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Influence of Turbidity on Fish Abundance in Western Lake Superior

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INFLUENCE OF TURBIDITY ON FISH ABUNDANCE IN WESTERN LAKE SUPERIOR

by

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FOREWORD

From the standpoint of the area affected and the tonnage of material in the water, turbidity from silt and clay erosion is probably one of the most significant water pollution problems in the United States. Because of the multiple inputs of suspended material producing turbidity from an enormous number of man's activities, the control of turbid water is an extremely expensive and elusive matter. While there is general agreement among biologists that turbid water has adverse effects on aquatic communities, there is little information on which to prove such effects. On the South Shore of Lake Superior in the western end of the lake, there is a band of red clay which erodes as a result of wave action on the shore line and man's activities on the land. This red clay gives an aesthetically displeasing appearance to the otherwise clearwater lake and much public concern has been expressed about it. Various committees and agencies have tried to find solutions to this problem. The high cost of control measures has frustrated the recommendations of such groups.

The study reported here was initiated to see what adverse effects if any the suspended material might have on the aquatic community in order to provide justification for the cost of control measures. While strongly contested by some of the experts, this report proposes a fascinating relationship between turbidity caused by red clay, smelt and the herring population in Lake Superior. Turbudity was thought to favor herring abundance through the input of nutrients to support plankton food supplies and to reduce predation by lake trout which avoid turbid water. After the introduction of smelt into Lake Superior, there seems to be an inverse relationship between the numbers of smelt and the abundance of herring. Evidence has been gathered to suggest that smelt may be more predacious on the young herring in turbid water than in clear water, and that turbidity is now having an adverse effect on the herring population through enhanced smelt predation. While not conclusively proven, such a relationship offers insight into the subtle ways in which turbidity could have a major effect on the species considered most beneficial to man.

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ABSTRACT

This research project was developed to improve understanding of the influence of turbidity on fish populations and the mechanism through which its effects are induced.

Field and laboratory studies emphasized measurement of behavioral response of fish and resulting changes in fish species interrelationships in western Lake Superior. Direct effects of red clay turbidity on survival and growth of larval lake herring (Coregonus artedii) were also measured.

Field measurements demonstrated that light penetration in western Lake Superior is reduced significantly even at very low levels of red clay turbidity. Zooplankton and fish abundance and distribution were influenced by turbidity. Zooplankton abundance and distribution was highest near the surface in red clay plumes. Smelt (Osmerus mordax) move into the upper 12 m of water in response to turbidity where their predation on larval fish increases. Predation by smelt on larval lake herring was identified as a factor contributing to the decline of the formerly abundant western Lake Superior lake herring population and the commercial fishery which depended upon it.

Walleye (Stizostedion vitreum vitreum) and lake trout (Salvelinus namaycush) demonstrated opposite responses to turbidity. Walleye concentrated in turbid water where food availability was apparently greater. Lake trout showed partial avoidance to turbidity in the lake and in laboratory turbidity gradients.

This report was submitted in fulfillment of Grant R-802455 by the University of Wisconsin-Superior, Center for Lake Superior Environmental Studies under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period from 4 May 1973 to 31 October 1976, and work was completed 12 February 1978.

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ACKNOWLEDGMENTS

Mr. James Jonasen assisted in all phases of the field and laboratory work. Ms. Mary Balcer performed the zooplankton work, shared responsibilities for the laboratory studies including data analysis, and developed the graphic illustrations used in this report. Mr. Wayne Schaefer performed the computer analysis of field data. Mr. Douglas Standen assisted in the field sampling and feeding studies. The special performance of these students is gratefully acknowledged.

The project officer, J. Howard McCormick, actively participated in some phases of the field work and took primary responsibility for the laboratory predation studies. I gratefully acknowledge his exceptional effort and continued support throughout the project. Equipment and laboratory space were provided through Mr. Bernard Jones of the EPA Environmental Research Laboratory-Duluth. Robert Drummond, Richard Carlson, and Walter Dawson of the laboratory staff provided valuable technical assistance to the laboratory phases of the study.

INTRODUCTION

The influence of turbidity on fish in lakes has not been critically measured. Field studies on the problem are inadequate and contradictory. Turbidity in Lake Erie has been cited as the cause for both fishery decline (Langlois 1941) and high fish production (Doan 1941, Van Oosten 1945). Studies on post larval stages of many fish species show levels of turbidity greatly exceeding those found in lakes are required to influence survival or growth under controlled laboratory conditions (Cordone and Kelley 1961; Herbert and Merkens 1961). However, because suspended solids generally alter nutrient and light conditions in natural systems, behavioral responses of fish are implied. Effects of turbidity on distribution, feeding or other aspects of behavior may be significant to the success of responding species populations within the community and may indirectly influence nonreactive species by altering relationships with responsive populations.

This study was undertaken to measure the influence of turbidity on distribution, feeding and interrelationships between major fish populations in western Lake Superior and to identify the mechanisms through which effects of turbidity on fish are induced. Western Lake Superior provides an excellent environment for measuring the general effects of low levels of turbidity on fish populations because turbidity varies spatially and temporally in what is generally a stable system with respect to other physical conditions, such as oxygen. Decline of lake herring (*Coregonus artedii*) and increased abundance of rainbow smelt (*Osmerus mordax*) in western Lake Superior has resulted in significant reductions in commercial fish production. Relationships between changes in fish stocks and turbidity were studied to provide information essential to fishery management.

Turbidity in western Lake Superior results primarily from erosion of glacial-lacustrine red clays deposited during an earlier high water stage of the lake. These unconsolidated sediments are most prominent in northern Wisconsin and are thickest at the western end of the lake near Superior, Wisconsin. The sediments occur in a continuous zone from Superior, eastward along 75 km of shoreline to Port Wing, Wisconsin, and cover approximately 3,600 km^2 (Red-Clay Inter-Agency Committee, 1972; Figure 1).

Startz *et al*. (1976) identified major sources of clay and distribution of turbidity using Earth Resources and Technology Satellite (ERTS) images, settling rates and measurements of turbidity in the drainage basin. They found that erosion of shoreline bluffs by storm wave activity is the principal source of turbidity. Approximately 2.3×10^6 metric tons are eroded from the Douglas County shoreline annually. Douglas County includes one-half of the shoreline characterized by exposed clay bluffs. Approximately

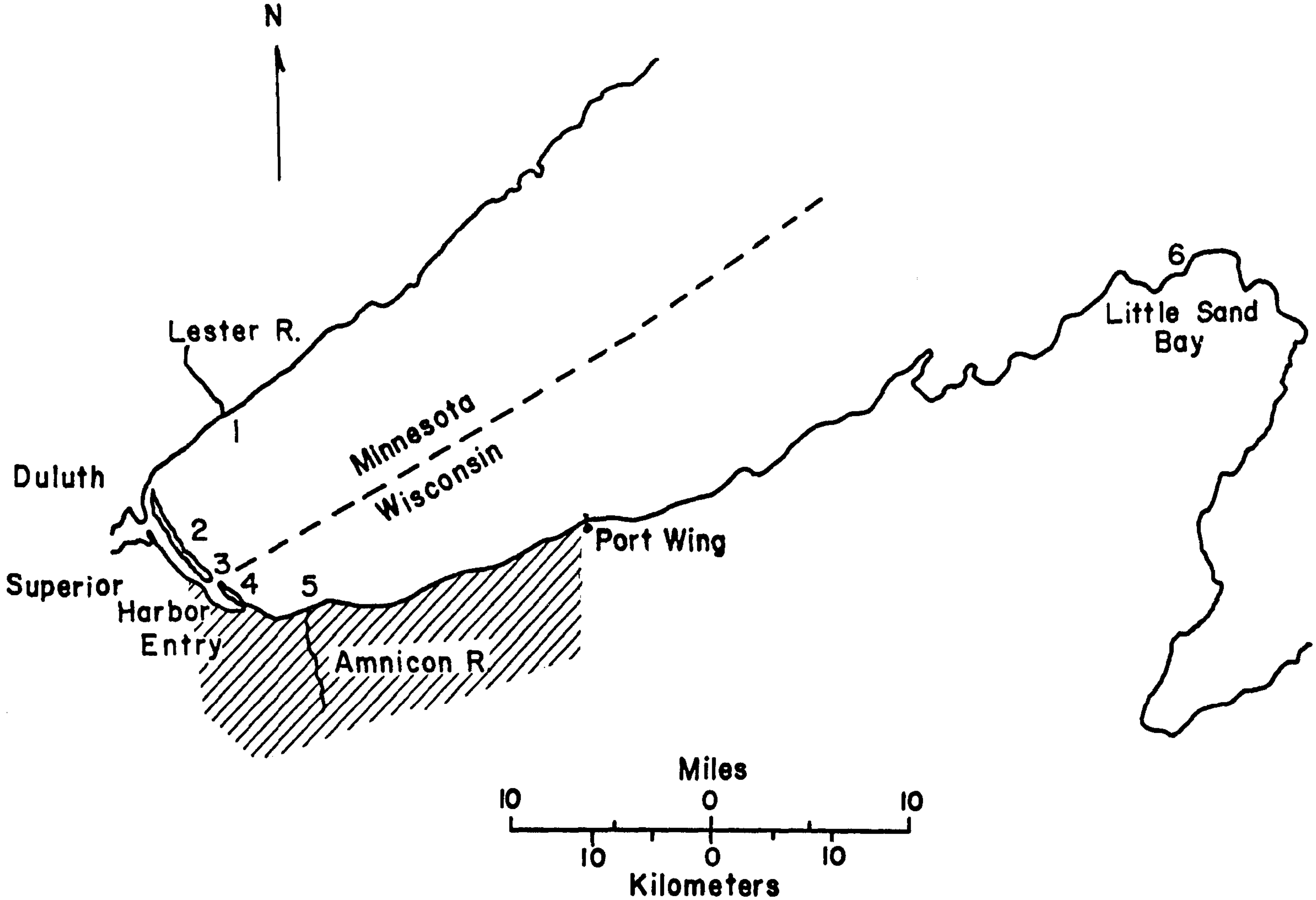

Figure 1. Map of western Lake Superior identifying the red clay soil formation (barred) and field sampling stations (numbered).

5.6×10^5 metric tons are resuspended from the lake bottom, and 3.2×10^5 metric tons are added by stream erosion annually. Average turbidity for the 1972-1975 study period was estimated at less than 1 Formazin Turbidity Unit (FTU) in mid-April (Sydor 1975). Turbidity rose to approximately 5 FTU from mid-April through May in association with ice breakup, then decline slowly through the summer (average of 3.5 FTU). In November and December, turbidity averaged 8 FTU as a result of autumn storms (Sydor 1975). Turbidity was higher in red clay plumes but rarely exceeded 50 FTU except in the nearshore wave surge zone.

Bahnick (1977) estimated that slightly over 300 metric tons of orthophosphate are released annually to Lake Superior water from suspended red clay soils. Red clay was found to contribute 20.7×10^4 metric tons of dissolved solids, 19.7×10^3 metric tons of alkalinity, 14.4×10^3 metric tons of silica, 3.5×10^3 metric tons of potassium and smaller quantities of various metals including iron (64 metric tons), aluminum (76 metric tons), zinc (<8 metric tons) and copper (3 metric tons) (Bahnick 1975).

CONCLUSIONS

Red clay turbidity does not directly influence survival of even the most sensitive life stages of fish in western Lake Superior. Red clay does cause dramatic changes in the quality and intensity of light even at low turbidity levels. Behavioral responses of fish to turbidity and associated changes in light have a major influence on important fish populations.

Lake trout (Salvelinus namaycush) demonstrated some avoidance to turbid water in Lake Superior and in laboratory turbidity gradients in contrast to walleye (Stizostedion vitreum vitreum) which prefer turbid water. Turbidity results in increased walleye production in western Lake Superior by reducing light intensity which directly enhances their feeding success and by causing rainbow smelt to become pelagic, increasing walleye food availability. Walleye fed almost exclusively on smelt in Lake Superior and have been found to require low light intensities and dense pelagic prey populations in order to maintain high food consumption rates (Swenson 1977).

Rainbow smelt apparently became abundant in western Lake Superior during the mid 1940's when commercial fishermen reportedly captured quantities in large mesh gill nets set for other species.[1] Commercial fishing for rainbow smelt was initiated in the early 1950's. During the period of increasing smelt abundance, which commercial catches suggest continued into the late 1950's, the valuable lake herring population underwent a sharp decline. High plankton densities identified by this study and increasing herring growth rates (Lake Superior Herring Subcommittee 1973) suggest that the herring decline did not result from food competition with smelt. However, the results of this study show that juvenile and adult smelt move into the upper 12 m of water under turbid conditions, the zone formerly occupied by larval herring. Cannibalism by pelagic smelt was found to induce high mortality. Smelt were also found to prey on larval herring in the laboratory and in Black Bay, Ontario, where both species are presently abundant. Turbidity apparently contributed indirectly to the decline of lake herring in western Lake Superior when smelt became a part of the community. Effects of turbidity were induced through its influence on the distribution and feeding behavior of smelt.

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[1]Personal communication from Mr. Stanley Sivertson, President, Sivertson Fishery, Duluth, Minnesota, and Mr. George King, Lake Superior Management Coordinator, Wisconsin Department of Natural Resources.

Prior to introduction of smelt, the findings indicate turbidity promoted lake herring production by stimulating high zooplankton densities in near surface waters where larval herring concentrate. If lake trout predation influenced herring survival, low abundance of lake trout in turbid water zones may have been a factor resulting in the former high abundance of herring in western Lake Superior. Addition of smelt to the community induced negative effects which resulted in reduction in the herring stock and significant economic loss to the commercial fishery.

Behavioral response of fish to the reduced light intensity associated with turbidity appears to represent the primary mechanism through which turbidity influences individual species populations, interspecific relationships, fish production and economic value of fish in lakes. This study of Lake Superior stocks shows that the effects of turbidity are dependent upon the fish species complex and that small changes in species composition will greatly alter the influence of turbidity.

RECOMMENDATIONS

Erosion of red clay in western Lake Superior represents a natural phenomenon accelerated by man's activities. Although partial control is technically feasible and is important with respect to several uses of the lake, it would be unrealistic to reduce turbidity to a level which would affect the Lake Superior fish community. Rather, the fish community should be managed directly to minimize the negative impact and maximize the beneficial aspects of the problem. Commercial exploitation of smelt should be stimulated by appropriate management agencies to control smelt population levels, increase economic returns and stimulate increased lake herring abundance. Success of ongoing planting programs to reestablish commercial concentrations of herring might be improved by stocking during periods of low turbidity, by stocking areas of reduced smelt density or by growing herring in the hatchery to a size less vulnerable to smelt predation. Walleye could be managed to reduce survival of young-of-the-year and juvenile smelt which concentrate in the near shore zone.

Smelt were introduced into the Great Lakes with little knowledge of the potential negative effects which have resulted through their interaction with lake herring. Although western Lake Superior herring apparently have adapted to red clay turbidity, this study indicates that smelt reduced the ability of herring to survive in the turbid water zone of western Lake Superior. The results demonstrate the need for strict control measures to curtail future species introductions.

Because turbidity induces significant effects on resource populations through its influence on behavior and species interrelationships, it is recommended that future research go beyond toxicology studies and concentrate on the analysis of behavior and community dynamics.

METHODS

FIELD STUDIES

Western Lake Superior Fish Sampling

Information on western Lake Superior fish populations was collected by bottom trawl, midwater trawl, seine and hydroacoustical techniques from six stations in western Lake Superior (Figure 1). Stations 2 and 4 are characterized by sandy, clay and organic substrates conducive to bottom trawling and were sampled intensively. Sampling zones included 3-5 km parallel to shore and up to 12 km off shore. Stations 1, 5 and 6 to the northeast and southeast respectively (Figure 1) were characterized by rocky bottom inshore which prevented or restricted sampling by bottom trawl. Turbidity is generally higher at Stations 4 and 5 due to erosion of red clay deposits along the shoreline and inflow of turbid waters from the Nemadji River. Stations 1 and 6 are characterized by low turbidity. High variability in turbidity level occurred at Stations 2 through 5 which facilitated measurement of behavioral response of fish.

During 1973 and May-August 1974, trawling was restricted to water less than 15 m deep. During September through November 1974 and June through October 1975-1976, trawling was extended to depths of 40 m. On most sampling days during the May 1973 through August 1974 sampling period, a 3 mm bar mesh bag seine was used to sample the 0.5-1.2 m depth zone (Table 1). Bottom trawling was conducted at depths of 1.8-4.7, 4.8-7.6 and 7.7-15 m with a 7.6 m headrope semiballoon trawl constructed of 18 mm bar mesh with a 6 mm mesh cod liner. Daylight seining and bottom trawling were followed by night trawling with a 6.1 m headrope level trawl constructed of 6 mm mesh with a 691μm cod liner. The smaller net was trawled at the surface and on the bottom in the 1.8-4.7 m depth zone; at the surface, 3 m from the surface and at the bottom in the 4.8-7.6 m depth zone; and at the surface, 3 and 6 m from the surface and on the bottom in the 7.7-15 m depth zone (Table 1).

After August 1974, sampling was conducted primarily during daylight hours at depths exceeding 20 m using a 9.5 m headrope semiballoon trawl constructed of 76 mm stretch mesh with a 6 mm cod liner (Table 1). During most days bottom trawling with the 9.5 m trawl was followed by midwater trawling (6.1 m net) near the surface and at 6, 12 and 18 m from the surface (Table 1).

Bottom trawling with the 6.1 m net was conducted at Station 6 in Little Sand Bay, Apostle Islands 'ational Lakeshore, during June, July and August

TABLE 1. FIELD SAMPLING EFFORT

Month	Year	No. Days	Station No.	Fishing Effort: Seine	Trawl Size: 6.1 m	Trawl Size: 7.6 m	Trawl Size: 9.5 m	Plankton Samples
May	1973	2	4-5	8	--	3	--	--
	1975	1	4	--	--	--	1	--
	1976	5	2-4	--	--	16	7	49
June	1973	7	2-4	18	68	18	--	41
	1974	7	1-2-4-5	10	48	14	--	48
	1975	5	1-2-4-6	4	31	--	22	--
	1976	5	2-4	--	9	--	11	--
July	1973	7	2-4	16	46	17	--	37
	1974	11	1-2-4-5	10	53	15	--	53
	1975	12	2-4-6	4	39	--	33	--
	1976	6	1-2-4	--	16	--	7	--
Aug.	1973	8	1-2-4	12	57	28	--	57
	1974	5	1-2-4-5	8	38	9	--	38
	1975	4	2-4-6	2	27	--	6	--
	1976	3	4	--	6	--	6	--
Sept.	1973	7	2-4-5	12	44	21	--	44
	1974	5	1-2-4-5	2	38	9	--	38
	1975	1	4	--	7	--	2	--
	1976	--	--	--	--	--	--	--
Oct.	1973	8	2-4	16	53	18	--	54
	1974	6	2-4-5	2	16	--	15	16
	1975	3	2-4	--	--	--	2	30
	1976	1	4	--	--	--	4	--
Nov.	1974	2	4	1	--	4	--	--
Totals		121		125	596	172	116	505

1975.[2] A total of 20 standard hauls were made during 3 days at depths of 1.8-4.7, 4.8-7.6 and 7.7-15 m.

Standard 10 min tows of the 7.6 m bottom trawl averaged 0.77 km and filtered an estimated 3,428 m^3. Ten minute tows of the 9.5 m trawl averaged 0.68 km and filtered an estimated 3,800 m^3 volume. Standard 10 min tows with the 6.1 m trawl averaged 0.81 km and filtered an estimated 1,800 m^3. Trawling distance and speed were measured for each haul by a meter mounted in a tow (Figure 2). Estimates of water volumes were derived from the distance measurements and SCUBA diver measurements of trawl openings.

Fish were counted in the field. Separate counts were made of adult and immature individuals of most species. Representative samples of smelt, walleye, burbot (Lota lota) and lake trout were measured in the field. Scale and stomach samples of larger individuals were collected for analysis in the laboratory. Stomach samples and whole fish were preserved in 10% formalin.

Length frequency distribution and age determination from scales were used in estimating abundance of Age 0, I, II and older smelt in trawl catches. Smelt scales mounted in a drop of water were magnified 30X and aged following the criteria for annulus identification of McKenzie (1958) and Bailey (1964). Stomachs from 858 smelt and 269 walleye were analyzed in describing their diets. Invertebrates and fish found in the stomach samples were identified using keys by Brooks (1957), Eddy and Hodson (1961) and Edmondson (1959) and by comparison to larval fish and plankton samples collected from the lake.

Midwater trawling was conducted at night to reduce net avoidance. Occurrence of older smelt in midwater trawl catches suggests the gear was partially successful in sampling larger fish. Although it is probable that some escapement occurred even at night, it was assumed that escapement at night was independent of turbidity and catch data could be used as unbiased estimates of changes in relative abundance at a location. Catch data were analyzed by regression analysis. Catch per 100 m^3 or the percentage of the total catch taken at each sampling location in a vertical column or horizontal stratum were considered the dependent variable in regression models in which turbidity and temperature at the location were independent variables.

Influence of turbidity on fish distribution during daylight hours was interpreted from bottom trawl catches and analysis of chart recordings from a Raytheon Model DE 731 fathometer. Fathometer chart records were made in association with bottom trawling and during selected dates by traveling known distances through and adjacent to red clay plumes. Temperature and turbidity observations were recorded with the chart records. The number of

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[2]Sampling in Little Sand Bay was supported by National Park Service Contract CX2000-5-0034.

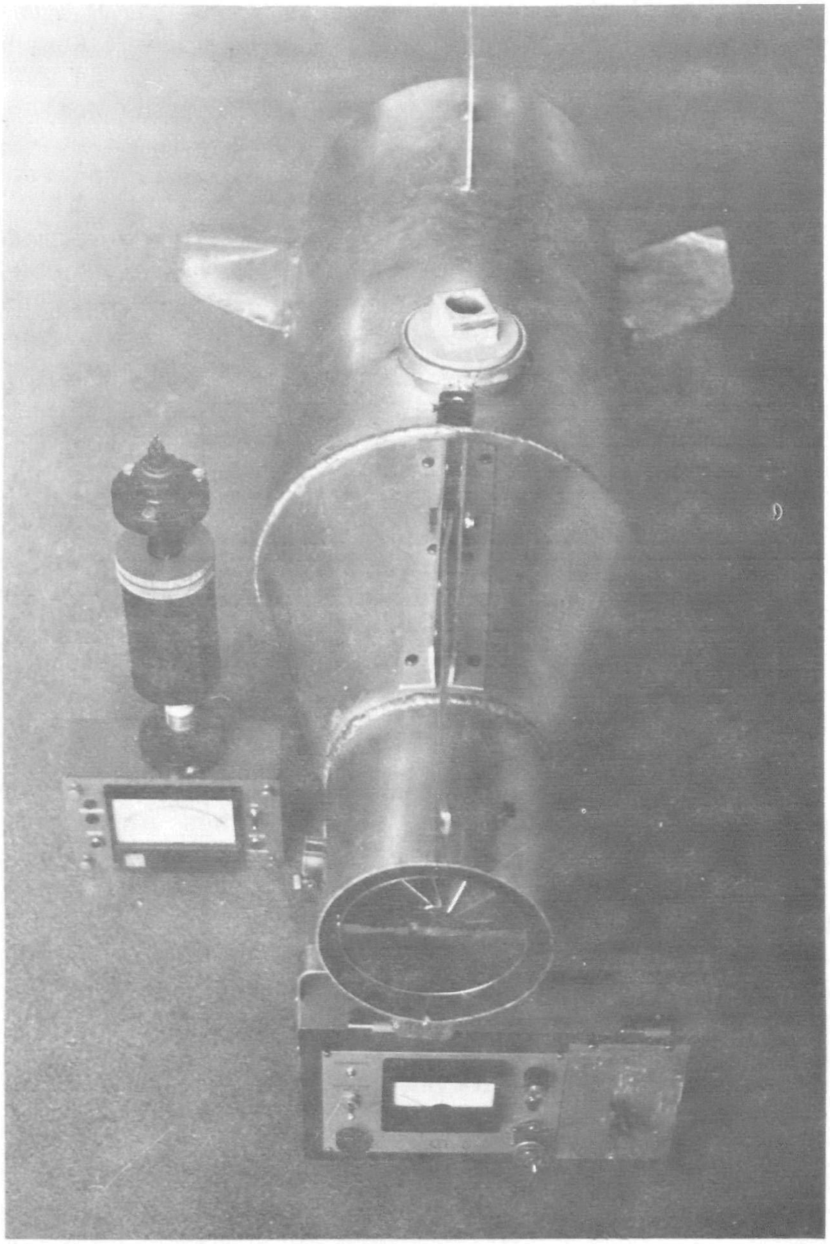

Figure 2. Probe tow with distance meter mounted forward. The tow and transmissometer probe are resting upon the Hydro-Products Model 410 Br transmissometer and Yellow Springs Instrument Model 43 temperature system used in the study.

