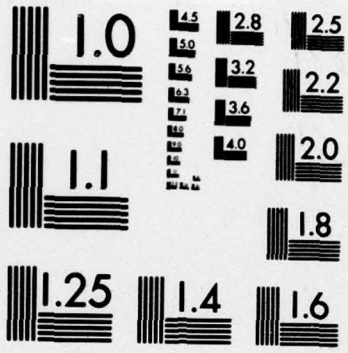
AD-A058 489 EFFECTS OF SUSPENDED DREDGED MATERIAL ON AQUATIC ANIMALS(U) CALIFORNIA UNIV BODEGA BAY BODEGA MARINE LAB R K PEDDICORD ET AL. JUL 78 WES-TR-D-78-29 1/2

UNCLASSIFIED F/G 13/2 NL



LEVEL II

DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-78-29

EFFECTS OF SUSPENDED DREDGED MATERIAL ON AQUATIC ANIMALS

by

Richard K. Peddicord, Victor A. McFarland

University of California
Bodega Marine Laboratory
Bodega Bay, Calif. 94923

July 1978

Final Report

Sponsored by Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under DMRP Work Unit No. D09

Monitored by Environmental Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ADA058489

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Technical Report D-78-29

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): EFFECTS OF SUSPENDED DREDGED MATERIAL ON AQUATIC ANIMALS

5. TYPE OF REPORT & PERIOD COVERED: Final report

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): Richard K. Peddicord, Victor A. McFarland

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: University of California, Bodega Marine Laboratory, Bodega Bay, Calif. 94923

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: DMRP Work Unit No. 1D09

11. CONTROLLING OFFICE NAME AND ADDRESS: Office, Chief of Engineers, U. S. Army, Washington, D. C. 20314

12. REPORT DATE: July 1978

13. NUMBER OF PAGES: 115

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): U. S. Army Engineer Waterways Experiment Station, Environmental Laboratory, P. O. Box 631, Vicksburg, Miss. 39180

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18 WES

19 TR-D-78-29

18. SUPPLEMENTARY NOTES

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

Aquatic animals
Dredged material
Invertebrates
Sediment
Suspended load

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes laboratory research designed to evaluate the impact of suspensions of relatively uncontaminated and contaminated harbor sediments on juvenile and adult marine, estuarine and freshwater fish and invertebrates. Studies of survival and tissue accumulation of contaminants were conducted for 21 days exposure to suspended sediments in a flow-through aquarium system. Even the most sensitive fish survived days of continuous exposure to suspensions of relatively uncontaminated sediment on the order of grams per litre,

(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

410 836

20. ABSTRACT (Continued).

and the invertebrates generally survived similar exposures to tens of grams per litre of relatively uncontaminated sediment. Exposure to suspensions of contaminated sediment decreased survival substantially, but, even so, mortality occurred only after exposure to higher concentrations for longer time periods than are created in the water column by the typical dredging operation. Only fingerling striped bass Morone saxatilis showed a sensitivity great enough to indicate a potential cause for concern from continuous pipeline discharge of highly contaminated dredged material.

While water column impacts generally appeared to warrant little concern, the data indicate the potential for impact of contaminated fluid mud on benthic infauna and relatively immobile epifauna. Fluid muds with suspended sediment concentrations of tens of grams per litre can be created on the bottom by pipeline, and perhaps hopper, disposal of hydraulically dredged fine-grained sediment. These can persist for sufficient periods to have a potential for impact on relatively immobile bottom dwellers, particularly if highly contaminated sediments are involved.

Tissue uptake of contaminants from suspensions of highly contaminated sediment was limited. Of 100 species-salinity-contaminant combinations where uptake might have been measured, it actually occurred in less than one fourth of the cases.

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESYV

31 August 1978

SUBJECT: Transmittal of Technical Report D-78-29

TO: All Report Recipients

1. The technical report transmitted herewith was undertaken as Work Unit 1D09, Effects of Dredging and Disposal on Aquatic Organisms, of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 1D was a part of the Environmental Impacts and Criteria Development Project (EICDP), which had a general objective of determining on a regional basis the direct and indirect effects on aquatic organisms due to dredging and disposal operations. The study reported on herein was a part of a series of research contracts developed to achieve the EICDP objective.

2. The purpose of this research was to determine the limits of tolerance of a variety of adult or juvenile marine, estuarine, and freshwater fish and invertebrates to suspensions of relatively uncontaminated harbor sediments. The tissue accumulation of contaminants from suspensions of contaminated sediments was also investigated.

3. Experiments were conducted for 3-week exposures in a flow-through aquarium system. Survival in each concentration was determined over time. Animals used in the tissue accumulation study were removed from the sediment suspensions after 3 weeks and analyzed for selected metals and chlorinated hydrocarbons. Exposed animal data were compared to similarly analyzed control animals to determine the occurrence and extent of contaminant accumulation.

4. Suspensions of the more highly contaminated sediment were more harmful than uncontaminated sediment. Even so, mortalities occurred only after longer exposures to higher concentrations of suspended sediment than typically occur in the water column during dredging or disposal. Fluid muds of highly contaminated sediment, which may be present at disposal sites for hydraulically dredged fine-grained material for periods of weeks before consolidation, have the potential for adverse impacts on several of the species tested. This should be considered in evaluating the possibility of environmental impacts of operations from which such conditions might result.

WESYV 31 August 1978
SUBJECT: Transmittal of Technical Report D-78-29

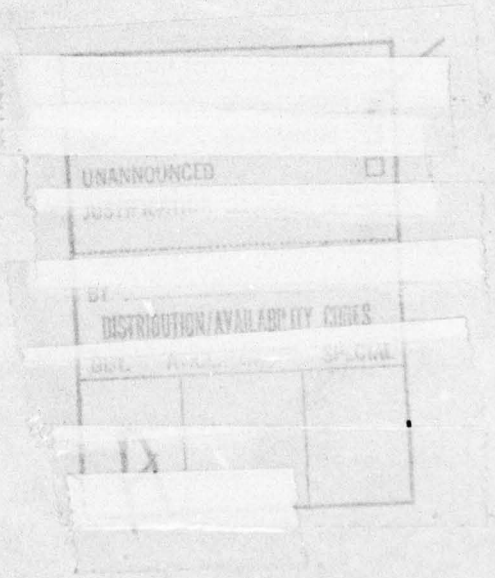
5. Tissue accumulation of contaminants from suspensions of contaminated sediment proved to be the exception rather than the rule. Of 100 species-salinity-contaminant combinations for which uptake was investigated, tissue accumulation was found in less than 25 percent of the cases. Most of these were metals with only three cases of tissue accumulation of chlorinated hydrocarbons documented. In those cases where tissue accumulation did occur, concentrations were only a few times higher than in the corresponding control animal tissues.

6. The information and data published in this report are contributions to the further understanding of the complex nature of sediment, water, and chemical/biological interactions and establish a baseline from which to develop meaningful evaluations for the selection of an environmentally compatible disposal alternative. It is expected that the methodology employed in this study and the resulting interpretation of the chemical/biological interactions will be of significant value to those persons concerned with CE dredged material regulatory programs.

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

iia

THE CONTENTS OF THIS REPORT ARE NOT TO BE USED FOR ADVERTISING, PUBLICATION, OR PROMOTIONAL PURPOSES. CITATION OF TRADE NAMES DOES NOT CONSTITUTE AN OFFICIAL ENDORSEMENT OR APPROVAL OF THE USE OF SUCH COMMERCIAL PRODUCTS.



SUMMARY

The purpose of this research was to determine the limits of tolerance of a variety of adult or juvenile marine, estuarine, and freshwater fish and invertebrates to suspensions of relatively uncontaminated and contaminated harbor sediments. The tissue accumulation of contaminants from suspensions of contaminated sediments was also investigated.

Experiments were conducted for 3-week exposures in a flow-through aquarium system. Survivors were counted daily, and percent survival in each concentration was plotted versus exposure time. Time-concentration mortality curves for 50, 20, and 10 percent mortality were also constructed. Animals used in the tissue accumulation study were removed from the sediment suspensions after 3 weeks and placed in clean water of the same temperature and salinity for 4 days to purge the digestive tracts and body surfaces of sediment. Tissues were then analyzed for selected metals and chlorinated hydrocarbons. Exposed animal data were compared to data for similarly analyzed control animals to determine the occurrence and extent of contaminant accumulation.

All species tested were able to survive exposure for much longer periods to much higher concentrations of relatively uncontaminated sediment than are created in the water column by typical dredging or disposal operations. However, survival of some species was affected by days of exposure to sediment suspensions of tens of grams per litre. Such conditions occur in the field in fluid mud, which may cover the bottom at disposal sites for hydraulically dredged, fine-grained material for periods of weeks before consolidation. Fluid mud may adversely affect sensitive, relatively immobile benthic infauna and epifauna.

Suspensions of highly contaminated sediment were more harmful than those of relatively uncontaminated sediment. Even so, mortalities occured only after longer exposures to higher concentrations of suspended sediment than typically occur in the water column during dredging or disposal. Fluid muds of highly contaminated sediment have the potential for adverse impact on several of the species tested and should be considered in evaluating the possibility of environmental impacts of

operations in which such conditions might result.

Tissue accumulation of contaminants from suspensions of contaminated sediment proved to be the exception rather than the rule. Of 100 species-salinity-contaminant combinations for which uptake was investigated, tissue accumulation was found in less than 25 percent of the cases. Most of these involved metals; only three cases of tissue accumulation of chlorinated hydrocarbons were documented. Even in those cases where tissue accumulation did occur, concentrations were only a few times higher than in the corresponding control animal tissues.

PREFACE

This report is the culmination of a study of the effects of suspensions of sediment particles on a variety of aquatic organisms. This work was conducted as part of the Dredged Material Research Program (DMRP) sponsored by the Office, Chief of Engineers, U. S. Army, and managed by the Environmental Laboratory (EL), U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss. The investigation was conducted under an interagency agreement with the National Oceanic and Atmospheric Administration at the University of California, Bodega Marine Laboratory, Bodega Bay, Calif.

The authors gratefully acknowledge the invaluable contributions of many persons to the completion of this research. Chief among these are Daniel Belfiori, who contributed to the design, refinement and operation of the laboratory facility and developed calculator programs for the data monitoring and storage system and for analysis of the biological data, and Terry Byrd, who performed many of the operational tasks required by such a facility, collected the experimental animals, and performed many of the data analyses. Nanette Cordon Fyfe assisted with the animal collections, data analyses and operational tasks. All animal observations were made by Ellen Letterman, whose dependability through weekends and holidays is much appreciated. The chemical analyses were performed by Dr. William Patrick, Louisiana State University, and Dr. Kenneth Chen, University of Southern California. Special thanks are due to Dr. Cadet Hand, Director of Bodega Marine Laboratory, to whom this research contract was awarded, and the administration and office staff at the Laboratory, who capably met the needs of the project.

The report was prepared for the Environmental Impacts and Criteria Development Project of the DMRP (Dr. Robert M. Engler, Project Manager) as part of Task 1D, "Effects of Dredging and Disposal on Aquatic Organisms." The contract was monitored by Ms. Susan Palmer under the general supervision of Dr. John Harrison, Chief, EL.

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

CONTENTS

	Page
SUMMARY	2
PREFACE	4
LIST OF TABLES	6
LIST OF FIGURES	7
CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT	10
PART I: INTRODUCTION	11
PART II: HISTORICAL BACKGROUND	13
PART III: EXPERIMENTAL METHODS	16
Laboratory Facilities	16
Sediment Collection and Handling	21
Sediment Characterization	22
Animal Collection	24
Experimental Conditions	25
Data Analysis	27
Chemical Uptake Study	29
PART IV: EXPERIMENTAL RESULTS	32
Sediment Characterization	32
Freshwater Experiment	38
Marine Experiment	40
Estuarine Experiment	57
Chemical Uptake--Marine Test with Contaminated Sediment	65
Chemical Uptake--Estuarine Test With Contaminated Sediment	76
PART V: DISCUSSION	83
PART VI: CONCLUSIONS	98
REFERENCES	99
APPENDIX A: CONDITIONS IN FRESHWATER EXPERIMENTS	A1
APPENDIX B: CONDITIONS IN MARINE EXPERIMENTS	B1
APPENDIX C: CONDITIONS IN ESTUARINE EXPERIMENTS	C1

LIST OF TABLES

No.	Title	Page
1	Chemical characterization of freshwater sediment	33
2	Chemical characterization of uncontaminated sediment used in the estuarine and marine tests	34
3	Chemical characterization of contaminated sediment used in the estuarine and marine tests	35
4	Comparison of chemical characteristics of the contaminated and uncontaminated sediments used in the marine and estuarine experiments	37
5	Summary of the time-concentration mortality curves for Enallagma sp. in uncontaminated sediment	42
6	Summary of the time-concentration mortality curves from the marine experiments	45
7	Summary of the time-concentration mortality curves from the estuarine experiments	58
8	Whole body concentrations of selected metals in chemical uptake study with contaminated sediment in the marine test	67
9	Whole body concentrations of selected chlorinated hydrocarbons in chemical uptake study with contaminated sediment in the marine test	70
10	Contaminant concentrations in the tissue of the mussel Mytilus edulis in the chemical uptake study in the contaminated sediment phase of the estuarine test	77
11	Comparisons of 10-day and 21-day LCX estimates in g/l for suspensions of kaolin clay, bentonite clay, uncontaminated natural sediment, and contaminated natural sediment	87

LIST OF FIGURES

No.	Title	Page
1	Schematic representation of the slurry proportioning and dilution water systems	17
2	Percent survival of 8- to 10-cm crayfish Pacifastacus leniusculus in suspensions of uncontaminated sediment . . .	39
3	Percent survival of 4- to 5-cm-long clams Corbicula fluminea in suspensions of uncontaminated sediment	39
4	Percent survival of larval damselflies Enallagma sp. in suspensions of uncontaminated sediment	41
5	Time-concentration mortality curves for larval damselflies Enallagma sp. in suspensions of uncontaminated sediment . .	41
6	Percent survival of western toad Bufo boreas tadpoles in suspensions of uncontaminated sediment	43
7	Percent survival of 4.5- to 5.5-cm golden shiners Notemigonus crysoleucas in suspensions of uncontaminated sediment	43
8	Percent survival of fingerling rainbow trout Salmo gairdneri in suspensions of uncontaminated sediment	44
9	Percent survival of 4- to 6-cm black-tailed sand shrimp Crangon nigricauda in suspensions of uncontaminated sediment at 33 °/oo	46
10	Percent survival of 5- to 6.5-cm spot-tailed sand shrimp Crangon nigromaculata in suspensions of uncontaminated sediment at 33 °/oo	46
11	Percent survival of 6- to 8-cm spot-tailed sand shrimp Crangon nigromaculata in suspensions of contaminated sediment at 33 °/oo	47
12	Percent survival of 2- to 2.5-cm blue mussels Mytilus edulis in suspensions of uncontaminated sediment at 33 °/oo.	49
13	Percent survival of 1.5- to 2.5-cm blue mussels Mytilus edulis in suspensions of contaminated sediment at 33 °/oo .	49
14	Time-concentration mortality curves for 1.5- to 2.5-cm blue mussels Mytilus edulis in suspensions of contaminated sediment at 33 °/oo	50
15	Percent survival of 2- to 2.5-cm coast mussels Mytilus californianus in suspensions of uncontaminated sediment at 33 °/oo	50
16	Percent survival of 1.5- to 2.5-cm coast mussels Mytilus californianus in suspensions of contaminated sediment at 33 °/oo	51

No.	Title	Page
17	Time-concentration mortality curves for 1.5- to 2.5-cm coast mussels Mytilus californianus in suspensions of contaminated sediment at 33 °/oo	51
18	Percent survival of tunicates Ascidia ceratodes in suspensions of contaminated sediment at 33 °/oo	53
19	Time-concentration mortality curves for tunicates Ascidia ceratodes in suspensions of contaminated sediment at 33 °/oo	53
20	Percent survival of 3- to 4-cm commercial crabs Cancer magister in suspensions of contaminated sediment at 33 °/oo	54
21	Time-concentration mortality curves for molting 3- to 4-cm crabs Cancer magister in suspensions of contaminated sediment at 33 °/oo	54
22	Histograms showing the effects of molting of 3- to 4-cm crabs Cancer magister	55
23	Percent survival of 4- to 6-cm black-tailed sand shrimp Crangon nigricauda in suspensions of uncontaminated sediment at 25 °/oo	59
24	Percent survival of 5- to 6-cm black-tailed sand shrimp Crangon nigricauda in suspensions of contaminated sediment at 24 °/oo	59
25	Percent survival of 1- to 2-cm blue mussels Mytilus edulis in suspensions of uncontaminated sediment at 24 °/oo . . .	60
26	Percent survival of 2- to 2.5-cm blue mussels Mytilus edulis in suspensions of contaminated sediment at 25 °/oo . .	61
27	Time-concentration mortality curves for 2- to 2.5-cm blue mussels Mytilus edulis in contaminated sediment at 25 °/oo	61
28	Shell growth of 1- to 2-cm blue mussels Mytilus edulis after 21 days in suspensions of uncontaminated sediment . .	63
29	Percent survival of 5- to 6-cm striped bass Morone saxatilis in suspensions of uncontaminated sediment at 25 °/oo	63
30	Percent survival of 4- to 6-cm striped bass Morone saxatilis in suspensions of contaminated sediment at 25°/oo . .	64
31	Time-concentration mortality curve for 5- to 6-cm striped bass Morone saxatilis in suspensions of contaminated sediment at 25 °/oo	64
32	Hematocrit of 5- to 6-cm striped bass Morone saxatilis after 21 days in suspensions of uncontaminated sediment . .	66
33	Mineral contents of stomachs of 5- to 6-cm striped bass Morone saxatilis after 21 days in suspensions of uncontaminated sediment	66

No.	Title	Page
34	Mytilus edulis metals concentrations in the contaminated sediment phase of the marine test	69
35	Mytilus californianus metals concentrations in the contaminated sediment phase of the marine test	72
36	Crangon nigromaculata metals concentrations in the contaminated sediment phase of the marine test	73
37	Cancer magister metals concentrations in the contaminated sediment phase of the marine test	75
38	Mytilus edulis metals concentrations in the contaminated sediment phase of the estuarine test	78
39	Mytilus edulis chlorinated hydrocarbon concentrations in the contaminated sediment phase of the estuarine test	81

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
gallons (U. S. liquid)	3.785412	cubic decimetres
inches	25.4	millimetres
tons (refrigeration)	3.5168	kilowatts

EFFECTS OF SUSPENDED DREDGED MATERIAL ON AQUATIC ANIMALS

PART I: INTRODUCTION

1. This report describes laboratory research designed to evaluate the impact of sediment suspensions on marine, estuarine and freshwater fish and invertebrates. The study was an extension of previous research (Peddicord et al., 1975) on the impact of suspensions of fine mineral particles which resembled the harbor sediments used here in mineralogy and particle size distribution but had been processed to remove the complicating chemical factors often associated with natural sediments. To this background knowledge of physical effects, the present study added chemical influences by exposing many of the same species to suspensions of physically similar natural sediments from relatively uncontaminated and contaminated harbors. Such a research program provides a basis for determining the extent to which the observed effects were due to the physical presence of the particles themselves or to some chemical conditions of the sediments.

2. Although there was a high degree of continuity between the processed mineral and harbor sediment research, funding was from different sources whose specific needs required somewhat differing experimental designs. The earlier research showed that physical effects were aggravated at summer temperature and reduced dissolved oxygen. Other considerations forced the harbor sediment experiments to be conducted at the less than worst-possible-case conditions of winter temperature and high dissolved oxygen levels. The experiments with harbor sediments were conducted at lower suspended sediment concentrations and for longer times than those with the processed minerals, thus requiring care in selecting truly similar conditions for comparison.

3. The experimental suspended sediment concentrations covered a wide range. The maximum far exceeded the highest concentrations created in the water column by dredging operations and was typical of fluid mud-

conditions. Because the tolerance of many of the test species to suspended sediments was unknown, death was selected as the primary measured response to establish outer limits and provide a framework within which future research can be conducted. It is extremely important to stress that only juvenile and adult macrofauna were studied and that the absence of death in 3 weeks in some cases does not necessarily imply that the animals were not affected or that other life stages might not have been killed under similar conditions. This study also investigated tissue accumulation of contaminants from suspensions of contaminated sediment.

PART II: HISTORICAL BACKGROUND

4. Studies of the direct effects of elevated suspended solids concentrations on aquatic animals have been conducted by several authors. Among the invertebrates, most work has concerned mollusks or crustaceans (Davis and Hidu, 1969; Johnson, 1971; Loosanoff, 1961; Paffenhofer, 1972; Peddicord et al., 1975). Lethal, sublethal and behavioral effects on various life stages of estuarine and freshwater fish have been documented (Heimstra et al., 1969; Morgan et al., 1973; Sherk et al., 1974; Southgate, 1960). The effects of many kinds of particles, including a variety of processed clay minerals, fuller's earth, powdered chalk, incinerator ash, coal washings and glass shards, have been studied (Herbert and Merkins, 1961; Peddicord et al., 1975; Rogers, 1969; Sherk et al., 1974). Several investigations have used "natural" sediments taken directly from aquatic or terrestial deposits (Schubel and Wang, 1973; U. S. Fish and Widlife Service, 1970; Wallen, 1951), usually sizing, drying or otherwise markedly altering their in situ physical, chemical and biological properties before using them in experiments.

5. The different metholologies employed in previous experiments make comparison of results difficult. A variety of techniques have been used to suspend particles, including periodic stirring with subsequent settling, continuous stirring, and mixing by aeration. Almost all laboratory work has been done in closed aquaria, requiring either short tests or frequent changing of the water with consequent handling of animals. Different methods of data analysis add to the difficulty of comparing results.

6. Many previous studies have not related biological responses to actual weight per volume concentration of particles in suspension. Most correlated response with turbidity, an optical property of water containing suspended material, even though it seems unlikely that the light-absorbing and scattering properties of suspended particles directly affect animals. The turbidity produced by suspended particulate matter is influenced by many factors, including particle size, shape, mineralogy and color, and there is no predictable correlation between the

turbidities produced by equal weight per volume concentrations of different materials. This matter has been discussed by Kunkle and Comer (1971), who showed that turbidity could be related to weight per volume concentration of particles only if all the particles were of uniform physical and chemical nature and instruments were calibrated against weighed samples.

7. Pickering (1976) recommends that the term "turbidity" be used only in a qualitative sense and that details of the precise optical property measured be given whenever quantitative data are presented. The term "turbidity" should be avoided, and weight per volume concentrations of suspended solids should be given when this is the parameter measured. At present, turbidity is often expressed in Jackson or Formazin Turbidity Units, or in earlier work as equivalent to that produced by stated parts per million of a standard silica flour. The latter is most unfortunate since statements like "turbidity of 1000 ppm" are easily misinterpreted as indicating a measured weight per volume concentration of particles.

8. The literature on the effects of suspended solids on aquatic animals has been reviewed by several authors. Cordone and Kelly (1961) concluded that adult freshwater organisms could probably tolerate the normal extremes of suspended solids but that deposition would kill eggs, larvae and insect fauna and alter the characterisitics of the bottom. Wilber (1971) concluded that most filter feeders are not affected below a certain concentration but that high suspended solids concentrations interfere with filtering mechanisms. He also speculated that a given suspended solids concentration might be more harmful in normally very clear water than in usually muddy water and that the efficiency of sight feeders might be reduced as turbidity increased.

9. A comprehensive and thorough review of the literature on effects of turbidity and suspended material in aquatic environments has been prepared by Stern and Stickle (1978).

10. Sherk (1971) discussed the concept that each environment has inherent physical, chemcial and biological limits beyond which significant effects will occur and that suspended and deposited sediments

affect living systems in many different ways. Lethal and sublethal stresses over long exposures may affect any life history stage in terms of behavior, activity or metabolic function and may eliminate certain species. A significant reduction in reproductive success or survival of eggs, larvae or juveniles may be of greater ecological importance than the loss of part of the existing adult population.

11. Sherk (1973) pointed out that the response of organisms may not be due to suspended solids concentration but perhaps to the number of particles in suspension, their densities, size distribution, shape, mineralogy, presence of organic matter and its form, metallic oxide coatings or sorptive properties of the particles. As this suggestion indicates, past research has not determined whether suspended solids effects are due primarily to physical or chemical properties of the particles. Nor has much research been directed toward the potential interactions of suspended solids with other environmental variables.

12. The present study is the culmination of a 3-year research program, utilizing the same species and experimental procedures throughout, providing partial answers to these questions. The initial phase (Peddicord and McFarland, in preparation; Peddicord et al., 1975) determined the tolerance of a wide variety of marine and estuarine organisms to suspended kaolin, a contaminant-free inert clay with a very narrow size distribution of uniformly fine-grained particles. The more sensitive species were chosen for study with suspended bentonite, a processed, contaminant-free clay very similar in mineralogy and particle size distribution to the fine sediments of San Francisco Bay (Peddicord et al., 1975). This research demonstrated that suspended solids tolerance generally decreased with increasing temperature of decreasing dissolved oxygen and that the combination of summer temperature and low dissolved oxygen was particularly adverse. The present research utilized harbor sediments physically similar to the bentonite, differing primarily in chemical properties. The first was chosen to be relatively free of potential pollutants, while the second was from a heavily industrialized shipyard area.

PART III: EXPERIMENTAL METHODS

Laboratory Facilities

13. The laboratory facility was a modified version of that described by Peddicord and McFarland (in preparation). Twenty-four aquaria were arranged in three sets of eight, each with a once-through flow of the desired concentration of particles and water. The temperature and salinity in the aquaria were also controlled, and these parameters plus dissolved oxygen and pH were automatically and continuously measured and the data stored on magnetic tape for later analysis. In addition to the experimental aquaria, three 400-gallon* animal holding tanks were also provided with temperature and salinity control. All surfaces exposed to seawater were of relatively inert materials; primarily PVC, titanium, 316 stainless steel, vinyl tubing or epoxy paint.

14. The experimental aquaria, constructed of fiberglass with an inert finish, were cylindrical with hemispherical bottoms and held approximately 84 litres of water. Particles were kept in suspension by individual circulating pumps which withdrew water from the side of each aquarium, passed it through a heat exchanger for temperature control, and reintroduced it through disperser heads in the center of the aquaria bottoms. The water was forced out horizontally in all directions and flowed up along the rounded bottom and sides, constantly resuspending any material that tended to settle out. The water movement was sufficient to keep high concentrations of particles in suspension yet did not disturb small test organisms.

15. The experimental animals were held in the aquaria in nylon mesh baskets, preventing them from being drawn into the pumps and allowing easy observation by gently lifting the baskets to the surface of the turbid water. Large animals were held in cylindrical flat-bottomed 1/4-in. mesh baskets slightly smaller than the aquaria themselves. To

---

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 10.

permit observations of individual organisms and to prevent cannibalization of molting decapod crustaceans, all mussels, shrimp, crabs and lobsters were tested in flat, tray-like containers divided into individual cells by thin perforated PVC sheets. A mesh bottom and top were attached to allow free circulation of the water. Smaller organisms were held in baskets of nylon window screen.

16. Sediment particles were introduced into the aquaria by a slurry proportioning system modified from the mineral dressing industry. A high shear impeller was used to mix sediment and water of the desired salinity into a slurry. This was pumped into two 400-gal polyethylene tanks with large stirrers and adjusted to precisely the desired concentration on a weight per volume basis. From these reservoirs the slurry was pumped to three distribution systems which fed the three sets of eight aquaria. Each system, illustrated schematically in Fig. 1,

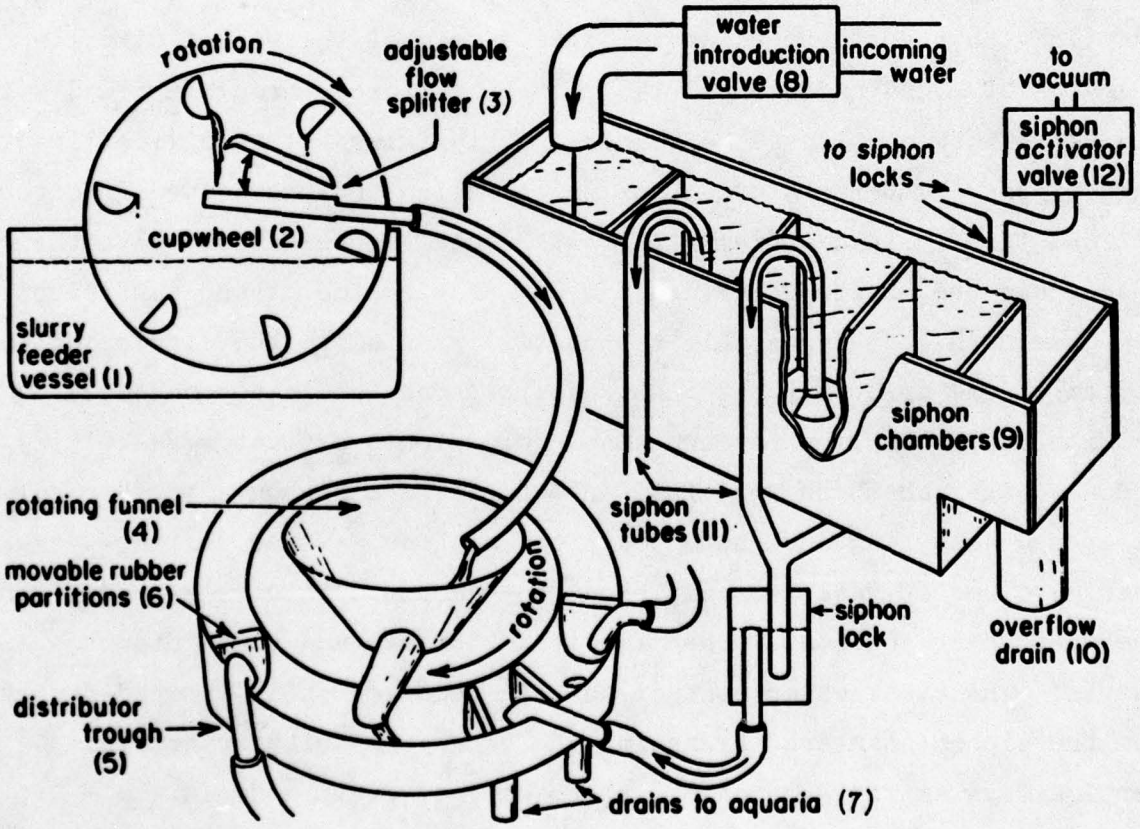


Fig. 1. Schematic representation of the slurry proportioning and dilution water systems. Numbers are keyed to the operating description in the text

consisted of a slurry feeder vessel (1) from which a cupwheel (2), driven at a constant speed by a gear motor, delivered slurry to a flow-splitter/receiver assembly (3). The opening in the splitter was adjustable to receive any required volume of slurry per unit of time, with the excess returning to the slurry feeder vessels. The predetermined amount of slurry flowed into a side-arm funnel (4) rotating at a constant speed in the center of a circular distributor trough (5) and was thus distributed evenly around the trough. Movable rubber partitions (6) divided the trough into sections whose size determined the amount of slurry each received. Each section had a drain (7) in the bottom from which the slurry flowed through a vinyl tube into the desired aquarium. Thus, an individually controlled and constant amount of slurry was continuously introduced to each aquarium.

17. To produce the desired suspended sediment concentrations, complementary volumes of water of the proper salinity were added to each aquarium with the slurry using a modified form of the serial dilution apparatus of Mount and Brungs (1967). Water flowed through a timed solenoid water introduction valve (8) into a Plexiglas trough divided into eight siphon chambers (9), each of which filled and overflowed into the next and finally into a drain (10). The water introduction valve then closed, and the excess water drained down to the top of the partitions. Each chamber had an adjustable siphon (11) running to the corresponding section of the distributor trough. The siphons were also connected to a common aspirator line through a solenoid siphon activator valve (12). When the water chambers were full and stable, the siphon activator valve was opened just long enough to start the siphons. These delivered the desired volume of water to complement the amount of slurry already introduced into each section of the distributor trough and thus into the aquaria. The clear water control aquaria received their water directly from the siphon chambers, bypassing the slurry distributor trough. An identical system fed each of the three sets of eight aquaria.

18. Salinity was controlled by mixing seawater from the laboratory system with fresh water from a spring-fed pond. The seawater recirculated through a 20-μm sand filter and passed through an

ultraviolet sterilizer into a head tank. The fresh water was drawn from middepth in the center of the pond and pumped directly into a second head tank. Valves regulated the flow of water from both tanks into a common pipe which delivered the controlled salinity water to the aquarium siphon chambers. All siphon chambers were filled through the same set of valves, producing similar salinities in all aquaria. The introduction of oxygen-saturated water and the action of the circulating pumps maintained high dissolved oxygen concentrations in all aquaria.

