	<i>Lumbrineris lagunae</i>	50013103??
*	<i>Lumbrineris latreilli</i>	5001310104
*	<i>Lumbrineris limicola</i>	50013103??
*	<i>Lumbrineris luti</i>	5001310109
*	<i>Lumbrineris zonata</i>	5001310106

Appendix 4 (continued).

*	Ninoe	50013102
*	Ninoe gemmea	5001310202
	Magelonidae	500144
*	Magelona	50014401
*	Magelona berkeleyi	50014401??
*	Maldanidae	500163
*	Asychis biceps	5001630104
*	Asychis similis	5001630102
*	Axiiothella	50016308
*	Euclymene	50016311
*	Euclymeninae	500163
*	Isocirrus longiceps	50016320??
*	Maldane	50016303
*	Maldane glebifex	5001630302
*	Maldane sarsi	5001630301
*	Nicomache lumbricalis	5001630501
*	Nicomache personata	5001630502
*	Nicomachinae	500163
*	Notoproctus	50016306
*	Notoproctus pacificus	5001630601
*	Petaloproctus	50016307
*	Petaloproctus tenuis	5001630701
*	Praxillella	50016309
*	Praxillella affinis	5001630903
*	Praxillella gracilis	5001630901
*	Praxillella praetermissa	5001630902
*	Praxillella sp. A	50016309
*	Praxillella sp. B	50016309??
*	Rhodine	50016310
*	Rhodine bitorquata	5001631001
	Nephtyidae	500125
*	Nephtys	50012501
*	Nephtys caeca	5001250103
*	Nephtys cornuta franciscana	5001250104??
*	Nephtys ferruginea	5001250111
*	Nephtys ferruginea - no pigment	5001250111??
*	Nephtys longosetosa	5001250109
*	Nereidae	500124
*	Nereis	50012404
*	Platynereis bicanaliculata	5001240501
*	Onuphidae	500129
*	Diopatra ornata	5001290202
*	Epidiopatra hupferiana monroi	5001290601??
*	Onuphis	50012901
*	Onuphis elegans	5001290111
*	Onuphis geophiliformis	5001290102
*	Onuphis iridescent	5001290103
*	Opheliidae	500158
*	Armandia brevis	5001580202
*	Ophelia limacina	5001580301
*	Ophelina	50015806
*	Ophelina acuminata	50015806??
*	Ophelina breviata	50015806??

Appendix 4 (continued).

*	Travisia	50015804
*	Travisia brevis	5001580401
*	Travisia forbesii	5001580402
*	Travisia pupa	5001580403
*	Orbiniidae	500140
*	Leitoscoloplos elongatus	500140
*	Leitoscoloplos pugettensis	500140????
*	Orbinia felix	50014005??
*	Scoloplos acmeceps	50014003??
*	Oweniidae	500164
*	Myriochele	50016402
*	Myriochele gracilis	50016402??
*	Myriochele oculata	5001640202
*	Owenia fusiformis	5001640102
*	Paraonidae	500141
*	Acesta	500141??
*	Acesta catherinae	500141????
*	Acesta cf. catherinae	500141?????
*	Tauberia gracilis	5001410801
*	Tauberia oculata	50014108??
*	Pectinariidae	500166
*	Pectinaria californiensis	50016603??
*	Pectinaria granulata	5001660303
*	Pholoididae	500104
*	Pholoides aspera	5001040101
*	Phyllodoceidae	500113
*	Eteone	50011302
*	Eteone dilatae	50011302??
*	Eteone longa	5001130205
*	Eteone pacifica	5001130203
*	Eulalia	50011303
*	Eulalia (Eumida)	50011303
*	Eulalia bilineata	5001130304
*	Eulalia cf. macroceros	5001130305??
*	Eulalia levicornuta	50011303??
*	Eulalia longicornuta	50011303??
*	Eulalia sanguinea	5001130302
*	Eulalia tubiformis	50011303??
*	Eulalia viridis	5001130301
*	Notophyllum imbricatum	5001130402
*	Phyllodoce	50011301
*	Phyllodoce (Anaitides)	50011301
*	Phyllodoce (Phyllodoce)	50011301
*	Phyllodoce groenlandica	50011301??
*	Phyllodoce hartmanae	50011301
*	Phyllodoce longipes	50011301??
*	Phyllodoce papillosa	50011301??
*	Phyllodoce polynoides	50011301??
*	Pilargiidae	500122
*	Pilargis berkeleyae	5001220301
*	Polynoidae	500102
*	Antinoella macrolepida	5001020201
*	Gattyana	50010206

Appendix 4 (continued).

