DREDGED MATERIAL RESEARCH PROGRAM

U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION

TECHNICAL REPORT D-77-24

AQUATIC DISPOSAL FIELD INVESTIGATIONS DUWAMISH WATERWAY DISPOSAL SITE PUGET SOUND, WASHINGTON

EVALUATIVE SUMMARY

by

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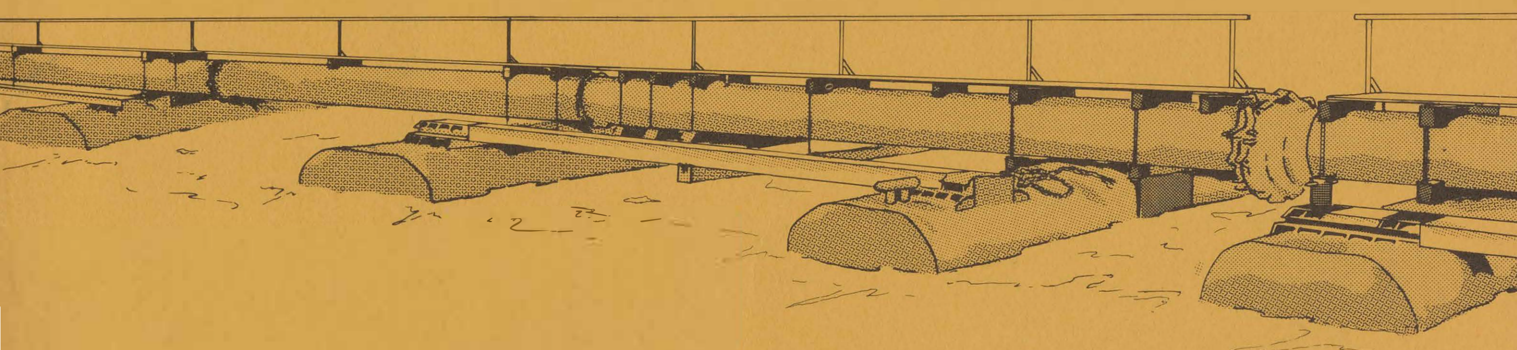

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Under DMRP Work Unit No. 1A10

AQUATIC DISPOSAL FIELD INVESTIGATIONS
DUWAMISH WATERWAY DISPOSAL SITE
PUGET SOUND, WASHINGTON

Appendix A: Effects of Dredged Material Disposal on Demersal Fish and Shellfish in Elliott Bay, Seattle, Washington

Appendix B: Role of Disposal of PCB-Contaminated Sediment in the Accumulation of PCB's by Marine Animals

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Appendix G: Benthic Community Structural Changes Resulting from Dredged Material Disposal, Elliott Bay Disposal Site

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31 July 1978

SUBJECT: Transmittal of Technical Report D-77-24

TO: All Report Recipients

1. The technical report transmitted herewith contains a summary of the results of several research efforts (work units) undertaken as part of Task 1A, Aquatic Disposal Field Investigations of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 1A was part of the Environmental Impacts and Criteria Development Project (EICDP), which had as a general objective evaluation of the effects of open-water disposal on the biota and on the water quality of disposal areas. This report is a summary of the physical, chemical, and biological studies that were conducted at the Duwamish Waterway disposal site, Puget Sound, Washington. This research site was one of five studied under the DMRP in various geographical regions of the United States.

2. This report, Aquatic Disposal Field Investigations, Duwamish Waterway Disposal Site, Puget Sound, Washington, Evaluative Summary, represents an overview of the various research efforts conducted at the site. The seven contractor-prepared reports form Appendices A-G to this report. The titles of all appendices of this series are listed on the inside front cover of this report. Appendix F is published in microfiche form and may be found at the back of this report. This summary report provides additional results, interpretations, and conclusions not found in the contractor reports and, in addition, provides a comprehensive summary and synthesis of the entire study.

3. The purpose of the Duwamish study was to determine the physical, chemical, and biological effects of open-water disposal of dredged material from the Duwamish River on Elliott Bay, a part of the Puget Sound estuary. Chemical analyses of sediment, water, and animal tissue were completed during the study, including analyses for metals such as mercury and organic contaminants such as polychlorinated biphenyls (PCB's). Demersal fish and shellfish were sampled throughout the study. A major part of this investigation involved the collection of benthic samples from the disposal and reference sites in Elliott Bay. The data revealed no adverse effect from the disposal operation on demersal fish and shellfish, and there was no significant accumulation of mercury, chromium, or PCB's by a variety of estuarine animals exposed to the dredged material at the disposal site. The primary impact was physical

and not chemical and was on the benthic fauna at the center of the disposal site. A mound of dredged material 2.0 to 2.5 m in height was created near the center of the disposal site. Transient increases in the levels of suspended solids, dissolved manganese, and total PCB's occurred in the water column following each disposal event.

4. The primary conclusion of this report, based on the data presented in the appendices, was that barge disposal of over 114,000 m^3 of dredged material did not result in any significant adverse impact to organisms at the disposal site or to the water quality of Elliott Bay. Elevation of levels of suspended solids, dissolved manganese, and PCB's in the water column lasted only a few hours or days. Animals at the disposal site did not accumulate or magnify the contaminants studied. Small benthic invertebrates living near the center of the disposal site were harmed physically by the operation, but there was no evidence of any chemical toxicity associated with these sediments.

5. Results of this research will be useful in a regional sense for evaluating the possible environmental impacts of open-water disposal in the Pacific estuarine environment of Puget Sound. These studies will be helpful in planning future dredging and disposal projects involving open-water disposal so as to minimize adverse environmental effects.

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Aquatic environment
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Waste disposal sites
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A multidisciplinary approach was utilized to study the physical, chemical, and biological effects of disposal of contaminated dredged material from the Duwamish River on a deepwater disposal site located in Elliott Bay, Puget Sound, Wash. A pilot survey, conducted in November and December 1975, was followed by a full-scale field assessment program.

Observation of individual disposal events indicated that the sediment left the split-hull barges as a well-defined slug and reached the bottom in

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20. ABSTRACT (Continued).

approximately 25 sec. A mound of dredged material 2.2 m high was created near the center of the disposal site. There was no physical or chemical evidence which indicated that any of the material reached the two reference sites located east and west of the disposal site. Chemical analyses of the in situ river sediment revealed concentrations of total sulfides and PCB's and interstitial water ammonia significantly higher than those for sediments from the disposal or reference sites. The disposal operation resulted in a rapid pulse of low levels of suspended solids in the water column which lasted less than 30 min. Increased levels of dissolved manganese and total PCB's in the water column were associated with the short-term increase in suspended particulate matter.

Chemical analyses of animal tissues collected at the disposal and reference sites indicated that the disposal operation did not result in higher levels of mercury and chromium in test animals. Mussels held at the disposal site for 3 weeks did accumulate PCB's to some extent; however, background levels of PCB's in Elliott Bay waters were found to be relatively high before the operation. No adverse effects on demersal fish or shellfish were demonstrated. These motile animals were found at the disposal site in large numbers during and after the disposal operation. Benthic communities at the center of the disposal site were impacted adversely. The density and biomass data from the central disposal site stations indicated fewer animals present after the disposal although the species data showed more species were present. The biomass and density of animals at the corner stations of the disposal site were found to be greater than the values determined for the two reference sites at 3 months after disposal. A number of opportunistic species were found to be actively recolonizing the central stations of the disposal site at 9 months after disposal.

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SUMMARY

The effect of open-water disposal of 114,250 m^3 of contaminated dredged material from the Duwamish River on an Elliott Bay disposal site was studied. The experimental disposal site had not been utilized in the past for dredged material disposal. A clamshell bucket dredge and two split-hull barges were used for the operation. Dredging began in February 1976 and was completed March 1976. The disposal site was located approximately 800 m from the mouth of the West Duwamish Waterway in 61 to 64 m of water.

A pilot survey was conducted during November and December 1975 to establish the location of the disposal and reference sites and to identify likely animals for later analyses. Sediment and animal samples were collected from stations in Elliott Bay and the Duwamish River. Based on these data and practical considerations, a square disposal site consisting of 16 equal stations and two reference sites consisting of two equal stations each were established.

Sediment, water, and organism samples were collected prior to the disposal operation and at various intervals for a 9-month period following the operation. Observed effects were divided into physical, chemical, and biological.

Physical effects were limited to the immediate area of the dump site. A mound of dredged material approximately 2.0 to 2.5 m high was created near the center of the disposal site which effectively buried the benthic organisms living there. Due to the method of disposal and the depth of the disposal area, water column turbidity was minimal. After disposal ceased, there was some evidence from changes in the distribution of polychlorinated biphenyls (PCB's) in the sediment that the material was spreading outward.

Chemical analyses of water, suspended particulate matter (SPM), and river and disposal site sediments were performed during this investigation. Differences between the dredged material and disposal site sediment revealed the location and movement of the material at the disposal site. Analyses showed that the dredged material contained

substantial levels of PCB's but that release of these contaminants was a highly transient event associated with the temporary increase in SPM during disposal. The contaminated sediments remained within the disposal area during the study period.

Prior to the disposal operation Duwamish River sediments were found to contain higher levels of total sulfide, interstitial water ammonia, and total PCB's and to have lower pH values than Elliott Bay sediments. Analyses of trace metals in the various sediments revealed no major differences before or after dredging and disposal activities. Significant but temporary increases of dissolved Mn, NH_4^+, PO_4, and total PCB's were noted in the water column following each disposal event. These increases were correlated with the short-term elevation of SPM at the disposal site. Chemical effects on the water column were negligible; however, certain parameters, such as total Hg and dissolved Mn and PCB's, exceeded recommended levels. In some cases, background values also exceeded current water quality criteria (see Table 10).

Chemical analyses showed that dredged river sediments contained higher concentrations of oil and grease and PCB's than disposal site sediments. Analyses during the investigation revealed that oil and grease and PCB levels were increased after disposal at the central disposal site stations and that eventually higher oil and grease and PCB levels were noted at the side and corner disposal site stations. There was no evidence that these contaminants increased at the two reference stations or that the impact of the disposal operation extended beyond the designated disposal site.

Biological studies included chemical analyses of local animals for PCB, Hg, and Cr concentrations, trawls for demersal fish and shellfish, and extensive benthic sampling before, during, and after the operation. There was no evidence that fish, shrimp, sea cucumbers, or mussels at the disposal site accumulated Hg or Cr from the dredged material. English sole and shrimp at the disposal site did not concentrate PCB's after the disposal. Mussels held in cages at the disposal site for up to 3 weeks did accumulate PCB's to levels slightly above background; however, the increase was not statistically significant.

Demersal fish and shellfish collections during the study presented highly variable data which were difficult to interpret (see Table 11). Dominant vertebrates were the soles and the shiner perch, while four species of shrimp seemed to be the most dominant invertebrate organisms. Fewer animals were taken at the disposal site during the predisposal period than at either reference site, yet during disposal similar numbers of animals were captured at the disposal site and at the west reference site. Dominant invertebrates at the disposal site increased dramatically from 457 individuals during disposal to 3210 individuals 3 months later. However, 9 months after the operation, in December, only 32 individual dominant invertebrates were found at the disposal site. At the same time, 31 invertebrates were found at the east reference site and 304 at the west reference site. Diversity indices revealed some significant differences between the three areas of Elliott Bay, but again the data were inconclusive. Generally, no adverse effects on these animals due to the dredged material were demonstrated.

Two of the Appendices to this Evaluative Summary (Appendices F and G) report on the benthic communities of the study area. The major effect of the dredged material was primarily physical in nature, and major changes in species composition at the disposal site were apparent, especially at the four central stations. Some species were eliminated from these central stations yet increased in numbers at the corner disposal stations. Other benthic species as well as fish and shrimp recolonized the central disposal stations rapidly. The average number of species at the central disposal stations was 30 before disposal, dropped to 3 by 1 month later, and increased to 25 by 9 months later. Species diversity for the central stations was twice as high 9 months after disposal than before disposal.

Appendix F, "Recolonization of Benthic Macrofauna Over a Deep-Water Disposal Site," discusses the benthic data and the results of the pilot study conducted during November and December 1975. The pilot study data were used to pick the disposal and reference sites and to identify animals which could be used for bioaccumulation studies. Benthic samples from Elliott Bay and the Duwamish River were taken, sediment characteristics described, and important gastropods, pelecypods (bivalves), and polychaetes identified. Individual species found during the course of the investigation at the various sites were analyzed in detail. This Appendix also includes discussion of the ecology of Puget Sound and its fauna. The dominant theme of the discussion is that 9 months after disposal the structure of the biological community at the disposal site had not returned to its predisposal composition. It is suggested by the authors that deepwater, protected habitats "recover" at a slow rate when disturbed.

Appendix G, "Benthic Community Structural Changes Resulting from Dredged Material Disposal, Elliott Bay Disposal Site," provides additional numerical analysis of the data from the benthic work. The data are divided into 5 groups--the 2 reference sites (separately) and the 4 central, 4 corner, and 8 side stations of the 16-station disposal site. Mean number of species, biomass, density, and species diversity were considered for all of the organisms collected. The major groups of organisms were gastropods, bivalves, errant polychaetes, sedentary polychaetes, and miscellaneous species. Some individual species are discussed in Appendix G. The data clearly show the effects of disposal on the central disposal stations while revealing the lack of adverse effects at the margins of the disposal site. In many cases (mean number of species, density, biomass), values for the corner disposal stations were greater than those for the two reference sites. Data from the central stations indicate that even these stations suffered no permanent damage since the mean number of species present climbed from a low of 3 to 25 at 9 months after disposal. Mean density and biomass remained fairly low however at 9 months for the central stations.

This investigation and interpretation of data suffered from the limited time span available, differences in the disposal and reference sites, and lack of sufficient predisposal data. Yet, the contractors and other participants in the investigation were in general agreement that the disposal operation did not increase the concentrations of contaminants in the waters of Elliott Bay or in the tissues of indigenous aquatic animals. The major effect of the operation seems to have been physical and not chemical. The benthic biota of the central disposal stations were depressed, which was expected, yet the available data indicate that a number of species were actively recolonizing the central disposal site within 6 to 9 months after disposal.

PREFACE

This report summarizes the results of a comprehensive investigation of the impact of open-water dredged material disposal by barges in Elliott Bay, a portion of the Puget Sound Estuary, Wash. This investigation was conducted as part of the Dredged Material Research Program (DMRP) which was sponsored by the Office, Chief of Engineers, U. S. Army, and was authorized by Congress in the 1970 River and Harbor Act. The program was a comprehensive nationwide study to provide more definitive information on the environmental impact of dredged material disposal operations and to develop new or improved disposal practices. The DMRP was managed by the Environmental Laboratory (EL) of the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss.

The research reported herein was conducted during the period of November 1975 to December 1976 by the Environmental Protection Agency, Corvallis Environmental Research Laboratory, Corvallis, Oreg., and the National Marine Fisheries Service, Northwest and Alaskan Fisheries Center, Seattle, Wash., under interagency agreements with WES; and by the University of Washington, Department of Oceanography, and Laboratory of Radiation, Seattle, Wash., and Yale University, Department of Geology and Geophysics, New Haven, Conn., under direct contract to WES.

The research was planned and managed by personnel from the Environmental Resources Division of EL. The report was prepared under the general supervision of Dr. John Harrison, Chief, EL. Dr. Robert M. Engler was Project Manager.

Acknowledgement is made to all those individuals who assisted in the conduct of the investigation. The Evaluative Summary was prepared by Mr. Jeffrey H. Johnson and Dr. Henry E. Tatem, EL. Dr. R. N. Dexter and Dr. S. P. Pavlou of the URS Company, Seattle, Wash., summarized the chemical data. Appreciation is extended to personnel of the U. S. Army Engineer District, Seattle, for their participation in the study which included logistic support and completion of the bathymetric surveys.

Directors of WES during the period of the investigation were COL G. H. Hilt, CE, and COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

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NOTE: Appendices A through E and G to this report were reproduced separately (see list of appendices on inside of front cover). Appendix F was reproduced on microfiche and is included in an envelope inside the back cover.