19. The heat exchangers were of baffled counter-current design with the aquaria water passing through titanium or 316 stainless steel tubes. The controlling water in the heat exchangers was maintained at the proper temperature by an electrical feedback system controlling a proportioning valve and a set of hot and cold water supply valves. These controlled flow from a 55-gallon drum with an immersion heater and a similar tank cooled by a 10-ton refrigeration unit. A thermistor in one of the aquaria provided a signal to the controller unit which actuated the appropriate set of valves, permitting hot or cold water to circulate through the heat exchanger body as needed to maintain a stable temperature in the aquaria. The proportioning valve allowed recirculation of the water in the heat exchanger body and bled in just enough of this new water to make the desired change. This design prevented large or rapid oscillation and minimized the load on the refrigeration unit.

20. A record of temperature, conductivity, dissolved oxygen, pH and suspended sediment concentration in each aquarium was provided by a remote automatic monitoring system. The pumped circulating water line of each aquarium had a branch line which diverted some water through a solenoid valve into a column containing sensors for the above parameters. An electronic scanner periodically energized each solenoid valve in turn, diverting a portion of the circulating water from each aquarium past the sensors. After 4 minutes the instrument outputs were recorded and sampling of the next aquarium began, providing monitoring of all five parameters in each aquarium every 96 minutes. The data were stored on magnetic tape for later analysis.

21. The temperature, conductivity, dissolved oxygen and pH

monitors were part of a Martek shipboard instrument package adapted for use in the flow-through sensor column. The temperature-sensing thermistors and conductivity induction cell were factory calibrated and verified against precise laboratory instruments. The dissolved oxygen meter was calibrated against Winkler titrations, and the pH meter was calibrated using standard buffer solutions.

22. Suspended sediment concentrations were monitored by one of two instruments through which the water passed after leaving the sensor column. Low concentrations were measured with a Dynatrol, in which the water sample is pumped through a tube set into mechanical vibration by and electric drive coil. Vibrational frequency, which is dependent upon the density of the medium in the tube, is sensed by a pickup coil and converted to an electrical output signal. Higher concentrations were monitored with a Densitrol, which consists of a plummet with a magnetic core submerged in a flow-through chamber. The chamber is surrounded by an induction coil in which a current is induced whose strength is determined by the vertical position of the plummet as it moves in response to density changes in the fluid surrounding it. The instruments were calibrated against filtered and weighed samples from the aquaria so that a weight per volume measurement of suspended sediment concentration could be obtained. Samples were pipetted from the aquaria, filtered through 0.45-μm-pore-size membrane filters, washed with distilled water, dried and weighed. A calibration curve was developed by comparing the means of three replicate pipette samples to simultaneously obtained instrument outputs, providing reliable measurements of concentration on a weight per volume basis.

23. Animals were held before testing in three 2- by 3- by 6-ft wooden tanks in which temperature and salinity were controlled. Water was mixed to the proper salinity by a pair of valves at the head tanks and introduced at a rate giving 50 percent replacement in approximately 4 hours. Temperature was controlled by continuously pumping the water through a thermostatically controlled three-way valve into a stainless steel coil in either the hot or cold water reservoir of the aquaria temperature control system.

Sediment Collection and Handling

24. The sites for collection of experimental sediment, all within the Sacramento River-San Francisco Bay system, were chosen to provide material physically similar to the bentonite used in earlier experiments, differing only in chemical characteristics. Antioch Harbor on the Sacramento River was the source of the freshwater experimental sediment, which was intended to be relatively free of potentially toxic contaminants. Uncontaminated sediment for the marine and estuarine experiments was from Mare Island Channel in the oligohaline reaches of the Napa River. Contaminated sediment for the marine and estuarine experiments was collected from Oakland Inner Harbor, a heavily industrialized shipyard area in the polyhaline reaches of San Francisco Bay.

25. All sediment was collected at in situ density in plastic-lined, 55-gallon drums. These were dragged into the bottom, sealed, and maintained at 1°to 4°C. Shortly after they were filled with sediment at each sediment collection site, a subsample for chemical and physical analyses was taken from 6 to 10 of the drums. These were sealed and stored at 1°to 4°C until analyzed.

26. When needed for the experiments, the contents of a drum were shovelled into a mixing tank, and water of approximately the salinity at which that experiment was to be conducted was added. The sediment and water were mixed into a slurry with a high shear impeller designed to disperse aggregates. While mixing, large debris such as twigs, plant remains, shell fragments, etc., were dipped out with a net of nylon window screen. The slurry was then pumped into the laboratory slurry reservoir tanks from which it was proportioned into the experimental aquaria. Slurry entered the reservoirs through a large bag of 500-µm nylon net which removed most of the coarse sand and fragments of shell and debris.

27. Once in the reservoir tanks, the slurry was diluted with water of the desired salinity to exactly the proper concentration on a weight per volume basis. For all experiments using Mare Island sediment, the slurry was mixed to 25 percent solids, while 10 percent slurry was used

in all experiments with Antioch and Oakland sediments. The slurry was kept suspended in the reservoir tanks by turbulent mixing with large stirrers which aerated the slurry, thus gradually changing its oxidation state and redox potential. In all experiments with uncontaminated sediments, slurry was mixed in batches, one of which was used completely before the next was mixed. Since use of each batch began shortly after it was mixed, the oxidation state of the material to which the animals were exposed progressed from reduced toward oxidized as each batch of slurry was used. The contaminated sediment experiments were begun with oxidized slurry to which small amounts of new slurry were added at frequent intervals to keep the reservoir full. Thus, the animals received material in a relatively uniform state of oxidation throughout these experiments. Regardless of its oxidation state in the slurry reservoirs, the material was rapidly oxidized when it entered the aquaria.

Sediment Characterization

28. *Chemical and physical characterizations* of the test sediments were performed on samples taken from the drums at the time of sediment collection. Samples were mixed thoroughly under a nitrogen atomosphere and separated into various operationally defined fractions for analysis as described below:

a. Interstitial water. While under the nitrogen atomsphere a sediment subsample was placed in a polycarbonate 500-ml centrifuge tube and centrifuged at 9000 rpm (13,000 g's) for 5 minutes at 4°C. The resultant liquid portion was vacuum-filtered through 0.45-µm-pore-size membrane filters and immediately acidified to pH 1 with HCl. The interstitial water so obtained was stored in prerinsed plastic bottles for analysis.

b. Exchangeable phase. A 20-g subsample was weighed into oxygen-free, tared 250-ml centrifuge tubes containing 100 ml of deoxygenated 1 N ammonium acetate adjusted to the in situ sediment pH. The centrifuged tubes were sealed and shaken for 1 hour. The liquid was separated by centrifugation and oxygen-free filtration through 0.45-µm-pore-size membrane filters then acidified to ph 1 with HCl and stored in prerinsed plastic bottles. This procedure also removed the interstitial water. Therefore, specific

concentrations of constituents were corrected for the mass of each constituent found in the interstitial water.

c. Elutriate tests. A portion of the sediment sample was placed in four parts water from the sediment collection site. This mixture was placed in a sealed flask and shaken vigorously for 30 minutes followed by 1 hour of settling. The supernatant was then centrifuged and filtered through a 0.45-μm-pore-size membrane filter.

d. Total metal analysis. Using a procedure modified from Smith and Windom (1972), a sediment subsample was air dried, ground, and digested with 15 ml of HF and 10 ml of HMO_3 in a covered Teflon beaker at approximately 175°C. Following evaporation to near dryness, 8 ml of fuming HNO_3 was added in 2-ml increments with evaporation to near dryness following the addition of each increment. The residue was then dissolved in hot 1:1 HCl and brought to a volume of 50 ml. Total mercury in the sediments was determined according to the method given in "Methods for Chemical Analysis of Water and Wastes" (EPA, 1974).

e. Total chlorinated hydrocarbons. These compounds were extracted from a wet sediment sample with 15 percent methylene chloride in hexane. The extract was passed through a sodium sulfate column, collected in a Kuderna-Danish concentrator and concentrated to 5 to 10 ml prior to elution on an activated florisil column. Elution was carried out first with 100 ml of petroleum ether and then with 50 ml of 6 percent ethyl ether and 94 percent petroleum ether. Polychlorinated biphenyls (PCB's) were recovered in the first elution, DDT and its derivatives in the second and other chlorinated hydrocarbons in the final elution. Each eluted sample was concentrated to a measured volume and treated with Hg to remove sulfur.

29. The interstitial water, exchangeable and elutriate phases were analyzed for orthophosphate ($O\text{-}PO_4$), ammonium nitrogen ($NH^+_4\text{-}N$) and the metals As, Cd, Cu, Fe, Hg, Mn, Ni, Pb, Se and Zn. Total sediment analyses were performed for the above metals, total sulfides ($TS^=$), total phosphorus (TP), total Kjeldahl nitrogen (TKN), the chlorinated hydrocarbons chlordane, heptachlor, dieldrin, aldrin, endrin, DDT and its metabolites and PCB's. Not all of the above parameters were measured on every sediment sample.

30. A Perkin-Elmer Model 503 atomic absorption spectrophotometer was used in all metal determinations except As and Hg. Direct flame aspiration with a deuterium arc background corrector was utilized when

concentrations exceeded instrument detection limits. For lower concetrations, extracts were analyzed by the method of standard additions using a Perkin-Elmer Model 2100 heated graphite atomizer. Arsenic was determined using a hydride generator (Perkin-Elmer Corp., 1974) or, when this method gave poor recovery of spikes, the heated graphite atomizer. Mercury in the elutriate was determined using the cold vapor method (EPA, 1974).

31. A Hewlett-Packard Research Gas Chromatograph Model 5750 equipped with a Ni^{63} electron capture detector and using a carrier gas of 95 percent argon and 5 percent methane was used for chlorinated hydrocarbon analysis. Sample components were identified by comparison of retention times of unknown peaks to known peaks of reference standard solutions and were quantified by comparison of peak height of the identified component to peak height of that component in the reference standard solution.

32. Ammonium nitrogen and orthophosphate concentrations in the interstitial water and elutriate were determined using a Technicon Autoanalyzer II. Cation exchange capacity was determined on a wet subsample of the well-mixed sediment samples using the method of Jackson (1958). The procedure involves saturating the wet sediment samples with ammonium acetate buffered at pH 7, removing the excess ammonium with isopropyl alcohol, and then extracting the ammonium saturated sediments with a series of 2N potassium chloride solutions.

33. Sediment samples were not chemically dispersed before particle size distribution was determined. Sand:silt:clay ratios were determined by wet screening and pipette analysis by the method of Folk (1974) using water from the sediment collection site.

Animal Collection

34. The experimental species represented a variety of phylogenetic groups and feeding types and were common, widely distributed and ecologically important. All species tested are shown in Appendix Tables A1, B1, B3, C1, and C3 with pertinent data on collection and holding

conditions. Where possible, species used by Peddicord et al. (1975) were also included here for maximum continuity and to allow comparison of effects of various types of particles.

Experimental Conditions

35. The 24 experimental aquaria were arranged in three sets of eight, each set containing two clear water control aquaria and six with suspended sediment concentrations spanning one order of magnitude in an approximately logarithmic progression. While this theoretical distribution was not precisely achieved, the concentrations were stable and close to the intended values. Most organisms were tested over a nominal concentration range of 2 to 20 g/l, but the larval freshwater organisms, the rainbow trout and the striped bass were tested over a nominal range of 0.4 to 4 g/l.

36. All experiments were run for 21 days except the contaminated sediment phase of the marine experiment, which was continued for 25 days of exposure. All mortality experiments included 15 to 20 individuals of a species in every suspended sediment concentration. In some cases two nonantagonistic species, isolated in separate baskets so no direct contact could occur, were tested simultaneously in the same aquaria. During the chemical uptake study about 30 shrimp, 100 mussels and 70 fish for chemical analyses were placed in the aquaria in addition to, but isolated from, those to be observed for mortality. Throughout every experiment all animals were fed three times per week, the filter feeders with Phaeodactylum tricornutum, the fish with adult brine shrimp and the crustaceans with squid.

37. All experiments were conducted within $\pm 2^{\circ}C$ of the temperature and ± 3 °/oo of the salinity at which the animals were collected. Dissolved oxygen was not controlled but, due to the active circulation in the aquaria and constant introduction of well-aerated water, remained near or above 8 ppm in all cases. All marine organisms were tested at 33 °/oo salinity and at $10^{\circ}C$ with the uncontaminated sediment and

12°C with the contaminated sediment. The estuarine species were all tested at 24 °/oo salinity and at 12°C with uncontaminated sediment and 14°C with contaminated sediment. The freshwater species were tested with uncontaminated sediment at 15°C. Slurry and water were introduced to the aquaria at a rate producing 50 percent replacement of the aquaria contents in 6 hours for the uncontaminated sediment experiments. Fifty percent replacement in 12 hours was used in the contaminated sediment experiments for all species except striped bass Morone saxatilis for which the 6-hour rate was used.

38. To begin an experiment, the aquaria were filled with water of the desired temperature, salinity and suspended solids concentration. The animals, which had previously been counted into baskets in the holding tanks, were then placed in the aquaria. All mussels were allowed to form firm byssal attachments to their test containers before being introduced to the test aquaria. Animals were observed daily at approximately 24-hour intervals throughout the experiments. The death criterion was the absence of any detectable movement in response to gentle probing of some sensitive area, usually the eye, siphon tips, mantle edge or mouth region. Tunicates whose condition was uncertain were placed in clear water of the same temperature and salinity for 30 minutes and considered dead if still unable to close the inhalent siphon upon probing after that time. Daily records were kept of the crustaceans that died in the process of molting, the number which molted successfully and the number of dead animals bearing eggs. The number of mussels in each aquarium which had lost their byssal thread attachments was recorded at each observation.

39. After the experiments with contaminated sediment, the aquaria were refilled with clear water of the same temperature and salinity. Survivors were observed for an addition 4 days (marine test) or 5 days (estuarine test) to determine whether mortalities continued to occur during a postexposure period after removal from high suspended sediment concentrations.

40. Prior to the uncontaminated sediment phase of the estuarine experiment, the shell length of individual Mytilus edulis was measured

to the nearest 0.1 mm. After the 21-day exposure period, 11 survivors from each aquarium were again measured and the individual increments of shell length increase determined.

41. At the end of the estuarine uncontaminated sediment experiment, 10 surviving striped bass Morone saxatilis from each aquarium were sacrificed for examination. The hematocrit, or percentage of the whole blood volume that is blood cells, was determined by a method modified from Snieszko (1960). The fish were individually netted from the aquaria, the caudal peduncle immediately severed and one to three heparinized microhematocrit tubes filled from the caudal artery. Tubes were centrifuged for 20 minutes at 3675 rpm and hematocrit determined. Stomachs of the fish were then excised, dried for 48 hours at 80°C, and the weight of each stomach and its contents was determined. They were then ashed at 500°C for 20 minutes and the residue weighed. This residue included a small contribution from the stomach tissue, which was determined from the control fish, but increases above this value were attributed to sediment contained in the stomachs of the exposed fish. The influence of fish size on the results was overcome by expressing ashed weight as a percent of dry weight for each individual.

Data Analysis

42. The mortality data are presented in plots of percent survival in each aquarium versus exposure time. Where sufficient mortalities occurred, LC50, LC20 and LC10 values (the concentration lethal to the stated percent of the sample) were calculated. The LCX values for all time intervals were then regressed on exposure time to estimate the time-concentration mortality response. By calculating the concentration lethal to 10, 20 and 50 percent of the animals, the effects on the most sensitive portions of the population were evaluated.

43. The mean concentration of the suspended solids in each aquarium prior to the time of every animal observation was determined for correlation with the mortalities. The observed mortalities in each test aquarium were adjusted for any deaths in the control aquaria by the method of Bliss (1935).

44. The mean concentration and adjusted mortality data were used to derive LCX estimates for every observation time by the logit method of Berkson (1953). The mortality data adjusted for control tank deaths were converted to logits (defined as ln (P/1-P), where P is the proportion responding, or dying). The logits of the mortalities in every aquarium were then regressed on the corresponding suspended solids concentrations to determine the relationship of mortality to concentration. Least-squares regressions were calculated using both arithmetic concentration values and natural logarithms of the concentrations, and the equation having the highest coefficient of determination (r^2) was used. From this equation the concentration producing any logit, that is, any percent mortality, could be estimated.

45. The LCX values were then regressed on exposure time to estimate the time-concentration mortality response. A family of curvilinear least-squares regression equations describing smooth curves were fitted to the data points. The equation that fit the data best, as indicated by the highest r^2, was used to describe each set of data. The time-concentration mortality curves did not include any LCX estimates higher than the highest suspended solids concentration tested and began with the first estimate derived after X percent mortality was actually reached.

46. Shell growth data of individual Mytilus edulis during the estuarine uncontaminated sediment experiment were converted to increments of length increase for analysis. The relationship of length increase to suspended sediment concentration was determined by a least-squares regression with multiple observations of Y (individual increments of shell length increase) for every observation of X (suspended sediment concentration), as presented by Sokal and Rohlf (1969).

47. The same statistical procedure was applied to the striped bass Morone saxatilis stomach contents from the uncontaminated sediment phase of the estuarine experiment. The means of the replicate hematocrit values from each fish were taken as representative of the individual fish, and these means were also regressed on suspended sediment concentration by the same technique.

Chemical Uptake Study

48. A study of the uptake of selected chemicals was conducted in conjuction with the mortality experiments with contaminated sediment. Survivors from the contaminated sediment phase of the marine test were analyzed for the metals As, Cd, Cu, Fe, Hg, Mn, Ni, Pb and Zn, the chlorinated hydrocarbons chlordane, heptachlor, dieldrin, aldrin and endrin, DDT and its derivatives and PCB's. Those organisms analyzed were Mytilus edulis, M. californianus, Crangon nigromaculata and Cancer magister from the controls, a pooled sample of survivors from all suspended sediment concentrations at the end of the exposure period and a pooled sample from all concentrations after the 4-day postexposure period in clear water.

49. A more detailed study of uptake of the above chemicals was conducted with the mussel Mytilus edulis in the contaminated sediment phase of the estuarine test. When the mussels were collected from the field, 25 were preserved for analysis. Sufficient animals in addition to those for the mortality test were placed in each aquarium to allow periodic sampling of 25 M. edulis for chemical analysis. Control animals were sampled on days 3, 10, 15 and 21 of the experiment. Animals exposed to nominal suspended sediment concentrations of 4, 12 and 16 g/l for the 21-day test period were placed in clear water for 5 days to purge the sediment from the digestive tract and body surfaces. Twenty-five mussels which had been exposed to each suspended sediment concentration, as well as 25 control mussels, were sacrificed for analysis at the end of this purging period.

50. Mussels were removed from the shell with stainless steel knives, placed in acid-washed plastic vials and stored at 1° to 2°C until analyzed. When prepared for analysis, the inner portions of each sample not touching the plastic container were analyzed for organic compounds, and the outer portions were used for metals analysis. Part of each water sample was collected in glass for organics analysis and part in plastic for metals analysis. All water samples were stored at 1° to 2°C until analyzed.

51. For metals analyses the tissue samples were ground in an acid-rinsed porcelain mortar. About 0.5 g of ground sample was digested for 6 to 8 hours at 80° to 90°C in 5 ml Ultrex HNO_3 and a few drops of HF. The water samples were well shaken to resuspend all particulates and a 15-ml subsample digested as described above. Mercury was determined on whole water or tissue samples to which 5 ml Ultres HNO_3 and 4 drops of HF had been added. This mixture was sealed in a Teflon bomb and heated to 90°C for 5 to 8 hours. All digests were analyzed for metals on a Perkin-Elmer Model 305B atomic absorption spectrophotometer. Flame atomic absorption was used for high concentrations, but direct injection into a heated graphite atomizer was required to measure most metals. A deuterium arc background corrector lessened interferences from volatile salts. Mercury was measured by flameless atomic absorption. All metals concentrations were expressed on a wet weight basis.

52. Chlorinated hydrocarbons were determined by grinding a 1- to 5-g tissue sample to a powder with an equal amount of anhydrous crystalline sodium sulfate. This powder was placed in a soxhlet apparatus and extracted at 70°C for 4 hours with 200 ml of petroleum ether. Water samples were extracted by liquid-liquid partition. A 1-litre whole water sample was shaken in 15 percent methylene chloride in hexane in a separatory funnel. The extract, which for water samples was first passed through a sodium sulfate column, was collected in a Kuderna-Danish concentrator and concentrated to 5 to 10 ml prior to elution on an activated florisil column. Elution was carried out first with 100 ml of petroleum ether, then with 50 ml of 6 percent ethyl ether and 94 percent petroleum ether and finally with 75 ml of 15 percent ethyl ether and 85 percent petroleum ether. PCB's were recovered in the first elution, DDT and its derivatives in the second and other chlorinated hydrocarbons in the final elution. Each eluted sample was concentrated to a measured volume and treated with Hg to remove sulfur before injection into the gas chromatograph.

53. A Hewlett-Packard Research Gas Chromatograph Model 5750 equipped with a Ni^{63} electron capture detector and using a carrier gas of 95 percent argon and 5 percent methane was used for analyses. Sample

components were identified by comparison of retention times of unkown peaks to known peaks of reference standard solutions and were quantified by comparison of peak height of the identified component to peak height of that component in the reference standard solution.

PART IV: EXPERIMENTAL RESULTS

Sediment Characterization

54. The uncontaminated and contaminated sediments used in the saltwater tests were shown to be generally similar in particle size distribution, as indicated in the following tabulation:

	Uncontaminated Saltwater Sediment			Contaminated Saltwater Sediment		
	% Sand >50 μm	% Silt 2-50 μm	% Clay <2 μm	% Sand >50 μm	% Silt 2-50 μm	% Clay <2 μm
Mean	5	83	12	33	65	2
Standard deviation	3.0	10.1	9.3	15.3	16.2	4.1
Number of samples	6	6	6	8	8	8

An unknown but substantial portion of the sand-sized particles was reremoved while screening the slurry as it entered the reservoir tanks and, by sedimentation in those tanks, before the material was proportioned into the test aquaria. Therefore, the animals were exposed primarily to the silt and clay fractions. A Student's t-test did not show differences at the 0.05 probability level between the percentages of silt or clay in the two sediments. It is these fractions which remain in suspension for the longest periods in the field. No particle size analyses are available for the freshwater sediment, although it was selected to have a size distribution generally similar to the other sediments.

55. General chemical characterizations of all experimental sediments are provided in Tables 1, 2 and 3. Table 4 summarizes the results of statistical comparisons of contaminant concentrations in the three sediments. From these tables it can be seen that the choice of sediments from Mare Island as relatively uncontaminated for comparison with relatively more contaminated Oakland sediment was appropriate on the basis of the parameters measured. No materials of potential toxicological concern were higher in the uncontaminated sediment than in the contaminated sediment (Table 4). The only material which exceeded water quality criteria (EPA, 1976) in the uncontaminated elutriate was NH_4^+-N

Table 1

Chemical characterization of freshwater sediment. Data on a wet-weight basis are presented as mean over standard deviation.

Parameter	Sediment Fraction			
	Total mg/kg*	Exchangeable mg/kg*	Interstitial Water - mg/l*	Elutriate mg/l*
pH	6.3 0.06	--	--	--
Eh	-148 48.8	--	--	--
Cd	6.0 3.0	--	--	--
Cu	40 14.6	0.21 0.07	0.02 0.01	0.01 0.01
Fe	23.8 g/kg 2.6	2.4 g/kg 0.8	3.4 1.3	0.9 0.4
Mn	322 85.5	99 33.7	3.2 3.2	0.3 0.07
Ni	123 13.5	--	--	--
Pb	11.3 3.3	--	4 µg/l 2.3	<0.02 µg/l
Zn	79 32.5	--	--	0.05 0

* Unless other unit is indicated. Five samples represented in elutriate data; other fractions represent six samples. -- indicates not analyzed.

Table 2

Chemical characterization of uncontaminated sediment used in the estuarine and marine tests. Data on a wet-weight basis are presented as mean over standard deviation. Means in brackets exceed water quality criteria for the protection of marine life (EPA, 1976).

	Sediment Fraction			
Parameter	Total mg/kg*	Exchangeable mg/kg	Interstitial Water - mg/l*	Elutriate mg/l*
Ortho-P	--	--	8.3 2.5	0.43 0.12
NH_4^+-N	--	--	7.6 2.8	[1.78] 1.37
As	2.3 1.4	<0.25	26 µg/l 15.6	5.3 µg/l 1.6
Cd	1.1	<0.002	5.2 ng/l 3.4	0.93 µg/l 0.21
Cu	35.3 2.8	<0.005	5.9 µg/l 6.1	4.2 µg/l 3.0
Fe	2.6% 0.2	121.1 88.1	6.1 0.9	0.54 0.68
Hg	0.48 0.07	--	--	--
Mn	329 26.0	54.0 8.0	3.3 1.0	0.18 0.06
Ni	63.0 g/kg 6.8	<0.02	<0.2	<0.2

* Unless other unit is indicated. Ten samples are represented in total data while the other factions represent thirteen samples. -- indicates not analyzed.

Table 3

Chemical characterization of contaminated sediment used in the estuarine and marine tests. Data on a wet-weight basis are presented as mean over standard deviation of 8 samples. Means in brackets exceed water quality criteria for the protection of marine life (EPA, 1976).

	Sediment Fraction			
Parameter	Total mg/kg	Exchangeable mg/kg	Interstitial Water - mg/l	Elutriate mg/l
% water	48.3 4.4	--	--	--
pH	7.8 0.2	--	--	--
Eh	-414 58.8	--	--	--
Total Sulfides	6148 606	--	--	--
Total Phosphates	878 197	--	--	--
Ortho-P	--	--	2.3 0.6	1.4 0.6
TKN	0.15% 0.03	--	--	--
NH_4^+-N	--	88.8 10.5	--	[3.49] 0.67
As	128 33.6	0.50 0.35	0.12 0.04	0.14 0.03
Cd	2.3 0.74	1.09 0.22	0.16 0.03	[0.14] 0.02
Cu	158 73.6	1.6 0.4	0.10 0.08	0.06 0.02
Fe	3.62% 1.15	--	2.5 1.4	0.18 0.05
Mn	333 85.6	114 63	5.1 3.5	0.49 0.23

(Continued)

-- indicates not analyzed.

Table 3 (Concluded)

Parameter	Sediment Fraction			
	Total mg/kg	Exchangeable mg/kg	Interstitial Water - mg/l	Elutriate mg/l
Hg	1.47	0.55	0.15	[0.16]
	0.93	0.20	0.06	0.04
Ni	104	62.4	6.4	9.6
	18.5	14.8	1.3	0.4
Se	1.49	0.62	0.48	0.46
	0.39	0.06	0.04	0.05
Zn	381	4.0	0.12	0.04
	301	1.8	0.07	0.01
Total PCB's	1.30 *	--	--	--
Total DDT**	0.750 *	--	--	--

-- indicates not analyzed.
* All organics were measured on only one sample.
** Chlorinated hydrocarbon pesticides below detection limits were: aldrin, dieldrin and heptachlor < 0.004 ng/g; clordane < 0.008 ng/g; endrin < 0.1 ng/g.

Table 4

Comparison of chemical characteristics of the contaminated and uncontaminated sediments used in the marine and estuarine experiments.

	Sediment Fraction			
Parameter	Total	Exchangeable	Interstitial Water	Elutriate
As	C	C	C	C
Cd	C	C	C	C
Cu	C	C	C	C
Fe	C	N.D.	U	U
Mn	=	C	=	C
Hg	C	N.D.	N.D.	N.D.
Ni	U	C	C	C
Ortho-P	N.D.	N.D.	U	U
NH_4^+-N	N.D.	N.D.	N.D.	C

Note: Entries as defined below are based on results of t-tests (P = 0.05).

C - indicates significantly higher concentration in contaminated sediment.

U - indicates significantly higher concentration in uncontaminated sediment.

N.D. - indicates no comparative data available.

= - indicates no significant difference in concentration in contaminated and uncontaminated sediments.

(Table 2). In contrast, the parameters measured in the contaminated elutriate exceeded water quality criteria (EPA, 1976) for every material for which numerical limits for the protection of marine life have been established (Table 3).

Freshwater Experiment

56. The conditions under which the experimental animals were collected, held in the laboratory and tested are presented in Appendix A.

Crayfish Pacifastacus leniusculus

57. Most of the freshwater test species proved relatively tolerant to suspensions of uncontaminated sediment. Very little mortality occurred during the 21-day experiment with crayfish Pacifastacus leniusculus 8 to 10 cm in total length. The only deaths were at 8.2 and 12.8 g/l, in both of which 1 of the 16 test animals died (Fig. 2). This lack of substantial mortality directly attributable to the experimental conditions indicates a tolerance to suspended sediment concentrations of at least 20 g/l for 21 days under the experimental conditions of sediment composition, temperature, dissolved oxygen, animal size and condition, etc.

Asiatic clam Corbicula fluminea

58. No mortality occurred during the first 16 days with 4- to 5-cm-long Asiatic clams Corbicula fluminea, but by 21 days of exposure mortality had reached 37 percent at 20.7 g/l and 20 percent at 15.8 and 12.8 g/l (Fig. 3). In all lower concentrations and the controls, there was total survival throughout the test. This relatively sharp mortality toward the end of the test may indicate a maximum tolerance of about 16 to 20 days exposure to suspended sediment concentrations of 12 to 16 g/l for C. fluminea under the experimental conditions.

Damselfly larvae Enallagma sp.