*	Gattyana cirrosa	5001020603
*	Gattyana treadwelli	5001020606
*	Harmothoe	50010208
*	Harmothoe lunulata	5001020810
*	Harmothoinae	500102
*	Lepidasthenia berkeleyae	5001021801
*	Lepidasthenia longicirrata	50010218??
*	Lepidonotinae	500102
*	Lepidonotus squamatus	5001021103
*	Sabellariidae	500165
*	Idanthyrus armatus	5001650102
*	Sabellaria cementarium	5001650201
*	Sabellidae	500170
*	Chone	50017001
*	Chone duneri	5001700104
*	Chone magna	5001700106
*	Fabriciinae	500170
*	Megalomma splendida	5001700401
*	Potamilla	50017006
*	Potamilla intermedia	50017006??
*	Potamilla ocellata	50017006??
*	Sabella	50017008
*	Sabella crassicornis	5001700801
*	Sabella media	5001700802
*	Sabellinae	500170
*	Sigalionidae	500106
*	Pholoe minuta	5001060101
*	Sphaerodoridae	500126
*	Sphaerodoropsis	50012602
*	Sphaerodoropsis sphaerulifer	5001260202
*	Spionidae	500143
*	Laonice	50014302
*	Laonice cirrata	5001430201
*	Paraprionospio cirrifera	50014317??
*	Paraprionospio pinnata	5001431701
*	Polydora	50014304
*	Polydora (Boccardia)	50014304
*	Polydora (Polydora)	50014304
*	Polydora brachycephala	50014304??
*	Polydora cardalia	50014304??
*	Polydora hamata	50014304??
*	Polydora pugettensis	50014304??
*	Polydora pygidialis	5001430417
*	Polydora quadrilobata	5001430408
*	Polydora socialis	5001430402
*	Polydora sp. 1	50014304??
*	Polydora websteri	5001430412
*	Prionospio	50014305
*	Prionospio cf. cirrifera	5001430502
*	Prionospio cirrifera	5001430502
*	Prionospio steenstrupi	5001430506
*	Pseudomalacoceros	50014325
*	Pseudomalacoceros maculata	50014325??

Appendix 4 (continued).

*	<i>Pygospio elegans</i>	5001431302
*	<i>Scoelelepis</i>	50014320
*	<i>Scoelelepis squamata</i>	5001432001
*	<i>Scoelelepis foliosa</i>	50014320??
*	<i>Spio</i>	50014307
*	<i>Spio cirrifer</i>	5001430703
*	<i>Spio filicornis</i>	5001430701
*	<i>Spiophanes</i>	50014310
*	<i>Spiophanes berkeleyorum</i>	5001431004
*	<i>Spiophanes bombyx</i>	5001431001
*	<i>Spiophanes kroyeri</i>	5001431002
*	Syllidae	500123
*	<i>Autolytus</i>	50012301
*	<i>Autolytus cf. cornutus</i>	5001230101??
*	<i>Autolytus magnus</i>	5001230102
*	Eusyllinae	500123
*	<i>Eusyllis</i>	50012306
*	<i>Eusyllis assimilis</i>	5001230601
*	<i>Eusyllis blomstrandii</i>	5001230602
*	<i>Exogone</i>	50012307
*	<i>Exogone lourei</i>	5001230703
*	<i>Exogone molesta</i>	5001230704
*	<i>Exogone verugera</i>	5001230706
*	<i>Odontosyllis</i>	50012313
*	<i>Odontosyllis phosphorea</i>	5001231303
*	<i>Pionosyllis gigantea</i>	5001230201
*	<i>Pionosyllis uraga</i>	5001230204
*	<i>Syllis</i>	50012303
*	<i>Syllis alternata</i>	5001230501
*	<i>Syllis armillaris</i>	50012303??
*	<i>Syllis cf. armillaris</i>	50012303????
*	<i>Syllis harti</i>	50012303??
*	<i>Syllis heterochaeta</i>	50012303??
*	<i>Syllis sp. 1</i>	50012303??
*	<i>Syllis sp. 2</i>	50012303??
*	<i>Syllis sp. 3</i>	50012303??
*	Terebellidae	500168
*	<i>Amaeana occidentalis</i>	50016823??
*	Amphitritinae	500168??
*	<i>Artacama conifera</i>	5001681101
*	<i>Betapista dekkeri</i>	500168????
*	<i>Lanassa gracilis</i>	50016813??
*	<i>Neoamphitrite edwardsii</i>	50016804??
*	<i>Neoamphitrite robusta</i>	5001680401
*	<i>Pista</i>	50016807
*	<i>Pista brevibranchiata</i>	5001680710
*	<i>Pista cristata</i>	5001680701
*	<i>Pista elongata</i>	5001680703
*	<i>Pista pacifica</i>	5001680706
*	<i>Pista sp. 2</i>	50016807??
*	Polycirrus	50016808
*	<i>Polycirrus californicus</i>	50016808??
*	<i>Polycirrus sp. 2</i>	50016808??

Appendix 4 (continued).

*	Polycirrus sp. 3	50016808??
*	Polycirrus sp. 5	50016808??
*	Proclea graffii	5001681702
*	Scionella japonica	5001681802
*	Streblosoma	50016825
*	Streblosoma bairdii	50016825??
*	Thelepinae	500168
*	Thelepus	50016810
*	Thelepus cincinnatus	5001681003
*	Thelepus crispus	5001681001
*	Thelepus japonicus	50016810??
*	Thelepus setosus	5001681004
	Trichobranchidae	500169
*	Artacamella hancocki	5001681201
*	Terebellides stroemi	5001690101
	Trochochaetidae	500145
*	Trochochaeta multisetosa	500145????
*	Mollusca	5085
	Aplacophora	54
	Chaetodermatida	5402
	Chaetodermatidae	540201
*	Chaetoderma	54020101
*	Gastropoda	51
	Archaeogastropoda	5102
	Trochidae	510210
*	Margarites	51021003
	Cephalaspidea	5110
	Acteonidae	511001
*	Rictaxis punctostriatus vancouverensis	511001
	Aglajidae	511006
*	Aglaja	51100601
	Gastropteridae	511007
*	Gastropteron pacificum	5110070101
	Haminoeidae	511012
*	Haminoea	51101201
	Philinidae	511005
*	Philine bakeri	51100501??
*	Retusidae	511013
	Melanellidae	51????
*	Balcis	51035301
	Mesogastropoda	5103
	Calyptraeidae	510364
*	Calyptraea fastigata	5103640101
*	Crepidula	51036402
*	Crepipatella	51036403
*	Crepipatella lingulata	5103640301
	Cerithiidae	510346
*	Bittium	51034601