"fish targets" recorded by the instrument per 1.5 min interval were counted and averaged by 3 m depth intervals. Counts were made for 3-6 m, 6.1-9.1 m, 9.2-12.2 m and the average 3 m for all depths exceeding 12.2 m but at least 2 m from the lake bottom. The percentage of the total number of "fish targets" occurring in each stratum was calculated and made the dependent variable in regression models in which turbidity was the independent variable.

Analysis of Catch Records

Variation in gill net catches obtained during 1973-1974 by the Wisconsin Department of Natural Resources was used with trawl catches from this study in defining relationships between turbidity and fish abundance. Gill nets 10.97 m long, consisting of 7 equal length sections of mesh graduated from 38 to 178 mm, stretch measured, were fished for approximately 20 h at 15 western Lake Superior stations (King and Swanson 1974). Gill net stations were classified as shallow turbid, shallow clear, deep turbid or deep clear from secchi disc readings and sampling depth measurements made during setting or lifting. Classification was also assigned according to station location in relation to the zone of red clay erosion and turbidity. Two shallow water turbid and two deep water turbid stations located west of Port Wing, Wisconsin, were compared with catches from four shallow clear water stations and seven deep clear water stations located east of Port Wing.

Commercial catch records for Minnesota District M-1 (Smith et al. 1961) were analyzed to identify the influence of turbidity in spawning streams and in Lake Superior on abundance of smelt. Percentage deviation in mean catch per unit of fishing effort (Hile 1962) by the Minnesota pound net fishery, during the periods 1952 through 1976 and 1957 through 1976, were used as indices of smelt abundance. Data for 1972 were omitted due to unusual ice conditions which interferred with smelt spawning and influenced fishing success in the harbor.

Precipitation and wind records from the Duluth, Minnesota, weather station were used to develop an index of relative turbidity. Percentage deviation from mean January through May precipitation during the period 1949 through 1972 was used as an index of turbidity in spawning streams. Based on Sydor (1975), indices of turbidity during May through July and May through September were developed by counting the number of storm days occurring each month. Storm days were defined as any day, occurring in a sequence of at least three consecutive days, in which the fastest mile of wind exceeded 15 mph and was from the north, northeast or east. Deviations from the average number of storm days for the 1949 through 1972 period were used as the index of relative turbidity in the lake each year.

Correlation analysis was used to measure relationships between the smelt abundance index and lake or stream turbidity indices three or four years earlier. The approach is based on the assumptions that year-class strength is determined during the first year of life, that a single factor is significant in controlling year-class success and that catch is dependent on smelt starting their third (Age II) or fourth (Age III) summer of life.

Black Bay, Ontario, Fish Sampling

Smelt and larval herring were collected from Black Bay during May 4 and 5, 1973. Although Black Bay represents a clear water environment, smelt and lake herring are abundant and sampling in the bay provided an opportunity to identify whether smelt predation will occur if herring larvae are available. Samples were collected approximately one-third of the way up the bay from the main lake and 1.6 km off shore in an area identified by local commercial fishermen as an important herring spawning ground. Herring larvae were collected in 5 tows with 1/2 and 1 m diameter larval nets with 530μm and 750μm mesh. Depth of sampling was determined by warp length and angle. Smelt were collected during daylight hours with 5 tows of a 5 m headrope, 25 mm stretch mesh otter trawl. Night samples were collected with two 15 x 2.7 m, 13 and 16 mm stretch mesh gill nets set at depths of approximately 12 to 18 m. Gill nets were set overnight for 15 h, picked and reset for 6 h during the day. Larval lake herring were identified from characteristics described by Fish (1932).

Sampling on Black Bay was not continued after 1973 because the U.S. Bureau of Sport Fisheries and Wildlife and the Ontario Ministry of Natural Resources initiated a research program to measure smelt and herring interactions in Black Bay during 1974.

Zooplankton Sampling

Zooplankton distribution was studied to identify the influence of turbidity on food availability. Samples were collected using a 16 liter Kemmerer bottle constructed of PVC with transparent end caps. During 1973 and 1974, zooplankton were collected immediately after most midwater trawls at the trawling depth. During autumn 1974, Stations 1, 2, 3, 4 and 6 were sampled allowing comparison of abundance levels over a broad area. During 1975, plankton were collected in clear and turbid areas within and adjacent to distinct red clay plumes at Stations 1, 2 and 3 (Figure 1). Zooplankton were collected on October 10 and 16, 1975, at the surface, 6.1, 12.2 and 18 m from the surface in water 20-25 m deep.

To determine if zooplankton could avoid the decending sampler in clear water, comparisons were made between 30 paired samples. One member of each pair was collected by lowering the Kemmerer directly to the desired depth. The other pair member was obtained by lowering the sampler below the sampling depth and then raising it to the collection depth. Comparisons were also made between 30 paired samples collected by the Kemmerer bottle and by a 25 liter Schindler sampler (Schindler 1969) constructed from clear PVC.

Samples were reduced to 200 ml by filtering through a 50μm screen and preserved in 5-10% formalin. Further concentration was performed in the laboratory prior to examination in a Sedgewick-Rafter cell at 50 to 100 X.

Complete counts were made, except on samples collected during 1973 when high concentration required splitting. Two subsamples, each equaling 25% of the total sample, were removed by pipette after agitation and counted. Identification was made using keys by Brooks (1957), Eddy and Hodson (1961) and Edmondson (1959). Density is estimated as number/m^3.

Depth, Temperature, Turbidity and Light Measurements

Bottom depth was measured and recorded by fathometer (Raytheon Model DE-731). Cable length and wire angle were measured to estimate depth of the midwater trawl and probe tow. Accuracy of depth estimates for the upper 6 m was verified to within 0.5 m by a SCUBA diver's capillary depth gauge. A Vexilar Model 510 fathometer, mounted in a second vessel, was used to verify estimated sampling depth of the trawl at 12 and 18 m.

Turbidity and temperature were monitored during or after each trawl or plankton sample by probes carried in the tow. Measurements were made at the sampling depth for midwater trawls or within 2 m of the bottom for bottom hauls in water under 13 m. Resistance on the wires leading from the probes to the deck monitors prohibited lowering the tow beyond 13 m during trawling. Temperature and turbidity were therefore measured after each trawl by lowering the tow to the trawling depth. During trawls at depths exceeding 13 m the tow was pulled at various depths (0.5–10 m) to provide measurements of distance and the depth and density of near-surface red clay turbidity plumes.

Water temperature was measured by a Yellow Springs Model 43 telethermometer or Rustrak Model 2133 recording telethermometer. Turbidity was defined from measurements of percentage light transmittance over a 10 cm path using a Hydro-Products Model 410 Br Transmissometer. Light transmittance (T) readings less than 90% were converted to Formazin Turbidity Units (FTU; American Public Health Association 1971) using the relationship:

$$FTU = 84.5413 + (-1.5894) \quad (T) + (0.0077) \quad (T^2)$$

The relationship was based on 83 paired measurements of the two turbidity indices (Figure 3). Correlation analysis showed 95% of variation in percentage light transmittance and FTU is explained by the relationship. Because estimates of FTU derived for light transmittance readings exceeding 90% were high, a separate relationship for observations between 90 and 100% transmittance was developed and is given by the equation:

$$FTU = 27.7976 - 0.2733 \ (T)$$

A portable Nephelometer, Ecologic Model 104, was used to measure turbidity (FTU).

Twenty-two water samples of known FTU were filtered through 0.45μm filters and weighed to determine their suspended solid concentration (American Public Health Association 1971) in order to identify the relationship between FTU and suspended solid level (ppm) (Figure 3). Correlation analysis

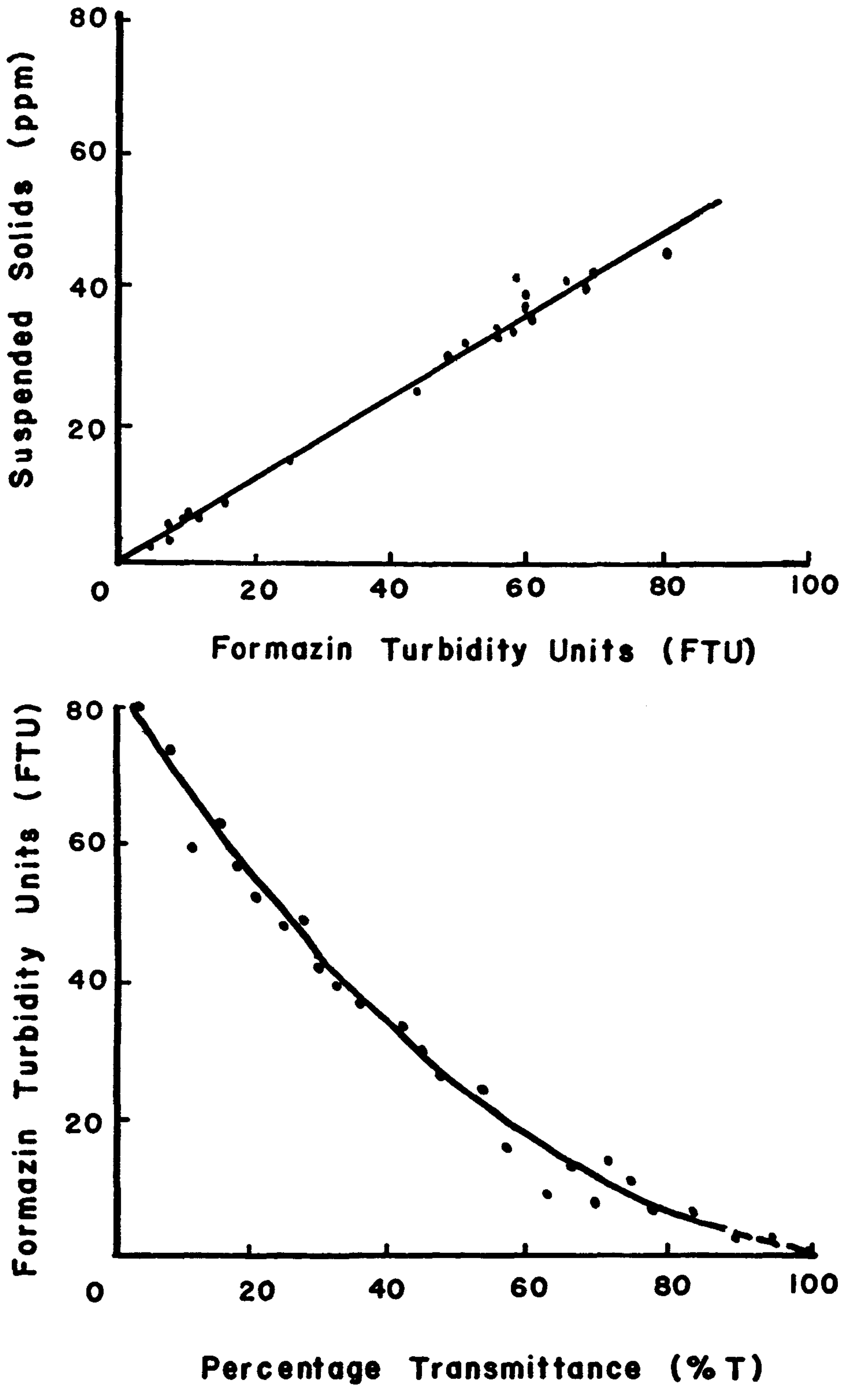

Figure 3. Relationships between percentage light transmittance (T) and Formazin Turbidity Units (FTU), and between Formazin Turbidity Units and suspended solid concentration (ppm).

demonstrated 98% of the variation in suspended solid concentration (ppm) and FTU readings are explained by the relationship:

$$ppm = 0.1552 + 0.6089 (FTU)$$

Surface light intensity (footcandles) was measured with each trawl or seine using a Photovolt Model 200 Photometer. During 1975 and 1976 light intensity profiles were obtained with a Kahl Submarine Photometer (Model 268WA-320) equipped with clear, red, blue and green color filters. The instrument provided measurement of light energy in $\mu w/cm^2/nm$ for clear, red, blue and green wave bands (Appendix Figure 1).

LABORATORY STUDIES

Turbidity Gradients

The responses of walleye and lake trout to laboratory turbidity gradients were studied to define turbidity preference ranges of the two species. Responses to the range of turbidity levels found in western Lake Superior were measured under day and night conditions at the U.S. E.P.A. Environmental Research Laboratory-Duluth.

Two 55 liter (125 x 25 x 19.5 cm) and two 135 liter (152 x 31 x 31 cm) electrode chambers partially partitioned to restrict mixing of water entering each of 4 sections but to insure free movement of fish (Spoor and Drummond 1972; Figure 4) were used in the study. Turbid water was mixed in a 200 liter head tank by spraying water over a clay source (Figure 4). Turbidity was controlled at approximately 50 ±10 FTU by a photoelectric cell and a light located on opposite sides of the tank. Light reaching the sensor at reduced turbidity caused the sensor to activate a pump which sprayed water over the clay source (Figure 4) until light received by the sensor was reduced sufficiently by increased turbidity to cause the photocell to break the circuit. Turbid water flow was directed to a 185 liter constant head mixing tank and then to a 70.4 liter manifold. The mixing tank reduced variation in turbidity caused by cycling of the pump in the source tank. The manifold and a similar structure connected to a clear water source distributed water to the four sections of each gradient chamber through calibrated standpipes and funnels providing proportional dilution and flow control (Figure 4). Flow into each section ranged between 100-300 ml/min for the smaller chambers and 200-500 ml/min in the larger chambers. Turbidity level varied between experiments and ranged between 5-51 FTU within the chambers (Table 2). In order to isolate the influence of preference for a specific area of the chamber from response to turbidity, midway through each experiment the chambers were flushed with clear water and the gradient was reversed. Experiments ran 6-10 days (Table 2).

Lake trout and walleye were captured during the 1974-1975 field sampling program and acclimated in the laboratory until feeding commenced (approximately two weeks) prior to testing. Walleye ranged in size from 126-264 mm TL (12-139 g) and lake trout from 128-275 mm (15-141 g) (Table

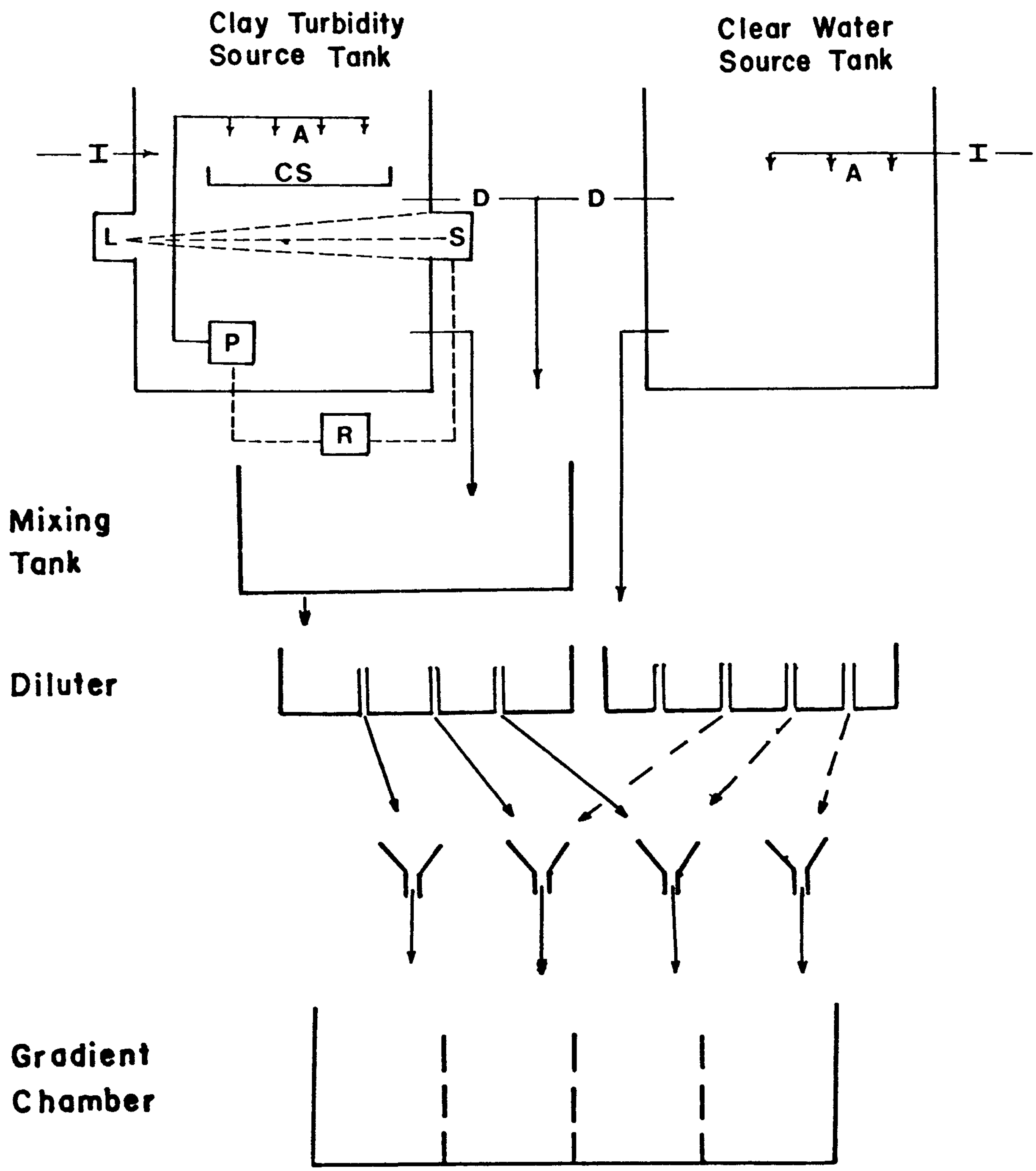

Figure 4. Continuous flow turbidity system. In the clay turbidity source tank, water from the inlet (I) is pumped (P) over a clay source (CS) and aerated (A) when a sensor (S) is activated by light (L). Inflow (I) exceeds outflow to the mixing tank and excess is drained (D). Turbid water from the mixing tank and clear water from a second source tank are directed to diluters and metered by standpipes into gradient chambers.

TABLE 2. LABORATORY GRADIENT TEST SUMMARY

Test Fish		Temp	Turbidity (FTU)		Duration		
Ln	Wt	Range	Avg	Avg	No.	Hours Observ.	
(mm)	(g)	(°C)	Min	Max	Days	Day	Night
			Salvelinus namaycush				
227	95	9.6-10.5	16.4	35.2	6	--	22
155	34	9.6-10.4	8.0	37.0	6	33	40
156	32	9.6-10.3	5.9	37.6	6	26	38
228	96	9.6-10.5	9.4	37.4	6	26	37
177	46	7.9-11.1	8.5	31.5	9	48	--
130	15	7.8-11.0	5.5	34.8	9	21	29
128	15	7.9-11.0	7.5	43.5	9	21	29
151	28	8.8-13.8	12.3	42.5	10	88	69
140	24	8.6-13.8	17.3	44.4	10	76	66
195	44	8.0-13.9	8.0	40.0	10	87	75
275	141	8.0-13.9	13.5	41.2	10	89	75
146	30	7.9- 9.7	10.4	44.7	7	74	54
156	36	7.6- 9.1	14.0	46.8	7	74	54
257	132	7.0- 8.5	14.0	51.4	7	73	54
195	55	7.0- 8.5	18.9	46.0	7	73	54
			Stizostedion vitreum vitreum				
213	73	9.8-11.8	13.8	41.2	8	49	52
242	90	9.5-10.2	13.4	43.6	8	52	61
264	139	9.5-10.2	15.0	46.7	8	54	59
230	82	13.0-15.1	13.0	37.7	8	55	60
249	109	12.8-15.0	12.0	46.0	8	76	45
250	121	12.8-15.0	16.9	42.9	8	84	49
167	31	15.5-20.9	16.3	45.5	9	60	56
197	55	15.2-20.7	12.0	44.7	9	52	50
239	97	15.2-20.7	12.2	43.0	9	71	60
206	58	15.2-20.8	13.4	42.1	9	34	37
142	22	15.0-20.1	12.6	44.4	10	55	44
126	12	15.0-20.1	15.6	44.4	10	59	49
196	50	15.0-20.2	14.7	46.1	10	59	44
194	59	15.0-20.2	15.6	49.7	10	63	44

2). Turbidity and temperature of Lake Superior water entering the gradient chambers were measured twice daily. Lake trout and walleye experiments were conducted at 7.0-13.9 C and 9.5-20.9 C respectively (Table 2). Temperature variation within and among experiments corresponded with changes in Lake Superior. Temperatures usually did not vary within experimental chambers, at any point in time, by more than 1 C. The laboratory lighting system (Drummond and Dawson 1970) simulated a natural diurnal pattern. Light intensity ranged from 37.6-64.6 lux over the chambers throughout most of 13 h photoperiod.

Location of test fish in the gradients was monitored 15 min/h, 24 h a day by physiograph (Narco Model PMP-4 1460 or Gilson Model ICT-5). A pair of electrodes in each of the four chamber sections was connected to a physiograph channel through a rotary switch which switched the physiograph to another chamber every 15 min. The system was sensitive to most activity including movement associated with maintaining station or breathing (finning and opercular movements). Location of fish in the chambers was determined by the channel and associated chart record identifying activity in a chamber section (Spoor and Drummond 1972).

The length of time experimental fish were located in a chamber section was counted for 600 sec periods from each 15 min monitoring period. Periods less than ten seconds were considered to represent movement through a section rather than selection of a location and were not counted. Differences in the time a fish resided in a given chamber section during high and low turbidity periods, caused by reversing the gradient midway through the experiment, were measured. The difference in the time fish resided in a specific chamber section was related to the change in turbidity within the section resulting from gradient reversal to determine effects of turbidity on distribution. Clear water flowed through the chambers at the start, end or midway through the experiment when activity was also monitored. Three fish did not move from the initial chamber section under turbid or clear water conditions. It was concluded that the unusual performance of these fish resulted from failure to acclimate to experimental conditions; therefore, the data were not used in the analysis. Counts were analyzed separately for light and dark phases of the 24 h cycle by regression analysis.

Counts of the number of times fish changed chamber sections during the 600 sec monitoring periods were used to determine day-night activity patterns of walleye and lake trout during clear and turbid water periods. Activity of lake trout was also monitored in 3 liter electrode chambers (Spoor et al. 1971) at four levels of turbidity ranging from 54 to 6 (FTU). Tests using the small chambers were conducted with three fish held at a constant turbidity (FTU) and one control. Activity associated with fin and body movements was monitored at 54, 28, 9 and 6 FTU. The percentages of the monitoring time lake trout were active under turbid water and in the control chamber (0 FTU) were compared. Lake trout were acclimated to the test turbidity for 1.5 to 76 h prior to monitoring. Laboratory conditions were similar to those described for the gradient experiments. Flow rates through the experimental chambers ranged from 100-130 ml/min.