59. The experiment with final instar naiad larvae of the damselfly Enallagma sp. was marred by deaths in the control aquaria and by escapes from the baskets and loss in the circulating pumps. However, the data did indicate an erratic trend toward increasing mortality with

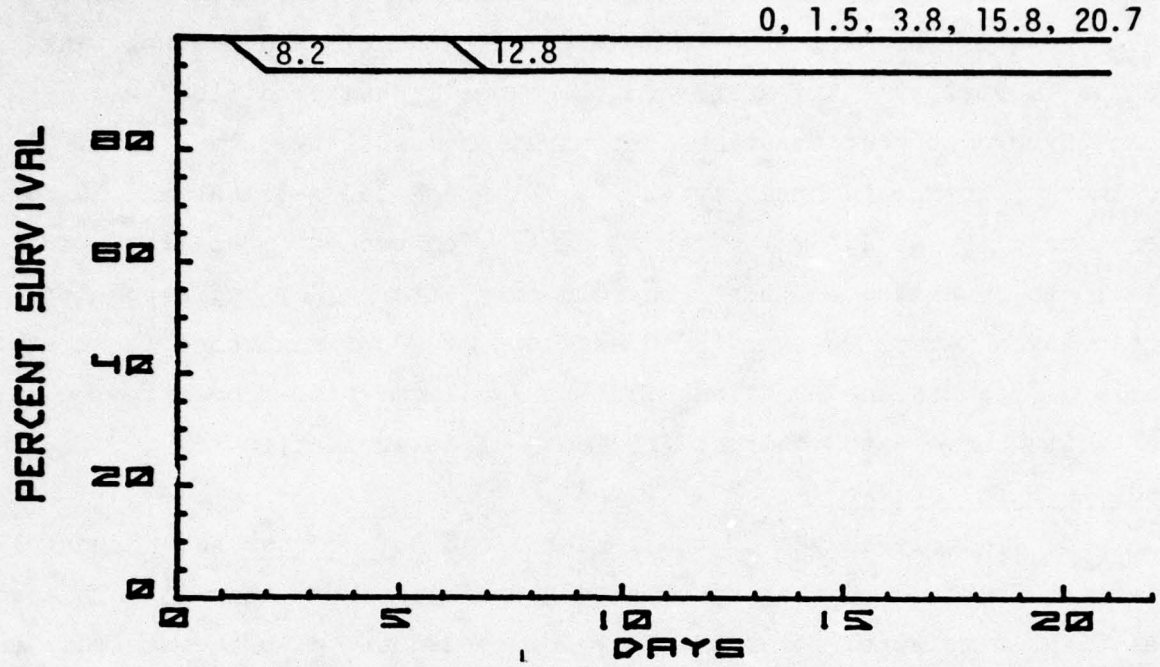


Fig. 2. Percent survival of 8- to 10-cm crayfish Pacifastacus leniusculus in suspensions of uncontaminated sediment at 16°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

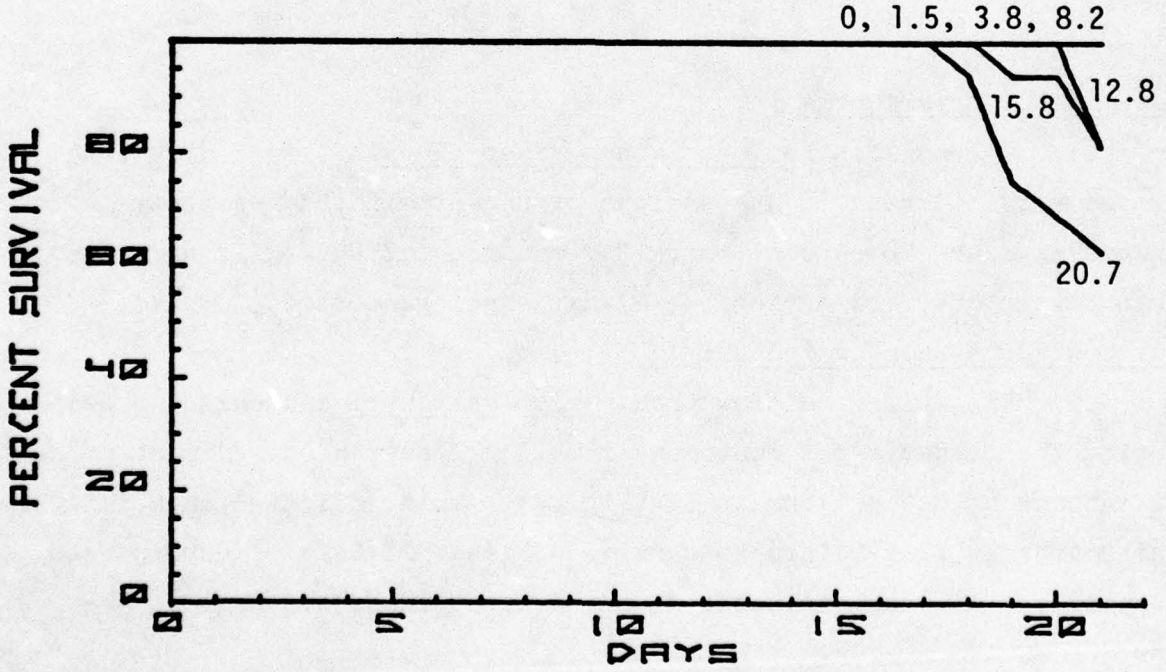


Fig. 3. Percent survival of 4- to 5-cm-long clams Corbicula fluminea in suspensions of uncontaminated sediment at 16°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

increasing exposure time and suspended sediment concentration (Fig. 4). When the data were adjusted for the missing animals and control tank deaths, mortality attributable to the experimental conditions was less than 50 percent, but the time-concentration mortality curves (Fig. 5) estimate 10 percent mortality at 0.8 g/l suspended sediment and 20 percent mortality at 2.1 g/l after 21 days. Ten percent mortality attributable to suspended sediment occurred only after 4 days of exposure, producing a 4-day (96-hour) LC10 estimate of 2 g/l suspended sediment. Table 5 presents the equations for the Enallagma time-concentration mortality curves and their coefficients of determination (r^2).

Tadpole Bufo boreas

60. Tadpole larvae of the western toad Bufo boreas had no mortalities attributable to the experimental conditions until day 13. This was the first time mortalities at 4.5 g/l exceeded those in the controls and lower concentrations. Survival had decreased to 40 percent at 4.5 g/l by day 21 (Fig. 6). Thus, these larvae appear able to survive in suspensions of 2.7 g/l of uncontaminated sediment for at least 21 days, compared to about 13 days in 4.5 g/l.

Golden shiner
Notemigonus crysoleucas

61. Golden shiners Notemigonus crysoleucas 4.5 to 5.5 cm long proved very tolerant to suspensions of uncontaminated sediment. After 4 days exposure 20 percent mortality occurred at 20.7 g/l; no other deaths were observed during the 21-day exposure period (Fig. 7).

Rainbow trout Salmo gairdneri

62. Fingerling rainbow trout Salmo gairdneri had only two deaths during the 21-day experiment, one in 4.3 g/l suspended sediment on day 12 and one at 0.2 g/l on day 19 (Fig. 8). This indicates an ability for rainbow trout fingerlings to survive at least 21 days of exposure to suspensions of uncontaminated sediment of at least 4.3 g/l.

Marine Experiment

63. The conditions under which the experimental animals for the marine test were collected, held in the laboratory and tested are shown

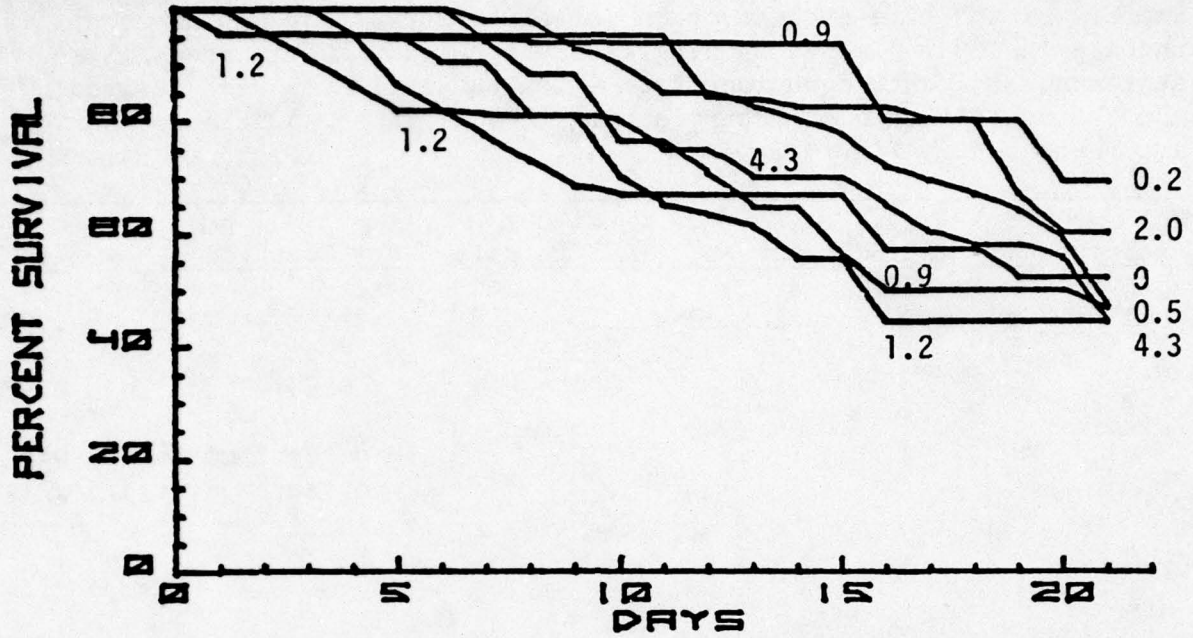


Fig. 4. Percent survival of larval damselflies Enallagma sp. in suspensions of uncontaminated sediment at 15°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

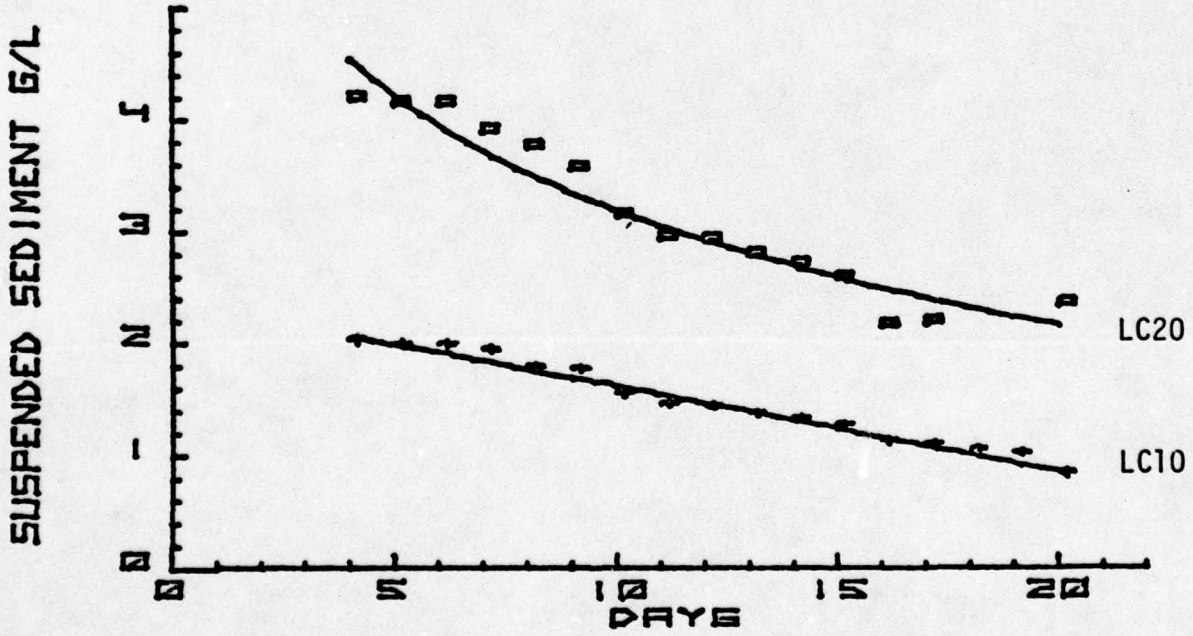


Fig. 5. Time-concentration mortality curves for larval damselflies Enallagma sp. in suspensions of uncontaminated sediment at 15°C and 8 ppm dissolved oxygen

Table 5

Summary of the time-concentration mortality curves for Enallagma sp. in uncontaminated sediment, showing estimated 21-day LCX in grams/litre of suspended sediment, equations from which the estimates were derived, and the coefficients of determination (r^2) of those equations. Curves are presented in Fig. 5.

Species	Sediment	21-day LCX in g/l	Equation	r^2
Enallagma sp.	Uncontaminated	LC10 = 0.8	y = 2.36 - .76 X	0.98
		LC20 = 2.1	y = 6.59 - 1.48 lnX	0.93
		LC50	50 percent mortality was not reached at 4.3 g/l	

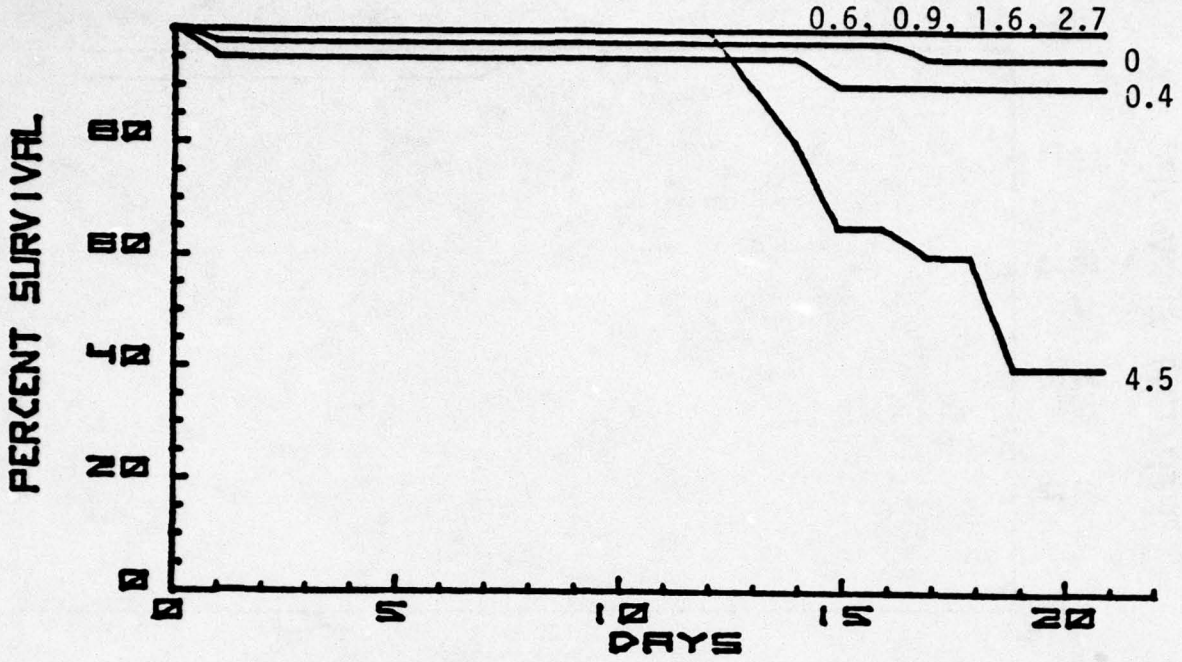


Fig. 6. Percent survival of western toad Bufo boreas tadpoles in suspensions of uncontaminated sediment at 15°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

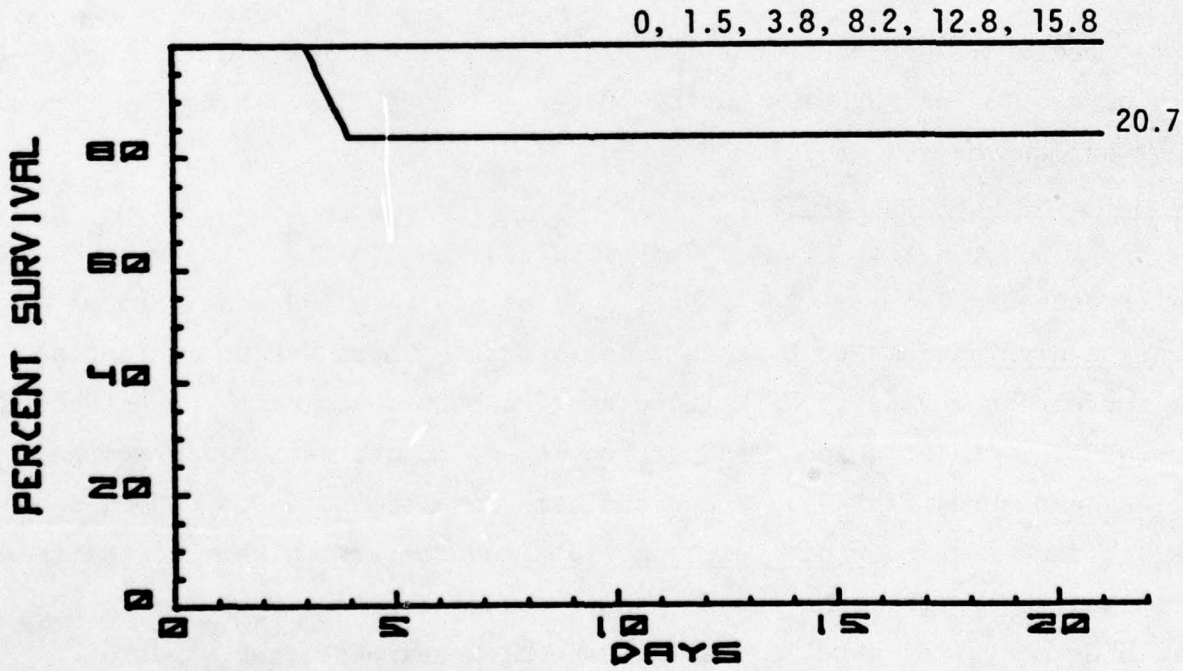


Fig. 7. Percent survival of 4.5- to 5.5-cm golden shiners Notemigonus crysoleucas in suspensions of uncontaminated sediment at 16°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

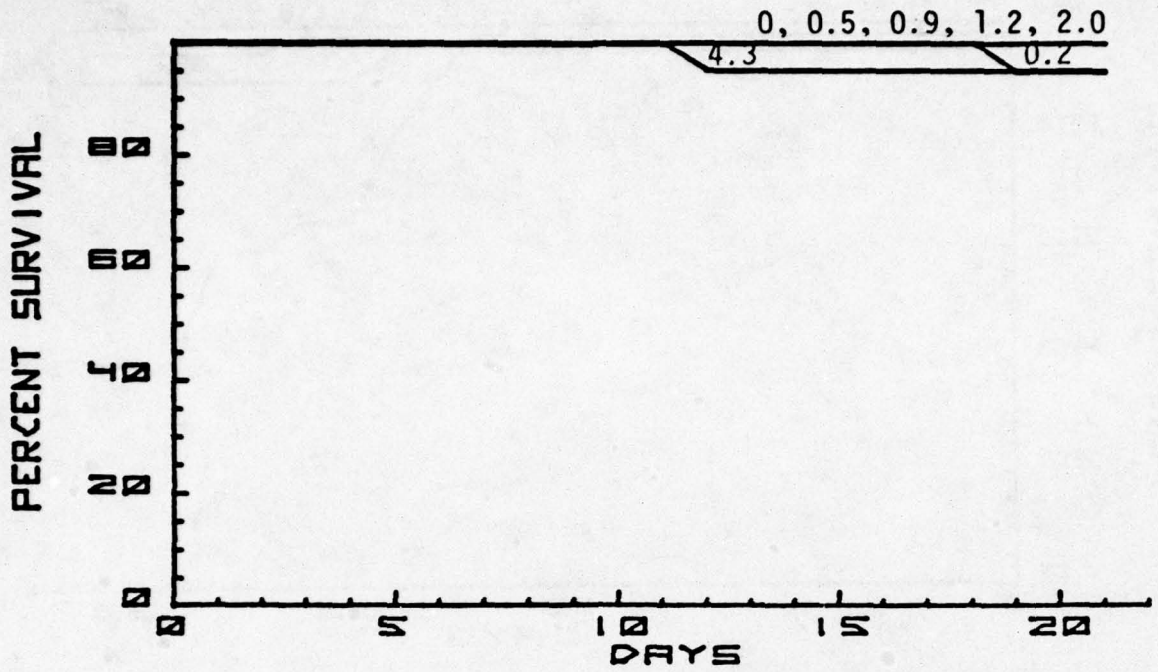


Fig. 8. Percent survival of fingerling rainbow trout Salmo gairdneri in suspensions of uncontaminated sediment at 15°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

in Appendix B. The equations describing the time-concentration mortality curves for all species having 50 percent mortality during the marine test are summarized in Table 6.

Sand shrimp Crangon spp.

64. Suspensions of uncontaminated sediment in full strength seawater caused relatively few mortalities of black-tailed sand shrimp Crangon nigricauda 4 to 6 cm in total length. There was no indication of increasing mortality with increasing suspended sediment concentration. Mortalities did not exceed 15 percent in any concentration during the 21-day exposure (Fig. 9). Under the same conditions, 5- to 6.5-cm spot-tailed sand shrimp Crangon nigromaculata had somewhat higher mortalities. Despite two control tank deaths, there was an erratic trend toward increasing mortality with increasing suspended sediment concentration, reaching 32 percent at 19.7 g/l after 21 days (Fig. 10).

65. The marine contaminated sediment experiment with C. nigromaculata was marred by equipment failures causing highly variable physical

Table 6

Summary of the time-concentration mortality curves from the marine experiments, showing species, sediment type, estimated 21-day LCX in grams/litre of suspended sediment, equations from which the estimates were derived, and the coefficients of determination (r^2) of those equations, and the number of the figure in which the data are shown.

Species	Sediment	21-day LCX in g/l	Equation	r^2	Fig. No.
Mytilus edulis	Contaminated	LC10 = 2.3	y = 2.59 + 103 (1/X)	0.96	14
		LC20 = 3.6	lny = .378 + 18.7 (1/X)	0.97	
		LC50 = 6.6	1/y = .221 - 1.46 (1/X)	0.97	
Mytilus californianus	Contaminated	LC10 = 3.0	1/y = .539 - 4.33 (1/X)	0.83	17
		LC20 = 3.9	1/y = .436 - 3.74 (1/X)	0.96	
		LC50 = 6.0	1/y = .299 - 2.75 (1/X)	0.92	
Ascidia ceratodes	Contaminated	LC10 = 2.3	lny = 2.61 - .0844 X	0.84	19
		LC20 = 4.1	lny = 3.18 - .0841 X	0.95	
		LC50 = 10.7	lny = 3.66 - .0614 X	0.97	
Cancer magister	Contaminated	LC10 = 3.5	y = 23.1 - 6.44 lnX	0.97	21
		LC20 = 5.5	lny = 3.35 - .0784 X	0.93	
		LC50 = 12.1	lny = 0.04 - .0737 X	0.97	

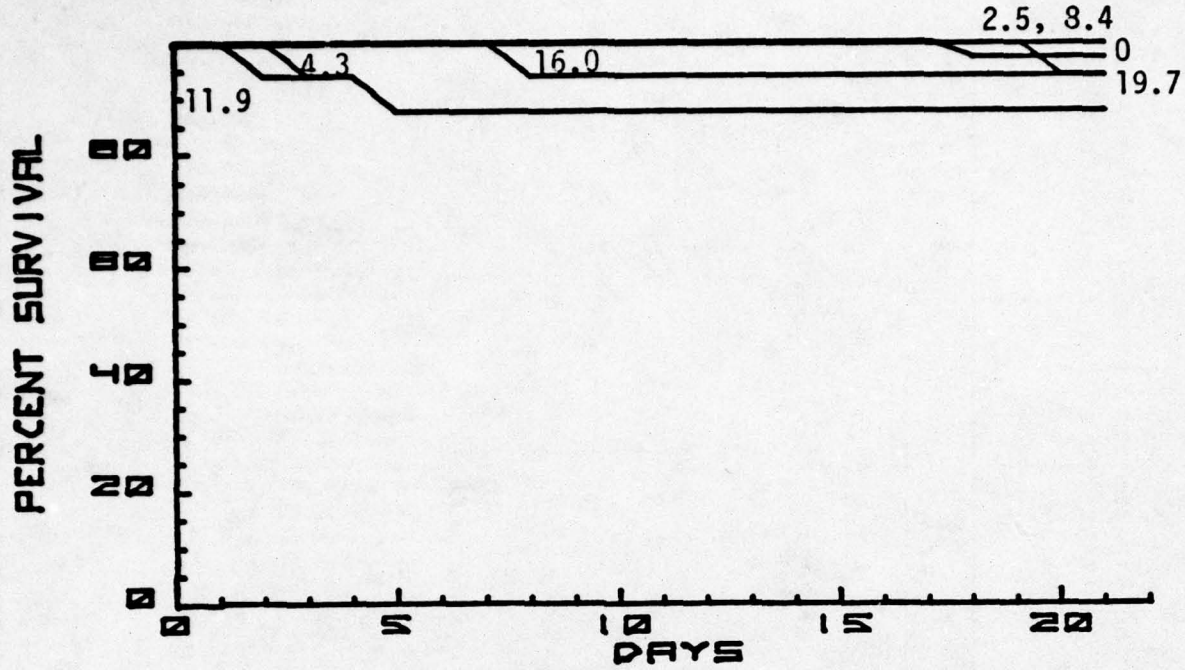


Fig. 9. Percent survival of 4- to 6-cm black-tailed sand shrimp Crangon nigricauda in suspensions of uncontaminated sediment at 33 °/oo, 11°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

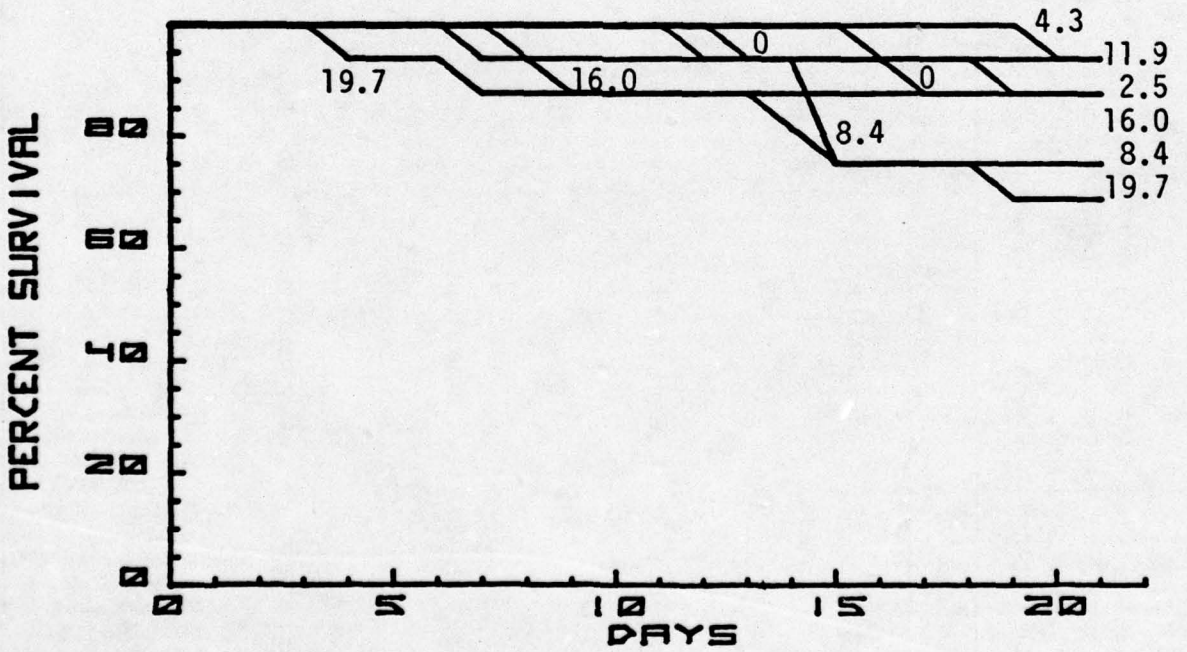


Fig. 10. Percent survival of 5- to 6.5-cm spot-tailed sand shrimp Crangon nigromaculata in suspensions of uncontaminated sediment at 33 °/oo, 11°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

conditions in the aquaria and resulting in an erratic mortality pattern (Fig. 11). Although the data were too variable to permit definitive evaluation, the contaminated sediment appeared to produce greater mortalities than the uncontaminated sediment. Even so, no deaths occurred before the third day of exposure to suspensions of contaminated sediment as high as 18.9 g/l. During the 4-day post-exposure period in clear water, deaths occurred among shrimp that had survived 25 days of exposure to two of the six concentrations of suspended sediment. In tests with both sediments no abnormalities of either species of shrimp were noted in association with molting, nor did death seem to occur more frequently at the time of molt.

Blue mussel Mytilus edulis

66. When exposed to suspensions of uncontaminated sediment at 33 °/oo salinity, 2.0- to 2.5-cm blue mussels Mytilus edulis had 10 percent mortality in the control aquaria, 20 percent mortality at 15.5 g/l

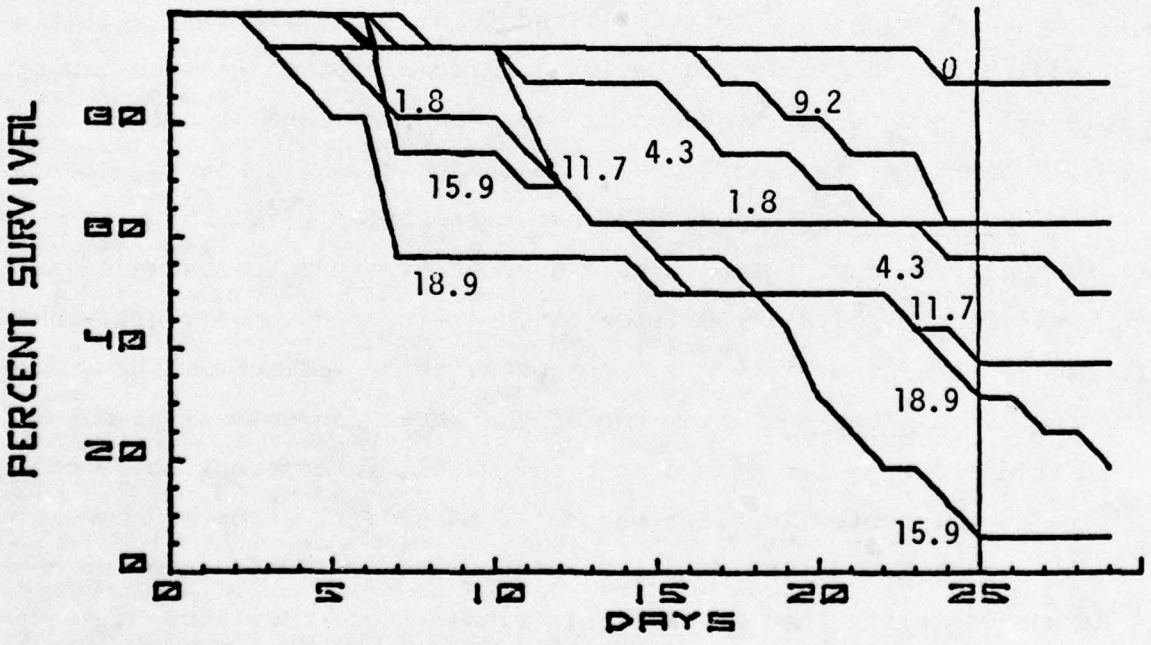


Fig. 11. Percent survival of 6- to 8-cm spot-tailed sand shrimp Crangon nigromaculata in suspensions of contaminated sediment at 33 °/oo, 13°C and high dissolved oxygen and during a post-exposure period in clear water. Numbers on lines are suspended sediment concentrations in g/l

and no deaths in the other suspended sediment concentrations after 21 days (Fig. 12). Because of the few deaths, no LCX curves could be calculated. When M. edulis 1.5 to 2.5 cm long were exposed to contaminated sediment under similar conditions, mortalities did not occur until day 7 and by day 12 had reached 100 percent at 20.0 g/l (Fig. 13). Mortality began later and was less severe in each progressively lower suspended sediment concentration but, at the end of 21 days, had reached 20 percent at 3.0 g/l, equalling the mortality at 15.5 g/l of uncontaminated sediment. After day 18 of the 25-day exposure to suspended sediment, mortalities were stable in all concentrations and only one death occurred during the postexposure period in clear water. The time-concentration mortality curves for M. edulis in contaminated sediment at 33 °/oo salinity are presented in Fig. 14.

Coast mussel Mytilus californianus

67. When exposed to uncontaminated sediment at 33 °/oo salinity, 2- to 2.5-cm coast mussels M. californianus (Fig. 15) had no mortalities during the first 9 days of exposure, and total mortalities were similar to M. edulis in uncontaminated sediment. The exception was the aquarium at 15.5 g/l where mortality began on day 10 and reached 35 percent by day 21. Under similar conditions in contaminated sediment, 1.5- to 2.5-cm M. californianus had much higher mortalities (Fig. 16). No mortalities occurred during the first 9 days of exposure to suspended sediment, but after 21 days mortalities reached 7 percent at 3.0 g/l, compared to 12 percent at 19.5 g/l in uncontaminated sediment. The surviving M. californianus from two of the three concentrations continued to die during the period in clear water, in contrast to M. edulis, only one of which died in clear water. Deaths first occurred somewhat later than with M. edulis; M. californianus then suffered more rapid and higher mortality than M. edulis in similar concentrations of contaminated sediment. This is reflected in the time-concentration mortality curves in Fig. 17, where the LCX values are 9 to 21 percent lower than the corresponding values for M. edulis in Fig. 14.

68. Most individuals of both Mytilus species maintained byssal attachments throughout the marine experiments with both sediments.

