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March 1980

INFLUENCE OF ADVANCED WASTEWATER TREATMENT ON THE FISHERY RESOURCE OF SHAGAWA LAKE, MINNESOTA

by

William A. Swenson

Department of Biology
University of Wisconsin
Superior, Wisconsin 54880

Project Officer

Paul D. Smith
Corvallis Environmental Research Laboratory
Corvallis, Oregon 97330

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FOREWORD

Effective regulatory and enforcement actions by the Environmental Protection Agency would be virtually impossible without sound scientific data on pollutants and their impact on environmental stability and human health. Responsibility for building this data base has been assigned to EPA's Office of Research and Development and its 15 major field installations, one of which is the Corvallis Environmental Research Laboratory (CERL).

The primary mission of the Corvallis Laboratory is research on the effects of environmental pollutants on terrestrial, freshwater, and marine ecosystems; the behavior, effects, and control of pollutants in lakes and streams; and the development of predictive models on the movement of pollutants in the biosphere.

This study was initiated to define what effects, if any, reduced nutrient loading had on the fish species complex in lakes. This information is essential to relating cost and benefits of the regulatory and enforcement activities of EPA as they relate to the national eutrophication problem. Although quantification of effects proved to be impractical within the time frame of this study, this report provides some new insights into the subtle mechanisms by which the fish species complex of temperate lakes is controlled by changes in their trophic status. A conceptual model developed to define the changes which occurred in Shagawa Lake will have application in predicting the general effects of controlling nutrient loading in other lake systems.

Thomas A. Murphy
Director
Environmental Research Laboratory-Corvallis

ABSTRACT

This project was conducted to measure the response of the warmwater fish populations in Shagawa Lake, Minnesota, to altered trophic conditions brought about by phosphate removal from sewage discharges entering the lake. The project also served to provide basic information on the mechanisms through which a lake's trophic status controls its fish species complex.

Abundance, distribution, growth, and feeding interrelationships of walleye (Stizostedion vitreum vitreum), northern pike (Esox lucius), yellow perch (Perca flavescens), and lake herring (Coregonus artedii) were described in relation to changes in prey density and other environmental factors. A conceptual model based on the "niche concept" was developed to identify the influence of changes in various parts of the system on individual fish populations and on the total fish species complex. Information on physical-chemical parameters and the response of other segments of the lake's community to the lake restoration process was provided by concurrent investigations conducted by or coordinated through the EPA Environmental Research Laboratory-Corvallis, Oregon.

Recycling of nutrients was found to slow the response of the system to the restoration program. Zooplankton density was not altered significantly, and hypolimnetic oxygen remained low throughout the three year period of study following the initiation of phosphate removal. Transparency and abundance of macrophytes increased. The field data and model suggest that production of walleye is being reduced by increased transparency, higher macrophyte abundance and continued low hypolimnetic oxygen concentrations. These factors restrict walleye feeding and their distribution. They also promote increased cannibalism and northern pike predation. Growth and production of yellow perch and lake herring appears to be limited by some of the same factors which control production of walleye and by apparent changes in the zooplankton assemblage. The "niche" and production of the northern pike population is expanding in response to changes in several feeding-related "niche dimensions."

It is recommended that advanced wastewater treatment and the fish studies be continued to allow for improved precision in measuring the effects of altered trophic conditions on fish production and to promote higher hypolimnetic oxygen concentrations and related fish production in Shagawa Lake.

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The coordinating efforts of Mr. Paul Smith, the EPA project officer, were significant to efficient operation in the field and in insuring that information developed through related Shagawa Lake research was available for our analysis.

INTRODUCTION

Shagawa Lake, St. Louis County, Minnesota, is a softwater Canadian shield lake on the edge of the Boundary Waters Canoe Area, where tourism represents a significant part of the regional economy. Paleolimnological studies indicate Shagawa Lake was mesotrophic prior to the arrival of European settlers around the turn of the century and subsequently became eutrophic (Bradbury and Waddington, 1973; Gorham and Sanger, 1976). Municipal effluent from the city of Ely represents the probable cause for the change in trophic status. Sediment deposition resulting from inlake disposal of mine tailings and logging in the region may have contributed to the eutrophication process (Bradbury and Megard, 1972).