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DUWAMISH WATERWAY DISPOSAL SITE
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PART I: INTRODUCTION

Background

1. The U. S. Army Corps of Engineers has responsibility for the dredging and disposal of approximately 230 million m^3 of sediment annually. Each year about 190 million m^3 of this dredged material is disposed of in open waters of the ocean, estuaries, and inland rivers and lakes.[1] The environmental and engineering problems associated with open-water disposal as well as other aspects of dredging and disposal were investigated in the Dredged Material Research Program (DMRP). The DMRP, initiated in FY 1973 under the River and Harbor Act of 1970 (PL 91-611, Sec. 123), was a four-phase comprehensive program of research and experimentation. Its major objectives were to provide definitive information on the environmental impact of dredged material disposal operations and to develop technically satisfactory, environmentally compatible, and economically feasible dredging and disposal alternatives, including consideration of dredged material as a manageable resource. The planning and implementation of the DMRP were accomplished by an interdisciplinary team from the Environmental Laboratory (EL) of the U. S. Army Engineer Waterways Experiment Station (WES).

2. The aquatic disposal field investigation (ADFI) of the Duwamish Waterway disposal site (located in Elliott Bay) was a part of the Environmental Impacts and Criteria Development Project (EICDP), one of four major research projects within the DMRP. The goal of the ADFI's was to evaluate the ecological effects of open-water disposal of dredged material.

3. The selection of Elliott Bay as the site for an ADFI was made following premature termination of the ADFI at one of the four originally selected coastal area disposal sites, Eatons Neck in Long Island Sound. The selection was made late in the EICDP and thus somewhat limited the study time frame.

4. Following this termination, a survey of potential study sites along the North Atlantic, South Atlantic, South Pacific, and Pacific Northwest coasts was conducted. Potential disposal sites were evaluated on the basis of availability of background ecological data, logistic support for a comprehensive field investigation, and characteristics that represent the major types of open-water disposal activities for these coastal regions. The representative characteristics included sediment type and chemical characteristics of the dredged material, type of substrate in the proposed disposal area, volume of material to be disposed of, frequency of disposal, and depth of water at the disposal site. Based on this evaluation, a portion of Elliott Bay that had no previous history of dredged material disposal was selected.

5. The study site in Elliott Bay was of particular interest because it represented the DMRP's only deepwater estuarine research site where the environmental effects of dredged material disposal by barges (instead of other disposal modes) could be studied. Additionally, recent studies had addressed another factor that made this site important for study purposes--the potentially adverse biological consequences that could result from an accidental spill of 984 ℓ of polychlorinated biphenyls (PCB's) in September 1974 into the Duwamish River where maintenance dredging would be required. It was determined that the PCB's had been adsorbed to a great extent by the sediment in the area of the spill. A joint operation by personnel of the Seattle District of the Corps of Engineers (CE) and the Region X Office of the Environmental Protection Agency (EPA) was conducted to remove the contaminated material. Reports on this operation[2-4] indicate that most of the PCB-contaminated sediment at Slip 1 in the Duwamish Waterway was successfully removed, with a minimum of PCB release to the water column.

Sediment from the immediate spill area had PCB concentrations of over 100 μg/g.[2] Mean concentrations of PCB's in water were found to be 12 to 24 ng/ℓ (parts per trillion) and in suspended particulate matter to be 1.0 to 1.8 μg/g (parts per million).[4] Analyses of Duwamish River sediment samples presented in Appendix E to this report revealed sediment PCB levels as high as 7.0 μg/g. Other considerations which made this study site of particular interest included the potential regional applicability of the Elliott Bay Estuarine study results and the potential for comparison of the effects of the open-water disposal methods employed in Elliott Bay with those of the methods planned for use at a proposed upland disposal project consisting of confining contaminated sediments dredged from the Duwamish River in onshore settling ponds.[4]

6. Until 1975, upland disposal from hydraulic pipeline dredges had been typical for operations on the Duwamish River. Since 1975, clamshell dredging with disposal by barge in open-water areas has constituted the only other method used in this area. Open-water disposal became necessary due to the limited availability and increasing costs of upland sites. Table 1 lists annual dredged material volumes, dredging methods, and disposal locations of sediments removed from the river in years for which records have been kept. Maintenance dredging of approximately 8.2 km of the river is required on a 3- to 4-year frequency. Maintained dimensions of the upper river reach include a width of 46 m and a depth of 5 m; the mouth of the river is dredged to a width of 61 m and a depth of 9 m.

7. Sediment deposited in this 8.2-km river reach is derived principally from natural processes. Much of the dredged material has been characterized as fine, silty sand of a cohesive nature. While some of the material is acknowledged to be acceptable for open-water disposal, most is classified as "polluted" due to the location and industrial uses of the Duwamish River and hence has been deposited in onshore settling ponds.

Table 1

Dredged Material Volumes, Dredging Methods and Disposal Locations for the Duwamish River

Year	Dredged Material Volume m3	Dredging Method	Disposal Location
1951	453,850	Pipeline	Upland areas
1954	338,100	Pipeline	Upland areas
1957	510,050	Pipeline	Upland areas
1960	321,250	Pipeline	Upland areas
1961	131,500	Pipeline	Upland areas
1964	670,900	Pipeline	Upland areas
1968	603,550	Pipeline	Upland areas
1971	248,600	Pipeline	Upland areas
1975	219,350	Clamshell	Open water
1976	259,950	Clamshell	Open water

Purpose

8. The goals of the ADFI were to:

a. Determine the possible release of chemical species, including PCB's, from the dredged material to the water column during disposal operations and following the completion of these operations.

b. Determine the dispersion characteristics of the dredged material and the quantity of suspended sediment released to the water column during disposal operations.

c. Determine the spatial and temporal changes in the physical and chemical characteristics of sediment and water in the study area caused by dredged material disposal.

d. Determine the spatial and temporal effects of dredged material disposal on the composition, abundance, and distribution of benthic and demersal assemblages and the rate and extent of benthic recolonization of the experimental disposal site.

e. Determine if PCB's and selected heavy metals are accumulated by important species of demersal fish and shellfish during and following disposal operations.

Scope of the Investigation

9. The ADFI consisted of a 1-year assessment of the environmental effects associated with open-water disposal of Duwamish River sediments in Elliott Bay. Systematic studies of water and sediment chemistry, dispersion characteristics during disposal operations, benthic and demersal assemblages, and potential uptake of toxicants by selected organisms were initiated in November 1975 and were continued through December 1976. The emphasis of the studies was to evaluate both the short-term environmental effects of the disposal of approximately 114,250 m^3 of dredged material over a 19-day period (17 February-6 March 1976) and the longer term effects through systematic field activities for a 9-month period following completion of disposal operations. Two reference sites were sampled simultaneously with a larger experimental disposal site to separate natural fluctuations in the parameters being measured from effects at the disposal site.

10. Several groups participated in the research; the results of their studies are published in the Appendices to this report, which are bound separately. The EPA Corvallis Environmental Research Laboratory, Corvallis, Oreg., cooperated under an interagency agreement with WES to conduct the water and sediment chemical studies through June 1976. Dr. Donald J. Baumgartner, EPA, was the principal investigator. Dr. Spyros P. Pavlou, Department of Oceanography, University of Washington, Seattle, Wash., was subcontracted with by the EPA to conduct the PCB and oil and grease portions of the chemical studies. Following completion of EPA's involvement in the study, Dr. Pavlou and Dr. William R. Schell, Laboratory of Radiation Ecology, University of Washington, were contracted with by WES to continue the water and sediment chemical studies. Dr. Robert Gordon, Yale University, New Haven, Conn., was the principal investigator for the physical dispersion studies conducted during disposal operations. To aid Yale University in this research, predisposal and postdisposal bathymetry surveys were also conducted by the Seattle District to define the bathymetric changes of the study area.

11. The National Marine Fisheries Service (NMFS), Seattle, Wash., under an interagency agreement with WES, conducted the biological studies. Fish diet studies and spatial and temporal changes in the abundance, distribution, and composition of benthic and demersal assemblages in the study area were investigated by the Northwest and Alaskan Fisheries Center, NMFS. Mr. John R. Hughes was the principal investigator. The Northwest and Alaskan Fisheries Center subcontracted the benthic and fish diet portions of the studies to Messrs. Jack Serwold and Bob Harman, principal investigators, Shoreline Community College, Seattle, Wash. Mr. C. Rex Bingham of the Environmental Resources Division, EL, WES, wrote Appendix G to this report as a supplement to Appendix F which was prepared by Harman and Serwold.

12. The potential uptake of PCB's and selected heavy metals by important species of demersal fin and shellfish during and following the disposal operations was investigated by Dr. Virginia F. Stout and Dr. Fuad M. Teeny, principal investigators, NMFS. Part V of this report contains overviews of the individual Appendices prepared by the researchers mentioned above.

PART II: SUMMARY OF LITERATURE

13. The Appendices prepared by the participating research groups as part of the ADFI cover a wide range of topics from dredging and disposal effects on water chemistry to possible changes in the distribution of benthic and demersal organisms in the study area. Animals captured from Elliott Bay were analyzed for PCB's and selected heavy metals. Each of the Appendices contains a literature section which discusses research pertinent to its subject. Thus, this Part will not attempt to consider all of the literature on the diverse range of subjects investigated but will guide the reader to some important reviews and recent papers. Consequently, the reader should consult the Appendices for detailed reviews.

14. Two recently completed annotated bibliographies are available which directly relate to this ADFI. They summarize both published literature and research in progress and provide supplemental reference lists. The first covers papers concerned with the effects of dredging and disposal on aquatic organisms in the Pacific Northwest.[5] The second bibliography discusses papers relating to the Duwamish River-Elliott Bay complex.[6] This latter work was prepared in conjunction with this ADFI. It presents brief summaries of papers which discuss the physical parameters of the Duwamish River area, the biological communities of the Puget Sound region, the accumulation in and effects on marine organisms of PCB's and heavy metals and the life histories of most of the organisms studied in the ADFI.

15. A report published by EPA[7] includes discussions of dredging equipment and methods and disposal practices and a review of the literature on environmental problems associated with dredging in the Northwest.

16. A number of papers have been published which present data on the biology of Puget Sound or the Duwamish River. Most of these papers are included in the bibliography of Smith and Snyder;[6] however, two deserve special mention here. In the first, a discussion of the benthic fauna of Puget Sound during February and March 1969 is presented by Lie.[8] Organisms and sediment samples were collected from 48 stations.

Animals were identified and counted, and the data were statistically analyzed using factor analysis procedures. Discrete benthic communities were not identified, yet a wealth of information on the benthic animals of Puget Sound is presented. In the second paper, Wellings et al.[9] discuss the incidence of fin erosion disease among two species of fish found in the Duwamish River Estuary. The levels and possible effects of chemical pollutants such as PCB's found in fish exhibiting fin erosion are also discussed.

17. The bibliography of Ellinger and Snyder[5] mentioned previously provides summaries of many dredging studies. However, some additional reports are now available. The April 1976 issue of <u>Environmental Science and Technology</u> contains three articles on dredging and dredged material disposal problems.[10-12] These articles discuss current laws which authorize the CE and EPA to regulate dredging activities. Current research being conducted or administered by the CE is summarized, and future research needs are considered.[12]

18. A report by McCauley, Parr, and Hancock[13] on the effects of a small maintenance dredging operation in Coos Bay, Oreg., is now available. They determined from their data that, in general, many benthic organisms are adapted to the unstable conditions present in maintenance dredging areas. Benthic infauna were found to readjust to predredging conditions within 28 days in the dredged area. Maintenance dredging was termed a relatively normal event for harbor and industrial areas. McCauley, Parr, and Hancock[13] also discuss a number of useful references related to dredging, benthic ecology, and pollution. Rosenberg[14] studied dredging operations in a Swedish estuary where the top layer of sediment was contaminated with mercury (1 to 6 ppm) and PCB's (0.7 to 7.0 ppm). He speculated that recently settled larvae in the dredged area were adversely affected by the increased sediment particles in suspension. The benthic fauna in the dredged area were found to have elevated levels of heavy metals after the dredging operation. The effects lasted approximately 1.5 years.

19. One of the primary reasons that the Duwamish River-Elliott Bay complex was chosen as a research site is the fact that the sediment was

contaminated with PCB's. There have been published reports that marine and estuarine organisms can accumulate PCB's from contaminated sediments.[15] In a recent paper, Pavlou et al.[16] examined the topic of PCB's in the Puget Sound ecosystem. (Pavlou and his associates were involved in the EPA study of the dredging of Slip 1, the site of the PCB spill in 1974.[3]) They presented data on the levels of PCB's in various components of Puget Sound from 1973-1977 and reported on laboratory work on the effects of PCB's on algal growth. As stated previously, they contributed to this ADFI; their results are presented in Appendix E to this report.

PART III: DESCRIPTION OF STUDY AREA

Regional Setting

20. Puget Sound is located in the northwestern part of the State of Washington, extending southward about 145 km from the Strait of Juan de Fuca (Figure 1). The sound is characterized by a number of channels, sounds, and inlets. It is naturally separated from the Strait of Juan de Fuca and is divided into two major basins by two sills. The northern basin reaches a depth of about 250 m and the southern basin about 100 m. The topography of Puget Sound is primarily a result of glaciation, and the surface geology is characterized as glacial tills and moraines with bedrock rarely occurring along the shores. The bottom sediment of Puget Sound is derived from river transport, shore erosion, and erosion of submarine banks. The sediment types are a very soft silty clay on the basin floors, fine sand to gravel on the slopes, and boulders and gravel in the narrows and on the sills where the current is particularly strong. The water in Puget Sound is characterized by small vertical gradients in physical and chemical parameters and small seasonal and annual variations. Cold ocean water entering the Strait of Juan de Fuca as a deep current is thoroughly mixed over the sill between the outer and inner parts of the strait. The mixed water flows as a deep current into Puget Sound through Admiralty Inlet. This water mass is again mixed with less saline waters of the upper strata over the sills in Puget Sound because of the strong tidal currents. The tides in Puget Sound are of a semidiurnal mixed type with large differences between succeeding low tides. The average diurnal tide range is about 3.3 m. The tidal currents are very strong in the sounds and narrows, up to 13 km/hr in the Tacoma Narrows, with the average velocity in the deeper and wider parts of the sound considerably lower. Normally there is a net outflow at the surface and a net inflow in the deeper layers, but occasionally there is a net outflow at all depths. The topography and the strong tidal currents result in a good mixing of the water

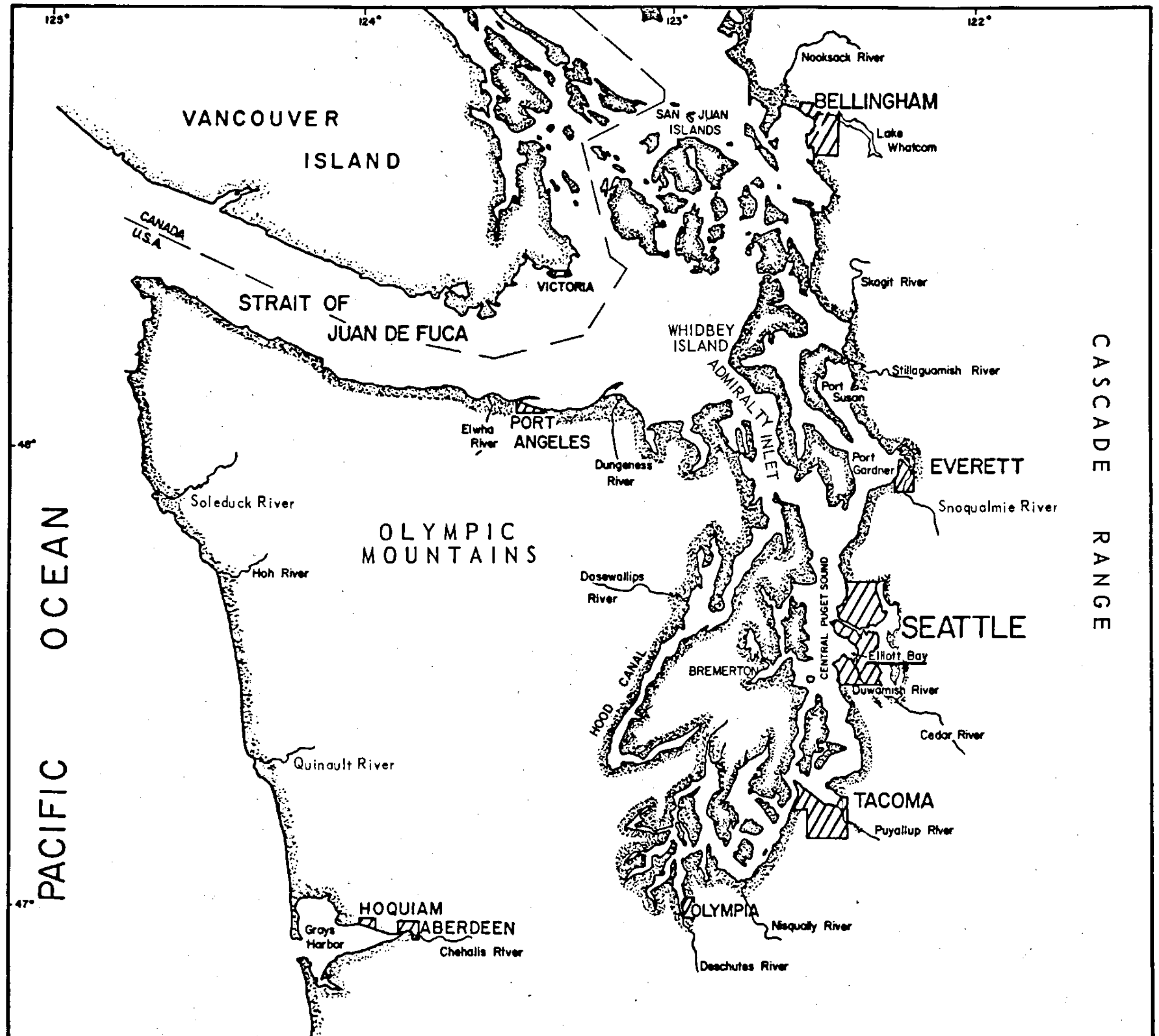

Figure 1. Location map

masses, reflected in the vertical uniformity of hydrographic variables such as temperature, salinity, and oxygen.