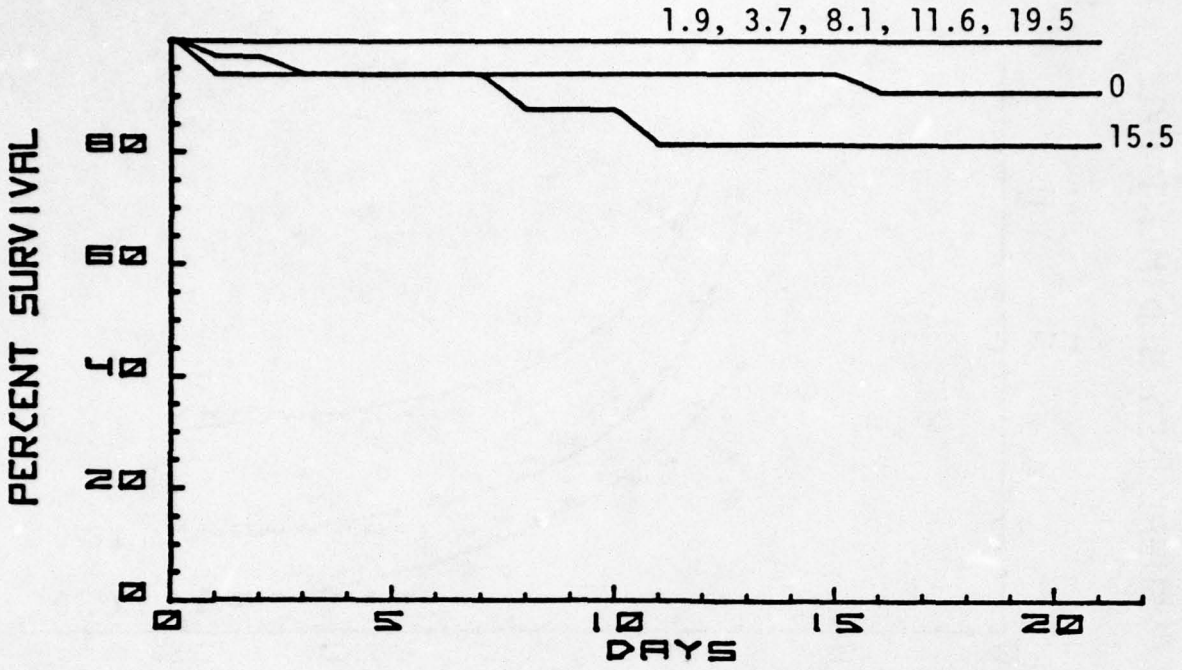


Fig. 12. Percent survival of 2- to 2.5-cm blue mussels Mytilus edulis in suspensions of uncontaminated sediment at 33 °/oo, 10°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

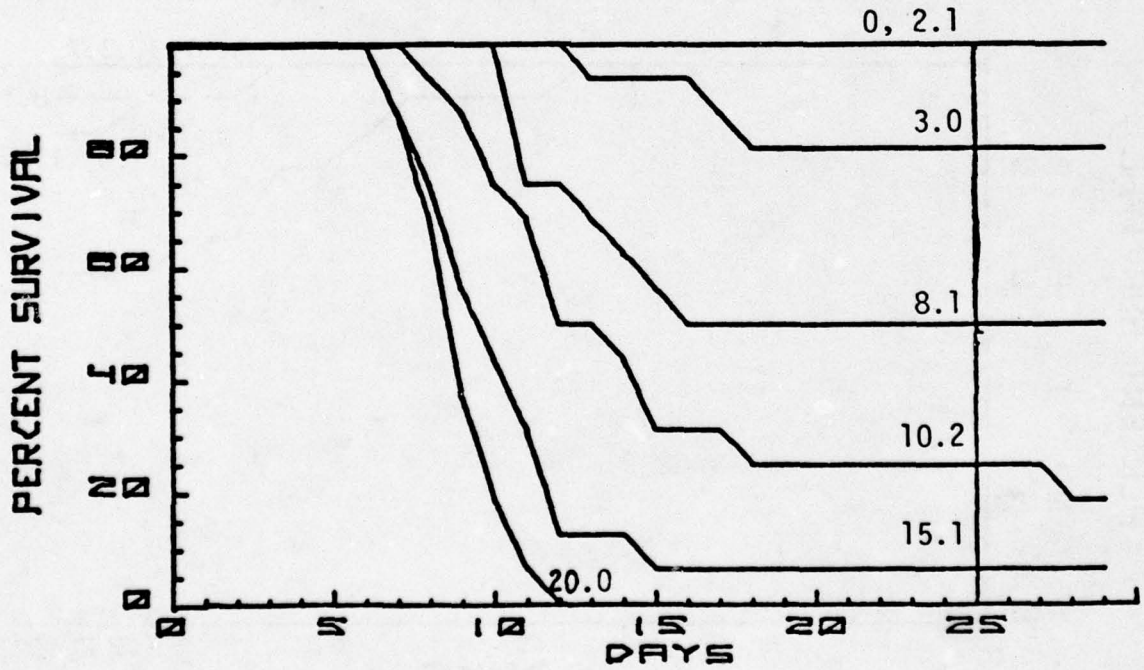


Fig. 13. Percent survival of 1.5- to 2.5-cm blue mussels Mytilus edulis in suspensions of contaminated sediment at 33 °/oo, 12°C and high dissolved oxygen and during a postexposure period in clear water. Numbers on lines are suspended sediment concentrations in g/l

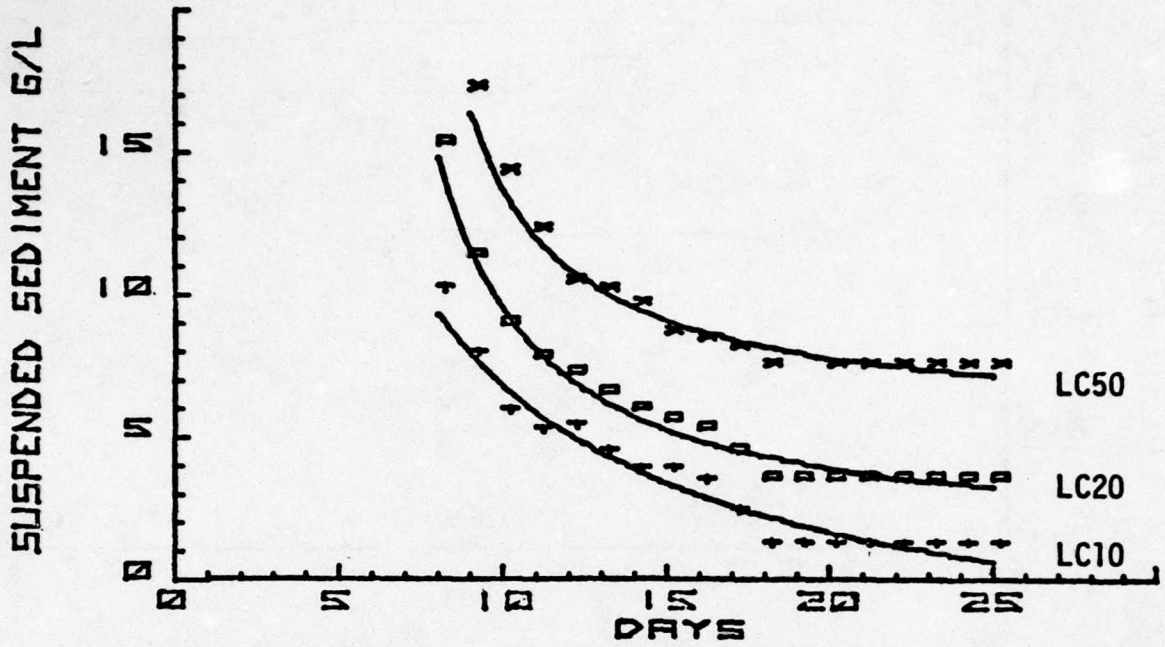


Fig. 14. Time-concentration mortality curves for 1.5- to 2.5-cm blue mussels Mytilus edulis in suspensions of contaminated sediment at 33 °/oo, 12°C and high dissolved oxygen

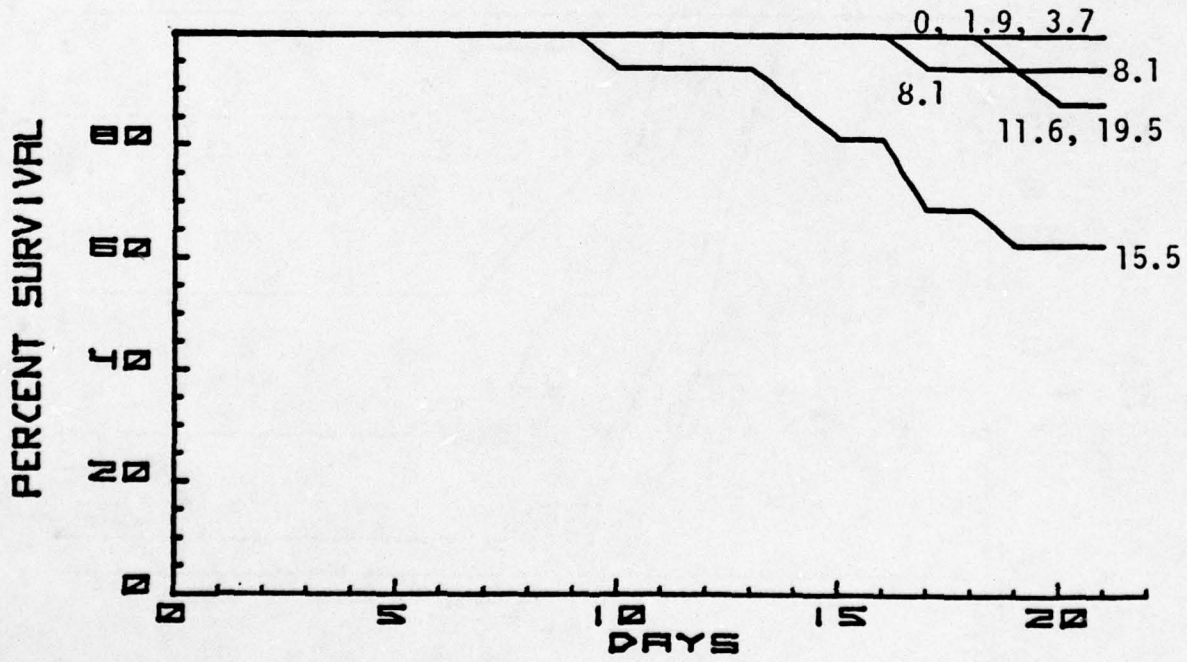


Fig. 15. Percent survival of 2- to 2.5-cm coast mussels Mytilus californianus in suspensions of uncontaminated sediment at 33 °/oo, 10°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

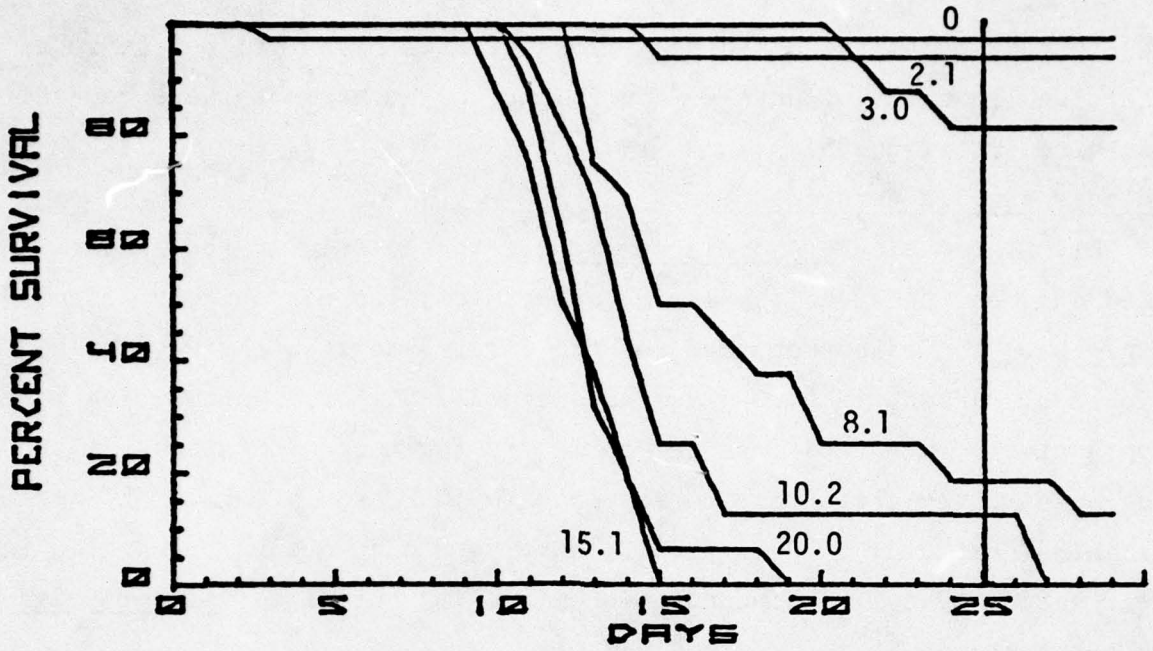


Fig. 16. Percent survival of 1.5- to 2.5-cm coast mussels Mytilus californianus in suspensions of contaminated sediment at 33 °/oo, 12°C and high dissolved oxygen and during a postexposure period in clear water. Numbers on lines are suspended sediment concentrations in g/l

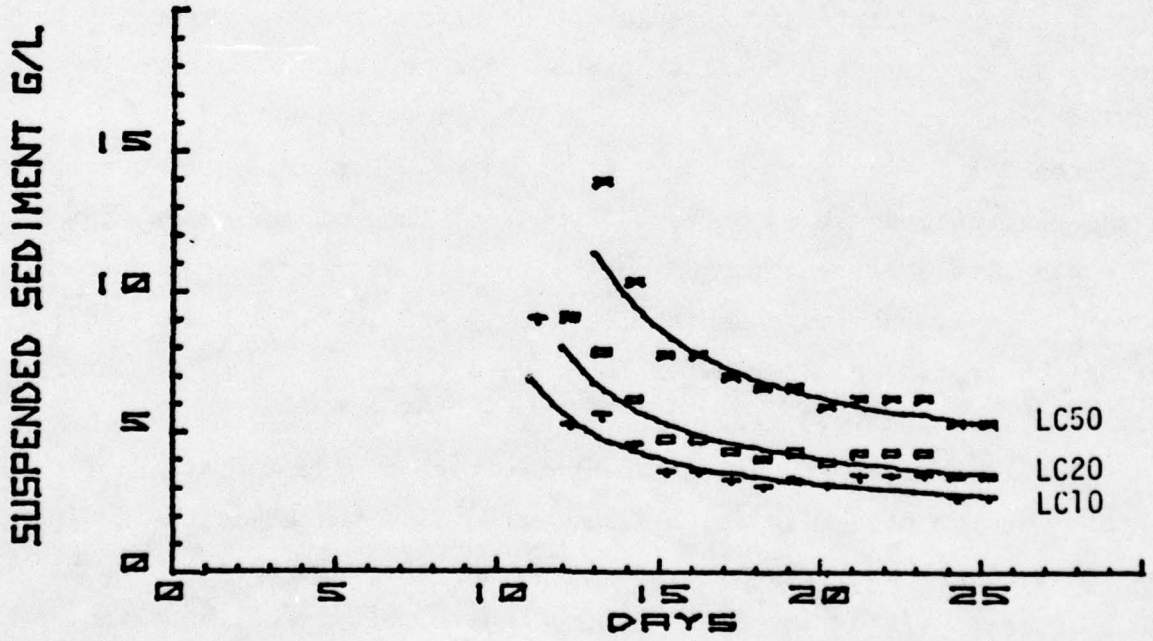


Fig. 17. Time-concentration mortality curves for 1.5- to 2.5-cm coast mussels Mytilus californianus in suspensions of contaminated sediment at 33 °/oo, 12°C and high dissolved oxygen

Even in the contaminated sediment, loss of attachment did not serve as a sensitive indicator of adverse conditions, as attachments were generally maintained until death.

Tunicate Ascidia ceratodes

69. The tunicate Ascidia ceratodes, tested only in the contaminated sediment phase of the marine experiment, was also highly affected (Fig. 18). No deaths occurred for the first 3 days but by 21 days had reached 87 percent in 20.0 g/l of suspended sediment. Mortalities were progressively later and less severe in the lower concentrations, although there was little difference in response to 10.2 and 15.1 g/l. By day 21 one animal had died at 2.1 g/l. No survivors died during the period in clear water. The time-concentration mortality curves for A. ceratodes are presented in Fig. 19.

Crab Cancer magister

70. Juvenile Dungeness crabs Cancer magister 3 to 4 cm in carapace width were also tested only in the marine experiment with contaminated sediment. No mortality occurred during the first 3 days of exposure (Fig. 20). Since no mortality occurred at 4.3 g/l, those deaths occurring at lower concentrations could not be attributed to suspensions of contaminated sediment. The lowest suspended sediment concentration causing death was 9.2 g/l, at which deaths first appeared after 9 days and reached 38 percent by 25 days of exposure. Deaths occurred earliest in the highest concentration, but throughout much of the experiment there was little correlation of mortality with increasing concentration above 11.7 g/l, the responses to 11.7, 15.9 and 18.9 g/l being similar. During the period in clear water, one death occurred among the survivors from both 11.7 and 18.9 g/l.

71. Perhaps as significant as the extent of the mortality of C. magister is the manner in which it occurred. Of the 40 deaths during the test, 37, or 92 percent, occurred during the molting process, killing 34 percent of the 108 crabs attempting to molt in all aquaria. Since death was so intimately associated with molting, time-concentration mortality curves are presented in Fig. 21 for molting crabs. These estimate that with 25 days of exposure to 9 g/l, 50 percent of the crabs

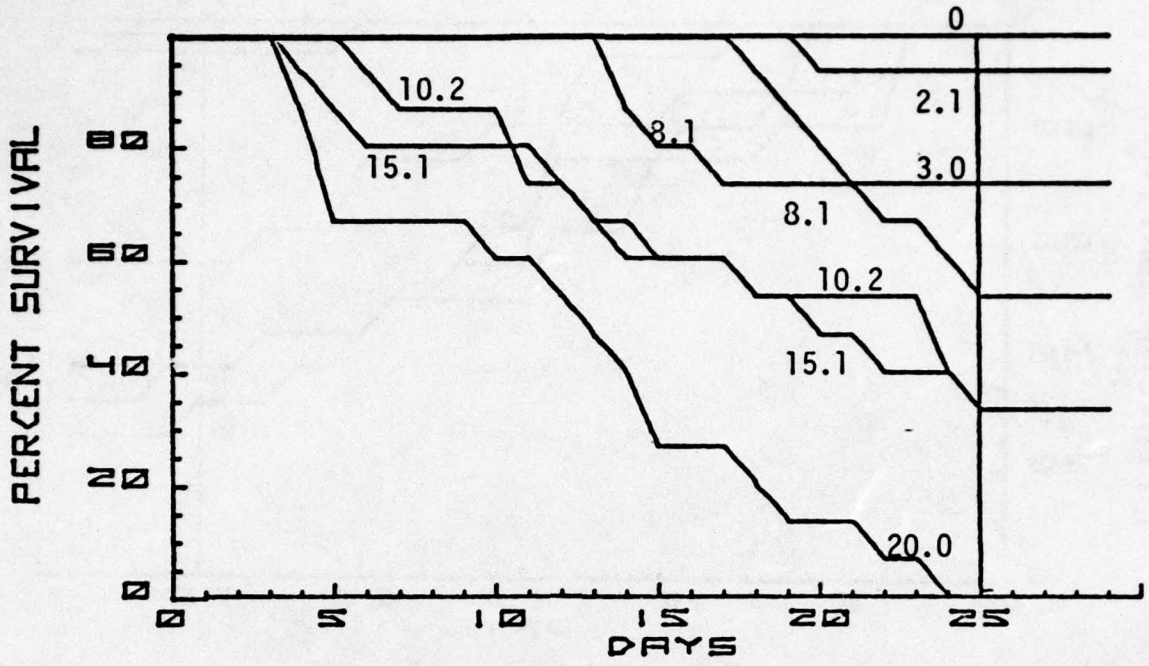


Fig. 18. Percent survival of tunicates Ascidia ceratodes in suspensions of contaminated sediment at 33 o/oo, 12°C and high dissolved oxygen and during a postexposure period in clear water. Numbers on lines are suspended sediment concentrations in g/l

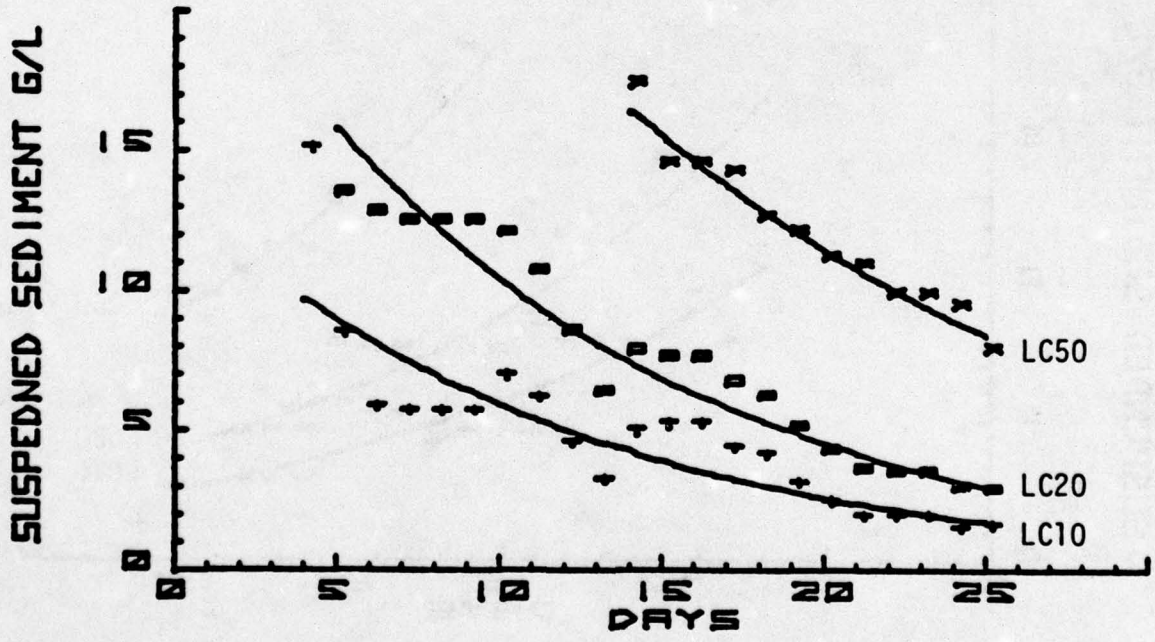


Fig. 19. Time-concentration mortality curves for tunicates Ascidia ceratodes in suspensions of contaminated sediment at 33 o/oo, 12°C and high dissolved oxygen

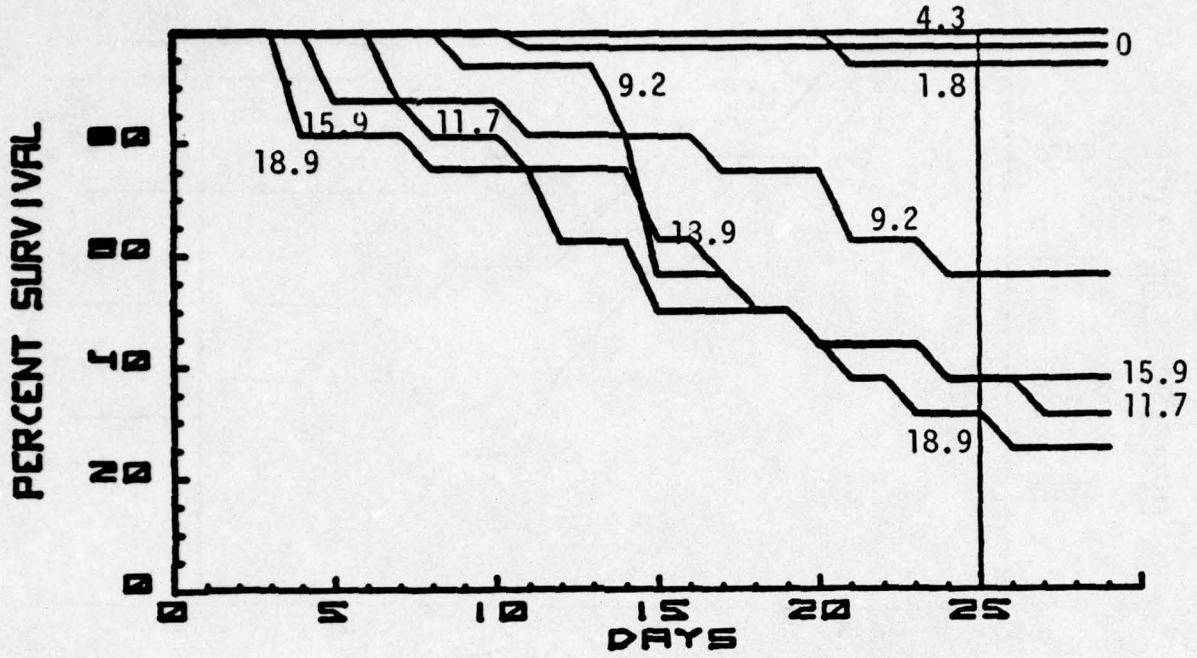


Fig. 20. Percent survival of 3- to 4-cm commercial crabs Cancer magister in suspensions of contaminated sediment at 33 o/oo, 13°C and high dissolved oxygen and during a postexposure period in clear water. Numbers on lines are suspended sediment concentrations in g/l

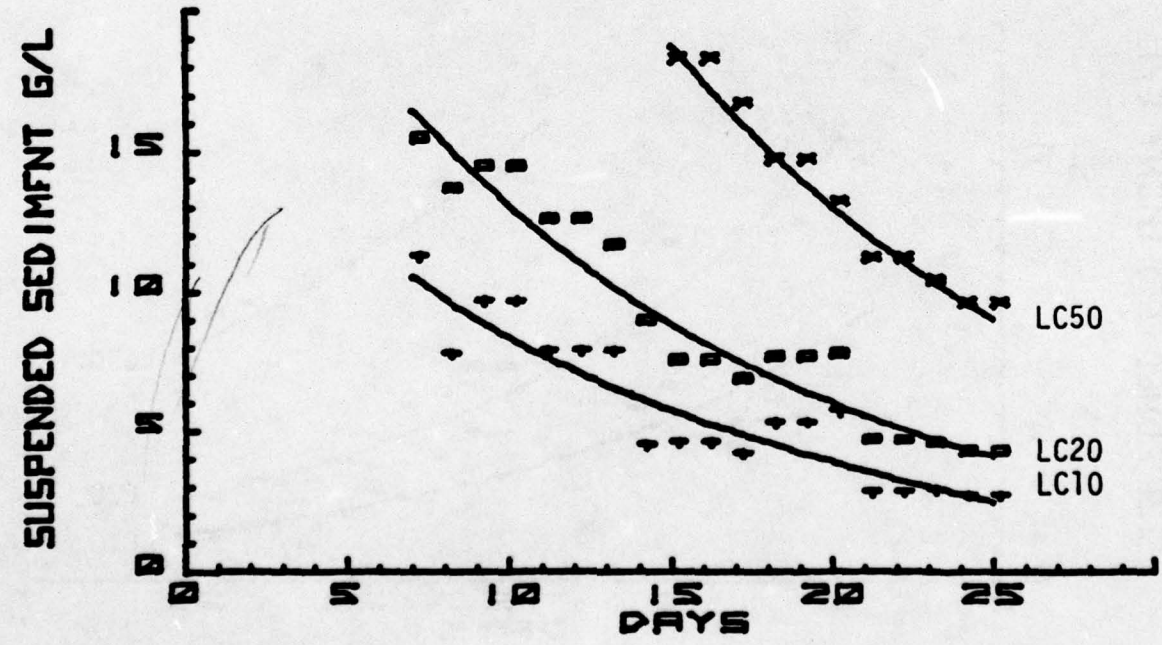


Fig. 21. Time-concentration mortality curves for molting 3- to 4-cm crabs Cancer magister in suspensions of contaminated sediment at 33 o/oo, 13°C and high dissolved oxygen

that molted would die; i.e., the 25-day LC50 for molting crabs is 9 g/l. The estimated lethal concentration for 20 percent of the molting crabs is 4 g/l after 25 days.

72. Many nonlethal abnormalities were also associated with molting. Figure 22 shows that the molting frequency of the original 16 crabs was about the same in all aquaria and that no deaths or abnormalities occurred in association with molting in the controls. At 1.8 g/l the only effect observed was the death of one crab while molting. No mortalities occurred at 4.3 g/l but one crab was delayed in molt and two emerged from the old shell deformed. At suspended sediment concentrations of 9.2 g/l and above, at least half of all molting crabs struggled for

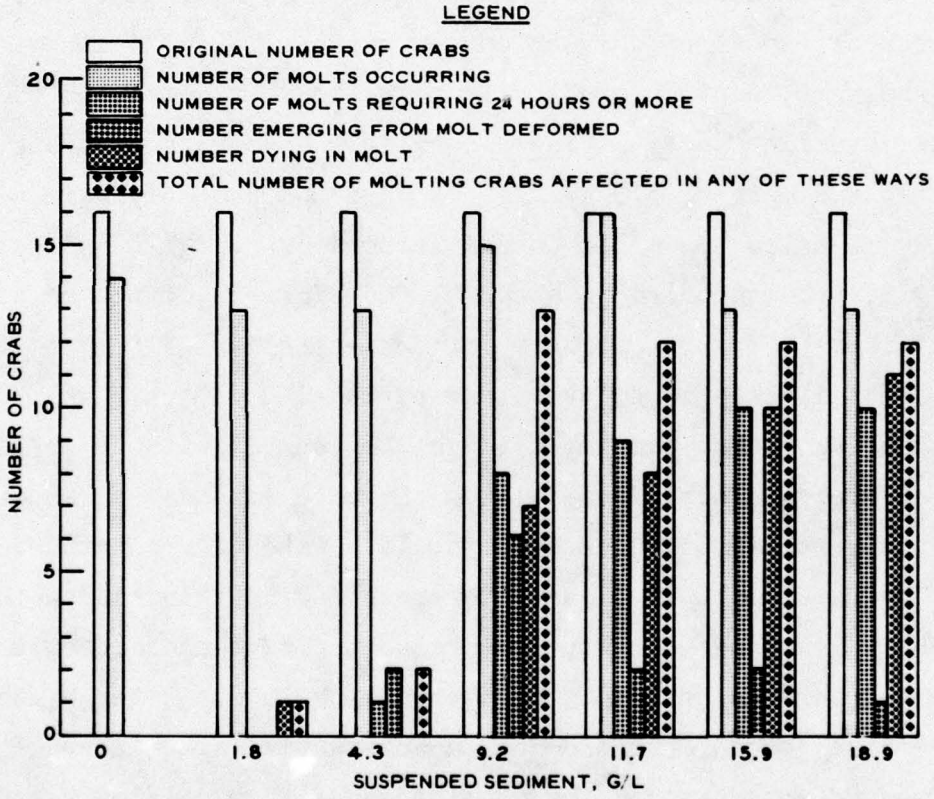


Fig. 22. Histograms showing the effects on molting of 3- to 4-cm crabs Cancer magister during 25 days exposure to seven concentrations of suspended contaminated sediment at 33 °/oo, 13°C and high dissolved oxygen. The numbers are not additive since some crabs appear in more than one column; e.g. those emerging deformed after more than 24 hours in molting

24 hours or more before completing ecdysis or dying in the effort. Throughout the test fourteen crabs spent over 48 hours and 8 over 5 days in molting. At least 75 percent of all crabs exposed to concentrations of 9.2 g/l or higher were adversely affected during the molting process, with a higher proportion of affected crabs dying in molt as concentration increased. At 9.2 g/l the six crabs which emerged deformed nearly equalled the number dying in molt. At all higher concentrations the majority of the affected crabs died while molting and very few completed the process, so that the number emerging deformed decreased rapidly.

73. Concentrations of 4.3 g/l or less were not lethal in 25 days, but 15 percent of the molting crabs showed serious abnormalities. At 9.2 g/l molting abnormalities became frequent and mortalities occurred after a week of exposure. Higher concentrations caused death after shorter exposures, and few crabs attempting to molt completed the process. Thus juvenile Cancer magister seem able to survive suspensions of contaminated sediment of 4.3 g/l for 25 days but probably have a lethal threshold well below 9.2 g/l. Concentrations of 4.3 g/l, and perhaps even 1.8 g/l, produced serious abnormalities in some of the molting crabs and might be better estimates of concentrations likely to have an adverse effect if maintained over long periods.

74. One crab that completed ecdysis on day 25 without chelipeds and with severely deformed and twisted thoracic appendages, whose terminal segments were missing, was kept in clean water for continued observation. The first molt in clear water resulted in little size increase, only slightly less deformed appendages and the continued absence of chelipeds and terminal segments of the walking legs. After 2 months in clear water the second molt produced a substantial size increase and normally shaped appendages. The chelipeds and terminal leg segments were present and not deformed but were disproportionately small. Since two molting cycles may normally be required by many crabs to regenerate a lost appendage, there appeared to be little lingering physiological impairment due to exposure to suspensions of contaminated sediment.

Lobster Homarus americanus

75. In contrast to the other decapod crustaceans tested, juvenile

American lobsters Homarus americanus 3 to 4 cm long suffered no mortalities during 25 days in suspensions of contaminated sediment as high as 20.0 g/l. A total of 29 molts occurred, all of which were completed normally in less than 24 hours, except that one animal at 20.0 g/l began ecdysis on day 21, spent 4 days in molt and emerged with deformed appendages.