Larval Herring Bioassay

Direct influence of red clay turbidity on survival, growth and distribution of larval herring was measured in the laboratory by holding larvae for 62 days at 9 turbidity levels. The bioassay study was supported primarily through a grant from the University of Wisconsin, Sea Grant College Program, and is described in detail by Swenson and Matson (1976). Partial support was derived from this EPA program. Because the results represent an integral part of the analysis of red clay turbidity on western Lake Superior fish populations, methods and results are outlined in this report.

Turbid water source tanks, clear water source tanks and manifolds (Figure 4) were used to deliver a constant flow of Lake Superior water at 400 ml/min to each of 20, 70.5 liter (61 x 20.3 x 61 cm) test chambers. Eight concentrations ranging from 6 to 46 FTU were run in replicate. Four control chambers were maintained between 0 to 2 FTU. Turbidity levels included in the experiment covered the normal range for western Lake Superior.

A feeding system (Anderson and Smith 1971a) distributed approximately 400 brine shrimp (*Artemia salina*)/h to each chamber 12 h each day. Light from two 15 watt incandescent bulbs located 10 cm above each chamber was passed through translucent fiberglass covers to reduce glare and increase dispersion over the water surface. A constant 13 h photoperiod was maintained throughout the tests. Light intensities averaged 15.3 lux in the upper 10 cm of the water column. Intensity 51 cm below the surface was reduced by 34% in the lowest concentration (1-6 FTU), 48% in intermediate concentrations (12 to 28 FTU) and 53% in the higher concentrations (34 to 46 FTU).

Turbidity and temperature were monitored twice daily. Temperature changes of 3 to 8 C during the study corresponded to similar changes in Lake Superior. Mean daily temperatures between chambers within replicates did not vary by more than 1 C. Weekly measurements of oxygen, pH and conductivity showed pH increased slightly with turbidity. Oxygen was maintained near saturation.

Counts and measurements of herring larvae were made from photographs. Behavioral response was defined from direct counts of larvae in upper, intermediate and lower sections of the chambers (Swenson and Matson 1976).

Predation Studies

Several attempts at maintaining adequate numbers of smelt in the laboratory failed. However, limited information on smelt predation was obtained from two Age I+ smelt, 62 and 80 mm T.L., captured during November 1973. The two young smelt were maintained in a 20 liter aquarium receiving a continuous flow of Lake Superior water and fed brine shrimp at the E.P.A. Enviromental Research Laboratory-Duluth until 29 March 1974 when predation studies were initiated. The studies measured relative preference of the two smelt for brine shrimp, lake herring eggs (embryos) and lake herring larvae. The rates at which lake herring larvae were eaten by smelt under light and dark conditions were also estimated. Information on the rate of gastric digestion at 12.6 C was obtained by sacrificing one smelt 1-3/4 and the other 4 h after feeding.

Estimated rates of gastric digestion from this study and by Foltz (1974) were used with information on the occurrence of young smelt in older smelt stomachs and estimates of smelt density in Lake Superior to determine the importance of smelt cannibalism on survival. Estimates of the number of young smelt consumed daily and monthly were calculated by correcting the percentage occurrence of young smelt in the stomachs of older smelt for the rate of digestion and the average number of young smelt found in smelt stomachs. The corrected percentage occurrence value is an estimate of the percentage of the smelt population (Age II and older) which ate the equivalent of one Age 0 smelt daily. Multiplying the value by the density of Age II and older smelt and by the days in a month gave a gross estimate of the number of young smelt consumed monthly by older members of the population. The number of young smelt consumed monthly by older smelt/100 m^3 and the average density of young smelt (number/100 m^3) were used to estimate the percentage mortality resulting from cannibalism during various sampling months. Food consumption of walleye and the number of smelt consumed daily by walleye/100 m^3 were estimated using the method described by Swenson and Smith (1973).

RESULTS

TURBIDITY AND TEMPERATURE IN WESTERN LAKE SUPERIOR

Turbidity and temperature of near-surface and near-bottom waters in western Lake Superior were monitored during 1973 through 1976. The highest turbidity occurred at Stations 3 and 4 located closest to the red clay source area (Table 3; Figure 1). Monthly averages for Station 4 often exceeded 30 FTU in contrast to Station 1 along the north shore where turbidity did not exceed 7 FTU and Station 2 where monthly average turbidity seldom exceeded 10 FTU except in the wave surge zone (1 m depth).

Measurements at the surface, 3, 6 and 9.1-15 m, made during 16 days of 1973, showed turbidity was highest during June, September and October when temperature averaged less than 11 C (Table 3; Figure 5). Surface and bottom temperature in the 1 to 15 m depth zones averaged above 14 C during July and August when turbidity was usually low (Table 3; Figure 5).

Both turbidity and temperature decreased with distance from shore. Near-surface temperature dropped slowly, but bottom water temperature declined rapidly as depth increased offshore (Table 3). The rate of decline in turbidity was slower in near-bottom than in near-surface waters. At depths exceeding 3 m, turbidity of near-bottom water often exceeded that of water near the surface (Table 3; Figure 5). During 1975 and 1976 a total of 22 temperatures and turbidity profiles were recorded in water exceeding 15 m (Appendix Table 1). Although turbidity was comparatively low due to distance from shore and the mild climatic conditions encountered during 1975 and 1976, turbidity in bottom waters averaged approximately 6 FTU and often exceeded surface water turbidity. Increased turbidity below the surface appears to be caused by settling of suspended solids, resuspension of solids from the lake bottom and sinking of higher density turbid water to levels where increased density associated with the clay load reaches equilibrium with cold high density bottom water. Occurrence of higher turbidity in offshore bottom water suggests red clay turbidity is more extensive spatially and temporally than surface water plumes would indicate.

LIGHT INTENSITY IN WESTERN LAKE SUPERIOR

Turbidity in western Lake Superior significantly reduced light penetration even at every low concentrations. Light profile measurements made during 1975 and 1976 on 21 days (Appendix Table 2) showed the depth of 1% surface incidence was reduced from approximately 16.5 m in clear water

TABLE 3. NEAR SURFACE (S) AND BOTTOM (B) WATER TEMPERATURE AND TURBIDITY
Temperature is °C. Turbidity is FTU (in parenthesis).

Station No.	1	2					4				
Bottom Depth (M)	9-12	1	3	6	9	12+	1	3	6	9	12+
June											
1973-S	--	13(11)	13(8)	12(6)	13(8)	--	13(36)	12(37)	13(27)	12(17)	--
1973-B	--	--	13(10)	11(9)	11(7)	--	--	12(35)	12(29)	11(11)	--
1974-S	5(5)	15(38)	12(11)	12(10)	9(10)	--	19(15)	13(23)	12(20)	13(27)	--
1974-B	--	--	11(9)	8(9)	6(7)	--	--	12(24)	19(14)	9(15)	--
1975-S	--	--	--	--	--	12(7)	--	--	--	--	9(7)
1975-B	12(3)	--	--	--	11(11)	8(9)	--	--	11(19)	11(30)	--
1976-S	--	--	--	--	--	14(2)	--	--	--	--	14(3)
1976-B	--	--	--	11(1)	--	--	--	13(9)	12(6)	--	5(6)
July											
1973-S	--	18(4)	14(5)	14(7)	14(6)	--	18(29)	17(8)	18(13)	17(5)	--
1973-B	--	--	15(5)	12(5)	11(5)	--	--	16(16)	14(29)	13(8)	--
1974-S	12(7)	18(3)	14(3)	13(4)	11(4)	--	17(14)	15(16)	15(14)	15(9)	--
1974-B	--	--	14(3)	9(4)	8(5)	--	--	13(16)	13(12)	12(11)	--
1975-S	--	--	--	--	11(4)	14(5)	19(18)	--	--	15(28)	18(10)
1975-B	--	--	11(8)	8(5)	5(3)	5(6)	--	--	12(9)	9(8)	9(6)
1976-S	17(1)	--	--	--	--	19(1)	--	--	--	19(17)	17(14)
1976-B	16(1)	--	--	--	--	16(1)	--	19(21)	16(6)	14(20)	4(5)
August											
1973-S	16(2)	20(6)	18(5)	18(4)	19(4)	--	20(49)	19(42)	18(7)	19(9)	--
1973-B	--	--	19(4)	17(4)	16(4)	--	--	19(29)	17(16)	16(10)	--

(continued)

TABLE 3. (continued)

Station No.	1	2					4				
Bottom Depth (M)	9-12	1	3	6	9	12+	1	3	6	9	12+
1974-S	12(3)	18(2)	14(5)	16(4)	16(4)	--	18(50)	15(30)	14(19)	14(13)	--
1974-B	--	--	14(3)	11(4)	10(3)	--	--	15(31)	14(32)	10(4)	--
1975-S	--	--	--	18(2)	--	18(2)	--	--	18(2)	--	18(3)
1975-B	--	--	16(5)	--	--	5(4)	--	--	14(7)	--	4(10)
1976-S	--	--	--	--	--	--	--	--	22(5)	19(3)	18(2)
1976-B	--	--	--	--	--	--	--	--	--	--	--
September											
1973-S	--	17(14)	18(9)	18(8)	18(9)	--	16(31)	16(7)	16(8)	16(8)	--
1973-B	--	--	16(7)	15(8)	14(7)	--	--	15(7)	15(7)	15(5)	--
1974-S	--	--	9(4)	9(4)	10(4)	--	12(118)	11(77)	7(40)	4(18)	--
1974-B	7(2)	--	9(3)	10(3)	10(3)	--	--	11(70)	11(60)	8(40)	--
1975-S	--	--	--	--	--	--	--	--	--	--	13(1)
1975-B	--	--	--	--	--	--	--	--	--	--	11(7)
1976-S	--	--	--	--	--	--	--	--	--	--	--
1976-B	--	--	--	--	--	--	--	--	--	--	--
October											
1973-S	--	11(5)	6(5)	6(5)	11(6)	--	11(47)	10(42)	10(38)	10(29)	--
1973-B	--	--	10(4)	10(4)	9(4)	--	--	10(44)	10(43)	10(43)	--
1974-S	--	--	--	--	--	--	8(30)	--	--	--	--
1974-B	--	--	--	8(4)	--	8(4)	--	8(7)	8(5)	--	9(5)
1975-S	--	--	--	--	--	--	--	--	--	--	11(1)
1975-B	--	--	--	--	--	--	--	--	--	--	11(1)
1976-S	--	--	--	--	--	--	--	--	--	--	--
1976-B	--	--	--	--	--	--	--	9(4)	9(5)	--	--

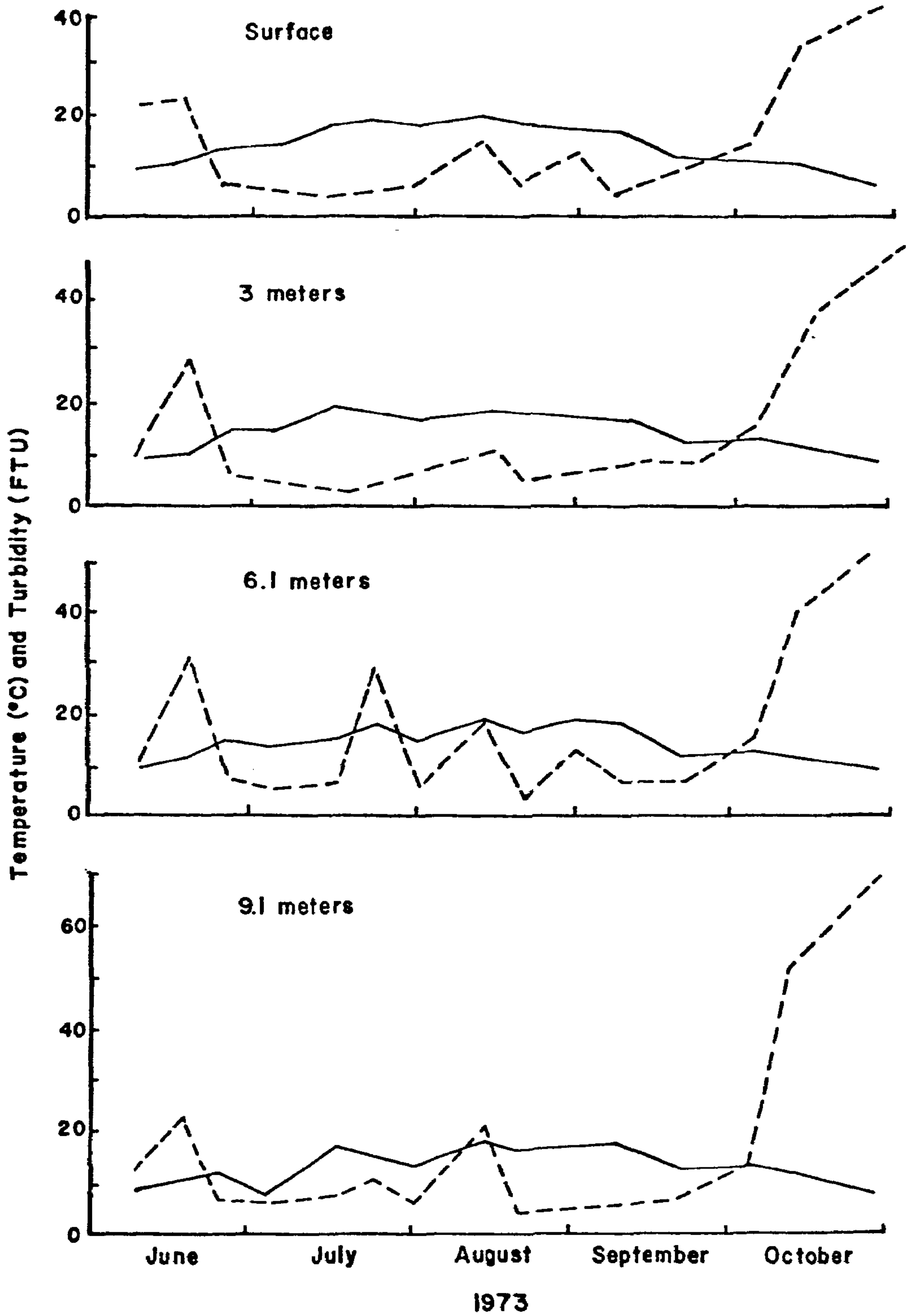

Figure 5. Station 4, turbidity (dashed lines) and temperature (solid lines) during 1973 at the surface, 3, 6.1 and 9.1-15 m in 9.1-15 m water columns.

(0-2 FTU) to an average of 2.5 m in turbid water (10-12 FTU).

Relationships between the $\log_{10}$ of light intensity ($\mu w/cm^2/nm$) and water depth showed the rate of light penetration decreased with increased turbidity (Figure 6). However, the degree of change in the rate of penetration (penetration coefficient) was found to be higher at low turbidities (Figure 7). The rate of penetration is estimated by the equation:

$$PC = a^{-c(ppm)}$$

where

PC = rate of light penetration
ppm = suspended solid concentration in parts per million
a = 0.1968
c = 0.2261

Measurements of penetration by blue (400 to 530 nm) and red (595 to 730 nm) spectra (Appendix Figure 1) made at five red clay concentrations showed rate of penetration was higher for blue light only in clear water. With 0.6 FTU (0.5 ppm) the slopes of least square regression lines defining rate of penetration were +0.743 for blue light and +0.627 for red light (Table 4). At 2.9 FTU (1.8 ppm) rate of penetration of red light exceeded that for blue (Table 4). At 10.7 FTU (7.7 ppm) rate of penetration of blue light was reduced to 10% of clear water, whereas rate of penetration by red light was 41% of clear water. As a result of the high rate of absorbance of shorter wave energy in turbid water, low concentrations of red clay caused a dramatic change in the quality and intensity of light in western Lake Superior.

ZOOPLANKTON ABUNDANCE AND DISTRIBUTION

Plankton densities estimated from samples obtained by lowering the 16 liter Kemmerer bottle were compared with those obtained from samples collected by raising the Kemmerer and with a Schindler sampler. Analysis of variance showed estimates of abundance were not influenced by the sampling procedures ($P > 0.1$).

Species composition and abundance of western Lake Superior zooplankton at Stations 1, 2, 4, 5 and 6 were compared. Comparisons were based on samples collected during September and October 1975, within a 32 day period when temperatures ranged from 6.9-10.8 C. Zooplankton composition was generally similar throughout the western end of the lake although certain species of minor importance with respect to abundance were not found at all sites (Table 5). Rotifers were the dominant group at all sampling sites. Conochilus, Kellicottia, Polyarthra and Keratella were the dominant genera (Table 5). Although composition was similar, the number of organisms differed greatly between locations. Stations 1 and 6, characterized by clear water, had few zooplankton when compared to the other sites. Stations 2 and 4 at the extreme western end of the lake averaged 14,200 more

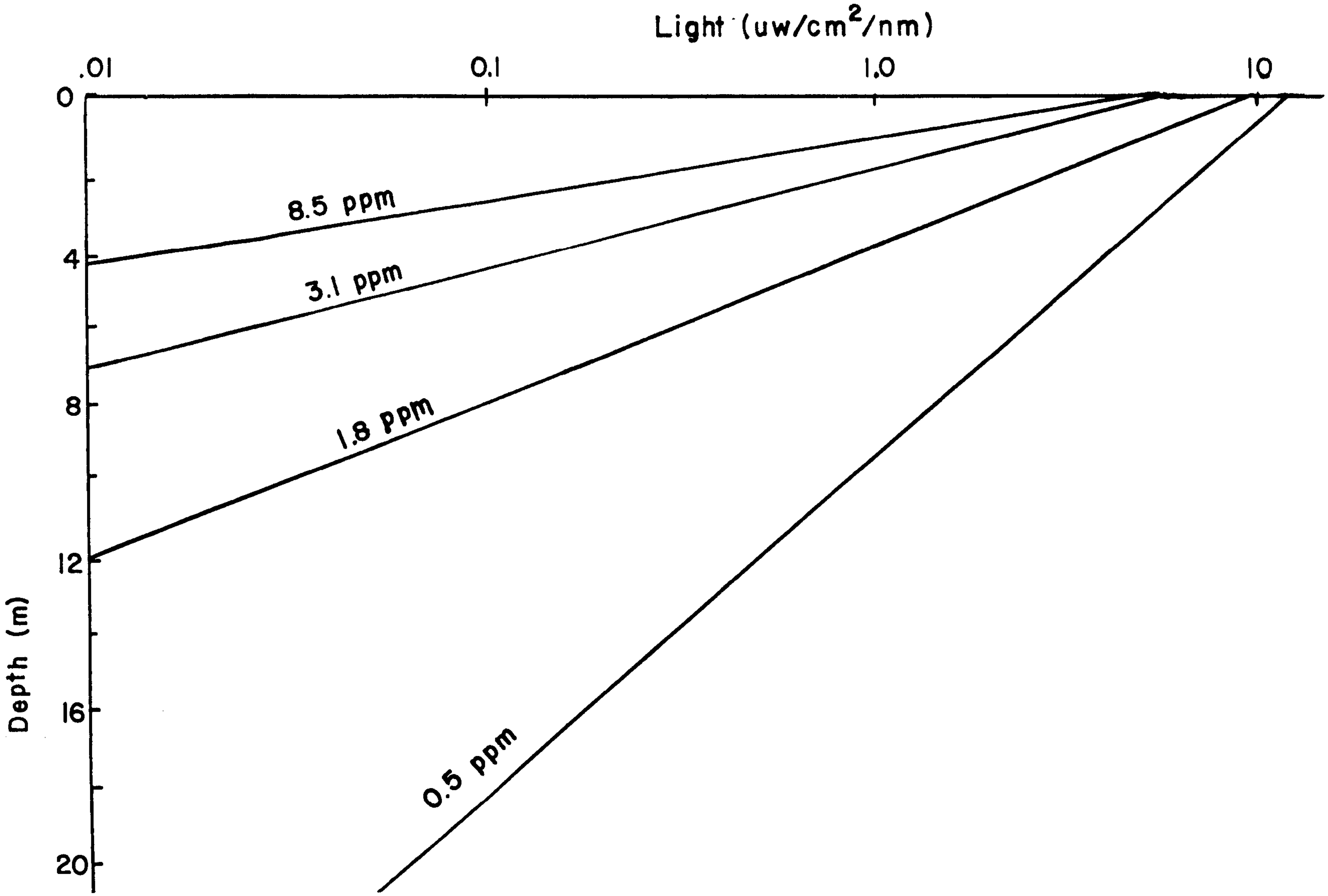

Figure 6. Light penetration in western Lake Superior at different concentrations of red clay turbidity.

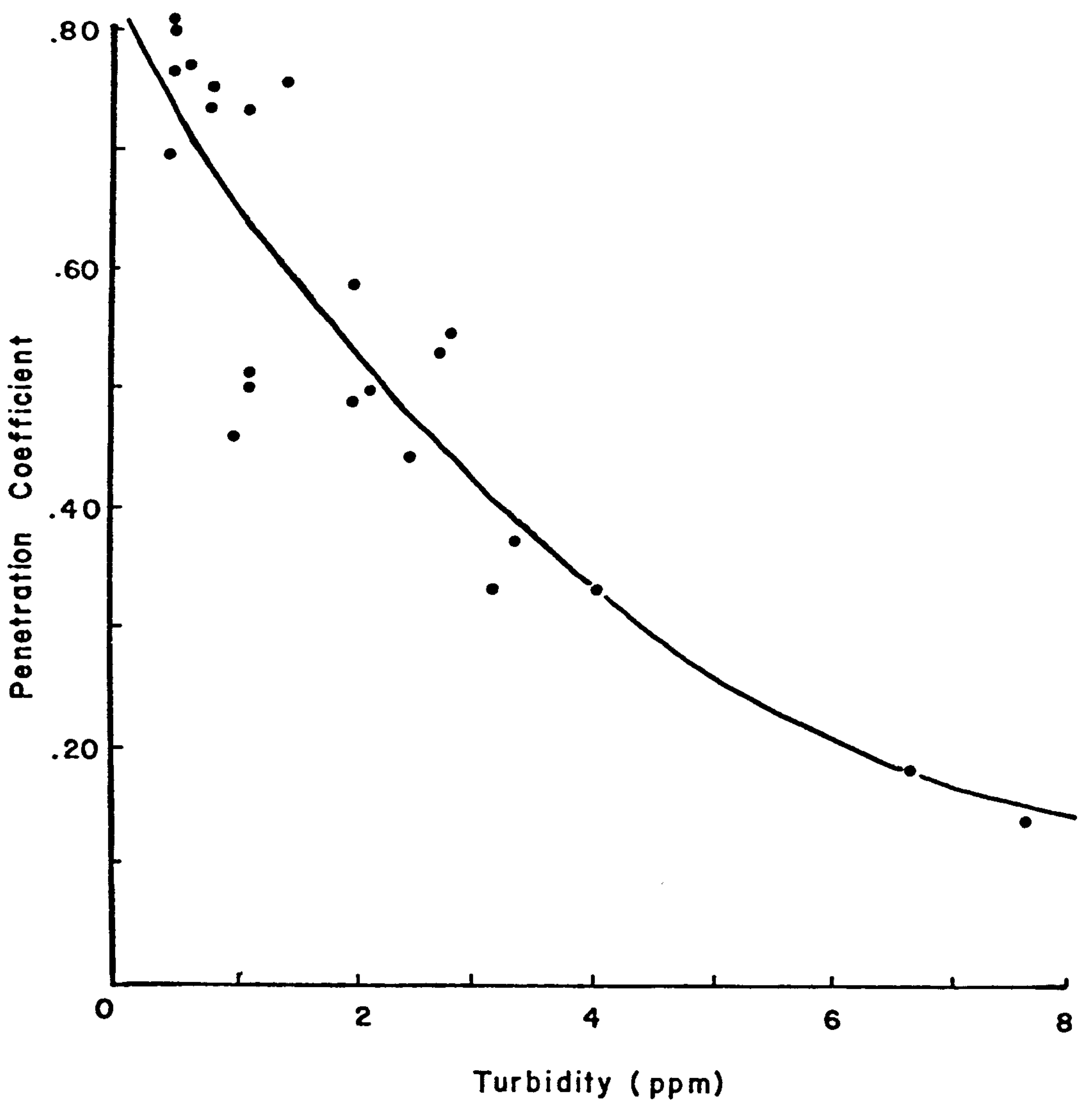

Figure 7. Relationship between change in rate of light penetration and turbidity in western Lake Superior.

