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FIELD BIOASSAY STUDIES ON THE TOLERANCES OF JUVENILE SALMONIDS TO VARIOUS LEVELS OF SUSPENDED SOLIDS

by

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INTRODUCTION

Information on the impact of dredging operations on the behavior and survival of juvenile salmonids, especially in the marine environment, is limited. Much of the research to date deals with the toxic effects of suspended sediment on non-salmonids and benthic invertebrates. No information was found on the effects of suspended sediment on the behavior of salmonids in salt water. Therefore, the objectives of this research were to determine the lethal levels of suspended sediments on juvenile chum salmon and, secondarily, to determine if juvenile chum salmon would avoid suspended sediment.

Prior to this research, a review of the literature on the effects of dredging on juvenile salmonids was prepared by Mortensen et al. (1976). This review covers the literature pertinent to this study.

An annotated bibliography on the effects of dredging and dredge disposal on the aquatic organisms in the Pacific Northwest (Ellinger and Snyder, 1975) includes additional literature not cited by Mortensen et al. (1976).

MATERIALS AND METHODS

Description of Study Area

Bioassay and avoidance behavior studies were conducted aboard the University of Washington (UW) research barge, R/V *Kumtuks*, which was anchored approximately (300 m) south of the proposed Trident drydock-refit pier located in the Devil's Hole area of the Keyport, Bangor Annex (Fig. 1). This location is representative in water chemistry and bottom sediments of the proposed dredge site. Thus, ambient water was used for all studies.

Bottom Sediments

Source

The bottom sediments used in all tests were obtained from the proposed dredging site. SCUBA divers filled (20 l) buckets with bottom sediments by the use of a small shovel and then the sediments were stored undisturbed in a water bath at ambient temperatures. Before each bioassay the bottom sediments were wet-sieved through a 100-μ sieve. All particles larger than 100 μ were discarded and all particles less than 100 μ were used to develop a stock solution of suspended sediments.

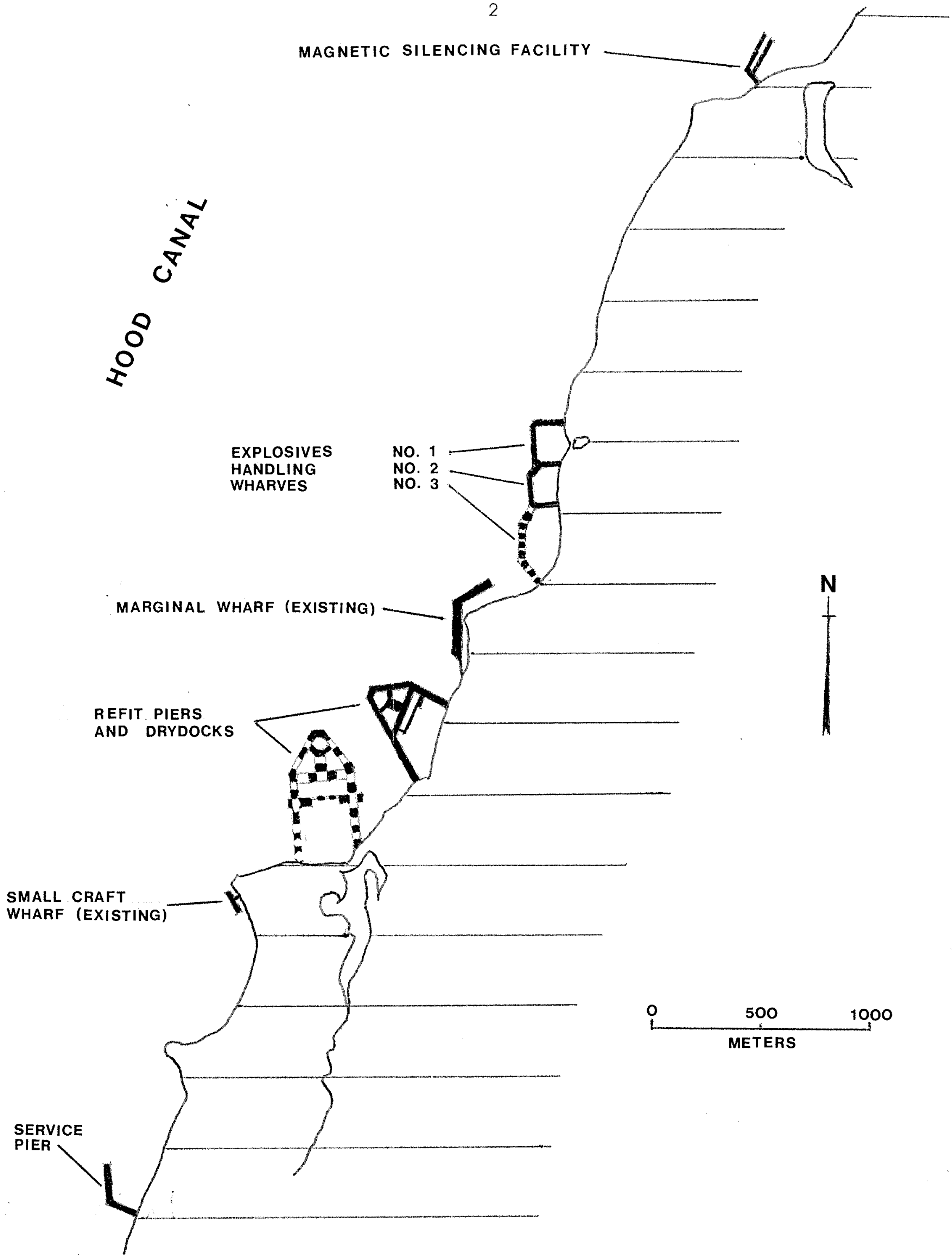

FIG. 1. Existing and Proposed Docking Facilities
Bangor Annex, Hood Canal, WA, 1976

Composition

The size distribution and shape of sieved bottom sediments were determined from representative samples, the former by hydrometer analysis method (Mike Currie, UW College of Forest Resources) and the latter by electron micrographs of the sediment particles (Yorko Tsukada, UW Quaternary Research Center).

The chemical composition of unsieved and sieved bottom sediment was determined for representative samples by Laucks Testing Laboratories, Seattle, Washington.

Determination of Concentrations

The concentration of suspended sediments in the bioassays was determined by the nephelometric and filtration methods (APHA 1971). The nephelometric method measures the turbidity of water samples in Formazin Turbidity Units (FTU's) and is an expression of the optical property of a water sample which causes light to be scattered and absorbed rather than transmitted in straight lines through the sample (APHA 1971). The filtration method measures the concentration of suspendable solids in mg/liter, using Whatman GF/C-type filters, and is an expression of the quantity of solids in a water sample.

Static Bioassay Procedures

Water Quality

Seawater for all static bioassays was obtained from on-site. With the exception of temperature, water quality did not vary much during the study period. Dissolved oxygen remained at 100% saturation, salinity averaged 28 $^{o}/oo$, and the pH averaged 7. The water temperature ranged from 11°C in early May to 17°C in mid-July.

Fish

Chum salmon (*Oncorhynchus keta*) was the principal species used in the static bioassay tests. Pink salmon (*O. gorbuscha*) were also used but in this particular case were considered of minor importance because juvenile outmigrants will not be present during the proposed dredging period. All fish tested prior to June 6 were captured by beach seine in the Devil's Hole vicinity. After June 6, the majority of the test fish were acquired from the Washington State Department of Fisheries Hatchery at Hoodsport and from the U.S. Fish and Wildlife Service Hatchery at Quilcene. Some test fish were also obtained from the University of Washington hatchery at Big Beef Creek. All test fish were held on the R/V Kumtuks in 1200-2000 liter aquaria. Water in the aquaria was saturated with dissolved oxygen and held at ambient temperature by continuous flow. Test fish were fed Oregon Moist

Pellets daily, and the fish also consumed small zooplankton which entered the aquaria through the water supply system.

The size of the test fish depended upon the location and time they were acquired. Table 1 shows the mean length and range of chum salmon used in the bioassays.