Shagawa Lake supports important sport fisheries for walleye (*Stizostedion vitreum vitreum*), northern pike (*Esox lucius*) and lake herring (*Coregonus artedii*). Yellow perch (*Perca flavescens*) are also abundant. Walleye and northern pike are fished during all seasons. Lake herring are taken during the autumn spawning period when gill netting is permitted. Importance of the fisheries is suggested by the presence of four active resorts and by the almost continuous line of marker buoys which dot much of the shoreline during the herring netting season. Herring fishing is stimulated by the relatively low parasite infestation rates (*Triaenophorus* sp.) and large size of fish in the Shagawa Lake population. Fishery surveys conducted by the Minnesota Department of Natural Resources suggest densities of walleye, northern pike and lake herring in Shagawa Lake exceed averages for Northern Minnesota lakes.[1]

Shagawa Lake was selected by the U.S. Environmental Protection Agency to demonstrate the effectiveness of advanced wastewater treatment in reducing nutrient loading and promoting return of culturally enriched waters to their natural trophic level. An advanced wastewater treatment plant was constructed and began operation in 1973 reducing total phosphorus loading to the lake by 75% (Larsen *et al.*, 1975). The recovery process was studied extensively by agency and cooperating scientists to define the response of the system and the mechanisms that controlled the changes which occurred.

This fish population study was performed to measure the response of the fish species complex to lake restoration. The primary objective was to develop a conceptual model that would describe significant changes in the fish stocks and the mechanisms which control change. Development of the model

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[1]Minnesota Department of Natural Resources, Shagawa Lake Survey Reports for 1959, 1966 and 1967.

was based on existing information, analysis of habitat alterations in Shagawa Lake (conducted primarily by cooperating scientists) and on a comprehensive study of the Shagawa Lake fish species complex. Niche theory served as the framework for the model. The geographic extent of the cultural eutrophication problem, the cost of lake restoration and the need for information on the influence of lake restoration on fishery resources represent the stimuli which resulted in the study.

Altered hypolimnetic oxygen concentration is frequently identified as the cause for shifts in the fish species complex of lakes subject to cultural eutrophication or restoration (Beeton, 1969; Lukowics, 1967; Colby and Brooke, 1969; Colby, 1972; Leach et al., 1977). Where anoxic conditions occur or are approached, production of coldwater species has declined. Population changes have been identified with two types of stress. Fish inhabiting the hypolimnion are stressed directly by low oxygen and may exhibit reduced growth or survival (Colby, 1972). Reduced growth and survival also occur when oxygen stress stimulates migration into the epilimnion and results in thermal stress or increased interaction with warmwater species. These modes of action have been identified as the mechanisms through which eutrophication results in reduced production or extirpation of many coldwater species, including the lake herring (Frey, 1955; Beeton, 1969; Colby and Brooke, 1969; Colby et al., 1972). Conversely, where lake restoration has resulted in increased hypolimnion oxygen concentrations, production of coldwater fish has been stimulated (Lukowics, 1967).

Although hypolimnetic oxygen depletion may restrict populations from habitat which would normally be available, a positive relationship between fish growth and trophic status of lakes appears to be characteristic except under conditions of advanced eutrophication. The positive relationship is attributable to increased energy availability (Leach et al., 1977; Oglesby, 1977). Analysis of fish populations in several lakes undergoing eutrophication shows that the optimum trophic condition for yellow perch and walleye is high with the optimum for yellow perch exceeding that of walleye (Leach et al., 1977). Eggers et al. (1978) found growth and production of yellow perch and other benthic-littoral species declined as Lake Washington recovered from advanced cultural eutrophication. Production of pelagic planktivores in Lake Washington was not influenced by shifts in the plankton community associated with the recovery process. Eggers et al. (1978) attributed the difference in responsiveness to the strength of refuges that each habitat provides. Because benthic-littoral species are provided greater cover and protection from predation, it is suggested that they are more likely to be resource limited and responsive to changing trophic status.

Relationships between prey density and feeding rates of walleye (Swenson and Smith, 1976; Swenson, 1977) show prey densities exceed the levels limiting to walleye feeding in mesotrophic Lake of the Woods, Minnesota, during most of the growing season, but are below the limiting level throughout the year in oligotrophic Lake Superior. These observations and those of Beeton (1969), who suggests destruction of spawning habitat occurs under eutrophic conditions, indicate the mechanisms which control the relationship between trophic level and walleye production.

Destruction of spawning and cover habitat has been suggested as the mechanism which controls the relationship between northern pike production and trophic status of Oneida Lake. On the basis of historic information, Forney (1977) suggests that production of northern pike was higher during early years when the lake was mesotrophic and supported an extensive growth of macrophytes. With cultural enrichment, abundance of macrophytes and northern pike declined. Forney's (1977) observations are supported by Makowecki (1973) who showed northern pike density is positively correlated with abundance of macrophytes and by Hurley and Christie (1977) who found macrophyte abundance declines in eutrophic lakes in response to reduced transparency.

Forney (1977) proposes that reduced abundance of northern pike in Oneida Lake stimulated production of walleye because interspecific food competition and predation were reduced. Food densities and light levels favorable to walleye feeding have been found to occur under mesotrophic and moderately eutrophic conditions (Swenson, 1977) and represent alternate or additional mechanisms which may have resulted in accelerated walleye production in Oneida Lake in recent years.