Estuarine Experiment

76. The experimental animals for the estuarine test were collected, held in the laboratory and tested under the conditions shown in Appendix C. Table 7 summarizes the time-concentration mortality curves for all species having greater than 10 percent mortality in the estuarine experiments.

Sand shrimp Crangon nigricauda

77. Suspensions of uncontaminated sediment in water of 25 °/oo salinity caused few deaths among black-tailed sand shrimp Crangon nigricauda 4 to 6 cm long (Fig. 23). The 15 percent mortality at 16.4 g/l after 21 days only slightly exceeded that in the controls. The contaminated sediment phase of the estuarine test also resulted in few mortalities during the 21-day exposure to suspended sediment (Fig. 24). Since no mortalities occurred at a suspended sediment concentration of 14.7 g/l, only those deaths at higher concentrations are definitely attributable to the experimental conditions. The only mortality during the clear water period was among the shrimp that had been exposed to the lowest suspended sediment concentration.

Blue mussel Mytilus edulis

78. Blue mussels Mytilus edulis 1 to 2 cm long had less than 20 percent mortality after 21 days of exposure to uncontaminated sediment at 24 °/oo salinity (Fig. 25). Equal numbers of deaths occurred in the controls and at 19.5 g/l, and one more mussel died at both 10.4 and 14.5 g/l. In contaminated sediment mortalities began somewhat earlier and were slightly higher at concentrations up to 12.1 g/l. Concentrations of 15.9 and 21.2 g/l, however, produced much higher mortalities

Table 7

Summary of the time-concentration mortality curves from the estuarine experiments, showing species, sediment type, estimated 21-day LCX in grams/litre of suspended sediment, equations from which the estimates were derived, and the coefficients of determination (r^2) of those equations, and the number of the figure in which the data are shown.

Species	Sediment	21-day LCX in g/l	Equation	r^2	Fig. No.
Mytilus edulis	Contaminated	LC10 = 6.5	1/y = 0.111 + 0.361 (1/X)	0.52	28
		LC20 = 9.9	1/y = 0.120 - 0.1403 (1/X)	0.61	
		LC50 = 13.9	1/y = 0.107 - 0.736 (1/X)	0.88	
Morone saxatilis	Contaminated	LC10 = *			
		LC20 = *			
		LC50 = *	y = - 0.195 + 2.012 (1/X)	0.85	32

* Over 25 percent of the test animals were dead in all suspended sediment concentrations by the times of the first observation; thus, LC10 and LC20 values could not be calculated. The LC50 could not be calculated beyond day 5 due to the high mortality.

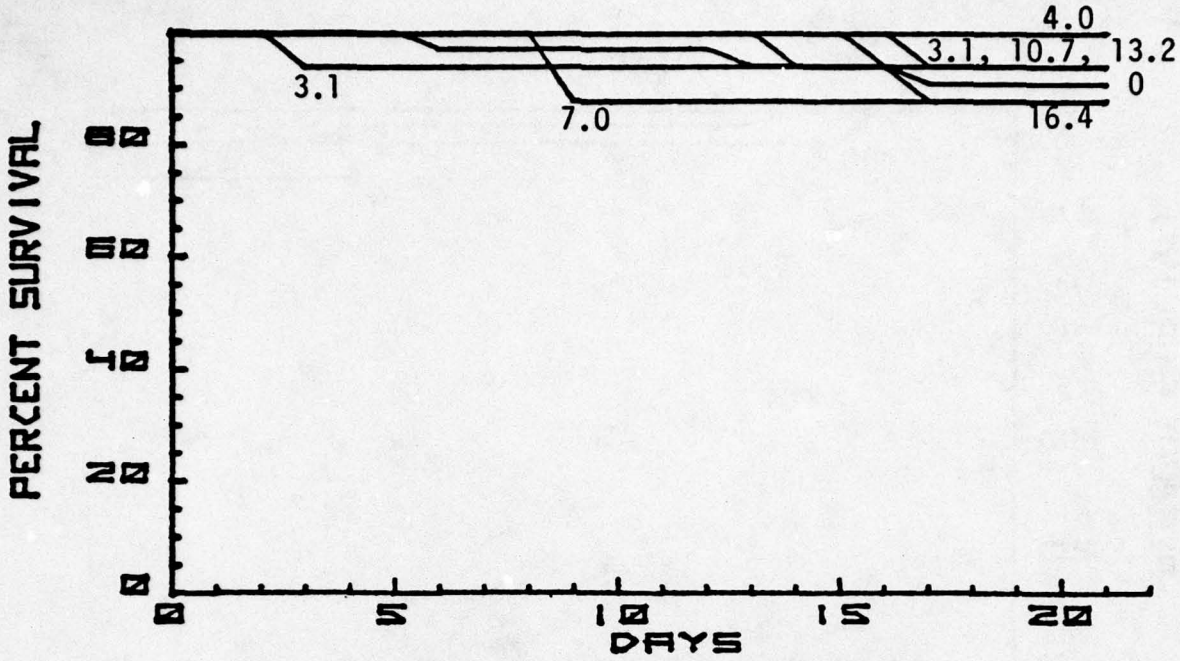


Fig. 23. Percent survival of 4- to 6-cm black-tailed sand shrimp Crangon nigricauda in suspensions of uncontaminated sediment at 25 °/oo, 13°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

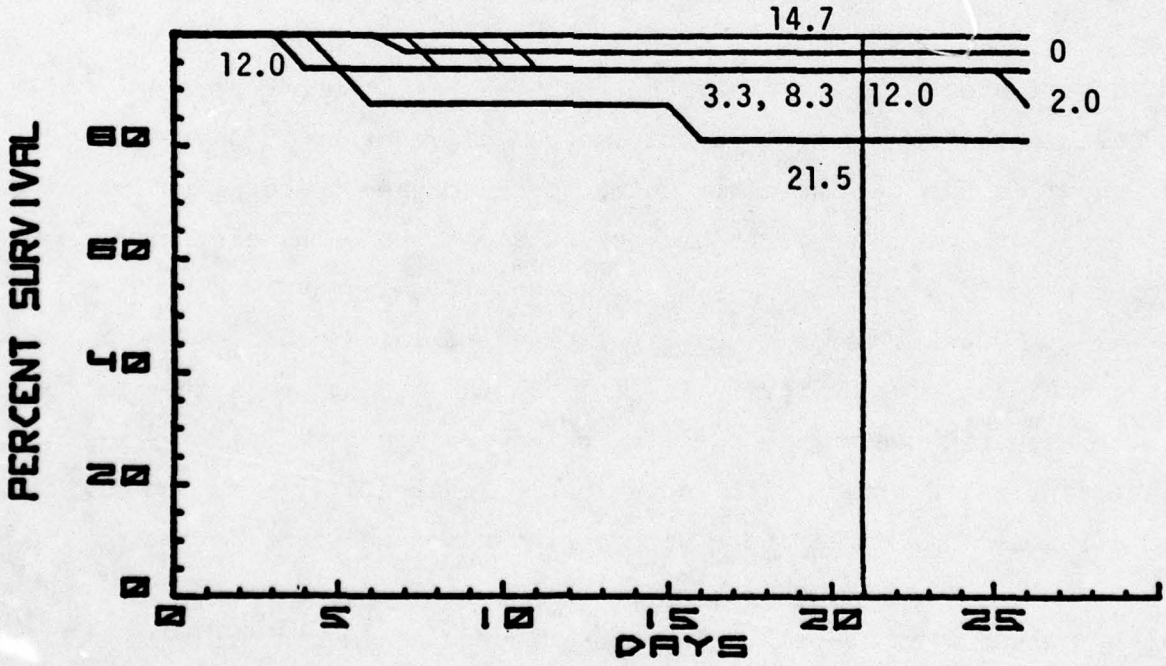


Fig. 24. Percent survival of 5- to 6-cm black-tailed sand shrimp Crangon nigricauda in suspensions of contaminated sediment at 24 °/oo, 14°C and 8 ppm dissolved oxygen and during a postexposure period in clear water. Numbers on lines are suspended sediment concentrations in g/l

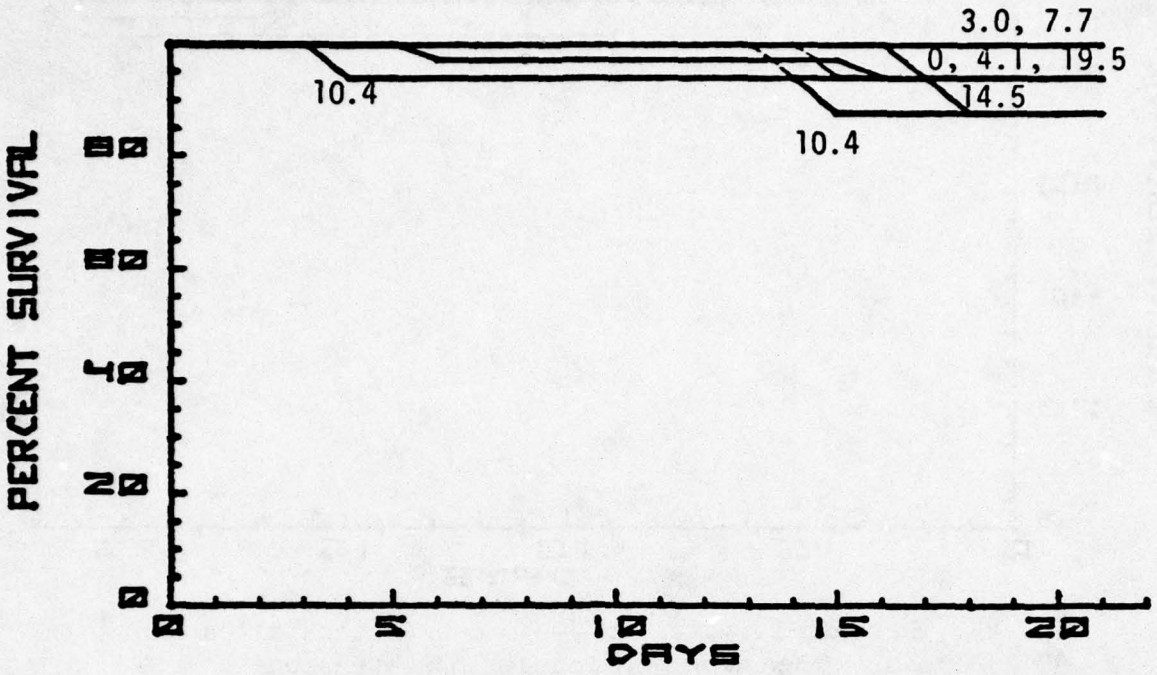


Fig. 25. Percent survival of 1- to 2-cm blue mussels Mytilus edulis in suspensions of uncontaminated sediment at 24 °/oo, 12°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

in contaminated sediment (Fig. 26) than had similar concentrations of uncontaminated sediment. The only mussel alive after 17 days at 21.2 g/l survived through the clear water postexposure period. Two deaths occurred during the postexposure period among those mussels surviving exposure to 15.9 g/l.

79. Mortalities of M. edulis exposed to suspensions of uncontaminated sediment were uniformly low in both the marine and estuarine tests. In the estuarine test with uncontaminated sediment, mortalities were considerably lower than with contaminated sediment. By far the highest mortalities of M. edulis were with contaminated sediment in the marine experiment. This can be seen by comparing the time-concentration mortality curves from the estuarine contaminated sediment test (Fig. 27) with those from the marine contaminated sediment test (Fig. 14). In the estuarine test 50 percent mortality was not reached until 4 days later than in the marine test, and the 21-day LC10 in the estuarine experiment was nearly identical with the marine 21-day LC50.

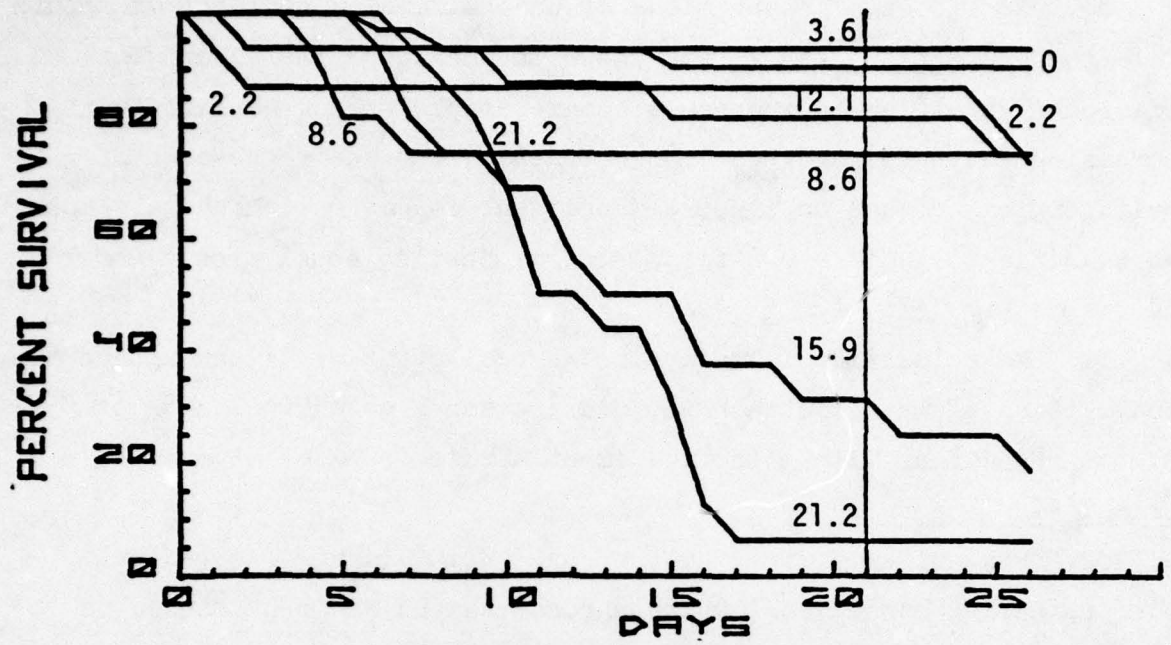


Fig. 26. Percent survival of 2- to 2.5-cm blue mussels Mytilus edulis in suspensions of contaminated sediment at 25 o/oo, 14°C and 8 ppm dissolved oxygen and during a postexposure period in clear water. Numbers on lines are suspended sediment concentrations in g/l

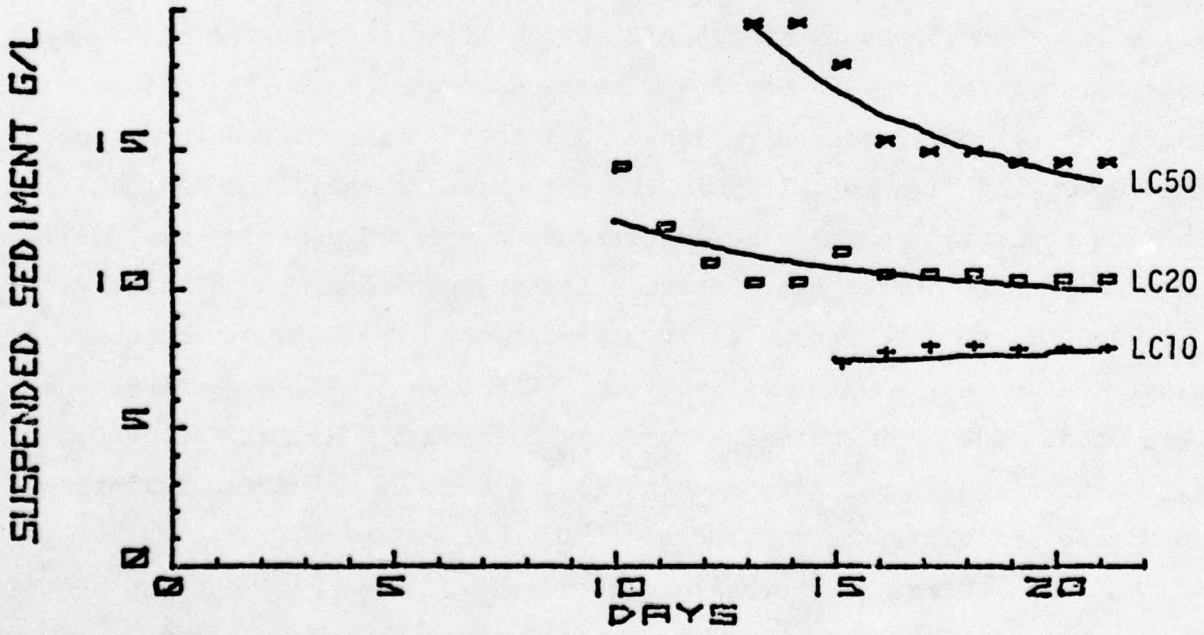


Fig. 27. Time-concentration mortality curves for 2- to 2.5-cm blue mussels Mytilus edulis in suspensions of contaminated sediment at 25 o/oo, 14°C and 8 ppm dissolved oxygen

80. No effect of suspensions of uncontaminated sediment on growth of 1- to 2-cm Mytilus edulis was shown in the estuarine experiment. Individual shell length increases became slightly less variable with increasing suspended sediment concentration, but the regression of shell length increase on suspended sediment concentration had a slope not significantly different from zero, indicating equal growth under all conditions (Fig. 28).

81. Most individuals maintained byssal attachments throughout the study. Loss of byssal attachment did not serve as an indicator of adverse conditions with either sediment studied.

Striped bass Morone saxatilis

82. Fingerling striped bass Morone saxatilis were tested only under estuarine conditions, where uncontaminated sediment caused no mortalities at 1.5 g/l or less (Fig. 29). At 2.3 g/l mortalities reached 35 percent, but only one fish died at 3.9 g/l. In the contaminated sediment phase of the estuarine test, mortalities were dramatically higher. By the time of the first daily observation, over 25 percent of the fish were dead at 0.5 g/l, the lowest suspended sediment concentration tested (Fig. 30). After day 12 the only fish remaining alive were two survivors at 0.5 g/l, which lived through the clear water postexposure period. By day 2 at least 75 percent mortality had occurred at all other concentrations. All control fish lived throughout the test. The high mortality in the estuarine contaminated sediment test is reflected in the time-concentration mortality curve (Fig. 31). No LC10 or LC20 curves are plotted since these percent mortalities were exceeded by the time of the first observation. The LC50 curve is terminated after day 5 when well over half the fish in all concentrations were dead. The LC50 estimates for days 2 through 5 are all below 0.5 g/l, making the impact of contaminated sediment at estuarine salinity on Morone saxatilis the most severe found.

83. No effect of suspensions of uncontaminated sediment on the hematocrit of 5- to 6-cm Morone saxatilis could be conclusively demonstrated at the end of the estuarine experiment. There was a slight trend toward declining hematocrit with increasing concentration, but

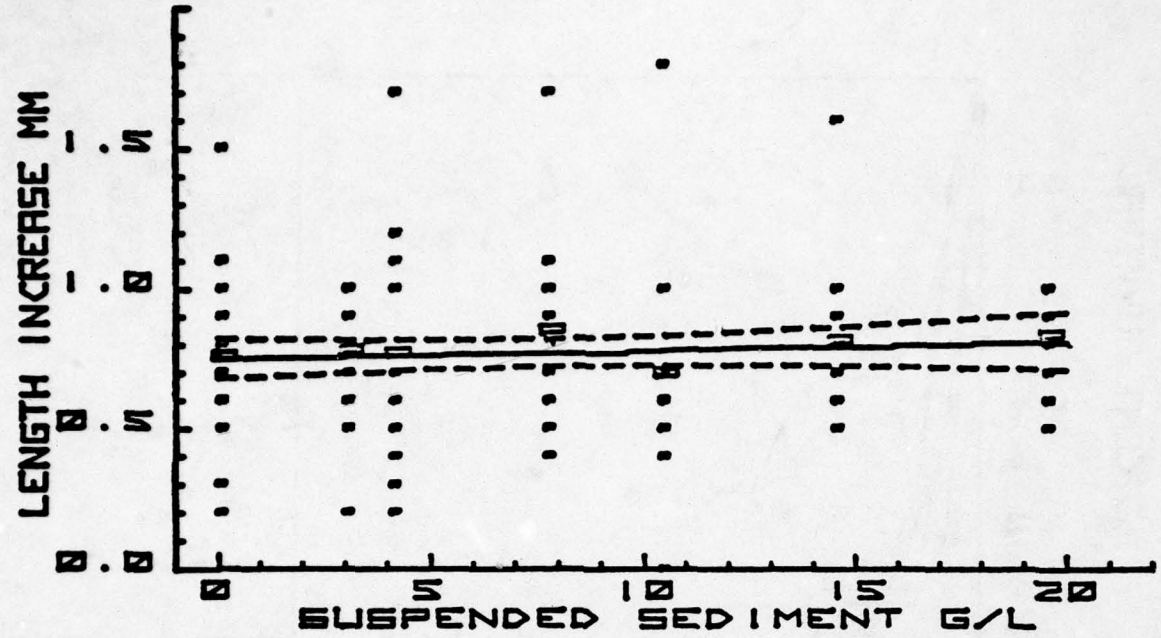


Fig. 28. Shell growth of 1- to 2-cm blue mussels Mytilus edulis after 21 days in suspensions of uncontaminated sediment at 24 °/oo, 12°C and 8 ppm dissolved oxygen. Symbols illustrate individual data points, means of the replicate observations at each concentration, the regression estimate and the 95 percent confidence interval about that estimate

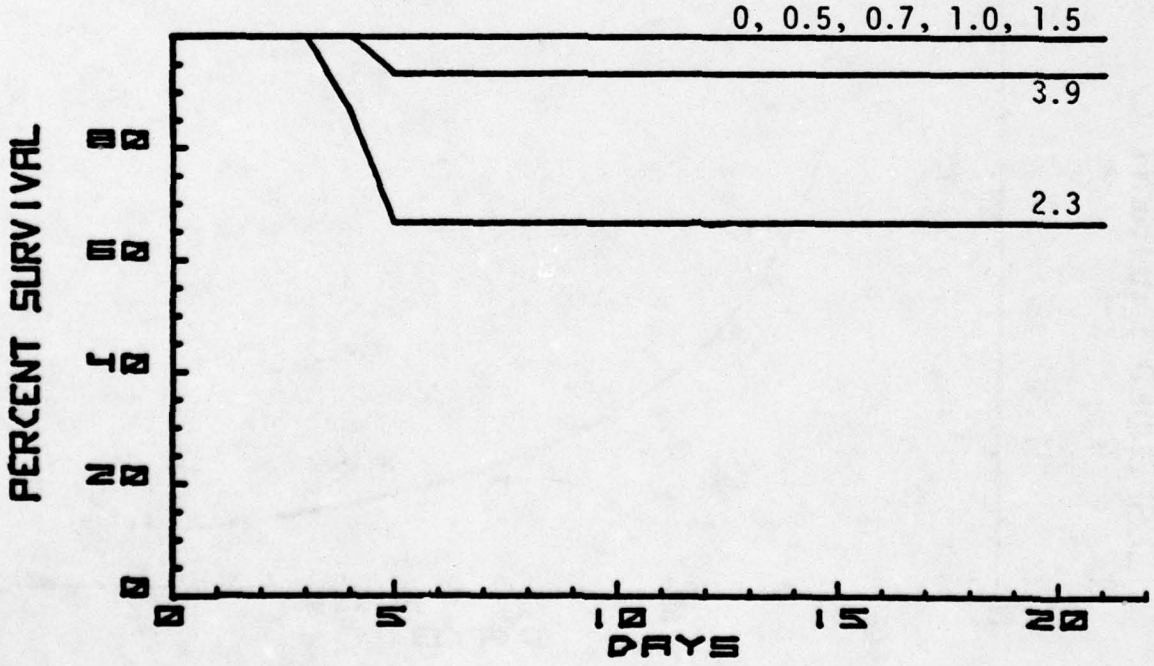


Fig. 29. Percent survival of 5- to 6-cm striped bass Morone saxatilis in suspensions of uncontaminated sediment at 25 °/oo, 12°C and 8 ppm dissolved oxygen. Numbers on lines are suspended sediment concentrations in g/l

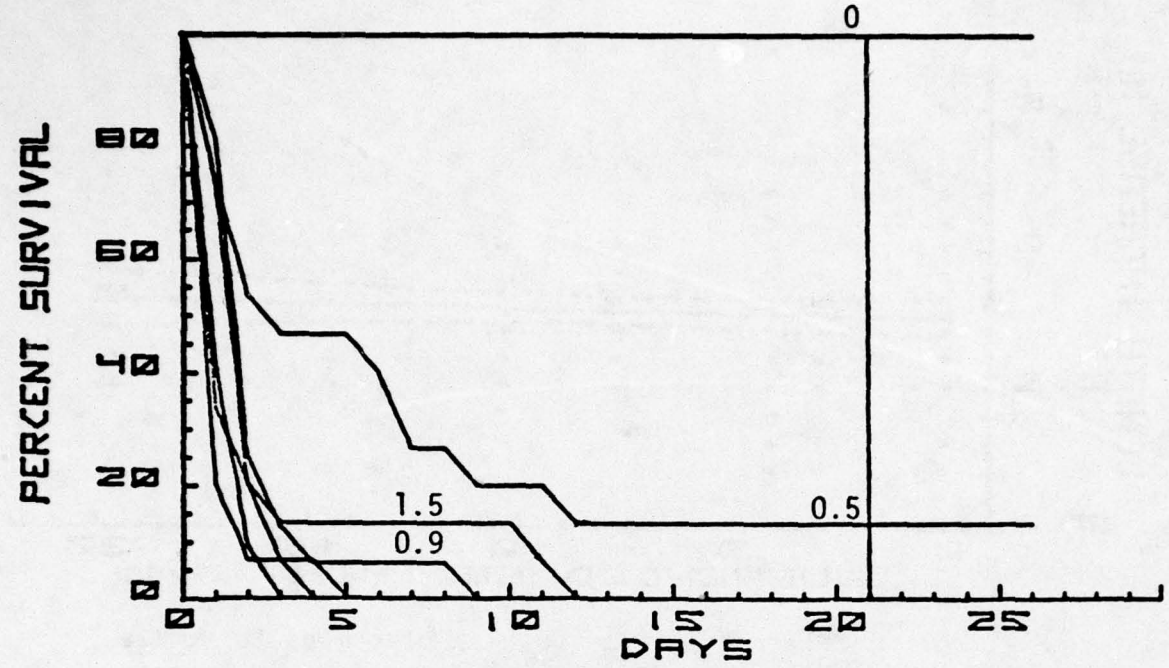


Fig. 30. Percent survival of 4- to 6-cm striped bass Morone saxatilis in suspensions of contaminated sediment at 25 o/oo, 14°C and 8 ppm dissolved oxygen and during a postexposure period in clear water. Numbers on lines are suspended sediment concentrations in g/l

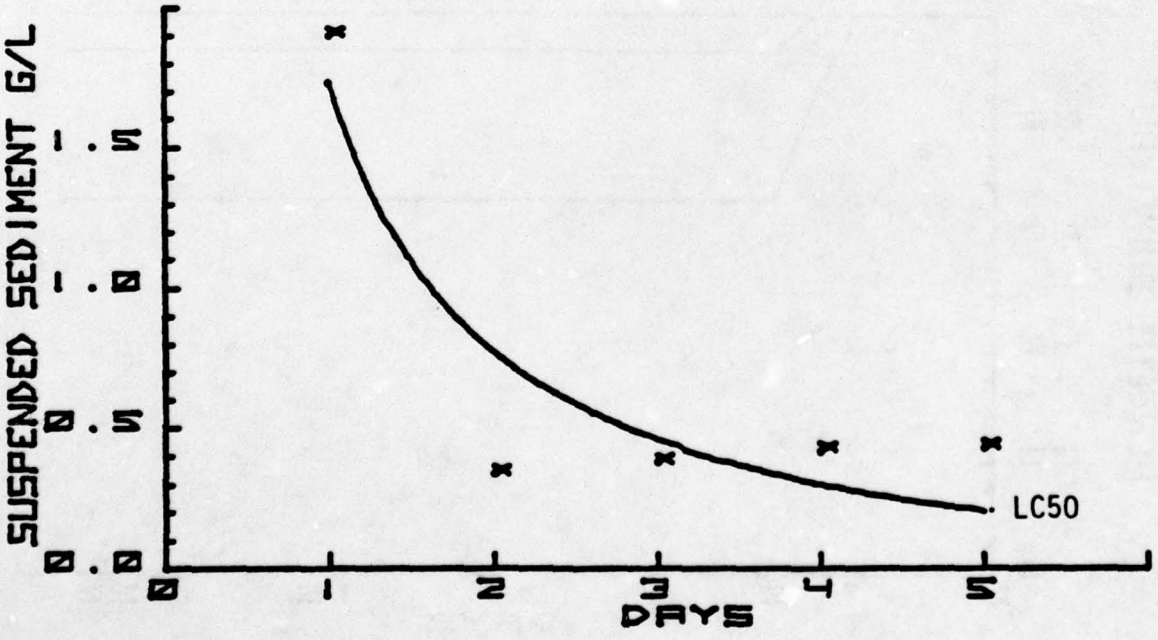


Fig. 31. Time-concentration mortality curve for 5- to 6-cm striped bass Morone saxatilis in suspensions of contaminated sediment at 25 o/oo, 14°C and 8 ppm dissolved oxygen

the data were so variable that the regression line had a slope not significantly different from zero (Fig. 32).

84. The amount of minerals in the stomachs of these fish did show a slight but statistically significant increase with increasing suspended sediment concentrations. The ashed weight of the stomachs of the control fish was uniformly near 5 percent of the dry weight. As suspended sediment concentration increased, both the variability and the mean increased also, reaching a mean of over 7 percent at 3.9 g/l. The regression of ashed weight as a percent of dry weight on suspended sediment concentration was significant, and is illustrated in Fig. 33.

Chemical Uptake--Marine Test with Contaminated Sediment

85. The conditions of tissue sample storage placed a constraint on the results of the studies of biological uptake of selected chemicals from contaminated sediment. During the approximately 8 months of storage at 1° to 2°C, some tissue dehydration and decomposition occurred, even though the sample containers were sealed. Thus, the concentrations measured were increased by an unknown amount due to the loss of water and subsequent tissue weight reduction. This increase may have been partially offset by losses due to volatilization, although dehydration is considered to be the dominant factor influencing the concentrations of metals and chlorinated hydrocarbons. Since all samples were stored under the same conditions, dehydration and decomposition effects were similar on all samples. Therefore, internal relative comparisons within the data of this report are valid, but tissue concentrations reported here should not be compared to those found in other studies or regarded as quantitative estimates of uptake that could occur under field conditions.