Static Bioassay Apparatus

The static bioassay apparatus consisted of a 60-liter aquarium, suspended sediment circulation system, and a live net to hold test fish (Fig. 2). The aquarium was a non-toxic Brute-resin round food storage container. Inserted in the bottom of the container was a shallow funnel made from polyethylene. The sediment suspension system consisted of a Little Giant submersible mild-chemical pump (avg pump rate 16.2 liter/min), an intake pipe located at the bottom and center of the aquarium, and an outlet elbow located just below the surface near the edge of the aquarium. The suspension was introduced through the elbow at the surface; this, coupled with the intake at the bottom, caused a vortex which drew the sediment to the center and eventually to the bottom as it settled. The intake at the bottom removed the settled material so that the suspension was continuously being introduced at the surface. The live net was a cylinder composed of a 6-mm Vexar screen attached to a wood support at the top. The sediment suspension apparatus worked quite well, but the concentration of suspended sediment would fluctuate over the bioassay test period. The bioassay aquaria were placed in a water bath in order to maintain ambient temperatures.

Bioassay Test Procedure

Static bioassays were run in replicate with five test aquaria in each replicate, four of which had suspended sediment concentrations in geometric series. One test aquarium had no suspended sediment and was used as the control. Ten chum salmon were placed into each test aquarium by random distribution.

Static bioassay tests were run for 96 hours, or until all test fish were dead. Death was the response recorded. The fish were considered dead when there was no operculum movement, and no response to gentle prodding; they were then removed and checked under a dissection scope for external and internal signs of damage.

Data Analysis Procedures

The graphic method of Litchfield and Wilcoxon (1949) was used to determine the LC50 for suspended sediment on a preliminary basis. The data were re-analyzed, using the method of probits in the BMD03S computer program (Dixon 1970).

Table 1. Mean length and range of chum salmon used in static bioassays

Fish source	Mean length (mm)	Range (mm)
Captured in wild prior to June 6	55	42 to 88
Hoodsport Hatchery	57	38 to 72
Quilcene Hatchery	69	62 to 75
Big Beef Creek Hatchery	93	82 to 102

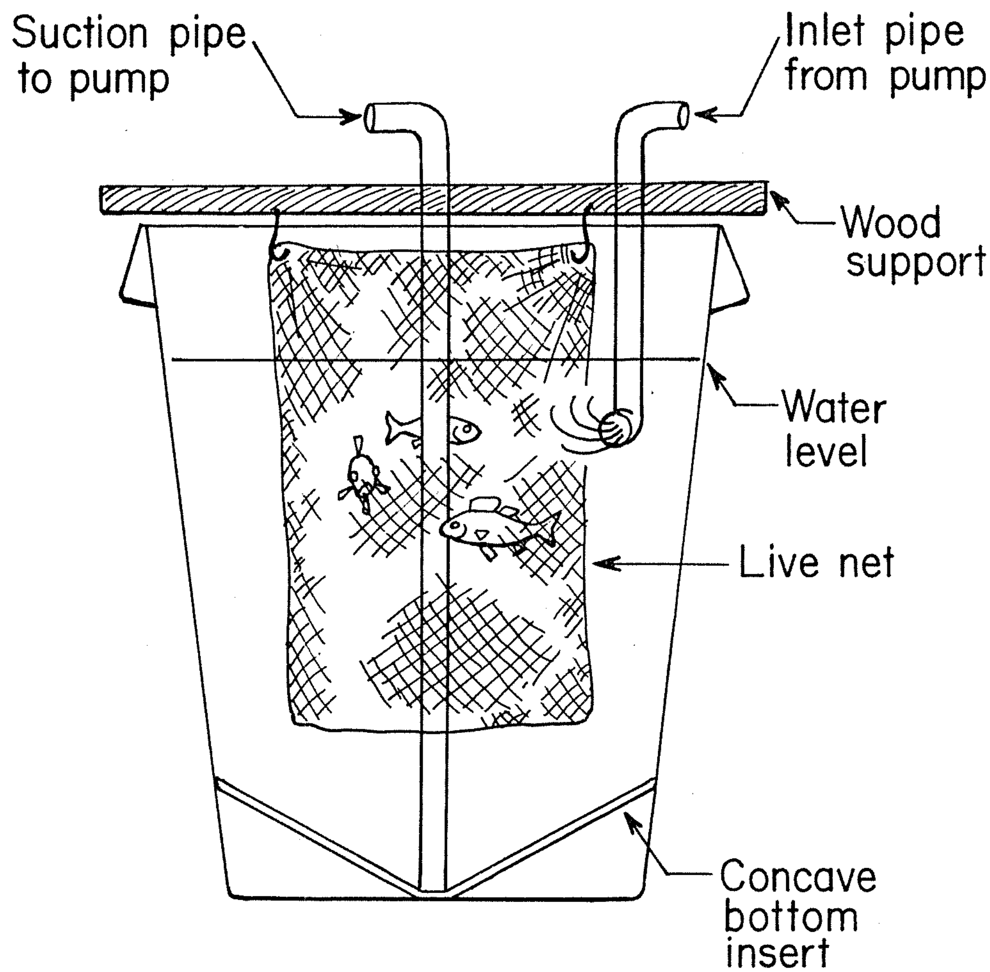

FIG. 2. Suspended sediment static bioassay apparatus.

Avoidance Behavior Experiments

Description of Tank

The behavior tank consists of a Fiberglas-coated wooden trough with a water inlet at each end and a drain in the center (Fig. 3). Water was introduced into each end of the tank simultaneously at a rate of 16 liters/min by two Little Giant mild chemical pumps. The tent-shaped center drain was constructed of 6-mm Plexiglass, and was adjustable so that the water level in the tank could be changed. Preliminary experimentation indicated that a water level of 12.2 cm was best for separating suspended sediment water from clear water at the center drain. Intrusion of suspended sediment water across the drain occurred only when the tank was not level, as a result of rocking caused by wave action against the research vessel.

The behavior tank was enclosed in a fiberboard chamber painted white to exclude extraneous stimuli. Two slits were cut at each end of the enclosure for observation.

Indirect lighting was provided by two 40-W Gro-Lux fluorescent lamps hung in an inverted position approximately 110 cm above the center drain. Light intensity at the water surface, measured by a Li-Cor quantum light meter, was 133 lux on one side, 149 lux on the other side, and 153 lux in the center.

Procedures

Ten chum salmon were placed into the behavior tanks in ambient water conditions for a 15-minute acclimation period. At the end of the acclimation period, the experimenter observed the fish for 15 minutes, recording at 10-second intervals the number of fish present at one end of the behavior tank. A predetermined concentration of suspended sediments was then introduced from one end and observations were made for another 15 minutes at 10-second intervals. This time, the number of fish present on the suspended-sediment side of the behavior tank was recorded. Water samples were taken from both sides of the tank by siphoning and analyzed for suspended sediments, temperature, and dissolved oxygen. New fish were used for each trial.

Data Analysis

Data from the avoidance behavior experiments were converted to an avoidance response parameter and expressed as a percentage. The avoidance response was calculated by summing the number of fish observed in the clearwater side and converting this sum to a percentage of 900, which equals 90 observations of 10 fish for 15 minutes.