The importance of light intensity as an isolation mechanism between walleye, yellow perch and other species has been considered by Kerr and Ryder (1977) on the basis of niche theory. They suggest that the reduction in light intensity which occurs at higher trophic levels in lakes serves to isolate feeding of yellow perch and walleye in time, expanding the niche of both species by reducing their feeding interactions. Because most physical and biological requirements of a population can be identified as individual niche dimensions and are subject to measurement, they suggest the niche concept provides a useful framework for development of models which explain the response of resource populations to changes in lake systems.

CONCLUSIONS

This study demonstrated that no dramatic changes have occurred in the fish species complex of Shagawa Lake during the first three years of tertiary wastewater treatment plant operation. Internal cycling of nutrients within the lake slowed the response of the entire system to reduced nutrient loading. The rates at which changes are occurring suggest that internal processes are effective in maintaining system stability and in controlling the rate at which lake systems proceed from one trophic equilibrium condition to another. The rate of system response substantiates the need for extended research in measuring the influence of lake restoration on lake communities. Although the duration of this project did not provide for quantitative measurements of the effects of lake restoration in the Shagawa Lake fish species complex, the general responses of major species populations were described and a conceptual model useful in defining the changes which occurred and the mechanisms responsible for bringing them about was developed.

The field data and model indicate that increased transparency and expanded distribution of macrophytes are resulting in higher production of light-tolerant species which associate with macrophytes, particularly northern pike. Production of walleye and other species not well adapted to high light intensities or the occurrence of macrophytes appear to be declining. This study indicates that macrophytes are expanding their distribution to water 4 m deep as a result of increased transparency and that walleye do not distribute near macrophytes. Feeding success of walleye was reduced during periods of increased light intensity and when age 0 yellow perch concentrated in areas with macrophytes. Availability of yellow perch appears to control walleye production through its influence on feeding and growth and by regulating walleye cannibalism which increases when yellow perch are not available. In addition to cannibalism, an expanding northern pike population appears to be increasing predation pressure on the walleye population. Northern pike prey heavily on walleye during July-August when age 0 walleye concentrate in inshore areas. Increased northern pike production is demonstrated by above average growth during 1974 and 1975. Northern pike appear to be taking advantage of high yellow perch availability in areas with macrophytes.

Depressed oxygen conditions during the 1974-1976 sampling period limited distribution of walleye and troutperch (*Percopsis omiscomaycus*), the two most abundant light-sensitive species, to water less than 5 m deep during much of the open water season. At the same time, increased light intensity and macrophytes restricted their distribution and feeding in the inshore area. If continued lake restoration results in maintenance of hypolimnetic oxygen concentrations above 5 ppm, the habitat available to troutperch and walleye would expand. Increased production and availability of troutperch and macroinver-

tebrates should result in improved feeding, growth and production of walleye. Increased availability of alternate foods in the deep water areas should promote higher walleye survival by limiting walleye cannibalism. Increased availability of macroinvertebrates in deep water (>5 m) should also stimulate faster growth and production of the yellow perch and lake herring.

RECOMMENDATIONS

It is recommended that research on the effects of lake restoration activities on Shagawa Lake be continued. Although it is recognized that wastewater treatment plant operation and ongoing research represent sizable investments, continuation of the project is important from several points of view. The project is providing information on the benefits and costs of lake restoration essential to the development of effective national and international pollution control programs. At a time when government is requiring major expenditures for pollution control, the identification of benefits and costs to the resources that these expenditures are expected to improve must be a prerequisite. Studies conducted under the Shagawa Lake program represent a primary source for such information. Shagawa Lake research has demonstrated that a variety of mechanisms exist which can slow a lake's response to reduced nutrient loading. Further study should provide an opportunity to accurately identify the relative influence of these homeostatic mechanisms and to predict which mechanisms will exert the greatest control in Shagawa Lake and similar lake systems. Understanding of these mechanisms and the ability to predict their effects is important in identifying the influence of pollution control activities on fisheries and to the general area of fishery management. Because fish represent a primary pollution-related concern of the public, an important recreational resource and an important source of protein, information gained through continued study of the Shagawa Lake fish species complex would have broad application.

Under present conditions, changes brought about by lake restoration measures have resulted in a loss of walleye habitat, the principal species in the fishery. The results of this study suggest that continued control of nutrient loading will benefit the Shagawa Lake fish community if higher oxygen concentrations are maintained in the hypolimnion, thereby enlarging the niches of walleye, troutperch, yellow perch and lake herring.

