

INTERNATIONAL PACIFIC SALMON
FISHERIES COMMISSION

PROGRESS REPORT

No. 23

**MARINE DISPOSAL OF SEDIMENTS FROM
BELLINGHAM HARBOR AS RELATED TO
SOCKEYE AND PINK SALMON FISHERIES**

BY

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NEW WESTMINSTER, B. C.

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FISHERIES COMMISSION

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in the Fraser River System

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ABSTRACT

A recent proposal for dredging and marine disposal of sediment from Whatcom Waterway, Bellingham was of concern to fisheries agencies since the proposed disposal area was utilized by several fish stocks, including migrating Fraser River sockeye and pink salmon. Laboratory study indicated that two types of sediment were involved. Sediment from the inner harbor consisted primarily of putrefying pulp fibers which exerted a significant oxygen demand, created substantial turbidity, and were toxic to juvenile sockeye salmon because of their hydrogen sulfide content. Hydrogen sulfide was readily dissipated from inner harbor sediment by diffused air but was not removed by exposure for a few hours to the atmosphere. Various methods of widespread dispersal to dilute the sediment appeared impractical, and it was concluded that land disposal of inner harbor sediment would be necessary to protect fish stocks. Sediment from the outer harbor was a natural silt, not containing hydrogen sulfide, but exerted an oxygen demand and created a highly turbid mixture which settled very slowly. Because dumping of this sediment at the proposed site could also prove harmful to fisheries, hydraulic dredging and local disposal adjacent to the outer harbor was recommended.

TABLE OF CONTENTS

	PAGE
INTRODUCTION	1
MATERIALS AND METHODS	5
Collection and Storage of Sediments	5
Analytical Methods	6
Bioassay Methods	7
RESULTS	9
Physical Characteristics of Sediments	9
Inner Harbor Sediment	9
Outer Harbor Sediment	10
Turbidity Created by Sediments	10
Inner Harbor Sediment	10
Outer Harbor Sediment	13
Oxygen Demand and Hydrogen Sulfide Content of Sediments	13
Inner Harbor Sediment	13
Outer Harbor Sediment	16
Toxicity of Sediments	18
Inner Harbor Sediment	18
Outer Harbor Sediment	26
Tests to Remove Hydrogen Sulfide from Inner Harbor Sediment	26
Aeration	26
Washing and Resettling	29
DISCUSSION	30
Inner Harbor Sediment	30
Outer Harbor Sediment	33
RECOMMENDATIONS	34
Inner Harbor Sediment	34
Outer Harbor Sediment	35
CONCLUSIONS	36
LITERATURE CITED	38

MARINE DISPOSAL OF SEDIMENTS FROM
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TO SOCKEYE AND PINK SALMON FISHERIES*

INTRODUCTION

In 1968, it was proposed that a part of Bellingham Harbor, Whatcom Waterway, be dredged and the sediment dumped in an area southeast of Lummi Island, Washington (FIGURE 1). Since the proposed disposal area was on the general migratory routes of Fraser River sockeye (Oncorhynchus nerka) and pink salmon (O. gorbuscha), it was the responsibility of the International Pacific Salmon Fisheries Commission, under its terms of reference, to investigate possible harm to these fisheries from the project and to recommend alternatives if necessary.

Whatcom Waterway, the principal harbor facility of the Port of Bellingham, consists of an inner and an outer harbor (FIGURE 2). The entire waterway is subject to shoaling by river silt and sediments from the adjacent area. Bottom deposits have accumulated in the inner harbor primarily by deposition of pulp fiber from the Georgia-Pacific Corporation sulfite pulp, board and paper mills; a smaller contribution of sediment has originated from the Bellingham sewage treatment plant and Whatcom Creek (Fed. Water Pollution Control Admin. and Wash. State Pollution Control Comm., 1967). Sediment in the outer harbor has accumulated largely from the silt load of the Nooksack River.

To maintain adequate depth for seagoing vessels, Whatcom Waterway has been dredged several times in the past. Sediment removed during the past decade was transported on flat barges and washed overboard in the vicinity of Post Point, south of Bellingham, where a shoal was eventually created and disposal discontinued in that area (FIGURE 2). Land disposal was also used, with the sediment utilized for land fill at the site of the present Georgia-Pacific Corporation chlorine plant. Because of its high organic content and low sand content (less than 10%), the material was not suitably compacted for more than 5 years.

* This study was financed by the Governments of Canada and the United States with a part of United States contribution originating from the Federal Water Pollution Control Administration of the U.S. Department of the Interior.

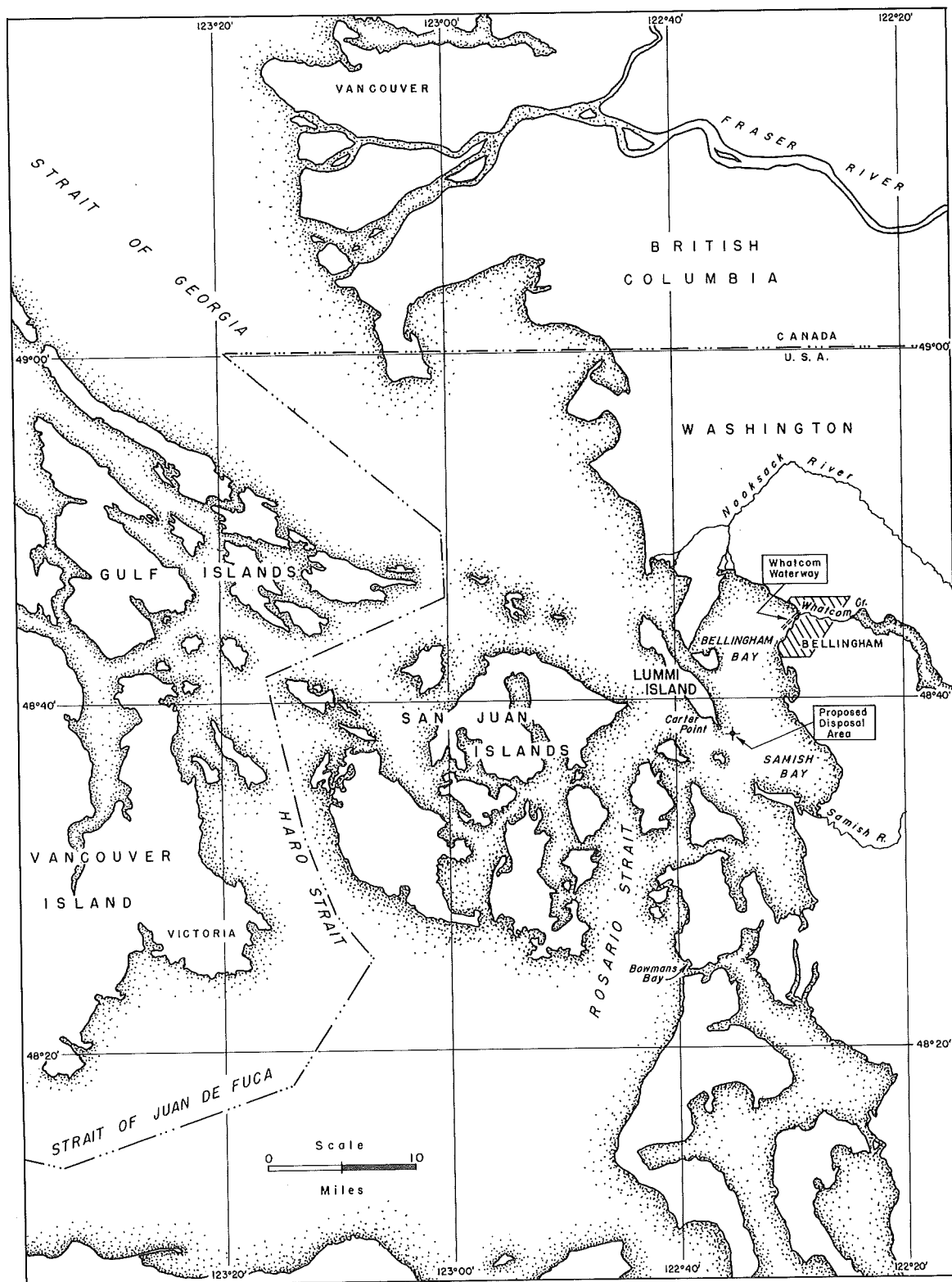


FIGURE 1 - Waters south of the Fraser River showing Whatcom Waterway and the proposed sediment disposal area.