Preliminary observation of fish in the behavior tank under clearwater conditions indicates that the fish had no preference for either side of

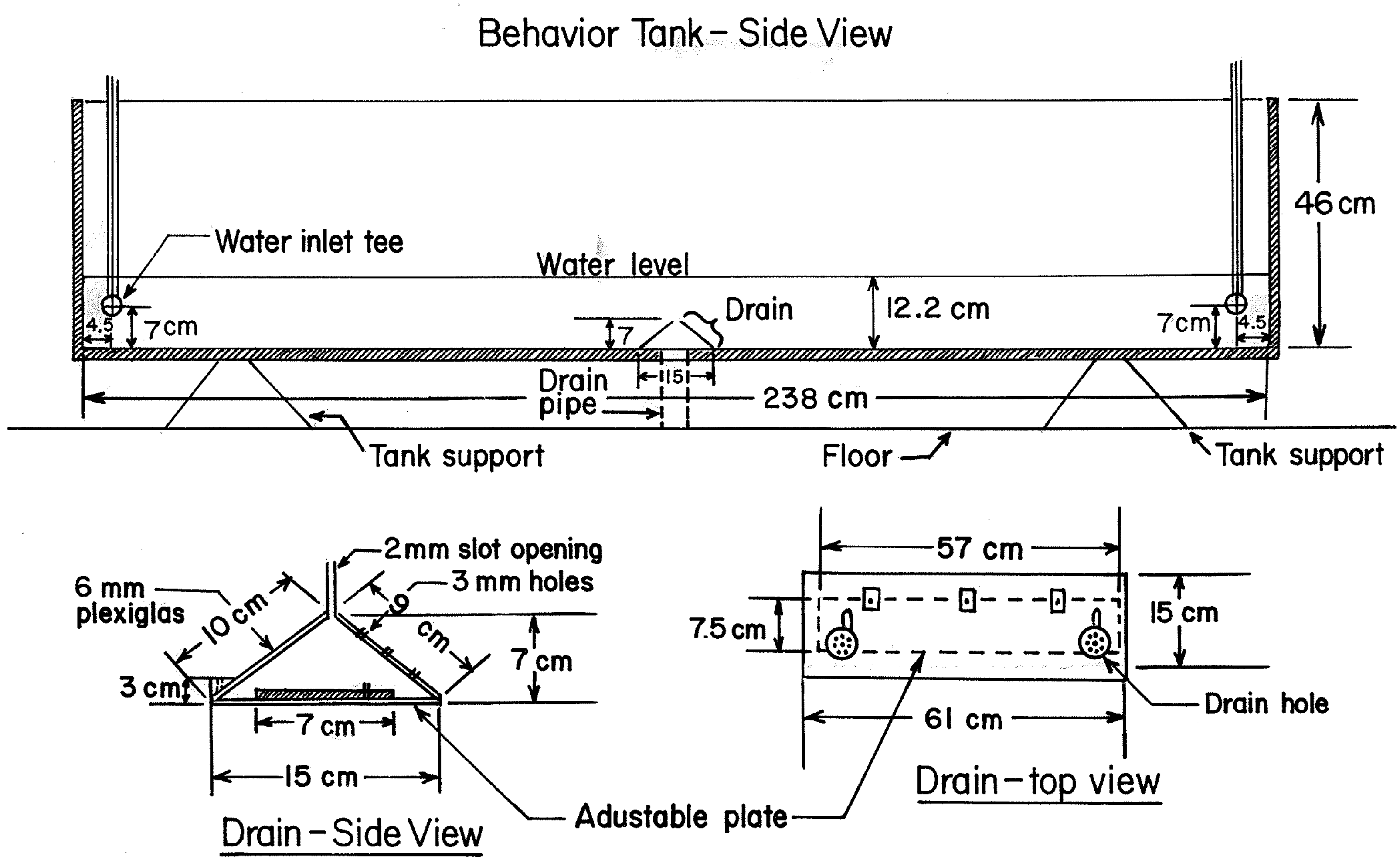

FIG. 3. Behavior tank diagram.

the tank. Therefore, an expected distribution of 50% on either side of the tank was assumed under clearwater conditions. Chi-square analysis was used to determine if the avoidance response was significantly different from a 50% distribution on either side of the behavior tank.

RESULTS

Sediment Composition

The particle size distribution of bottom sediments and glacial till is shown in Table 2. The bottom sediments were sampled from experiments 13 and 14, and the glacial till was taken from a gravel pit located on the Trident submarine base. Originally, we proposed to use glacial till and bottom sediments in the static bioassays, however, the percentage of particles < 50 μ is very low in the glacial till (Table 2). Also, the glacial till is relatively inert and has a low toxicity associated with compounds. Sieved and unsieved bottom sediments were used in all the experiments.

The shape of the suspended sediment particles is illustrated by an electron micrograph (5000 X) of sediment from Experiment 12 (Figure 4). The particle shape is considered "angular" based on a geologist's roundness scale which ranges from very angular to well-rounded (Blatt et al. 1972).

The chemical composition of the bottom sediments in the dredging area was determined from seven bottom cores (Table 3).

The concentration of suspended sediment used in the bioassays and the behavior experiments was measured by the filtration method. The nephelometric method was not satisfactory in the analysis of high sediment concentrations. However, a correlation of NTU readings with mg/liter for suspended sediment was developed during the bioassay study. A plot of the resulting data with the predicted regression line is shown in Fig. 5. The correlation is significant ($P < .05$) with an r of 0.76. This relationship indicates that the NTU method of measuring turbidity could be used in a turbidity monitoring program to speed the analysis of water samples. However, the low correlation of 0.76 indicates that predicting the exact suspended sediment concentration in mg/liter is not possible without error. Furthermore, if different types of sediment particles other than those used to develop this regression curve are encountered, an error in prediction could result.

Toxicity of Suspended Sediment

A condensation of 22 static bioassays performed during the field research period is shown in Table 4. The early experiments were conducted with fish captured in the wild, while the later experiments were conducted mostly with hatchery fish. The salient features of these experiments will be discussed in numerical order. The results are presented in Appendix Table A.

Table 2. Particle size distribution of suspended sediments and glacial till

Particle size (μ)	Sample number (percentage)				
	13A	13B	14A	14B	Glacial till
1,000					7.3
500					10.7
250					13.4
106	.01	.01	1.4	1.2	24.2
50	21.0	13.6	27.6	26.2	14.3
< 50	78.99	86.39	71.0	72.6	30.1

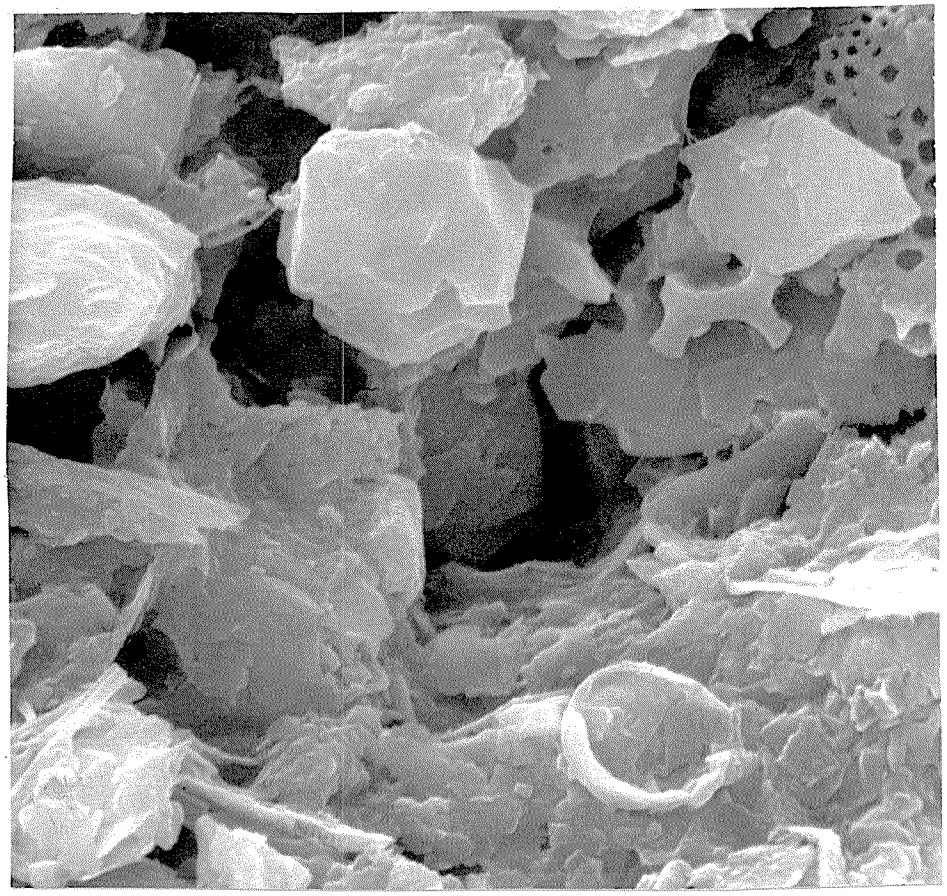

FIG. 4. Electron micrograph (5000X) of suspended sediment particles from experiment 12.