21. The climate of the Seattle-Tacoma area is modified by the imposing barrier of the Cascade Range to the east and, to a lesser extent, by the comparatively short Olympic Range to the west and northwest. It is characterized by equable temperatures, a pronounced rainy season, and considerable cloudiness, particularly during the winter months. The Cascades are effective in excluding continental influences from the Seattle-Tacoma area. The prevailing southwesterly circulation keeps the average winter daytime temperatures between 4°C and 10°C and the nighttime temperatures between 0°C and 4°C. Summertime temperatures are moderated by the relative proximity to the ocean. During the summer months, nighttime temperatures range between 10°C and 13°C; afternoon readings vary between 21°C and 26°C. The dry season is centered around July and early August. July is normally the driest month of the year and December the wettest. However, the precipitation is rather evenly distributed through the winter and early spring months. Over 75 percent of the yearly average falls from 1 October-31 March. Since the southern end of the Puget Sound Trough is open to the southwesterly winds generated by the storms moving in off the ocean, the prevailing wind for the 8 months encompassing the storm season is southwesterly. The Puget Sound Trough also is open to the north. Hence, the occasionally severe winter storm that develops to the south or moves inland to the south of the Seattle-Tacoma area will result in strong winds from the northern quarter. Winds are relatively light during the summer months.

Study Area Description

Duwamish River

22. The Duwamish River discharges through two channels--the East and West Duwamish Waterways--into Elliott Bay, a small pocket on the east shore of Puget Sound (Figure 2). The river originates as the Green River in the Cascade Range of western Washington. It flows

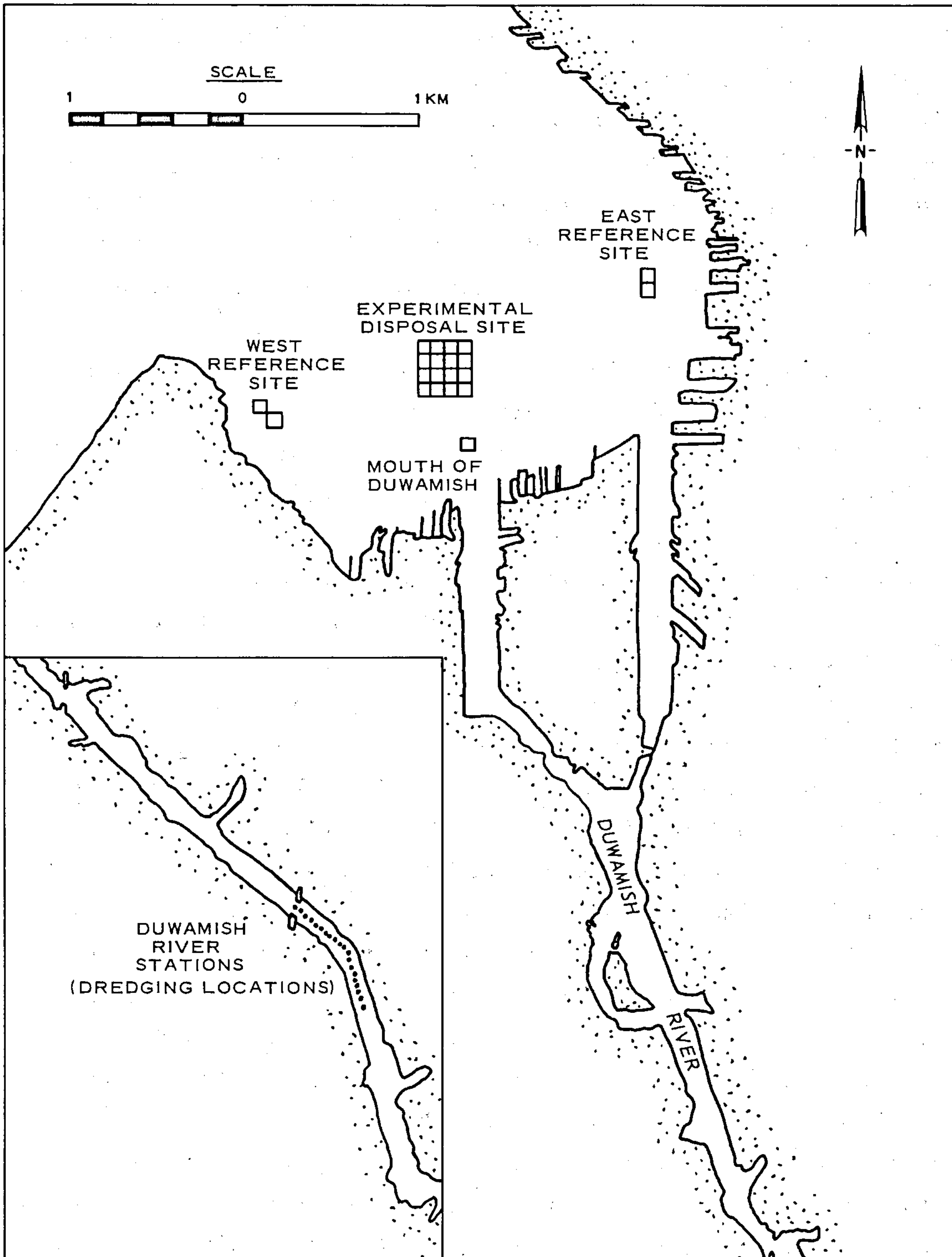

Figure 2. Study area

northwesterly through heavily wooded conifer forests from the Cascade Crest to Eagle Gorge where it is impounded by the Howard A. Hanson Reservoir. This project has been used to control floods in the lower Green River Valley, including Seattle's industrial district along the Duwamish Waterways, since November 1961. After passing through the Hanson reservoir, the Green continues to flow northwesterly through Green River Gorge and the broad, flat Green River Valley to Seattle, where it becomes the Duwamish and discharges into Puget Sound at Elliott Bay. The Duwamish-Green system drains an area of about 1251 km^2.

23. Average annual flow of the Duwamish River at Auburn is approximately 41 m^3/sec. Higher flows, up to 283 m^3/sec, occur during the rainy season, late fall and winter, and the spring snowmelt period. During July, the runoff decreases rapidly, and minimum flows (8 m^3/sec) usually occur in August. Low summer flows are augmented by discharges from Howard A. Hanson Dam, primarily a flood control structure.

24. Tidal effects on river stages can be observed for the entire Duwamish River during high tides. Depending on inflow and tidal stage, some salinity has been noted 16 km above the mouth of the river. The mean tidal range in the Duwamish River is 2.3 m, and the mean diurnal range is 3.4 m. The salinity distribution in the Duwamish Estuary varies vertically and longitudinally with time. Lateral variations are expected to be small for freshwater inflows ranging from 8.5 to 50.1 m^3/sec.[5] The vertical and longitudinal variations of salinity are dependent upon freshwater inflow and tidal stage. U. S. Geological Survey (USGS) data[17] indicate the presence of a saline wedge which is typical of a stratified estuary. Stratification at lower inflows in the lower estuary is not as pronounced as the stratification which exists at all inflows in the upper estuary. The depth of the upper layer of less saline water increases with increasing inflow. An important characteristic of a stratified estuary such as the Duwamish is its circulation pattern. Vertical salinity profiles and dye studies by the USGS indicate that there is very little mixing of the surface fresh water into the saline wedge. Rather, the primary mixing is entrainment of the salt water by the fresh water. This entrainment

causes the net circulation to be upstream in the saline wedge to compensate for the entrained salt water.

25. Very little data on sediment transport conditions for the Green-Duwamish River system are available. The USGS collected suspended sediment data for 3 years and estimated the suspended sediment loads to be 113,400, 340,200, and 51,700 metric tons per water year for the water years 1964, 1965, and 1966, respectively.[17] Yearly suspended sediment loads appeared to vary with peak discharge.

26. The lower reaches of the Duwamish River have been extensively monitored by several investigators to determine water quality conditions. An important characteristic of the Duwamish River which affects water quality is the presence of the saline wedge. The effect of the velocity pattern is that some of the material which is transported downstream in the surface water will sink into the wedge, thereby being transported upstream again along the bottom. As the water in the wedge moves upstream, the dissolved oxygen concentration decreases, while nutrients, biochemical oxygen demand (BOD), and phytoplankton increase. Minimum dissolved oxygen concentrations of less than 3 mg/ℓ occur near the bottom during periods of small tidal changes and low inflow (July-October).

27. Studies of PCB distribution and bioaccumulation within the Duwamish River and Elliott Bay were also conducted following the accidental spill of 984 ℓ of pure Aroclor 1242 (a mixture of predominantly 2-, 3-, and 4-chlorobiphenyls) into the river where maintenance dredging is required. PCB concentrations in water and suspended particulate matter have been measured both in the Duwamish River and open areas of Puget Sound, and, despite cleanup efforts, investigators have concluded that the Duwamish River may be considered a major source of PCB's to Puget Sound.[18]

28. Fishery resources are extremely important to the Duwamish Basin. An average 35,500 adult coho and 14,000 adult chinook migrate through the lower Duwamish annually along with significant numbers of adult chum and pink salmon and searun cutthroat trout. In addition, an average 16,000 (approximately half of the total which migrates upstream) adult winter steelhead are harvested in the Duwamish and Green Rivers

annually. Salmonoid smolts also pass through the lower Duwamish during their spring seaward migration. They take up residence in the saltwater-freshwater interface for a period of time to acclimate to the salt water. Resident fish include sculpins, sole, and sand dab.

29. The Duwamish Estuary and adjacent lands are highly developed for industry and shipping commerce. Commercial waterborne transportation in 1969 consisted of 6,607,514 metric tons of cargo through the East and West Duwamish Waterways. Deep draft commerce occurs in the lower 3.2 km of the river; shallow draft barge traffic and log rafting occur throughout the entire waterway. The present pattern of land use in the area of the Duwamish Waterway ranges from extensive industrial and commercial developments to some areas of sparse residential use. The present zoning of the total 769-ha area is no constraint for further water-oriented industrial development since 91 percent is zoned for industrial activity. The remaining 9 percent is zoned for residential or commercial purposes.

Elliott Bay

30. Elliott Bay forms a small pocket on the east shore of Puget Sound and is bounded by Duwamish Head to the south and Magnolia Bluff to the north. The Duwamish River discharges into the southeast corner of Elliott Bay through the East and West Waterways. Most (about 70 percent) of the Duwamish River flow discharges through the West Waterway. The shoreline along the east bank of the East Waterway and along the east shore of Elliott Bay is indented by numerous slips, which are bounded by piers and terminals.

31. Water circulation in Elliott Bay is controlled primarily by tidal exchange. Tides are of the strongly mixed type with the following characteristics: the mean tide level in Elliott Bay is 2.0 m above mean lower low water; the mean tide is 2.3 m; and the average diurnal tide is 3.4 m. Record high and low tide levels in Elliott Bay are 4.4 and 1.4 m, respectively.

32. Water quality in Elliott Bay is dominated by tidal exchange and tidal currents. Also important, however, are discharges from the Duwamish River and wind effects. Current directions have been observed

to be relatively inconsistent, indicating that complicated current patterns may result from the mixing of the river discharge and tidal currents. Overall, currents tend to be weak and variable in Elliot Bay; consequently, wind may be a factor.[19]

33. Elliott Bay waters are characterized by a two-layer system consisting of a shallow (5- to 15-m-deep), less saline surface layer overriding the deeper, more saline waters of the bay. The less saline surface layer results from precipitation, river discharge, and runoff mixed with seawater and generally flows northward. During the winter months, Puget Sound waters tend toward isothermal conditions. Under these conditions, wind stress, especially in western Washington, may become a significant factor in vertical mixing. Density stratification in Elliott Bay is not well-developed in the winter months. Cold oxygen-rich fresh water enters the bay in winter, entrains deeper, saline waters, and is mixed throughout the water column. In contrast, low summer river flows are warm, relatively low in oxygen content, and tend to stay stratified in a surface layer over the colder Elliott Bay waters.

34. Relatively few intensive investigations have been conducted in Elliott Bay to characterize benthic and demersal fish assemblages. Parametrix, Inc., surveyed the southeast harbor area and the northern shoreline of the bay to identify benthic and fish populations that might be affected by redevelopment alternatives being considered for these areas.[20] Areas sampled in this study were primarily inshore areas of relatively shallow depths. Parametrix investigators noted that "soft mud" was the characteristic substrate type over the major portion of the study areas. Macrofauna of the soft mud bottom was primarily polychaete worms and small bivalve molluscs. Polychaetes were the most abundant organisms collected from both study areas. The pilings and riprap, composed almost exclusively of rock riprap, timber, or concrete, were inhabited by a wide variety of invertebrates requiring a firm substrate. These included the coonstripe shrimp, which is sometimes harvested by sports fisheries in other areas, sponges, hydrozoans, bryozoans, molluscs, crustaceans, and echinoderms. On the basis of 97 benthic samples

collected from inshore and offshore areas in Elliott Bay, Harman and Serwold[21] made several observations relative to benthic assemblages inhabiting the bay and those physical factors that appear to control them. They noted that the Duwamish River's suspended load is deposited primarily in the eastern portion of the bay and that the distribution of polychaetes, pelecypods, gastropods, diatoms, and foraminifer organisms is influenced by this suspended load distribution. The greatest number of polychaete worms were found within the river and eastern portions of Elliott Bay. This area of the bay was also characterized as having reduced numbers of pelecypods and gastropods, which probably reflect greater sedimentation rates in this area due to deposition of the river's suspended load. The greatest number of pelecypods was found near the 91-m depths where correspondingly higher concentrations of wood fragments were also observed. The western portion of Elliott Bay supported more diverse benthic assemblages than the eastern portion.

35. Pelagic and demersal fish populations associated with inshore areas (piers and slips) of Elliott Bay were surveyed by capture techniques that included floating and diving gill nets.[20] The observations indicated that a wide variety of fish utilize the pier and slip areas common to the southeastern shore of the bay. Fish species residing among the pilings and rock riprap of sampled inshore areas were primarily striped perch, shiner perch, staghorn sculpin, dogfish, and blennies. Demersal fish species collected from the sampling stations were dominated by walleye pollock and other members of the cod family. Pelagic herring, anchovy, and, to a lesser extent, salmon were also captured during the study.