Blue mussels Mytilus edulis

86. Metals. There was no indication of tissue accumulation of the metals Cd, Mn or Hg in M. edulis as a result of exposure to suspensions of metals-contaminated sediment (Table 8). Mussels from the clear water control aquaria had higher concentrations of Cd, Mn and Hg than the

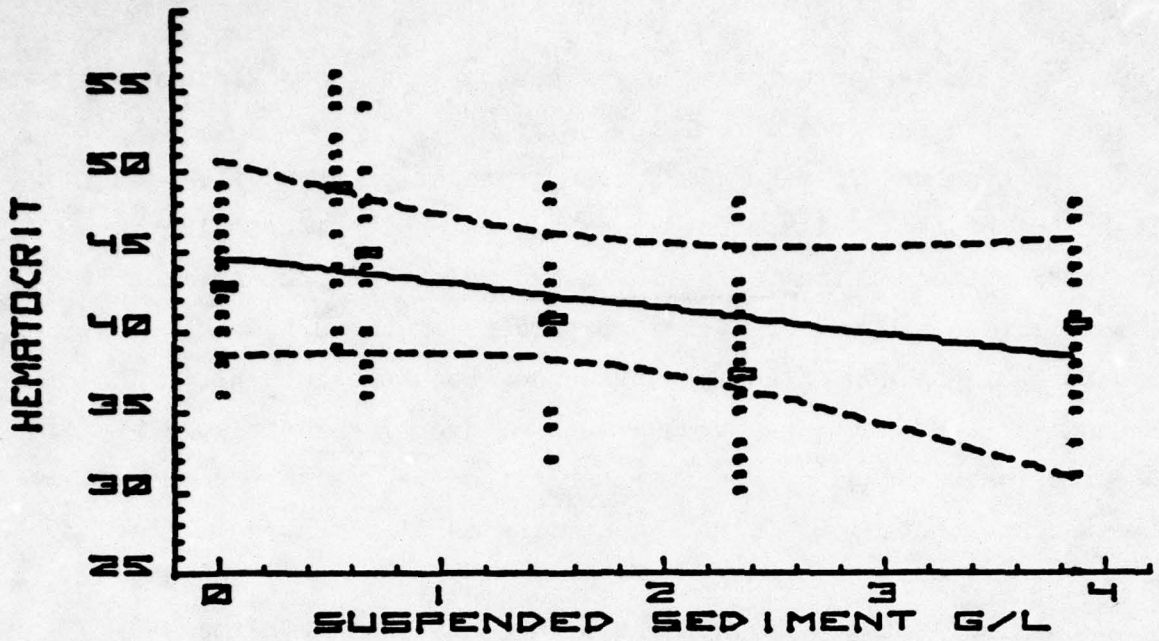


Fig. 32. Hematocrit of 5- to 6-cm striped bass Morone saxatilis after 21 days in suspensions of uncontaminated sediment at 25 °/oo, 12°C and 8 ppm dissolved oxygen. Symbols illustrate individual data points, means of the replicate observation at each concentration, the regression estimate and the 95 percent confidence interval about that estimate

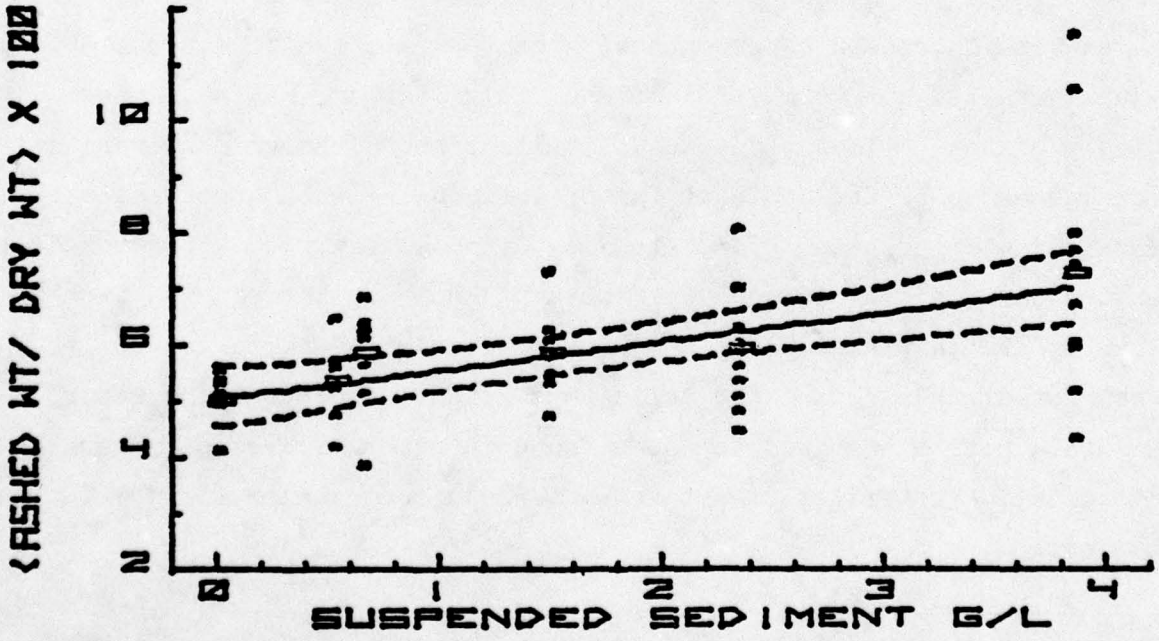


Fig. 33. Mineral contents of stomachs of5- to 6-cm striped bass Morone saxatilis after 21 days in suspensions of uncontaminated sediment at 25 °/oo, 21°C and 8 ppm dissolved oxygen. Symbols illustrate individual data points, means of the replicate observations at each concentration, the regression estimate and the 95 percent confidence interval about that estimate

Table 8

Whole body concentrations of selected metals in chemical uptake study with contaminated sediment in the marine test. Data are in µg/g wet tissue, excluding the shell of molluscs.

Species	Suspended Solids Exposure	As	Cd	Cu	Fe	Pb	Mn	Hg	Ni	Zn
Mytilus edulis	Control	0.12	0.34	2.48	154.0	2.14	2.53	0.63	0.04	25.7
	Purged	0.20	0.20	7.66	215.0	3.89	2.48	0.02	0.05	33.6
Mytilus californianus	Control	0.17	0.51	3.52	162.0	0.97	1.62	0.21	0.08	22.7
	Purged	0.12	0.45	9.23	88.8	2.28	0.95	0.03	0.004	25.0
Crangon nigromaculata	Control	0.03	0.06	4.95	38.8	0.55	0.87	0.13	0.01	7.2
	Purged	0.08	0.23	9.08	25.6	0.27	8.20	0.14	0.52	22.7
Cancer magister	Control	0.03	0.10	16.8	55.9	0.31	1.00	*	0.19	13.3
	Purged	0.03	0.13	13.2	51.4	0.38	8.06	*	0.37	16.8

* = Insufficient sample for analysis.

sediment-exposed animals after being purged of sediment in clear water. There was some indication of possible uptake of Ni, but the difference of only 0.01 µg/g between control and purged samples provides no clear evidence of Ni uptake.

87. Mytilus edulis did take up As, Cu, Fe, Pb and Zn from suspensions of contaminated sediment in the marine test (Table 8 and Fig. 34). In all cases except Cu, the tissue concentration in the purged animals relative to the controls was increased only by a factor of less than two. Even in the case of Cu, which had the greatest increase of any metal studied, the purged animal concentrations were only 3 times those of the controls.

88. Chlorinated hydrocarbons. There was no indication of uptake of PCB's directly or indirectly from suspended sediment by M. edulis during the marine test. Concentrations in all mussel samples were below the detection limit of 0.1 µg/g (Table 9). Thus, the maximum possible concentration in the mussels was far below the bulk sediment PCB concentration of 1.3 µg/g (Table 3). There was also no indication of uptake of aldrin, chlordane, dieldrin, endrin or heptachlor, as all were below detection limits in all samples of M. edulis (Table 9) and in the sediment (Table 3). Concentrations of total DDT plus its degradation products were slightly lower in the purged animals than in the controls, again indicating the absence of tissue accumulation from suspended sediment. Most of the total DDT present was in the form of DDE, and DDD was below detection limits of 0.006 µg/g in the tissues (Table 9). Thus, there was no indication of tissue accumulation by M. edulis of PCB's or DDT, which were present in the sediment, or any of the five other chlorinated hydrocarbons which were below detection limits in the sediment.

Coast mussels Mytilus californianus

89. Metals. There was no indication of tissue accumulation of As, Cd, Fe, Mn, Hg or Ni by M. californianus from suspensions of contaminated sediment in the marine test (Table 8). All were markedly lower in the purged animals than in the controls. Zinc may have been accumulated to a slight degree, although the purged animals had a concentration only 2.3 µg/g, or 1.1 times, higher than the controls. While a

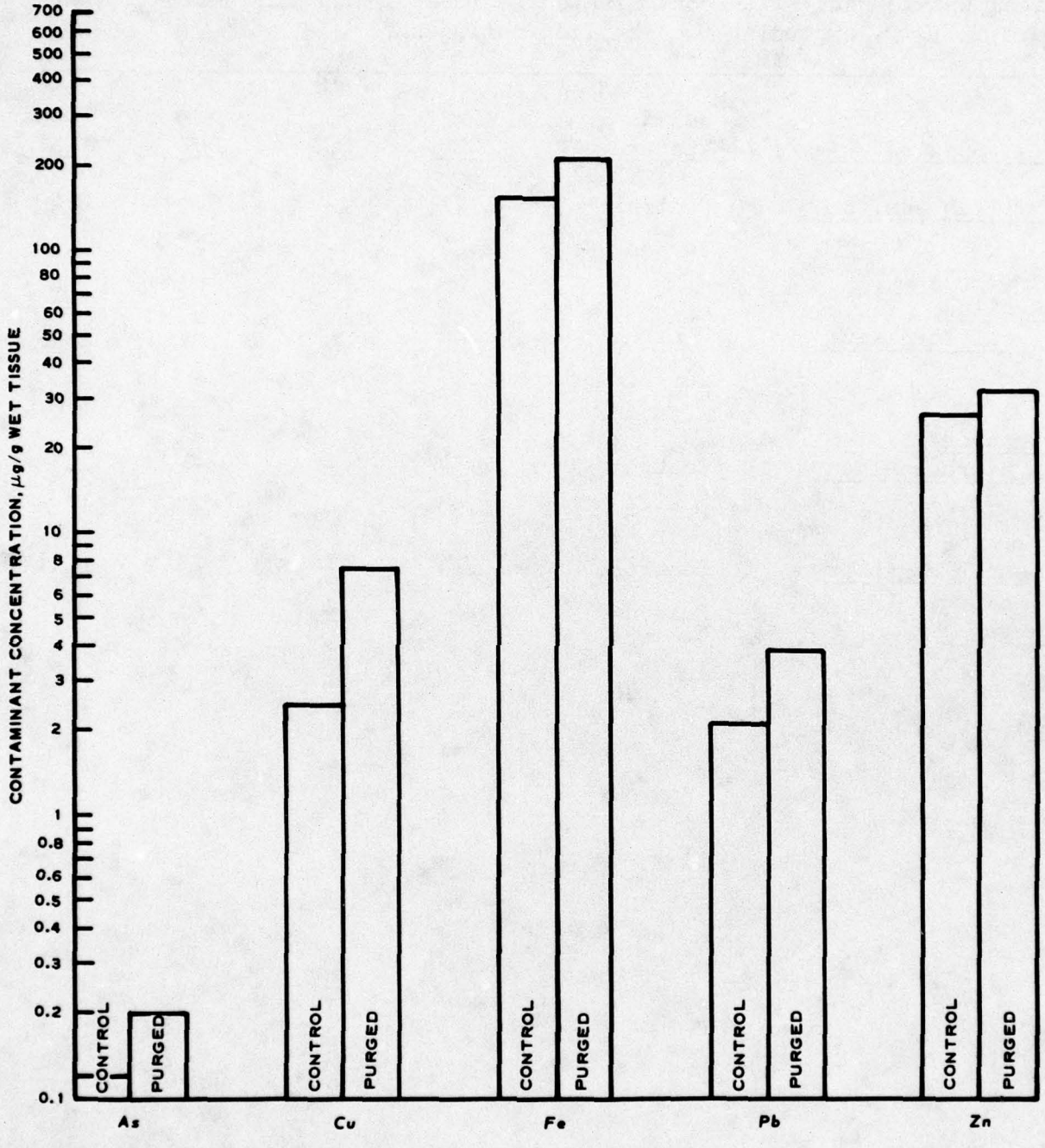


Fig. 34. Mytilus edulis metals concentrations in the contaminated sediment phase of the marine test

Table 9

Whole body concentrations of selected chlorinated hydrocarbons in chemical uptake study with contaminated sediment in the marine test. Data are in µg/g, excluding the shell of molluscs.

Species	Suspended Solids Exposure	DDE	DDD	DDT	Total DDT
Mytilus edulis	Control	1.71	-	0.69	2.40
	Purged	2.02	-	-	2.02
Mytilus californianus	Control	1.66	-	-	1.66
	Purged	2.57	-	-	2.57
Crangon nigromaculata	Control	1.54	-	-	1.54
	Purged	1.39	-	-	1.39
Cancer magister	Control	0.14	-	-	0.14
	Purged	0.14	-	-	0.14

- = Below detection limits; DDD < 0.006 ng/g; DDT < 0.008 ng/g. Also below direction limits were aldrin, dieldrin, heptachlor < 0.004 ng/g; chlordane < 0.008 ng/g; endrin, PCB's < 0.1 ng/g.

possibility of uptake of Zn is indicated, this small difference does not provide clear evidence that it was accumulated in the tissue of M. californianus as a result of exposure to suspended contaminated sediment.

90. The purged M. californianus did accumulate Cu and Pb to levels 2.6 and 2.3 times the control levels (Table 8 and Fig. 35). This was similar to uptake patterns of M. edulis for these metals when exposed to the same sediment. However, M. edulis also accumulated As, Fe, and Zn, which were not accumulated by M. californianus.

91. Chlorinated hydrocarbons. Mytilus californianus was similar to M. edulis in that it did not take up PCB's from suspended sediments during the marine test. The total sediment concentration of PCB's (Table 3) was more than 4 orders of magnitude higher than the tissue detection limit, the highest concentration that could possibly have been in the tissue samples. Aldrin, chlordane, dieldrin, endrin and heptachlor were below detection limits in all mussel samples (Table 9) and in the sediment (Table 3). The total DDT concentration in the purged animals was only 0.9 µg/g, or 1.5 times, higher than that in the controls (Fig. 35), indicating a potential for slight uptake of DDT by M. californianus. All the total DDT measured was in the form of DDE (Table 9).

Spot-tailed sand shrimp Crangon nigromaculata

92. Metals. The metals Fe, Pb and Hg were not accumulated in the tissue of C. nigromaculata as a result of exposure to suspensions of contaminated sediment (Table 8). Concentrations of Fe and Pb were markedly lower in the purged animals than in the control animals. The purged sample had a Hg content 0.01 µg/g, or 1.07 times, higher than the controls. This is well within sampling and analytical error and cannot be considered an indication of Hg accumulation in the tissues of C. nigromaculata.

93. Crangon nigromaculata accumulated As, Cd, Cu, Zn, Mn and Ni in its tissues as a result of exposure to suspensions of contaminated sediment (Table 8 and Fig. 36). The first four of these metals were only accumulated to levels 2 to 4 times the tissue concentration in the

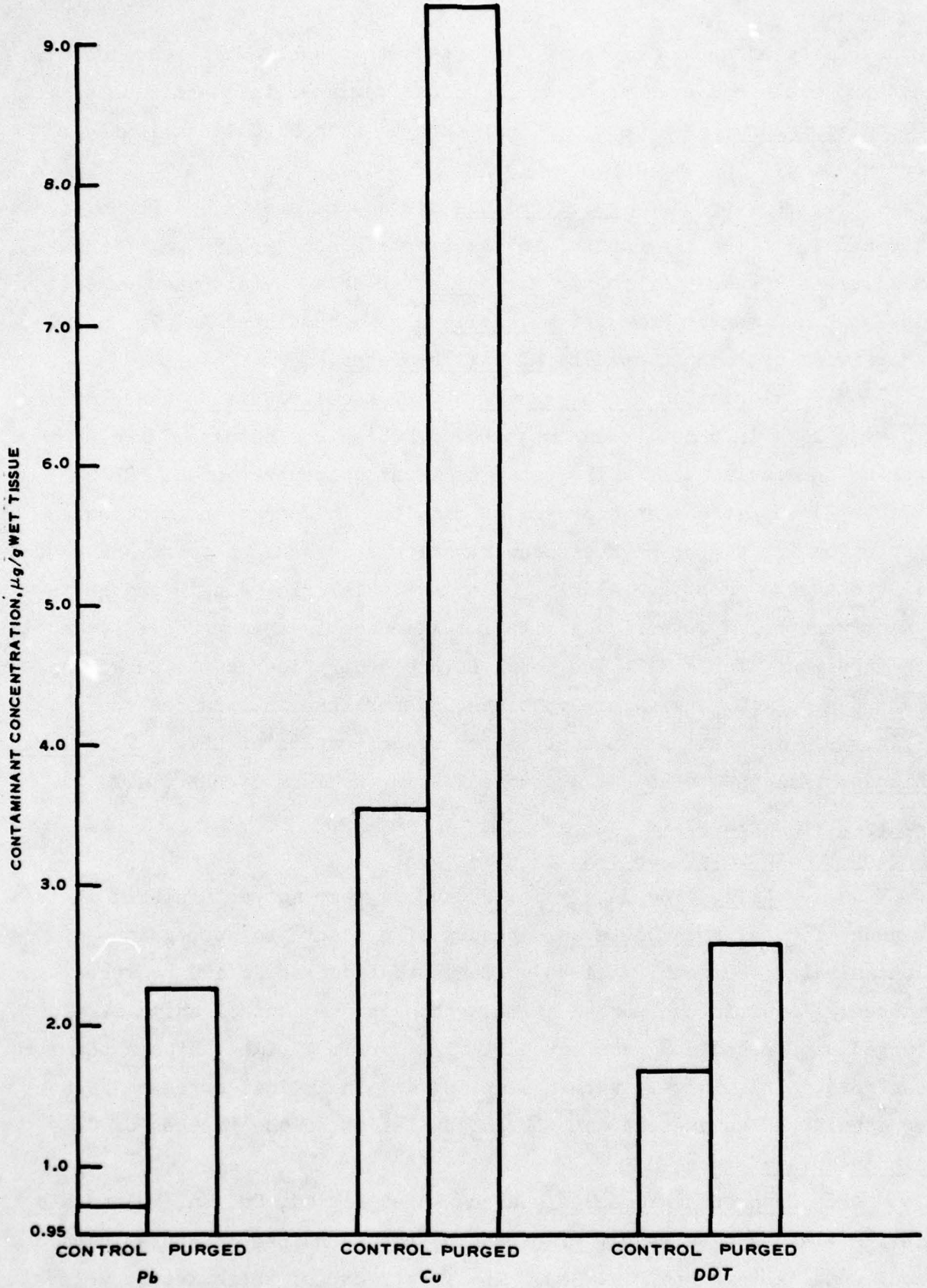


Fig. 35. Mytilus californianus metals concentrations in the contaminated sediment phase of the marine test

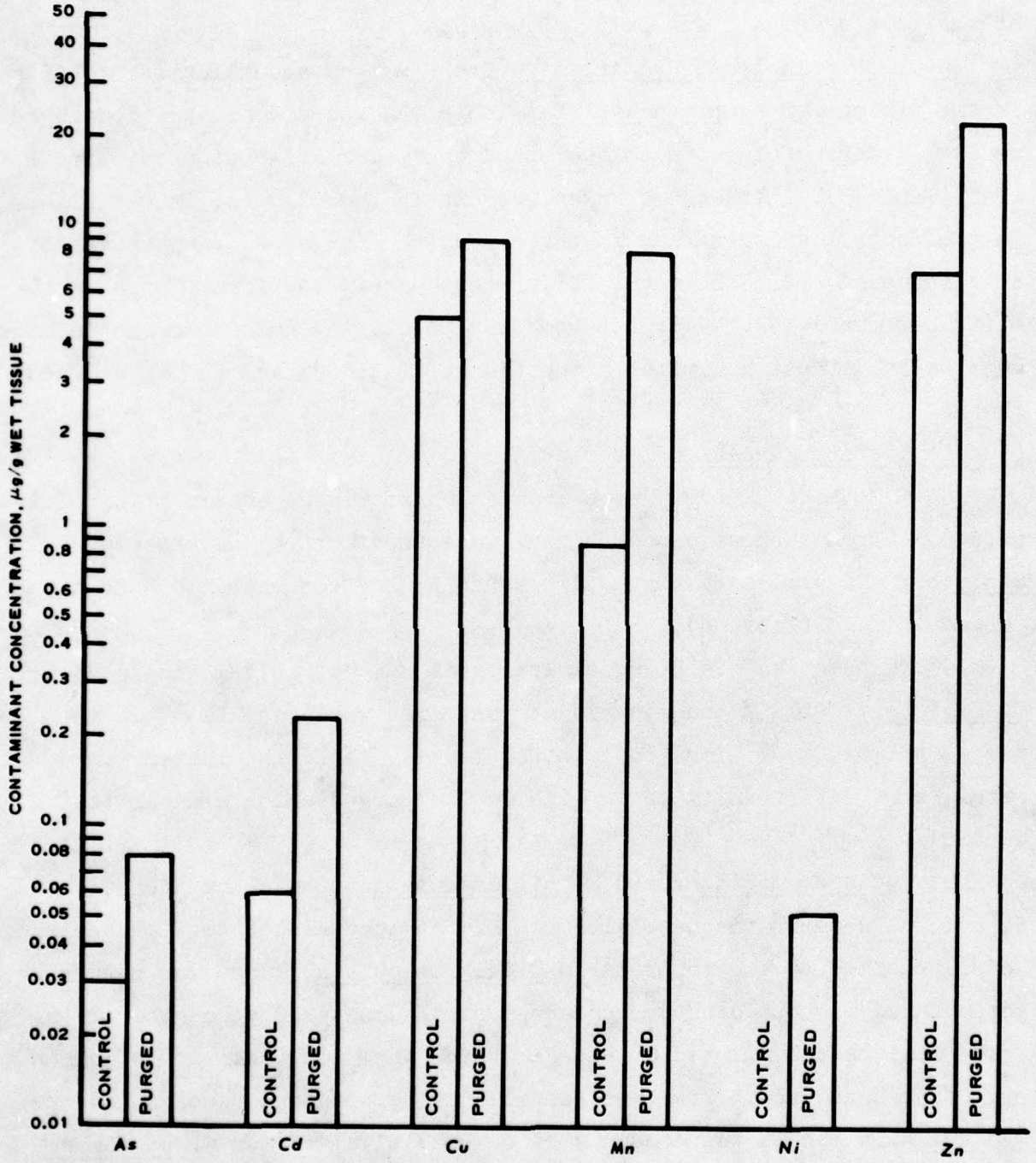


Fig. 36. Crangon nigromaculata metals concentrations in the contaminated sediment phase of the marine test

control animals. Manganese in the purged animals reached 8.20 µg/g and was 9.4 times the concentration in the controls. Nickel was accumulated to a level 52 times the controls, but even so the tissue concentration of the purged animals was only 0.52 µg/g.

94. Chlorinated hydrocarbons. There was no accumulation of PCB's in the tissues of C. nigromaculata (Table 9), where concentrations were several orders of magnitude lower than the total PCB content of the sediment (Table 3). Although DDT was present in the tissues, it was higher in the control animals than in the purged shrimp, showing no uptake of this compound. All the total DDT present was in the form of the metabolite DDE (Table 9). Aldrin, chlordane, dieldrin, endrin and heptachlor were below detection limits in the tissue (Table 9) and in the sediment (Table 3).

Dungeness crabs Cancer magister

95. Metals. There was no indication of tissue accumulation of As, Cu, or Fe from suspensions of contaminated sediment by juvenile C. magister. In all cases the controls had higher concentrations than the purged animals (Table 8).

96. There was tissue accumulation of Mn, Cd, Pb, Ni and Zn in C. magister (Table 8 and Fig. 37). The first was accumulated in the purged animals to 8 times the control levels, while the latter two metals were less than twice as high in the purged animals as in the controls.

97. Cancer magister and C. nigromaculata both accumulated Cd, Mn, Ni and Zn in their tissues, although Ni was accumulated to a much higher level relative to the controls in C. nigromaculata. The four metals accumulated by both crustaceans were not accumulated by both bivalves. Both bivalves accumulated Cu and Pb, which were not taken up in common by both crustaceans. Zinc was accumulated by both crustaceans and by M. edulis, while Cu was accumulated by both bivalves and C. nigromaculata. All other metals were accumulated by two or less of the test species.

98. Chlorinated hydrocarbons. As was the case with every other species studied, concentrations of PCB's in the tissues of C. magister

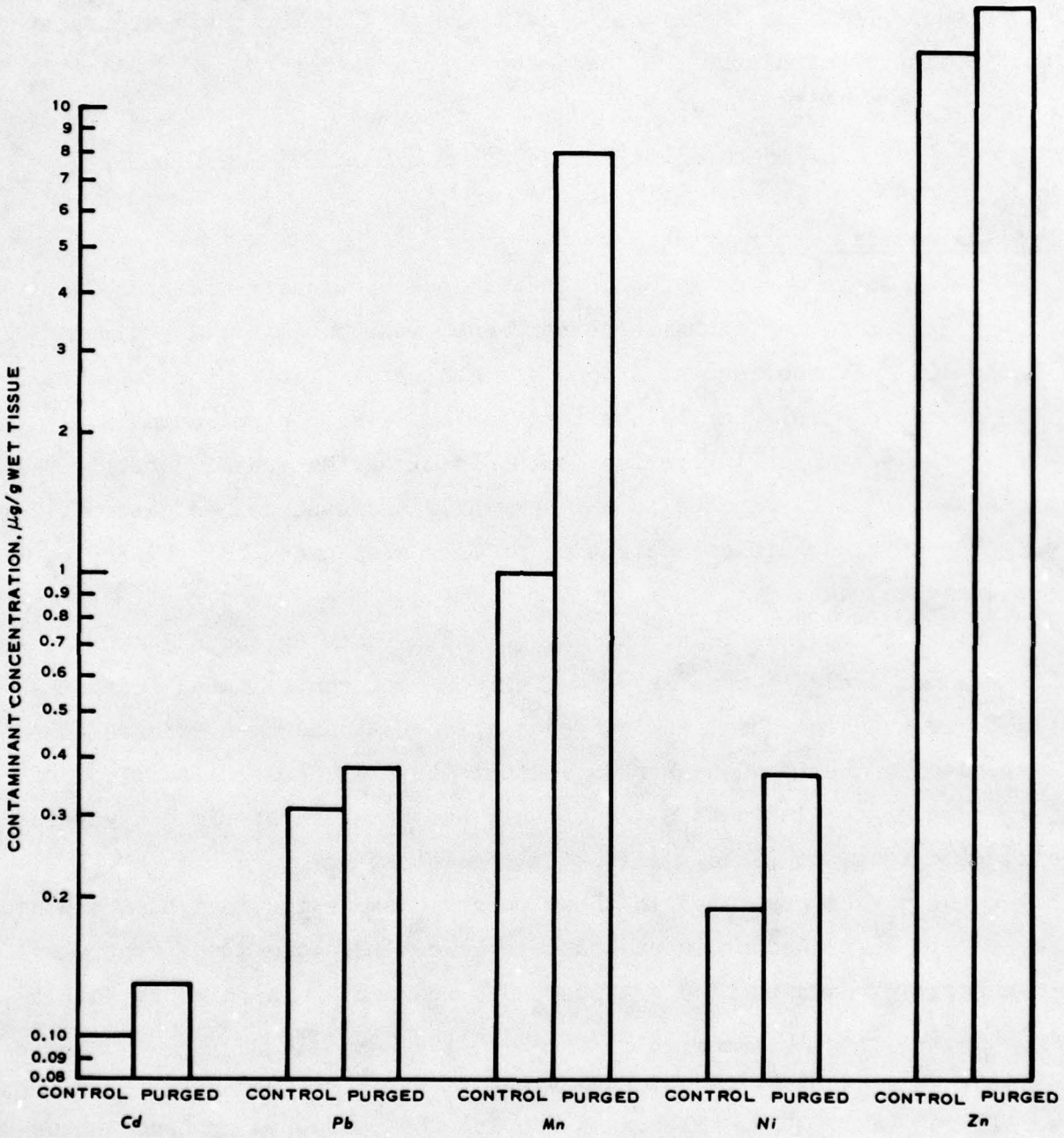


Fig. 37. Cancer magister metals concentrations in the contaminated sediment phase of the marine test

were below detection limits (Table 9). Aldrin, chlordane, dieldrin, endrin, and heptachlor were below detection limits in both the tissues (Table 9) and the sediment (Table 3). All the total DDT present was in the form of DDE, but there was no evidence this compound was accumulated in the tissues as a result of sediment exposure (Table 9).

Chemical Uptake--Estuarine Test With Contaminated Sediment

Mytilus edulis metals uptake

99. There was no evidence of tissue accumulation of Mn or Ni by M. edulis during the estuarine experiment with contaminated sediment (Table 10). Tissue concentrations of both metals fluctuated considerably in the controls during the test period. The control animals at the end of the 5-day purging period contained higher Mn and Ni concentrations than mussels exposed to any suspended sediment concentration. The purged control sample concentration of Mn was exceeded only by the control sample on day 3.

100. In contrast, Cd, Cu, Pb, Zn and perhaps Hg accumulated in the tissues of M. edulis as a result of exposure to contaminated sediments (Table 10 and Fig. 38). The purged samples that had been exposed to suspended sediment had higher Cd contents than all control samples and were also higher in Cd than the mussels had been at the time they were collected from the field. Tissue Cd concentrations were highest (7.7 times the purged controls) in those purged mussels that had been exposed to 3.6 g/l suspended sediment and were lowest (3.8 times the controls) in mussels exposed to 15.9 g/l suspended sediment. The highest Cu concentration of the experiment occurred in the controls on day 3, and control Cu concentrations decreased throughout the remainder of the experiment (Fig. 38). All purged samples that had been exposed to suspended sediment were 2.8 to 6.1 times higher in Cu than the purged controls, with the highest concentration among the exposed animals occurring at 3.6 g/l suspended sediment.

101. Zinc and Pb were also accumulated in the tissue of M. edulis from suspended sediments, although to a lesser degree than Cd and Cu

Table 10

Contaminant concentrations in the tissue of the mussel Mytilus edulis in the chemical uptake study in the contaminated sediment phase of the estuarine test. Data are in µg/g wet tissue, excluding shell.

		Metals								
SS g/l	Exposure days	As	Cd	Cu	Fe	Pb	Mn	Hg	Ni	Zn
At collection		0.09	0.96	2.05	71	0.19	2.71	0.15	0.68	38.4
0	3	0.15	0.09	5.98	176	0.15	7.74	0.12	1.24	45.6
0	10	0.15	0.32	1.74	131	0.19	3.29	0.05	0.94	25.3
0	15	0.28	0.26	1.16	100	0.23	1.16	0.02	1.74	20.2
0	21	0.06	0.44	1.14	95	0.18	3.09	0.06	2.60	39.1
0	P	0.06	0.28	0.85	49	0.15	3.49	0.02	3.15	27.5
3.6	P	0.16	2.15	5.22	154	1.68	2.99	*	2.72	100.0
12.1	P	0.10	1.16	2.43	55	0.34	2.92	*	1.46	55.9
15.9	P	0.08	1.07	2.83	58	0.18	1.95	0.11	1.17	50.0

		Chlorinated Hydrocarbons							
SS	Exposure				Total	Aroclor			Total
g/l	days	DDE	DDD	DDT	DDT	1242	1254	1260	PCB's
At collection		0.68	0.32	-	1.00	0.02	0.05	0.01	0.08
0	3	1.18	0.38	-	1.56	0.02	0.06	0.01	0.09
0	10	0.52	0.84	-	1.36	0.02	0.03	0.01	0.06
0	15	0.50	0.46	-	0.96	0.02	0.06	0.02	0.10
0	21	0.18	0.85	-	1.03	0.04	0.02	0.01	0.07
0	P	0.55	0.40	-	0.95	0.06	0.02	0.01	0.09
3.6	P	0.75	0.83	-	1.58	0.07	0.07	0.02	0.16
12.1	P	0.49	1.10	-	1.59	0.05	0.03	0.02	0.10
15.9	P	0.47	0.68	-	1.15	0.05	0.02	0.01	0.08

P = Animals were exposed to indicated suspended solids concentration for 21 days then placed in clear water 5 days to purge the sediment from the digestive tract and body surfaces before analyses.

* = Insufficient sample for analysis.

- = Below detection limits; DDT < 0.008 ng/g. Also below detection limits were chlordane < 0.008 ng/g; aldrin, dieldrin, heptachlor < 0.004 ng/g; endrin < 0.1 ng/g.