Table 3. Bottom sediment analysis of samples taken from the drydock dredging site

	Sample number						
	#1	#2	#3	#4	#5	#6	#7
Total solids mg/kilogram	431,000	547,000	717,000	758,000	744,000	687,000	754,000
5 day B.O.D. mg/kilogram	ND	ND	ND	ND	ND	ND	ND
IDOD, mg/liter dilution factor vol/vol							
.5/300	0.4	--	0.6	--	0.3	--	--
1/300	0.8	1.3	0.9	0.7	0.7	1.0	1.0
2/300	1.4	1.5	2.0	0.9	2.0	1.5	1.6
	Reported as milligrams per kilogram on dry basis						
Volatile solids	40,000	32,000	24,000	19,000	20,000	21,000	20,000
Chemical oxygen demand	20,000	14,000	13,000	9,800	14,000	13,000	12,000
Oil and grease	380	250	220	180	220	180	100
Mercury	ND	ND	ND	ND	ND	ND	ND
Lead	20.	8.7	8.4	6.6	7.4	7.3	7.
Zinc	46.	42.	25.	21.	27.	25.	28.
Copper	23.	13.	14.	9.4	13.	10.	12.
Cadmium	1.7	0.9	1.4	1.3	1.0	0.7	0.
Chromium	14.	12.	11.	9.3	10.	8.9	9.
Nickel	20.	17.	17.	16.	15.	13.	14.
Manganese	140.	100.	110.	100.	99.	84.	91.
Iron	7800	6600	5800	5500	5500	5200	5400
Arsenic	4.4	0.6	2.4	2.1	0.4	2.0	2.
Sulfide	56.	37.	22.	21.	13.	26.	13.

ND = None detected.

Lower limits of detection: 5 day B.O.D. 200; Mercury 1.0

[1]Laucks Testing Laboratory report on spoil analysis May 19, 1976, Seattle, Washington.

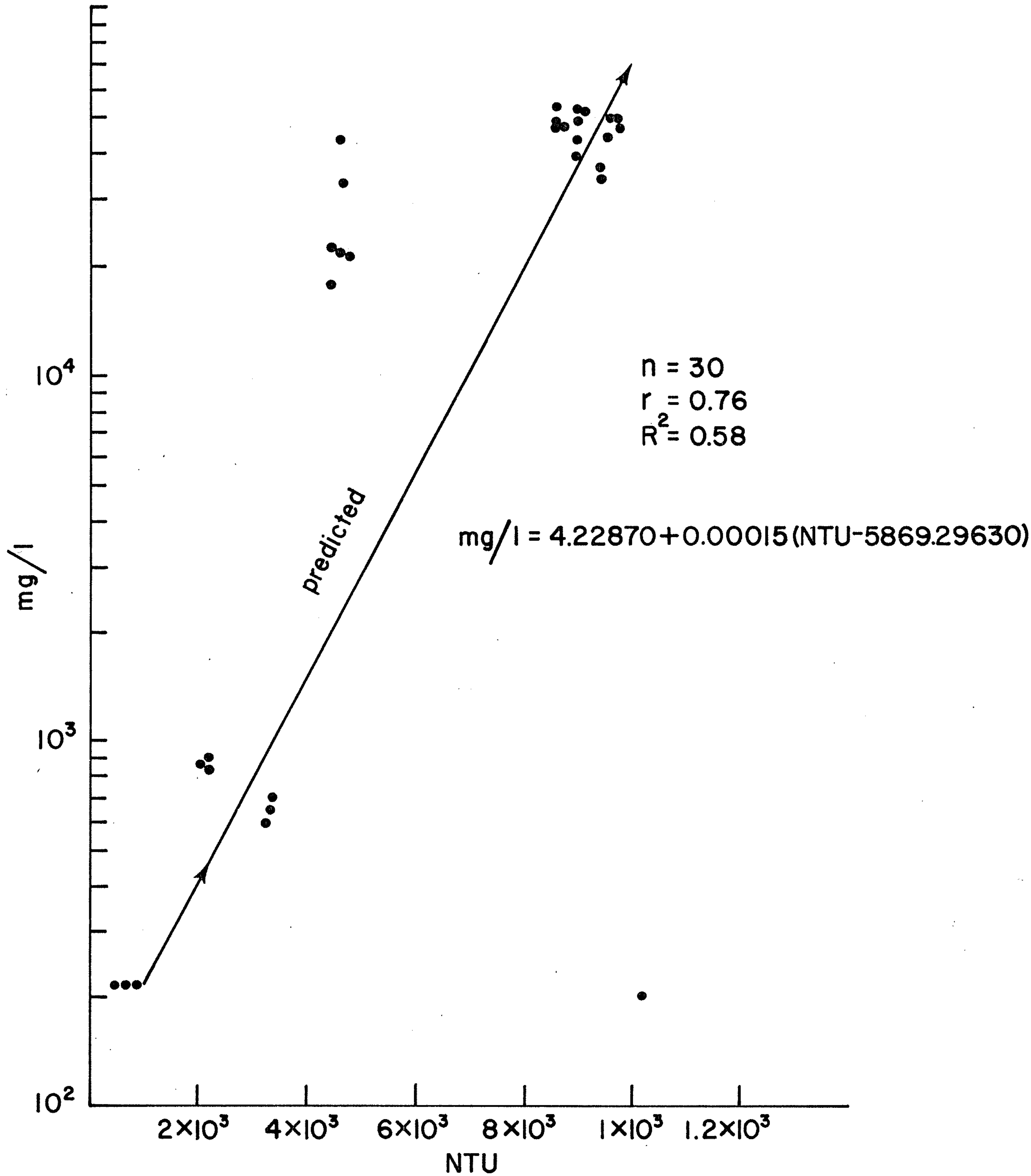

FIG. 5. Correlation of NTU readings with mg/liter for suspended sediment.

Table 4. Summary of chum salmon suspended sediment bioassay

Experiment number	Date	Fish source	Acclimation period (days)	Maximum mean suspended sediment concentration (mg/l)	Control % mortality	Comments[3]
4	5-14	Carlson	7	3954	10	Good response
5	5-20	Carlson	14	1780	0	Signs of disease
6A	5-25	Carlson	21	1895	0	Signs of disease
6B	5-25	Marginal Carlson	8	2789	70	Signs of disease
7A	6-02	S. Carlson	1	1505	90	Signs of disease
7B	6-02	Carlson	28	762	0	Signs of disease
8[1]	6-03	Carlson	28	1253	0	Low response
9A[2]	6-06	Hoodsport	3	8941	0	Few signs of disease, low response
9B[2]	6-06	Hoodsport	3	8415	0	No response
10A	6-15	Hoodsport	11	367	60	Disease present
10B	6-15	S. Carlson	14	459	20	Signs of disease
10C	6-15	Hoodsport	11	563	20	Disease present
11A	6-21	Big Beef	3	1016	0	No response
11B	6-21	Quilcene	3	844	0	No response
11C	6-21	Quilcene	3	747	0	No response
12A	6-28	Big Beef	10	2036	0	No response
12B	6-28	Quilcene	10	1749	0	Disease present, good response
12C	6-28	Quilcene	10	1684	0	Disease present, low response
13A	7-06	Quilcene	18	1996	70	Disease present
13B	7-06	Quilcene	18	946	100	Disease present
13C	7-06	Quilcene	18	1392	100	Disease present
14	7-12	S. Carlson	3	2423	50	Disease present

[1] Conducted with pink salmon.
[2] Conducted with unsieved sediment cores.
[3] No response indicates no mortalities at the levels tested; low response indicates mortalities were too low to be significant.

Wild Fish

Experiment (Expt) 4 was conducted with chum salmon captured from the Carlson Point area. The test fish responded* as expected to suspended sediment; i.e., there was an increasing mortality associated with an increasing concentration. The gill filaments of dead fish were coated with mucus and silt, indicating that the probable cause of death was suffocation (see Mortensen et al. 1976).