PART IV: METHODS AND MATERIALS

36. The ADFI was divided into the five phases briefly described in Table 2.

Table 2

Outline of the ADFI

Phase	Description
I	Pilot survey of general study area to choose one experimental disposal site and two reference sites
II	Collection of predisposal baseline data from sampling stations within the experimental disposal site and the reference sites prior to disposal
III	Monitoring the disposal of sediments dredged from the Duwamish River
IV	Collection of postdisposal data from sampling stations within disposal and reference sites to determine the extent and duration of any effects of disposal on the aquatic ecosystem
V	Analysis and report preparation

37. To give the reader a perspective of this investigation, which was initiated in November 1975 and completed in December 1976, a general discussion of each phase emphasizing the experimental design is provided below. More detailed information related to each contractor's participation during the phases is provided in Appendices A-G.

Phase I: Pilot Survey

38. A pilot survey of the study area was conducted in November and December 1975. During this survey, 55 stations were sampled for biological, chemical, and physical characterizations (Figure 3). Thirteen stations in Elliott Bay were sampled for demersal assemblages. Current direction and velocity were measured from 3 locations throughout the water column at ebb and flood stages. A general bathymetric survey consisting of 14 transects was also completed.

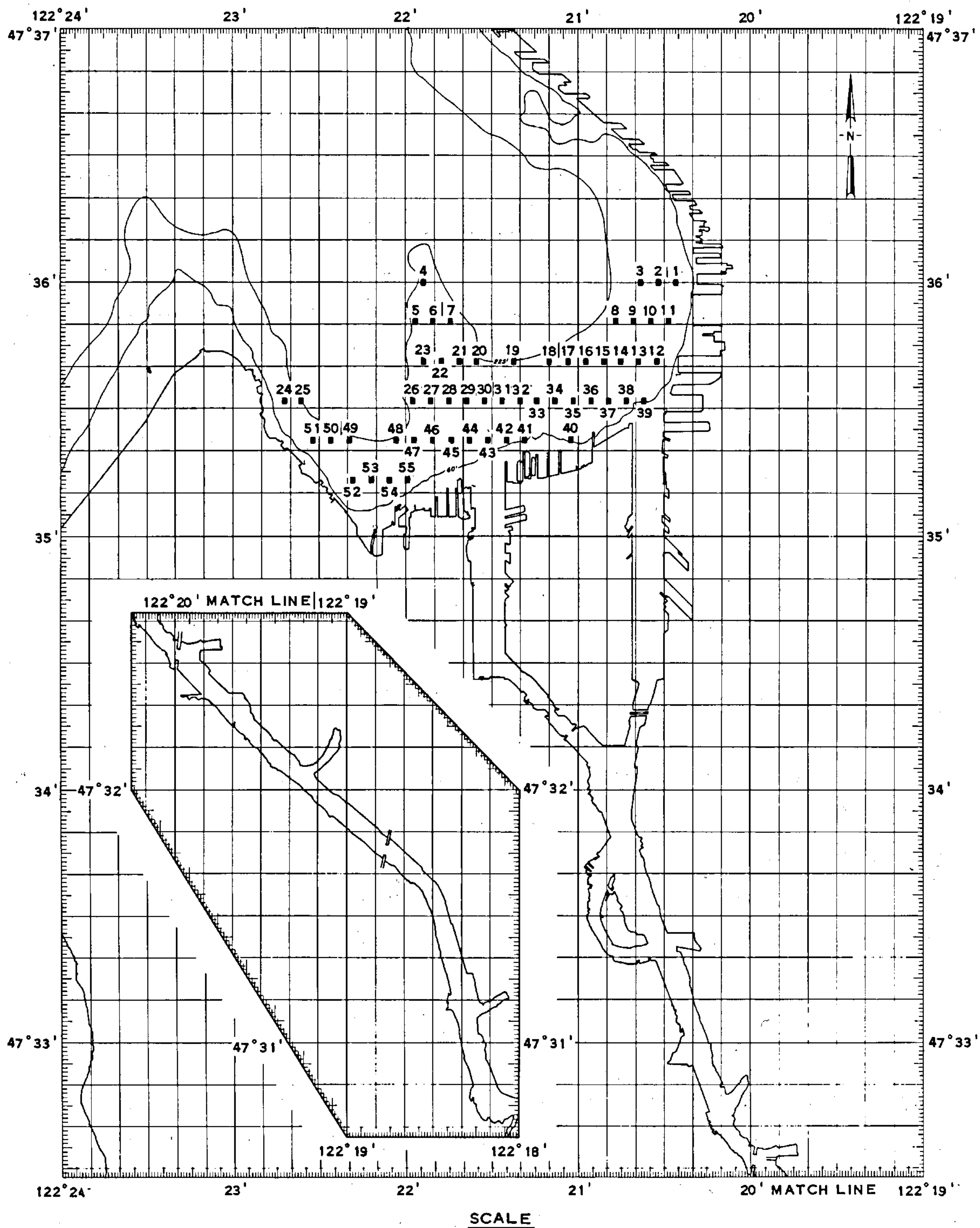

Figure 3. Station locations for benthic, chemical, and physical characterizations during Phase I

39. Data from the pilot survey were used to select the station locations for the experimental disposal site and reference sites in the study area. Site selection was based on the similarity of benthic and demersal assemblages and physical and chemical nature of bottom sediment, prevailing water current patterns, and water column depth. The experimental disposal site, located off Harbor Island near the mouth of the West Waterway, consisted of a 4 by 4 sampling grid of 16 stations (Figure 4). Each station measured 91.4 m on a side, so the 4 by 4 grid area was 365.6 m square. Reference sites were located near the east and west shores of Elliott Bay and consisted of 2 stations each. Since sediment characteristics of the riverbed material to be dredged were likely to differ from sediment characteristics at the experimental disposal site, it was theorized that the selection of two reference sites would allow for one location to serve as a reference for comparison purposes before disposal and the other location to serve as a reference following disposal.

Phase II: Predisposal

40. Predisposal physical, chemical, and biological data were collected in February 1976 from all designated sampling stations within the experimental disposal site and the east and west reference sites. Collection of water chemistry and current data was not included in the predisposal phase. These data were collected in Phase III just prior to the disposal monitoring activities. Replicate sediment samples were analyzed for the elutriate variables listed in Table 3. Accurate station locations were determined utilizing a Del Norte Model 210 Microwave Trisponder positioning system. In addition, Van Veen grabs and core samples were collected at 20 stations from the proposed dredging area of the Duwamish River (Figure 4) in order to characterize the sediment and benthic community structure. Only the upper 10 cm of each core collected from Elliott Bay sampling stations was analyzed during this phase. Based on the chemical characterization of river sediment collected during this phase as well as data provided by EPA, those metals shown in Table 3 were selected for analysis.

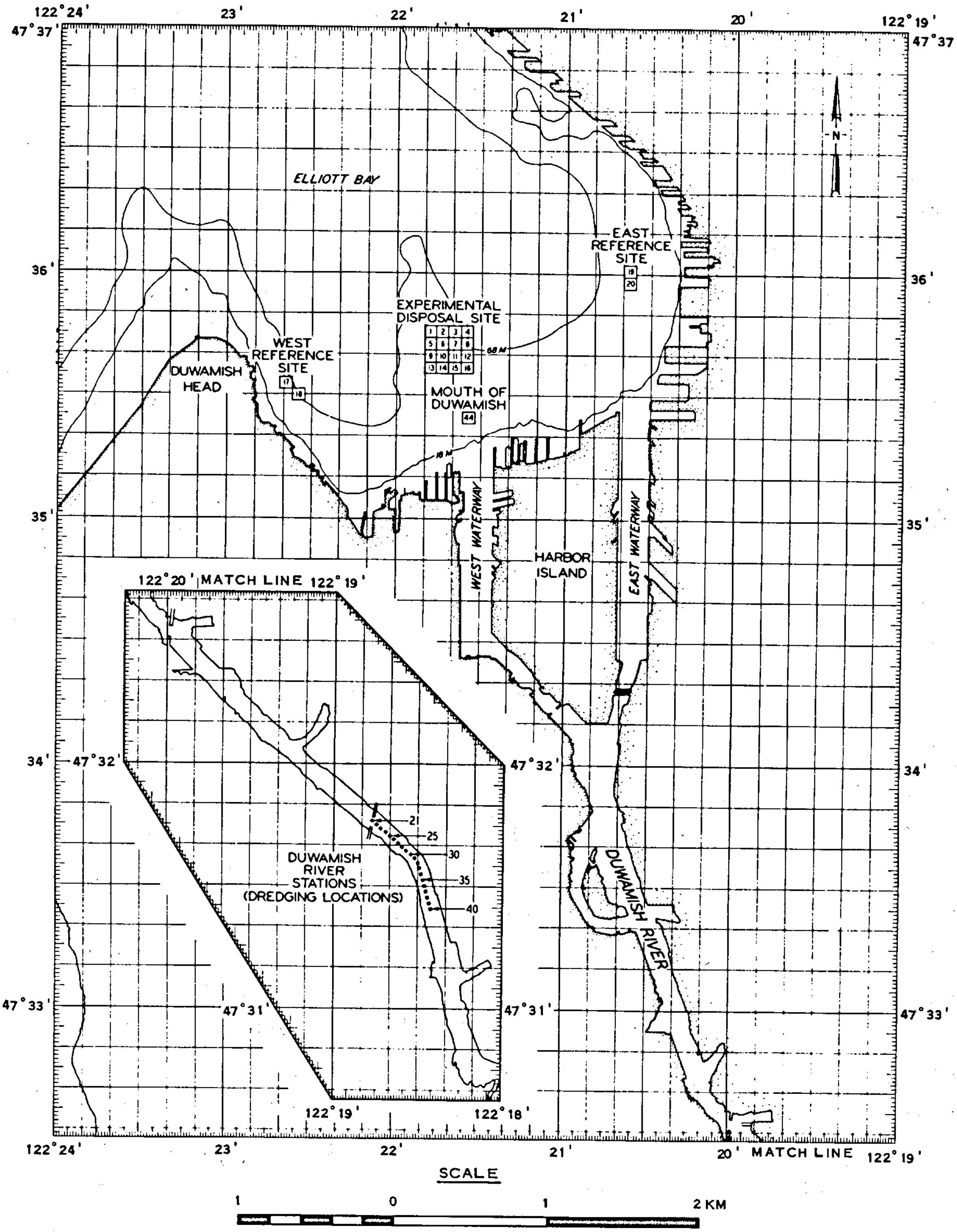

Figure 4. Station locations for the experimental disposal site, west and east reference sites, and Duwamish River

Table 3

Sediment Physicochemical Variables Measured During Phase II

Total (Bulk) Sediment	Interstitial Water	Elutriate
Particle-size distribution	Orthophosphate	Orthophosphate
Percent water	Ammonia-ammonium-N	Ammonia-ammonium-N
Volatile solids	PCB's	PCB's
Total organic carbon	Metals: Mn, Cr, Hg, As	Metals: Mn, Cr, Hg, As
Total sulfides		
Free sulfides		
Eh		
pH		
Oil and grease		
PCB's		
Metals: Mn, Cr, Hg, As		

41. A detailed bathymetric survey, consisting of 41 survey tracks spaced 15.2 m apart, covered an area 609.5 m on a side centered on the experimental disposal site. Nine tracks 91.4 m apart and 1829 m long were run to define the bathymetry outside of the area anticipated to be affected by the disposal activity.

42. Biological characterization of replicate Van Veen grabs included species composition, density, and biomass determinations. Demersal organisms were collected from replicate 5-min trawl samples along with supporting hydrographic data (temperature, dissolved oxygen, salinity) from the experimental disposal site and east and west reference sites. Trawl samples were characterized by number of organisms per unit effort and species composition; length and weight were recorded for seven dominant species of finfish. Diet studies for some of the dominant finfish were attempted.

43. Tissue concentrations of PCB's were determined for replicate samples for English sole and two species of pink shrimp. Concentrations of As, Hg, and Cr in tissues of these same organisms were also determined.

Phase III: Disposal Monitoring

44. Dredging of 114,250 m^3 of sediment from 1.9 km of the Duwamish River began on 17 February 1976 and was completed on 6 March 1976. Discharge was near the center of the experimental disposal site marked by a lighted buoy deployed by the U. S. Coast Guard. All dredging and disposal operations were accomplished using a clamshell dredge and 380- to 535-m^3-capacity barges with bottom-opening doors.

45. Six individual disposal operations were monitored during Phase III, three each on 24 and 26 February 1976. Although dredging-disposal operations began on 17 February 1976, the disposal monitoring efforts were not initiated until 24 February 1976. Each of the six disposal operations consisted of monitoring the release of dredged material from two barges transported in tandem to the experimental disposal site. There was approximately 2-1/2 hours between individual disposal operations.

46. During all monitoring efforts, two boats were anchored down current from the disposal area. Water samples were collected simultaneously from three depths at both boats via a pumping system according to the following frequency: 15 min at time of disposal and 5, 10, 15, 25, 45, 75, and 120 min after disposal. To account for possible changes resulting from river discharge and natural fluctuations, water samples and water column profiles were also taken at a station near the mouth of the river and at both reference sites prior to and following each day's monitoring effort.

47. Samples were analyzed for those water quality variables listed in Table 4. Transmissivity, temperature, pH, dissolved oxygen, and salinity profiles were measured continuously throughout the water column. An exception to the sampling frequency given above was the measurement of PCB levels which followed a sampling frequency of 30 min before disposal, during disposal, and 30, 60, and 120 min after disposal. Additionally, analyses of the short-term fate of dredged material released from the barges, including dispersion and entrainment during descent and the areal distribution of suspended material in near-bottom waters, were undertaken during the disposal phase. These studies were conducted using current meters, a modified transmissometer that also measured temperature and depth, and a 200-kHz fathometer.

48. Bottom trawl samples were also collected from the study sites during the course of the disposal operations to evaluate movements of demersal populations into and out of the disposal site during disposal. To determine the potential biological uptake of PCB's and heavy metals, spot shrimp, a commercially important species, were suspended in cages on the bottom at the experimental disposal site and one reference site during the disposal operations. Analyses of spot shrimp samples for PCB, Cr, Hg, and As concentrations were planned following exposure times of 0, 3, and 6 days; however, due to rough seas, samples exposed during the disposal phase for 6 days were not recovered.

Table 4

Water Quality Variables Measured During Phases III and IV

Temperature	Ammonia-ammonium-N
Turbidity	Nitrate-nitrite-N
Transmissivity	Orthophosphate
Suspended solids	PCB's
Dissolved oxygen	Metals: Mn, Cr, Hg, As
Salinity	
pH	

Phase IV: Postdisposal

49. Several short- and long-term postdisposal studies were initiated to evaluate effects on the biota and water and sediment characteristics. Water column chemical profile measurements were taken at sampling stations located in the experimental disposal site and reference sites and at the mouth of the Duwamish River approximately 24 hours (7 March 1976), 1 week (16 March 1976), 1 month (8 April 1976), 3 months (18 June 1976), 6 months (September 1976), and 9 months (December 1976) following completion of disposal operations.

50. Replicate sediment samples for physical, chemical, and biological analyses to assess recolonization were collected at approximately the same times from 20 stations in Elliott Bay 1 week, 1 month, 3 months, 6 months, and 9 months following disposal. During the postdisposal sampling periods, sediment cores collected from the 16 disposal site stations were sectioned and analyzed in two parts--the upper 10 cm and the remaining lower portion. Cores collected from the reference stations were not sectioned but were analyzed as a whole. To determine the changes in the size and shape of the experimental disposal mound, detailed bathymetric surveys like those described in paragraph 41 were conducted 1 week, 1 month, and 3 months following disposal.

51. Diet studies of dominant demersal fish captured from the experimental disposal site and both reference sites 2 weeks, 1 month, 3 months, 6 months, and 9 months following disposal were conducted in addition to uptake studies of PCB's and metals by English sole, pink shrimp, and other organisms following the same sampling frequency. Unfortunately, because English sole were not captured in sufficient numbers during most of this period, PCB and metal concentration data for this species were limited to those before disposal and 2 weeks after disposal.

52. A special uptake study was conducted immediately following the completion of the disposal operations. Two organisms, a mussel, *Mytilus edulis*, and a sea cucumber, *Parastichopus californicus*, were suspended in cages on the bottom at the experimental disposal site and

the west reference site. Replicate samples of both organisms collected from the cages following exposure times of 0, 7, 14, and 21 days were analyzed for PCB's, Hg, Cr, and As.

Phase V: Analysis and Report Preparation

53. Evaluation continued for 9 months following completion of disposal operations. All Appendices prepared by the various contractors were completed by March 1978.