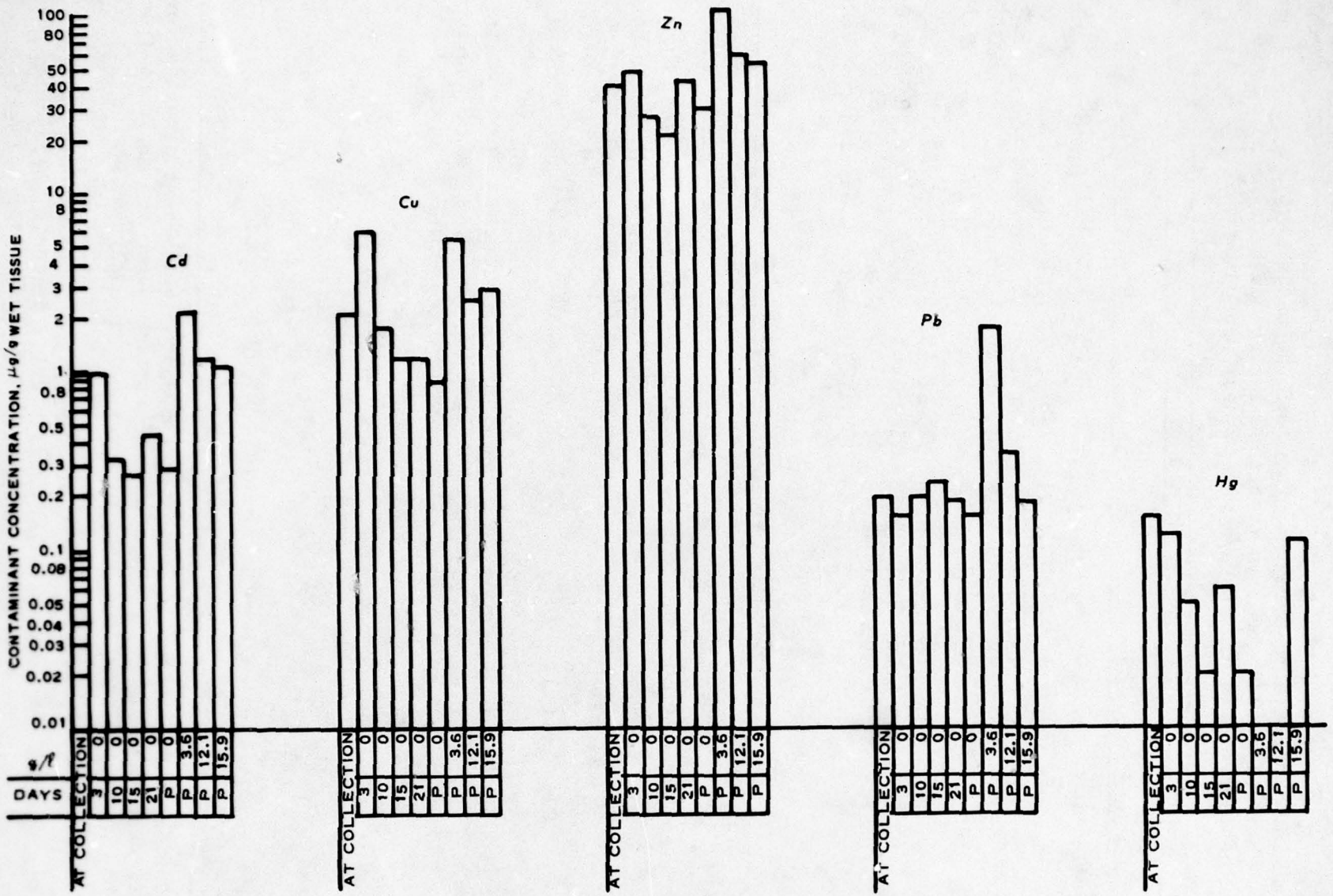


Fig. 38. Mytilus edulis metals concentrations in the contaminated sediment phase of the estuarine test

(Table 10 and Fig. 38). The pattern of accumulation for Zn was similar to that for Cd in that all exposed and purged samples were higher than all control samples and those mussels exposed to 3.6 g/l suspended sediment had the highest metal content. However, Zn concentrations were only 1.8 to 3.6 times the purged control values. Lead showed the most varied accumulation of any metal studied. The Pb concentration in animals exposed to 3.6 g/l suspended sediment was 11.2 times the concentration in the purged controls. However, in the animals exposed to 15.9 g/l suspended sediment, the Pb concentration was only 1.2 times the purged controls and was exceeded by three of the five control samples and by the mussels at the time they were collected from the field.

102. Although the data are incomplete, there is an indication that Hg accumulation may have occurred to some extent. The only datum available on exposed animals is for 15.9 g/l suspended sediment, where the Hg concentration was 5.5 times that in the purged controls (Table 10 and Fig. 38). Even so, the exposed animals had less Hg than the mussels had when they were collected from the field or after 3 days in the control aquaria. Thus, with the limited data base it is impossible to determine whether Hg accumulation actually took place under the experimental conditions.

103. Concentrations of Fe were higher in the exposed mussels after purging than in the purged controls. The mussels purged after exposure to 12.1 and 15.9 g/l suspended sediment exceeded the purged control level by less than 1.2 times and were below all other control values (Table 10). Even though the animals purged after exposure to 3.6 g/l suspended sediment exceeded the purged controls by a factor of approximately 3, they were still within the range of the other control values. Arsenic values in all mussels purged after exposure to suspended sediment exceeded the purged controls by factors of 1.3 to 2.7, yet again all fell within the range of the other control values. The data seemed at most to indicate a possibility of tissue accumulation of Fe and As by M. edulis.

104. The metals Cu, Pb, and Zn were accumulated in the tissues of M. edulis as a result of exposure to suspensions of contaminated sediment in both the marine and estuarine tests. There was some possible

indication of the potential for low-level accumulation of As and Fe in both tests. In the estuarine test Cd was accumulated in the tissues, while it was not in the marine test. Data on Hg are incomplete. There was no tissue accumulation of Mn or Ni in either test.

Mytilus edulis chlorinated hydrocarbons uptake

105. There was no evidence of accumulation of DDT, aldrin, chlordane, dieldrin, endrin or heptachlor from suspensions of contaminated sediment by M. edulis, as all were below detection limits in all tissue samples (Table 10). All the above except DDT were below detection limits in the sediment also (Table 3). The exposed and purged samples contained higher levels of the DDT metabolites DDD and DDE than the purged controls but total DDT content was very similar to the controls on day 3 (Table 10 and Fig. 39).

106. Those mussels exposed to 3.6 and 12.1 g/l suspended sediment had total DDT concentrations of 1.58 and 1.59 µg/g in the tissues, which was only 1.7 times that in the purged controls (Table 10). This increase over control concentrations was only 0.85 times the bulk sediment DDT concentration (Table 3). Thus, while there was DDT accumulation as a result of exposure to suspended sediment, the increase in tissue concentration was relatively small. The parent compound DDT was not detected in the tissues. The metabolite DDD:DDE ratio in the exposed mussels was 0.44 to 0.90, while it was 1.37 in the purged controls. This ratio was highly variable in the controls over time, ranging from 0.21 to 3.10 (Table 10 and Fig. 39).

107. Mytilus edulis accumulated PCB's in the tissues when exposed to 3.6 g/l suspended sediment but not from 12.1 g/l or 15.9 g/l (Table 10 and Fig. 39). Mussels exposed to 3.6 g/l suspended sediment had total PCB concentrations in the tissues 0.07 µg/g, or 1.8 times, higher than in the purged controls. This increase due to suspended sediment exposure was only 0.05 of the bulk sediment PCB concentration (Table 3). Thus, there was some increase in tissue concentration of PCB's, but tissue concentrations did not reach the levels in the sediment.

108. Both DDT and PCB showed small increases in tissue

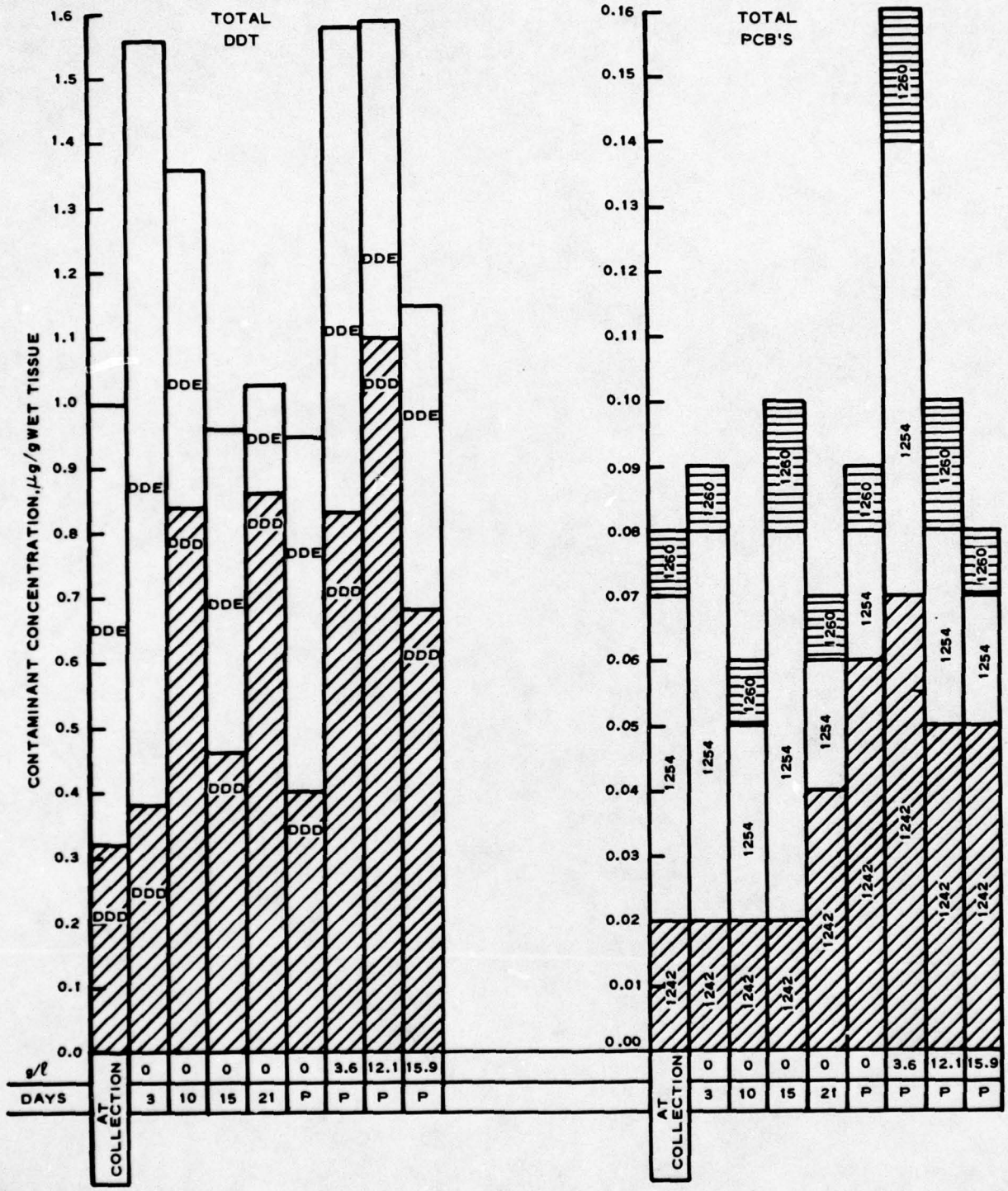


Fig. 39. Mytilus edulis chlorinated hydrocarbon concentrations in the contaminated sediment phase of the estuarine test

concentrations as a result of exposure to suspensions of contaminated sediment in the estuarine test, but neither was accumulated by M. edulis when exposed to the same sediment in the marine test.

PART V: DISCUSSION

109. The suspended sediment concentrations and exposure times used in this study were not intended to duplicate the range of conditions in the water column considered representative of dredging and disposal operations. Rather, they were intended to be rigorous enough to determine the upper limits of survivability and to determine whether bioaccumulation from suspensions of contaminated sediment is possible and of sufficient potential magnitude and frequency of occurrence to warrant concern. Therefore, the fact that a particular species suffered some mortality or bioaccumulated a certain contaminant in this study does not predict the occurence of similar effects around a dredging operation in a similar sediment. This shows only the potential response of the species if conditions similar to those used in this study were ever created.

110. The nature, degree and extent of sediment suspension around a dredging or disposal operation are controlled by many factors, as discussed by Barnard (1978). Chief among these are: the particle size distribution, solids concentration and composition of the dredged material; the dredge type and size, discharge/cutter configuration, discharge rate, solids concentration of the slurry and operational procedures being implemented; and finally the characteristics of the hydrologic regime in the vicinity of the operation, including water composition, temperature and hydrodynamic forces (i.e., waves, currents, etc.) causing advection and turbulence. The relative importance of the different factors may vary significantly from site to site.

111. Depending on the above factors, clamshell or bucket dredges might be generally expected to create plumes in the water column with suspended solids concentrations not exceeding 0.5 g/l and with average concentrations probably less than 0.1 g/l (Barnard, 1978). Hydraulic cutterhead or pipeline dredged generally do not create suspended solids levels in excess of a few hundred milligrams per litre in the water column near the dredging site. Hopper dredges probably do not create water column suspended solids concentrations in excess of 1 g/l over

any appreciable area of the dredging site (Barnard, 1978). In addition, these levels are intermittent as the hopper dredge moves between dredging and disposal sites, often with a cycle time of an hour or more.

112. A study of hopper dredge disposal at Carquinez Strait, San Francisco Bay, showed concentrations of dredged material in the water column were generally less than 0.2 g/l above background and persisted only for a few tens of minutes. However, 1 to 2 metres above the bottom, concentrations reached 20 g/l in a fluid mud layer (U. S. Army Engineer District, San Francisco, 1976). Similar occurrences of low suspended sediment concentrations in the water column with concentrations on the order of several tens of grams per litre just above the bottom have been discussed for pipeline dredge discharges by Barnard (1978), May (1973), Masch and Espey (1967) and Nichols et al. (1978). These conditions persist for the duration of the disposal operation at the site and for varying times thereafter as the material consolidates to typical sediment density.

113. Therefore, evaluations of potential environmental impacts of suspended dredged material must consider two distinct sets of conditions. The first is the low-concentration, finite duration, often intermittent, suspended sediment loading created in the water column by every dredging and disposal operation. In the present study, suspended sediment concentrations and exposure times far in excess of typical dredging or disposal-created conditions in the water column were tolerated without effect by all species studied, even with the most contaminated sediment. The only possible exception among 22 species-sediment-salinity combinations was striped bass fingerlings M. saxatilis in contaminated sediment, for which mortality occurred at conditions near the upper range considered possible in the water column around dredging or disposal operations. Even M. saxatilis was unaffected by suspensions of uncontaminated sediment and exposure times far in excess of those created in the water column by dredges. Peddicord et al. (1975) documented similar tolerances far in excess of dredging-related water column conditions for 26 species-sediment combinations. Sherk et al. (1974) have shown suspended solids tolerances for a variety of estuarine

fish to exceed the time-duration conditions typical of the water column near dredging or disposal operations.

114. A comprehensive review of the literature led Stern and Stickle (1978) to conclude that ecological effects of suspended sediment conditions in the water column typically created by dredging operations are generally minimal and transient. They concluded that typical dredging-created water column suspended sediment conditions generally do not cause irreversible ecological impacts, although they may well create aesthetically objectionable conditions.

115. The second and potentially more serious type of sediment suspension generated by dredged material disposal is fluid mud, which can cover benthic organisms with tens of grams per litre of suspended sediments for periods of weeks. This study and Peddicord et al. (1975) have shown that such conditions could impact a variety of species, particularly if the suspended sediment is highly contaminated. In addition, Peddicord et al. (1975) have shown that low dissolved oxygen, which has been documented in fluid mud by May (1973), increases the impact of suspended solids. Since fluid mud is confined to a distinct and relatively thin layer on the bottom, it probably poses little threat to water column fish, which are unlikely to encounter it and can easily avoid it if they find the conditions adverse. However, benthic and perhaps even motile epibenthic organisms could be covered by a high-suspended-sediment, low-dissolved-oxygen layer which is not dense enough to physically support the weight or activity of organisms attempting to move upward to reestablish contact with the clearer overlying water.

116. Although the above-mentioned laboratory research indicates the potential biological effects of fluid mud, only one field study has specifically addressed this topic. Diaz and Boesch (1977) studied impacts on a low-diversity community adapted to physically rigorous conditions in the tidal freshwater James River, Virginia. Fluid mud created by a hydraulic pipeline disposal operation had a pronounced immediate impact on the benthos, affecting insect larvae the most. However, the resilient and opportunistic nature of the fauna buffered

the impacts at this site, and by 3 months after disposal ceased the community was again similar to that of nearby areas.

117. Where fluid muds are created, they have the potential of causing biological impacts. It seems clear that hydraulic pipeline disposal of predominantly fine-grained dredged material will create fluid mud to some degree at the disposal site (Barnard, 1978). This is also considered likely with hopper dredges (U. S. Army Engineer District, San Francisco, 1976) but has not been widely documented.

118. The tolerance of a wide variety of marine and estuarine organisms to suspensions of kaolin and bentonite clays, and the effects of temperature and dissolved oxygen on that tolerance, was determined by Peddicord et al. (1975). At winter temperatures and dissolved oxygen levels near saturation, all invertebrates tested were able to tolerate continuous exposure to suspended solids concentrations in the range of tens of grams per litre for several days to several weeks with no substantial mortality. Fish tolerated concentrations in the range of grams per litre for similar periods under similar environmental conditions. As temperature increased and/or dissolved oxygen concentrations decreased, tolerance decreased. Yet even at summer temperatures and 2 ppm dissolved oxygen, most invertebrates tolerated continuous exposure to 60 g/l suspended bentonite for several days before mortality occured.

119. Peddicord et al. (1975) provided a basis for the present study by using a processed, contaminant-free bentonite clay selected to be similar in mineralogy and particle size distribution to the natural sediments used here. Thus, it is possible in some cases to compare tolerances of similar-sized organisms of the same species under similar experimental conditions to suspensions of clean, uniformly fine-grained kaolin, clean bentonite in a range of particle sizes, similarly sized uncontaminated sediment and contaminated sediment. As indicated by the LCX estimates in Table 11, tolerance to suspensions of both processed clays was high for all species. Bentonite and uncontaminated harbor sediment, which were physically and mineralogically similar and differed primarily in the presence of chemical constituents, produced similar low mortalities. This implies that the effects of the uncontaminated

Table 11

Comparisons of 10-day and 21-day LCX estimates in g/l for suspensions of kaolin clay, bentonite clay, uncontaminated natural sediment and contaminated natural sediment. (Kaolin and bentonite data from Peddicord et al., 1975.)

Species	LCX	10-day Kaolin	10-day Bentonite	Uncontaminated Sediment		Contaminated Sediment	
				10-day	21-day	10-day	21-day
Mytilus edulis (marine test)	LC50	--	>60	>20	>20	14	8
	LC20	--	>60	>20	>20	9	4
	LC10	--	>60	>20	>20	6	2
Mytilus californianus (marine test)	LC50	84	--	>20	>20	>20	6
	LC20	36	--	>20	>20	>20	4
	LC10	21	--	>20	20	>20	3
Crangon nigricauda (estuarine test)	LC50	--	>60	>20	>20	>20	>20
	LC20	--	>60	>20	>20	>20	20
	LC10	--	>60	>20	20	>20	20
Cancer magister (marine test)	LC50	32	--	--	--	>20	11
	LC20	18	--	--	--	14	5
	LC10	10	--	--	--	10	3
						2-day	
Morone saxatilis (estuarine test)	LC50	--	>2	>4	>4	0.4	
	LC20	--	>2	>4	>4	<0.4	
	LC10	--	>2	4	4	<0.4	

harbor sediment were primarily physical, and that those chemical constituents associated with it (Table 2) were not biologically available in lethal quantities when the sediment was suspended.

120. Mussels Mytilus edulis suffered less than 10 percent mortality during the tests at the highest concentration of suspended bentonite and uncontaminated sediment used (Table 11). This precludes quantitative comparison of tolerances but demonstrates that M. edulis was able to tolerate at least 21 days of exposure to suspensions of at lease 20 g/l of uncontaminated solids. Since the contaminated sediment was physically similar to the uncontaminated sediment (Table 4), its much greater impact on M. edulis (Table 11) must have been due, to chemical pollutants. Even so, the 10-day LC10 value of 6 g/l far exceeds the concentrations and durations of suspended solids created in the water column by typical dredging and disposal operations. However, lethal conditions could occur if M. edulis were ever covered by fluid mud.

121. The related coast mussel M. californianus was more affected by kaolin suspensions than M. edulis was by bentonite (Table 11), yet its tolerance to physical effects of uncontaminated sediment suspensions was also high. The 10-day tolerance of M. californianus to contaminated sediment was greater than M. edulis, but their 21-day LCX values were equal. As indicated by the delayed but rapid patterns of mortality in Figures 13 and 16, both species may have remained closed during the early days of the test, dying only when physiological needs forced them to open their shells and begin pumping water, exposing themselves fully to the adverse experimental conditions. The 10-day tolerance of M. californianus may have been greater than that of M. edulis due simply to a physiological ability to remain closed slightly longer.

122. Both M. edulis and M. californianus generally maintained byssal attachments throughout the tests or until death in suspensions of both contaminated and uncontaminated sediments. Peddicord et al. (1975) found that increasing temperature and suspended solids concentrations combined to reduce byssal attachment of M. edulis, as did lowered dissolved oxygen concentrations. Since this loss of byssal attachment

occured after much shorter exposure times than those causing death, the authors suggested that this might be an early and sensitive indicator of effective death. Reish and Ayers (1968) found that byssal thread production by M. edulis decreased greatly at low dissolved oxygen levels while mussel survival remained high. Thread formation by M. edulis decreased with increasing size and increasing temperature (Van Winkle, 1970) and was greatest at salinities near 31 parts per thousand (Glaus, 1968). Martin et al. (1975) found that thread production by M. edulis decreased as concentrations of solution Cd, Cu, Cr, Pb, Hg and Zn increased. Fifty percent mortality occurred at about the concentrations of Cr, Cu and Hg that caused 50 percent decrease in thread production. The effective concentration of solution Cd causing 50 percent reduction in thread production (EC50) was one fifth the LC50 after 7 days, and while the 7-day LC50 for Zn and Pb could not be determined, it was at least 3 and 10 times the EC50, respectively (Martin et al.,1975).

123. Although the whole water concentrations of Zn and Cu in the contaminated sediment phase of the present study were 3 and 10 times the EC50 values determined by Martin et al. (1975) and both metals were accumulated in the tissues of M. edulis, no loss of byssal attachment was noted. The data available from the literature and this study seem to indicate that changes in byssal thread production by M. edulis may be a sensitive indicator of physical stresses such as low dissolved oxygen and of solutions of some metals. However, some contaminants or combinations of contaminants appear to cause death before thread production is affected. It appears that byssal thread production by M. edulis should not be universally assumed to be a sensitive tool for environmental evaluations.

124. Juvenile Dungeness crabs Cancer magister were affected by suspensions of both materials in which they were tested. The 10-day LCX estimates in kaolin (Table 11) were lower than those for most other invertebrates tested in suspensions of processed clay by Peddicord et al. (1975). This indicates a relatively greater sensitivity than the other species to physical effects of mineral particles. The LCX values in contaminated sediment were similar to the comparable values

in kaolin after 10 days exposure but decreased by approximately 67 percent by day 21. The polluted nature of this sediment revealed itself in its effects on the molting of C. magister. In kaolin the molting process was unaffected, but in contaminated sediment 92 percent of all mortalities occurred at the time of ecdysis (Figure 22), and many surviving crabs completed the molt with deformed appendages. The exposure times and suspended sediment concentrations necessary to cause death, even with contaminated sediment, are far above those likely to be created in the water column by most dredging and disposal operations. However, juvenile C. magister could be killed if covered by contaminated fluid mud. Even though these organisms are motile, it is impossible to know whether they are able to move fast and far enough in a proper direction to escape the effects of fluid mud.

125. The response of the crabs is in contrast to the black-tailed sand shrimp Crangon nigricauda, which was relatively unaffected by suspensions of bentonite, uncontaminated sediment or contaminated sediment (Table 11). The shrimp molted normally throughout all tests and the few deaths that did occur did not appear to be associated with molting. Similarly, juvenile American lobsters Homarus americanus suffered no mortalities in 20 g/l contaminated sediment for 25 days and only one molting abnormality occurred. Thus, while C. magister was greatly affected by contaminated sediment, this was not true for other crustaceans tested. The above data indicate that the effects with contaminated sediment were chemical in nature, although the causative agent(s), mechanisms of effects and reasons the molting impacts were confined to C. magister were not investigated.

126. Fingerling striped bass Morone saxatilis survived 10-day exposure to 2 g/l bentonite and 21-day exposure to 4 g/l uncontaminated sediment with no more than 10 percent mortality (Table 11). That they were very sensitive to some chemical associated with the physically similar contaminated sediment is shown by the fact that the contaminated sediment 2-day LC50 is one order of magnitude below the 21-day LC10 in uncontaminated sediment (Table 11). The short exposure times and low estimates for M. saxatilis in contaminated sediment are

within the upper range of conditions which could conceivably be created by dredging and disposal operations. This is the only species tested which showed a sensitivity sufficient to cause possible concern about effects of suspensions of contaminated dredged material. Even this potential might be realized only with a typically high suspended sediment concentration persisting in the water column for unusually long periods in an area and at a time of year when fingerling striped bass M. saxatilis were present.

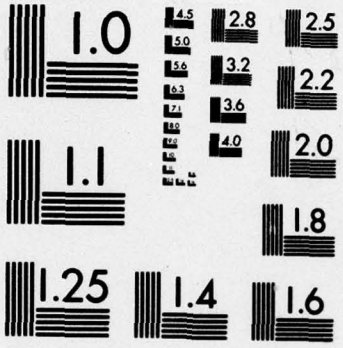
127. Fingerling rainbow trout Salmo gairdneri in the experiment with uncontaminated freshwater sediment suffered considerably less mortality than indicated by previous literature. Herbert and Merkins (1961) tested 10-cm rainbow trout in suspensions of kaolin clay and diatomaceous earth and found survival of approximately 42 percent after 21 days exposure to 270 mg/l suspended solids. Southgate (1960) found 50 percent mortality of adult rainbow trout after 11 days exposure to 270 mg/l diatomaceous earth. In the present study fingerling rainbow trout survived 21 days with no mortality definitely attributed to suspensions of uncontaminated harbor sediment as high as 4.3 g/l, or 16 times higher than the suspended solids concentrations discussed from Herbert and Merkins (1961) and Southgate (1960).

128. This discrepancy is even more striking in light of the fact that much smaller fish were used in the present study. Sherk et al. (1974) found that small estuarine fish were more susceptible to suspended solids than were larger fish of the same species. The authors speculated that the smaller gill openings of juveniles may have become clogged with sediment at the same time the higher metabolic rate demanded more oxygen than adults, resulting in the greater sensitivity of juveniles. While reasons for the differences between previous studies and this one, which used natural harbor sediments, are unclear, it is apparent that rainbow trout should not be considered universally hypersensitive to suspended sediments. Indeed, in the present study, fingerling rainbow trout were more tolerant to suspensions of natural river sediment than were tadpole larvae of the western toad Bufo boreas.

129. That substantial amounts of sediment can accumulate in the

AD-A058 489 EFFECTS OF SUSPENDED DREDGED MATERIAL ON AQUATIC ANIMALS(U) CALIFORNIA UNIV BODEGA BAY BODEGA MARINE LAB R K PEDDICORD ET AL. JUL 78 WES-TR-D-78-29 2/2

UNCLASSIFIED F/G 13/2 NL



guts, even of nonfilter- and nondeposit-feeding organisms, was demonstrated for striped bass M. saxatilis in the estuarine experiment with uncontaminated sediment (Figure 33). If this sediment is not removed before analysis of tissue samples for bioaccumulation, it will bias the data in one or both of two opposing and unpredictable ways. It has been recognized for some time that sediment in the gut contains tightly bound materials that remain associated with the particles and are not incorporated into the tissues (Bertine and Goldberg, 1972). Thus, if sediments are not removed from the tissues before analysis, materials passing through the gut in biologically unavailable forms will incorrectly be interpreted as "bioaccumulated." Conversely, the inert minerals of the sediment are much more dense than tissue, raising the sample weight and thus lowering the apparent sample concentration of the material being analyzed. Thus, the sediment contains metals and perhaps other contaminants at much higher concentrations than in the tissues, which tends to raise the apparent concentration in the sample, at the same time the sediment contributes weight of inert minerals, which tends to lower the apparent sample concentration. Depending on the relative weights of sediment and tissue in the sample and the relative amounts of contaminant in each of these compartments, "bioaccumulation" data for sediment-containing samples could be either elevated or lowered artificially and incorrectly. Thus, only sediment-free tissue samples can validly be analyzed to determine bioaccumulation.

130. The practice of removing sediment from animals by purging in clean water before analysis is discussed by Flegal and Martin (1977), who point out that it is not foolproof due to lack of knowledge of the time required for total purging, and possible reingestion of the purged material. In the present study the latter difficulty was overcome by purging the animals in a once-through flow of filtered water and maintaining them above the aquarium bottoms so that voided material settled away from the animals and was carried away with the water. Although the time for complete purging is unknown, animals of the size studied would be expected to empty the gut in less than the 4- or 5-day purging period. After the first day or two, no sediment could be seen in the

aquaria. However, it is possible that some of the apparent tissue accumulation was in reality due to contaminants associated with sediments remaining in the gut or on the body surfaces.

131. As pointed out in the chemical uptake results section, the limitations imposed on these data by the sample storage conditions permit only comparisons of trends, rather than quantitative values, with results from other bioaccumulation studies. Even if this were not the case, the environmental interpretation of bioaccumulation data is extremely difficult. This is due to the fact that in most cases the state of knowledge is inadequate to quantify the consequences of a given concentration of a bioaccumulated constituent in the tissues of an animal, not to mention the impossibility of quantifying the overall ecological consequences of that tissue concentration in the population in question.

132. Part of the reason for this is that animals vary in their uptake potential and tolerance with species, age, reproductive condition and physiological condition. There is also great variation in uptake mechanisms and sensitivity to the various contaminants. For instance, Cu and Zn are essential micronutrients which are required at low levels and become toxic only when much higher concentrations are accumulated in the tissues. This is especially true of Cu in crustaceans, where it is essential to the oxygen-carrying capacity of the blood. Some metals such as Fe and Mn are not toxic even at very high tissue concentrations, and their bioaccumulation cannot be considered to have any ecological significance except in rare cases of extreme concentrations. Others, such as Cd and Hg, have no known micronutrient function, and, although they may be found at low levels even in animals from pristine environments, their bioaccumulation must be regarded as potentially hazardous. The chlorinated hydrocarbons similarly serve no useful function and must be viewed as potentially hazardous when bioaccumulated, even though very low levels may be tolerated by some life stages with no apparent ill effects.

133. Since the ecological significance of a particular tissue concentration of a specific constituent in a given species can be

determined in very few cases, bioaccumulation data must be interpreted on the basis of tissue concentrations of exposed animals relative to concentrations in control animals of the same species. In using this approach, it is critical to recognize the possibility that even the control animals before the test is begun could have an undesirably high tissue burden, or conversely that even the highest concentration found in the exposed animals at the end of the test might not be sufficient to cause any biological impact.

134. When dealing with bioaccumulation from sediments it is not technically valid to calculate a bioconcentration factor (BCF) from the tissue:medium concentration ratio as may be done when assessing tissue uptake from solutions. It is known that the total or bulk sediment concentration of contaminants is generally not biologically available for tissue accumulation (Bertine and Goldberg, 1972; Brannon et al., 1976; Luoma, 1977; Turekian, 1977), yet no method has been devised for determining what portion of the total amount present is biologically available. Therefore, there is no valid basis for determining a sediment concentration of contaminant which can be compared to the tissue concentration of exposed animals to calculate a BCF. With properly designed experiments it is possible to determine the BCF by the uptake-depuration kenetics approach. The tissue concentrations in these studies were less than one to several times higher than the total concentration of contaminants in the sediment to which the animals were exposed. Certainly tissue concentrations were not several orders of magnitude higher than the total contaminant concentrations present, as is often the case when uptake is directly from solution.

135. In the study of chemical uptake from contaminated sediment, tissue accumulation of contaminants proved to be the exception, rather than the rule. Four species in the marine test and one species in the estuarine test were analyzed for 9 metals (45 contaminant-species combinations) and 11 chlorinated hydrocarbons (55 contaminant-species combinations) for a total of 100 instances where uptake would have been measured if it had occurred. Of the 45 metal combinations, uptake to some degree was documented in 22 cases and possibly indicated in one

other, or somewhat less than half the possible cases. Chlorinated hydrocarbon uptake was documented in two cases and possible indicated in one other, actually occurring in only about 5 percent of the possible cases. Of the total of 100 contaminant-species combinations where uptake might have been measured, it was found in 24 cases with two others giving indications of possible uptake, so that tissue accumulation actually occurred in no more than one fourth of the total cases in which it was possible. While generalizations can be made concerning the likelihood of limited bioavailability of sediment contaminants, it is clear that case-by-case evaluations are necessary before conclusions can be drawn about specific situations.

136. Uptake of DDE was possibly indicated in the marine experiment with coast mussels M. californianus and occurred in bay mussels M. edulis in the estuarine experiment, where PCB uptake was also documented. Even in these cases the highest tissue concentrations were less than twice the levels in the comparable controls. This very limited and low-level uptake of these chlorinated hydrocarbons, which generally have a high tissue affinity when in solution, indicates the tightness with which these man-made organics can be associated with sediment particles. This binding can effectively prevent or limit tissue uptake, even from sediments contaminated with relatively high total amounts of PCBs and DDT (Table 3). Strong sediment associations can also effectively limit the biological availability of metals for tissue uptake (Brannon et al., 1976; Luoma, 1977; Neff et al., 1978). Perhaps more concern about tissue bioaccumulation has centered on Hg than any other metal. Yet, even though the contaminated sediment contained 1.5 mg/kg total Hg (Table 3), uptake was not demonstrated in any case studied, and was possibly indicated only in M. edulis in the estuarine test.