TABLE 4. LIGHT PENETRATION AND TURBIDITY RELATIONSHIPS

Regression constants defining relationships between light intensity (Y), ($\mu w/cm^2/nm$) and depth X, (m) for blue and red spectra at five concentrations of red clay turbidity in western Lake Superior. Light intensity is estimated by the equation: $Y = ab^X$.

Turbidity (FTU) (ppm)	Color	Regression Constants: Ordinate Intercept a	Regression Constants: Regr. Coef. b
1.0 (0.5)	Blue	+10.16	+0.743
	Red	+ 4.64	+0.627
2.9 (1.8)	Blue	+12.67	+0.437
	Red	+11.35	+0.454
4.1 (3.1)	Blue	+ 7.81	+0.371
	Red	+ 6.75	+0.432
10.7 (7.7)	Blue	+ 6.23	+0.071
	Red	+ 5.24	+0.255
12.3 (8.5)	Blue	+10.95	0.077
	Red	+18.59	0.213

TABLE 5. ZOOPLANKTON ABUNDANCE AT FIVE STATIONS DURING 1974
Number of zooplankton/m^3 represent averages of four to six samples collected at 3 m intervals from 10 m water columns.

	Sampling Location and Date				
	1 9/16/74	2 9/13/74	4 9/11/74	5 9/26/74	6 10/13/74
Rotifera	2,922	12,687	10,551	11,437	6,042
Conochilus sp.	1,625	6,396	1,125	4,385	1,917
Asplanchna spp.	16	188	238	229	219
Kellicottia longispina	453	3,521	2,825	2,719	2,125
Keratella cochlearis	16	260	1,962	1,865	73
Polyarthra spp.	78	1,833	3,087	1,146	396
Synchaeta spp.	734	489	312	802	1,312
Cladocera	640	3,042	1,787	979	1,458
Bosmina longirostris	312	292	825	312	906
Daphnia galeata mendotae	328	2,625	862	635	438
Daphnia pulex	--	62	62	10	--
Holopedium gibberum	--	31	12	21	62
Leptodora kindtii	--	--	12	--	--
Others	--	--	12	--	52
Adult Copepoda	651	2,375	1,837	1,562	3,146
Cyclops spp.	31	375	525	385	1,906
Diaptomus spp.	406	1,969	1,262	1,156	1,104
Epischura lacustris	--	21	25	10	62
Limnocalanus macrurus	203	10	25	10	31
Others	16	--	--	--	42
Copepoda nauplii	297	2,417	2,800	1,177	2,687
Total Zooplankton	4,516	20,521	16,975	15,156	13,333

zooplankton/m^3 than Station 1 on the north shore, 3,600 more zooplankton/m^3 than Station 5 on the south shore and 5,400 more zooplankton/m^3 than Station 6 located in the Apostle Islands area (Table 5).

Sampling in clear and turbid water zones within Stations 2 and 3 (October 10, 1975) and at Station 4 (October 16, 1975) showed the greatest zooplankton densities occur in turbid water (Table 6; Figure 8). A significant positive relationship between zooplankton density and turbidity was identified for all major groups except Copepoda (Table 7).

A significant increase in zooplankton in surface waters (0.1-1.0 m) at higher turbidities was demonstrated by relationships between the percentage of zooplankton in surface samples and turbidity. Percentage in surface water was calculated from the total number of zooplankton found in all samples in the water column and the number in surface samples. Rotifers and Cladocerans showed the greatest increases in surface waters at higher turbidities (Table 7). Surface abundance of zooplankton and light intensity in surface water were negatively correlated (Table 7). The correlation was the strongest for rotifers.

During both 1973 and 1974, zooplankton densities were usually higher at Station 2 having lower average turbidity than Station 4 characterized by higher turbidity. Differences appeared to result from higher densities of rotifers at Station 2 (Table 8). Variation between Stations 2 and 4 fails to support a conclusion that zooplankton densities are directly influenced by turbidity. The zooplankton studies did show that the highest food availability for plankton feeding larval fish occurs at the extreme west end of the lake (Stations 2, 3, 4 and 5) and in near-surface waters of red clay plumes.

FISH ABUNDANCE AND TURBIDITY

Spacial Variations in Fish Abundance

Trawl and seine catches from the six locations sampled during this study and experimental gill net catches at 15 Wisconsin Department of Natural Resources survey stations (King and Swanson 1974) were analyzed to identify relationships between relative abundance of fish and red clay turbidity in western Lake Superior. Trawl and seine catches during 1973-1976 were summarized by geographic location, gear type and vertical location (bottom or midwater; Table 9). Average gill net catches for the period 1973-1974 were summarized according to sampling depth and turbidity (Table 10). The sampling programs demonstrate the occurrence of 38 species of fish and suggest smelt, longnose suckers (*Catastomus catastomus*) and walleye are most abundant. Troutperch (*Percopsis omiscomaycus*), shiners (*Notropis atherinoides*, *N. hudsonius*) and sculpin (*Cottus cognatus*, *C. rici*, *C. bairdi*) were common in trawl catches but were not captured by gill nets. Burbot, white suckers (*Catastomus commersoni*), round white fish (*Prosopium cylindraceum*), lake herring and chubs (*Coregonus hoyi*) were common in gill net catches (Table 10) and occurred or were common in trawl

TABLE 6. ZOOPLANKTON ABUNDANCE IN TURBID AND CLEAR WATER DURING 1975

Number of zooplankton/m^3 represent averages of six or eight paired samples taken at the surface and at 6 m intervals in 16 to 20 m water columns.

Zooplankton and Turbidity	Sampling Location					
	Station 2		Station 3		Station 4	
Turbidity (ppm)	1.75	0.5	7.67	3.12	8.5	1.8
Rotifera	7,234	4,211	13,676	6,851	21,248	6,019
Conochilus sp.	1,856	359	875	1,101	729	760
Asplanchna spp.	203	70	157	54	292	260
Kellicottia longispina	1,516	1,554	1,750	1,507	843	1,000
Keratella cochlearis	1,656	367	6,916	1,797	14,177	1,771
Polyarthra spp.	687	531	1,135	774	1,510	1,322
Synchaeta sp.	1,523	1,289	2,812	1,586	3,676	906
Others	7	39	31	32	21	--
Cladocera	1,101	250	3,051	1,227	9,509	2,645
Eubosmina coregoni	62	--	541	78	2,791	166
Bosmina longirostris	211	62	1,176	226	4,708	1,687
Daphnia galeata mendotae	805	188	1,177	890	1,999	792
Daphnia pulex	23	--	55	31	--	--
Copepoda (Adult)	6,148	3,351	5,427	5,610	4,260	3,479
Cyclops bicuspidatus	1,812	977	1,427	1,687	1,812	961
Cyclops vernalis	8	--	63	8	--	--
Diaptomus spp.	4,328	2,312	3,874	3,906	2,447	2,510
Limnocalanus lacustris	--	47	--	8	--	--
Mesocyclops macrurus	--	16	--	--	--	--
Copepoda nauplii	3,812	2,391	5,729	3,343	3,354	1,562
Total	18,295	10,203	27,884	17,024	38,364	13,654

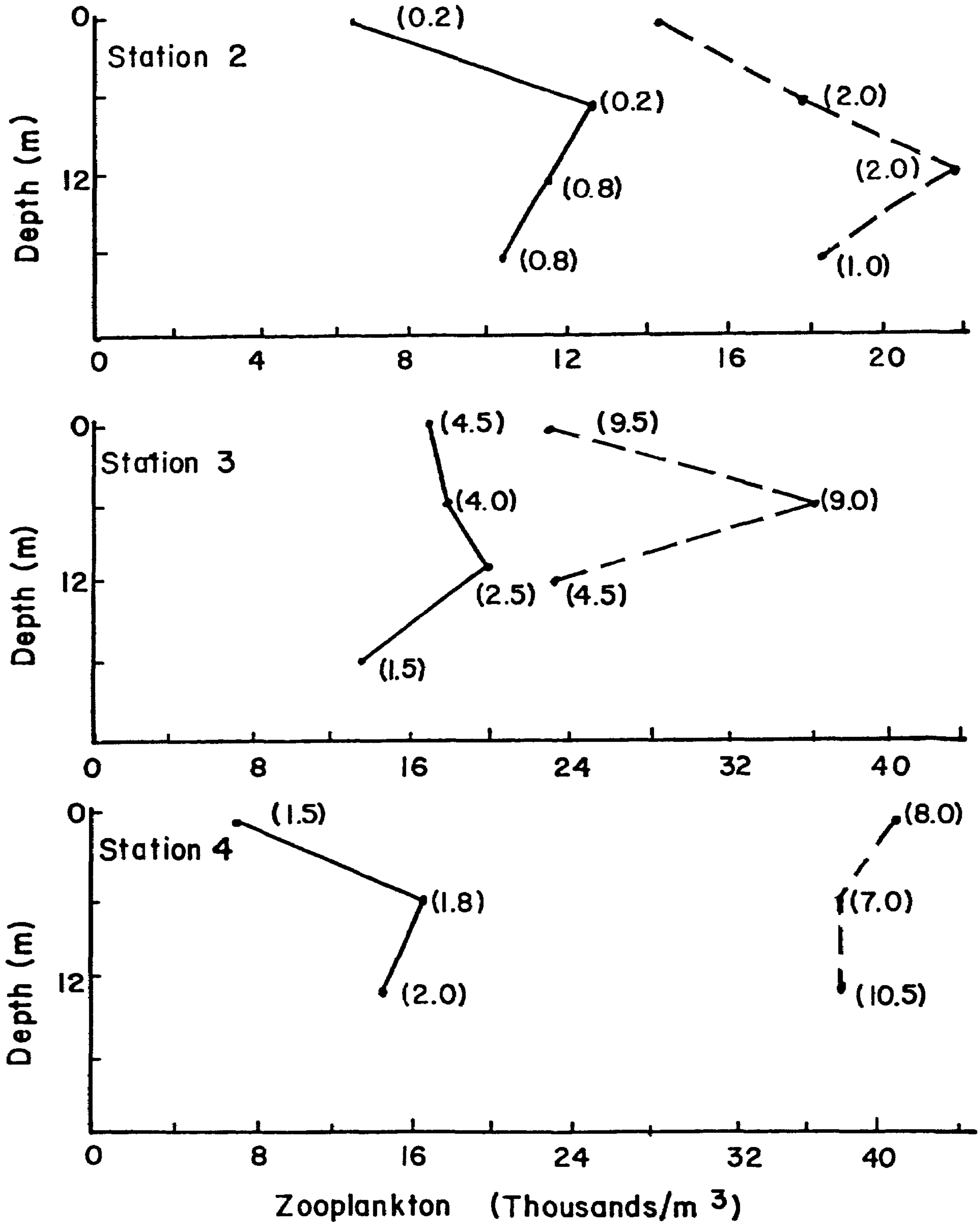

Figure 8. Zooplankton density in low (solid line) and high (dashed line) turbidity zones of Stations 2, 3 and 4. The number associated with each plotted point is the turbidity (FTU) at each sampling point.

TABLE 7. ZOOPLANKTON DENSITY, TURBIDITY, DEPTH AND LIGHT PENETRATION RELATIONSHIPS

Regression constants are for relationships between zooplankton abundance indices (Y), red clay turbidity or light penetration (X) in western Lake Superior.

Model and Zooplankton Group	Regression Coefficient (b)	Intercept (a)	Coefficient of Variation (r^2)	Students-t for b = 0 (t)
Zooplankton/m^3 (Y) and Turbidity (X)				
Rotifera	1802.1	2871.5	.88	8.72**
Cladocera	795.9	-147.6	.54	3.42**
Copepoda (adult)	90.4	4406.9	.06	.76
Copepoda (nauplii)	242.6	2345.5	.37	2.45*
Percentage Zooplankton in Surface Samples (Y) and Turbidity (X)				
Rotifera	1.61	19.6	.43	2.72**
Cladocera	2.96	17.7	.33	2.22*
Copepoda (adult)	.38	16.9	.03	.54
Copepoda (nauplii)	-.02	22.0	.00	-.02
Percentage of Zooplankton in Surface Waters (Y) and Light (μw/cm^2/nm; X)				
Rotifera	-1.06	29.9	.38	-2.84**
Cladocera	- .41	32.2	.03	- .54
Copepoda (adult)	- .37	20.8	.14	-1.27
Copepoda (nauplii)	- .20	23.6	.03	- .58

*Indicates statistical significance at $P < 0.05$.

**Indicates statistical significance at $P < 0.01$.

TABLE 8. ZOOPLANKTON ABUNDANCE AT TWO STATIONS DURING 1973-1974

Number of zooplankton/m^3 are averages of five samples collected at the surface and 3 m intervals in 6.1 to 9.1 m water columns.

Zooplankton and Turbidity	Sampling Location and Date					
	4 8/16/73	2 8/19/73	4 9/1/73	2 9/2/73	4 10/14/73	2 10/19/73
Turbidity (ppm)	15.0	2.0	8.0	3.0	25.0	2.5
Rotifera	38,020	153,714	21,692	72,653	25,857	15,765
Cladocera	15,870	20,952	3,896	19,238	15,810	7,163
Copepoda (adult)	6,946	19,619	14,133	37,605	10,993	14,272
Copepoda (nauplii)	9,156	9,904	9,502	11,319	10,585	9,789
Total	69,992	204,189	49,223	140,815	63,245	46,989

TABLE 9. AVERAGE TRAWL CATCH (Number 100/m^3)

Year	1973-74	1975	1973-74	1975-76	1975-76
Station	2 and 4	6	2 and 4	2 and 4	2 and 4
Gear Type	6.1 m Trawl	6.1 m Trawl	7.6 m Trawl	9.5 m Trawl	9.5 m Trawl
Location	Bottom 1.8-15 m	Bottom 1.8-15 m	Bottom 1.8-15 m	Bottom < 15 m	Bottom > 15 m
Osmerus mordax (yy)†	22.167	17.185	4.544	.534	.075
O. mordax (older)	6.667	13.347	3.194	7.368	3.230
Stizostedion vitreum v.	.267	.127	.296	.104	.026
Salvelinus namaycush	.004	--	<.001	.002	.018
Salmo trutta	--	--	<.001	--	--
S. gardneri	--	--	<.001	--	--
Coregonus sp.	<.001	--	<.001	.020	.018
Prosopium cylindraceum	--	.089	--	--	--
Catostomus catostomus	.113	.465	.105	.080	.062
C. commersoni	.016	.005	.044	.042	.004
Notropis sp.	.040	--	.066	.002	.002
Percopsis omiscomaycus	1.122	1.410	.898	.316	.001
Cottus sp.	.279	.958	.040	.032	.134
Alosa pseudoharengus	.014	--	<.001	--	--
Couesius plumbeus	.053	.066	.014	.012	.002
Perca flavescens	--	.033	--	.001	<.001
Percina caprodes	<.001	--	<.001	--	--
Etheostoma nigrum	--	1.101	--	--	--
Gasterosteidae	<.001	1.360	<.001	--	--
Esox lucius	<.001	--	<.001	--	--
Ictalurus sp.	<.001	--	--	--	--
Pomoxis nigromaculatus	<.001	--	<.001	--	--
Ambloplites rupestris	--	--	--	--	--
Cyprinus carpio	--	--	<.001	--	--
Lota lota	.009	--	.016	.535	.004

†(yy) refers to Age 0.

(continued)

TABLE 9. (continued)

Year	1973-76	1973-76	1975-76	1973-74
Station	2 and 4	1	2 and 4	2 and 4
Gear Type	6.1 m Trawl	6.1 m Trawl	6.1 m Trawl	Seine
Location	Midwater 1.8-15 m	Midwater 1.8-15 m	Midwater > 15 m	Bottom .5-1 m
Osmerus mordax (yy)†	2.393	1.082	.242	213.900
O. mordax (older)	.818	.020	.036	21.800
Stizostedion vitreum v.	--	.001	--	1.089
Salvelinus namaycush	--	--	--	--
Salmo trutta	--	--	--	--
S. gardneri	--	--	--	--
Coregonus sp.	.002	.001	.002	.044
Prosopium cylindraceum	--	--	--	--
Catostomus catostomus	.002	--	< .001	5.860
C. commersoni	< .001	--	--	.039
Notropis sp.	.063	--	.001	26.070
Percopsis omiscomaycus	.014	.002	--	.233
Cottus sp.	.009	.003	.019	--
Alosa pseudoharengus	< .001	--	--	.293
Couesius plumbeus	< .001	--	--	.100
Perca flavescens	--	--	--	--
Percina caprodes	< .001	--	--	.035
Etheostoma nigrum	--	--	--	--
Gasterosteidae	< .001	.001	--	.007
Esox lucius	--	--	--	.019
Ictalurus sp.	--	--	--	1.308
Pomoxis nigromaculatus	--	--	--	.123
Ambloplites rupestris	--	--	--	.014
Cyprinus carpio	< .001	--	--	--
Lota lota	.006	--	< .001	--

†(yy) refers to Age 0.

TABLE 10. AVERAGE GILL NET CATCH PER SET AND PERCENT SPECIES ABUNDANCE (IN PARENTHESIS)

Zone Type	Shallow Turbid	Shallow Clear	Deep Turbid	Deep Clear
Depth Range (m)	3.0 to 12.8	3.6 to 16.4	12.8 to 19.5	14.6 to 60
Secchi (average) (m)	5.5	15.5	9.5	21.7
Station No.†	15 and 17	14,19,22,23	19 and 25	1,8,9,11,12,18,28
Osmerus mordax	66.0(19.4)	27.6(11.1)	34.5(38.0)	37.0(28.0)
Stizostedion vitreum v.	74.6(21.9)	27.7(11.1)	1.3(1.4)	-- --
Salvelinus namaycush n. (Ad)	0.3(> 0.1)	0.6(0.2)	1.6(1.8)	5.6(4.2)
S. namaycush n. (ju)	-- --	1.7(0.7)	0.8(0.9)	5.8(4.4)
S. namaycush siskowet	-- --	-- --	-- --	0.3(0.2)
S. fontinalis	-- --	0.2(0.1)	-- --	-- --
Salmo gairdneri	-- --	-- --	-- --	-- --
S. trutta	0.2(> 0.1)	1.7(0.7)	-- --	-- --
Oncorhynchus kisutch	-- --	0.5(0.2)	-- --	-- --
Splake = S.f x S.n	-- --	0.2(0.1)	-- --	-- --
Coregonus artedii	0.3(> 0.1)	2.3(0.9)	5.1(5.6)	5.5(4.1)
C. hoyi	27.8(8.2)	9.5(3.8)	5.2(5.7)	9.2(7.0)
C. clupeaformis	-- --	6.4(2.6)	4.8(5.3)	1.3(1.0)
Prospium cylindraceum	0.8(0.2)	32.5(13.0)	2.1(2.3)	25.2(19.0)
Lota lota	34.6(10.1)	3.6(1.5)	11.0(12.1)	2.3(1.7)
Catostomus catostomus	127.0(37.2)	72.3(29.0)	19.2(21.1)	40.0(30.2)
C. commersoni	8.8(2.6)	60.6(24.3)	5.0(5.5)	-- --
Alosa pseudoharengus	0.2(> 0.1)	0.6(0.2)	0.2(0.2)	0.4(0.3)
Acipenser fulvescens	-- --	0.3(0.1)	-- --	-- --
Esox lucius	0.3(> 0.1)	0.2(0.1)	-- --	-- --
Perca flavescens	-- --	0.3(0.1)	-- --	-- --
Cyprinus carpio	-- --	0.3(0.1)	-- --	-- --
Semotilus atromaculatus	-- --	-- --	0.2(0.2)	-- --
Total	340.9(100.0)	249.1(99.9)	91.0(100.1)	132.6(100.1)

†Station locations are identified by King and Swanson (1974) and are suggested in the text.

catches (Table 9).

Comparisons of 6.1 m bottom trawl catches in turbid areas (Stations 2 and 4) with catches from stations characterized by clear water (Station 6) suggested that abundance of several species was influenced by turbidity. Although trawl catches of smelt, white sucker and troutperch were generally similar, catches of longnose sucker, round whitefish, Gasterosteidae (primarily Pungitius pungitius), sculpin and darters (Etheostoma nigrum) were higher at Station 6 (Table 9). Trawl catches of walleye and burbot were higher at the more turbid Stations 2 and 4. Gill net catches from turbid and clear water locations support the trends suggested by trawl catches for most species and indicate abundance of lake trout (particularly juveniles) is lower in the turbid water zones (Table 10). Gill net catches provided some evidence that smelt and chubs are more abundant in turbid water. Comparison of midwater trawl catches from Station 1 (1973-1976) with catches from Stations 2 and 4 (Table 9) provides additional evidence that smelt abundance is higher in turbid water.

Temporal Variations in Fish Abundance

Analysis of commercial catches of herring and smelt from Minnesota district M-1 confirmed previous findings by Anderson and Smith (1971b) which showed abundance (CPE) of lake herring has declined in the Duluth-Superior area and abundance of smelt has increased (Figure 9). Abundance of the two species is negatively correlated ($r = 0.5$, $P > 0.05$). Smelt abundance was not correlated with spring runoff 3-4 years previous. No relationship was found between percentage deviation in smelt abundance (CPE) for a given year and percentage deviations in turbidity indices for May through June or May through October 3-4 years previous.

INFLUENCE OF TURBIDITY ON SMELT POPULATIONS

Smelt Growth and Turbidity

High abundance of Age 0 smelt and intensive sampling during 1973 permitted estimation of growth at Stations 2 and 4 (Figure 10). Comparison of mean length measurements suggested growth was similar. Comparison of average lengths calculated for five months of sampling at Stations 1, 2 and 4 suggested Age 0 smelt in the more turbid Stations 2 and 4 were 9% longer than those at Station 1 but differences were not significant ($P > 0.05$).

Smelt Distribution and Water Temperature

Catches in bottom trawls and seine hauls showed juvenile and adult smelt (Age II and older) move offshore to depths exceeding 10 m after June when near-shore waters exceed 11 C. The association with temperature is suggested by higher June catches (Table 11).