Because the study design minimized impact on the species complex and provided precise measurements of those dynamic characteristics which are most responsive to system energetics, continued analysis of the fish species complex should follow a similar design. It is recommended that additional work be initiated during 1981 or 1982. The delay is recommended to insure that the response of the fish species complex will have progressed enough to be measured accurately.

Continued work on Shagawa Lake should provide general estimates of production for major warmwater species under varying trophic conditions. Predictive models developed through such studies would find broad application in designing lake restoration programs.

METHODS

FIELD SAMPLING

The field sampling program was designed to provide information on abundance, growth, feeding and distribution of resource populations and abundance and distribution of prey. Fish were collected during 1974-1976 on 52 days from 25 stations (Table 1, Figure 1).

A 7.6 m (25 ft) headrope semiballoon trawl, 3 cm (1-1/4 in) bar-mesh with a 0.6 cm (1/4 in) cod liner was the principal gear used in collecting samples. A total of 337 tows were made at depths from 1.2 to 13 m. The occurrence of rocks on the bottom made trawling impossible in most inshore areas. Trawling was limited to three shallow water (<5 m) stations (Stations I, II, III; Figure 1) and three deep water (>5 m) locations (Stations IV, V, VI; Figure 1) where the substrate was composed primarily of sand and organic materials. Sampling was stratified on the basis of fish abundance with most trawling occurring at inshore stations during June through mid-September and at the deeper water stations during late-September through November. However, tows were made in shallow and deep water during most days to provide information on distribution.

Tow distances were estimated from readings of a Clarke-Bumpus meter which was towed with the net on selected dates during 1974-1975 and from readings of a net meter mounted in a Tri-Vane which was towed with each trawl during 1976. Standard 5 min trawls covered 365 m. Average trawling distance was equivalent to approximately one twentieth of the maximum length of Shagawa Lake and one eighth of its maximum width. Measurement of the net opening permitted estimation of the average volume sampled (1,600 m^3). Depth was measured by fathometer (Vexilar Model 510) or by dropping a lead line at one or two minute intervals during trawling. Temperature was measured at most trawling locations with a Yellow Springs Instrument Model 43 Telethermometer or a Model 54A oxygen-temperature system. Oxygen was measured on selected dates. Presence of aquatic macrophytes or other debris in the net was generally noted. Gross estimates of the volume of macrophytes in tows made at different depths served as an index of macrophyte abundance and distribution.

Gill nets and seines were used to sample areas and segments of the fish species complex not effectively captured by trawl. Nets similar to those used during the Minnesota Department of Natural Resources surveys were employed so catches could be compared. Experimental gill nets were 77 m (250 ft) by 1.9 m (6 ft) with 5 meshes of 1.9, 2.5, 3.2, 3.8 and 5.1 cm (0.75, 1, 1.25, 1.5, 2.0 in) bar mesh. Gill nets were used on 15 sampling days and a total of 41 sets were made (Table 1). Three nets were usually set overnight

TABLE 1. SAMPLING EFFORT, SAMPLING STATIONS, WATER DEPTH, TEMPERATURE AND OXYGEN CONCENTRATION IN THE SAMPLING ZONE

Days	Stations[a]	Sampling Effort: Seine 15 m	Sampling Effort: Seine 61 m	Sampling Effort: Trawl	Sampling Effort: Gill Net	Trawling Depth Range (m)	Temperature °C and Oxygen (ppm)[b]: Surface	Temperature °C and Oxygen (ppm)[b]: Bottom
1974								
June 5, 6	I,II,III,A,B,D,E, 1,3	4	--	16	2	1.5 - 10	16(10.5)	12(2.8)
July 12	II,III,B,D,E,1,2	3	--	11	2	1.5 - 6	22(9.0)	15(3.8)
Aug. 21, 22	II,III,B,E,4,5	2	--	9	2	1.5 - 9	21(9.6)	20(4.5)
Sept. 20	II,III,E,8	2	--	6	2	1.5 - 11	13(8.4)	12(8.3)
1975								
May 29, 30	II,III,IV,A,E,F	2	2	11	--	1.5 - 12	19(10.2)	10(5.1)
June 10-12	II,III,IV,C,E,1	2	--	11	3	1.8 - 12	16(9.9)	8(1.3)
June 27, 28	II,III,IV,VI,A,E	2	--	17	--	1.5 - 13	20(8.9)	12(0.5)
July 11, 12	II,III,IV,VI,C,E	2	--	16	--	2.4 - 13	21(8.1)	11(0.3)
July 29-31	II,III,IV,VI,1	--	--	16	3	1.5 - 9	22(9.0)	19(0.2)
Aug. 20, 21	II,III,IV,VI,1,8	--	--	15	3	1.5 - 13	20(8.6)	20(0.8)
Sept. 12, 13	II,III,IV,V,8,11	--	--	15	3	1.5 - 10	15(8.6)	15(8.0)
Sept. 26-28	I,II,III,IV,V	--	--	22	--	1.5 - 12	13(8.5)	13(7.3)
Oct. 27, 28	II,III,IV,V,9,11	--	--	11	3	1.2 - 10	8(10.0)	8(10.1)
Nov. 13, 14	II,III,V,6,10,12	--	--	7	4	1.8 - 9	5(10.8)	5(10.6)