54. A summary of the sampling schedule for the various biological, physical, and chemical studies conducted in the Duwamish River and Elliott Bay for Phases I-V is provided in Table 5.

55. Numerous contractors participated in the ADFI and, due to the variety of physical, chemical, and biological studies conducted over the testing period, several field procedures and laboratory methods were used to collect and analyze samples. Table 6 summarizes these methods by presenting in tabular form the physical, chemical, and biological study variables, including field procedures and laboratory methods. This Part is not intended to provide a detailed description of these techniques since this information is available in Appendices A-G.

Table 5

Summary of Sampling Schedule, 1975-76

Study Categories	Nov	Dec	Jan	Feb	Disposal Monitoring	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Duwamish River															
Biological															
Benthic				√											
Physical															
Sediments				√											
Chemical															
Sediments				√											
Elliott Bay															
Biological															
Benthic	√					√	√		√			√			√
Demersal	√			√		√	√		√			√			√
Uptake studies															
Field				√	√	√	√		√			√			√
Caged					√	√	√								
Physical															
Sediments	√			√		√	√		√			√			√
Water					√	√	√		√			√			√
Bathymetry				√		√	√	√							
Transmissivity and temperature profiles					√	√	√		√			√			√
Currents	√				√										
Chemical															
Sediments	√			√		√	√		√			√			√
Water					√	√	√		√			√			√
DO, salinity, and pH profiles					√	√	√		√			√			√

Table 6

Procedures Used in the Physical Chemical, and Biological Studies

Variable	Procedure
	Physical Studies
	Field Procedures
Sediment	
Phase I	Subsample Van Veen grab
Phases II, IV	Benthos gravity corer (100 kg)
Currents	
Phase I	Bendix meter
Phase III	Braincon Savonius meter
	General Oceanographic meter
Bathymetry	Raytheon 200-kHz fathometer
Transmissivity	
Phase III	Bendix meter
	Hydroproduct transmissometer
	Transmissometer developed by Yale Univ.
Phase IV	Bendix meter
Temperature	
Phase III	Hydrolab surveyor
Phase IV	Hydrolab surveyor and reversing thermometer
Suspended solids	
Phase III	Pump
Phase IV	Scott Richards bottle and pump
	Laboratory Methods
Particle-size distribution	
Phases I, IV	Sieve and hydrometer
Phase IV	Sieve and pipette
Percent water	Weight loss after drying at 105°C
Suspended solids	Millipore filter (0.45 μm)
	Mettler H54 analytical balance

(Continued)

Table 6 (Continued)

Variable	Procedure
	Chemical Studies
	Field Procedures
Water	
Nutrients	
Phase III	Pump
Phase IV	Scott Richards bottle and pump
PCB's	Stainless steel sampler
Metals	
Phase III	Pump
Phase IV	Scott Richards bottle and pump
Dissolved oxygen	
Phase III	Hydrolab surveyor
Phase IV	Hydrolab surveyor and Scott Richards bottle and pump
Salinity	
Phase III	Hydrolab surveyor
Phase IV	Hydrolab surveyor and Scott Richards bottle and pump
pH	
Phase III	Hydrolab surveyor
Phase IV	Scott Richards bottle and pump
Sediment	
Sediment collection	Benthos gravity corer (100 kg)
	Laboratory Methods
Water	
NH_4^+	Alkaline phenol-hypchlorite, Technicon Auto Analyzer II
NO_2^{-1}-NO_3^{-1}	Cadmium reduction, Technicon Auto Analyzer II
Ortho-PO_4	Ascorbic acid method, Technicon Auto Analyzer II
PCB's	Hexane extraction, gas chromatography
As	
Phases III, IV	Volatile arsine gas generation, atomic absorption spectrophotometry
Phase IV	Fe $(OH)_3$ coprecipitation, neutron activation

(Continued)

Table 6 (Continued)

Variable	Procedure
	Chemical Studies
	Laboratory Methods (Continued)
Water (continued)	
Hg	
Phases III, IV	1 percent HHO_3 and Au stabilization, cold-vapor atomic absorption spectrophotometer, flameless atomic absorption
Cr	Varian CRA-90 carbon rod atomizer, Varian AA-6 atomic absorption spectrophotometer
Mn	Flameless atomic absorption
Dissolved oxygen	
Phase IV	Standard Winkler method
Salinity	Inductive salinometer
pH	Radiometer model p14 meter
Sediment	
PCB's	Acetone extraction, gas chromatography
Total sulfides	Sulfide antioxidant buffer, H_2SO_4, titration
Free sulfides	
Phases II, III, IV	Sulfide antioxidant buffer, H_2SO_4, titration
Phase IV	Orion specific ion electrode chemtrix model 60A pH/pion meter
Eh	Platinum-calomel electrode with Radiometer model 26 readout
Oil and grease	Hexane extraction, weight loss after evaporation and dessication
Total organic carbon	
Phases II, IV	Oceanography International Corp., Model 303 Total Carbon System, Cahn Model 4700 Automatic Electro-balance
Phase IV	Peroxide digestion
Volatile solids	Ashing-gravimetric
pH	Chemtrix model 60A pH/pion meter
As	
Phases II, IV	Freeze-dried, HNO_3 digestion, ARL inductively coupled plasma emission spectrophotometer
Phase IV	Neutron activation
Mn	Flame atomic absorption

(Continued)

Table 6 (Continued)

Variable	Procedure
	Chemical Studies
	Laboratory Methods (Continued)
Interstitial water	
NH_4^+	Same as described under Laboratory Methods for water
NO_2-NO_3	Same as described under Laboratory Methods for water
Ortho-PO_4	Same as described under Laboratory Methods for water
PCB's	Same as described under Laboratory Methods for water
As	Same as described under Laboratory Methods for water
Hg	Same as described under Laboratory Methods for water
Cr	Same as described under Laboratory Methods for water
Mn	Same as described under Laboratory Methods for water
	Biological Studies
	Field Procedures
Macrobenthos	0.1-m^2 Van Veen grab, 1-mm sieve
Demersal shell and finfish	Semiballoon otter trawl
Uptake studies	
Field (Phases II, III, IV) collections of fish and shrimp	Subsampling from semiballoon otter trawl
Caged	
Phase III (spot shrimp)	Subsampling from suspended cages
Phase IV (mussel and sea cucumber)	Subsampling from suspended cages
	Laboratory Methods
Macrobenthos	Sorting, identification, enumeration, and biomass estimates
Demersal shell and finfish	Sorting, identification, enumeration, and length-weight measurements

(Continued)

Table 6 (Concluded)

Variable	Procedure
	Biological Studies
	Laboratory Methods (Continued)
Uptake studies	
Hg	Subsampling
Cr	Subsampling
PCB's	Subsampling, isopropyl/benzene extraction, gas chromatography

PART V: SUMMARY OF FINDINGS

Physical Studies

56. Studies of the physical parameters associated with the disposal of Duwamish River sediment were conducted by Bokuniewicz et al.[22] as a part of another study. A brief discussion of their findings follows.

57. Disposal site observations were made on 24-26 February 1976. Release of the dredged material at the disposal site was observed by a downward-looking echo sounder adjacent to the barge, a setup which allowed the fall velocity of the plume to be determined. The material left the barges as a well-defined slug of sediment and quickly reached a maximum fall velocity as high as 180 cm/sec. The descent of the discrete clumps of dredged material could be seen in the echo sounder records, and their fall velocity could be measured and various sizes inferred.

58. Entrainment of ambient water occurred as the material descended through the water column. This expanded the size of the dredged material cloud and decreased its fall velocity. By the time the cloud reached the bottom, approximately 25 sec had elapsed, and the radius of the cloud was approximately 18 m. A dense surge of material flowed out from the impact point with an initial speed of 36 cm/sec decreasing to 20 cm/sec at 49 m from the impact point.

59. Observations with profiling transmissometers indicated that the thickness of this surge was generally greater than 5 m but less than 20 m and extended for approximately 183 m from the impact point. At the release point, the material settled to the bottom quickly and became undetectable with the transmissometers within 10 min after disposal. Suspended sediment data indicated that, 91 m away from the impact point, the suspended sediment concentration 1 m off the bottom decreased from 94 to 35 mg/ℓ in 30 min.

60. Data from the current meters indicated relatively low fluctuating velocities throughout the water column, with speeds generally

not exceeding 10 cm/sec during the 3-day monitoring period.

61. Analysis of sediment samples collected from various depths within several barges indicated that the dredged material was a moderate to highly plastic, black, sandy organic silt with an average bulk density of 1.6 $g/cm.^3$

62. Of the more than 114,000 m^3 of dredged material reportedly released, volumetric calculations from bathymetric survey data indicated that 41,300 m^3 was on the bottom within the radius of the disposal site. Though there are no data indicating the actual bulk density, water content, or shear strength of the deposit, it is assumed that the mode of disposal effectively compacted the dredged material on the bottom and is the most probable reason why only 36 percent of the reported volume can be accounted for. Suspended sediment concentrations and dispersion monitoring during disposal indicate that the material reached the bottom and was restricted to an area with a maximum radius of approximately 183 m.

Chemical Studies

63. In attempting to interpret the results of the chemical studies performed during this ADFI, three major factors were considered:

a. The Duwamish River-Elliott Bay system is dynamic and complex due to the highly variable riverine and estuarine processes and the proximity to high municipal and industrial activity. Consequently, differences in the values of the various chemical parameters measured were often greater among replicates from the same station than were the differences between the averages of the stations.

b. Some of the parameters, e.g., trace metals and nutrients, were measured by more than one research group. This procedure resulted in inconsistencies in the numerical values reported by the laboratories performing the analyses, reflecting apparent difficulties with sample handling and analytical methodology. Table 7 illustrates this problem. Values available from the open literature have also been included for comparison. Only some of the apparent discrepancies are reasonable even if the high

Table 7

Comparisons of Mean Concentrations of Certain Parameters Reported to be Present in Various Sediments

Parameter	Mean Concentration as Reported in Cited Source					
	Appendix D Vol I*	Lee[23]*	Appendix D Vol II**	Appendix E	Crecelius, Bothner, and Carpenter[24]†	Schell and Nevissi[25]††
Total sulfide, mg/kg	291	250	≈2900‡			
Total arsenic, mg/kg	<23	1.6	13.3		19	
Total cadmium, mg/kg	2.2	<0.5				
Total chromium, mg/kg	69	15	73		70	60
Total iron, mg/kg	40,000	15,850			38,200	
Total mercury, mg/kg	16.4	0.064	0.126		0.5	0.5
Total manganese, mg/kg	505	540	267			
Total lead, mg/kg	76	19				
Total PCB's, mg/kg		0.41		2.05*		
Oil and grease, mg/kg		702		920*		
Total organic carbon, g/kg	27	36		32**		

* Mean values for sediments from Duwamish River dredging locations.
** Mean values from central disposal mound in September 1976.
† Values from a single station at the mouth of the West Duwamish Waterway.
†† Values from a single station in Central Puget Sound near the West Point sewage outfall, Seattle, Wash.
‡ Reported as 1466 mg/kg on a wet weight basis; converted to approximate dry weight by assuming 50 percent water.

variability of these parameters in the sediments is considered. Given this type of disagreement in the reported values, any conclusions as to whether the sediments are "polluted" or attempts to estimate toxic effects are not warranted, and sediment pollution potential cannot be estimated through chemical analyses. Furthermore, further inspection of Table 7 shows considerable disagreement in the concentrations of sulfide, total mercury, and total manganese. Under these conditions, it is difficult to estimate temporal trends for these sediment parameters over the extent of the ADFI.

c. Some of the data are not supported by reasonable physical or chemical explanation. For example, Eh values in the postdisposal sediments were reported to become more oxidizing with time, eventually becoming positive at many stations. Over the same time period, the levels of sulfide also increased, suggesting a less oxidizing environment. Similarly, total sediment mercury concentrations were reported to decrease markedly after disposal, but there was no increase in the water column nor was there a similar decrease in any other trace metal.

64. While a concerted effort has been made to account for these problems in interpreting the data, it is recommended that these factors be kept in mind during the discussion that follows.

65. Details of the results discussed in this section are included in the Appendices and in a related report.[23] Appendix D, Volume I, contains most of the water column and sediment physical and chemical parameters for the predisposal and disposal periods and the first 3 months of the postdisposal period. The rest of these data (for the 6- and 9-month cruises) are presented in Appendix D, Volume II. All PCB and oil and grease data are presented in Appendix E.

Predisposal characterization of the dredged sediment

66. The physical and chemical characteristics of the study sites prior to dredging and disposal are summarized in Table 8. These data are presented in detail in Appendices D, Volume I, and E.

67. Only a few parameters showed significant differences between sites. In general, the data indicate that the river sediments were the most contaminated, as shown by the significantly higher levels of

Table 8

Statistical Comparisons of Mean Concentrations of Sediment Chemical Parameters Prior to Disposal

Parameter	Mean Concentration: River Site (R)	Disposal Site (D)	W. Reference Site (W)	E. Reference Site (E)	Statistical Significance for Cited Comparison*: R/D	R/W	R/E	D/W	D/E	W/E
Bulk Constituents										
Grain Size	3.96	3.25	4.19	4.27	ND	ND	ND	ND	ND	ND
pH	6.99	7.63	7.54	7.35	+	+	+	-	-	-
Total sulfide, mg/kg	291	40	16	18	+	+	+	-	-	-
Total arsenic, mg/kg	<23.9	<47.0	<19.8	<28.0	-	-	-	-	-	-
Total cadmium, mg/kg	2.2	4.7	0.3	2.3	-	-	-	-	-	-
Total chromium, mg/kg	69	53	82	68	-	-	-	-	-	-
Total iron, mg/kg	40,000	35,400	25,900	29,000	-	+	+	-	-	-
Total mercury, mg/kg	16.4	6	0.24	4.4	-	+	-	+	-	+
Total manganese, mg/kg	505	452	434	425	-	-	-	-	-	-
Total palladium, mg/kg	76	100	66	151	-	-	-	-	-	-
Total organic carbon, g/kg	26.8	16.8	12.0	23.4	-	+	-	-	-	-
Oil and grease, g/kg	0.92	0.61	0.53	1.07	-	+	-	-	+	+
Total PCB's, mg/kg	2.05	0.25	0.06	0.31	+	+	+	+	-	+
Interstitial Water										
Dissolved arsenic, mg/ℓ	19	15	22	18	-	-	-	-	-	-
Dissolved cadmium, mg/ℓ	0.83	1.1	0.87	2.4	-	-	-	-	-	-
Dissolved chromium, mg/ℓ	7	14	10	3	-	-	-	+	-	+
Dissolved mercury, mg/ℓ	6.8	12.2	8.5	0.67	+	-	+	-	+	+
Dissolved palladium, mg/ℓ	6.0	25	4.0	5.0	+	-	-	+	+	-
Dissolved iron, mg/ℓ	4.9	0.73	0.72	0.23	+	+	+	-	-	-
Dissolved manganese, mg/ℓ	2.6	1.2	0.56	0.67	+	+	+	-	-	-
Dissolved NH_4^+, mg/ℓ	16.3	2.16	1.99	1.29	+	+	+	-	-	-
Dissolved orthophosphate, mg/ℓ	0.24	0.26	0.20	0.88	-	-	-	-	-	-
Dissolved PCB's, ng/ℓ	155**	123	47	161	-	-	-	-	-	-

* The + sign indicated that mean values were significantly different ($\alpha = 0.05$); the - sign indicates that mean values were not significantly different. ND denotes not determined.

** Mean value from the central disposal mound immediately after disposal.

total sulfide, interstitial ammonia, and total PCB's. These sediments also had high concentrations of dissolved iron and manganese in the interstitial water. The PCB's were relatively enriched in lower chlorinated biphenyls compared to those measured in the bay. The qualitative difference does not seem as ecologically significant as the elevated levels, yet it provides a good means of tracing the riverine sediments.

68. Within sites in Elliott Bay, differences in levels of chemical constitutents were relatively small; however, they indicate that the east reference site, which is closest to the Seattle waterfront, had been receiving the greatest contaminant input, while the west area, site A, had been least impacted. An observed east to west gradient was indicated for a number of bulk sediment parameters but was only significant for oil and grease, PCB's, and Hg.

69. Relatively high levels of dissolved Cd, Pb, and Hg were reported in the interstitial water of predisposal sediments collected at the disposal site. The significance of their magnitude for impact assessment cannot be determined at this point.