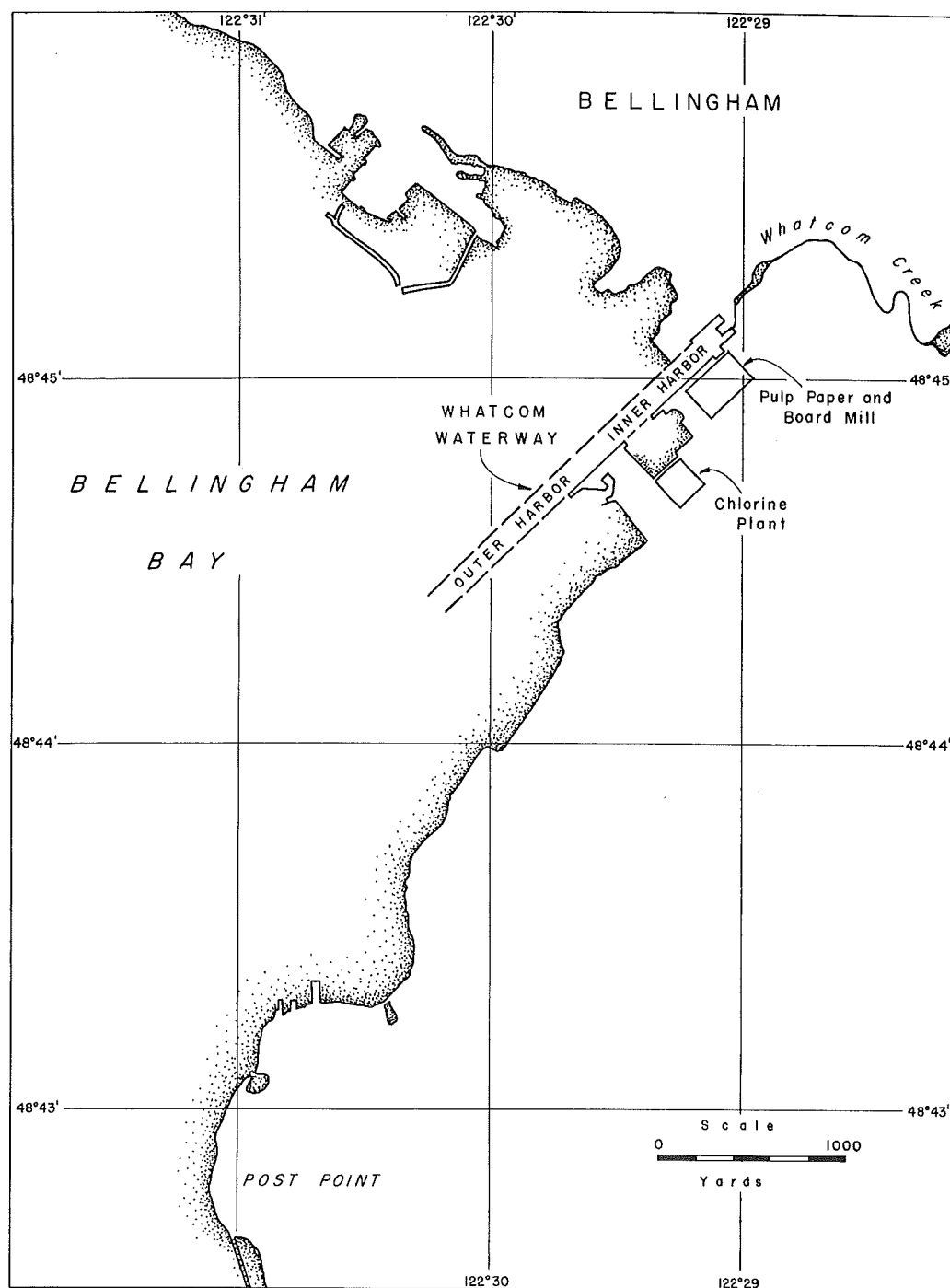


FIGURE 2 - Whatcom Waterway showing inner and outer harbor areas.

The project proposed by the Port of Bellingham and the U.S. Army Corps of Engineers called for removal of approximately 62,600 cu yd of sediment from the inner harbor area and 69,000 cu yd from the outer harbor. The dredged material was to be transported in bottom dump barges and released in 47 fathoms of water at a site southeast of Carter Point, off Lummi Island.

The proposed disposal site is important from the fisheries standpoint. Many of the adult sockeye and pink salmon bound for the Fraser River pass through the area during their summer and autumn migration and thus would be subject to any adverse conditions created by sediment disposal. Any substance which would be harmful or cause fish to detour from their historic migration route would result in an economic loss to the commercial purse seine, gill net and reef net fisheries in the area. The reef net fisheries, located along the west side of Lummi Island between 4.5 and 7 miles from the proposed disposal site, obtain fish from schools which turn northwest as they enter the general area of Lummi Island. Reef net fishermen could be especially affected by increased turbidity caused by sediment disposal, not only because of their stationary gear, but also because visual observation to a depth of 15 ft is necessary in order to fish effectively.

Juvenile sockeye salmon from the Fraser River migrate seaward in April, May and June, primarily along a route through Haro Strait and thus would not be expected in significant numbers near the proposed dumping site. A few juvenile pink salmon of Fraser River origin might be present in the proposed disposal site, but the majority spend their first spring and summer farther west in the Gulf and San Juan Islands.

The proposed disposal area is also of importance to chinook (O. tshawytscha), coho (O. kisutch), chum (O. keta) and pink salmon from the Nooksack and Samish Rivers, both adult and juvenile fish, which move through the area on their historic migrations during spring, summer and autumn. Chinook, coho and chum salmon from the Fraser River also may migrate through this area. Pacific herring (Clupea harengus pallasii) are taken commercially during winter months in the proposed disposal area and a bottom trawl fishery operates throughout most of the year. Finally, the area is a commercial crab fishing ground during winter (E. Limbacher, personal communication).

Previous surveys indicated that sediments in the inner harbor would contain considerable hydrogen sulfide and would be devoid of normal benthic organisms such as crabs and clams (F.W.P.C.A. and W.P.C.C., 1967). Hydrogen sulfide, a respiratory depressant, has been reported lethal to salmon and trout at concentrations above 0.3 ppm (McKee and Wolf, 1963) and thus it was advisable to investigate whether toxic conditions might arise during sediment disposal. Other factors, such as oxygen demand of the inner harbor sediment and turbidity which might be created during dumping, were of concern as well.

The aforementioned survey found sediment in the outer harbor to support a benthic community typical of a muddy marine bottom. Crabs, clams, and starfish were noted, and hydrogen sulfide was not detected. These characteristics suggested that sediment in the outer harbor was less hazardous than that from the inner area. However, its oxygen demand and potential for creating turbidity were unknown and required investigation.

An experimental study was conducted to answer the various questions raised above and the results are reported herein. Subsequent to completion of the study but prior to compilation of this report, the Washington State Water Pollution Control Commission, the Washington State Department of Fisheries, and the U.S. Army Corps of Engineers agreed on a modified dredging plan. The modified plan called for retention of the inner harbor sediment until a land disposal plan could be developed and hydraulic dredging of the outer harbor sediment with disposal in the local area. The contents and recommendations of this report formed part of the testimony used in formulating the modified dredging plan.

MATERIALS AND METHODS

Collection and Storage of Sediments

Bottom sediments used in these experiments were obtained from Whatcom Waterway on April 3, April 22, and May 6, 1969 with the assistance of Washington State Department of Fisheries who provided a patrol boat. An Ekman dredge was used to collect samples from the inner harbor area and a Petersen dredge was used in the outer harbor (Standard Methods, 1965). A total of 35 individual dredge samples from throughout the inner harbor and 18 dredge

samples from the outer harbor were collected and combined for storage as shown in TABLE 1.

TABLE 1 - Collection and storage of sediments from Whatcom Waterway, 1969.

Location	Sampling Date	No. Dredge Samples	Storage
Inner Harbor	April 3	10	Seven 1-gal glass jars
	April 22	25	Three 5-gal covered pails
Outer Harbor	April 3	3	One 1-gal glass jar
	May 6	15	One 5-gal covered pail

All samples were transported to the laboratory within 3 hr of collection and were stored at 45°F until prepared for use. Normally, sediments were removed from storage and warmed to approximately 60°F for at least 2 hr before use in tests, as it was expected that sediment would similarly be warmed while awaiting disposal on a barge. Exceptions to this procedure occurred where noted.

Analytical Methods

Sediments collected from Whatcom Waterway were examined for total and volatile solids and specific gravity. The settling rate (turbidity), oxygen demand and hydrogen sulfide production of mixtures of sediment in sea water were also investigated.

Total solids were obtained by evaporating a known weight (approximately 100 gm) of sediment to dryness at 103°C in 20 hr. Volatile solids were determined by igniting the total residue in a muffle furnace at 600°C for 20 min. Specific gravity was determined by dividing the weight of 100 ml of sediment, as collected, by 100 (Standard Methods, 1965). Turbidity was measured with a Hellige turbidimeter using a 20 mm cell depth.

Dissolved oxygen was measured with an oxygen meter (Yellow Springs Instrument Co., Model 54) equipped with a Clark type polarographic oxygen sensor. The instrument was calibrated daily in sea water against the high

dissolved oxygen or organic content modification of the Winkler method (Standard Methods, 1965).

Hydrogen sulfide was measured using the methylene blue colorimetric method (Standard Methods, 1965) with certain modifications (Von Gernerden, personal communication). The modified method utilizes an acidified p-amino N:N dimethyl aniline solution and a ferric ammonium sulfate solution to develop the typical methylene blue color. Absorbance (extinction) of the sample was measured at 670 m μ with a Bausch and Lomb Spectronic 20 spectrophotometer. The volume of sample taken for analysis varied between 10 and 80 ml, depending upon the estimated amount of hydrogen sulfide present.

Samples taken for hydrogen sulfide analysis were turbid and required clarification for analysis. Since hydrogen sulfide concentrations decreased with time due to oxidation, the time required for flocculation and sedimentation was considered impractical. Hence, samples were filtered under mild suction for up to 2 min. Tests on standard clear solutions before and after filtration indicated a 15% loss of hydrogen sulfide, thus results reported herein have been corrected accordingly.

Bioassay Methods

Bioassays of sediments were conducted in sea water using sockeye salmon smolts of 11 cm fork length as the test animals. Fish were reared at the Sweltzer Creek Field Station where they had a history of good health. The tests were conducted during April when smolts were normally tolerant of sea water and thus the fish were acclimated without sign of distress for 48 hr in sea water of 30 ‰ salinity before bioassays commenced.

A total of seven bioassays, designated A₁, A₂, B, C, D, E and F, were conducted under the various aquarium conditions shown in TABLE 2. Diffused aeration, which kept solids (fibers, silt, etc.) in suspension, was used only in the 15-liter units. Contents of the 3-liter aquaria were kept in suspension with a 6-unit mechanical laboratory stirrer operated continuously at 70 rpm. Solutions in the 10-liter aquaria were mixed only at the outset. Since temperatures in the area of disposal were expected to be between 50°F and 52°F (Kincaid, Wennekens and Sylvester, 1954, 1955), all but one of the

TABLE 2 - Origin, age of sediment, and aquarium conditions during bioassays.

BIOASSAY	SEDIMENT ORIGIN	DATE COLLECTED	SEDIMENT STORAGE TIME	AQUARIUM CONDITIONS				Temp. °F
				Volume liters	No. Fish	Aeration	Mixing	
A ₁	Inner Harbor	April 3	4 hr	15	10	Yes	Constant	50
A ₂	"	April 3	4 hr	15	2	Yes	Constant	50
B	"	April 3	11 days	10	2	No	Initial	50
C	"	April 22	4 hr	3	2	No	Constant	50
D	"	April 22	3 days	3	2	No	Constant	57
E	Outer Harbor	April 3	11 days	10	2	No	Initial	50
F	"	May 6	8 hr	3	2	No	Constant	50

bioassays were conducted at 50°F. Sea water was collected from Bowman's Bay, Washington and maintained under aeration at 45°F until warmed for the tests.

Sediment concentrations used for each bioassay were determined by volume. Sediment was measured in a graduated cylinder when taken from the storage container, and bioassays were carried out after storage intervals ranging from 4 hr to 11 days (TABLE 2). Dissolved oxygen was monitored in bioassays C and F; hydrogen sulfide was measured in bioassays C, D and F.