137. Both Cu and Zn were taken up in four of the five cases studied, but the highest tissue concentration reached by either metal was less than 7 times the level in the comparable control. Lead was accumulated in all three of the cases involving mussels. Tissue concentrations in the marine test were 2.4 and 1.8 times the controls

in M. californianus and M. edulis, respectively, but were 11.2 times the controls in M. edulis in the estuarine test. Similar increases in uptake with decreasing salinity were seen with Cu and Zn in M. edulis, where the ratio of controls to exposed tissue levels increased from 3.08 in the marine test to 6.28 in the estuarine test for Cu and from 1.30 to 3.60 for Zn. This is in agreement with Phillips (1976), who found generally higher concentrations of Zn and Cu in M. edulis in low-salinity areas than in more saline environments. The tissue uptake of Cd from solution by M. edulis, Mya arenaria, Mulinia lateralis, and Nucula proxima increases as salinity decreases (Jackim et al., 1977). The estuarine bivalve Macoma balthica was shown by Anderlini et al. (1977) to take up increasing amounts of Ag, Cd, Cu, Hg and Pb from solution as salinity decreased.

138. Both Mn and Ni were accumulated in the tissues of both crustaceans but neither mullusc, in contrast to Fe which was taken up by both mulluscs but neither crustacean. Both Mn and Fe are of negligible concern as toxicants in relation to dredging. In C. magister Ni was only accumulated to less than twice the control level. However, C. nigromaculata accumulated Ni to 0.52 µg/g as compared to 0.01 µg/g in the controls. While this is still a low level of tissue Ni, it does indicate a potential for Ni uptake from sediment for some species under certain conditions.

139. In the estuarine test with M. edulis, tissue concentrations of all contaminants, whether or not uptake was shown relative to the controls, were always higher in animals exposed to 3.6 g/l suspended sediment than in mussels exposed to higher sediment concentrations (Table 10). The only exception was DDT for which tissue concentrations were higher at 12.1 g/l than when exposed to 3.6 g/l. The reason for declining tissue levels with increasing suspended sediment and whole water contaminant concentrations, at least at sediment concentrations above 3.6 g/l, is unclear. Peddicord et al. (1975) showed that oxygen consumption of M. edulis decreased with increasing suspended solids concentration. They speculated that this was due to decreased respiratory activity caused by direct interference or prolonged cessation

of pumping activity under adverse conditions. Similarly, clogging of the gills and digestive tract with sediment or a reduction in pumping could reduce contaminant uptake as observed in this study.

140. The effects of the contaminated sediment were clearly chemical rather than physical in nature. Yet relatively little tissue accumulation of contaminants was documented in the chemical uptake study. This may indicate that the effects were due to synergistic interactions of several contaminants, each of which was present in small amounts. A more likely explanation, however, is that the effects were due to some contaminant(s) not chosen for analysis. Any number of potentially toxic materials might conceivably be present in biologically available forms in sediments, making it practically impossible to analyze for all materials which might cause an effect. The fact that analyses are likely to overlook the critical contaminant(s) is a basic weakness of all dredged material evaluations dependent entirely upon chemical analyses.

PART VI: CONCLUSIONS

144. These experimental results, assessed in light of the literature reviewed for this study, lead to the following conclusions:

a. Ecological degradation due to the direct or indirect effects of typical suspended sediment conditions created in the water column by most dredging or disposal operations is unlikely. Water column suspended sediment levels created by most such operations are lower than lethal levels and exist for times far shorter than lethal exposure times for most adults and larvae. Coral reef communities may be an exception to this generalization.

b. Fluid muds have the potential for producing conditions of high suspended sediment concentration and low dissolved oxygen for periods sufficient to cause mortality of a variety of organisms. This potential exists in uncontaminated fluid muds and is increased in contaminated fluid muds. Whether, and to what extent, this potential is actually realized at a particular site will depend upon the occurrence and areal distribution of the fluid mud, its suspended sediment and dissolved oxygen concentrations, contamination status, persistence, and whether it covers susceptible species. Fluid mud can have substantial acute impacts of finite duration on relatively immobile benthic infauna and epifauna. Fluid mud may be created on the bottom by pipeline disposal, and perhaps by hopper disposal, of hydraulically dredged, fine-grained sediment, and is unlikely under other conditions. The present knowledge of fluid mud formation, characteristics, and behavior is summarized in Barnard (1978) and Nichols, et al. (1978).

c. Tissue accumulation of contaminants, even from contaminated sediments, was the exception rather than the rule in the present study. That uptake which did occur was seen only after days of exposure to suspended sediment concentrations typical of fluid muds. When uptake occurred, the contaminants were concentrated in the tissues to levels only a few times higher than in the sediment.

d. Suspensions of contaminated sediment are potentially more harmful than uncontaminated sediments, but even so the lethal conditions are unlikely to be created in the water column by most typical dredging or disposal operations. Contaminated fluid muds are of more concern than either uncontaminated fluid mud or water column suspensions of contaminated sediment, as discussed in (b.) above.

REFERENCES

Anderlini, V. C., Chapman, J. W., Girvin, D. C., McCormick, S. J., Newton, A. S., and Risebrough, R. W., 1977. Pollutant uptake study. Report to U. S. Army Engineer District, San Francisco, Dredge Disposal Study, Appendix H. 88 pp.

Aplin, J. A., 1967. Biological survey of San Francisco Bay, 1963-1966. Calif. Dept. Fish and Game, Mar. Res. Operations Lab. Report No. 67-4. 131 pp.

Barnard, W. D., 1978. Prediction and control of dredged material dispersion around dredging and open-water pipeline disposal operations. Technical Report DS-78-13 (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

Berkson, J., 1953. A statistically precise and relatively simple method of estimating the bioassay with quantal response based on the logistic function. J. Amer. Stat. Assoc. 48:565-599.

Bertine, K. K. and Goldberg, E. D., 1972. Trace elements in clams, mussels and shrimp. Limnol. Oceanogr. 17:877-884.

Bliss, C. I., 1935. Calculation of the dosage-mortality curve. Ann. Appl. Biol. 23:134-167.

Brannon, J. M., Engler, R. M., Rose, J. R., Hunt, P. G., and Smith, I., 1976. Selective analytical partitioning of sediments to evaluate potential mobility of chemical constituents during dredging and disposal operations. Technical Report D-76-7. U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

Cordone, A. J. and Kelley, D., 1961. The influence of organic sediment on the aquatic life of streams. Calif. Fish and Game. 47:189-228.

Davis, H. C. and Hidu, H., 1969. Effects of turbidity-producing substances in sea water on eggs and larvae of three genera of bivalve mullusks. The Veliger. 11(4):316-323.

Diaz, R. J. and Boesch, D. F., 1977. Impact of fluid mud dredged material on benthic communities of the tidal James River, Virginia. Technical Report D-77-45, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

Environmental Protection Agency, 1974. Methods for chemical analysis of water and wastes. EPA-625/6-74-003, July, 1974. National Environmental Research Center, Analytical Quality Control Laboratory, Cincinnati, Ohio.

Environmental Protection Agency, 1976. Quality criteria for water. EPA-440/9-76-023, Washington, D. C.

Flegal, A. R. and Martin, J. H., 1977. Contamination of biological samples by ingested sediment. Mar. Pollut. Bull. 8:90-92

Folk, R. L., 1974. Petrology of Sedimentary Rocks. Hemphills, Austin, Texas. 182 pp.

Glaus, K. J., 1968. Factors influencing the production of byssus threads in Mytilus edulis. Biol. Bull, Mar. Biol. Lab., Woods Hole. 135:420.

Heimstra, N., Damkot, D. and Benson, N., 1969. Some effects of silt turbidity on behavior of juvenile largemouth bass and green sunfish. U. S. Bur. Sport Fish. and Wildlife, Tech. Paper 20. 9 pp.

Herbert, D. and Merkins, J., 1961. The effect of suspended mineral solids on the survival of trout. Int. J. Air Wat. Poll. 5:46-55.

Jackim, E., Morrison, G. and Steele, R., 1977. Effects of environmental factors on radiocadmium uptake by four species of marine bivalves. Mar. Biol. 40:303-308.

Jackson, M. L., 1958. Soil Chemical Analysis. Prentice-Hall, Inc. Sixth printing, 1970, by the author. Department of Soil Science, University of Wisconsin, Madison.

Johnson, J. K., 1971. Effect of turbidity on the rate of filtration and growth of the slipper limpet, Crepidula fornicata Lamarck, 1799. The Veliger. 14(3):315-320.

Kunkle, S. H. and Comer, G. H., 1971. Estimating suspended sediment concentrations in streams by turbidity measurements. J. Soil and Water Cons. 26(1):18-20.

Loosanoff, V. L., 1961. Effect of turbidity on some larval and adult bivalves. Proc. Gulf Carib. Fish. Inst. 14:80-95.

Luoma, S. N., 1977. The dynamics of biologically available mercury in a small estuary. Estuarine Coastal Mar. Sci. 5:643-652.

Martin, J. M., Piltz, F. M. and Reish, D. J., 1975. Studies on the Mytilus edulis community in Alamitos Bay, California, V: the effects of heavy metals on byssal thread production. The Veliger. 18:183-188.

Masch, F. D. and Espey, W. H., 1967. Shell dredging: a factor in sedimentation in Galveston Bay. Tech. Report HYD 06-6702, Center for Research in Water Resources, University of Texas, Austin.

May, E. B., 1973. Environmental effects of hydraulic dredging in estuaries. Alabama Mar. Res. Bull. No. 9:1-85.

Morgan, R. P. II, Rasin, V. J. and Noe, L. A., 1973. Effects of suspended sediment on the development of eggs and larvae of striped bass and white perch. Univ. Md. Nat. Res. Inst. Ref. No. 73-110. 21 pp.

Mount, D. I. and Brungs, W. A., 1967. A simplified dosing apparatus for fish toxicology studies. Water Res. 1:21-29.

Neff, J. W., Foster, R. S. and Slowey, J. F., 1978. Availability of sediment-absorbed heavy metals to benthos with particular emphasis on deposit feeding infauna. Technical Report (in preparation), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

Nichols, M. M., Thompson, G. S., and Faas, R. W., 1978. A field study of fluid mud dredged material: its physical nature and dispersal.

Technical Report D-78-40, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

Paffenhofer, G. A., 1972. The effects of suspended "red mud" on mortality, body weight and growth of the marine planktonic copepod, Calanus helgolandius. Water, Air and Soil Poll. 1:314-321.

Peddicord, R. K. and McFarland, V. A. (in preparation). Effects of suspended kaolin on marine and estuarine organisms. Submitted to Marine Biology.

Peddicord, R. K., McFarland, V. A., Belfiori, D. P. and Byrd, T. E., 1975. Effects of suspended solids on San Francisco Bay organisms. Report to U. S. Army Engineer District, San Francisco, Dredge Disposal Study, Appendix G. 158 pp.

Perkin-Elmer Corp., 1974. Hydride generation sampling system. Perkin-Elmer Instruction Manual 990, p 3832.

Phillips, D. J. H., 1976. The common mussel Mytilus edulis as an indicator of pollution by zinc, cadmium, lead and copper, I: effect of environmental variables on uptake of metals. Mar. Biol. 38:71-80.

Pickering, R. J., 1976. Measurement of "turbidity" and related characteristics of natural waters. U. S. Geol. Surv. Open-file Report 76-153.

Reish, D. J. and Ayers, J. L., 1968. Studies on the Mytilus edulis community in Alamitos Bay, California, III: the effects of reduced dissolved oxygen and chlorinity concentrations on survival and byssus thread formation. The Veliger. 10(4):384-388.

Rogers, B. A., 1969. Tolerance levels of four species of estuarine fishes to suspended mineral solids. M.S. Thesis, University of Rhode Island. 60 pp.

Schubel, J. R. and Wang, J. C. S., 1973. The effects of suspended sediment on the hatching success of Perca flavescens (yellow perch), Morone americana (white perch), Morone saxatilis (striped bass), and Alosa pseudoharengus (alewife) eggs. Johns Hopkins Univ. Ches. Bay Inst. Spec. Rept. 30. 77 pp.

Sherk, J. A., 1971. The effects of suspended and deposited sediments on estuarine organisms: literature summary and research needs. Univ. Md., Nat. Res. Inst. Contrib. No. 443. 73 pp.

Sherk, J. A., 1973. Current status of the knowledge of the biological effects of suspended and deposited sediments in Chesapeake Bay. Chesapeake Sci. 13(Suppl.):S137-S144.

Sherk, J. A., O'Connor, J. M., Neumann, D. A., Prince, R. D. and Wood, K. V., 1974. Effects of suspended and deposited sediments on estuarine organisms, phase II. Final Report, U. S. Army Corps of Engineers Contract No. DACW72-71-C-0003. Univ. Md., Nat. Res. Inst. Ref. No. 74-20. 410 pp.

Smith, R. G. and Windom, H. L., 1972. Analytical Handbook for the Determination of As, Cd, Co, Cu, Fe, Pb, Mn, Ni, Hg and Zn in the Marine

Environment. Georgia Mar. Sci. Center Tech. Rept. pp 72-76.

Snieszko, S. F., 1960. Microhematocrit as a tool in fishery research and management. U. S. Fish Wildlife Serv., Spec. Rept. - Fish. No. 341. 15 pp.

Sokal, R. R. and Rohlf, F. J., 1969. Biometry, the principles and practice of statistics in biological research. W. H. Freeman Co., San Francisco, California. 776 pp.

Southgate, B. A., 1960. Water Pollution Research, 1959. Cited in: Klein, L. (ed.), River pollution, II: causes and effects. Butterworth Co., London. 456 pp.

Stern, E. M. and Stickle, W. B., 1978. Effects of turbidity and suspended material in aquatic environments; literature review. Technical Report D-78-21, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Mississippi.

Turekian, K. K., 1977. The fate of metals in the oceans. Geochim. Cosmochim. Acta. 41:1139-1144.

U. S. Army Engineer District, San Francisco, 1976. Dredge disposal study, San Francisco Bay and Estuary, Appendix C - water column.

U. S. Fish and Wildlife Service, 1970. Effects on fish resources of dredging and spoil disposal in San Francisco and San Pablo Bays, California. Unnumbered Special Report. 36 pp.

Van Winkle, W., Jr., 1970. Effect of environmental factors on byssal thread formation. Mar. Biol. 7:143-148.

Wallen, I. E., 1951. The direct effect of turbidity on fishes. Bull. Oklahoma Ag. and Mech. College. 48:1-27.

Wilber, C. G., 1971. Turbidity. Cited in: Kinne, O. (ed.), Marine ecology: a comprehensive integrated treatise on life in oceans and coastal waters. Vol 1, part 2. Wiley-Interscience. pp 1157-1194.

APPENDIX A: CONDITIONS IN FRESHWATER EXPERIMENTS

Table A1

Collection and Holding Data

List of species tested; date, method and site of collection; and the temperature from which the animals were collected. Also presented are the length of time each species was maintained in the laboratory before testing began and the temperature at which each was held.

	Collection Data				Holding Data	
Species	Date (1975)	Method	Site	Temp °C	Days Held in Lab	Temp °C
Pacifastacus leniusculus	6/2	Trap	Sacramento River Delta	18	22	15
Corbicula fluminea	6/2		Bait shop		22	15
Enallagma sp.	6/13	Dip net	Pond	17	20	15
Bufo boreas	6/4	Dip net	Russian River	18	20	15
Notemigonus crysoleucas	6/5		Bait shop		19	15
Salmo gairdneri	5/28		Hatchery fish		27	15

Table A2

Experimental Conditions

Summary of species tested, duration of the experiments, and the suspended solids concentration, temperature, dissolved oxygen and pH in each aquarium. Values presented are means ± 1 standard deviation. Species listed together were tested simultaneously in the same aquaria.

Species	Suspended Sediment g/l	Temp °C	D.O. ppm	pH
Pacifastacus leniusculus	Control	16.3 ± 0.2	7.5 ± 0.6	9.4 ± 0.2
	Control	16.8 ± 0.3	7.3 ± 0.6	9.3 ± 0.2
	1.5 ± 0.4	16.2 ± 0.1	7.6 ± 0.6	9.2 ± 0.2
Corbicula fluminea	3.8 ± 0.5	16.1 ± 0.1	7.5 ± 0.6	9.1 ± 0.2
	8.2 ± 1.0	16.3 ± 0.1	7.7 ± 0.6	8.6 ± 0.3
	12.8 ± 1.3	16.2 ± 0.1	7.6 ± 0.7	8.2 ± 0.2
Notemigonus crysoleucas	15.8 ± 2.1	16.2 ± 0.1	8.0 ± 0.7	8.1 ± 0.2
	20.7 ± 2.4	16.3 ± 0.1	7.5 ± 0.6	8.9 ± 0.2
Test length: 21 days				
Enallagma sp.	Control	15.0 ± 0.2	7.5 ± 0.5	9.3 ± 0.3
	Control	14.9 ± 0.2	7.3 ± 0.5	9.4 ± 0.3
Salmo gairdneri	0.2 ± 0.1	14.7 ± 0.2	7.3 ± 0.6	9.4 ± 0.2
	0.5 ± 0.1	14.6 ± 0.2	7.7 ± 0.6	9.4 ± 0.3
	0.9 ± 0.3	14.7 ± 0.1	7.7 ± 0.6	9.3 ± 0.3
Test length:	1.2 ± 0.5	14.7 ± 0.1	7.5 ± 0.6	9.3 ± 0.2
21 days	2.0 ± 0.5	14.6 ± 0.1	7.8 ± 0.6	9.1 ± 0.3
	4.3 ± 0.8	14.6 ± 0.1	7.7 ± 0.6	9.0 ± 0.3
Bufo boreas	Control	14.8 ± 0.1	7.8 ± 0.7	9.0 ± 0.2
	Control	14.8 ± 0.1	8.1 ± 0.7	9.8 ± 0.2
	0.4 ± 0.1	14.7 ± 0.1	8.0 ± 0.7	9.7 ± 0.2
Test length:	0.6 ± 0.2	14.7 ± 0.1	8.1 ± 0.7	9.7 ± 0.2
21 days	0.9 ± 0.2	14.7 ± 0.1	7.9 ± 0.4	9.7 ± 0.1
	1.6 ± 0.4	14.7 ± 0.1	8.1 ± 0.7	9.7 ± 0.2
	2.7 ± 0.4	14.7 ± 0.1	8.2 ± 0.7	9.4 ± 0.2
	4.5 ± 0.6	14.6 ± 0.1	9.0 ± 0.8	9.3 ± 0.2

APPENDIX B: CONDITIONS IN MARINE EXPERIMENTS

Table B1

Collection and Holding Data - Uncontaminated Sediment Phase

List of species tested; date, method and site of collection; and the salinity and temperature from which the animals were collected. Also presented are the length of time each species was maintained in the laboratory before testing began and the temperature and salinity at which each was held.

	Collection Data					Holding Data		
Species	Date (1975)	Method	Site	Sal °/oo	Temp °C	Days Held in Lab	Sal °/oo	Temp °C
Crangon nigricauda	4/8	Otter Trawl	Bodega Bay	32	9	25	32	10
Crangon nigromaculata	4/8	Otter Trawl	Bodega Bay	32	9	25	32	10
Mytilus edulis	4/8	Hand	Bodega Harbor	32	10	25	32	10
Mytilus californianus	4/7	Hand	Bodega Head	32	10	26	32	10

Table B2

Experimental Conditions - Uncontaminated Sediment Phase

Summary of species tested, duration of the experiments, the salinity common to all aquaria, and the suspended solids concentration, temperature, dissolved oxygen and pH in each aquarium. Values presented are means ± 1 standard deviation. Species listed together were tested simultaneously in the same aquaria.

Species	Suspended Sediment g/l	Temp °C	D.O. ppm	pH
Crangon nigricauda	Control	10.5 ± 0.2	7.8 ± 0.9	7.8 ± 0.1
Crangon nigromaculata	Control	10.9 ± 0.3	7.5 ± 0.7	7.8 ± 0.1
	2.5 ± 0.6	10.5 ± 0.3	7.9 ± 1.2	7.8 ± 0.1
	4.3 ± 0.8	10.4 ± 0.3	7.7 ± 0.8	7.8 ± 0.1
	8.4 ± 1.2	10.5 ± 0.3	8.0 ± 0.9	7.7 ± 0.1
	11.9 ± 1.0	10.5 ± 0.3	8.0 ± 1.5	7.6 ± 0.1
Test Length:	16.0 ± 2.2	10.5 ± 0.3	8.9 ± 1.0	7.5 ± 0.1
21 days	19.7 ± 4.1	10.7 ± 0.3	8.1 ± 0.6	7.5 ± 0.1
Salinity: 33.2 ± 0.3 °/oo				
Mytilus californianus	Control	10.4 ± 0.1	7.6 ± 0.6	7.9 ± 0.3
Mytilus edulis	Control	10.2 ± 0.1	8.4 ± 1.0	7.9 ± 0.1
	1.9 ± 0.0	10.1 ± 0.1	7.7 ± 0.7	7.9 ± 0.1
	3.7 ± 0.8	10.1 ± 0.2	7.7 ± 1.2	7.8 ± 0.1
	8.1 ± 1.2	10.1 ± 0.1	8.5 ± 1.9	7.7 ± 0.1
	11.6 ± 1.3	10.1 ± 0.1	7.4 ± 0.9	7.6 ± 0.1
Test Length:	15.5 ± 2.7	10.0 ± 0.1	7.7 ± 0.1	7.6 ± 0.1
21 days	19.5 ± 3.1	10.0 ± 0.1	8.1 ± 1.8	7.5 ± 0.1
Salinity: 33 ± 0.4 °/oo				

Table B3

Collection and Holding Data - Contaminated Sediment Phase

List of species tested; date, method and site of collection; and the salinity and temperature from which the animals were collected. Also presented are the length of time each species was maintained in the laboratory before testing began and the temperature and salinity at which each was held.

	Collection Data					Holding Data		
Species	Date (1975)	Method	Site	Sal °/oo	Temp °C	Days Held in Lab	Sal °/oo	Temp °C
Crangon nigromaculata	9/10	Otter Trawl	Bodega Bay	33	12.5	26	33	13
Mytilus edulis	9/2	Hand	Bodega Harbor	33	13	31	33	13
Mytilus californianus	9/3	Hand	Bodega Head	33	13	30	33	13
Ascidia ceratodes	9/12	Otter Trawl	Bodega Harbor	33	13	24	33	13
Cancer magister	9/11	Otter Trawl	Bodega Bay	33	12.5	25	33	13
Homarus americanus	10/7	Cultured at BML		33	20	3	33	13

Table B4

Experimental Conditions - Contaminated Sediment Phase

Summary of species tested, duration of the experiments, the salinity common to all aquaria, and the suspended solids concentration, temperature, dissolved oxygen and pH in each aquarium. Values presented are means ± 1 standard deviation. Species listed together were tested simultaneously in the same aquaria.

Species	Suspended Sediment g/l	Temp °C	D.O. ppm	pH
Mytilus edulis	Control	12.5 ± 0.4		7.5 ± 0.1
	Control	12.4 ± 0.4		7.5 ± 0.1
	2.1 ± 0.7	12.4 ± 0.5		7.5 ± 0.1
Mytilus californianus	3.0 ± 1.1	12.3 ± 0.5		7.6 ± 0.1
	8.1 ± 1.8	12.4 ± 0.3		7.4 ± 0.1
	10.2 ± 1.8	12.3 ± 0.4		7.3 ± 0.2
Homarus americanus	15.1 ± 2.4	12.4 ± 0.5	INSTRUMENT MALFUNCTION	7.3 ± 0.1
	20.0 ± 2.2	12.3 ± 0.4		7.2 ± 0.1
Ascidia ceratodes				
Test length: 25 days				
Salinity: 33.3 ± 0.8 °/oo				
Crangon nigromaculata	Control	12.8 ± 0.5		7.3 ± 0.2
	Control	12.7 ± 0.6		7.4 ± 0.2
	1.8 ± 0.6	12.7 ± 0.6		7.4 ± 0.1
Cancer magister	4.3 ± 1.2	12.3 ± 0.5		7.4 ± 0.1
	9.2 ± 2.0	12.6 ± 0.5		7.3 ± 0.3
	11.7 ± 1.8	12.7 ± 0.6		7.3 ± 0.1
Test length:	15.9 ± 2.0	12.3 ± 0.5	INSTRUMENT MALFUNCTION	7.2 ± 0.1
25 days	18.9 ± 2.4	12.4 ± 0.4		7.2 ± 0.1
Salinity: 33.3 ± 0.4 °/oo				

APPENDIX C: CONDITIONS IN ESTUARINE EXPERIMENTS

Table C1

Collection and Holding Data - Uncontaminated Sediment Phase

List of animals tested; date, method and site of collection; and the salinity and temperature from which the animals were collected. Also presented are the length of time each species was maintained in the laboratory before testing began and the temperature and salinity at which each was held.

	Collection Data					Holding Data		
Species	Date (1975)	Method	Site	Sal °/oo	Temp °C	Days Held in Lab	Sal °/oo	Temp °C
Mytilus edulis	2/17	Hand	Berkeley	18	12	26	23	12
Crangon nigricauda	2/24	Otter Trawl	Oyster Point	22	12	15	23	12
Morone saxatilis			Hatchery fish			>100	23	12

Table C2

Experimental Conditions - Uncontaminated Sediment Phase

Summary of species tested, duration of the experiments, the salinity common to all aquaria, and the suspended solids concentration, temperature, dissolved oxygen and pH in each aquarium. Values presented are means ± 1 standard deviation.

Species	Suspended Sediment g/l	Temp °C	D.O. ppm	pH
Mytilus edulis	Control	12.3 ± 0.6	8.3 ± 0.5	7.9 ± 0.1
	Control	12.2 ± 0.6	8.4 ± 0.7	7.9 ± 0.1
	3.0 ± 0.1	12.2 ± 0.6	8.3 ± 0.6	7.9 ± 0.1
Test length:	4.1 ± 0.1	12.2 ± 0.7	8.1 ± 0.6	7.9 ± 0.1
21 days	7.7 ± 1.6	12.1 ± 0.7	8.4 ± 0.9	7.7 ± 0.1
	10.4 ± 1.9	12.1 ± 0.7	7.6 ± 0.6	7.6 ± 0.1
Salinity:	14.5 ± 2.0	12.1 ± 0.7	8.0 ± 0.7	7.7 ± 0.1
23.6 ± 3.2 °/oo	19.5 ± 6.0	12.0 ± 0.7	7.9 ± 0.7	7.6 ± 0.2
Crangon nigricauda	Control	12.8 ± 0.2	8.3 ± 0.8	7.8 ± 0.1
	Control	12.9 ± 0.1	8.2 ± 0.6	7.8 ± 0.1
	3.1 ± 0.9	12.8 ± 0.1	8.6 ± 0.6	7.8 ± 0.1
Test length:	4.0 ± 1.2	12.7 ± 0.1	8.0 ± 0.7	7.8 ± 0.1
21 days	7.0 ± 1.9	12.8 ± 0.1	9.0 ± 0.7	7.7 ± 0.1
	10.7 ± 2.4	13.0 ± 1.0	8.5 ± 1.0	7.7 ± 0.7
Salinity:	13.2 ± 3.7	12.7 ± 1.1	8.0 ± 0.6	7.5 ± 0.7
24.9 ± 3.4 °/oo	16.4 ± 4.9	12.8 ± 1.2	8.5 ± 1.0	7.5 ± 0.7
Morone saxatilis	Control	12.4 ± 0.1	7.7 ± 0.5	7.8 ± 0.1
	Control	12.4 ± 0.1	7.4 ± 0.5	7.8 ± 0.1
	0.5 ± 0.7	12.2 ± 0.1	8.0 ± 0.5	7.9 ± 0.1
Test length:	0.7 ± 0.4	12.2 ± 0.1	7.9 ± 0.6	7.9 ± 0.1
21 days	1.0 ± 0.5	12.2 ± 0.1	8.2 ± 0.3	7.9 ± 0.1
	1.5 ± 0.5	12.2 ± 0.1	7.7 ± 0.8	7.8 ± 0.1
Salinity:	2.3 ± 0.9	12.2 ± 0.1	8.1 ± 0.4	7.9 ± 0.1
24.7 ± 2.1 °/oo	3.9 ± 1.0	12.1 ± 0.1	8.0 ± 0.4	7.8 ± 0.1

Table C3

Collection and Holding Data - Contaminated Sediment Phase

List of species tested; date, method and site of collection; and the salinity and temperature from which the animals were collected. Also presented are the length of time each species was maintained in the laboratory before testing began and the temperature and salinity at which each was held.

	Collection Data					Holding Data		
Species	Date (1975)	Method	Site	Sal °/oo	Temp °C	Days Held in Lab	Sal °/oo	Temp °C
Mytilus edulis	11/17	Hand	Berkeley	20	12	15	24	14
Crangon nigricauda	11/13	Otter Trawl	Oyster Point	20	12	20	24	14
Morone saxatilis	8/13	Dip net	San Joaquin Delta	0	20	>100	24	14

Table C4

Experimental Conditions - Contaminated Sediment Phase

Summary of species tested, duration of the experiments, the salinity common to all aquaria, and the suspended solids concentration, temperature, dissolved oxygen and pH in each aquarim. Values presented are means ± 1 standard deviation.

Species	Suspended Sediment g/l	Temp °C	D.O. ppm	pH
Mytilus edulis	Control	14.1 ± 0.6	7.7 ± 0.7	8.0 ± 0.2
	Control	14.2 ± 0.3	7.7 ± 0.7	8.0 ± 0.3
	2.2 ± 0.8	14.0 ± 0.8	7.9 ± 0.9	7.9 ± 0.8
Test length:	3.6 ± 0.2	14.0 ± 0.3	7.7 ± 0.8	7.9 ± 0.3
21 days	8.6 ± 1.6	14.2 ± 0.2	7.8 ± 1.0	7.8 ± 0.2
	12.1 ± 1.5	14.1 ± 0.2	7.8 ± 1.0	7.8 ± 0.7
Salinity:	15.9 ± 1.8	14.0 ± 0.3	8.0 ± 0.9	7.7 ± 0.2
24.8 ± 0.8 °/oo	21.2 ± 2.7	14.1 ± 0.3	7.8 ± 0.8	7.6 ± 0.3
Crangon nigricauda	Control	13.7 ± 0.2	7.6 ± 0.8	7.9 ± 0.2
	Control	13.8 ± 0.1	7.6 ± 0.7	7.9 ± 0.2
	2.0 ± 0.4	13.6 ± 0.2	7.7 ± 0.7	7.9 ± 0.2
Test length:	3.3 ± 1.6	13.7 ± 0.1	7.6 ± 0.7	7.9 ± 0.3
21 days	8.3 ± 1.4	13.6 ± 0.1	7.8 ± 0.8	7.7 ± 0.2
	12.0 ± 1.6	13.6 ± 0.3	7.5 ± 0.9	7.7 ± 0.2
Salinity:	14.7 ± 3.0	13.7 ± 0.3	7.6 ± 0.8	7.6 ± 0.3
24.4 ± 0.7 °/oo	21.5 ± 3.0	13.6 ± 0.3	7.6 ± 0.8	7.6 ± 0.2
Marone saxatilis	Control	13.8 ± 0.4	7.5 ± 0.8	7.9 ± 0.2
	Control	13.8 ± 0.5	7.3 ± 0.7	7.9 ± 0.2
	0.5 ± 0.2	13.6 ± 0.5	7.5 ± 0.7	7.9 ± 0.2
Test length:	0.9 ± 0.1	13.6 ± 0.2	8.1 ± 0.5	7.8 ± 0.1
21 days	1.3 ± 0.1	13.5 ± 0.1	7.8 ± 0.5	7.9 ± 0.1
	1.5 ± 0.8	13.5 ± 0.1	7.7 ± 0.3	7.9 ± 0.8
Salinity:	1.9 ± 0.9	13.4 ± 0.1	8.1 ± 0.5	8.0 ± 0.3
24.5 ± 0.8 °/oo	4.3 ± 0.7	13.4 ± 0.1	8.0 ± 0.4	8.0 ± 0.4

END

FILMED

DATE: 7-90

DTIC