70. In summary, parameter concentrations were relatively homogeneous between all sites prior to the dredging and disposal operations. Only the bulk sediment values for sulfide and PCB's and interstitial water concentrations of NH_4^+, dissolved Fe, and dissolved Mn were significantly greater in the river sediments. The mean river sediment pH value was lower than any of those determined for sites within the bay.

Elutriate test results

71. The results of the elutriate tests performed on the sediment from the dredging locations are summarized in Table 9. It could be predicted that some release of Fe, NH_4^+, Mn, and PCB's should occur during dredging and disposal of these sediments, with negligible release of the other trace constituents.

72. Considering the nature of these anoxic sediments, it would be expected that an elutriate test performed under anoxic conditions would show significant releases of Fe, Mn, NH_4^+, and possibly PO_4.

Table 9

Comparisons of Results of Elutriate Tests
Performed on Sediment from the Dredging Locations

	Concentration as Reported in Cited Source			
Parameter	Appendix D Vol II	Lee[23]*	Lee[23]**	Appendix E
Dissolved arsenic, μg/ℓ	7.2/4.2	<2/<2	NM	NM
Dissolved cadmium, μg/ℓ	0.7/0.4	0.8/1.8	6.1/3.1	NM
Dissolved copper, μg/ℓ	3.5/3	<2/<2	<2/<2	NM
Dissolved iron, μg/ℓ	317/30	15,000/12	22,000/12	NM
Dissolved mercury, μg/ℓ	<1/<1	0.05/0.06	0.1/0.06	NM
Dissolved manganese, μg/ℓ	990/10	90/143	6,700/40	NM
Dissolved palladium, μg/ℓ	2/2	1.1/1.5	24/48	NM
NH_4^+, mg/ℓ	5.7/0.07	4/<0.05	4.8/0.13	NM
$NO_3^{-1} + NO_2^{-1}$, mg/ℓ	0.5/0.43	0.3/0.3	NM	NM
PO_4, mg/ℓ	0.02/0.076	0.30/0.08	NM	NM
PCB's, ng/ℓ		33/12	NM	86/4

* Average of three sediments, each tested in duplicate.

** Average of replicate tests on a single sediment, performed under oxic conditions. A replicate test of that reported in the previous column was performed for bioassay purposes.

Note: Results shown are elutriate water concentration/initial concentration in the dilution water. NM denotes not measured.

However, the two sets of data (Appendix D, Volume I, and Lee[23]) shown in Table 9 are not in total agreement even with this supposition. Both agree regarding the release of NH_4^+. Both indicate a release of Fe but disagree as to magnitude. Sediments from different locations within the site were sampled and the results represent sample heterogeneity. The expected release of Mn was reported in Appendix D, Volume I; however, Lee[23] at one point indicated that an uptake of Mn occurred during the elutriate test. Conversely, Appendix D, Volume I, reported a slight uptake of soluble PO_4, while Lee[23] indicated a significant release. These disparities may have resulted from sample variability, lab error, or a combination of both; however, the release trends for predictive purposes were identified.

<u>Disposal monitoring</u>

73. The impact of the disposal operation on the chemistry of the water column at the disposal site is consistent with the physical dispersion studies summarized in other sections of this report. Major pertubations to the water column were observed for NH_4^+, dissolved Mn, pH, and PCB's. In general, the pulses coincided with the opening of the barge and correlated well with the concentration-time profile of the suspended solids. Near predump conditions were usually attained within 10 min of disposal. Typical plots of concentration-time profiles for a number of parameters observed in deepwater samples over one dump episode are shown in Figure 5. Results were similar at both sampling stations. As would be expected, the "spikes" generally reached higher concentrations at the disposal site.

74. Of those metals analyzed in the predisposal period, only As, Cr, Hg, and Mn, due to their potential toxicity and elevated sediment levels, warranted further study. Water column arsenic concentrations were always less than the detection limit of the technique employed (<4 μg/ℓ). Transient increases in the concentration of dissolved Cr (as great as ≈ 8 μg/ℓ) were noted, but they were never associated with the disposal events. These "spikes" probably originate from natural and analytical variability. Similarly, intense but short-term increases in total Hg in the water column were observed, usually in the deeper layers

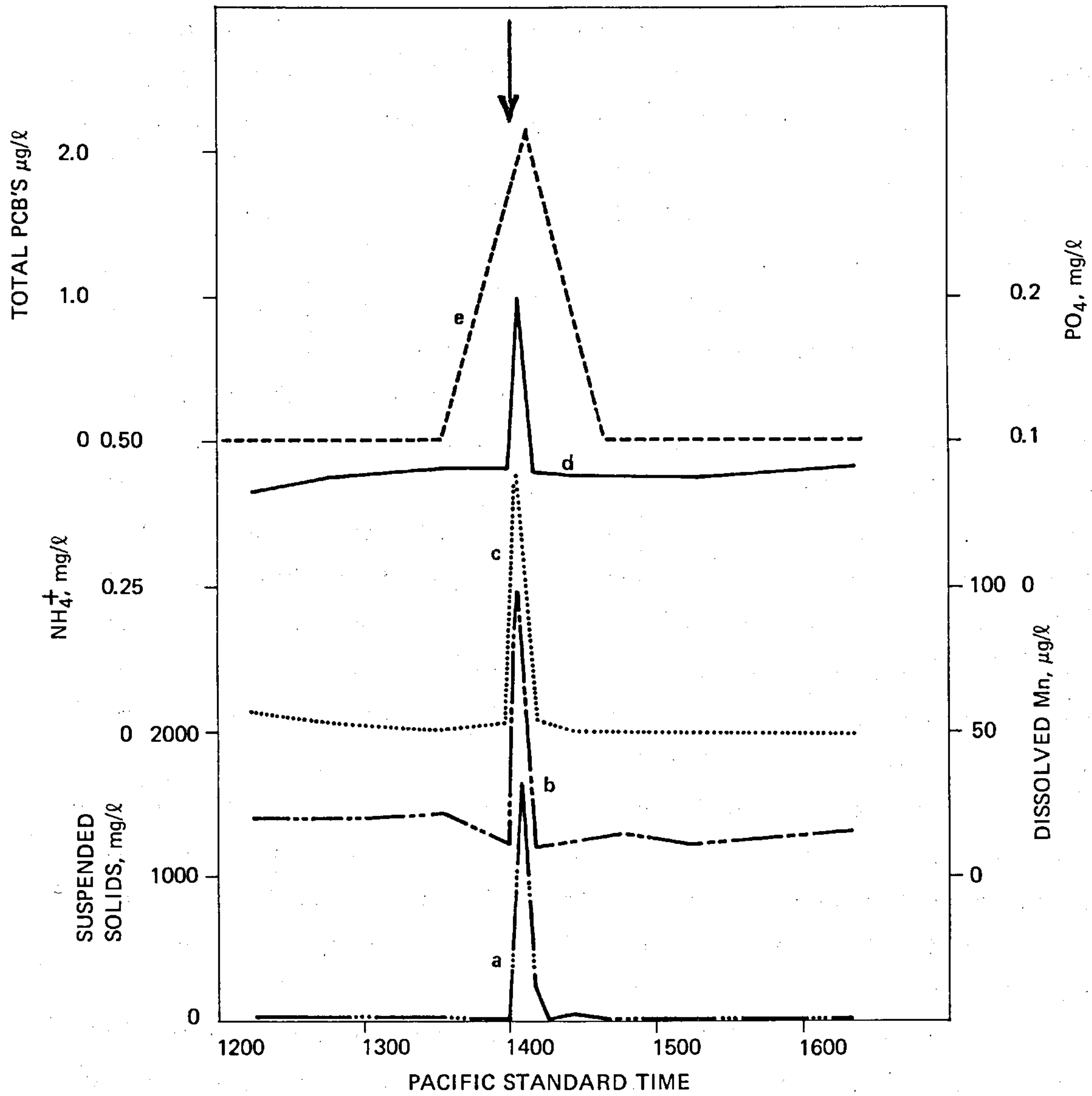

Figure 5. Plots of variation in the concentrations of a number of parameters as a function of time observed in deepwater samples for a disposal episode at approximately 1400 hours (arrow), 26 February 1976

and occurring in most cases shortly after a dump. However, problems with the Hg data should be noted: (a) many of the elevated levels occurred at times when no increases were seen in any other parameter, and (b) the concentrations observed during a number of these "spikes" (as high as 20 μg/ℓ) were greater than can be reasonably explained from any measured source (e.g., the highest interstitial water value reported was only 1.1 μg/ℓ), especially considering the low levels of suspended solids accompanying these spikes. These "spikes" then result as unexplainable anomalies.

75. Significant but transient increases in the concentration of dissolved Mn were observed in the bottom layer sampled. In all cases, release occurred simultaneously with an increase in the level of suspended solids. A similar behavior was observed in the concentrations of NH_4^+. Fluctuations in surface values were also noted, indicating both release and uptake of NH_4^+ associated with the disposal. However, since surface NH_4^+ levels are generally higher than those in deeper water, the apparent decrease in NH_4^+ concentrations may simply reflect intrusions of subsurface water induced by the movement of the barge and the disposal itself. In general, these fluctuations were small (changes of less than 0.05 mg/ℓ).

76. An increase in dissolved ortho-PO_4 concentrations apparently occurred simultaneously with the NH_4^+ releases. This is reasonable considering the anoxic nature of the sediments. Lee[23] projected release while Appendix D, Volume I, showed no phosphate release in the elutriate.

77. An inverse relationship was noted between suspended solids concentrations and the pH values. Variations of approximately ± 0.2 pH units were observed in the surface and near-bottom waters, most likely reflecting natural and analytical variability. Changes observed in deeper water were greater. A decrease as great as 0.7 pH units to a pH of 7.2 was noted for one disposal episode (day 57, third disposal) associated with the maximum increase in suspended solids.

78. Increased levels of PCB's were observed at all depths in the water column immediately after the disposal episodes. In all cases,

these increases were associated with increased suspended solids, and there was no direct evidence for major increases in dissolved PCB's. As with the other parameters, the pulse was transient, with concentrations decreasing to background levels within a few minutes (Appendix E). It should be noted, however, that in both monitoring periods there was a general trend toward increasing PCB concentrations in the water column at all depths. In addition, an increase of approximately 5 ng/ℓ in total PCB's was observed for all reference sites between predisposal and postdisposal samplings. This indicates that a release of PCB's did occur but was rapidly dispersed throughout Elliott Bay.

79. To estimate the degree of impact of the disposal operation, a comparison was made between the maximum concentrations of the chemical constituents measured and the corresponding EPA criteria levels for these species in water. These data are presented in Table 10 together with the average and maximum "background" concentrations observed at the reference stations during the days of the disposal operations.

80. The maximum concentrations observed for dissolved As and Cu and NH_4^+, ortho-PO_4, and dissolved oxygen (minimum) did not exceed the criteria levels and generally were not much greater than the fluctuations which apparently occurred naturally during the monitoring period. Although on occasion concentrations of total Hg in the water column greatly exceeded permissible levels, the values are suspect, as noted earlier.

81. The maximum values observed for both dissolved Mn and pH exceeded their corresponding criteria levels. However, even if a "worst case" estimate is made that these magnitudes were in fact achieved during all dumping episodes but were not observed due to the limitations of the sampling procedure, the cumulative perturbation would be minor, as compared to that possible from exposure of the entire sediment material, and would be insufficient to cause an increase in concentrations approaching the criteria levels except within a highly localized zone of direct impact.

Table 10

Comparisons of EPA Recommended Criteria[26] Levels for Water to Maximum Concentrations Observed in the Water Column During the Disposal Monitoring Period

Parameter	Criteria Level[26]	Maximum Value Observed*	Background Level**	
			Average	Maximum
Dissolved arsenic, µg/ℓ	ND	9	<4	9
Dissolved copper, µg/ℓ	100	19	2	9
Total mercury, µg/ℓ	0.1	20	<1	1.8
Dissolved manganese, µg/ℓ	100	105	12	39
NH_4^+, mg/ℓ	≈ 1	0.425	0.01	0.220
Ortho-PO_4, mg/ℓ	ND	0.200	0.07	0.095
pH, mg/ℓ	6.5-8.5; $\Delta<0.2$	7.09; $\Delta\approx0.7$†	7.8	7.47†
PCB's, ng/ℓ	1	3229	3	46
DO, mg/ℓ	>5.0	6.2†	9.0	8.0†

Note: ND denotes no data.

* The greatest single value observed in any water column sample from the disposal site.

** The background levels refer to the concentrations observed at all locations and depths before and after the disposal episodes. The maximum level is the greatest single value observed in any of these samples.

† Minimum values of pH and dissolved oxygen are presented, together with the approximate maximum change (Δ) in the pH levels.

82. The release of PCB's during the disposal operation appeared to be significant, and measurable increases throughout Elliott Bay were observed. However, the amount released was small compared to the total available in the contaminated sediments. The environmental implications of this release cannot be addressed since the background levels already exceeded the EPA criteria level established for these compounds, and the changes were never more than small multiples of the background conditions, except in very transient pulses associated with the dumping episodes.

83. In conclusion the data indicate that, while perturbations in dissolved Mn, NH_4, pH, DO, and PCB's were observed, neither the concentrations nor their persistence was sufficient to be of significant environmental concern.

Postdisposal monitoring

84. Water column chemistry. Hydrographic measurements during the last five cruises showed the normal seasonal variations. Low temperatures with predominantly salinity-induced stratification of the water column were noted both in the spring and late fall. During the summer, strong salinity gradients were absent, in part due to the low precipitation and low river discharge of 1976, and stability was primarily a function of the temperature gradient. Mean water column temperatures ranged from about $8^{\circ}C$ in the spring and late fall to about $12^{\circ}C$ in the late summer. Mean salinities increased throughout the year from about 28.6 to 31.1 ppt. Dissolved oxygen concentrations were normal, showing higher levels at the surface (generally about 80 percent to 90 percent of saturation) and decreasing with depth (to about 60 percent of saturation near the bottom). The water column below 20 m was nearly homogeneous in all parameters for all stations in Elliott Bay and showed no impact of the disposal site. More variability was noted in the surface layer (0 to 5 m), reflecting the variations in the freshwater input from the Duwamish River as influenced by discharge rate, tidal stage, and wind stress.

85. No significant temporal or spatial differences, attributable to the impact of the disposal operation, were observed in the water

column for suspended solids, pH, total Hg, dissolved As, Cr, NH_4^+, NO_3^{-1} and NO_2^{-1}, or ortho-PO_4. Dissolved Mn and total PCB's, for which a relatively large release was observed during the disposal operations, increased immediately (24 to 48 hours) after the cessation of dumping to higher levels than were noted during and before the disposal monitoring. Their concentrations decreased markedly by 1 week later to near "normal" values. PCB concentrations decreased with time and Mn levels increased slightly; however, these changes were not significant.

86. Temporal changes in the concentrations of NO_3^{-1}, NO_2^{-1}, and ortho-PO_4 were noted but can be explained by normal variations in biological activity. The levels of both parameters decreased approximately 30 percent during the summer and increased again in December.

87. Some spatial differences were also noted, but, with the exception of elevated suspended solids near the bottom at the disposal site (3 months after disposal), none of these appeared to be influenced by the disposal mound. NH_4^+, PCB, and Mn concentrations were higher but variable in the surface water, probably reflecting the influence of the Duwamish River discharge. These differences generally were not significant and were most likely due to the natural variations of this dynamic system.

88. Sediment chemistry. The results obtained from monitoring the physical and chemical characteristics of the sediments agree, in general, with the behavior demonstrated in the physical studies and what would be anticipated from the deposition of a cohesive mass of sediment centered around the disposal buoy. Considering the minimal reworking and mixing with site water which occurred during disposal, it is not surprising that the bulk sediment texture and chemistry of the disposal mound were essentially identical with the predisposal characteristics of the riverine sediments. This similarity extended to the deepest sediments collected from the central disposal stations, but was limited to the upper 10 cm of sediment at the side and corner stations. No impact was observed in either of the reference sites.