RESULTS

Physical Characteristics of Sediments

Inner Harbor Sediment

All sediment samples collected from the inner harbor were slurries consisting primarily of pulp fibers. A strong odor of hydrogen sulfide was present and sediment was black. Bubbles of gas were seen rising continually throughout the inner harbor area on all sampling trips and a group of bubbles was released whenever the Ekman dredge was dropped into the sediment. Presumably the bubbles consisted of hydrogen sulfide, carbon dioxide and methane (A.E. Werner, Fish. Res. Bd. Canada, personal communication). No bottom organisms such as crabs, worms, or algae were evident in the 35 dredge samples collected during the course of the study.

Laboratory tests indicated the sediment was 11% solids, of which 27% were volatile solids, and the specific gravity was 1.02 (TABLE 3). Similar volatile solids were reported in an earlier study where it was observed that there was a dearth of normal marine bottom life where volatile solids exceeded 10% (F.W.P.C.A. and W.P.C.C., 1967). When air-dried outdoors the sediment was similar to dewatered pulp fibers taken from a typical pulp mill settling pond.

TABLE 3 - Physical characteristics of sediments.

Sediment Origin	Total Solids %	Volatile Solids %	Specific Gravity
Inner Harbor	11	27	1.02
Outer Harbor	47	5	1.35

Outer Harbor Sediment

Sediments throughout the outer harbor appeared to consist of natural silt deposits. The odor of hydrogen sulfide was not evident in the samples upon collection. Small crabs and worms were noted in the samples and these remained alive during a 14-day storage period. The sediment was 47% solids with a volatile solids content of 5%; the specific gravity was 1.35 (TABLE 3). In a previous study, the volatile solids in the same general area ranged from 8 to 10% (F.W.P.C.A. and W.P.C.C., 1967), also indicating conditions suitable for bottom organisms.

Turbidity Created by Sediments

Sediment may create turbid conditions when dumped, depending upon the degree of mixing and break-up of particles. The objects of the following measurements were to determine the extent of turbidity and settling time of different concentrations of sediment in sea water at 50°F. A range of concentrations of sediment from the April 22 collection were mixed in 3-liter jars and stirred vigorously for 1 min. Samples for analysis were taken with a siphon from mid-depth (3 in.) in the jars.

Inner Harbor Sediment

Initial turbidity of inner harbor sediment decreased considerably during the first 1.5 hr and then more slowly thereafter (TABLE 4). After 24 hr, turbidity of sediment concentrations from 0.5 to 10% ranged between 7 and 96 ppm and remained proportional to initial sediment concentration. The 0.1% sediment concentration was clarified in 2.5 hr (FIGURE 3). A fraction of the sediment, probably natural silt originating from Whatcom Creek, was finely divided and settled very slowly.

TABLE 4 - Turbidity of sediment in sea water initially and after 1.5 and 24 hr settling.

SEDIMENT ORIGIN	CONCENTRATION %	TURBIDITY- ppm		
		Initial	1.5 hr	24 hr
Inner Harbor	10	1,200	250	96
	5	960	187	60
	2.5	450	50	27
	1.0	124	44	12
	0.5	70	18	7
	0.1	38	5	nil
Outer Harbor	10	11,000	140	20
	5	8,100	187	14
	2.5	3,750	103	10
	1.0	2,360	120	7
	0.5	650	146	7
	0.1	227	66	5

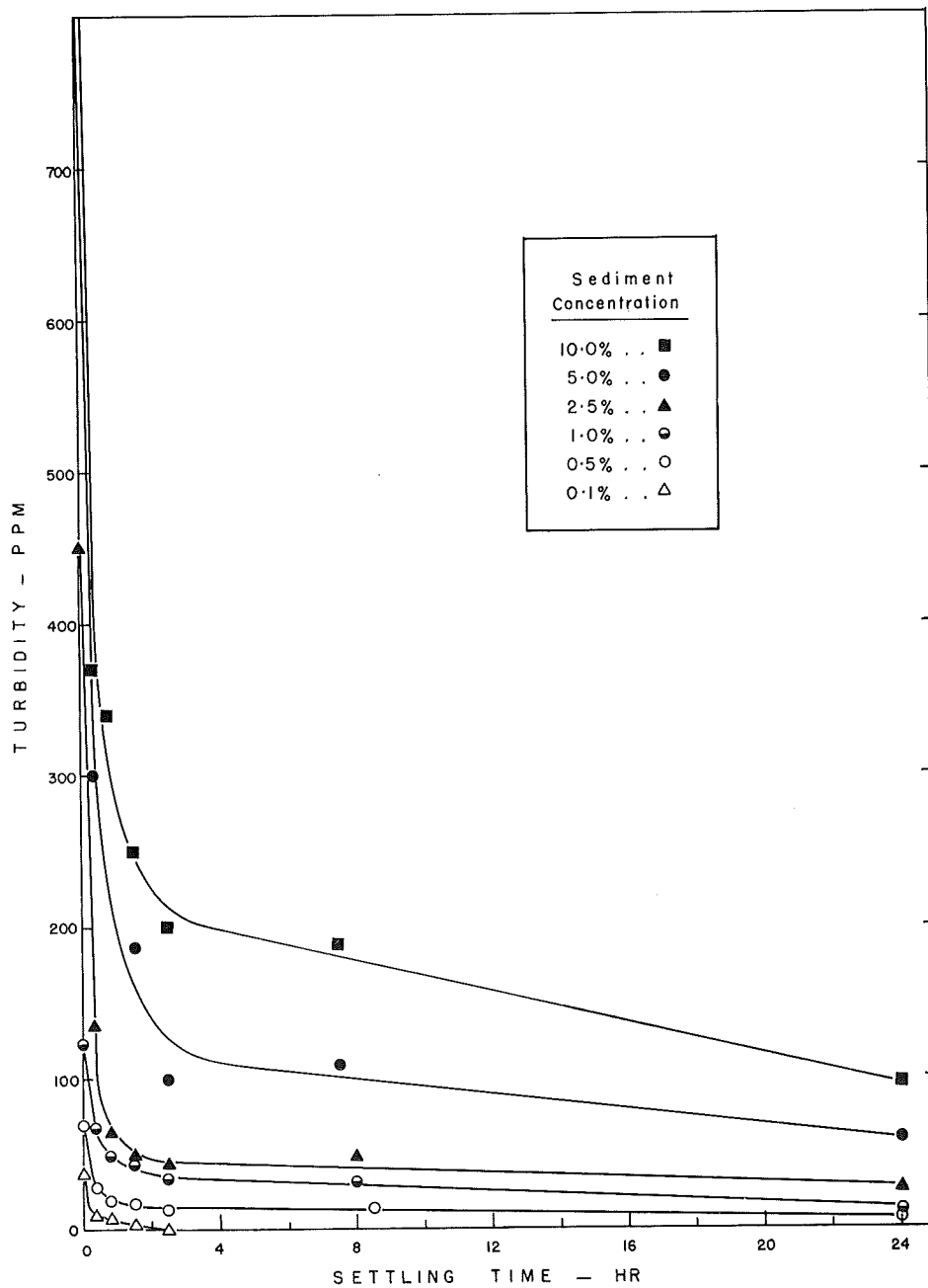


FIGURE 3 - Turbidity of inner harbor sediment.

Outer Harbor Sediment

Outer harbor sediment created much higher initial turbidities than did the inner harbor sediment (TABLE 4). However, the outer harbor sediment settled rapidly during the first 1.5 hr and turbidities were in the same general range as those created by inner harbor sediment. Following initial sedimentation the turbidities of the various sediment concentrations were restricted to a narrow range and thus a single curve was drawn through the points showing settling rate in FIGURE 4. Following the initial 3-hr period of rapid sedimentation, turbidity declined very slowly and after 24 hr was between 5 and 20 ppm. It is of interest to note that the 0.1% concentration of outer harbor sediment did not clarify as did the inner sediment, but had a turbidity of 5 ppm at 24 hr.

Oxygen Demand and Hydrogen Sulfide Content of Sediments

The strong odor of inner harbor sediment suggested an oxygen demand would be associated with oxidation of hydrogen sulfide to sulfur. In addition, sediments generally exert a biochemical oxygen demand owing to the presence of bacterial life. Thus oxygen demand of these sediments was expected to be composed of a combination of chemical and biochemical oxidations.

Inner Harbor Sediment

The oxygen demand and hydrogen sulfide concentrations of 2% mixtures (by volume) of inner harbor sediment sampled on April 22 were measured after the sediment had been stored 2 days. Tests were conducted at 50°F on two identical 3-liter samples mixed continuously with a mechanical stirrer at 70 rpm. Oxygen declined rapidly at first in each sample, decreasing to 5 ppm within 25 min in sample I and within 35 min in sample II (FIGURE 5). The oxygen demand apparently equaled the supply after about 90 min when oxygen stabilized at 2.3 and 3.2 ppm in the two samples.

Hydrogen sulfide concentrations in the two samples showed a rapid increase in the first 5 min, followed by a steady decline. The initial increase was probably created by dissolution of hydrogen sulfide as the particles of sediment were dispersed during initial mixing. The maximum