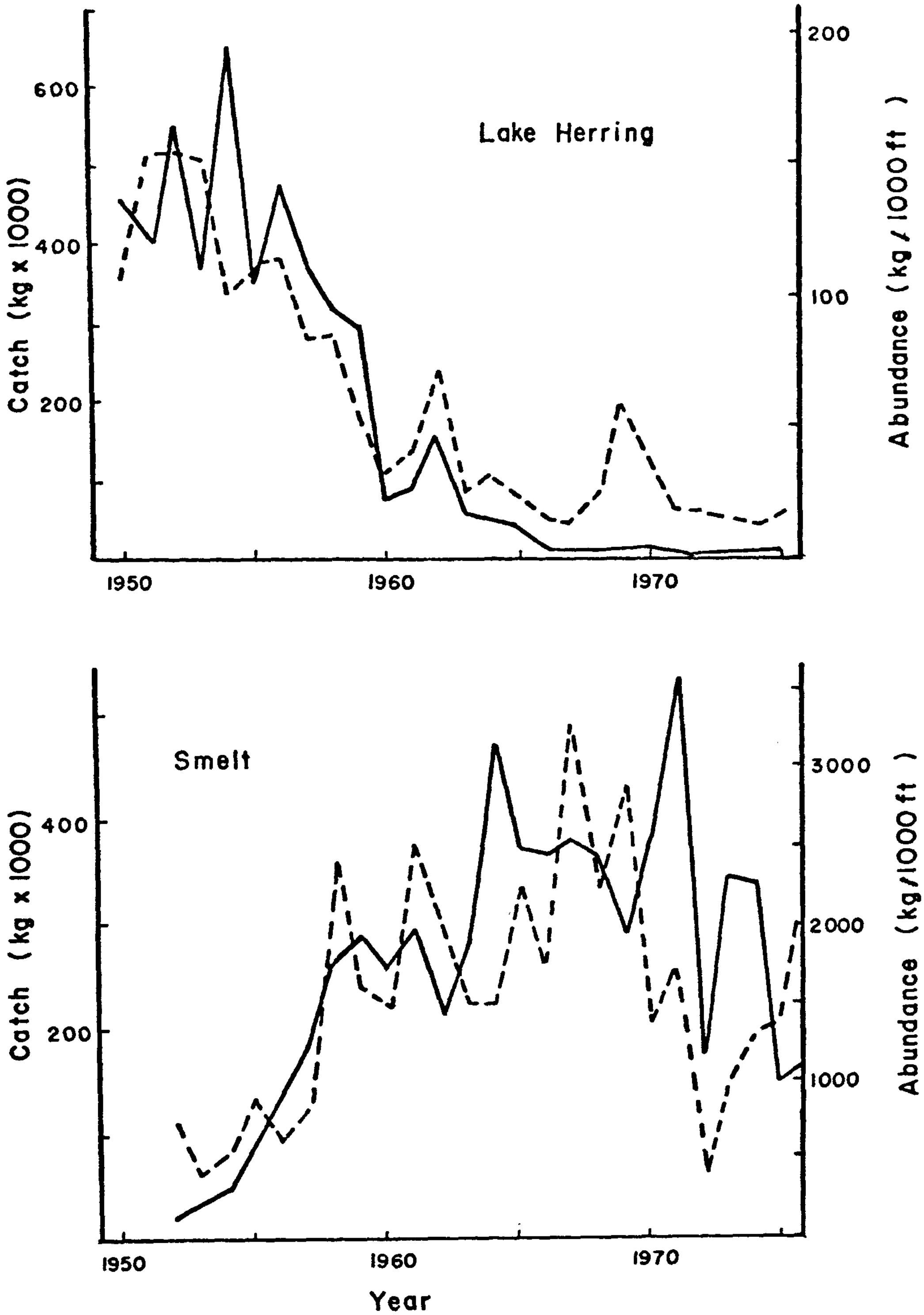

Figure 9. Catch (solid line) and abundance (CPE, dashed line) of lake herring and smelt in western Lake Superior, Minnesota Statistical District M-1. (See Hile (1962) for statistical district boundaries.)

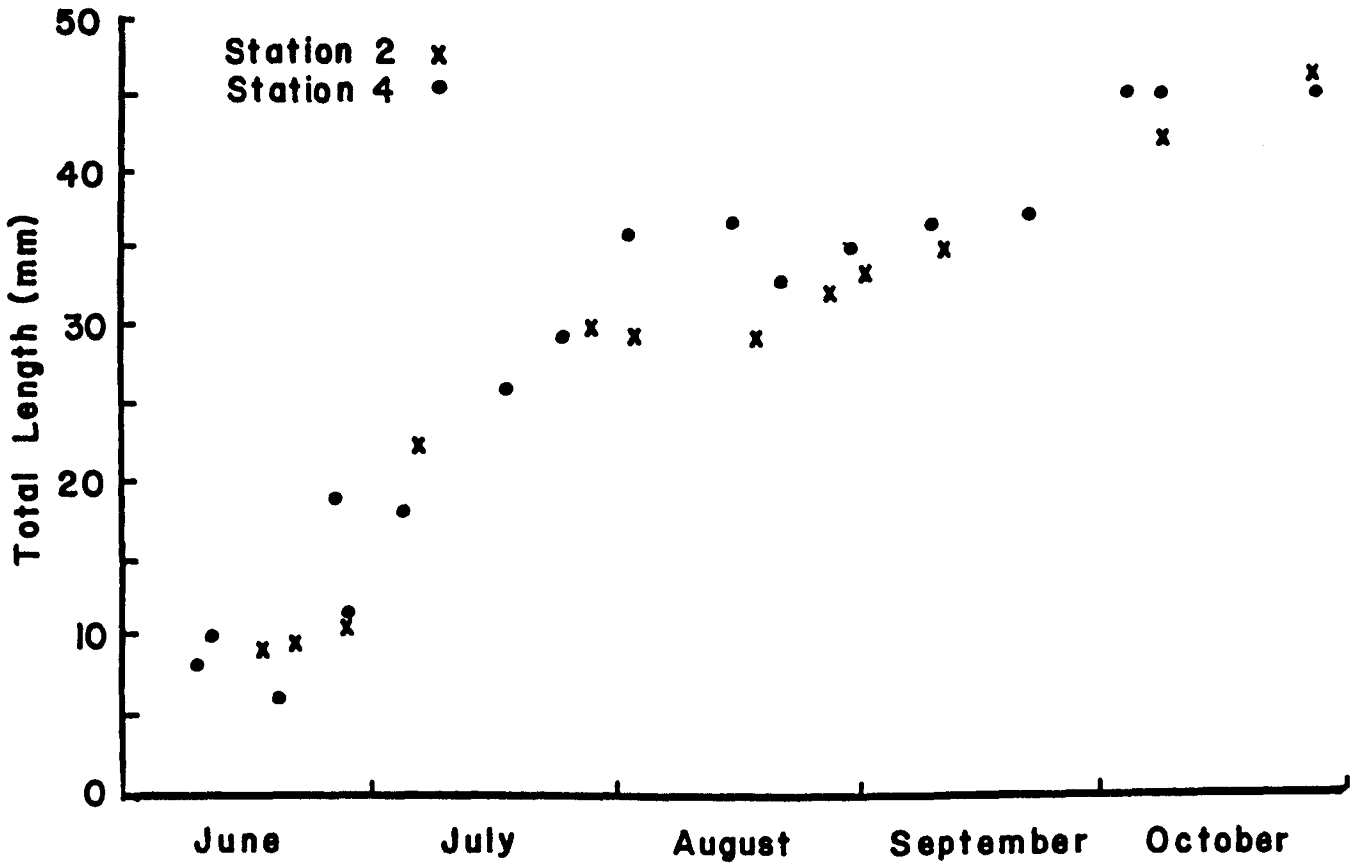

Figure 10. Average total length of Age 0 smelt at Stations 2 and 4 during 1973. Averages are calculated from measurements of 10-100 individuals.

TABLE 11. BOTTOM TRAWL CATCH BY SAMPLING MONTH

Catches are averages for 100 m^3 captured by 7.6 m bottom trawl at stations 2 and 4 during 1973 and 1974

Species	June	July	Aug.	Sept.	Oct.
Osmerus mordax (yy)	.016	.133	4.70	12.47	6.26
O. mordax (yl)	1.150	.750	1.450	3.366	.770
O. mordax (jv)	1.420	2.166	.480	.570	.030
O. mordax (ad)	1.150	.533	.580	.433	.300
Stizostedion vitreum v. (yy)	.067	.067	.133	.417	.300
S. vitreum v. (ad)	.100	.083	.200	.150	.067
Salmonidae	--	--	<.001	<.001	--
Coregonus sp.	<.001	<.001	--	--	--
Lota lota	.050	--	--	--	.020
Catostomus catostomus	.250	.066	.116	.033	.016
C. commersoni	--	.033	.033	.133	--
Notropis sp.	.016	--	--	.066	.433
Percopsis omiscomaycus	.883	.150	.417	2.400	.383
Cottus sp.	.016	--	--	.166	--
Alosa pseudoharengus	--	--	--	<.001	<.001
Couesius plumbeus	.016	--	.016	.033	--
Percina caprodes	--	--	<.001	--	--
Gasterosteidae	<.001	--	--	--	--
Esox lucius	--	--	<.001	<.001	--
Pomoxis nigromaculatus	--	--	--	<.001	--
Cyprinus carpio	--	--	--	<.001	--

Correlations between smelt catch/100 m^3 at sampling locations within Stations 2 and 3 demonstrated temperature preference influences distribution and varies with age. Correlations between temperature and catches of Age 0 smelt captured by seine and by trawling on the bottom, at midwater locations and near the surface were positive (Table 12). The analysis demonstrated that distribution of Age I smelt was not influenced by termperature. Correlation coefficients defining variability between catches of Age I smelt and temperature were both positive and negative and were not significant (Table 12). Catches of Age II and older smelt in bottom trawls (6.1 and 7.6 m nets) were negatively correlated with temperature demonstrating preference for colder water (Table 12).

Smelt Distribution and Turbidity

Night Distribution: Response of smelt to turbidity was analyzed by multiple regression models in which smelt density (number/100 m^3) estimated from 6.1 m trawl catches was the dependent variable, and temperature and turbidity were independent variables. Partial regression coefficients estimating rate of change in catch with temperature followed the general trends described previously from simple correlation analysis (Table 12). Smelt density near the surface in areas 1.8-15 m deep increased with turbidity. In contrast, regression coefficients describing change in smelt density near the bottom were negative. Partial regression coefficients relating change in catch 3 m from the surface to turbidity were generally positive whereas those defining change in catch with turbidity 6.1 m from the surface, in a 7.7 to 15 m column, were positive for some age groups and negative for others. The density changes suggest that smelt respond to change in turbidity by vertical movements. However, variation in catches between sampling nights was high, and few coefficients were significant ($P > 0.05$).

To control variability in catch between sampling nights, smelt in surface, midwater and bottom trawls (number/100 m^3) were totaled by age group for three of the horizontal depth zones sampled (1.8-4.7, 4.8-7.6, 7.7-15 m), and the percentage of the total captured at each vertical location was calculated. Multiple regression analysis was used to measure the influence of turbidity and temperature on the percentage of smelt captured in each vertical stratum. Percentages generally increased with turbidity near the surface and at midwater locations but declined near the bottom (Table 13; Figure 11). Coefficients estimating rate of change in percentage abundance with turbidity were significant for most tests with fish older than Age 0. Percentage abundance of Age 0 smelt was generally high at surface, midwater or bottom locations and did not change appreciably with turbidity. Abundance of Age II and older smelt increased from 1 to 3% in surface waters and from 8 to 24% at 3.1 m with increase in turbidity from 0 to 15 FTU (Figure 11).

TABLE 12. SMELT DENSITY AND TEMPERATURE CORRELATIONS

Correlations between water temperature and trawl catches of Age 0, I, and Age II or older smelt are given for surface, midwater and bottom sampling points in four depth zones.

Sampling Years	Gear		Number	Location (m)		Correlation Coefficient	Sign.
	Type	Size	(Obs.)	Net	Bottom	(r)	Level
Age 0							
1973	Seine	7.7 m	57	Bottom	0.5–1 m	+.24	0.1
1973	Trawl	6.1 m	56	Bottom	1.8–15 m	+.28	0.05
1973, 1974	Trawl	6.1 m	116	0.5 m	1.8–15 m	+.18	0.01
1973	Trawl	6.1 m	20	3 m	4.8–7.6 m	+.43	0.1
1973	Trawl	6.1 m	21	3 m	7.7–15 m	+.33	NS
1973	Trawl	6.1 m	21	6 m	7.7–15 m	+.55	0.05
Age I							
1973	Trawl	6.1 m	82	Bottom	1.8–15 m	-.10	NS
1974	Trawl	6.1 m	44	Bottom	1.8–15 m	+.11	NS
1973	Trawl	6.1 m	83	0.5 m	1.8–15 m	+.07	NS
1974	Trawl	6.1 m	59	0.5 m	1.8–15 m	+.08	NS
1973	Trawl	6.1 m	28	3 m	4.8–7.6 m	-.03	NS
1973	Trawl	6.1 m	29	3 m	7.7–15 m	-.31	NS
1973	Trawl	6.1 m	29	6 m	7.7–15 m	+.14	NS
Age II and Older							
1973, 1974	Trawl	7.6 m	141	Bottom	1.8–15 m	-.17	0.05
1973, 1974	Trawl	6.1 m	142	0.5 m	1.8–15 m	-.01	NS
1973	Trawl	6.1 m	28	3 m	4.8–7.6 m	-.28	NS
1973	Trawl	6.1 m	29	3 m	7.7–15 m	-.21	NS
1973	Trawl	6.1 m	29	6 m	7.7–15 m	-.10	NS

TABLE 13. PERCENT SMELT ABUNDANCE, TURBIDITY AND TEMPERATURE RELATIONSHIPS
Regression constants are given for relationships between the percentage of smelt sampled in a water column at a depth Y, turbidity X_1, and temperature X_2.

Age Class and No. Obs.	Location: Sampling Depth	Location: Bottom Depth	Regression Constants: Intercept a	Regression Constants: Turbidity b_1	Regression Constants: Temp b_2	Statistical Significance: b_1	Statistical Significance: b_2
Age 0							
38	0.5	1.8-4.7	+49.526	-0.083	-1.059	NS	NS
36	0.5	4.8-7.6	+28.685	+0.232	-0.833	NS	NS
37*	0.5	7.7-15	+27.153	+0.031	-0.989	NS	NS
111	0.5	1.8-15	+34.694	+0.108	-0.972	NS	NS
36	3.1	4.8-7.6	+34.383	+0.061	+0.018	NS	NS
37*	3.1	7.7-15	+ 1.684	+0.096	+1.535	NS	0.1
37*	6.1	7.7-15	+ 4.573	+0.210	+1.498	NS	NS
39	Bottom	1.8-4.7	+30.769	-0.344	+2.420	NS	NS
35	Bottom	4.8-7.6	+88.551	-0.341	-0.159	0.05	NS
37*	Bottom	7.7-15	+41.476	-0.132	-0.356	NS	NS
111	Bottom	1.8-15	+34.694	+0.108	-0.972	NS	NS
Age I							
37	0.5	1.8-4.7	- 1.233	+0.486	+0.523	0.05	0.1
35	0.5	4.8-7.6	- 0.682	+0.102	+0.058	0.1	NS
35*	0.5	7.7-15	- 3.019	+0.295	+0.384	NS	NS
107	0.5	1.8-15	- 3.606	+0.370	+0.400	0.01	0.01
35	3.1	4.8-7.6	+12.844	+0.418	-0.129	0.05	NS
35*	3.1	7.7-15	+ 5.893	+0.751	-0.410	0.01	0.05
35*	6.1	7.7-15	+ 4.796	+0.352	+1.488	NS	NS
38	Bottom	1.8-4.7	+97.567	-0.485	-0.235	0.05	0.1
35	Bottom	4.8-7.6	+88.551	-0.341	-0.159	0.05	NS
35*	Bottom	7.7-15	+86.467	-0.536	-1.868	NS	NS
108	Bottom	1.8-15	+79.586	-0.337	+0.072	0.05	NS
Age II and Older							
33	0.5	1.8-4.7	+16.624	+0.395	-1.112	0.01	0.05
32	0.5	4.8-7.6	- 0.744	+0.086	+0.040	0.01	0.1
32*	0.5	7.7-15	-12.224	+0.472	+0.802	0.05	0.1
102	0.5	1.8-15	+ 0.281	+0.327	-0.172	0.01	0.01
32	3.1	4.8-7.6	+34.116	+0.542	-1.602	0.05	0.05
37*	3.1	7.7-15	+11.463	+0.628	-0.308	0.05	0.1
39*	6.1	7.7-15	+20.045	+0.543	+0.253	NS	NS
33	Bottom	1.8-4.7	+98.715	-0.649	+0.320	0.01	0.01
32	Bottom	4.8-7.6	+52.190	-0.339	+2.572	NS	NS
37*	Bottom	7.7-15	+69.936	-0.712	-0.818	0.1	NS
102	Bottom	1.8-15	+61.680	-0.370	+1.330	0.05	0.05

*Regression models for 7.7-15 m water column were used to develop Figure 11.

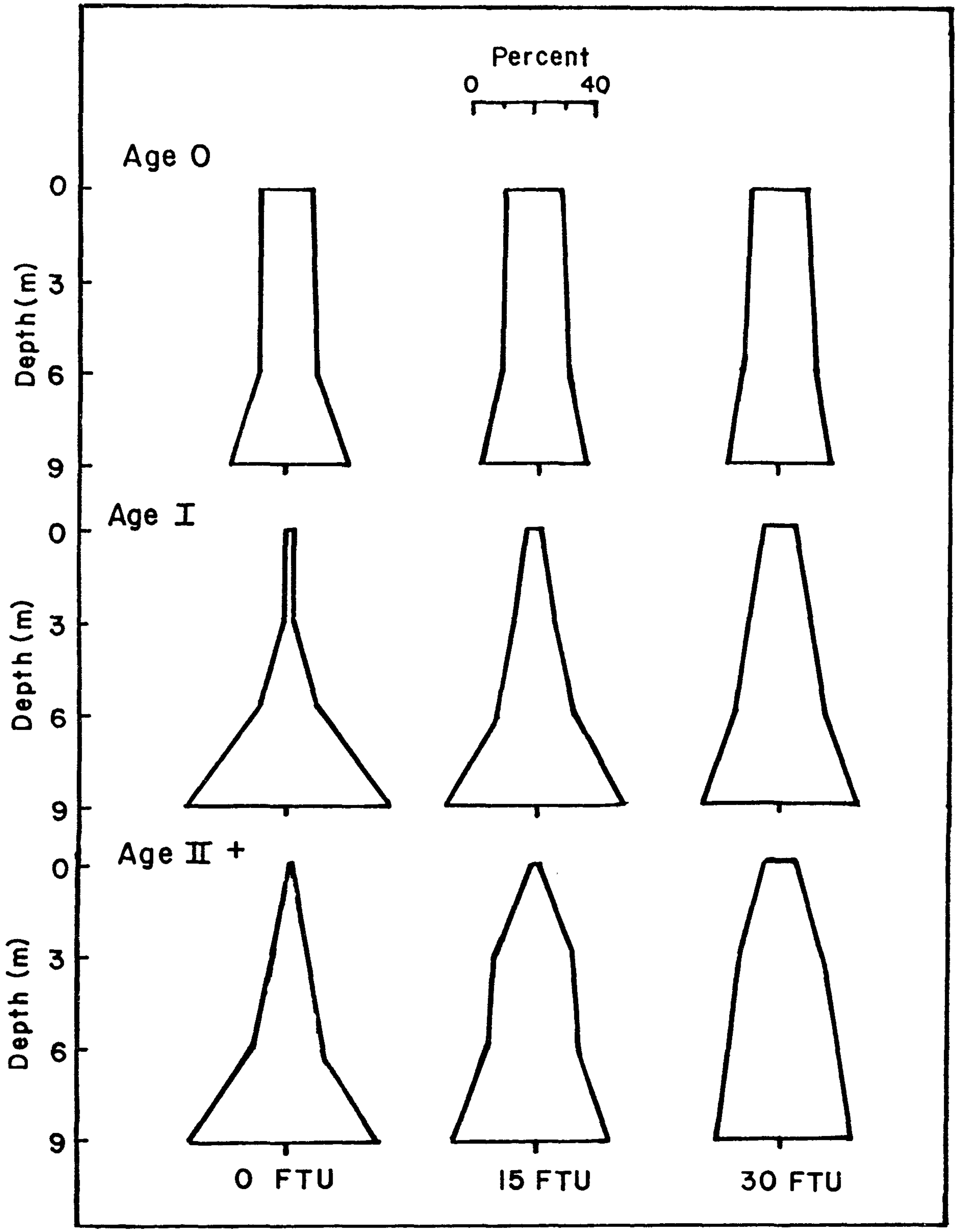

Figure 11. Vertical distribution of smelt in water 9.1 m deep at night. Percentage of Age 0, Age I and older smelt located near the surface, midwater and on the bottom is described for three turbidity levels (FTU).

Distribution during the day: Analysis of 7.6 m bottom trawl catches showed similar trends occurred during daylight hours. Catches at 4.8 to 7.6 m showed abundance declined by 12 and 23% with increase in turbidity from 0 to 15 and from 15 to 30 FTU respectively. At depths of 7.7 to 15 m, bottom catches of Age II and older smelt declined by 53 and 95% with increases in turbidity from 0 to 15 and from 15 to 30 FTU respectively ($P < 0.05$). Estimates of change in catch were calculated by multiple regression models in which temperature, the second independent variable, was held at 0 C.

Fathometer records made during daylight hours support a conclusion that reduction in bottom catches resulted from vertical movement by smelt toward the surface. Percentage of fish targets increased in 6.1 to 9.1 m and 9.2 to 12.2 m strata with increased turbidity and declined in deeper water (Figure 12).

Smelt Food and Predation

Food Habits: Copepoda and Cladocera were the major foods of smelt during all years sampled. Copepoda occurred in over 60% of the smelt captured and were more abundant in smelt under 110 mm T.L. (Appendix Table 3). Fish, primarily Age 0 smelt, occurred in approximately 50% of the older smelt sampled during September 1973 and 1974 (Tables 14 and 15). Fish were negligible in 1975-1976 smelt diets when sampling occurred off shore, where Age 0 smelt density was low (Appendix Table 3). During both 1973 and 1974 occurrence of larval fish in the diet of smelt was high in fish captured off the bottom by midwater trawl and in those captured on the bottom by bottom trawl. Occurrence of cannibalism in pelagic smelt increased from an average of 0% during June to 53% during September (Table 15) and for demersal smelt from 2% during June to 46% during September (Table 14).

Correlations between the number of larval fish or number of invertebrates in smelt stomachs and turbidity (FTU) at the collection location failed to show that turbidity directly influenced the quantity or quality of food eaten by smelt. The number of food items, the number of larval fish and the number of invertebrates found in smelt stomachs/g of smelt were similar for individuals taken from turbid and clear water zones.

Smelt Cannibalism: Estimates of the number of young smelt consumed daily and monthly by Age II and older smelt/100 m^3 were calculated from estimates of frequency of occurrence of Age 0 smelt in Age II and older smelt stomachs, multiplied by 2, and the average density of Age II and older smelt (number/m^3) in the 1.8-15 m depth zone. Although limited data from this study indicates digestion of larval fish would be completed in approximately 4 h, at 12.6 C, Foltz (1975) found digestion of invertebrates by smelt at 8 C required 24 h to reach 57%. It was assumed that young fish could be completely digested in from 12 to 24 h and multiplying by 2 would roughly correct for the average occurrence of 1.6 Age 0 smelt found in stomachs and for the digestion of young smelt in something less than 24 h.