89. The resulting decrease in average grain size at the disposal site as compared to predisposal conditions may suggest long-term

instability of the mound. However, no change in texture was noted during the 9-month monitoring period. Since no significant differences in the trace metals were observed between the sites and the river sediments prior to dredging, it is not surprising that none were observed after disposal. No temporal changes were noted in the concentrations of As and Cu. Appendix D, Volume II, reported increases in Mn and Hg from September to December at the disposal site. This result may be statistically justified; however, as shown in Table 7, any conclusions based on an analysis of these parameters would be questionable. In addition, it is difficult to rationalize the mechanism of uptake at depths greater than 10 cm in the sediment, particularly in light of the interstitial water chemistry (discussed below) which indicates mobilization of Mn with time.

90. Therefore, it appears reasonable to conclude that no major alteration of the sediment of Elliott Bay attributable to trace metal contamination occurred as a result of disposal. No temporal changes in bulk metal concentrations could be established, particularly in view of the difficulties in interpreting the large dissimilarities between the data presented by the two groups responsible for these analyses (Volumes I and II of Appendix D).

91. Following disposal, the sediment at the disposal site apparently approximated predisposal conditions in pH levels and in the concentrations of dissolved As, Cr, and Mn. The dissolved Hg values are unreliable. For dissolved As and Cr, no temporal changes occurred. The dissolved Mn values were greater after disposal (approximately a fourfold increase), consistent with the decrease in pH from about 7.5 to 7.0. No major temporal changes could be established in part due to the problem of variations between laboratories.

92. The concentrations of both soluble sulfide and NH_4^+ increased at the disposal site, but sulfide did not reach the levels which were observed in the river prior to dredging. The increases for both species in the corner and side stations were not as great as in the center and in fact were not significant for NH_4^+. Sulfide levels increased slightly by June at all disposal site stations (to about

120 to 150 mg/ℓ) and at the east reference site (to about 70 mg/ℓ). NH_4^+ levels were generally stable at about 1 to 5 mg/ℓ at all stations except the central stations. In the latter area, initial values of 26 mg/ℓ decreased to about 15 mg/ℓ by June. For both parameters, major inconsistencies in the levels reported by the two laboratories rendered the data from the last two cruises (6 months and 9 months after disposal) uninterpretable.

93. Total organic carbon. Considerable variability was observed in the concentrations of total organic carbon at all disposal site stations and the east reference station. For example, mean values at the central stations ranged from about 32 to 20 g/kg during the post-disposal period. This large variability prevented the delineation of significant spatial and temporal trends. The general characteristics, however, were similar to the trends in the other parameters. The total organic carbon concentrations at the central stations of the disposal site increased following disposal, while no major changes were noted at the corner, side, or reference stations. No temporal changes at any of the stations could be discerned during the postdisposal period.

94. Oil and grease. The distribution of oil and grease in the sediment was very similar to that of total organic carbon. Prior to dredging, the east reference site had significantly greater oil and grease levels than either the disposal site or the west reference site. After disposal, oil and grease concentrations approximately tripled at the central stations to 1.5 g/kg. The corner and side stations continued to increase in oil and grease concentrations during the course of the study. By the third month, the concentrations of oil and grease were not significantly different at any of the disposal stations or at the east reference station. All these stations had significantly greater levels than the west reference station. No temporal changes were noted at either reference station.

95. PCB's. Prior to disposal, the distribution of PCB's in Elliott Bay sediment was very similar to that of total organic carbon. The disposal site was similar to the east reference site, both having significantly greater concentrations than the west reference site.

Immediately after disposal, the PCB concentrations at all of the disposal stations increased significantly.

96. The increased PCB concentrations immediately after disposal showed quite clearly the radial distribution of riverine sediments around the disposal buoy, particularly when only the concentrations of the trichlorobiphenyl (relatively enriched in the riverine sediments) were considered. The concentrations were significantly different among the disposal stations and in the order central > side > corner.

97. Interestingly, the PCB concentrations in the corner and side stations increased during the course of the study. By the third month, differences in the PCB concentrations within the disposal site could not be distinguished. No temporal changes were noted in the levels at either reference station.

98. The data for sediment deeper than 10 cm show similar behavior. Increased PCB levels were noted immediately after disposal only at the center station, to levels comparable with those of the upper 10 cm. Neither the side nor the corner stations showed any increase. However, both these areas increased in PCB levels during the remainder of the study. After 6 months, the side stations depicted PCB concentrations significantly greater than for predisposal conditions. A similar behavior was observed at 9 months for the corner stations.

<u>Summary</u>

99. The barged disposal of the rather cohesive sediments dredged from the Duwamish River produced minimal and highly localized impacts. The disposal operation itself resulted in very transient increases in the levels of suspended solids, dissolved Mn, and total PCB's and coincident decreases in pH and dissolved oxygen. Only the potential impact of the increased PCB loading of the water column would seem to warrant a potential ecological concern, since the toxicological data required to evaluate biological consequences are not available at present.

100. Within the area of the bottom impacted by the dredged material, the observed changes consisted of a slight decrease in sediment

grain size, a decrease in pH, and elevated levels of NH_4^+, soluble sulfide, dissolved Mn, and PCB's. These changes extended over the entire disposal site for sediment texture, pH, sulfide, and PCB's. NH_4^+ was elevated primarily in the central stations, the zone of primary impact. While these alterations were not negligible from a chemical point of view, the supporting data are insufficient to assess accurately their environmental impact. It should be noted that the impact zone was well localized at the disposal site and there is no indication of extended impacts within the Duwamish River-Elliott Bay system.

Biological Studies

Accumulation of mercury and chromium by marine animals

101. The effect of the open-water disposal of dredged material from the Duwamish Waterway on five species of marine animals indigenous to Puget Sound was investigated by F. M. Teeny and A. S. Hall of the NMFS, Seattle, Wash. (see Appendix C). Hg and Cr concentrations in English sole, pink shrimp, spot shrimp, a sea cucumber, and a mussel were determined. Spot shrimp, sea cucumbers, and mussels were collected from locations outside of Elliott Bay. Predisposal specimens were analyzed for Hg and Cr, while postdisposal animals were placed in cages and set on the bottom of the bay at the disposal site and at the west reference site. English sole and two species of pink shrimp were collected before and after the disposal operation at the two sites. The data shown in Appendix C indicate that the open-water disposal of the contaminated dredged material did not result in increased levels of Hg and Cr in the organisms tested. The background levels found in the mussels and English sole were in agreement with the findings of other workers that have studied these species from various locations in Puget Sound.

Accumulation of PCB's by marine animals

102. Effects of the disposal operation on the accumulation of PCB's by marine animals were evaluated by V. F. Stout and L. G. Lewis of the NMFS (see Appendix B). The PCB levels in English sole and

Alaska pink shrimp from the disposal site were determined before and after the disposal operation. The disposal did not result in higher levels of PCB's in these animals. Spot shrimp, sea cucumbers, and mussels were held in cages at the disposal site for up to 3 weeks. Mussels were the only organisms that accumulated PCB's to levels higher than background determinations (see Table B8 of Appendix B); however, the increase was not statistically significant and should be treated as a trend. Animals collected from Elliott Bay contained relatively high body burdens of PCB's before the disposal operation; therefore, slight changes in these concentrations due to the operation may have gone undetected. Mussels have traditionally been used as indicators of bioaccumulation potential; thus, it would be expected that they would have shown significant amounts of PCB's in their tissues if PCB's had been released in significant amounts.

Demersal fish and shellfish

103. Demersal fish and shellfish were investigated by J. R. Hughes and associates of the NMFS, Mukilteo, Wash. (see Appendix A). The dredged material disposal site and the two reference sites were sampled for demersal fish and shellfish seven times during the study. Three replicate tows with a semiballoon otter trawl were made through each of the three sampling sites 1 week before disposal, during the disposal operation, and 1 week, 1 month, 3 months, 6 months, and 9 months after disposal. Additional information on the type of otter trawl and the experimental procedure can be found in Appendix A.

104. Fish and shellfish taken by the trawl were identified and counted, and subsamples of the numerically dominant species were measured and weighed. Approximately 17,800 invertebrates and 8,700 vertebrates were captured during the study.

105. The dominant vertebrates collected at the sites were the soles and the shiner perch. The dominant invertebrates collected were four species of shrimp. The total numbers of individuals of these species collected are presented in Table 11.

106. The data indicate that the disposal operation did not have any dramatic effect on the dominant demersal fish and shrimp of Elliott

Table 11

Dominant Vertebrates and Invertebrates from the Disposal and Reference Sites

	Feb (1 week Before)	During Disposal	Mar (1 week After)	Apr (1 month After)	Jun (3 months After)	Sep (6 months After)	Dec (9 months After)
East reference site							
Vertebrates	212	1952	599	372	155	271	46
Invertebrates	1453	631	641	624	770	195	31
Disposal site							
Vertebrates	178	827	464	45	45	81	8
Invertebrates	252	457	779	939	3210	1218	32
West reference site							
Vertebrates	591	857	403	285	44	47	55
Invertebrates	806	497	819	279	2406	1182	304

Bay. Before disposal, somewhat fewer vertebrates and invertebrates were caught at the disposal site than at either reference site. Trawls taken during disposal revealed fewer animals at the disposal site than at the east reference site but approximately the same number as at the west reference site. After disposal the vertebrates seem to have decreased at all three sampling sites, which suggests a seasonal trend rather than an adverse effect due to the open-water disposal of dredged material.

107. The invertebrates at the east reference site remained at the same level for 3 months after the disposal (about 640) and then declined, while those at the disposal site increased steadily from 457 individuals during disposal to 3210 individuals 3 months later. Invertebrates at the west reference site varied after disposal from a high of 2406 to a low of 279. Generally, there were fewer vertebrates at the disposal site than at either reference site; however, the data show that in several cases there were more invertebrates at the disposal site than at either reference site.

108. These data certainly do not demonstrate adverse effects due to the disposal operation. Yet, the data are inconclusive due to a variety of factors, not the least of which is the fact that these organisms are very mobile and gregarious in behavior. Thus, it is not likely that three 5-minute trawl samples separated by weeks or months would statistically reveal organism behavior at the sites. The variation between trawls on the same day was, in some cases, tremendous. The substrate at the sampling sites was different and probably contained different food organisms and would consequently be more attractive to some species. Baseline data were limited due to the short lead time from initial site selections to the disposal operation, a factor which renders interpretation of changes difficult.

109. Temperature, dissolved oxygen, and salinity were determined at each sampling station for each of the seven sampling periods. Temperature values at all three sites were similar for each sampling period. The lowest values were in February and March (6.5 to 7.5°C), while higher readings were obtained in September (11.0 to 13.0°C).

The dissolved oxygen measurements varied from >11.0 ppm down to 4.2 to 4.8 ppm; however, values from the disposal site were always in the same range as the dissolved oxygen values from the two reference sites. Salinity ranged from 27 to 30 ppt and was similar for all three sites. At times, the surface salinity was lower than the salinities determined for the remainder of the water column.

110. Demersal fish and shellfish data were analyzed statistically to determine whether differences in composition and abundance of species were significant. Diversity index values were calculated for each trawl sample and used for the statistical analyses. The values for vertebrates ranged from 0.59 to 2.34, while those for invertebrates were 0.0 to 1.53. Some significant differences were found; however, a major conclusion of Appendix A was that the variations noted in the composition and abundance of species at the three sampling sites were probably due to seasonal variations and not to any adverse effects of the dredged material.

Effects on benthic communities

111. Disposal at the Elliott Bay disposal site resulted in initial decreases in the number of species, mean biomass, and mean density at the disposal site. However, there were similar decreases in number of species and mean biomass at the two reference sites. Also, there was a greater variety (more species) of animals throughout the 9-month sampling period at the disposal site as a whole compared with the two reference sites. Additional considerations which make it difficult to determine whether there was an adverse impact on the Elliott Bay disposal site include the relative size of the disposal site compared to reference sites, the inadequate predisposal data, and the overriding influence of the Duwamish River on the disposal site.

112. Two reports on the data collected on the benthic communities of Elliott Bay are presented as Appendices F and G to this report. The authors of Appendix F examined individual species impacts in detail and concluded that the disposal site had not completely recovered to its predisposal community structure by 9 months. The author of Appendix G stated that there were substantial initial decreases at the center

of the disposal site in number of species, density of macrofauna, biomass, and species diversity. It is emphasized that the observed effects at the disposal site were most pronounced in the four central stations and least in the four corner stations (Figure 6). There was strong evidence that seasonal trends played an important role in the changes noted in the above parameters.

113. The following summary of the benthic data (drawn from Appendix G) illustrates the points mentioned above. Figure 6 presents the mean number of species collected at the two reference sites and at the disposal site, which was divided into central, corner, and side stations. Each data point represents the mean number of total species identified at each station averaged with similar values for like stations. The data clearly demonstrate the adverse physical effect of disposal on the benthic community at the central disposal stations. Central stations before disposal contained an average of over 29 species, while corner disposal stations had just over 30 species. Disposal decreased these values (there were also unexplained drops at the reference stations); however, the corner stations 3 months after disposal again contained over 30 species after a low of approximately 18 species 10 days after disposal. Nine months after disposal, the corner stations contained over 40 species, central stations had 25 species, and the side disposal stations were intermediate. Comparison of all five groups of stations shows between 26 and 39 species present 9 months after disposal. These data show that even the central disposal stations were recovering 9 months after the operation as shown by the number of species present.

114. The mean density (organisms per 0.1 m^2) and mean biomass (grams per 0.1 m^2) at the various sites are shown in Figures 7 and 8. These data reveal a slightly different picture from that in Figure 6. It appears that, although the mean number of species found at the central disposal stations increased rapidly from 1 to 9 months after disposal, their density and biomass were much lower than corresponding values at the corner disposal stations and at the reference stations. Ten days after disposal, mean density of animals from the central