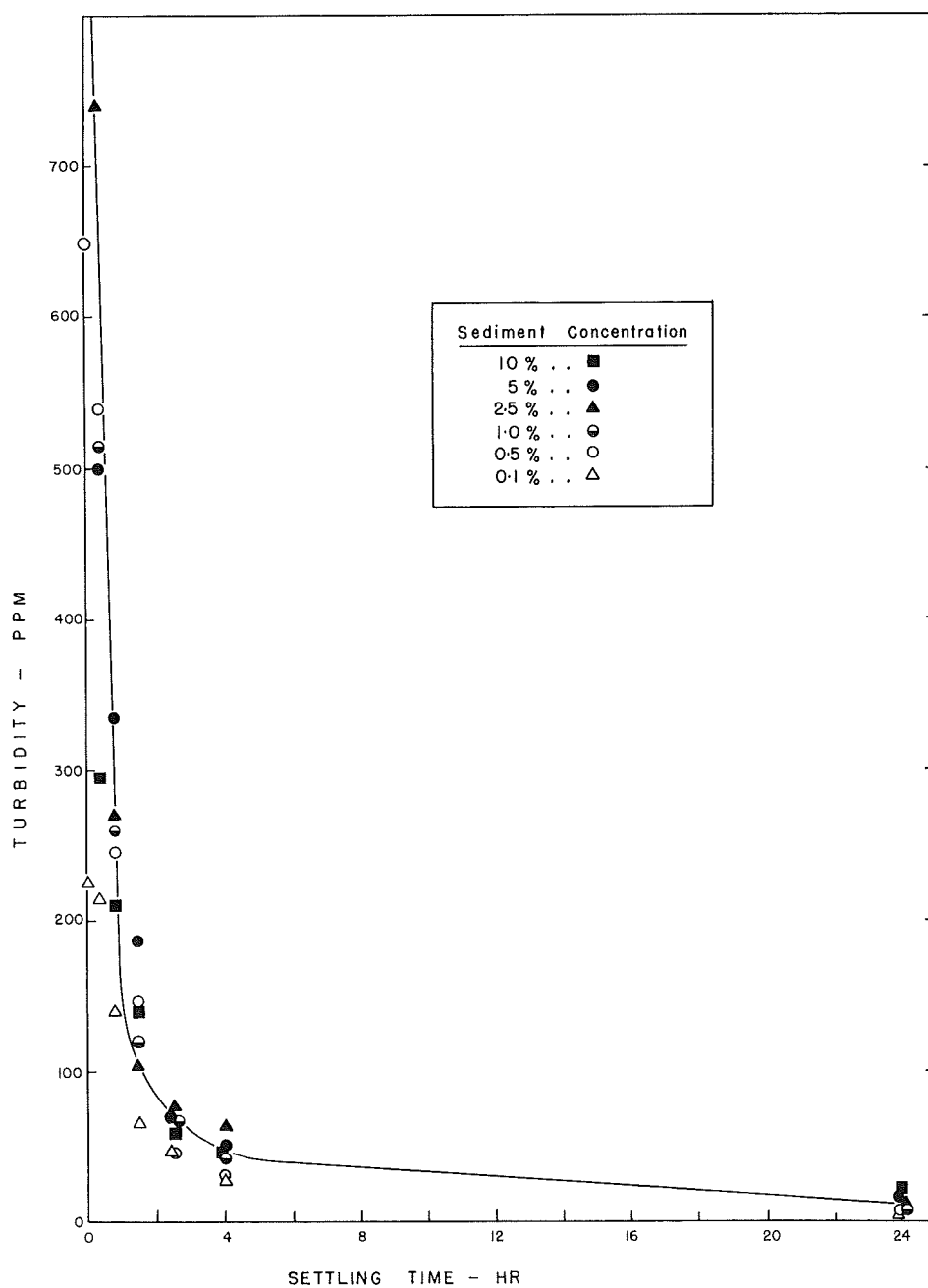


FIGURE 4 - Turbidity of outer harbor sediment.

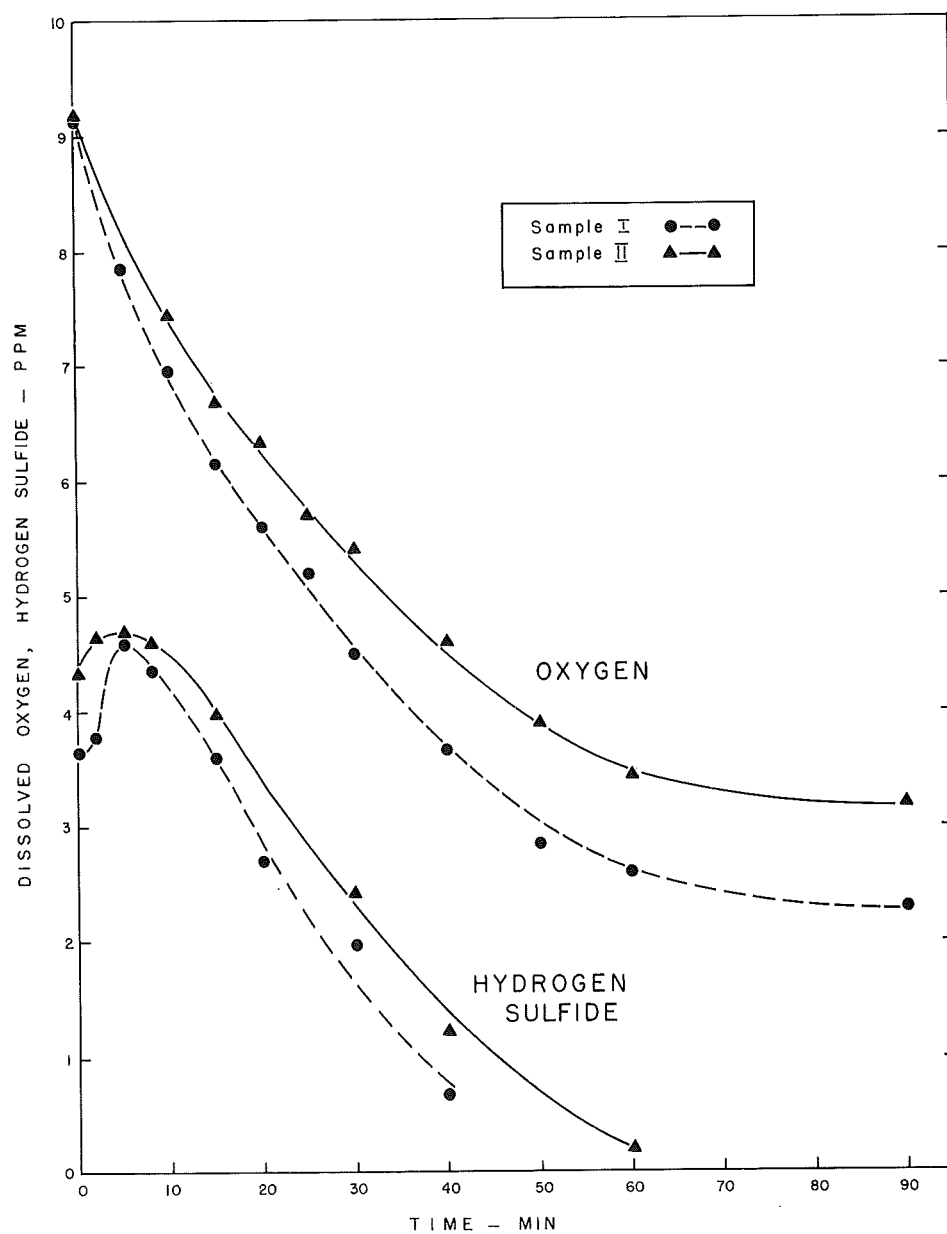


FIGURE 5 - Oxygen demand and hydrogen sulfide content of 2% concentrations of inner harbor sediment. (Continuous mixing, fish not included.)

hydrogen sulfide concentration in both samples exceeded 4 ppm and declined to 1 ppm after 40 to 50 min. The data in FIGURE 5 suggest that nearly all hydrogen sulfide in a 2% sediment concentration might be dissipated in about 1 hr.

The results showed a close correlation between oxygen demand and dissipation of hydrogen sulfide, indicating oxidation of hydrogen sulfide to the harmless sulfur state. However, the oxygen demand probably consisted of biochemical oxygen demand exerted by microorganisms as well as the chemical demand of hydrogen sulfide oxidation.

Outer Harbor Sediment

Although hydrogen sulfide was not detected, the outer harbor sediment also exerted a significant oxygen demand. Dissolved oxygen concentrations of 5, 3, 2, and 1% sediment mixtures (by volume) were measured at 50°F for a 2-hr period in the absence of fish. Each 3-liter mixture was continuously mixed with a mechanical stirrer at 70 rpm. Oxygen dropped to about 5 ppm within 2 min in a 5% concentration and reached 0.1 ppm after 2 hr (FIGURE 6). Oxygen demands were proportionately less at lower sediment concentrations.

The oxygen demand of outer harbor sediment was similar to that of the inner harbor as seen by comparing oxygen remaining after 20 min, at 2% sediment. Thus it was suspected that the demand consisted of chemical as well as biochemical oxidations. However, there was no evidence of hydrogen sulfide, which can be detected at very low concentration by its odor, nor were there any gas bubbles released to indicate the presence of other gases (e.g., methane) in the sediment. Oxidation of reduced sulfur, iron or manganese in the sediment may have been the cause of rapid chemical oxygen demand, but the topic was not pursued and should be the subject of further investigation.

Less oxygen was consumed by a 2% concentration of outer harbor sediment than a similar concentration of inner harbor sediment. For example, after 60 min the oxygen remaining was 5.1 ppm in the outer harbor sediment versus 3.1 ppm in the inner harbor sediment (FIGURES 6 and 5). Since initial dissolved oxygen concentrations were 9.1 ppm in each case, the oxygen demands were 4 and 6 ppm, making the oxygen demand of the outer sediment about 67% that of the inner sediment. Oxidation of hydrogen sulfide in the inner harbor sediment would probably account for much of the difference in oxygen demands.