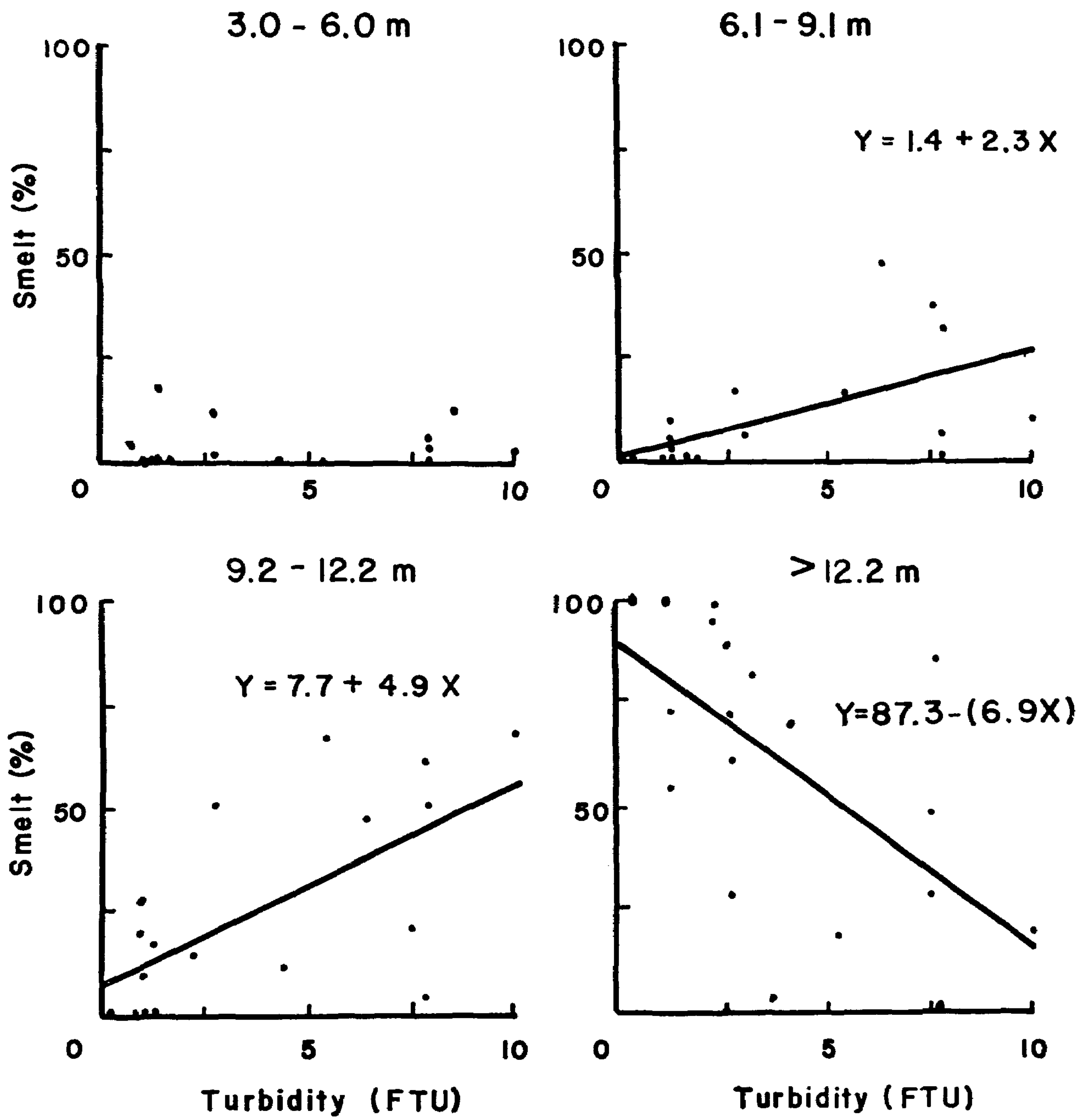

Figure 12. Relationships between the percentage of the total number of fish targets recorded by fathometer in four depth zones and turbidity. Simple regression formulas are provided for three significant relationships ($P < 0.05$).

TABLE 14. FOOD OF DEMERSAL SMELT

Food habits are given for smelt exceeding 100 mm captured by 6.1 and 7.6 m bottom trawls on the bottom during 1973-74. Values represent percentage frequency of occurrence and percentage by number (in parenthesis) for fish containing food.

Item	June	July	August	September	October
Number of Stomachs	57	78	68	100	120
Percentage Empty	24.6	20.5	20.6	32.0	29.2
Copepoda	88.4(81.8)	75.8(58.2)	25.9(5.4)	26.5(19.7)	38.8(15.7)
Cladocera (total)	51.2(17.5)	51.6(41.3)	81.5(94.0)	54.4(78.6)	81.2(84.1)
Daphnia sp.	48.8(7.7)	48.4(40.6)	79.6(88.5)	35.3(54.4)	77.6(80.9)
Bosmina sp.	27.9(9.8)	8.1(0.2)	--	5.9(1.2)	8.2(0.8)
Leptodora sp.	2.3(< .1)	8.1(0.5)	3.1(0.1)	2.9(< .1)	--
Amphipoda	--	4.8(< .1)	--	2.9(< .1)	3.5(< .1)
Pontoporeia affinis	--	4.8(< .1)	--	2.9(< .1)	3.5(< .1)
Isopoda	2.3(0.1)	1.6(< .1)	--	2.9(< .1)	2.4(< .1)
Mysis relicta	2.3(0.1)	1.6(< .1)	--	2.9(< .1)	2.4(< .1)
Plankton Eggs	7.0(0.3)	1.6(0.1)	3.7(0.1)	7.4(0.9)	2.4(< .1)
Insecta	11.6(0.3)	19.4(0.2)	13.0(0.4)	1.5(< .1)	1.2(< .1)
Diptera	2.3(< .1)	9.7(0.1)	--	--	--
Chironomidae	9.3(0.2)	8.1(0.1)	13.0(0.3)	--	1.2(< .1)
Ephemeroptera	--	1.6(< .1)	1.9(< .1)	--	--
Unidentified	--	--	--	1.5(< .1)	--
Fish	7.0(0.1)	4.8(0.1)	13.0(0.1)	47.1(0.7)	15.3(0.1)
Osmerus mordax	2.3(< .1)	3.2(0.1)	9.2(0.1)	45.6(0.7)	11.8(0.1)
Unidentified	4.7(< .1)	3.2(< .1)	3.7(< .1)	1.5(< .1)	3.5(< .1)

TABLE 15. FOOD OF PELAGIC SMELT

Food habits are given for smelt exceeding 100 mm captured by 6.1 m midwater trawl during 1973-74. Values represent percentage frequency of occurrence and percentage by number of food items (in parenthesis) for fish containing food.

Item	June	July	August	September	October
Number of Stomachs	45	34	52	26	65
Percentage Empty	48.9	25.0	21.2	34.6	12.3
Copepoda	82.6(70.5)	77.8(91.3)	65.9(23.3)	29.4(47.8)	42.1(9.3)
Cladocera (total)	78.3(28.6)	40.7(8.3)	78.0(75.9)	58.8(47.5)	84.2(90.6)
Daphnia sp.	60.9(11.2)	37.0(7.6)	65.9(72.0)	41.2(46.6)	84.2(90.6)
Bosmina sp.	56.5(16.9)	7.4(0.3)	12.2(1.2)	--	1.8(< .1)
Leptodora sp.	4.3(0.5)	7.4(0.4)	14.6(0.4)	11.8(0.3)	3.5(< .1)
Amphipoda (total)	--	--	--	17.6(0.3)	3.5(< .1)
Pontoporeia affinis	--	--	--	17.6(0.3)	3.5(< .1)
Isopoda	--	--	--	--	3.5(< .1)
Mysis relicta	--	--	--	--	3.5(< .1)
Insecta	4.3(0.1)	7.4(0.2)	43.9(0.8)	5.9(0.1)	7.0(< .1)
Chironomidae	4.3(0.1)	3.7(0.1)	39.0(0.7)	5.9(0.1)	--
Plecoptera	--	--	2.4(< .1)	--	--
Hemiptera	--	--	--	--	1.8(< .1)
Diptera	--	--	2.4(< .1)	--	--
Unidentified	--	3.7(0.1)	2.4(< .1)	--	4.3(< .1)
Fish	4.3(0.1)	11.1(0.2)	2.4(< .1)	64.7(4.3)	8.8(< .1)
Osmerus mordax	--	11.1(0.2)	2.4(< .1)	52.9(4.1)	5.3(< .1)
Notropis sp.	--	--	--	5.9(0.1)	--
Cottus sp.	--	--	--	5.9(0.1)	--
Unidentified	4.3(0.1)	--	--	--	3.5(< .1)

The corrected value represents an estimate of the percentage of Age II and older smelt which ate the equivalent of one Age 0 smelt daily. Multiplying this corrected estimate of occurrence by the density of Age II and older smelt gives an estimate of the number of young smelt consumed/100 m^3/day.

Estimates of the number of Age 0 smelt eaten by older smelt suggested that during June 4.3 young smelt were eaten/100 m^3 whereas during September Age II and older smelt consumed 33.5 Age 0 smelt (Table 16). Differences were related to varying density of young smelt during the two periods. Density of Age 0 (Age I were also included during June) in the 1.8-15 m zone averaged 3.7 during June and 73.7 in September (Table 16; Appendix Table 4). Monthly mortality resulting from cannibalism during August and September was estimated by dividing the number of Age 0 smelt eaten by Age II and older smelt by the average density of Age 0 smelt in the 1.8-15 m depth zone (Table 16). The analysis suggested cannibalism by both pelagic and demersal smelt is an important source of mortality during September when larger smelt were not segregated from Age 0 smelt because of difference in temperature preference and related distributions. Segregation during August appeared to be responsible for reduced cannibalism and mortality. Mortality was not estimated for June and July because trawl catches did not provide reliable estimates of relative abundance. During the June-July period, small size of Age 0 smelt permitted escapement through the trawl mesh resulting in low estimates of abundance.

Smelt Predation on Lake Herring: Although western Lake Superior field samples showed larval fish are an important constituent of smelt diets, no lake herring were identified in smelt stomachs. However, the probability that smelt predation on larval herring would be observed, even if it occurred, is low because larval herring are presently rare in western Lake Superior (Table 9).

An average of 12 herring larvae were captured/min with 1/2 and 1 m diameter nets on Black Bay, Ontario, establishing the presence of high concentrations of larval herring and potential for predation by smelt. The presence of a yolk-sac and the small size (10 mm average) of larval lake herring in the catches indicated a major hatch occurred prior to the May 4-5, 1973, sampling period. Analysis of stomachs from 63 Black Bay smelt captured during the day by trawl and 33 smelt captured at night by gill net demonstrated smelt will prey on larval lake herring if they are available. The remains of one larval fish was removed from the stomach of a 158 mm T.L. smelt captured by gill net. Comparison with herring captured in the bay showed similarity in size, general shape, and form of the caudal fin (Figure 13). Presence of 19 myomeres posterior to the anus, stellate chromatophores over the yolk-sac and ventral stellate chromatophores in the anal region are characteristic of larval herring (Fish 1932) and were observed in identifying the item as a larval lake herring.

Laboratory studies with two Age I+ smelt suggested larval herring were preferred as food over brine shrimp or herring eggs (embryos). Herring eggs were not consumed and smelt stopped feeding on brine shrimp when larval herring were available. Predation on larval herring was associated

TABLE 16. ESTIMATED CANNIBALISM AND RELATED MORTALITY IN SMELT

Month	Occurrence of Age 0 Smelt (%) No. With Food	Total† No.	Correct.††	Density Age II and Older Smelt (No./100 m^3)	Predation Rate No./100 m^3 (Daily)	(Month)	Prey Density (No./100 m^3)	Monthly Mort. (%)
June								
Pelagic	--	--	--	1.5	--	--	0.9	--
Demersal	2.3	1.7	3.4	4.0	0.14	4.3	3.7	--
July								
Pelagic	11.1	8.3	16.6	0.4	0.07	2.1	1.7	--
Demersal	3.2	2.5	5.0	6.6	0.33	10.2	8.5	--
August								
Pelagic	2.4	1.9	3.8	0.3	0.01	0.4	7.4	5
Demersal	9.2	7.3	14.6	0.6	0.09	2.7	20.5	13
September								
Pelagic	52.9	32.5	65.0	0.2	0.13	3.9	9.4	41
Demersal	45.6	31.0	62.0	1.8	1.12	33.5	73.7	45

†Percentage of smelt stomachs with young smelt estimated from the total number of stomachs in a sample.

††Percentage occurrence of young smelt in older smelt stomachs. This value represents the estimated percentage of the total number of Age II and older smelt which consumed an equivalent of one Age 0 smelt daily.

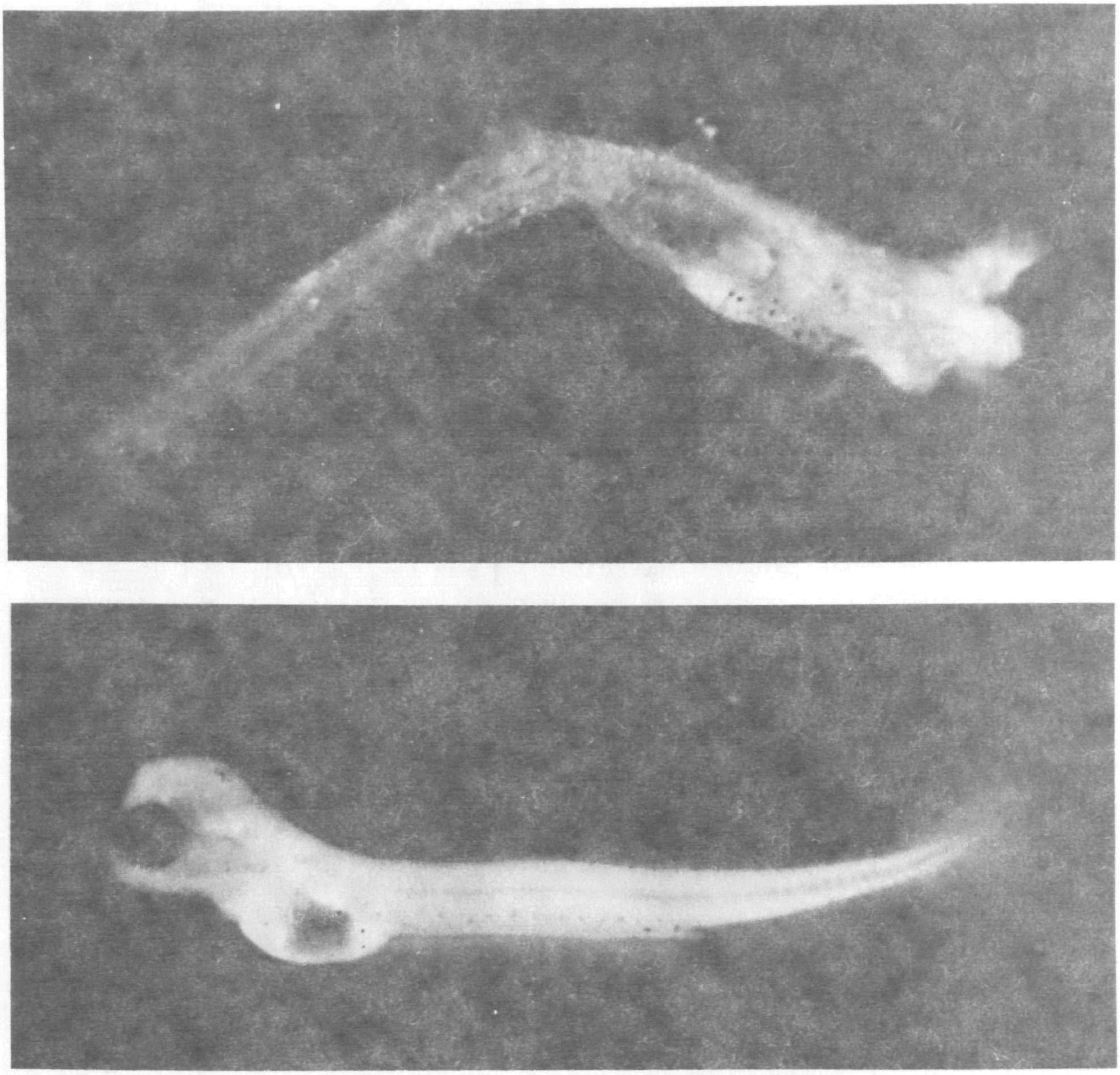

Figure 13. Lake herring larvae removed from 158 mm smelt (above) and from larval net catches (below).

with swimming activity. The two smelt did not feed on inactive herring larvae. Selection of active prey would result in preference for larval fish over fish eggs or zooplankton.

During one test in which observations occurred following a 2-1/2 day period without food, the two Age I+ smelt consumed 70 herring larvae, 1-3 days post-hatching, in 6 h, a consumption rate of approximately 5 herring/h/smelt. When previously fed an unrestricted diet of larval herring, the rate was reduced to 1.5 herring/h/smelt.

Influence of light on smelt predation was tested by measuring the time required for the two Age I+ smelt to consume 10 herring larvae. Consumption was faster under ambient laboratory light conditions where the 10 larvae were consumed in 8 min. In comparison, only 8 of 10 larvae were consumed in 1-1/2 h when the test chamber was completely darkened.

Rate of digestion was defined by examining stomach contents of the two Age I+ smelt 1-3/4 and 4 h after feeding at 12.6 C. Seven larvae consumed by the 62 mm smelt were 30% digested after 1-3/4 h. Six larvae consumed by a 80 mm smelt were digested to a semi-liquid mass after 4 h.

INFLUENCE OF TURBIDITY ON GROWTH, SURVIVAL AND DISTRIBUTION OF LARVAL HERRING

The 62-day larval herring bioassay showed red clay turbidity has no influence on survival or growth at the concentrations normally occurring in western Lake Superior. Size increased between 1.0 and 1.5 mm per week independent of turbidity. Mortality was generally low and unrelated to turbidity level in test chambers (Swenson and Matson 1976).

Herring larvae were active and located near the surface during the feeding period but moved down from the surface after feeding. Larvae maintained locations closer to the surface at higher turbidities ($P < 0.05$; Swenson and Matson 1976).

INFLUENCE OF TURBIDITY ON WALLEYE

Walleye Abundance and Distribution

Walleye were rare in trawl or gill net catches from depths exceeding 15 m (Tables 9 and 10). Density of walleye past the first year of life increased with turbidity in the 1.8-15 m zone (Table 17). Density of Age 0 walleye increased with water temperature independent of turbidity.

Multiple regression failed to demonstrate that temperature influenced distribution of older walleye; however, changes in temperature with sampling depth and time introduced variability which weakened the analysis. Influence of depth and seasonal temperature variation was controlled by ranking estimates of turbidity and temperature on a scale of 1 to 3 for

TABLE 17. REGRESSION CONSTANTS AND SIMPLE CORRELATIONS FOR WALLEYE DENSITY, TURBIDITY AND TEMPERATURE RELATIONSHIPS

Regression equations predict number of walleye/100 m^3. Estimates are based upon 135, 7.6 m trawl samples collected at depths from 1.8-15 m during 1973 and 1974.

	Regression Constants			Simple Correlation (r)	
Species	Intercept (a)	Turb. Coef. b_1	Temp. Coef. b_2	Turb.	Temp.
Walleye					
Age 0	+0.2735	-0.00181	--	--	--
Age 0	-0.2237	-0.00142	-0.03762	-.06	+.19*
Walleye					
Older	+0.0681	+0.00216	--	--	--
Older	-0.0243	+0.00223	-0.00699	+.23**	+.10

*(P < 0.05)

**(P < 0.01)

catches occurring within two week periods in each of three depth zones (1.8-4.7, 4.8-7.6 and 7.7-15 m) sampled during 1973 and 1974. Correlation between ranks suggested that walleye density increased with water temperature ($P < 0.1$). The rank correlation analysis and low density of walleye in deep water zones suggest distribution of walleye exceeding Age I ($\geq$160 mm T.L.) is dependent on temperature in addition to turbidity.

Response of Walleye to Laboratory Turbidity Gradients

Analysis of turbidity preference showed a linear increase in time spent in a gradient chamber section with increased turbidity for both day and night observations (Table 18; Figure 14) demonstrating that walleye preferred the highest available turbidity, which exceeded levels characteristic of western Lake Superior. Movement between chamber section showed walleye were more active during the dark phase of the light cycle under clear water conditions (t-test; $P < 0.01$) but became day active in turbidity gradients (t-test; $P < 0.05$). Differences in activity patterns explain why the association with turbidity was stronger for night observations (Table 18). Increased activity during the light period tended to decrease the amount of time walleye located in turbid water because movement between chamber sections required leaving areas of higher turbidity.

Walleye Feeding

Walleye fed almost exclusively on smelt in western Lake Superior. Larger individuals ($\geq$200 mm T.L.) utilized adult and juvenile smelt as their primary food source from June through August (Table 19). Age 0 smelt represented the primary food of larger walleye during September and October and of smaller walleye ($\leq$200 mm T.L.) from June through October (Table 19). Estimates of food consumption rate during five days, July through September 1973, showed walleye ate an average of approximately 2% of their weight per day (Table 20). Comparison with estimates of daily food consumption for Lake of the Woods and Shagawa Lake, Minnesota, walleye (Swenson 1977) showed consumption by Lake Superior walleye was lower. Relatively low density of Lake Superior prey populations represents the probable cause for the reduced consumption rates (Swenson 1977). Estimates of feeding by walleye/100 m^3 indicate they consume an average of 0.5 individual smelt/day during July, 0.6 smelt/day during August and 1.0 smelt/day during September (Table 20). Changes in the number of smelt eaten per day were related to a decrease in the average size of smelt consumed by walleye during September. Summation of daily consumption rates for all days in a month and comparison with average smelt densities (number/100 m^3) in the 1.8 to 15 m depth zone suggests predation by walleye may be an important source of smelt mortality (Table 20). However, because walleye distribution is restricted in comparison with that of smelt. accurate interpretation of effects on smelt populations is not possible.

TABLE 18. RESPONSE OF WALLEYE AND LAKE TROUT IN TURBIDITY GRADIENTS

Change in the amount of time (Y = seconds) juvenile walleye or lake trout selected a chamber section in relation to increased turbidity is estimated by the formula: $Y = a + bx$. Estimates are based on 56 observations on 14 fish of each species.

Species and Time	Regression Constants: Intercept (a)	Regression Constants: Slope (b)	Value of F
Walleye			
Day	- 3.1418	+1.2163	3.1
Night	-10.1108	+2.7336	10.6*
Lake Trout			
Day	15.2978	-3.3578	19.8*
Night	21.4220	-4.6381	31.1*

*($P < 0.01$)

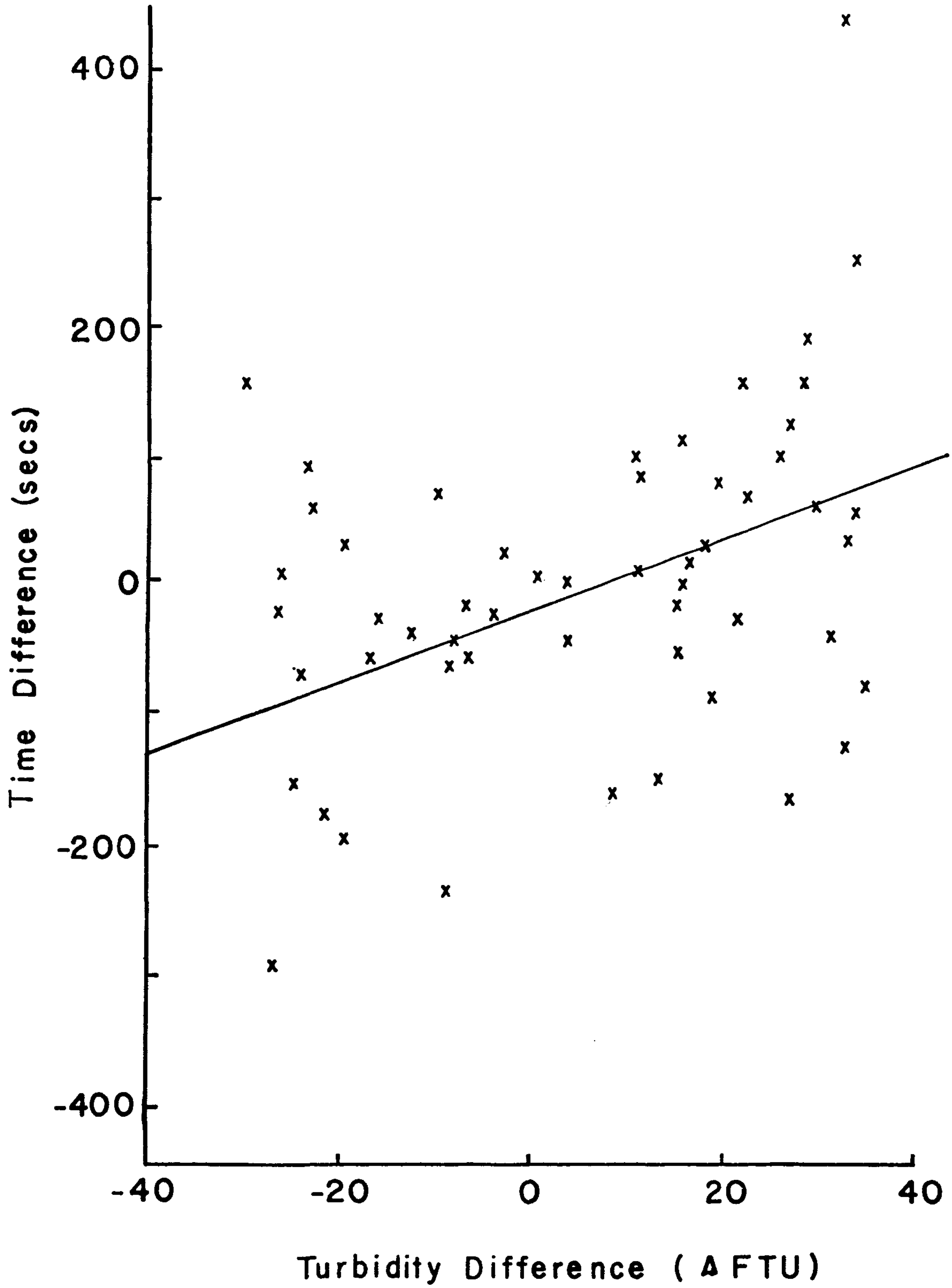

Figure 14. Response of juvenile walleye to turbidity gradients. The relationship is predicted using regression constants from Table 18.