Appendix 4 (continued).

	Naticidae	510376
*	Natica	51037602
*	Natica clausa	5103760201
*	Polinices	51037604
	Velutinidae	510366
*	Velutina velutina	5103660401
	Neogastropoda	5104
	Cancellariidae	510514
*	Admete couthouyi	5105140101
	Columbellidae	510503
*	Mitrella gouldi	5105030204
	Nassariidae	510508
*	Nassarius cooperi	51050801??
	Turridae	510602
*	Mangelia	51060203
*	Opisthobranchia	5181
	Pyramidellida	5108
	Pyramidellidae	510801
*	Odostomia	51080101
*	Odostomia (Chrysallida)	51080101
*	Odostomia (Odostomia)	51080101
*	Turbonilla	51080102
	Tectibranchiata	51??
*	Aeolidiacea	51??
*	Pelecypoda	55
	Myoida	5516
	Hiatellidae	551706
*	Hiatella arctica	5517060201
*	Lyonsiidae	552005
*	Lyonsia arenosa	5520050201
*	Lyonsia striata	5520050203
	Pandoridae	552002
*	Pandora bilirata	5520020103
*	Pandora filosa	5520020102
	Mytiloida	5507
	Mytilidae	550701
*	Crenella decussata	5507010201
*	Megacrenella columbiana	5507010301
*	Modiolus	55070106
*	Modiolus cf. rectus	5507010603??
*	Musculus olivaceus	5507010411
	Nuculoida	5502
	Nuculanidae	550204
*	Nuculana	55020402
*	Nuculana fossa	5502040203
*	Nuculana minuta	5502040202
*	Nuculana penderi	55020402??
*	Yoldia	55020405
*	Yoldia cf. scissurata	5502040504??
*	Yoldia scissurata	5502040504
*	Yoldia thraciaeformis	5502040507
	Nuculidae	550202
*	Acila	55020201

*	Acila castrenis	5502020101
*	Nucula	55020202
*	Nucula carlottensis	55020202??
	Pholadomyoida	5520
	Cuspidariidae	552010
*	Cardiomya californica	55201001??
	Pterioidea	5508
*	Pectinidae	550905
*	Chlamys	55090501
*	Delectopecten	55090506
*	Hinnites giganteus	55090503??
*	Leptopecten	550905??
	Veneroidea	5515
	Astartidae	551519
*	Astarte alaskensis	5515190102
*	Cardiidae	551522
*	Clinocardium	55152201
*	Clinocardium fucanum	5515220103
*	Nemocardium centifilosum	5515220301
	Carditidae	551517
*	Cyclocardia ventricosa	5515170101
	Lucinidae	551501
*	Lucinoma acutilineata	55150102??
*	Parvilucina tenuisculpta	5515010101
	Montacutidae	551510
*	Aligena	55151006
*	Mysella tumida	5515100102
	Solenidae	551529
*	Solen sicarius	5515290201
*	Tellinidae	551531
*	Macoma	55153101
*	Macoma balthica	5515310116
*	Macoma carlottensis	5515310112
*	Macoma cf. yoldiiformes	5515310111??
*	Macoma elimata	5515310102
*	Macoma moesta alaskana	551531010702
*	Macoma nasuta	5515310114
*	Macoma obliqua	5515310106
*	Macoma yoldiiformis	5515310111
*	Tellina	55153102
*	Tellina modesta	5515310204
*	Tellina nukuloides	5515310202
	Thyasiridae	551502
*	Adontorhina cyclia	5515020102
*	Axinopsida serricata	5515020201
*	Thyasira flexuosa	5515020301
	Veneridae	551547
*	Compsomyx subdiaphana	5515470301
*	Psephidia lordi	5515470501
*	Transennella tantilla	5515470101

Appendix 4 (continued).