(continued)

TABLE 1 (continued)

Days	Stations[a]	Sampling Effort: Seine 15 m	Sampling Effort: Seine 61 m	Sampling Effort: Trawl	Sampling Effort: Gill Net	Trawling Depth Range (m)	Temperature °C and Oxygen (ppm)[b]: Surface	Temperature °C and Oxygen (ppm)[b]: Bottom
1976								
June 2-4	I,II,III,V,A,E	3	--	19	--	1.5 - 11	21(9.1)	12(0.7)
June 18, 19	I,II,III,9	--	--	16	2	1.5 - 7	18(8.2)	16(6.6)
July 8-10	II,III,C,D,E	5	--	29	--	1.5 - 8	23(10.0)	19(1.4)
July 22, 23	III,IV,8,11	--	--	11	3	1.8 - 9	22(9.7)	20(3.5)
Aug. 4, 5	I,II,III,IV,C,D,E	4	--	16	--	1.8 - 12	22(7.1)	22(0.2)
Aug. 19, 20	I,II,VI,1,8	--	--	8	3	1.8 - 8	22(9.9)	21(3.7)
Sept. 1-3	I,II,III,IV,C,D,E	4	--	23	--	1.5 - 8	19(7.4)	19(5.0)
Sept. 17, 18	II,III,V,4,5	--	--	12	3	1.8 - 11	18(11.5)	17(5.5)
Oct. 6, 7	II,III,VI,C,D,E	4	--	15	--	1.8 - 10	12(8.8)	11(8.4)
Oct. 20, 21	II,VI,7,13	--	--	5	3	1.8 - 12	4(11.0)	7(9.7)
Total: 52		39	2	337	41			

[a]Trawl stations are denoted by Roman numerals, seining stations by letters and gill net stations by Arabic numerals. Physical location is identified in Figure 1.

[b]Oxygen concentrations for 1974, 1975 and June 1976 were collected by EPA project staff at Brissons Point (Station 8).