TABLE 19. FOOD OF WALLEYE

Values represent percentage frequency of occurrence and percentage by weight of food items (in parenthesis) for fish containing food captured during 1973-1976.

Item	June	July	August	September	October
Older Walleye (≥200 mm TL)					
Number of Stomachs	43	53	88	78	67
Percentage Empty	25.5	50.9	40.9	28.2	25.3
Insecta	6.2(4.3)	3.8(0.1)	--	--	--
Hexagenia sp.	3.1(0.2)	3.8(0.1)	--	--	--
Chironomidae	3.1(4.1)	--	--	--	--
Fish					
Osmerus mordax	100.0(95.5)	100.0(100.0)	100.0(100.0)	100.0(99.9)	100.0(99.9)
Age 0	46.8(1.0)	11.5(0.4)	3.8(0.3)	48.4(8.7)	48.0(8.9)
Age I	75.0(78.2)	50.0(7.0)	65.3(31.5)	43.9(26.5)	24.0(20.0)
Older	15.6(16.3)	53.8(92.6)	38.4(68.2)	30.3(64.7)	28.0(71.0)
Unidentified	18.0(0.1)	3.8(<0.1)	--	10.6(0.1)	16.0(<0.1)

(continued)

TABLE 19. (CONTINUED)

Item	June	July	August	September	October
Young Walleye (<200 mm TL)					
Number of Stomachs	11	38	56	37	29
Percentage Empty	54.5	52.6	40.3	48.6	44.8
Cladocera	--	5.8(<0.1)	10.0(<0.1)	--	--
Fish					
Osmerus mordax	100.0(100.0)	92.2(100.0)	89.9(98.4)	100.0(93.9)	75.0(94.6)
Age 0	40.0(7.9)	38.8(23.1)	36.6(9.7)	73.6(43.8)	75.0(94.6)
Age I	60.0(40.6)	27.7(9.6)	50.0(83.2)	31.5(50.1)	--
Older	20.0(51.5)	27.7(67.3)	3.3(5.5)	--	--
Unidentified	trace	11.7(<0.1)	20.0(0.6)	36.8(6.0)	25.0(5.3)

TABLE 20. WALLEYE FOOD CONSUMPTION AND PREY DENSITY DURING 1973

Month	Sample Size (No.)	Mean Wt. (g)	Total Consumption (mg/g/day)	Smelt Density		Smelt Eaten by Walleye	
				(mg/m^3)	(No./100 m^3)	Daily Consumption (No./100 m^3)	Monthly Consumption (No./100 m^3)
July	35	129	22.8	157	8.3	0.5	15.5
August	31	240	19.5	169	52.2	0.6	18.6
September	22	148	21.0	317	46.5	1.0	30.0

INFLUENCE OF TURBIDITY ON LAKE TROUT

Lake Trout Distribution in Lake Superior

Lake trout sampled during 1975 and 1976 were generally limited to water exceeding 15 m deep. Distribution of lake trout, as described by bottom trawl catches, (9.5 m net) appeared to be influenced by turbidity although turbidity was low during 1975 and 1976. Catches indicated that the number of lake trout/100 m^3 in water from 15 to 40 m deep increased exponentially with water clarity (Figure 15; $P < 0.05$).

Response of Lake Trout to Laboratory Turbidity Gradients

The time juvenile lake trout resided in a gradient chamber section descreased with turbidity (Figure 16). The inverse relationship between lake trout residence time in a chamber section and turbidity was stronger for observations made under dark conditions (Table 18). Differences between day and night appear to be explained by increased activity during the light phase of the 24 h cycle (t-test; $P < 0.001$). Activity during the daylight period resulted in more time being spent in turbid section of the gradient chamber as a result of increased movement. Activity of lake trout in gradient chambers was higher than that of walleye.

Experiments with 15 lake trout (145 to 240 mm T.L.) held at 0, 6, 9, 28 and 54 FTU in 3 liter electrode chambers showed that even low turbidity resulted in increased activity. Activity was higher in turbid water and ranged from 1.5 to 7.3 times the activity of control fish held at 0 FTU (Table 21). The results suggest that lake trout are sensitive to turbidity as low as 6 FTU.

INFLUENCE OF TURBIDITY ON OTHER FISH SPECIES

Bottom trawl catches of longnose sucker, white sucker, and troutperch indicated these species were abundant in western Lake Superior. Regression analysis showed that red clay turbidity did not influence their distribution. The data suggested that distribution of white suckers was limited to warmer water in contrast to longnose suckers which appeared to concentrate in cooler water; however, differences were not significant ($P > 0.05$).

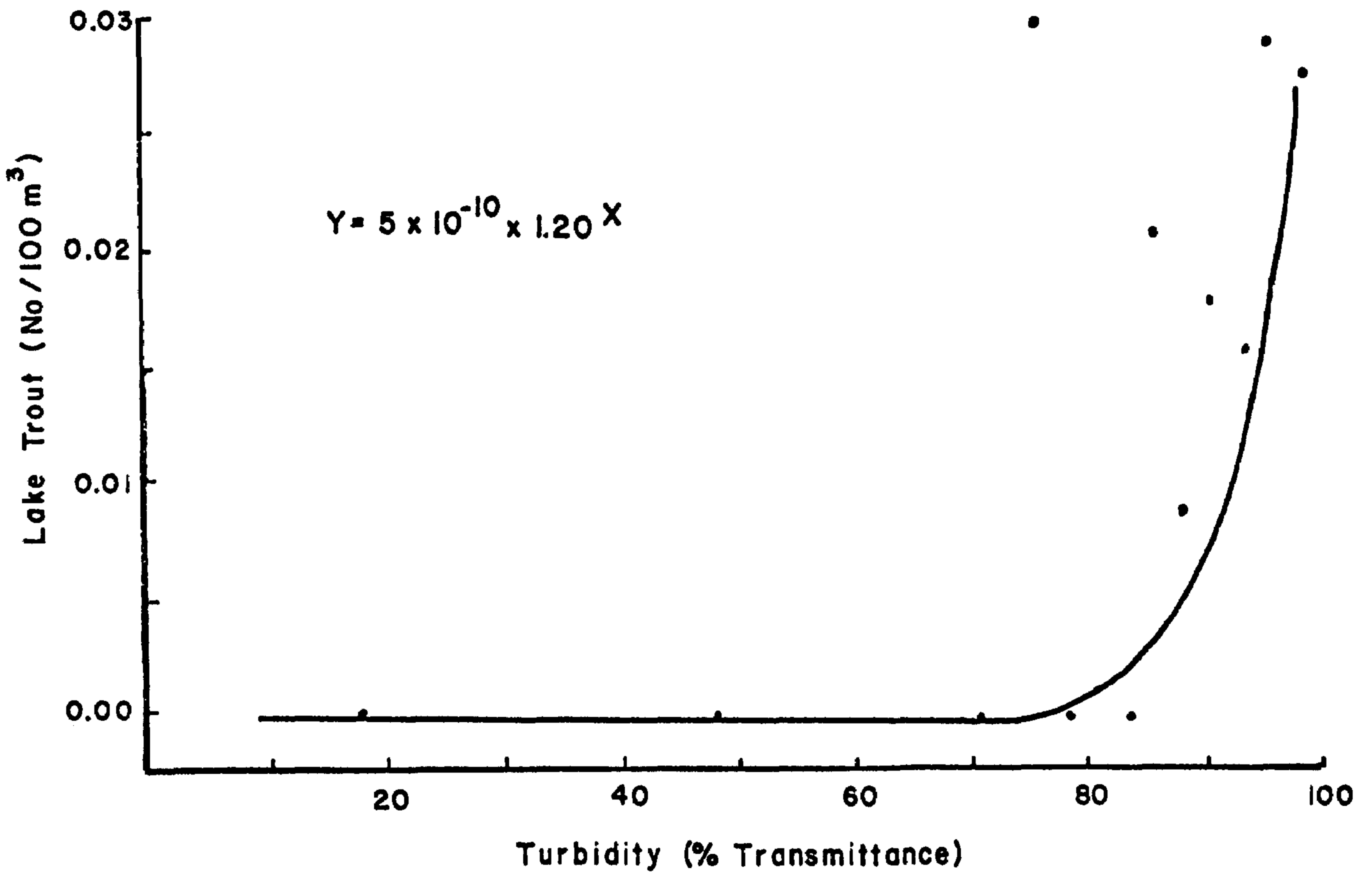

Figure 15. Relationship between percentage light transmittance (turbidity index) and the number of lake trout captured near the bottom at depths between 15 and 40 m.

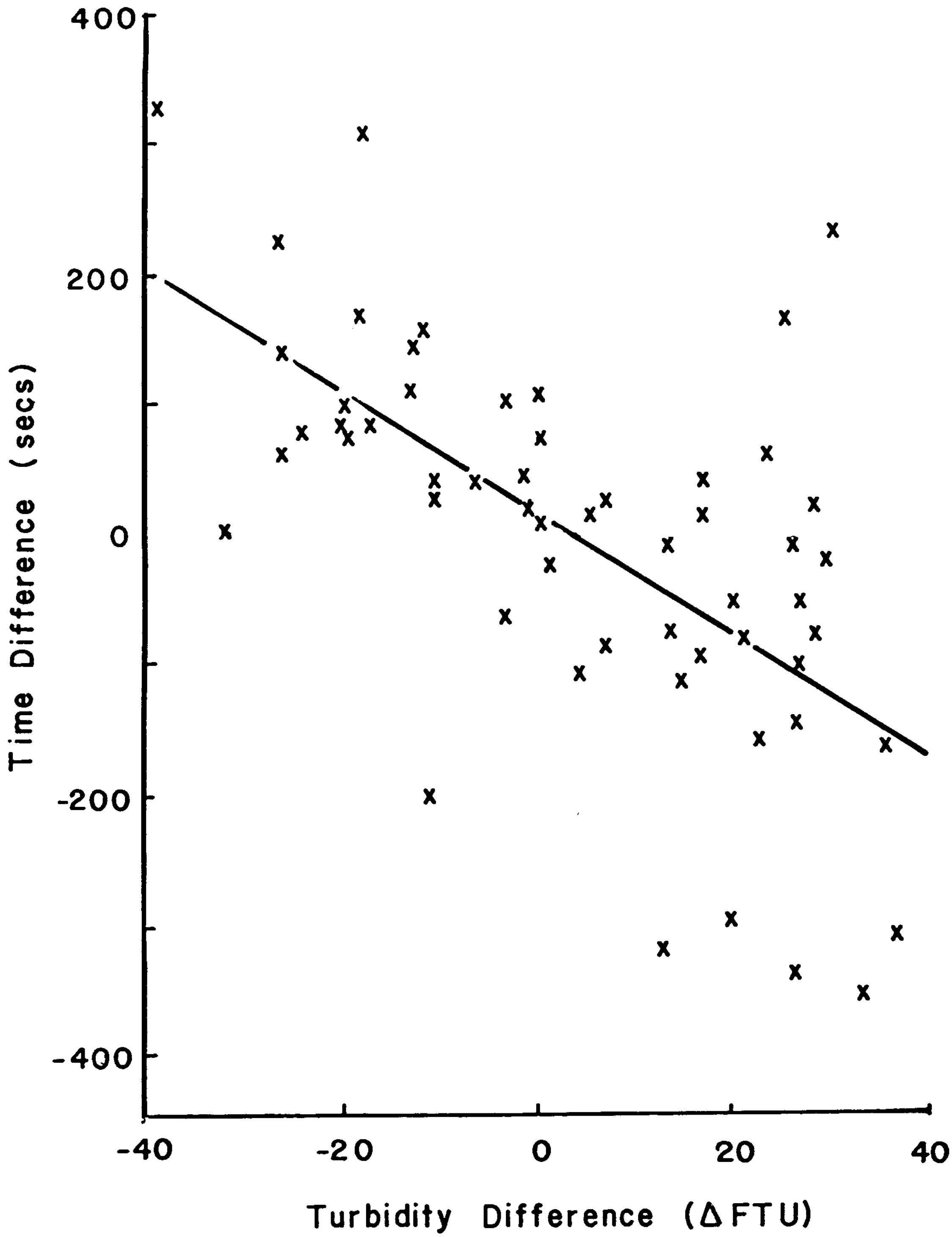

Figure 16. Response of juvenile lake trout in laboratory turbidity gradients. The relationship is predicted using the regression constants from Table 18.

TABLE 21. LAKE TROUT ACTIVITY AND TURBIDITY

Acclimation Time (h)	Test Duration (h)	Turbidity (FTU)	Number of Fish	Time Active %	Variation in Activity Between Fish (SD)	Activity† vs. Control
1.5	1.1	54	2	46.1	6.8	1.5
4.0	0.5	28	3	30.6	19.9	7.3
76.0	1.5	9	3	28.2	11.5	1.8
49.0	4.5	6	3	18.6	3.9	5.2
1.5-76	0.5-4.5	0 (control)	4	13.5	12.5	--

†Each test was performed with one fish in clear water (control). Division of percentage activity for lake trout subject to turbidity by activity in controls gave an estimate of the increase in activity associated with turbidity levels in these tests.

DISCUSSION

Several studies have shown that survival of advanced life stages of many fish species is not influenced by naturally occurring turbidity levels (see reviews by Cordone and Kelley 1961, Herbert and Merkens 1961). The larval herring bioassay conducted as part of this project indicates that natural levels of red clay turbidity in western Lake Superior have no direct influence on survival or growth during the sensitive larval stage. Although direct toxic effects were not identified, other phases of this project provide evidence that red clay turbidity is important to fish production in western Lake Superior.

The influence of red clay turbidity on fish production results from behavioral responses apparently brought about by reduced light penetration in turbid water. Light intensity was reduced significantly even at low levels of turbidity due to selective adsorption of shorter wavelengths.

The highest zooplankton densities occurred in surface waters (0.5-6.0 m) at stations characterized by red clay turbidity. High zooplankton densities appear to result from vertical migrations in response to reduced light penetration. Increased primary production may be stimulated by release of nutrients from red clays (Bahnick 1975). Higher primary production near the surface in turbid waters could also be responsible for high zooplankton densities.

Larval herring concentrated closer to the surface of laboratory test chambers at higher turbidity. Field observations demonstrate that smelt concentrate near the surface in turbid water (Figures 11 and 12) where plankton density is highest (Figure 8). Concentration of zooplankton and the fish which prey upon them in the same depth zone may be responsible for the former high abundance of lake herring in the Duluth-Superior area and present high abundance of smelt. Both species rely primarily on zooplankton as a food source. Because smelt feeding increases at dawn and dusk (Ferguson 1965), red clay turbidity may also influence smelt production by extending the period of low light intensity which stimulates feeding. Comparatively good growth of Age 0 smelt in turbid water stations is evidence that turbidity has a positive influence on smelt feeding.

Although red clay turbidity may have promoted production of the historically significant Duluth-Superior area lake herring stock by increasing zooplankton availability, the results of this investigation suggest that turbidity contributed to increased predation on larval herring by introduced smelt and was indirectly responsible for the extensive and rapid lake herring decline. Absence of larval lake herring from smelt stomachs is not unexpected with the present depressed herring stock in western Lake Superior. Commercial fishermen maintain that occurrence of young herring in smelt stomachs was common in the Duluth-Superior area prior to the herring decline.[3] Samples from Black Bay, Ontario, collected during 1973 verified that smelt prey on larval herring when they are available. Subsequent studies by the U.S. Bureau of Sports Fisheries and Wildlife and the Ontario Ministry of Natural Resources on Black Bay, Ontario, where herring are still abundant, showed that during a short period, apparently associated with the hatching of larval herring, 28% of the smelt population fed upon larval herring. Predation on larval herring was size dependent and 85% of the adult smelt contained larval herring in their stomachs. The average number of herring found in adult smelt stomachs was 35.8 (Selgeby et al., MS). Larval herring were not found in the stomachs of smelt captured by bottom trawls after the period, which lasted approximately ten days (Selgeby et al., MS). Failure of smelt to prey on larval herring after the period of hatching may result from changes in distribution. Herring larvae migrated toward the surface after hatching, whereas smelt concentrated on the bottom in clear water.

In the Duluth-Superior area, observations on smelt distributions made during this investigation and information on distribution of larval Coregonids (Anderson 1969) indicate that turbidity probably caused increased contact between smelt and larval lake herring. Anderson (1969) captured 7,109 Coregonid larvae in 673 larval net tows during 1966-1968 at stations near Duluth-Superior and in the Apostle Islands. The catches show larval herring densities were generally higher in water over 18 m deep and that larvae distributed throughout the water colum during April, May and early June but concentrate from 12 m to the surface during late June and July. Herring were not captured after July (Anderson 1969). This project demonstrated that during periods of red clay turbidity smelt move into the upper 12 m depth stratum. Percentage occurrence of young fish in smelt diets was high when they became pelagic although density of larval smelt was lower at midwater locations than near the bottom. Selection of larval fish by smelt was demonstrated in the laboratory where young smelt elected to feed on mobile larval herring over brine shrimp or herring embryos. Estimates of the number of young smelt consumed by older age groups and comparison with young smelt densities indicated cannibalism represents a significant source of mortality. Location of herring larvae further offshore (Anderson 1969) than young smelt increases the probability of contact between pelagic Age II and older smelt during turbid water periods and for predation on larval herring.

Analysis of commercial catch data shows inverse relationships exist between lake herring and smelt abundance in several of the Great Lakes, as summarized by Christie (1974) who concludes that smelt resulted in widespread decline of Great Lakes herring stocks. Anderson and Smith (1971b)

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[3]Personal communication, Mr. Stanley Sivertson, President, Sivertson Fishery Company, Duluth, MN.

show that important Duluth-Superior herring stock declined faster than herring inhabiting the clear waters of Lake Superior. They identified a significant negative relationship between herring and smelt abundance in western Lake Superior which was confirmed by this study. Although Anderson and Smith's (1971b) general conclusion is supported by the results of this study, they suggest that food competition was the primary mechanism resulting in change. High zooplankton densities, overlapping larval herring and smelt distribution, and significant predation by smelt on larval fish suggest that predation by smelt on larval herring rather than food competition contributed to the lake herring decline. In addition, ongoing surveys of the remnant herring stock show increasing dominance of older age groups and increased growth rates (Lake Superior Herring Subcommittee 1973). These observations would suggest that recruitment is failing in the presence of an adequate food resource and that food competition is not significant.

This study did not determine whether lake herring are attracted to turbid water areas. Lawrence and Scherer (1974) found white fish (Coregonus clupeaformis) in laboratory turbidity gradients preferred water with suspended drilling fluid concentrations of up to 1,000 ppm over clear water. In western Lake Superior, herring larvae would be subject to the same currents which distribute red clay. Sydor (1975) and Startz et al. (1977) found currents vary with wind condition and form back eddies which distribute turbid water along the Wisconsin south shore under northwesterly, northeasterly or northerly winds. Turbid water spreads out along the central axis (Minnesota District M-1) under easterly or westerly winds. High zooplankton densities and avoidance of red clay zones by lake trout represent environmental pressures which should result in increased survival of lake herring adapted to inhabit zones of red clay turbidity--a mechanism which lost its survival advantage with the addition of smelt to the system.

Abundance of lake trout was lower in western Lake Superior as a result of red clay turbidity. Net catches and laboratory results show lake trout are sensitive to low concentrations of red clay and partially avoid turbid water zones. Gill net catches showed differences in abundance between clear and turbid water stations were greater for juvenile lake trout. This variation may be attributable to sample size, location of lake trout plantings or to the persistence of red clay turbidity in near bottom water in the Duluth-Superior area. Turbidity of near bottom waters could isolate young lake trout from their principal food supply which Anderson and Smith (1971c) found was benthic crustaceans. Older lake trout fed primarily on smelt which became pelagic during turbid water periods. Pelagic smelt probably represent a highly available food resource for larger lake trout.

Red clay turbidity promotes production of walleye by reducing light to levels acceptable for feeding throughout the day and by causing smelt to become pelagic. Preference of walleye for turbid water was demonstrated by higher densities in turbid water areas and higher residence times in turbid water sections of laboratory gradients. Preference for turbidity is partially explained by adaptation of the eye of Stizostedion sp. for reduced light conditions (Ali and Anctil 1968). Other studies have demonstrated that walleye are usually crepuscular and night active predators which require high densities (>400 mg/m^3) of pelagic prey to maintain food consumption between 3 to 4% body weight, the level for maximum food consumption, food conversion efficiency and growth (Swenson and Smith 1973; Swenson 1977). Walleye were more active during high light periods in laboratory turbidity gradients and at night under clear water conditions, suggesting that the western Lake Superior population may have developed an activity pattern correlated with the low light conditions and pelagic distribution of prey resulting from periodic turbid water conditions.

Conditions encountered in Lake Superior made accurate estimation of walleye feeding rates impractical during most sampling days; however, estimates of consumption and prey density developed for five days during 1973 showed prey densities and food consumption were below optimum even in the turbid water zone which apparently represents an area of the lake where food availability is relatively high. Low abundance of walleye at clear water stations could result because food availability is near the minimum required for good production.

Walleye predation has been identified as the primary factor controlling survival of yellow perch in Oneida Lake (Forney 1971), Lake of the Woods, Minnesota, (Swenson and Smith 1976) and Shagawa Lake (Swenson 1977). Available information on walleye feeding rates and smelt density in Lake Superior provide some indication that walleye predation influences smelt survival. However, the major differences in distribution of walleye and smelt make interpretation of predation effects impractical.

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APPENDIX TABLE 1. TEMPERATURE AND TURBIDITY PROFILES

Temperature is °C, turbidity is FTU (in parenthesis) in waters exceeding 15 m sampled during 1975 and 1976.