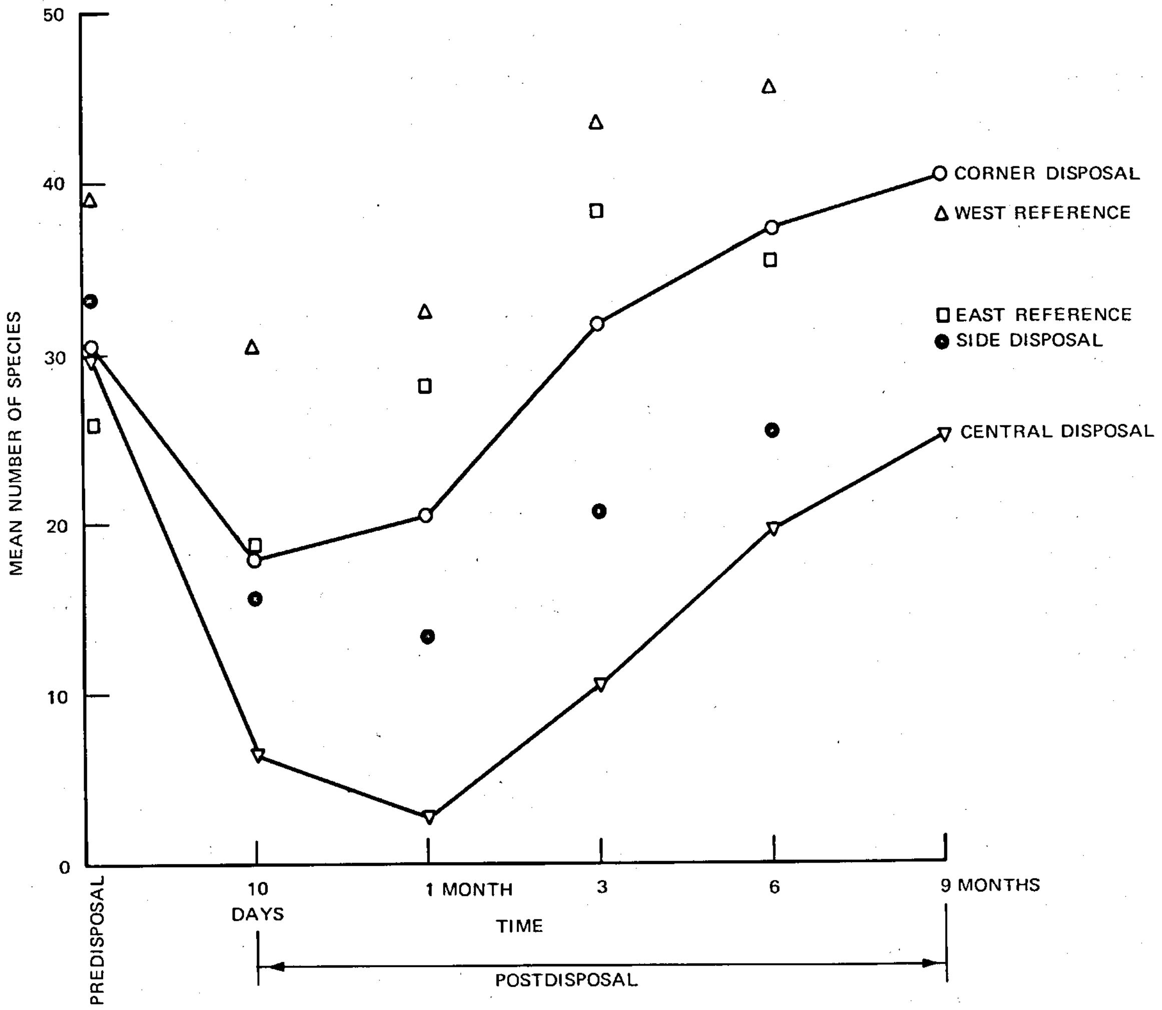

Figure 6. Mean number of species at the disposal and reference stations

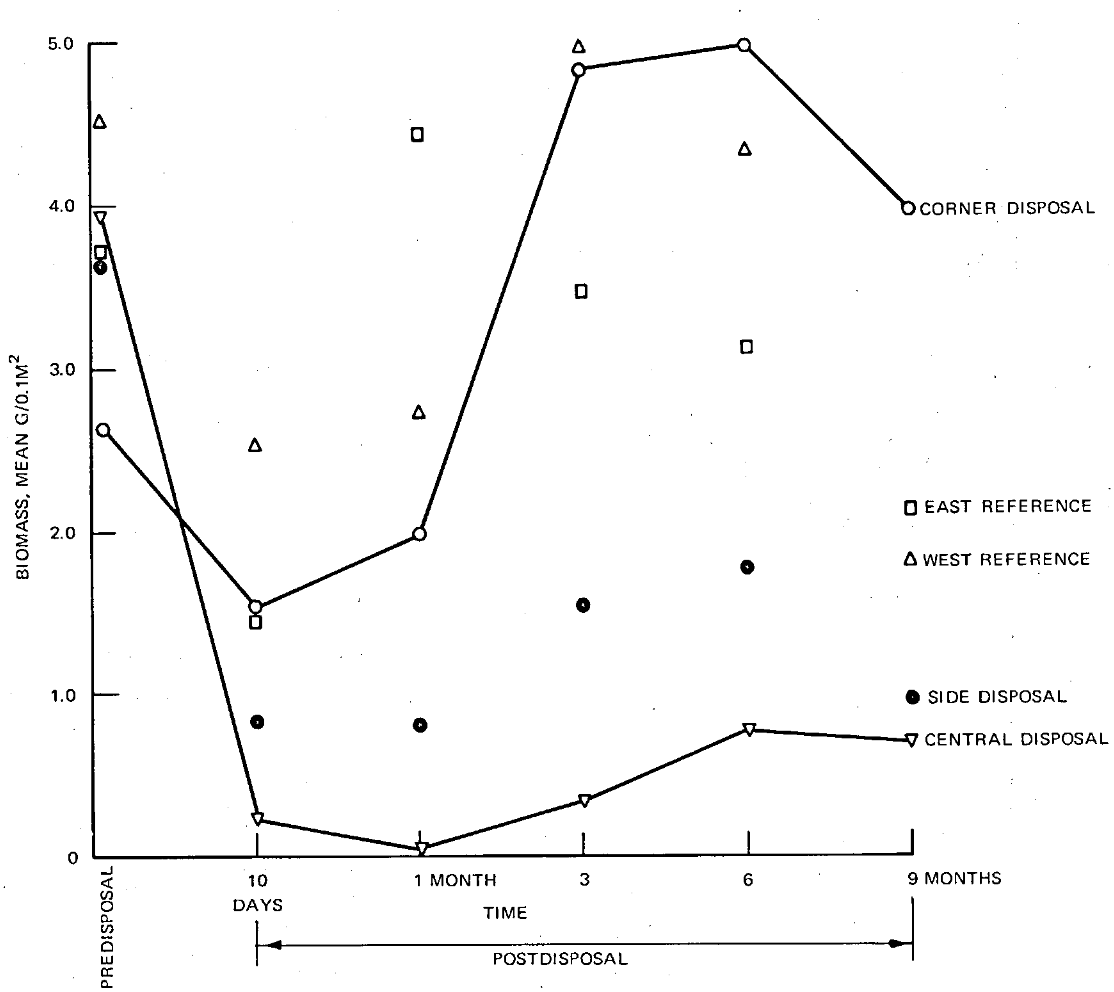

Figure 7. Mean density of animals at the disposal and reference stations

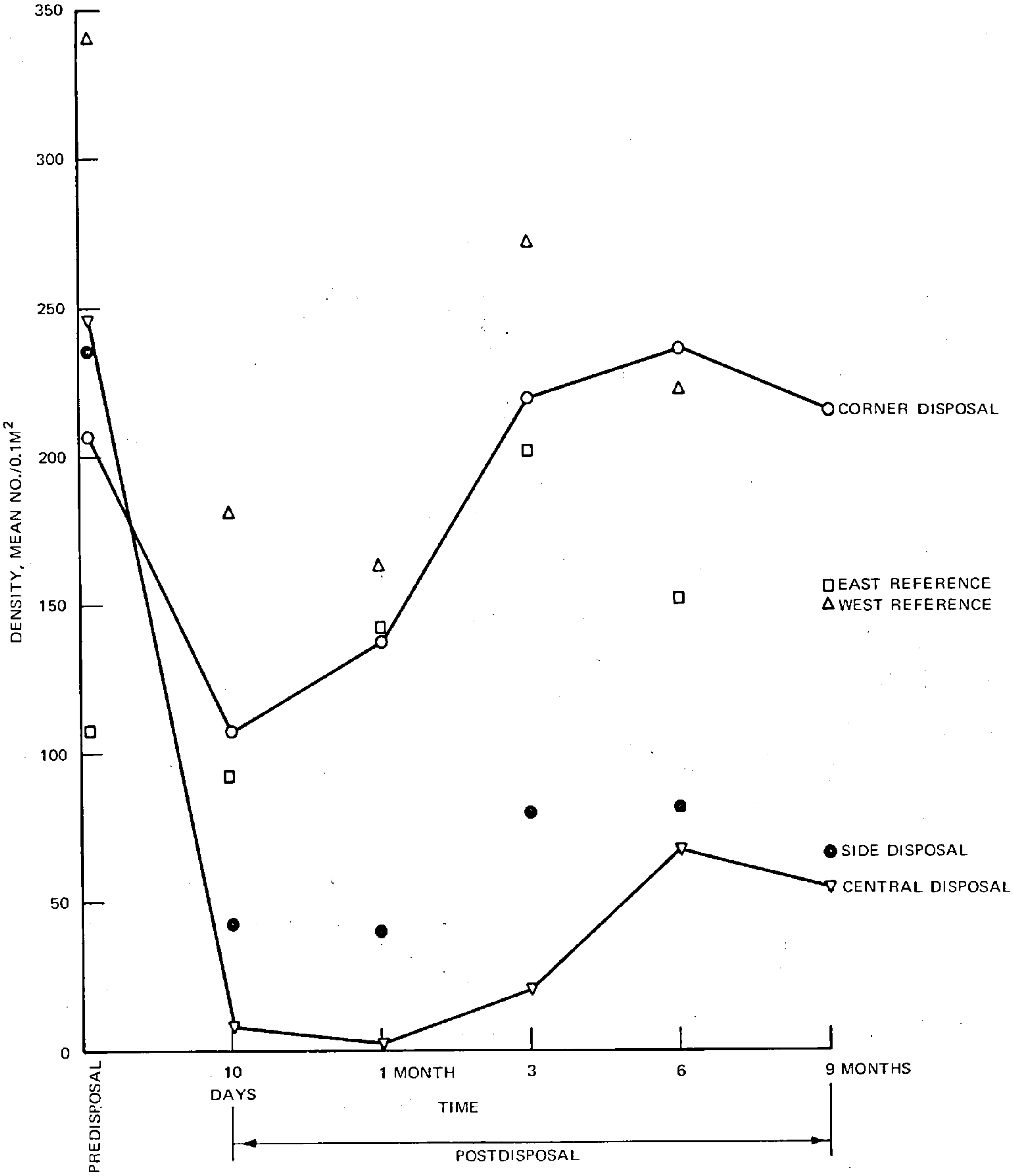

Figure 8. Mean biomass of animals at the disposal and reference sites

stations dropped from 240 to 8, while that from corner stations decreased from 205 to 107. The side stations of the disposal site were adversely affected when compared to the corner stations and the reference stations. The significance of these data is obscured somewhat by the wide differences between the disposal site and the reference sites before disposal. Both parameters for the corner disposal stations consistently ranked above those for the other disposal site stations as well as the two reference stations.

115. The diversity indices data are shown in Figure 9. Diversity at the disposal and reference sites was similar initially. The values ranged from 1.59 for the central disposal stations to 1.91 for the west reference station. Diversity decreased to 0.37 at 1 month for the central stations but climbed to 3.33 at 9 months after disposal. This value was just below that of the side disposal stations, with the reference station and corner station values lower. Thus, diversity increased in the central area of the disposal site after an initial decrease. The side stations did not show even a slight decrease in diversity values after disposal. The range of values at predisposal was 1.59 to 1.91, while the range after 9 months was 1.82 to 3.44.

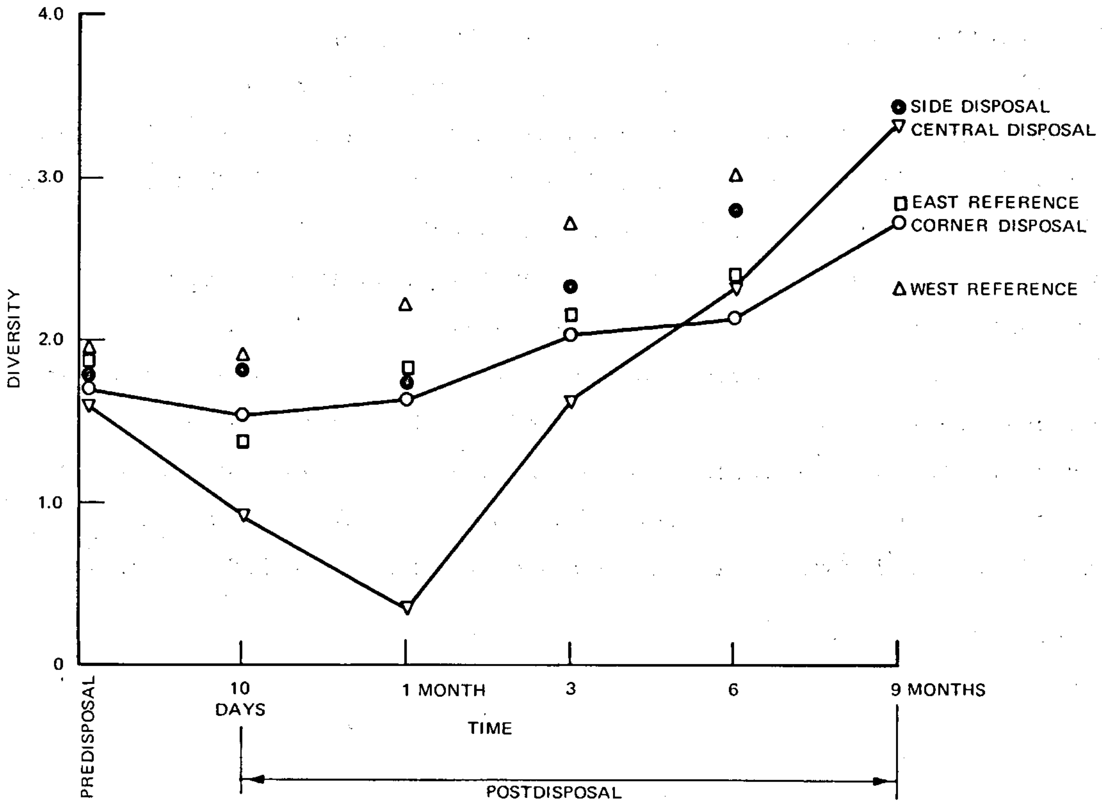

Figure 9. Shannon-Weaver diversity indices for the disposal and reference sites

PART VI: CONCLUSIONS

116. Approximately 114,250 m^3 of riverine sediment was removed by a clamshell dredge from a 1.9-km section of the Duwamish River during February and March 1976. The sediment was taken by barges to an experimental deepwater disposal site located in Elliott Bay and deposited. A total of 249 barge loads were deposited during the 16-day disposal operation. Physical data revealed that the dredged material left the barges in the form of one large slug of sediment and reached the bottom (60 m) in about 25 sec. Many small mounds of sediment ranging from 2.0 to 2.5 m were created near the central area of the 0.98-km^2 disposal site. During the postdisposal study period (9 months), chemical data showed that the material spread from the central area of the disposal site toward the margins; however, there was no evidence that the sediment spread beyond the edges of the disposal site.

117. Chemical analyses of the in situ sediment were made prior to dredging and showed that these sediments contained many of the contaminants normally found in sediment samples from industrial and urban areas, i.e., heavy metals such as cadmium and mercury, PCB's, and oil and grease. Comparison of the river sediment with sediment from Elliott Bay showed that the river sediment was significantly higher in levels of total sulfide and PCB's and higher in levels of total iron, mercury, and manganese. Dissolved heavy metals were present in the interstitial water from the river sediment at levels higher than water from Elliott Bay sediment. An accidental spill of PCB's from an electrical transformer in September 1974 was one of the original reasons for concern about the dredging and disposal of the Duwamish River sediment. PCB concentrations as high as 7.0 μg/g were found in the river sediment. Small "hot spots" of PCB contamination near Slip 1, an area below the dredging site, were found to contain PCB concentrations as high as 100 μg/g. Yet, the data obtained on the ecological/biological effects of the open-water disposal of the contaminated sediment indicated that the major adverse effect was physical in nature, not chemical, and was felt primarily by the

macrobenthic fauna at the center of the disposal site.

118. Analyses of animals such as fish, shrimp, and mussels at the disposal site revealed no significant increases in tissue concentrations of the metals mercury and chromium or PCB's. Since disposal resulted in only very transient increases in the water column of suspended solids, dissolved manganese, and free PCB's, the above results could have been expected. Demersal fish and shellfish were not harmed by the operation. Large numbers of these animals were found at the disposal site during and after disposal. Disposal did not affect temperature, salinity, or dissolved oxygen at the disposal site. Benthic organisms such as pelecypods (bivalves), polychaete worms, and gastropods were significantly depressed in the central stations of the disposal site; however, values for number of species, density, and biomass showed that these animals were more abundant at the margins of the disposal site after disposal than before. More animals were found at the corners of the disposal site at 9 months after disposal than at either reference site. Data from the central stations at 9 months after disposal indicated that a number of benthic species were actively recolonizing the dredged material mounds even though density and biomass values remained low.

119. Thus, it seems clear that the disposal of contaminated dredged material from the Duwamish River in the open waters of Elliott Bay resulted in no permanent environmental degradation of the area as shown by chemical analyses of animals, waters, and sediment samples. Some benthic animals were buried by the dredged material, yet other species began immediately to recolonize the area. The sediment now present at the disposal site is enriched with certain contaminants, mainly oil and grease and PCB's, compared to the surrounding sediment and will remain so for a number of years. It should be mentioned that the average background levels of PCB's in the waters of Elliott Bay exceeded the recommended criteria levels for PCB's before disposal. It is recommended that this disposal site continue to be monitored for important biological and chemical parameters.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Tatem, Henry E
Aquatic disposal field investigations, Duwamish Waterway disposal site, Puget Sound, Washington; evaluative summary / by Henry E. Tatem and Jeffrey H. Johnson. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
77 p. : ill. ; 27 cm. (Technical report - U. S. Army Engineer Waterways Experiment Station ; D-77-24)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under DMRP Work Unit No. 1A10.
Appendices A-E, G on microfiche in pocket.
References: p. 75-77.

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APPENDIX F: RECOLONIZATION OF BENTHIC MACROFAUNA OVER A DEEP-WATER DISPOSAL SITE.

DREDGED MATERIAL RESEARCH PROGRAM

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