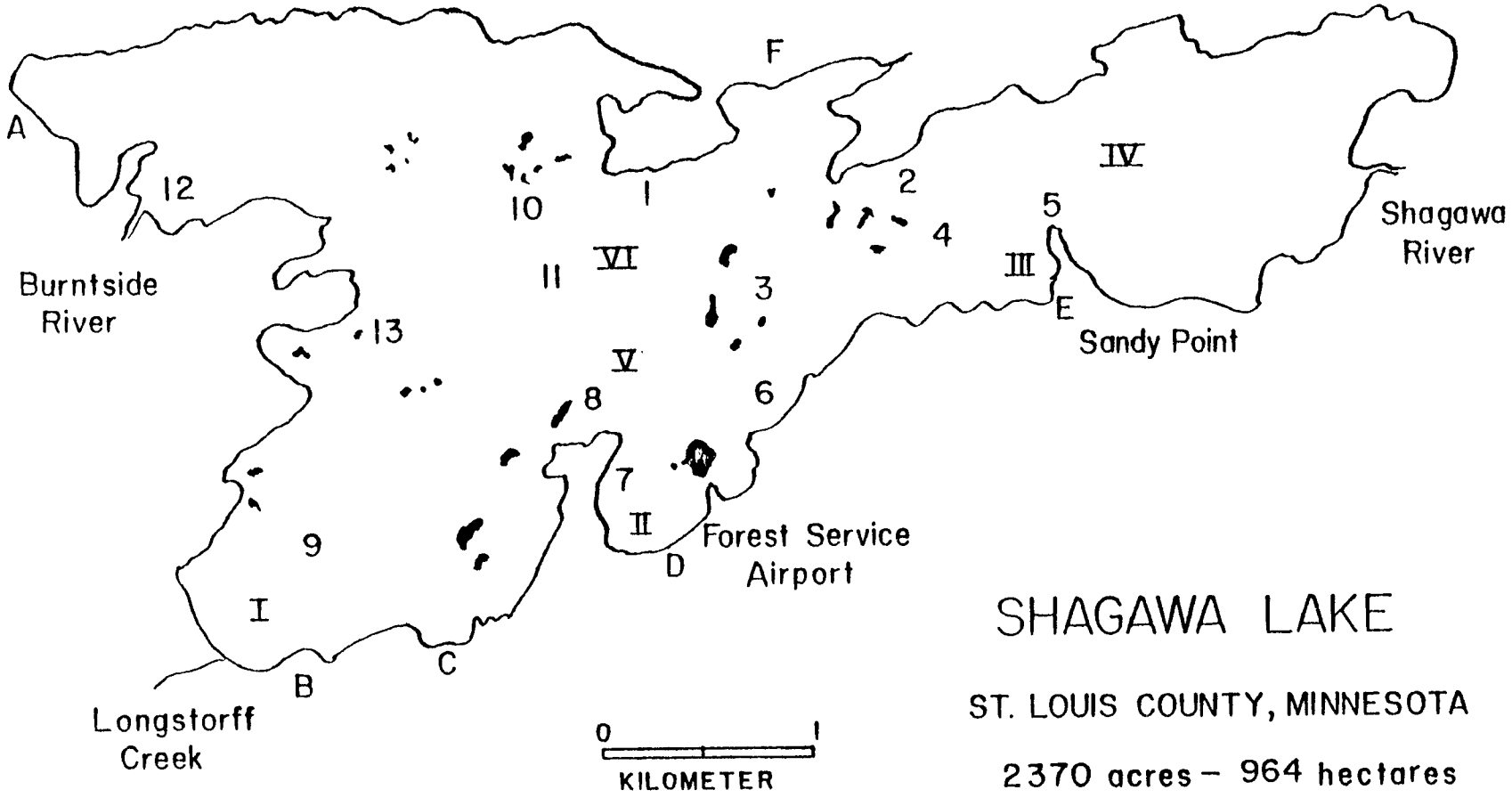

Figure 1. Map of Shagawa Lake, Minnesota, showing trawling (Roman numerals), gill net (Arabic numerals), and seining (lettered) stations.

(20-25 h) with one suspended near the surface (0.5 to 2.5 m), one suspended midwater (3-6 m) and one set on the bottom. The gill nets were more effective in capturing walleye exceeding 400 mm total length (TL) than the trawl (Swenson and Smith, 1976).

A 15.4 m (50 ft) by 1.9 m (6 ft) seine constructed of 0.6 cm (1/4 in) bar-mesh with a 1.1 m (3.5 ft) bag was used to sample the nearshore zone. The area seined was measured and sampling volumes were calculated from estimates of the area seined and average seining depth. Use of the seine was limited by the occurrence of rocks, depth inshore and dense growths of aquatic macrophytes which appeared to be more prevalent during 1975 and 1976. A larger seine (62 m x 1.9 m; constructed of 1.9 cm bar-mesh) was tested on two days to determine its effectiveness in capturing northern pike. However, aquatic macrophytes made use of the gear impractical. Ineffectiveness of the method limited the number of northern pike in the sample (Table 2).

Total catch was recorded for each species. Abundance of age 0 and older individuals was reported separately for larger species. Length, weight, scale samples and stomach samples or stomach content were collected in the field from walleye, northern pike, lake herring, yellow perch and white sucker (Catostomus commersoni) (Table 2). All walleye and yellow perch stomach samples were collected from trawl catches. Some northern pike and most lake herring samples were taken from gill net catches. A stomach pumping system (Swenson, 1972) was used to remove food from walleye exceeding 125 mm TL which were then returned to the lake alive. The portion of the digestive tract between the anterior end of the esophagus and terminus of the pyloric sphincter was removed from perch, lake herring and northern pike exceeding 125 mm TL. Stomach content from larger walleye, excised stomachs from other species and intact smaller fish (<125 mm) were preserved in 5 to 10% formalin.

ABUNDANCE AND DISTRIBUTION ANALYSIS

Densities of fish effectively sampled by trawl and seine were estimated from field counts and sampling volume estimates. Densities were expressed as number per 100 m^3 for both large and small species or size groups. Average weights of prey size fish were calculated for each sampling day (bimonthly, for less abundant species). Prey density was calculated as the total catch of all prey sized fish, expressed as milligrams prey per cubic meter of water ($mg \cdot m^{-3}$).

Changes in abundance of various fish species were related to indicies of primary production (chlorophyll α concentration), oxygen concentration, abundance of macrophytes, time, depth and predation rates to define the potential influence of these factors on distribution and abundance. Estimates of prey density ($mg \cdot m^{-3}$) were used in measuring the influence of food availability on food consumption by walleye and as a means of comparing energy availability in Shagawa Lake with other waters.