Expt. 5 was conducted with the same stock of fish as Expt. 4, but the acclimation period was 14 days. The concentration of suspended sediment was lower than in Expt. 4; yet the fish mortality was much greater (Appendix Table A). Post-mortality analyses on the fish indicated that the gill filaments were coated with mucus and silt. In addition, hemorrhaging was noticed at the base of pelvic, pectoral, and anal fins, indicating a disease may have been present.

Expts. 6A and 6B were replicates of Expt. 5, except that Expt. 6A fish were acclimated for 21 days and Expt. 6B fish were a new stock (Carlson-Marginal) acclimated for only 8 days. The response in Expt. 6A was similar to that in Expt. 5; likewise, the dead fish had hemorrhaging at the base of the fins. Expt. 6B was expected to have low mortality because a different stock of fish was used. On the contrary, all the fish died in the control tank. The Carlson-Marginal fish stock was apparently more susceptible to disease than the Carlson stock. On the other hand, water samples were collected from Expt. 6A (which was mixed from the same sediment stock solution as Expt. 6B) to determine if heavy metals in the suspended sediments were at toxic levels. The heavy metal concentrations (Table 5) were determined to be within salmon tolerance levels (*see* Mortensen et al. 1976).

Expts. 7A and 7B were replicates of the Expt. 6 series, except that fish captured from South Carlson and acclimated for 1 day were used in Expt. 7A. The purpose for a short acclimation period was to determine if the test fish had been infected by disease in their natural environment, or if holding the fish for long periods on the barge induced disease. The results of Expts. 7A and 7B were very similar to Expts. 6B and 6A, respectively. All the test fish died in Expt. 7A (Appendix Table A), demonstrating that disease was probably present in fish taken directly from the natural environment. Most of the dead fish show hemorrhages around the eye and at the base of pectoral and anal fins. It was suspected from these symptoms that the fish had vibriosis and/or furunculosis. Positive diagnosis of the disease required a pathological examination which was not readily available on the barge.

Expt. 8 was conducted with pink salmon acclimated for 28 days. Only one fish died in each test tank and no signs of disease were evident in

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*In this sense, a "response" indicates mortalities at the levels tested.

Table 5. Concentration of heavy metals in Experiment 6A water[1]

Heavy metal	Tank number (mg/liter)			
	1A	2A	3A	4A
Arsenic	< .05	< .05	< .05	< .05
Zinc	< .001	< .001	.058	.057
Cadmium	< .005	< .005	.010	.015
Nickel	.041	.048	.028	.010
Mercury	< .001	< .001	< .001	< .01
Lead	.006	.031	< .004	< .04
Copper	.057	.069	.029	.014
Chromium	< .03	< .03	< .03	< .03

[1] Laucks Testing Laboratories report on water analysis, June 14, 1976 Seattle, Washington.

any of the fish. The low response in this bioassay indicates the tolerance of pink salmon to suspended sediment and the higher resistance of this species to disease.

Expts. 10B and 14 were the only experiments conducted with fish captured in the wild after June 1. The results of these experiments were typical of the former experiments in which disease was suspected as the primary cause of death, rather than suspended sediment. The presence of vibriosis was confirmed for fish in Expt. 14 (Jim Wood, WSDF).

Hatchery Fish

Expts. 9A and 9B were conducted with Hoodsport Hatchery fish which were assumed to be free of vibriosis because the fish were held in water of low salinity (< 2 o/oo) at Hoodsport. The test fish were placed in suspended sediment solutions mixed from unsieved sediment cores taken directly from the proposed drydock area. The purpose of this experiment was to test the effects of high suspended sediment concentration and the possible associated toxicity of unsieved sediment. Only two fish died (Appendix Table A) in both experiments combined; however, hemorrhaging at the base of the pectoral and pelvic fins was observed in the dead fish. The low response in this experiment indicates that the concentration of toxic substances associated with the bottom sediments is probably below tolerance levels for chum salmon. The concentration of heavy metals and sulfide in Expts. 9A and 9B is shown in Table 6.

Expts. 10A and 10C were conducted with Hoodsport Hatchery fish acclimated for 11 days. The response to this experiment was variable with a high mortality in the controls. The symptoms of vibriosis and furunculosis were evident in the dead fish. The presence of both diseases was later confirmed by Jim Wood (WSDF).

Expts. 11A, 11B, and 11C were conducted with fresh hatchery fish previously held in freshwater. No mortalities were observed in these experiments, which indicates simply that the tolerance level of healthy chum salmon is above the concentration of suspended sediment tested.

Expts. 12A, 12B, and 12C were replicates of Expt. 11 except that the concentration of suspended sediment was increased. No fish died in Expt. 12A, which contained fish from the Big Beef Creek Hatchery. These fish are much larger (Table 1) and healthier than the other fish stocks. The larger size of a fish could be beneficial in passing sediment particles through the gills without clogging. Expts. 12B and 12C showed a good response, but disease was confirmed in the dead fish from both experiments.

Expts. 13A, 13B, and 13C were also conducted with Quilcene Hatchery fish acclimated for 18 days. The long acclimation period coupled with stress from the bioassay was enough to induce a high mortality from disease. Vibriosis and furunculosis was again confirmed by Jim Wood (WSDF).

Table 6. Concentration of heavy metals and sulfide in Experiments 9A and 9B water[1]

	Experiment tank number (concentration in mg/liter)									
Heavy metal	1A	2A	3A	4A	Control A	1B	2B	3B	4B	Control B
Arsenic	< .05	< .05	< .05	< .05	< .05	< .05	< .05	< .05	< .05	< .05
Zinc	< .001	< .001	< .001	< .001	.009	< .001	< .001	< .001	< .001	.005
Cadmium	.004	< .002	< .002	< .002	.005	.003	< .002	< .002	< .002	.014
Nickel	.086	.042	.038	.042	.016	.070	.058	.051	.040	.015
Mercury	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001	< .001
Lead	.063	.004	< .004	.004	< .004	.063	.004	.017	< .004	< .004
Copper	.054	.013	.014	.022	.003	.038	.026	.041	.016	.003
Total chromium	< .05	< .05	< .05	< .05	< .005	< .05	< .05	< .05	< .05	< .05
Sulfide, calculated as S	.7	.8	1.0			.5	.5	1.4		

[1]Laucks Testing Laboratory report on water analysis, June 30, 1976, Seattle, Washington.

Median Lethal Concentration of Suspended Sediment

Healthy Fish

Expt. 4 was the only bioassay in which a good response was obtained from healthy chum salmon (Table 4). Consequently, the median lethal concentration (LC50) of suspended sediment was calculated from Expt. 4 results, which are plotted in Fig. 6 with the predicted line fitted by computer. The calculated 96-hr LC10, LC50, and LC90 are shown in Table 7.

Diseased Fish

The calculated 96-hr LC50 for chum salmon showing signs of disease is considerably lower than for healthy fish (Table 7). The LC50 ranges from a low of 81 mg/liter to a high of 539 mg/liter.

The calculated 96-hr LC10 and LC90 for chum salmon showing signs of disease is quite variable. The slope of the predicted line for Expt. 7B is so flat (Fig. 7) that the LC10 and LC90 are unrealistic. The test fish in Expt. 7B are not responding to suspended sediment; otherwise, the slope of the line would be similar to Expts. 6A and 10B. Therefore, the tolerance level of unhealthy chum salmon to suspended sediment is illustrated best by Expts. 6A and 10B (Fig. 7).

Avoidance Behavior to Suspended Sediments

Twenty avoidance behavior experiments were carried out during the latter part of June and all of July. Consequently, most of the experiments were conducted with Quilcene Hatchery fish and only a few were conducted with fish captured in the wild. A complete summary of the avoidance experiment results is presented in Appendix Table B.

The avoidance response of juvenile chum salmon to suspended sediment was significant ($P < .05$) at all concentrations tested (Fig. 8). The chum salmon were able to detect the presence of suspended sediment immediately after it was introduced into one side of the behavior tank. The test fish would respond by swimming to the clear side of the behavior tank.

Observations of the test fish during the behavior experiments indicated the following general response: when test fish swam into the turbid water side, they appeared to be searching for an escape route from the behavior tank, and when one could not be found, the fish would return to the clear water side. Fish swimming in the turbid water side would swim near the surface, at higher sediment concentrations. Fish swimming on the clear water side always swam at mid-depth or near the bottom.