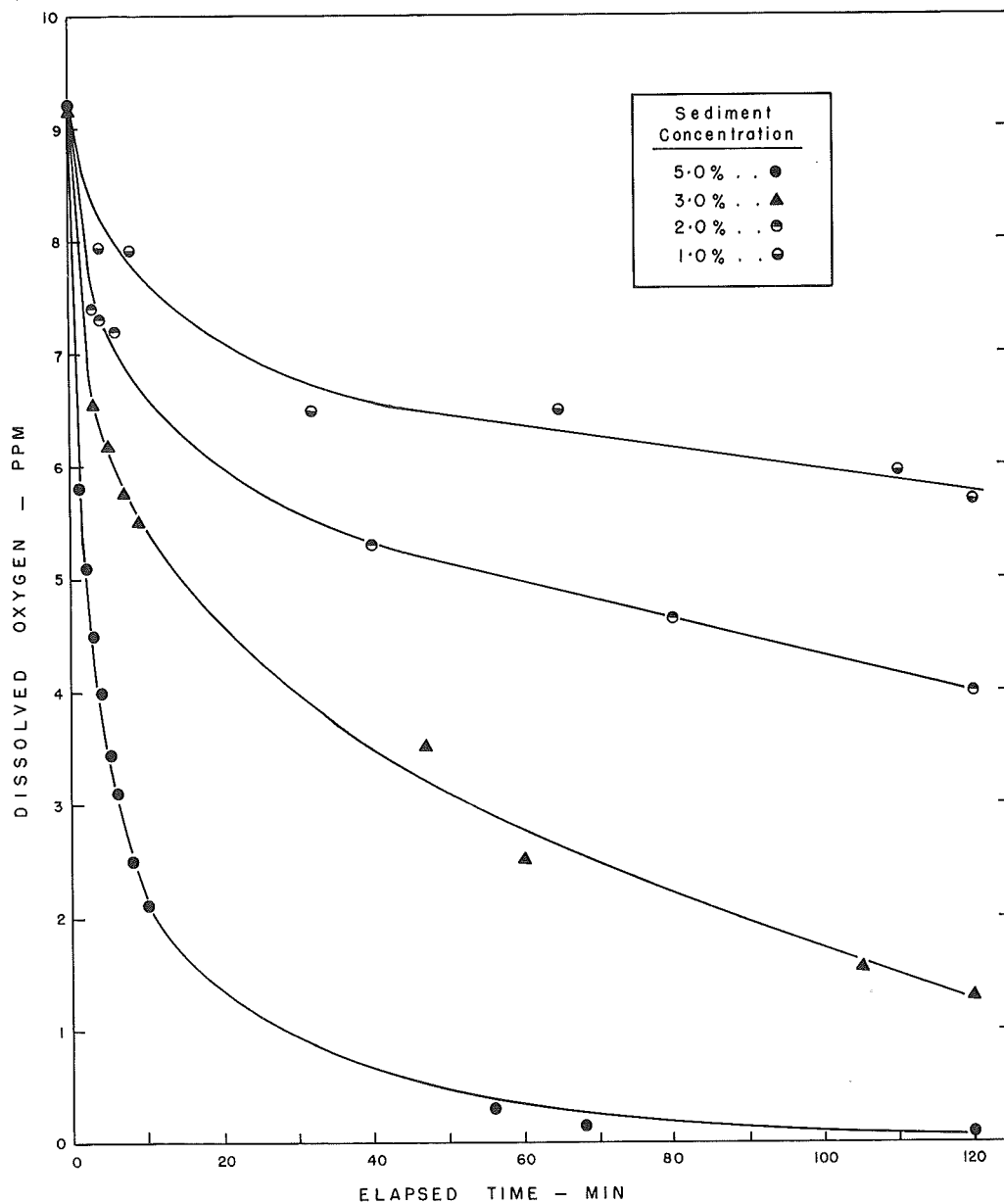


FIGURE 6 - Oxygen demand of various concentrations of outer harbor sediment. (Continuous mixing, fish not included.)

Toxicity of Sediments

Inner Harbor Sediment

Sediments collected from the inner harbor on April 3 and 22 were bioassayed using sockeye smolts in sea water to evaluate acute toxicity. Both loads were bioassayed initially within about 4 hr of procurement and again after sediment had been stored for several days.

Sediment collected on April 3 from the inner harbor was bioassayed 4 hr after collection using 10 sockeye smolts in a 15-liter aerated aquarium as described in bioassay A₁ (TABLE 2). Concentrations of 10% and 1% sediment by volume caused 100% mortalities in approximately 5 and 10 min, respectively (TABLE 5). Smolts in a 0.1% concentration were distressed for 5 min but recovered and were alive at 120 hr when the test was terminated. Distress was marked by frenzied swimming, surfacing, jumping and coughing. The strong odor associated with the sediment suggested that hydrogen sulfide probably was the primary toxicant.

In order to examine this possibility further, the 10% and 1% mixtures of inner harbor sediment were aerated overnight (approximately 16 hr) to remove hydrogen sulfide. The odor of hydrogen sulfide disappeared during aeration and the mixture changed from black to gray, the color change expected when hydrogen sulfide has been removed. Two smolts were reintroduced into each of the 10% and 1% concentrations (bioassay A₂). In the 10% concentration the smolts exhibited extreme cough reactions initially which moderated in 1 hr. One fish died with its gills clogged with fiber and the other was alive at 120 hr when the test was terminated (TABLE 5). Both smolts in the 1% sediment mixture survived 120 hr although they exhibited moderate cough reactions for the first hour. It was believed that the cough reaction was an attempt to clear suspended fiber from the gills. Smolts in a control aquarium (no sediment) survived without apparent distress for 120 hr. Since aeration reduced toxicity in this test, presumably through removal of hydrogen sulfide, subsequent bioassays were conducted without supplemental aeration.

A second bioassay of the April 3 sediment sample was conducted, as shown in bioassay B, after 11 days of storage and found to be only slightly less toxic than it was initially. Thus at 1% concentration, 100% mortality occurred in 30 min instead of 10 min as was the case originally (TABLE 5).

TABLE 5 - Toxicity of inner harbor sediment obtained April 3, 1969 to sockeye smolts during bioassays A₁, A₂ and B.

Bioassay	Sediment Concentration %	Mortality %	Time to Death or End of Bioassay	Behavior of Fish
A ₁	10.0	100	5 min	Distressed until death.
	1.0	100	10 min	Distressed until death.
	0.1	0	120 hr	Distressed for 5 min.
	0.0	0	120 hr	No distress.
A ₂ *	10.0	50	120 hr	Gills clogged with fiber.
	1.0	0	120 hr	Cough reaction for 1 hr.
	0.0	0	120 hr	No distress.
B	10.0	- Not Tested -		---
	1.0	100	30 min	Distressed until death.
	0.75	0	4 hr	Distressed for 45 min.
	0.50	0	4 hr	Distressed for 3 min.
	0.25	0	4 hr	Distressed for 2 min.
	0.0	0	4 hr	No distress.

* Using 10% and 1% concentrations from bioassay A₁ following aeration to remove hydrogen sulfide.

Fish at 0.75, 0.5 and 0.25% sediment were distressed initially but recovered and were alive after 4 hr when the bioassay was concluded. Dissolved oxygen was not monitored during the bioassay but subsequent tests, such as C, confirmed that mortality was caused by hydrogen sulfide and not lack of available oxygen.

The April 22 sample of inner harbor sediment was bioassayed initially within 4 hr in bioassay C and caused 100% mortality at both 2% and 1% sediment concentrations (TABLE 6). Smolts were distressed in 0.5% sediment, but no distress occurred at 0.1 and 0.05%. The time to death or the degree of distress appeared related to the initial hydrogen sulfide concentration. No distress was evident at hydrogen sulfide concentrations of 0.24 ppm or less. Dissolved oxygen was monitored in each aquarium during bioassay C in order to verify that mortalities were caused by hydrogen sulfide and not by lack of oxygen. Mortalities in 2% and 1% sediment occurred when dissolved oxygen was about 5.6 ppm. This concentration of oxygen is sufficient to support sockeye in an aquarium and thus hydrogen sulfide was considered responsible for the mortality.

It should be noted that dissolved oxygen declined most rapidly in the 2% sediment concentration and continued to do so following death of the fish (FIGURE 7), and thus the decline can be attributed to the oxygen demand of the sediment. Similar though less severe oxygen demands were noted in 1.0 and 0.5% mixtures. The oxygen decrease in the control group was initially greater than that in the 0.1 and 0.05% units, which suggests that initially the control group was consuming oxygen at a greater rate than the combination of fish and sediment in the two lowest sediment concentrations. Since the control fish did not seem abnormally active it was possible that the experimental fish were utilizing less oxygen than normal owing to the presence of hydrogen sulfide. These results coincide with the fact that hydrogen sulfide acts as a respiratory depressant, causing a reduced oxygen uptake by fish (Jones, 1964). Therefore, although no outward signs of distress were noted in the fish in 0.1 and 0.05% mixtures, respiration rate may have been reduced. However, the rate of oxygen consumption in the 0.1 and 0.05% mixtures increased and eventually surpassed that of the controls, suggesting that respiration rate returned to normal as hydrogen sulfide was dissipated.

The April 22 sample of inner harbor sediment was bioassayed again after 3 days storage (bioassay D) and found to have similar toxicity and hydrogen

TABLE 6 - Toxicity of inner harbor sediment obtained April 22, 1969 to sockeye smolts during bioassays C and D.

Bioassay	Sediment Concentration %	Mortality %	Time to Death or End of Bioassay	Initial Hydrogen Sulfide ppm	Final Dissolved Oxygen ppm	Behavior of Fish
C	2.0	100	15 min	3.13	5.7	Distressed until death.
	1.0	100	25	2.15	5.6	Distressed until death.
	0.5	0	85	0.90	3.2	Distressed for 7 min.
	0.1	0	90	0.24	5.0	No distress evident.
	0.05	0	95	0.10	4.9	No distress evident.
	0.0	0	95	0.00	5.5	No distress.
D	2.0	100	15 min	4.40	-	Distressed until death.
	1.0	100	25	2.40	-	Distressed until death.
	0.5	0	60	1.22	-	Distressed for 10 min.
	0.1	0	60	0.30	-	No distress evident.
	0.0	0	60	0.00	-	No distress.