Date	Stat. No.	Bottom Depth (m)	Sampling Depth								
			<1	3	6.1	9.1	12.2	15.2	18.3	21.3	24.4
1975											
June 21	2	24	10(9)	10(9)	10(9)	10(9)	10(9)	10(9)	9(8)	8(8)	--
June 23	2	24	12(5)	10(7)	10(7)	9(6)	9(6)	8(5)	6(5)	--	--
July 1	4	21	16(7)	14(7)	13(8)	13(7)	10(4)	8(7)	7(7)	--	--
July 4	4	25	20(8)	15(3)	15(3)	13(3)	11(3)	8(1)	6(3)	6(5)	5(6)
July 10	2	24	14(6)	14(6)	13(5)	10(3)	8(3)	6(3)	5(5)	4(7)	4(7)
July 15	4	25	18(6)	18(6)	15(4)	8(4)	6(3)	5(3)	4(3)	4(3)	--
July 16	2	23	14(7)	10(7)	7(5)	6(4)	5(7)	5(8)	5(8)	5(8)	5(8)
July 16	2	24	14(7)	10(7)	7(5)	6(4)	5(7)	5(8)	5(8)	5(8)	5(8)
July 22	2	23	8(2)	8(2)	7(2)	6(2)	6(2)	5(6)	5(6)	5(6)	--
July 30	2	24	21(4)	17(4)	11(3)	8(3)	7(5)	7(6)	7(6)	7(7)	7(8)
Aug. 13	2	24	18(2)	18(2)	17(2)	7(2)	5(4)	4(4)	4(4)	4(5)	4(5)
Aug. 18	4	27	18(3)	18(3)	18(3)	7(1)	5(1)	5(2)	4(3)	4(8)	4(8)
Sep. 5	4	24	13(1)	13(1)	13(1)	13(1)	13(1)	13(3)	12(5)	12(6)	11(8)
Oct. 13	2	18	11(1)	11(1)	11(1)	11(1)	11(1)	11(1)	11(1)	--	--
1976											
May 18	4	24	7(1)	7(1)	5(2)	5(3)	5(3)	5(3)	5(3)	--	--
May 27	2	19	13(5)	11(2)	10(2)	9(1)	8(2)	5(1)	--	--	--
June 8	4	27	14(1)	11(2)	7(1)	6(1)	6(1)	6(1)	6(1)	6(1)	3(1)
June 10	2	28	14(1)	13(1)	13(1)	10(1)	6(1)	6(1)	5(1)	5(4)	4(5)
July 2	4	27	16(3)	16(3)	11(1)	10(1)	9(1)	8(1)	6(1)	5(3)	4(6)
July 29	2	24	19(1)	18(1)	18(1)	18(1)	18(1)	18(1)	17(1)	4(1)	--
July 30	4	17	20(3)	19(3)	19(2)	18(1)	18(1)	17(1)	--	--	--
Aug. 11	4	26	21(1)	19(1)	19(1)	16(1)	13(1)	9(1)	7(2)	6(2)	6(3)

APPENDIX TABLE 2. LIGHT INTENSITY AND EXTINCTION IN RELATION TO TURBIDITY AND DEPTH

Average Turbidity (FTU)	Date	Station Number	Bottom Depth (m)	Deck	Light at Sampling Depths (m) 2	4	6	8	10	12	14	16	18	Ext. Coef. K
.465	7-29-76	2	22.6	74.1	35.6	20.1	10.7	4.99	3.25	2.01	1.71	1.49	1.04	.2157
.465	7-29-76	1	18.0	78.4	35.6	22.7	12.2	10.7	--	--	--	--	--	.2653
.465	5-27-76	2	23.2	64.1	14.5	5.56	2.48	1.23	0.64	0.31	0.15	60-3*	30-3*	.3624
.739	6-8-76	4	26.5	41.3	9.40	4.84	2.78	1.62	1.00	0.61	0.36	0.21	0.13	.2627
1.01	10-10-75	2	23.2	28.9	9.58	5.02	3.02	1.70	0.98	0.57	0.32	0.18	0.11	.2797
1.01	7-30-76	4	16.7	69.8	2.95	--	0.48	0.28	0.24	0.14	0.04	36-3*	--	.3079
1.28	5-20-76	4	10.1	49.9	6.13	1.24	0.25	0.06	0.01	--	--	--	--	.7765
1.50	7-29-76	2	22.6	83.4	4.48	2.74	1.48	0.76	0.41	0.25	0.14	84-3*	45-3*	.3038
1.56	8-11-76	4	8.2	78.4	13.2	3.33	--	--	--	--	--	--	--	.6812
1.83	8-11-76	4	24.7	78.4	35.9	23.1	15.8	11.1	7.84	5.27	3.42	2.05	1.17	.2231
2.10	5-18-76	4	23.8	92.6	38.5	22.2	12.4	6.70	3.46	1.97	1.13	0.67	0.38	.2771
2.92	10-10-75	2	22.6	31.2	5.51	1.52	0.56	0.18	59-3*	15-3*	45-4*	15-4*	56-5*	.5293
2.92	10-16-75	4	18.3	70.1	12.4	3.25	0.98	0.29	87-3*	29-3*	77-4*	42-5*	13-5*	.6292
3.20	5-18-76	4	13.4	88.4	2.99	0.35	70-3*	20-3*	70-4*	20-4*	--	--	--	.6971
3.89	6-10-76	4	5.2	82.6	6.69	1.50	0.23	--	--	--	--	--	--	.8194
4.14	5-18-76	4	6.7	89.8	13.2	2.48	0.90	--	--	--	--	--	--	.6106
4.14	10-10-75	3	19.5	21.4	0.64	81-3*	20-3*	40-4*	11-4*	51-5*	21-5*	77-6*	34-6*	.6292
4.98	5-27-76	4	9.8	34.2	1.50	0.14	15-3*	20-4*	--	--	--	--	--	1.103
5.29	7-2-76	4	4.6	85.5	7.41	1.03	0.14	--	--	--	--	--	--	.9835
6.31	6-16-76	4	7.6	45.6	1.75	0.19	27-4*	--	--	--	--	--	--	1.088
10.70	10-10-75	3	15.2	18.7	0.18	46-4*	25-5*	--	--	--	--	--	--	1.676
12.33	10-16-75	4	16.8	32.8	0.40	93-4*	56-5*	--	--	--	--	--	--	1.966

*Values given with negative exponents indicating the number of places the decimal point is to be adjusted to the left: for example, 60-3 is .060.

APPENDIX TABLE 3. FOOD OF SMELT

Food habits are for smelt captured during 1974-1976 by 6.1 or 7.6 m trawl. Smelt diets are described as percentage frequency of occurrence and percentage by number of items (in parentheses). Frequency of occurrence values are based on all stomachs analyzed.

Year	1974	1974	1975-1976
Length	<110 mm	>110 mm	
Number of Stomachs	132	254	211
Copepoda	67(64.6)	43(43.7)	65(46.5)
Cladocera			
Daphnia spp.	39(29.6)	41(39.0)	42(15.2)
Bosmina spp.	14(5.4)	17(14.7)	46(38.0)
Leptodora sp.	6(0.2)	4(0.3)	2(<.1)
Amphipoda			
Pontoporeia affinis	--	<1(<.1)	2(<.1)
Isopoda			
Mysis sp.	2(<.1)	2(<.1)	3(0.1)
Insecta	9(0.2)	13(<.4)	7(0.1)
Fish			
Osmerus mordax	>1(<.1)	8(0.1)	--
Other Fish	--	<1(<.1)	<1(<.1)
Unidentified	--	--	--

APPENDIX TABLE 4. CATCH BY SAMPLING DEPTH AND MONTH

Catch is number/100 m^3 estimated from seine (0.5 to 1 m) and 6.1 m trawl samples collected during 1973 and 1974 at stations 2 and 4.

	Sampling Depth (m)							
	June				July			
Species	0.5-1	1.8-4.7	4.8-7.6	7.7-15	0.5-1	1.8-4.7	4.8-7.6	7.7-15
Osmerus mordax (yy)	5.35	0.40	0.30	0.35	62.05	7.40	0.75	0.25
O. mordax (yl)	33.10	5.40	3.75	0.95	22.95	11.50	4.75	0.90
O. mordax (jv)	12.00	4.95	3.35	0.85	7.50	9.00	8.60	1.30
O. mordax (ad)	1.90	1.00	1.40	0.90	0.05	0.25	0.30	0.10
Stizostedion vitreum v. (yy)	0.30	0.20	--	--	0.25	0.30	--	--
S. vitreum v. (ad)	--	0.15	--	--	--	0.15	--	--
Salmonidae	--	--	--	--	--	--	--	--
Coregonus sp.	--	--	--	--	--	--	< .01	--
Lota lota	--	--	0.01	--	0.05	--	0.05	--
Catostomus catostomus	0.20	0.40	0.15	--	0.05	--	0.10	0.05
C. commersoni	--	--	0.05	--	--	0.10	--	--
Notropis sp.	1.65	--	--	--	5.55	--	--	--
Percopsis omiscomaycus	--	0.35	1.15	1.40	0.75	1.65	0.60	0.80
Cottus sp.	--	--	0.05	0.05	--	0.15	0.10	0.05
Alosa pseudoharengus	--	--	--	--	--	--	--	--
Couesius plumbeus	--	--	--	--	0.15	--	--	--
Percina caprodes	--	--	--	--	--	--	--	--
Gasterosteidae	0.03	< .01	--	--	--	--	--	--
Esox lucius	--	--	--	--	--	--	--	--
Pomoxis nigromaculatus	--	--	--	--	--	--	--	--
Cyprinus carpio	--	--	--	--	--	--	--	--
Ictalurus sp.	5.72	< .01	--	--	0.17	< .01	--	< .01
Ambloplites rupestris	--	--	--	--	--	--	--	--

(continued)

APPENDIX TABLE 4. (continued)

Species	Sampling Depth (m)							
	August				September			
	0.5-1	1.8-4.7	4.8-7.6	7.7-15	0.5-1	1.8-4.7	4.8-7.6	7.7-15
Osmerus mordax (yy)	279.2	24.35	30.05	6.80	597.1	129.1	45.95	46.05
O. mordax (yl)	15.75	3.40	3.00	2.30	2.05	4.35	7.35	2.20
O. mordax (jv)	1.05	0.40	0.45	0.55	0.40	1.75	2.20	0.65
O. mordax (ad)	--	0.20	0.15	0.15	0.45	0.50	0.10	0.25
Stizostedion vitreum v. (yy)	14.00	1.15	0.05	0.05	--	0.75	--	--
S. vitreum v. (ad)	--	0.15	0.15	0.05	--	0.05	--	0.05
Salmonidae	--	--	--	< .01	--	--	--	0.05
Coregonus sp.	--	--	< .01	--	--	--	--	--
Lota lota	--	--	--	--	--	--	--	--
Castostomus catostomus	26.10	0.45	0.50	--	--	--	0.25	0.05
C. commersoni	0.15	0.05	--	--	--	--	--	--
Notropis sp.	19.35	0.10	--	--	80.70	0.15	0.15	--
Percopsis omiscomaycus	0.25	0.90	3.15	0.20	--	2.90	0.55	0.70
Cottus sp.	--	0.05	0.25	0.20	--	0.30	0.30	1.80
Alosa pseudoharengus	0.45	--	--	--	0.80	--	--	--
Couesius plumbeus	0.75	--	--	0.05	--	--	--	--
Percina caprodes	0.12	< .01	< .01	--	--	--	--	--
Gasterosteidae	--	--	< .01	< .01	--	--	--	--
Esox lucius	--	--	--	--	0.08	< .01	--	--
Pomoxis nigromaculatus	0.55	--	--	--	--	< .01	--	--
Cyprinus carpio	--	--	--	--	--	--	--	--
Ictalurus sp.	5.719	< .01	--	--	0.17	< .01	--	< .01
Ambloplites rupestris	.061	--	--	--	--	--	--	--

(continued)

APPENDIX TABLE 4. (continued)

	Sampling Depth (m)			
	October			
	0.5-1	1.8-4.7	4.8-7.6	7.7-15
Osmerus mordax (yy)	38.05	5.25	4.65	5.35
O. mordax (yl)	1.30	.55	.40	.25
O. mordax (jv)	--	.05	.05	--
O. mordax (ad)	.20	.15	.20	.05
Stizostedion vitreum v. (yy)	--	.50	.05	--
S. vitreum v. (ad)	--	.05	.05	.05
Salmonidae	--	--	--	--
Coregonus sp.	--	--	--	--
Lota lota	1.20	--	--	--
Catostomus catostomus	--	--	--	--
C. commersoni	.05	--	--	--
Notropis sp.	20.15	--	.15	.10
Percopsis omiscomaycus	.10	--	.55	.85
Cottus sp.	--	.55	.05	.40
Alosa pseudoharengus	.13	.40	--	--
Couesius plumbeus	--	.50	--	--
Percina caprodes	--	--	--	--
Gasterosteidae	--	--	--	--
Esox lucius	--	--	--	--
Pomoxis nigromaculatus	--	--	--	--
Cyprinus carpio	--	--	--	--
Ictalurus sp.	--	--	--	--
Ambloplites rupestris	--	--	--	--

APPENDIX TABLE 5. CATCH BY SAMPLING DEPTH AND MONTH

Catch is number/100 m^3 estimated from 7.6 m trawl samples collected during 1973 and 1974 at stations 2 and 4.

	Sampling Depth (m)					
	June			July		
	1.8-4.7	4.8-7.6	7.7-15	1.8-4.7	4.8-7.6	7.7-15
Osmerus mordax (yy)	--	--	0.05	0.30	0.10	--
O. mordax (yl)	1.70	1.25	0.50	1.70	0.35	0.20
O. mordax (jv)	1.95	1.50	0.80	5.50	0.50	0.50
O. mordax (ad)	0.85	2.10	0.50	0.25	0.80	0.50
Stizostedion vitreum v. (yy)	0.10	0.10	--	0.15	0.05	--
S. vitreum v. (ad)	0.25	0.05	--	0.15	0.10	--
Salmonidae	--	--	--	--	--	--
Coregonus sp.	--	--	--	--	--	< .01
Lota lota	0.05	0.10	--	--	--	--
Catostomus catostomus	0.20	0.45	0.10	0.15	0.05	0.05
C. commersoni	--	--	--	0.10	--	--
Notropis sp.	0.05	--	--	--	--	--
Percopsis omiscomaycus	0.05	1.95	0.65	0.10	0.20	0.25
Cottus sp.	--	--	0.50	--	--	0.05
Alosa pseudoharengus	--	--	--	--	--	--
Couesius plumbeus	0.05	--	--	--	--	--
Percina caprodes	--	--	--	--	--	--
Gasterosteidae	--	< .01	--	--	--	--
Esox lucius	--	--	--	--	--	--
Pomoxis nigromaculatus	--	--	--	--	--	--
Cyprinus carpio	--	--	--	--	--	--

(continued)

APPENDIX TABLE 5. (continued

Species	Sampling Depth (m) August 1.8-4.7	August 4.8-7.6	August 7.7-15	September 1.8-4.7	September 4.8-7.6	September 7.7-15
Osmerus mordax (yy)	8.95	3.90	1.20	18.45	14.35	4.60
O. mordax (yl)	2.45	1.10	0.80	4.40	5.30	0.40
O. mordax (jv)	0.70	0.40	0.45	0.55	0.70	0.45
O. mordax (ad)	--	0.45	1.30	0.20	0.60	0.50
Stizostedion vitreum v. (yy)	0.30	0.05	0.05	0.80	0.35	0.10
S. vitreum v. (ad)	0.20	0.35	0.05	0.10	0.15	0.20
Salmonidae	--	< .01	< .01	--	< .01	--
Coregonus sp.	--	--	< .01	--	--	--
Lota lota	--	--	--	--	0.05	--
Catostomus catostomus	0.05	0.10	0.25	0.05	0.05	0.05
C. commersoni	0.05	0.05	--	0.04	--	0.05
Notropis sp.	--	--	0.10	0.20	--	--
Percopsis omiscomaycus	0.60	0.45	0.25	0.90	4.55	1.75
Cottus sp.	--	--	--	--	0.20	0.25
Alosa pseudoharengus	--	--	--	--	--	--
Couesius plumbeus	--	0.05	--	--	0.05	0.05
Percina caprodes	< .01	--	--	< .01	--	--
Gasterosteidae	--	--	--	--	--	--
Esox lucius	--	< .01	--	< .01	--	--
Pomoxis nigromaculatus	--	--	--	< .01	--	--
Cyprinus carpio	--	--	--	--	< .01	--

(continued)

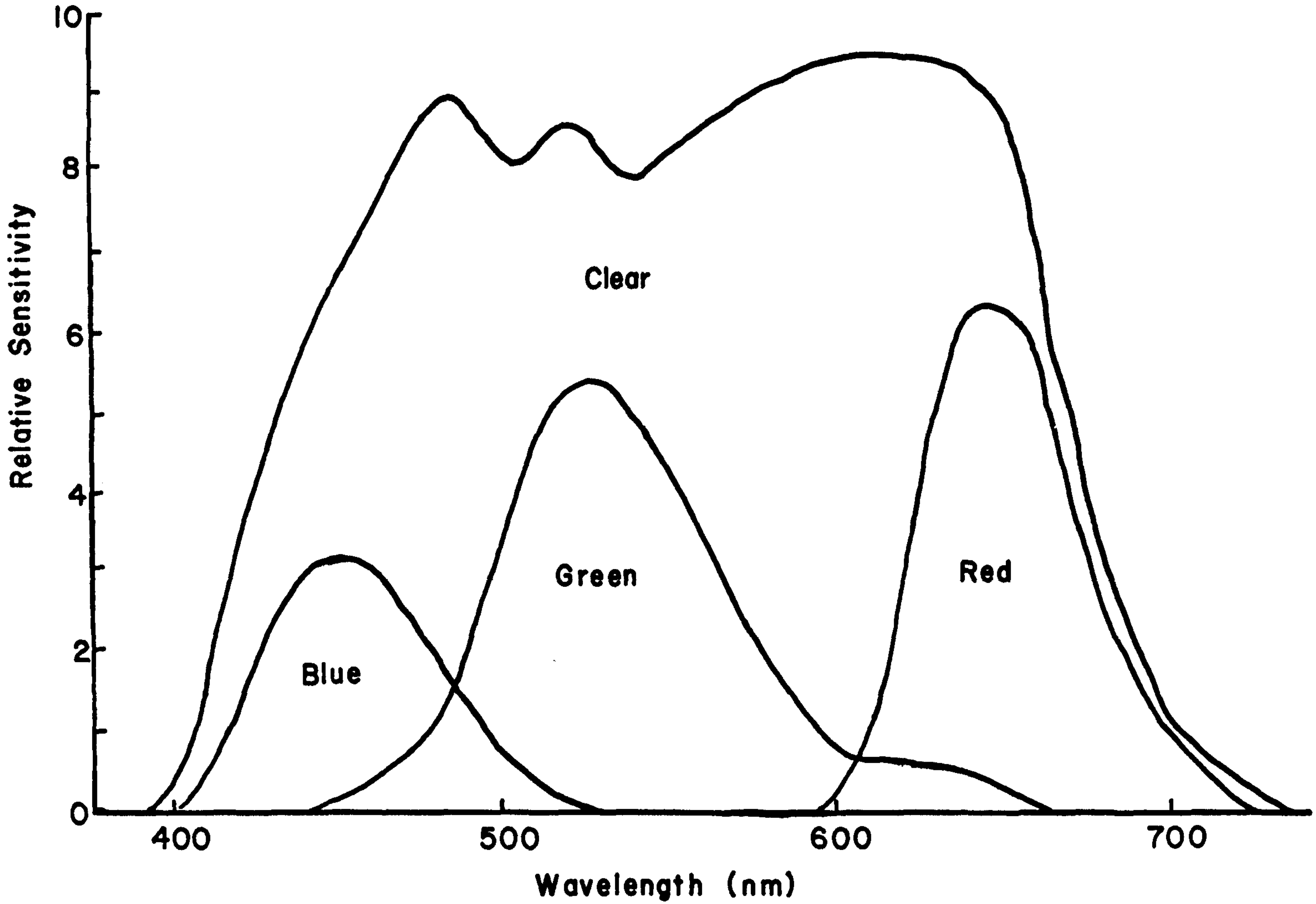
APPENDIX TABLE 5. (continued)

Species	Sampling Depth (m)		
	October		
	1.8-4.7	4.8-7.6	7.7-15
Osmerus mordax (yy)	8.50	9.30	1.00
O. mordax (yl)	1.20	1.00	0.10
O. mordax (jv)	1.10	--	--
O. mordax (ad)	0.50	0.30	0.10
Stizostedion vitreum v. (yy)	0.20	0.60	0.10
S. vitreum v. (ad)	0.10	0.10	--
Salmonidae	--	--	--
Coregonus sp.	--	--	--
Lota lota	--	--	--
Catostomus catostomus	--	--	0.10
C. commersoni	--	--	--
Notropis sp.	1.10	0.10	0.20
Percopsis omiscomaycus	0.70	1.30	0.30
Cottus sp.	--	--	--
Alosa pseudoharengus	--	--	--
Couesius plumbeus	--	--	--
Percina caprodes	--	--	--
Gasterosteidae	--	--	--
Esox lucius	--	--	--
Pomoxis nigromaculatus	--	--	--
Cyprinus carpio	--	--	--

APPENDIX TABLE 6. TURBIDITY CONVERSIONS

Units given in this table were converted using relationships provided in the text.

Percent Light Trans.	FTU	ppm	Percent Light Trans.	FTU	ppm
100	.465	.44	75	8.32	5.22
99	.739	.61	74	8.77	5.50
98	1.01	.77	73	9.23	5.78
97	1.28	.94	72	9.71	6.07
96	1.56	1.11	71	10.2	6.37
95	1.83	1.27	70	10.7	6.67
94	2.10	1.43	69	11.44	7.12
93	2.38	1.60	68	11.98	7.45
92	2.65	1.77	67	12.33	7.66
91	2.92	1.93	66	13.10	8.13
90	3.20	2.10	65	13.68	8.49
89	3.66	2.38	64	14.28	8.85
88	3.89	2.52	63	14.89	9.22
87	4.14	2.68	62	15.52	9.61
86	4.41	2.84	61	16.16	10.00
85	4.69	3.01	60	16.82	10.40
84	4.98	3.19	59	17.50	10.81
83	5.29	3.38	58	18.19	11.23
82	5.62	3.58	57	18.89	11.66
81	5.96	3.78	56	19.62	12.10
80	6.31	4.00	55	20.35	12.55
79	6.68	4.22	54	21.10	13.00
78	7.07	4.46	53	21.87	13.48
77	7.47	4.70	52	22.65	13.94
76	7.89	4.96	51	23.45	14.43
			50	24.26	14.98



APPENDIX FIGURE 1. Color response curves for Kahl Submarine Photometer (Model 268WA-320)

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/3-78-067	2.	3. RECIPIENT'S ACCESSION NO.
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15. SUPPLEMENTARY NOTES

Project Officer: J. Howard McCormick, ERL-Duluth

16. ABSTRACT This research project was developed to improve understanding of the influence of turbidity on fish populations and the mechanism through which its effects are induced.

Field and laboratory studies emphasized measurement of behavioral response of fish and resulting changes in fish species interrelationships in western Lake Superior Direct effects of red clay turbidity on survival and growth of larval lake herring (Coregonus artedii) were also measured.

Field measurements demonstrated that light penetration in western Lake Superior is reduced significantly even at very low levels of red clay turbidity. Zooplankton and fish abundance and distribution were influenced by turbidity. Zooplankton abundance and distribution was highest near the surface in red clay plumes. Smelt (Osmerus mordax) move into the upper 12 m of water in response to turbidity where their predation on larval fish increases. Predation by smelt on larval lake herring was identified as a potentially important factor contributing to the decline of the formerly abundant western Lake Superior lake herring population and the commercial fishery which depended upon it.

Walleye (Stizostedion vitreum vitreum) and lake trout (Salvelinus namaycush) demonstrated opposite responses to turbidity. Walleye concentrated in turbid water where food availability was apparently greater. Lake trout showed partial avoidance to turbidity in the lake and in laboratory turbidity gradients.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Turbidity Zooplankton	Red clay Predation Rainbow smelt Lake herring Cisco Walleye Species interactions Lake trout Lake Superior Avoidance Light penetration	06/F

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