The behavior of wild fish vs. hatchery fish in the behavior experiments seem to differ. Hatchery fish in the behavior tank tended to swim in a school. The pattern was almost always from one end of the tank to

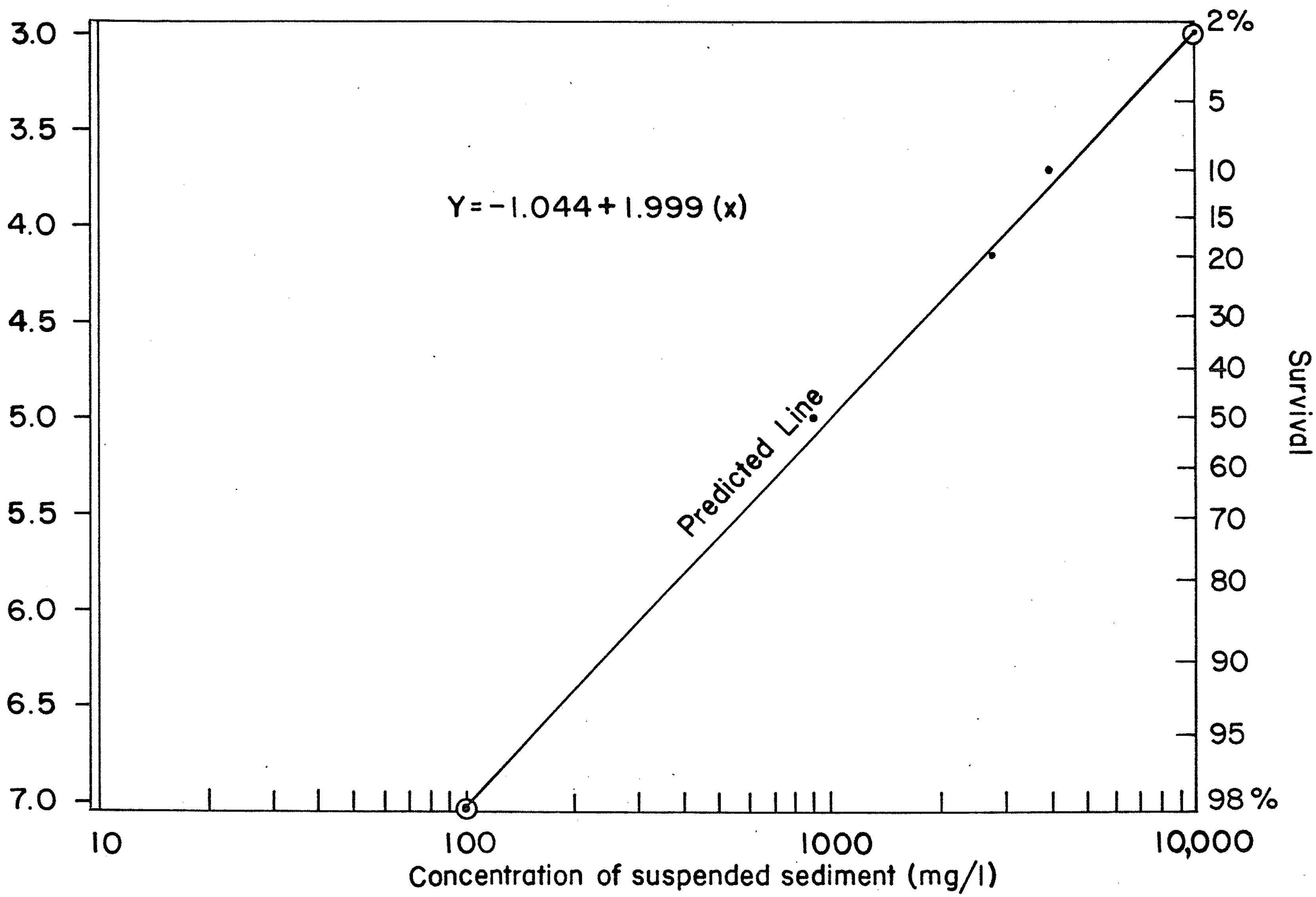

FIG. 6. Relationship between suspended sediment concentration and juvenile chum salmon survival for Experiment 4.

Table 7. Calculated 96-hr LC10, LC50, and LC90 for juvenile chum salmon exposed to suspended sediment

Experiment	96-h LC10 (mg/l)	96-h LC50 (mg/l)	96-h LC90 (mg/l)	Equation for predicted line
4	241	1047	4611	$\hat{y} = -1.044 + 1.999\ (x)$
6A	8	81	769	$\hat{y} = 2.505 + 1.308\ (x)$
7B	< 1	539	29.7×10^6	$\hat{y} = 4.262 + .270\ (x)$
10B	45	415	3810	$\hat{y} = 1.521 + 1.329\ (x)$

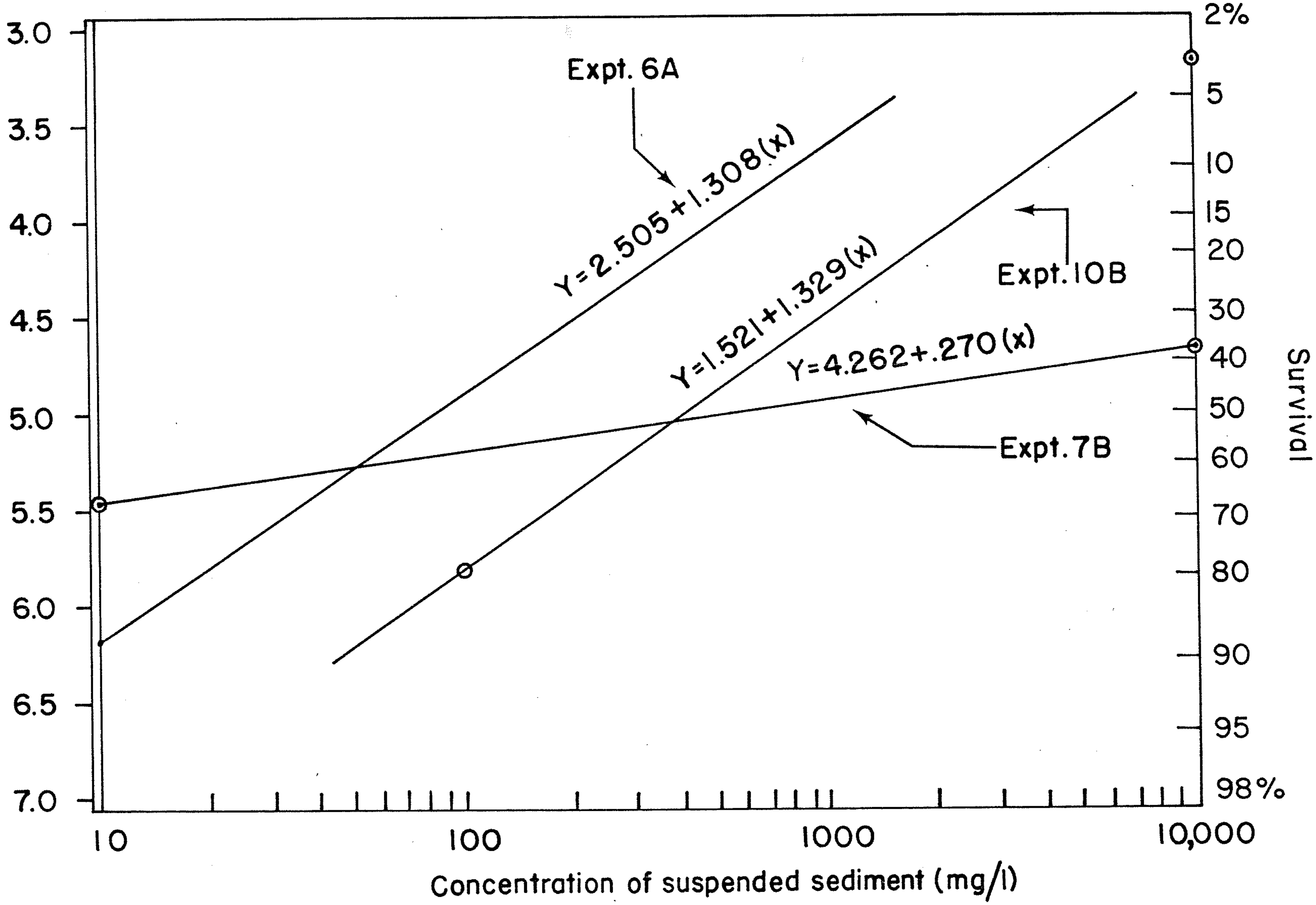

FIG. 7. Relationship between suspended sediment concentration and juvenile chum salmon survival for Experiments 6A, 7B, and 10B.