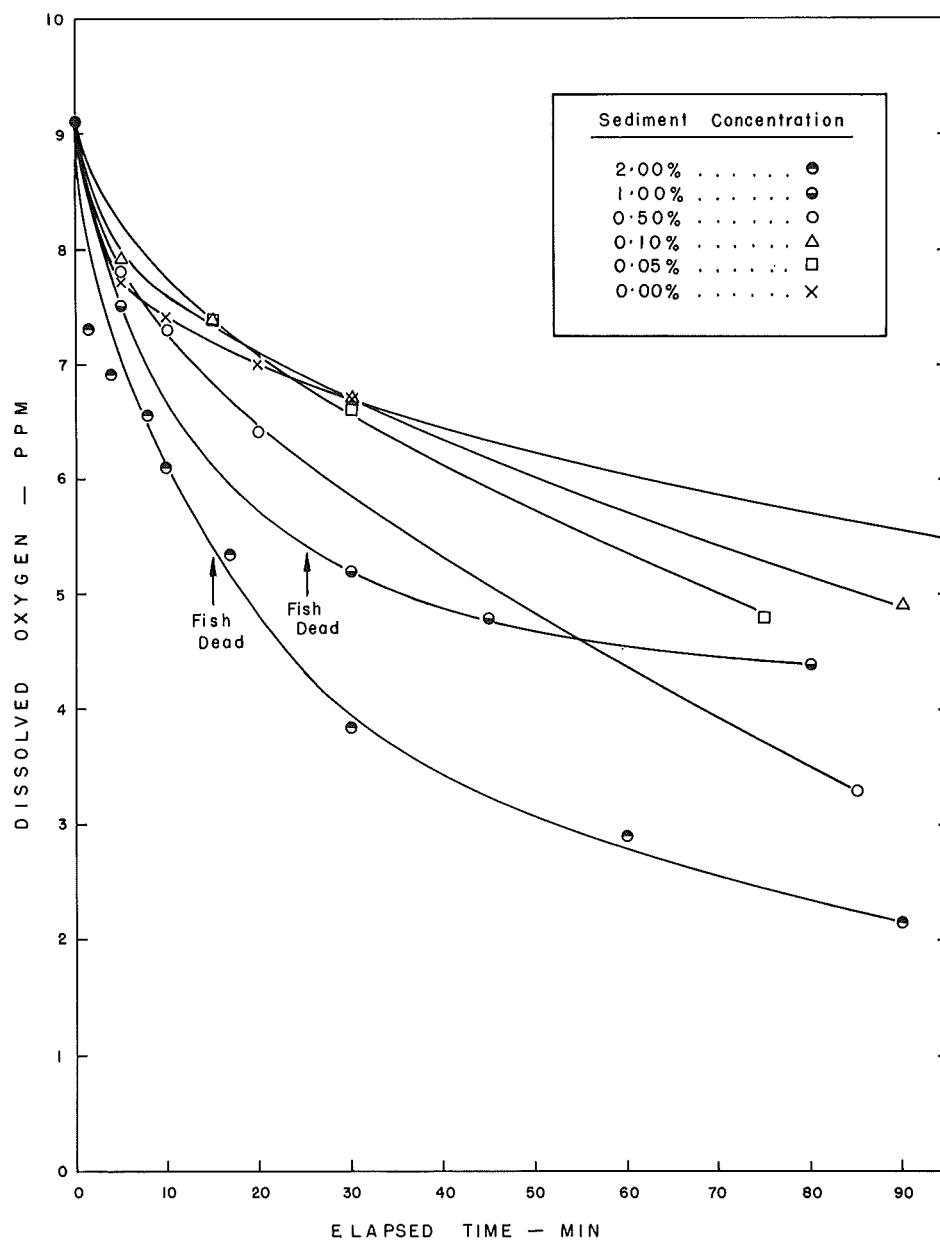


FIGURE 7 - Oxygen demand of various concentrations of inner harbor sediment and a control during bioassay C. Fish alive at the end of all tests except where noted.

sulfide content as in the initial test (bioassay C). Thus complete mortalities occurred at 2 and 1% sediment concentrations and no mortalities at 0.5% and 0.1% (TABLE 6). The concentration of hydrogen sulfide in 1% sediment declined from an initial value of 2.4 ppm to about 0.4 ppm in 25 min which coincided with death of the fish (FIGURE 8). Distress among smolts in 0.5% sediment ceased after hydrogen sulfide declined to about 0.6 ppm after 10-min exposure. No distress was noted at 0.1% sediment where initial hydrogen sulfide concentration was 0.30 ppm.

A decline in hydrogen sulfide during the bioassay is considered a realistic approach in evaluating marine disposal of sediments because dissolved oxygen in sea water would oxidize hydrogen sulfide. Whether or not the rate of decline would match that shown in FIGURE 8 cannot be stated and would be the subject for another study. However, it is interesting to speculate that due to their distressed state, fish at 0.5% sediment would have succumbed had hydrogen sulfide remained at 1.22 ppm and not declined during the bioassay.

It should also be noted that the rate of hydrogen sulfide dissipation recorded in bioassay D differed from that recorded previously in a sediment mixture alone. In both cases, initial hydrogen sulfide concentrations were between 3.1 and 4.4 ppm in a 2% sediment mixture. However, there was a slight increase in hydrogen sulfide noted during the first 5 min in the absence of fish (FIGURE 5), whereas in the presence of fish a decline commenced immediately (FIGURE 8). The brief increase noted in FIGURE 5 may have been caused by dissolution of hydrogen sulfide during initial mixing. On the other hand, the immediate decline noted in the presence of fish may have been related to reaction of fish with hydrogen sulfide, removing it from solution. Dissipation of hydrogen sulfide was also more rapid when fish were present. For example, hydrogen sulfide dropped to 1 ppm in about 25 min when fish were present, whereas 40 min or more were required for a similar decline when fish were absent.

The hydrogen sulfide content and hence the toxicity of the April 3 and 22 samples of sediment varied somewhat but this was expected since not all samples from such a wide area as the inner harbor could be identical. In

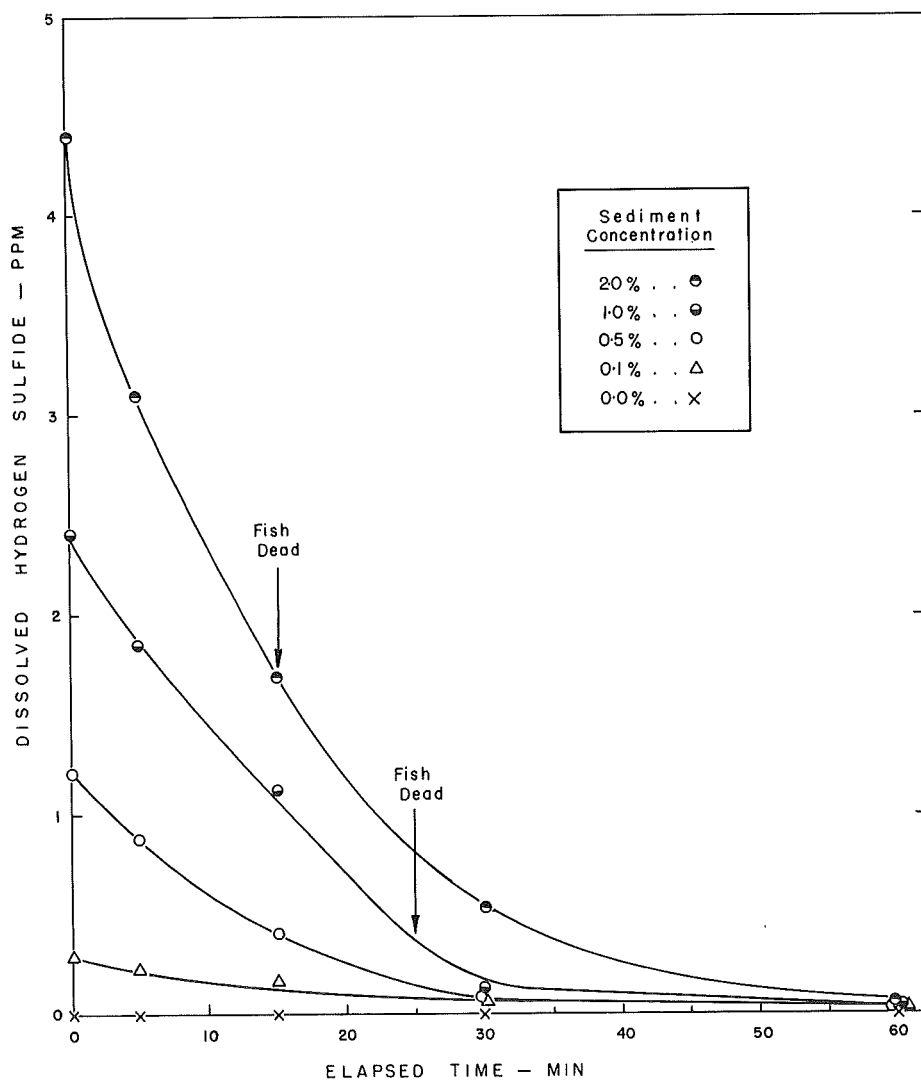


FIGURE 8 - Hydrogen sulfide content of various concentrations of inner harbor sediment and a control during bioassay D. Fish alive at the end of all tests except where noted.

addition, some variation in hydrogen sulfide content was probably related to handling of the sediment. These slight differences are of minor concern when the overall sediment disposal problem is considered.

In summary, the foregoing bioassays showed that toxicity of the inner harbor sediment was related primarily to its hydrogen sulfide content. Complete mortality occurred in a few minutes at a 1% or greater concentration of inner harbor sediment when average initial hydrogen sulfide concentrations were 2.3 ppm or greater (TABLE 7). Fish were distressed at concentrations between 0.1 and 1.0% sediment where initial hydrogen sulfide concentrations were greater than 0.3 but less than 2.3 ppm. It appeared that a 0.1% sediment concentration was the incipient level for visible evidence of distress of sockeye smolts. However, it was suggested that respiration was being depressed even at 0.1 and 0.05% sediment (FIGURE 7), although further work would be required to verify this. Once hydrogen sulfide was removed, distress and toxicity appeared related to clogging of gills by suspended fibers at concentrations over 1% sediment. It is likely that fiber acts to compound the respiratory problems created by hydrogen sulfide when both are present together.

TABLE 7 - Summary of toxic effect and hydrogen sulfide content of various concentrations of inner harbor sediment.

Sediment Concentration % by Volume	Average Initial Hydrogen Sulfide ppm	Toxic Effects
10	-	Mortality in approximately 5 min.
2	4.1	Mortality in approximately 15 min.
1	2.3	Mortality in approximately 20-25 min.
0.75	-	Possible mortality.
0.50	1.1	Distress - coughing - frenzied swimming.
0.25	-	Distress - coughing - frenzied swimming.
0.10	0.3	Possible distress.
0.05	0.1	No visible distress.

Outer Harbor Sediment

The April 3 sample of sediment from the outer harbor was bioassayed after 11 days storage at a 2% concentration and found non-toxic in a 24-hr bioassay (bioassay E). The next sediment load, collected on May 6, was bioassayed within 8 hr of procurement (bioassay F). There was no evidence of distress among fish introduced into 5, 3, 2 and 1% sediment mixtures although there was some random swimming as though the fish had become disoriented in the turbid water. Hydrogen sulfide was not detected, and thus it was apparent that the sediment exerted no direct toxic effect. However, the 5% sediment mixture exerted a significant oxygen demand, as described earlier (FIGURE 6), causing dissolved oxygen to decline to about 2 ppm in 10 min at which time the fish appeared to lose equilibrium.

Tests to Remove Hydrogen Sulfide From Inner Harbor Sediment

Aeration

It was noted earlier that overnight aeration of 10% and 1% concentrations of inner harbor sediment used in bioassay A removed all evidence of toxicity caused by hydrogen sulfide. The object of the two following tests was to determine how rapidly hydrogen sulfide could be removed from sediment by aeration of aqueous mixtures and by exposure to air.