Catch per gill net set was compared with Minnesota Department of Natural Resources Fishery Survey catches to identify changes in abundance. Catches

TABLE 2. TOTAL NUMBER OF FIVE MAJOR FISH SPECIES CAPTURED FROM SHAGAWA LAKE WITH THE NUMBER OF INDIVIDUALS EXCEEDING AGE 0 SUBSAMPLED FOR STOMACH CONTENTS, TOTAL LENGTH MEASUREMENT AND AGE DETERMINATION

Fish Species	Year	Total Captured	Number Sampled for Stomach Contents	Number Measured for Total Length	Number Sampled for Age Determination
Stizostedion vitreum v.	1974	1,106	425	995	356
	1975	1,491	901	1,275	656
	1976	4,454	945	1,973	506
Perca flavescens	1974	22,464	0	263	89
	1975	55,359	427	517	186
	1976	76,727	675	628	394
Coregonus artedii	1974	72	0	33	45
	1975	464	188	457	275
	1976	173	76	158	80
Esox lucius	1974	82	2	71	45
	1975	95	54	91	90
	1976	83	44	62	62
Catostomus commersoni	1974	1,958	20	196	67
	1975	5,366	98	539	180
	1976	4,414	0	402	0
Totals		174,308	3,855	7,660	2,899

from gill nets set at different depths were used to describe vertical distribution.

GROWTH, POPULATION STRUCTURE AND MORTALITY MEASUREMENTS

Walleye age and growth were estimated from 366 scale samples subsampled from 1974-1976 collections and 86 scale samples subsampled from collections made during the 1967 Minnesota Department of Natural Resources Survey.[2] Scale samples from 331 lake herring, 669 yellow perch and 192 northern pike subsampled from the 1974-1976 collections and from 69 northern pike collected during 1967 were used in measuring growth.

Determination of age was made from cellulose acetate impressions with annuli in walleye and perch distinguished on the basis of criteria for ctenoid scales (Hile, 1941; Regier, 1962). Lake herring annuli showed accessory checks after the first year. Checks were distinguished from true annuli by the degree of lateral cutting and intensity of circuli in the posterior field. All scales were read at least twice to assure accuracy using an Eberbach projector which magnified the image 44X (walleye and lake herring) or 100X (perch and northern pike). Growth to each annulus was back-calculated using body-scale relationships and corrected nomographs (Carlander and Smith, 1944).

Body-scale relationships were developed from total length measurements and measurement of anterior scale fields for 137 walleye and 70 northern pike collected during 1967 by the Minnesota Department of Natural Resources and from 400 walleye, 259 northern pike, 669 yellow perch and 331 lake herring collected during this study (1974-1976). Separate body-scale relationships were developed for the 1967 and 1974-1976 sampling periods to control variation between the two periods.

Growth of walleye is described for each year-class from 1966 through 1975. Growth of the 1967-1976 yellow perch year-classes, 1966-1974 lake herring year-classes and 1961-1966 and 1969-1975 northern pike year-classes was measured. Grand average length was calculated and compared to growth estimates for other waters. Percentage deviation in mean annual growth (Hile, 1941) and changes in annual growth increments were used to identify potential effects of lake restoration on growth and production.

Length modes of age 0 walleye and yellow perch were estimated for each sampling period and used to describe growth variation between 1974, 1975 and 1976. Differences between sampling seasons, comparisons with other waters and variations between the two species were used to identify the conditions which control growth during the first year of life.

Age structure of walleye, northern pike and lake herring populations was described from the selected aged samples and the larger random sample of fish

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[2]Scale samples collected during 1967 were provided by Dennis Ernst, Minnesota Department of Natural Resources, Fisheries Manager.

measured in the field. Assignment of age to fish measured in the field was based on the procedure of Ketchen (1950). Population structure was used to compare the general success of year-classes during years following lake restoration and those immediately preceding treatment. Walleye age structure was used to construct a catch curve and estimate annual mortality (Ricker, 1975).

FEEDING ANALYSIS

Food habits of walleye, yellow perch, lake herring and northern pike were described through analysis of samples from 2,791 fish. Prey fish were identified on the basis of anatomical characteristics including features on scales, structure of vertebrae and structure of the gastrointestinal tract. Invertebrates were sorted and identified using keys by Eddy and Hodson (1962), Brooks (1957) and Edmondson (1959). A dissecting microscope (20-40X) was used in identifying invertebrates and some fish. Food from lake herring and yellow perch stomachs consisted primarily of invertebrates and was quantified volumetrically. The food of walleye and northern pike consisted primarily of fish and was quantified gravimetrically. Diets are described as percentage frequency of occurrence and percentage by volume or weight for stomachs containing food. Diets are reported separately for young-of-the-year walleye and for yellow perch less than 70 mm TL.