* Arthropoda	58
* Araneae	5911
* Pycnogonida	60
* Pantopoda	6001
Nymphonidae	600101
* Nymphon pixellae	6001010107
Phoxichilidiidae	600106
* Anoplodactylus	60010602
* Anoplodactylus erectus	6001060201
* Phoxichilidium femoratum	6001060102
Insecta	62
* Diptera	6501
Crustacea	61
* Calanoida	6118
Calanidae	611801
* Calanus	61180102
Centropagidae	611817
* Centropages	61181701
* Centropages sp. 2	61181701??
Pontellidae	611827
* Epilabidocera amphitrites	6118270101
* Harpacticoida	6119
Scalpellidae	613201
* Scalpellum californicum	6132010104
* Scalpellum columbianum	6132010101
* Scalpellum sanctipetrense	6132010105
* Amphipoda	6168
* Caprellidea	6171
* Caprellidae	617101
* Caprella	61710107
* Caprella gracilior	6171010709
* Caprella irregularis	6171010708
* Caprella laeviuscula	6171010710
* Caprella mendax	6171010719
* Mayerella banksia	6171010301
* Tritella	61710106
* Tritella laevis	6171010601
* Tritella pilimana	6171010602
* Gammaridea	6169
* Ampeliscidae	616902
* Ampelisca	61690201
* Ampelisca agassizi	6169020111
* Ampelisca brevisimulata	61690201??
* Ampelisca hancocki	6169020113
* Ampelisca lobata	61690201??
* Ampelisca macrocephala	6169020101
* Byblis veleronis	6169020206
Amphilochoidea	616903
* Amphilocheus	61690302
Aoridae	616906
* Aoroides	61690602
* Aoroides columbiae	6169060202
Calliopidae	616912

Appendix 4 (continued).

*	Calliopius	61691202
	Corophiidae	616915
*	Corophium acherusicum	6169150201
	Dexaminidae	616917
*	Guernea	61691702
	Eusiridae	616920
*	Eusirus	61692008
*	Pontogeneia	61692012
*	Pontogeneia rostrata	6169201208
*	Rhachotropis	61692013
*	Rhachotropis clemens	61692013??
*	Rhachotropis inflata	6169201304
*	Haustoriidae	616922
*	Ischyroceridae	616927
*	Ischyrocerus	61692702
*	Ischyrocerus anguipes	6169270202
*	Microjassa litotes	61692704
*	Lysianassidae	616934
*	Acidostoma	61693401
*	Anonyx liljeborgi	6169340303
*	Cyphocaris challengerii	6169341101
*	Hippomedon	61693414
*	Hippomedon denticulatus	6169341402
*	Hippomedon propinquus	6169341405
*	Lepidepecreum	61693421
*	Lysianassa holmesi	61693422??
*	Opisa tridentata	61693428??
*	Orchomene	61693429
*	Orchomene pinquius	6169342904
*	Pachynus barnardi	6169343101
*	Schisturella cocula	61693438??
	Melitidae	616921
*	Melita	61692110
*	Melita desdichada	6169211008
	Melphidippidae	616935
*	Melphisana	616935??
*	Oedicerotidae	616937
*	Bathymedon	61693705
*	Monoculodes	61693708
*	Monoculodes hartmanae	61693708??
*	Synchelidium	61693714
*	Synchelidium rectipalium	6169371403
*	Synchelidium shoemakeri	6169371402
*	Westwoodilla caecula	6169371502
	Pardaliscidae	616940
*	Halicella halona	616940????
*	Pardalisca	61694003
*	Pardalisca cuspidata	6169400302
*	Pardalisca tenuipes	6169400303
	Photidae	616926
*	Gammaropsis thompsoni	6169260401
*	Photis	61692602
*	Photis brevipes	6169260201

Appendix 4 (continued).

*	Photis sp. A	61692602??
*	Protomedeia	61692603
*	Protomedeia articulata	6169260307
*	Phoxocephalidae	616942
*	Eyakis robustus	616942????
*	Harpiniopsis fulgens	61694202??
*	Heterophoxus oculatus	6169420301
*	Mandibulophoxus gilesi	6169421201
*	Metaphoxus	61694206
*	Metaphoxus frequens	61694206??
*	Metaphoxus fultoni	61694206??
*	Paraphoxus oculatus	6169420925
*	Rhepoxynius abronius	61694209??
*	Rhepoxynius daboius	616942????
*	Pleustidae	616943
*	Parapleustes pugettensis	6169430302
*	Pleusymtes subglaber	6169430501
*	Podoceridae	616944
*	Dulichia	61694401
*	Dyopedos	616944??
*	Paradulichia typica	61694403??
*	Podocerus cristatus	6169440401
*	Stenothoidae	616948
*	Metopa	61694815
*	Tironidae	616950
*	Bruzelia	61695001
*	Bruzelia tuberculata	61695001??
*	Syrrhoe longifrons	61695003??
*	Hyperiididae	617001
*	Parathemisto pacifica	6170011003
*	Cumacea	6154
*	Campylaspididae	615407
*	Campylaspis canaliculata	6154070102
*	Campylaspis hartae	6154070105
*	Campylaspis rubromaculata	61540701??
*	Diastylidae	615405
*	Diastylis paraspinulosa	6154050115
*	Diastylis pellucida	6154050114
*	Diastylis sp. B	61540501??
*	Leptostylis	61540504
*	Leptostylis sp. A	61540504??
*	Leptostylis villosa	6154050401
*	Leuconidae	615404
*	Eudorella pacifica	6154040202
*	Eudorellopsis integra	6154040301
*	Eudorellopsis longirostris	61540403??
*	Leucon	61540401
*	Leucon nasica	6154040101
*	Leucon subnasica	61540401??
*	Nannastacidae	615408
*	Cumella	61540801
*	Cumella sp. A	61540801??

Appendix 4 (continued).