In the first test, identical 1% sediment mixtures by volume were set up in 3-liter jars at 50°F using the April 3 sample of sediment after 11 days of storage. One mixture was vigorously aerated with compressed air while the other was stirred only initially to suspend and disperse the sediment. Hydrogen sulfide decreased more rapidly in the aerated mixture, being virtually eliminated in 50 min (FIGURE 9), while the non-aerated mixture retained more than half its original hydrogen sulfide concentration. Initial hydrogen sulfide concentrations were less than those measured at a 1% concentration in bioassays C and D, probably because only a small amount of the initial load of sediment remained to retain hydrogen sulfide by the 11th day when the aeration test was performed. However, based upon the summary of toxic effects shown in TABLE 7, it appears that toxicity of the aerated 1% mixture would be eliminated

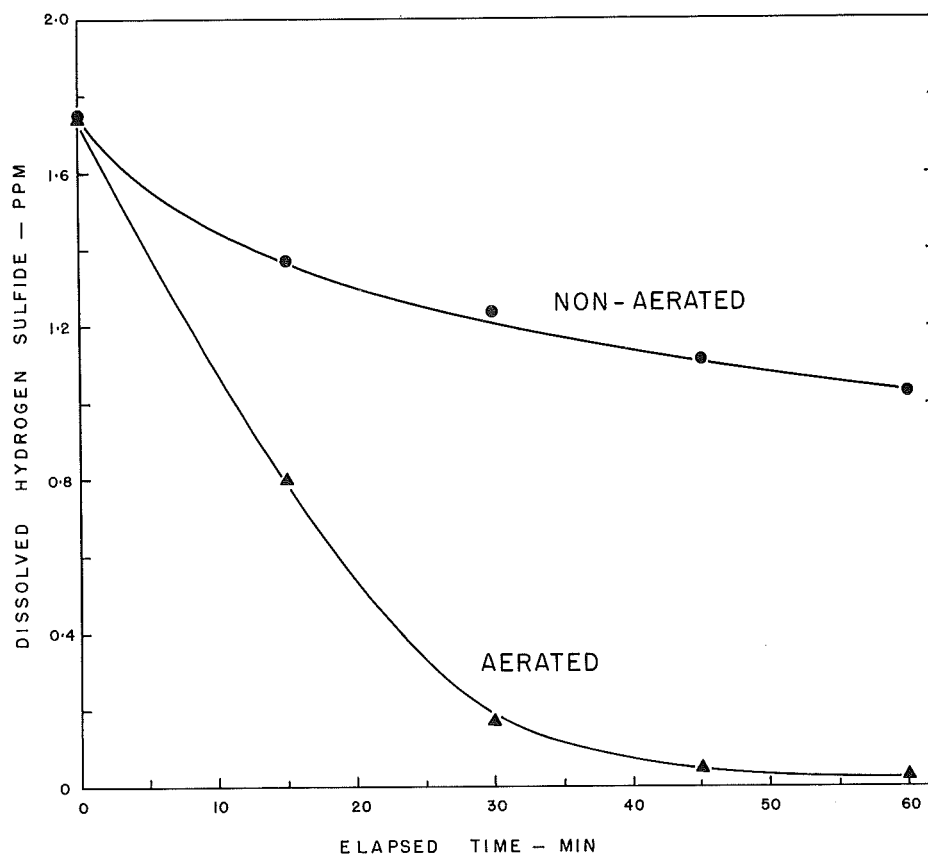


FIGURE 9 - Hydrogen sulfide content of aerated and non-aerated 1% concentrations of inner harbor sediment.

within about 30 min. The non-aerated mixture contained about 1 ppm hydrogen sulfide after 1 hr and would have still created some degree of toxicity.

Comparison of hydrogen sulfide in the non-aerated, unstirred 1% mixture with that in a stirred 2% mixture shows that continuous mixing was instrumental in decreasing hydrogen sulfide (FIGURES 9 and 5). The static sample of 1% sediment contained 1 ppm hydrogen sulfide after 60 min, compared with about 0.1 ppm in a stirred sample of 2% sediment. Thus increasing the opportunity for oxygen contact by mixing resulted in dissipation of hydrogen sulfide and is of interest when disposal is considered.

Since vigorous aeration of a sediment mixture successfully removed hydrogen sulfide, a second test was performed to determine whether exposure of sediment to the atmosphere might also dissipate hydrogen sulfide. Accordingly, a 1-in. thick layer of inner harbor sediment was spread in a tray outdoors, and samples of the sediment were taken at intervals, made into a 1% mixture by volume with sea water at 50°F, and the hydrogen sulfide measured.

The initial hydrogen sulfide concentration was 3.28 ppm but after 1 hr exposure this value was reduced by about 45% (TABLE 8). Approximately 51% of the hydrogen sulfide was lost in 5 hr of exposure and 90% in 24 hr. The low rate at which hydrogen sulfide was lost from a 1-in. layer of sediment suggests that it was being produced continuously by bacteria. Temperature of the sediment would influence the rate of hydrogen sulfide production, the greater production occurring as temperature increased. Hence, the increase in temperature from 45°F to 62°F noted in TABLE 8 would have played a role in maintaining a significant hydrogen sulfide content in the sediment.

TABLE 8 - Hydrogen sulfide content of inner harbor sediment following exposure to the atmosphere.

Time of Exposure hr	Temperature of Sediment °F	Hydrogen Sulfide* ppm	Reduction %
0	45	3.28	0
1	--	1.81	45
2	--	1.86	43
4	59	1.55	53
5	57	1.60	51
7	55	0.98	70
24	54	0.29	90
28	62	0.32	90

* Measured in a 1% sediment concentration by volume in sea water.

The situation studied herein does not duplicate that expected if sediment were piled on a barge for removal and dumping, but some application of the experimental results appears reasonable. Since atmospheric contact for 5 hr reduced the hydrogen sulfide content of a 1-in. layer of sediment by less than 50%, sediment piled several feet deep on a barge would probably lose very little hydrogen sulfide before it was dumped. In fact on a warm day, solar heating of sediment on a barge could conceivably increase the hydrogen sulfide concentration owing to more vigorous bacterial metabolism.

Washing and Resettling

When sediment is dumped in sea water it is with the intention that it will settle to the bottom. Washing will occur as the sediment settles and it was questioned whether this might eliminate subsequent hydrogen sulfide production. If a 300 cu yd barge load of sediment were dumped at the proposed location in 47 fathoms of water it would be washed at the rate of about 40 to 1 if it descended vertically. This is a minimum value, and mixing created by tidal currents could increase the degree of washing. However, in order to assess the possible effects of mixing, a 40 to 1 washing ratio was evaluated.

Sediment from the inner harbor was washed at a ratio of 40 to 1 in sea water at 50°F, allowed to settle and the sea water discarded. Washed sediment was then added to a depth of 1.5 in. in a 1-liter graduated cylinder and to 3.0 in. depth in another. Fresh, aerated seawater was added so as not to mix the sediment and it was allowed to stand for 48 hr at 45°F. This temperature was considered a realistic estimate of that occurring on the bottom off Carter Point. Samples of supernatant were drawn from mid-depth for hydrogen sulfide and oxygen analyses and compared with a control cylinder containing only sea water.

Significant amounts of hydrogen sulfide were found in the cylinders containing sediment (TABLE 9). Furthermore, dissolved oxygen was nil in one cylinder and 2.4 ppm in the other, indicating a significant oxygen demand exerted by the sediment. Dissolved oxygen remained at 9.4 ppm in the control and hydrogen sulfide was not detected. Thus it was evident that washing during dumping would not preclude synthesis of hydrogen sulfide once the

TABLE 9 - Hydrogen sulfide and dissolved oxygen content of sea water overlying washed sediment for 48 hr.

Sediment Depth in.	Hydrogen Sulfide ppm	Dissolved Oxygen ppm
3.0	0.55	0.0
1.5	0.25	2.4
0.0	0.00	9.4

sediment resettled on the bottom. The result was not unexpected since the fiber itself is undergoing decay and would not be altered by washing.

DISCUSSION

The results have shown that four factors should be considered if disposal of sediment in sea water is contemplated: (1) turbidity created during sediment disposal, (2) oxygen demand of the sediment, (3) toxicity due to hydrogen sulfide released during disposal, and (4) generation of hydrogen sulfide by sediment after it resettles. The first three factors are of direct concern to pink and sockeye fisheries while the fourth concerns bottom fisheries such as sole and crabs. All four factors are of importance insofar as disposal of inner harbor sediment is concerned, but only turbidity and oxygen demand are of importance when outer harbor sediment is considered.

The proposed disposal area for sediment is one which would affect adult Fraser River sockeye and pink salmon and possibly juvenile Fraser pink salmon, as well as local stocks of salmon and other fish. Toxicity of sediment was measured using sockeye smolts since adult fish were not obtainable, but it seems reasonable to apply the results to adult sockeye and pink salmon, bearing in mind that a safety factor should be assigned to waste disposal projects to allow for variation in tolerance because of size, species and unforeseen environmental factors.

Inner Harbor Sediment

Inner harbor sediments were found to cause considerable turbidity and had a high oxygen demand. However, the major hazard to fish was toxicity created by

hydrogen sulfide which dissolved as the sediment was mixed with sea water. Hydrogen sulfide is formed in an anaerobic environment from the activity of specialized bacteria (genus Desulfovibrio) which convert sulfate to hydrogen sulfide as they metabolize organic matter (Stanier, Doudoroff and Adelberg, 1957). In this instance, sulfate was supplied by sea water and the organic matter by the fiber deposits. Hydrogen sulfide is a respiratory depressant, similar to cyanide, and at lethal concentrations reacts quickly to arrest respiratory functions (Jones, 1964). Thus the sediment was responsible for imposing the additive stresses of reduced oxygen supply, owing to its oxygen demand, and depressed respiration caused by hydrogen sulfide.

The maximum concentration of hydrogen sulfide at which salmon or trout would survive has been reported as varying between 0.3 and 1.0 ppm (McKee and Wolf, 1963). The results obtained herein fall within this range as smolts were highly distressed at 1.0 ppm hydrogen sulfide, but not visibly so at 0.1 ppm. The threshold level for visible distress of sockeye salmon smolts appeared to be around 0.3 ppm, which coincided with a 0.1% concentration of sediment (TABLE 7). Respiration of sockeye smolts may have been depressed at a 0.05% concentration of sediment but this was not confirmed in the present study, therefore the higher concentration of 0.1% was used as the maximum tolerable level in considering disposal requirements.

Experimental studies indicated that toxicity of the inner harbor sediment would decline only slightly during exposure to the atmosphere and therefore the sediment probably would be as toxic when dumped from a barge as when first dredged. This result was to be expected since conditions for hydrogen sulfide production would remain favorable in the barge where the combination of rich organic material (fiber), sulfate (sea water) and bacteria would be maintained. In fact, solar heating could raise the temperature of sediment on a barge, increasing the rate of bacterial metabolism and consequently increasing hydrogen sulfide production and potential toxicity.