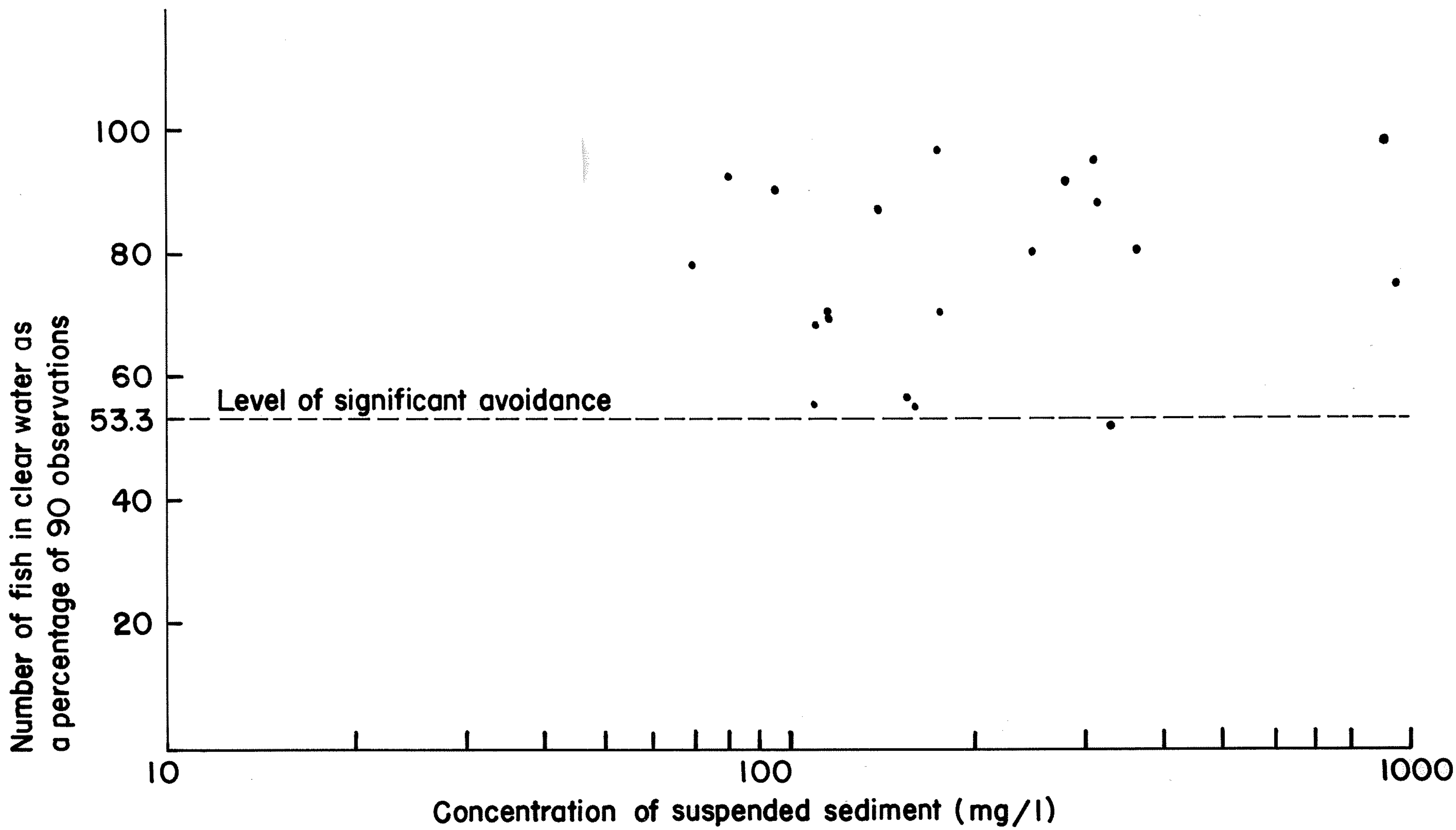

FIG. 8. Relationship between suspended sediment concentration and avoidance response of juvenile chum salmon.

the other during the clear water phase of the experiment. During the sediment introduction phase, the hatchery fish school would remain together, except on occasion the school would break up. The wild fish tended to swim in all directions at random in small schools of two to three fish during the clear water phase. When sediment was introduced, the wild fish tended to avoid it, but one to three fish would investigate the turbid water side, sometimes staying there for long periods.

DISCUSSION

Toxicity of Suspended Sediment to Chum Salmon

The toxicity of suspended sediment to chum salmon is a function of suspended sediment composition and fish condition. The sediment from the proposed drydock area appears to be moderately toxic, the toxic components being the particle size and angular shape rather than any associated toxic element. The associated toxicity of the bottom sediments appears to be of no concern, as demonstrated by Expts. 9A and 9B.

The condition of chum salmon is the most important factor determining the toxicity of suspended sediment in the Devil's Hole area. Healthy fish can withstand very high concentrations of suspended sediment. Suspended sediment concentrations as high as 3056 mg/liter had no apparent effect on Big Beef Creek chum salmon (Expt. 12A). On the other hand, fish infected by vibriosis and/or furunculosis have a very low tolerance to suspended sediment, as demonstrated by most of the experiments.

The presence of vibriosis in the test fish makes it very difficult to differentiate the relative toxicity of suspended sediment. After all, the toxicity measurement is a function of response. If the response is high, the toxicity is also high. Does this indicate that suspended sediment is highly toxic to chum salmon infected with vibriosis? Suspended sediment undoubtedly creates stress which may or may not weaken a fish to the point at which it is overcome by disease. Fish in the static bioassays were subject to stress from laboratory procedures which could also weaken the fish. The question is, what amount of stress is induced by suspended sediment?

The results obtained from the static bioassays are only an indication of the toxicity of suspended sediment on chum salmon. Caution should be used when interpreting these results as they pertain only to chum salmon of similar condition taken in the same locale.

Avoidance of Chum Salmon to Suspended Sediment

The results of the avoidance experiments demonstrate beyond doubt that juvenile chum salmon avoid suspended sediment, but they were all conducted under light conditions so it is not known if avoidance would be significant in the dark. Chum salmon in these experiments were observed swimming at the surface when on the turbid water side, which could mean that the fish were unable to see when swimming deeper in the turbid water. This suggests that vision may be the mode of sediment detection by fish. If so, fish probably would not avoid suspended sediment at night. On the other hand, fish observed swimming at the surface in the turbid water may be trying to avoid the suspended sediment. A fish swimming near the surface would encounter fewer sediment particles because the concentration of suspended sediment would be less due to settling. Therefore, the mode of sediment detection by fish could be through a number of mechanisms--i.e., chemoreception, vision, and gill irritation, to name a few.

The avoidance response recorded in this experiment was an all-or-nothing response, and its magnitude could not be measured. In other words, it is not known how far a fish will swim to avoid suspended sediment or how long a fish will avoid suspended sediment. Application of these results to the natural environment should be treated with caution.