	Decapoda	6175
*	Axiidae	618302
*	Axiopsis	618302??
*	Axiopsis spinulicauda	618302????
*	Paguridae	618306
*	Paguristes	61830601
*	Pagurus	61830602
	Pinnotheridae	618906
*	Pinnixa	61890604
*	Pinnixa schmitti	6189060404
*	Pinnotheres	61890602
*	Pinnotheres pugettensis	6189060204
	Cancridae	618803
*	Cancer	61880301
	Majidae	618701
*	Oregonia gracilis	6187010101
*	Caridea	6179
	Crangonidae	617922
*	Crangon	61792201
*	Mesocrangon munitella	617922????
*	Hippolytidae	617916
*	Eualus	61791604
*	Eualus herdmani	6179160409
*	Eualus pusiolus	6179160408
*	Spirontocaris sp. 1	61791602??
	Pasiphaeidae	617905
*	Pasiphaea pacifica	6179050101
*	Thalassinidea	
	Euphausiacea	6174
	Euphausiidae	617402
*	Euphausia pacifica	6174020101
*	Thysanoessa	61740209
*	Isopoda	6158
	Anthuridae	616001
*	Haliophasma geminata	616001????
*	Asellota	6163
	Munnidae	616312
*	Pleurogonium rubicundum	6163120202
	Aegidae	616107
*	Rocinela belliceps	6161070202
*	Mysidacea	6151
	Mysidae	615301
*	Mysidella americana	6153011301
*	Pseudomma	61530119
*	Pseudomma truncatum	6153011902
	Nebaliacea	6145
	Nebaliidae	614501
*	Nebalia	61450101
*	Nebalia pugettensis	6145010102
*	Leptostraca	6145
*	Tanaidacea	6155
*	Paratanaididae	615702
*	Leptocheilia	61570201

Appendix 4 (continued).

*	Leptochelia dubia	6157020103
*	Leptognathia	61570202
*	Leptognathia longiremis	61570202??
	Myodocopa	6111
*	Cylindroleberididae	611103
	Philomedidae	611107
*	Euphilomedes carcharodonta	6111070301
*	Euphilomedes producta	6111070303
*	Rutidermatidae	611106
*	Rutiderma lomae	6111060103
	Podocopa	6113
*	Cyprididae	611303
Brachiopoda		80
	Articulata	8004
	Rhynchonellida	8005
	Dallinidae	800511
*	Terebratalia	80051102
*	Terebratalia transversa	8005110201
Chaetognatha		83
Chordata		8388
	Osteichthyes	8717
	Perciformes	8834
	Gobiidae	884701
*	Lepidogobius lepidus	8847010301
*	Asciadiacea	8401
	Molgulidae	840603
*	Eugyra arenosa	8406030402
*	Molgula	84060301
	Pyuridae	840602
*	Pyura	84060201
	Styelidae	840601
*	Styela coriacea	8406010502
*	Styela gibbsii	8406010505
Cnidaria		37
*	Anthozoa	3740
	Pennatulacea	3752
	Pennatulidae	375402
*	Ptilosarcus gurneyi	3754020201
*	Actiniaria	3758
	Halcampidae	375904
*	Halcompa	37590401
*	Hydrozoa	3701
*	Hydroida	3702

Appendix 4 (continued).

	Tubulariidae	370303
*	Tubularia	37030302
*	Echinodermata	81
	Asteroidea	8104
	Spinulosida	8112
	Solasteridae	811301
*	Crossaster	81130101
*	Crossaster papposus	8113010103
	Valvatida	8109
	Goniasteridae	811104
*	Hippasteria spinosa	8111040403
*	Mediaster aequalis	8111040501
	Echinoidea	8136
	Echinoida	8149
	Strongylocentrotidae	814903
*	Strongylocentrotus	81490302
	Spatangoida	8160
	Schizasteridae	816204
*	Briaster latifrons	81620401??
	Holothuroidea	8170
	Apodacea	8179
*	Molpadiidae	817901
*	Molpadia	81790101
*	Molpadia intermedia	8179010101
	Apodida	8178
*	Synaptidae	817801
*	Leptosynapta	81780102
*	Leptosynapta clarki	8178010203
	Dendrochirotida	8172
*	Cucumariidae	817206
*	Cucumaria	81720601
*	Cucumaria calcigera	8172060101
*	Cucumaria chronhjelmi	8172060102
*	Cucumaria piperata	8172060111
*	Cucumaria populifera	81720601??
*	Eupentacta	81720602
	Ophiurida	8126
	Ophiuridae	812701
*	Ophiura lutkeni	8127010607
*	Amphiuridae	812903
*	Amphioplus	81290309
*	Amphipholis squamata	8129030202
*	Amphiodia urtica	8129030104
*	Ophiuroidea	8120
*	Echiura	73
	Echiuroinea	7301
*	Bonellidae	730101

Appendix 4 (continued).