The amount of mixing and dispersion which would occur during discharge of sediment from a barge is unknown, however zones of high hydrogen sulfide, low dissolved oxygen and excessive turbidity may occur. Therefore, elimination of potential hazards to fish through adequate dilution during dumping would be necessary. Bioassay results indicated the concentration of inner harbor sediment should not exceed 0.1%. This concentration corresponds to the visible

threshold of distress for salmon, exerts an insignificant oxygen demand and creates a turbid condition which would clarify within approximately 1 hr. Thus if requirements for eliminating stress and toxicity caused by hydrogen sulfide could be satisfied by dispersal and dilution, turbidity and oxygen demand would not be significant factors.

In order to not exceed a 0.1% concentration of sediment, methods must be found to dilute the sediment at a ratio of 1,000 to 1 during disposal. To obtain this dilution, each 300 cu yd barge load of sediment would need to be dispersed in a volume of 300,000 cu yd of sea water (60.6×10^6 gal). There is little knowledge to predict how the sediment would disperse and mix when released from a typical bottom dump barge with a bottom opening 16 ft wide by 65 ft long. However, if the barge could be towed to disperse the sediment evenly in the upper 20 ft of water, creating a 1,000 to 1 dilution, each load would have to be dispersed over a distance of 4.8 mi. In practice, however, the bottom of a barge opens suddenly and cannot be controlled for uniform dispersion of the contents. Consequently, the only practical method of operation is to dump the barge contents at a single site. Thus if the sediment from a single 300 cu yd barge load were mixed in the 47 fathom water column beneath the barge at the disposal site, the concentration of sediment would be about 2.8%; 28 times greater than that considered marginally safe for fishes.

These comparisons serve to illustrate the magnitude of the problem faced in obtaining safe dispersal of the sediment in sea water. Of course, the theoretical sediment concentration of 2.8% may not be reached since some material may sink quickly with little mixing. However, the theoretical concentration which could occur is so much greater than that which is considered minimally safe that a substantial risk to fish and fisheries operations could be associated with dumping.

Inner harbor sediment could also alter the character of the bottom at the disposal site and, after resettling, form a continuing hazard to bottom-dwelling species. As noted earlier, normal marine bottom life was absent from the original collections of inner harbor sediment. If the 62,600 cu yd of inner harbor sediment were redistributed over an area of 1 million sq yd (3,000 ft x 3,000 ft), it would form a deposit about 2.25 in. deep. Results showed a 1.5-in. depth of sediment exerted a significant oxygen demand and continued to produce hydrogen sulfide, a condition which could destroy normal bottom

life. Dispersal of sediment over an area of 10 million sq yd (9,000 ft x 10,000 ft) would form a deposit about 0.25 in. deep which would probably be harmless. But to achieve uniform distribution of sediment over a wide area would require careful planning and further knowledge of mixing and settling of the sediment during dumping. Previous sediment dumping in Bellingham Bay created a shoal opposite Post Point.

Outer Harbor Sediment

Sediment from the outer harbor had two characteristics which are of concern when marine disposal is considered, turbidity and oxygen demand.

Turbidity may divert salmon from their usual migration route. Furthermore, turbid water seriously reduces the efficiency of reef net fishermen who require very clear water in order to see fish entering their nets at a depth of 15 ft. The turbidity of various concentrations of sediment declined sharply to between 40 and 70 ppm during the first 3 hr of settling (FIGURE 4). From that time on, the turbidity declined very slowly and there was little difference in turbidity of mixtures which had initial concentrations of 0.1% to 10% sediment. For example, after 8 hr of settling turbidity ranged between 20 and 50 ppm, a level which would interfere with reef net operations as tidal currents carried the sediment northward, since normal turbidity in the general fishing area averages 2.6 ppm and does not exceed 4 ppm (Kincaid et al., 1954).

A deoxygenated zone may also serve to divert salmon from their normal migration route with serious reductions in catch by commercial fishermen pursuing the fish in their accustomed places. In this regard, oxygen levels less than 6 ppm may be avoided by some coho and chinook salmon (Whitmore, Warren and Doudoroff, 1960) and presumably by sockeye and pink salmon as well. Oxygen demand of the sediment was great enough to lower dissolved oxygen to less than 6 ppm in a matter of minutes, depending upon the concentration of sediment. Thus diversion of salmon during marine disposal of sediment is a distinct possibility.

Furthermore, although most fish, including Pacific salmon, will avoid zones of low oxygen, avoidance is not necessarily complete and some salmon may enter a deoxygenated zone and perish (Whitmore et al., 1960). The oxygen demand of a 5% sediment mixture was great enough to reduce dissolved oxygen to values less

than 2 ppm in about 16 min (FIGURE 6). Such low oxygen levels lead to loss of equilibrium as already seen in bioassay F. Since mixing characteristics during dumping of sediment are unknown, the time **required** for a zone of oxygen-poor water to be reaserrated through mixing with oxygen-rich water is unknown.

The impracticality of dispersing inner harbor sediment to obtain substantial dilutions was discussed earlier and applies to the outer harbor sediment as well. Thus it appears that adequate dilution to eliminate the effects of turbidity and oxygen demand could not be obtained by any practical method of widespread dispersal.

An alternative proposal to dump sediment only on ebbing tides also has certain impractical aspects. The net movement of sea water entering the area from Juan de Fuca Strait is northward through Rosario Strait past Lummi Island; the net outflow leaves via Haro Strait, westward of Rosario Strait (FIGURE 1). Because of this circulation, sediment dumped on an ebb tide would be carried away from Lummi Island initially, but material remaining in suspension would be carried **past** Lummi Island again on the flooding tide. Furthermore, there are only two ebb tides per day which restricts the dumping period considerably and makes the logistics of sediment disposal more complex than could be reasonably regulated or controlled. This is especially true when one considers that there would be about 230 barge loads of sediment from the outer harbor alone.

RECOMMENDATIONS

Inner Harbor Sediment

Sediment from the inner harbor has been shown to be highly toxic and its disposal by dumping would be a hazard to both surface and bottom marine life. There appears to be no practical feasible method of either detoxifying the sediment before dumping, or dispersing it to assure adequate dilution. Hence it is recommended that sediment in the inner harbor not be disposed of in waters south of 48° 40'N or west of 122° 35' (i.e. Bellingham Bay) between March and October to assure safety and normal migration of adult sockeye and adult and juvenile pink salmon of Fraser River origin. From the standpoint of total fisheries protection, it appears ill-advised to dump this sediment in any

area inhabited by fish, crabs, or shellfish.

As noted earlier, this sediment consists of pulp fibers in various stages of decay. When dewatered it is very much like the waste pulp dredged from settling basins or otherwise discarded by pulp mills. Such material has been used successfully for land fill. An odor problem would probably accompany land fill in the initial stages but once the sea water either drained away or was washed away by rain, the sulfate supply would be removed and hydrogen sulfide would no longer be produced. In this regard, pulp fibers have remained on the bottom of treatment plant settling basins without production of hydrogen sulfide since sulfate is in insufficient supply. Thus the odor associated with land disposal of sediment would not be continuous but would exist only during the dredging period.

Outer Harbor Sediment

Sediment from the outer harbor would constitute a threat to adult sockeye and pink salmon fisheries if disposal occurred in the proposed area during the months of June through October. Furthermore, juvenile Fraser River pink salmon might be affected if dumping took place between March and August. Hence it is recommended that sediment disposal not be outside of Bellingham Bay (south of $48^{\circ} 40'N$ or west of $122^{\circ} 35'$) between March and October.

This sediment appears amenable to local disposal in the northern area of Bellingham Bay as it is a naturally occurring bottom material similar to that of the immediate area and was found to support a normal bottom population in this and in other studies (F.W.P.C.A. and W.P.C.C., 1967). Some degree of hazard to fishes from low dissolved oxygen would accompany disposal, caused by the oxygen demand of the sediment. However, a previous study indicated that hydraulic (suction) dredging of a channel in Chesapeake Bay did not cause gross damage to marine life. Although some bottom animals were smothered, other species began repopulation soon after dredging (Flemer et al., 1968). Unfortunately, dissolved oxygen was not measured during the foregoing study.

In the present situation, it appears that a hydraulic dredge could dispose of the sediment in the immediate area of the outer harbor, but outside the shallow water (4 fathoms) used by juvenile bottom fishes. This proposal suggested by the Washington Pollution Control Commission and Washington State

Department of Fisheries could probably be completed with minimal harm. The problem of turbidity would be minimized if the work were done during summer (as suggested by the aforementioned agencies) when Bellingham Bay is already turbid due to discharge of the Nooksack River. Additional turbidity originating from natural sediments could probably be tolerated for the few weeks required for dredging.

CONCLUSIONS

1. Sediments from the inner harbor were found to consist of pulp fibers undergoing decomposition with a consequent production of hydrogen sulfide. When collected, the sediments were devoid of normal marine life. These sediments created turbidity, exerted an oxygen demand and were toxic to sockeye salmon smolts due to a high concentration of hydrogen sulfide. Sediment concentrations greater than 1% were lethal to smolts, and a concentration of 0.1% appeared to be the threshold of visible distress. These sediment concentrations represented initial hydrogen sulfide concentrations of 2.3 and 0.3 ppm, respectively.

2. Air exposure of inner harbor sediment, as might occur during dredging and transport to the disposal site, was not adequate to eliminate hydrogen sulfide. Washing, as might occur during marine disposal and resettling, did not prevent subsequent hydrogen sulfide formation. When dewatered, as can occur during land disposal, the sediment resembled fiber taken from a typical pulp mill sedimentation pond and used for land fill. Dewatered sediment had no offensive odor.

3. Because of the potential danger to Fraser River sockeye and pink salmon it was recommended that sediment from the inner harbor not be dumped outside of the north end of Bellingham Bay during the period from March through October. In the interest of all fisheries, surface and bottom, it was suggested that the sediment be disposed of on land.

4. Sediments from the outer harbor consisted of natural silts, probably of Nooksack River origin, and supported a typical marine bottom life. These sediments exerted a considerable oxygen demand and created turbid mixtures which cleared very slowly.

5. Because oxygen depletion and creation of turbid water during sediment disposal would probably interfere with normal migration patterns of sockeye and pink salmon, and might also cause toxicity, it was recommended that the outer harbor sediment not be dumped outside of the north end of Bellingham Bay during the period from March through October.

6. Alternatively, it was suggested by the Washington State Department of Fisheries and the Water Pollution Control Commission that sediment from the outer harbor be removed by hydraulic dredge and deposited in the local area, but avoiding the shallows used by juvenile bottom fish. It was further suggested that dredging take place during summer when Bellingham Bay is turbid because of Nooksack River discharge.

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