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APPENDICES

Appendix Table A. Static bioassay results (water quality parameters are averages)

Experiment No.	Date 1976	Tank No.	Temperature °C	Dissolved Oxygen (mg/1)	Salinity (o/oo)	pH Units	Sediment Conc. (mg/1)	Mortality total
4	May 14-23	1	12.27	6.63	-	-	2777	8
		2	12.23	6.04	-	-	3954	9
		3	12.20	7.13	-	-	884	5
		Control	12.19	8.13	-	-	11	1
5	May 20-23	1	13.37	8.06	-	6.4	1780	9
		2	12.90	8.40	-	6.5	1622	10
		3	13.32	8.75	-	6.4	543	8
		4	13.38	8.90	-	6.3	326	8
		Control	13.23	8.89	-	6.3	10	0
6A	May 25-30	1	12.54	8.76	27.25	5.6	1895	9
		2	13.30	8.68	27.32	6.1	1596	10
		3	12.42	8.69	27.14	5.5	429	9
		4	12.36	8.68	27.15	5.5	161	6
		Control	12.56	9.45	27.17	5.5	-	0

Appendix Table A. Static bioassay results (water quality parameters are averages) Continued

Experiment No.	Date 1976	Tank No.	Temperature °C	Dissolved Oxygen (mg/1)	Salinity (o/oo)	pH Units	Sediment conc. (mg/1)	Mortality total
6B	May 25-30	1	11.47	7.46	-	5.4	2789	10
		2	11.57	7.71	-	5.9	1087	10
		3	11.65	-	-	5.8	607	10
		4	11.28	9.07	-	5.9	295	10
		Control	11.43	8.65	-	5.9	-	7
7A	June 2-6	1	11.60	8.15	28.15	6.6	1505	10
		2	11.55	8.21	28.03	6.5	935	10
		3	11.55	7.88	28.21	6.5	398	10
		4	11.45	8.50	28.06	6.5	197	10
		Control	11.65	8.43	27.89	6.6	-	9
7B	June 2-6	1	11.87	8.10	29.34	6.7	762	4
		2	11.93	8.20	29.33	6.5	424	5
		3	11.92	8.30	29.29	6.7	273	7
		4	11.96	8.09	29.38	6.7	111	3
		Control	11.90	8.18	29.28	6.6	-	0

Appendix Table A. Static bioassay results (water quality parameters are averages) Continued

Experiment No.	Date 1976	Tank No.	Temperature °C	Dissolved Oxygen (mg/l)	Salinity (o/oo)	pH Units	Sediment conc. (mg/l)	Mortality total
8	June 3-7	1	12.53	7.83	29.28	-	1253	1
		2	12.38	8.02	29.54	-	653	1
		3	12.46	7.36	29.66	-	313	1
		4	12.43	8.06	29.90	-	136	1
		Control	12.40	7.53	29.66	-	-	0
9A	June 6-11	1	12.31	3.41	27.02	-	8941	2
		2	12.32	4.85	26.05	-	4620	0
		3	12.31	4.82	27.48	-	2007	0
		4	12.30	4.59	28.26	-	1357	0
		Control	12.41	5.45	25.85	-	-	0
9B	June 6-11	1	12.14	3.69	28.36	-	8415	0
		2	12.16	4.36	28.52	-	5456	0
		3	12.20	4.98	27.90	-	2817	0
		4	12.26	4.93	27.85	-	1308	0
		Control	12.26	4.52	28.35	-	-	0

Appendix Table A. Static bioassay results (water quality parameters are averages) Continued)

Experiment No.	Date 1976	Tank No.	Temperature °C	Dissolved Oxygen (mg/l)	Salinity (o/oo)	pH Units	Sediment Conc. (mg/l)	Mortality Total
10A	June 15-19	1	12.92	7.55	27.96	-	367	4
		2	12.96	7.02	29.61	-	314	0
		3	13.17	6.32	29.63	-	178	4
		4	13.18	6.68	29.59	-	118	2
		Control	12.94	6.76	29.27	-	-	6
10B	June 15-19	1	12.59	7.29	28.61	-	459	7
		2	12.57	6.81	29.02	-	298	4
		3	12.58	7.67	27.31	-	185	5
		4	12.56	6.82	29.27	-	107	4
		Control	12.60	7.25	29.42	-	-	2
10C	June 15-19	1	12.48	6.88	26.74	-	563	4
		2	12.46	7.34	29.05	-	244	2
		3	12.44	7.47	28.53	-	229	2
		4	12.62	7.15	28.13	-	222	2
		Control	-	-	-	-	-	-

Appendix Table A. Static bioassay results (water quality parameters are averages) Continued

Experiment No.	Date 1976	Tank No.	Temperature ^{o}C	Dissolved Oxygen (mg/1)	Salinity (o/oo)	pH Units	Sediment Conc. (mg/1)	Mortality Total
11A	June 21-25	1	13.80	8.58	28.78	6.5	1016	0
		2	13.90	8.18	27.46	6.5	401	0
		3	14.10	7.65	27.91	6.6	353	0
		4	14.00	7.49	26.10	6.7	108	0
		Control	14.10	7.34	27.72	6.7	-	0
11B	June 21-25	1	13.90	8.91	27.57	7.6	844	0
		2	13.80	8.31	27.18	6.7	427	0
		3	13.90	8.77	28.43	6.7	298	0
		4	14.00	8.70	26.67	6.8	111	0
		Control	13.80	8.81	26.88	6.8	-	0
11C	June 21-25	1	13.90	8.58	28.25	6.7	747	0
		2	14.00	8.29	29.45	6.8	337	0
		3	14.00	7.99	28.56	6.9	154	0
		4	13.80	8.53	27.01	6.8	66	0
		Control	-	-	-	-	-	-

Appendix Table A. Static bioassay results (water quality parameters are averages) Continued

Experiment No.	Date 1976	Tank No.	Temperature °C	Dissolved Oxygen (mg/l)	Salinity (o/oo)	pH Units	Sediment conc. (mg/l)	Mortality total
12A	Jun 28–Jul 2	1	15.20	7.28	29.34	7.7	2036	0
		2	15.10	6.18	29.84	7.6	781	0
		3	15.30	7.36	29.84	7.6	484	0
		4	15.40	6.52	29.86	7.6	220	0
		Control	15.50	6.68	29.43	7.6	-	0
12B	Jun 28–Jul 2	1	14.80	7.90	29.13	7.8	1749	10
		2	14.90	6.32	29.90	7.6	941	3
		3	15.20	7.63	29.95	7.6	499	1
		4	15.40	7.00	29.95	7.6	227	1
		Control	15.40	7.29	29.77	7.6	-	0
12C	Jun 28–Jul 2	1	15.50	7.29	29.10	7.7	1684	2
		2	15.10	6.87	29.56	7.6	641	1
		3	14.80	7.17	29.68	7.6	365	1
		4	15.20	7.30	29.90	7.7	142	2
		Control	-	-	-	-	-	-

Appendix Table A. Static bioassay results (water quality parameters are averages) Continued

Experiment No.	Date 1976	Tank No.	Temperature °C	Dissolved Oxygen (mg/l)	Salinity (o/oo)	pH Units	Sediment conc. (mg/l)	Mortality total
13A	July 6-9	1	15.6	7.86	30.37	7.8	1996	8
		2	15.4	7.04	30.36	7.6	1107	10
		3	15.6	7.53	30.33	7.6	525	9
		4	15.6	7.51	30.34	7.6	187	5
		Control	15.7	7.21	30.44	7.8	-	7
13B	July 6-9	1	15.5	8.16	29.52	7.6	946	8
		2	15.5	6.59	30.19	7.5	633	8
		3	15.7	7.46	30.37	7.4	504	8
		4	15.8	7.39	30.19	7.5	452	10
		Control	15.1	7.85	30.29	7.6	-	10
13C	July 6-9	1	15.5	7.01	30.32	7.5	1392	9
		2	15.2	7.29	30.29	7.5	571	8
		3	15.2	7.74	30.33	7.6	398	8
		4	15.4	7.78	29.90	7.5	275	9
		Control	-	-	-	-	-	-

Appendix Table A. Static bioassay results (water quality parameters are averages) Continued

Experiment No.	Date 1976	Tank No.	Temperature °C	Dissolved oxygen (mg/l)	Salinity (o/oo)	pH Units	Sediment conc. (mg/l)	Mortality total
14	July 12-16	1	13.9	7.71	29.84	7.3	2423	6
		2	13.7	9.16	30.10	7.3	707	8
		3	13.9	9.44	30.21	7.1	360	8
		4	14.0	7.80	30.27	7.2	215	4
		Control	13.8	8.21	30.25	7.3	-	5