* Ectoprocta	78
Gymnolaemata	7801
* Cheilostomata	7814
Alcyonidiidae	780301
* Alcyonidium mammillatum	7803010102
* Cyclostomata	7808
Tubuliporidae	781002
* Hemichordata	82
* Nematoda	47
* Platyhelminthes	39
Turbellaria	3901
Polycladida	3906
Callioplanidae	390608
* Pseudostylochus furchami	39060801
Protozoa	34
Rhizopodea	3439
* Foraminifera	3448
* Rhynchocoela	43
Anopla	4301
Heteronemertea	4303
Lineidae	430302
* Lineus	43030204
* Sipuncula	72
* Golfingiidae	720002
* Golfingia	72000201
* Golfingia minuta	7200020106
* Miscellaneous taxa	
* Anothrus gracilis	
* Histella arctica	
* Ilyarachna	61631501
* Odontorhina cyclia	
* Pachycerianthus fimbriatus	
* Philinacea	

APPENDIX 5

Benthic taxa identified from sites
in central Puget Sound. After
Armstrong et al. (1980).

TABLE 2
MACROFAUNA COLLECTED AT SITES 9- AND 13-m BELOW MILLW. THE DATA FROM THE 13-m SITES ARE IN PARENTHESES

Taxa ^a	1	2	3	4	5	6	7
Annelida:							
<i>Amage anops</i> ^S	2		1		(1)		
<i>Ampharete arctica</i> ^S	5	1	1 (1)		(1)		3
<i>Amphiteis scaphobranchia</i> ^S					(1)		
<i>Aricidea lopezi</i> ^B	(1)	1 (3)	(2)		(2)	1	1
<i>Armandia brevis</i> ^B	1	1	1 (1)				
<i>Aricidea conifera</i> ^S	1	2 (4)	(1)				
<i>Axiostella rubrocineta</i> ^B							
<i>Barantolla americana</i> ^B							
<i>Capitella capitata</i> ^{BB}		(3)	396 (6)	366 (4)	458	6	1
<i>Capitellid sp. 1</i> ^B				(3)	(2)		
<i>Chaetozone setosa</i> ^{BS}	37	5	4	1			5
<i>Cirratulus cirratus</i> ^S							
<i>Diopatra ornata</i> ^S		3 (1)	(1)			1 (1)	
<i>Diosoma franciscorum</i> ^S							
<i>Dorvillea japonica</i> ^S	(1)	(1)	5	1	3		1
<i>Eteone longa</i> ^S					1		
<i>Eulalia quadrioculata</i> ^C		3	2				
<i>Exogone gemifera</i> ^S	6 (5)	6 (6)	2 (1)	2 (1)	(1)	2 (7)	2
<i>Glycera capitata</i> ^{BS}	5 (1)	6 (2)	12 (1)	9 (4)	4 (1)	4	4
<i>Glycinde polygnatha</i> ^{BS}	1						
<i>Goniada brunnea</i> ^S	5		1				
<i>G. maculata</i> ^S							
<i>Gyptis brevipalpa</i> ^S						1	
<i>Harmathoe extenuata</i> ^S	5	1	5	1	5	6	
<i>H. imbricata</i> ^S			1	1 (1)	3		
<i>H. lunulata</i> ^S			5	1		1 (7)	1
<i>Heteromastus filobranchus</i> ^{BS}	(4)	(1)	(2)	1			1
<i>Laonice cirrata</i> ^S	(1)						
<i>Leichone columbiana</i>	(2)						
<i>Lumbrineris lutea</i> ^{BS}	47 (49)	28 (42)	69 (18)	26 (4)	4 (16)	19 (34)	52
<i>malanid sp. 1</i> ^B	3 (1)				(1)		
<i>sp. 2</i> ^B							
<i>sp. 4</i> ^{BS}	15 (7)		(1)			(9)	
<i>sp. 6</i> ^B	1					(2)	
<i>sp. 7</i> ^B	1					(1)	
<i>sp. 9</i> ^B						(1)	
<i>sp. 11</i> ^B	1		1				
<i>sp. 12</i> ^B	4						
<i>Mediomastus capensis</i> ^B							
<i>Micropodarkie dubia</i> ^S							
<i>Nephtys ferruginea</i> ^{BS}	16 (9)	17 (12)	8 (9)	12 (6)	(8)	5 (13)	5
<i>Nereis sp. 1</i> ^S				9			
<i>Notomastus lineatus</i> ^B	5 (2)	2 (1)	1	(2)		1	1
<i>N. tenuis</i> ^B		(1)					
<i>Onuphis iridescens</i> ^S							
<i>Owenia fusiformis</i>	1 (1)	1	1			1	
<i>Pectinaria granulata</i> ^B							
<i>Peisidice aspera</i>	4		4	4	1	1	
<i>Pholoe minuta</i> ^S		(1)			2		
<i>Phyllodoce groenlandica</i> ^S			10	3			
<i>P. maculata</i> ^S	2	2					
<i>P. maderiensis</i> ^S							

TABLE 2—contd.

Taxa ^a	1	2	3	4	5	6	7
<i>P. multiseriata</i> ^S	5			5			
<i>P. williamsi</i> ^S				1			
<i>Pista cristata</i>							
<i>Platynereis bicanaliculata</i>		6	14		29	1	1
<i>Polydora caulleryi</i> ^S			1				
<i>P. hamata</i> ^S					(1)		
<i>P. natrix</i> ^{BS}	33	119	51	65	16	3	3
<i>P. socilais</i> ^{BS}	63	59	58	57	11	13	6
<i>P. sp. 1</i> ^S	(2)		(1)			(1)	
<i>Praxillella affinis v. pacifica</i> ^B	10 (3)	2 (3)	1			(1)	1
<i>P. gracilis</i> ^{BS}	58 (36)	1 (2)	2		(4)	(5)	
<i>Prionospio cirrifera</i> ^{BS}		(1)	15	7	11	11	6
<i>P. pinnata</i> ^S	3	13 (2)	41 (7)	10 (3)	4 (2)	39 (1)	18
<i>P. steenstrupi</i> ^{BS}	1	(1)	7 (1)	2			
<i>Scoloplos pugetensis</i> ^B	1						
<i>Spiochaetopterus costarum</i>	1						
<i>Spiophanes berkeleyorum</i> ^S	2						
<i>Syllis alternata</i> ^S	3 (2)	(1)			(1)		
<i>Tenotonia kitsapensis</i>							
<i>terebellid sp. 1</i> ^S							
<i>sp. 2</i> ^S							
<i>Terebellides stroemi</i> ^S		1 (1)	1			(2)	
<i>Tharyx sp. 1</i> ^{BS}	30 (13)	13 (14)	8 (4)	1 (2)	1 (12)	1 (18)	12
<i>oligochaete</i>	2						
Nemertea:							
<i>Cerebratulus sp.</i>		2 (1)					
<i>nemertean sp.</i>	(1)	3 (1)			(1)	3	
Sipuncula:							
<i>Golfingia sp.</i>	1					(1)	
<i>nr. Phascolosoma agassizii</i>	2						
Platyhelminthes:							
Mollusca:							
<i>Acania sp. 1</i>			1		1	1 (1)	
<i>Axinopsida serricata</i> ^B	178 (120)	44 (41)	60 (19)	12 (20)	(90)	9 (304)	47
<i>Bankia setacea</i>							
<i>Cardiomya oldroydi</i>	1	(1)					
<i>Compsonyx subdiaphana</i>							
<i>Entodesme saxicola</i>							
<i>Lucinoma annulata</i>		(1)				(1)	
<i>Lyonsia californica</i>	2						
<i>Macoma carlottensis</i> ^B	67 (21)	26 (24)	26 (4)	24 (14)	23 (56)	24 (34)	10
<i>M. elmata</i>	22	4 (2)	7	(3)	1	3	
<i>M. nasuta</i>		3	2 (1)	4 (3)	1	6	4
<i>M. obliqua</i> ^B	12	9	23	22 (1)	7		
<i>M. yoldiformis</i>	1						
<i>Megacrenella columbiana</i>	1 (1)				(1)	(1)	
<i>Mitrella tuberosa</i>	(1)				(3)	(7)	
<i>Mysella sp.</i>							
<i>Nassarius sp.</i>	1		1				
<i>Natica clausa</i>	1						
<i>Nemocardium centifoliosum</i>	4	1			(1)	(1)	1
<i>Nucula tenuis</i> ^B	15 (9)	(2)				(2)	

TABLE 2—contd.

Taxa ^a	1	2	3	4	5	6	7
<i>Nuculana hamata</i>	(3)	1			(1)		
<i>Parvulucina tenuisculpta</i>							
<i>Protothaca</i> sp.	2 (1)	1	1	2	(5)	(3)	1
<i>Psephidia lordi</i> ^b	1 (2)	2	3	2	(1)	(2)	1
<i>Tellina bodegensis</i>							
<i>Thyasira flexuosa</i>	2	(2)			(1)		
<i>Tranzenella tantilla</i>							
<i>Turbonella</i> sp. 1							
clam sp. y							
Arthropoda:							
amphipod sp.		(1)	1	(1)			
<i>Aoroides columbiae</i> ^b		27	12	22	1	2	
<i>Byblis veleronis</i>							
<i>Calianassa gigas</i>	2	2			1	1	
<i>Cancer magister</i>					(1)		
<i>C. productus</i>			2				
carid shrimp							
<i>Cirrolana</i> sp. 1	1	(3)					
cumacean sp. 1							
<i>Cumella vulgaris</i>		(1)	2	1 (1)	(2)	(1)	1
<i>Diatylis</i> sp. 1							
<i>Fabia subquadrata</i>							
<i>Gninospheroma oregonensis</i>							
<i>Leptochelita dubia</i>	13	1 (1)	4 (6)	1			
<i>Leucon</i> sp. 1	3		(1)				
<i>Melita desdichada</i>	2	6	10 (1)	12			
<i>Nebalia pugettensis</i>			3	22	1		
? <i>Oligochinus lighti</i>			(1)				
<i>Orchomene pinguis</i>		2	1				
<i>Oregonia gracilis</i>							
ostracod ^b	35 (10)	51 (48)	59 (4)	66 (12)	(18)	(5)	3
<i>Pachynus</i> sp. 1	1 (1)					(1)	
<i>Pandanus jordani</i>						2	1
<i>Paraphoxus spinosus</i>	(1)						
<i>Parapleustes pugettensis</i>		1	2				
<i>Photis brevipes</i>			4	2 (1)	1		
<i>Pinnixia occidentalis</i>	1 (2)	1		2 (2)	1	(2)	1
<i>Pontogenia rostrata</i>			21	6	3		
<i>Synchelidium</i> sp. 1	2		31	7	5	1	1
<i>Westwoodilla caecula</i>	1		1 (2)			1 (1)	

^a = All species which were collected at two or more sites at a given depth were used in the classification analysis for that depth.

^b = Species used in ordination analysis.

^c = Carnivorous.

^d = Burrowing deposit feeder.

^e = Surface deposit feeder.

TABLE 3

SUMMARY OF INVERTEBRATE ABUNDANCES AND BIOMASS FROM TWO 0.1 m² VAN VEEN GRABS AT EACH SITE. NOTE THAT ORGANISMS IN MISCELLANEOUS PHyla ARE INCLUDED IN TOTALS

Site	Phyla	Depth, 9 m		Depth, 13 m		Depth, 24 m	
		Number of species	Number of individuals	Number of species	Number of individuals	Biomass	Biomass
1	Polychaeta	33	377	19	141	4.70 g	0.68 g
	Mollusca	15	310	9	159	1.48	1.76
	Arthropoda	8	45	4	14	—	—
	Total	57	732	33	315	6.18	2.44
2	Polychaeta	25	298	20	102	1.88	0.41
	Mollusca	8	90	6	71	1.91	1.88
	Arthropoda	8	79	4	53	—	—
	Total	46	477	32	228	3.79	2.30
3	Polychaeta	38	759	18	60	2.30	0.30
	Mollusca	13	128	3	23	5.04	0.67
	Arthropoda	16	169	4	8	—	—
	Total	68	1051	26	91	5.44	0.99
4	Polychaeta	25	588	10	30	0.22	0.76
	Mollusca	8	70	4	38	11.22	7.80
	Arthropoda	9	107	8	25	—	—
	Total	43	766	22	93	11.87	8.56
5	Polychaeta	17	568	16	56	0.72	0.21
	Mollusca	4	32	11	163	1.84	0.08
	Arthropoda	9	70	3	21	—	—
	Total	30	670	31	241	3.14	0.30
6	Polychaeta	22	123	17	105	1.13	0.83
	Mollusca	7	46	11	358	4.10	4.49
	Arthropoda	12	26	5	10	—	—
	Total	43	196	37	474	5.31	5.32
7	Polychaeta	20	125	—	—	—	—
	Mollusca	7	67	—	—	—	—
	Arthropoda	9	12	—	—	—	—
	Total	36	204	—	—	—	—

from the 9-m (Fig. 5) and 13-m sites. While the 95% confidence intervals for samples of 60 individuals have not been included in Fig. 5, the following groups of 9-m sites contained individual sites whose polychaete species richnesses were not significantly different from one another: 1, 6 and 7; 6, 7, 3 and 2; and 2 and 4. Site 5 had a significantly lower species richness curve than all the other sites. Sites nearest the overflow generally had the lowest species richness. There were no significant differences in polychaete species richness among the 13-m sites.

Species richness curves calculated for the molluscs collected from the 9- and 13-m sites indicated no significant differences in species richness among the sites at each depth. Species richness curves were not calculated for the crustacean samples because of the low number of individuals collected at several of the sites.

The proportion of polychaetes of various feeding types were also compared among sites. Individual polychaetes were classified as carnivores, surface deposit feeders or burrowing deposit feeders after Jumars & Fauchald (1977). The feeding

PASSIVE

Mal'danidae(Po)
Onuphidae(Po)
Ampharetidae(Po)
Terebellidae(Po)

Owenia(Po)
Sabellidae(Po)
Serpulidae(Po)
Amphipholis(E)
Amphiodia(E)
Phoronis(Ph)
Caprellida(A)
Ampelisca I (A)

Nemocardium(Pe) _____
Crenella(Pe) _____
Ampelisca II(A) _____
Cucumaria(E) _____
Sthenelanelia(Pe) _____
Byblis(A) _____
Phoxocephalidae(A) _____

STATIONARY

Spionidae(Po)
Magelonidae(Po)
Cirratulidae(Po)
Myriochele(Po)
Axinopsida(Pe)
Myrella(Pe)
Calypptogena(Pe)
Photis(A)

Orbiniidae (Po)
*Capitellidae (Po)
 Mediomastus
 Decamastus
 Nephtys (Po)
 Glycera (Po)
 Goniada (Po)
 Tanaids (A)
*Ostracoda (A)
 Euphilomedes
 Cumacea (A)

Cistena
Californiensis (Po)

GROUP III: SURFACE DEPOSIT FEEDERS

STATIONARY

Parvilucina
tenuisculpta(Pe)

Macoma
carlottensis(Pe)

Nuculana(Pe)

Yoldia(Pe)

MOBILE

Travisia(Po)

Nereis(Po)

Bittium(G)

Mitrella

permodesta(G)

Nassarius(G)

GROUP IV: SUB SURFACE DEPOSIT FEEDERS

Capitella capitata(Po)

Armandia bioculata(Po)

Ophelina acuminata(Po)

Oligochaeta(An)

Solemya(Pe)

Stenothoidae(A)

Dorvilleidae(Po)

(A) = Arthropoda

(An) = Annelid

(E) = Echinodermata

(G) = Gastropoda

(Pe) = Pelecypoda

(Ph) = Phoronid

(Po) = Polychaeta