Food consumption rates and diel feeding periodicity were estimated from 1,270 walleye stomach samples taken from fish exceeding 200 mm TL during 30 days. Estimates are based on walleye digestion rates and the technique described by Swenson and Smith (1973). Food consumption was estimated as milligrams food consumed by the average individual in each day's catch ($mg \cdot g^{-1} \cdot day^{-1}$). The technique requires approximately 25 samples from a station, collected during a minimum of two sampling periods separated in time by no more than 12 h. To increase precision, stations were usually visited four to six times daily (Swenson and Smith, 1973). Estimates of average hourly consumption ($mg \cdot h^{-1}$) for 2 h periods were used to describe diel periodicity in feeding. The number of each prey species consumed by all walleye in a standard volume (walleye per 100 m^3) was estimated as the product of the weight of that species eaten by the average walleye ($mg \cdot g^{-1}$) multiplied by average walleye density ($g \cdot 100\ m^{-3}$) and divided by the average weight of the prey species (mg).

MEASUREMENT OF PARASITE INFESTATION RATES

Infestation of lake herring with the pleurocercoid stages of the tapeworm Triaenophorus sp. was defined by examination of fillets from 156 fish collected during 1974-1977[3] to determine if improved water quality resulted in changes in infestation rates. Fish were prepared for examination by a

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[3]Sampling was conducted September 16, 1977, specifically to collect herring for cyst analysis. Because of the limited nature of the 1977 sampling (3 gill net sets and 8 standard trawls), it has not been identified as a representative part of the field program.

filleting process which removed the backbone, rib bones and skin. Major muscle segments, muscles clinging to the bone and skin were examined visually.

RESULTS

PREY ABUNDANCE AND DISTRIBUTION

Analysis of 1974-1976 trawl catches shows density of smaller fish (<10 g) increases from June through August and then declines during September-October, in water less than 5 m deep (Table 3). The increase in abundance was associated with recruitment of age 0 yellow perch to July trawl catches and their rapid growth during the ensuing period. Comparisons between years show the highest densities occurred during 1975. Density was lowest during 1974 (Table 3). Comparison of estimated densities for Shagawa Lake (1974-1976) with those for Lake of the Woods, Minnesota (1969 and 1970) (Swenson and Smith, 1976), shows abundance of small fish in shallow water (<5 m) was consistently higher in Shagawa Lake. In contrast, density of small fish in deep water (>5 m) was higher in Lake of the Woods, due to an abundance of troutperch.

Low abundance of small fish in the deeper (>5 m) areas of Shagawa Lake during July and August (Table 3) reflects the influence of reduced oxygen concentrations and the preference of age 0 yellow perch for shallow water. Density estimates (Table 3) show age 0 yellow perch concentrate in shallow areas (<5 m) from July through September. A few sampling days occurred after autumn turnover and indicated yellow perch move into deep water (>5 m) during late September or early October. Variation in troutperch densities during July and August in deep water (>5 m) were positively correlated with oxygen concentrations at the sampling depth ($r = \pm 0.85$; $P < 0.01$). Regression analysis showed troutperch densities averaged approximately $0.8 \cdot 100\ m^{-3}$ when oxygen fell below 5 ppm but increased to $10.7 \cdot 100\ m^{-3}$ at higher oxygen concentrations. Positive relationships between oxygen concentration and abundance of age 0 and older yellow perch were indicated.

Possible improvement in spawning habitat or increased abundance of macrophytes may be responsible for the relatively high abundance of age 0 yellow perch and black crappie, *Pomoxis nigromaculatus*, during 1975. Catches of age 0 walleye were higher during 1975 and 1976. Abundance of age 0 walleye during 1976 may have been influenced by the planting of 2 million fry by the Minnesota Department of Natural Resources during May.[4]

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[4]Personal Communication, Mr. John Blakesley, Fisheries Manager, Minnesota Department of Natural Resources.

TABLE 3. ABUNDANCE OF VARIOUS SPECIES AND SPECIES GROUPS WITH NUMBERS IN PARENTHESIS REPRESENTING DEEP WATER SAMPLES (>5 m)

		Number per 100 m^3								Prey Density ($mg \cdot m^{-3}$)
		Yellow Perch		Trout-		Walleye		White	Other*	
Period	Lifts	Age 0-I	Older	perch	Shiners	Age 0	Older	Sucker	Prey	
1974										
June	14(2)	0.0(0.0)	0.8(1.8)	4.0(2.7)	2.4(0.2)	0.0(0.0)	0.9(0.2)	0.3(0.0)	0.2(0.0)	132(68)
July	8(3)	24.2(7.8)	0.3(0.1)	0.1(0.0)	0.4(0.1)	0.0(0.1)	4.1(0.1)	0.4(0.4)	0.9(0.0)	187(52)
Aug.	8(1)	61.5(3.0)	0.9(0.5)	10.1(2.9)	20.0(2.0)	0.2(0.0)	1.4(0.0)	0.3(0.0)	5.8(0.1)	1994(194)
Sept.	4(3)	3.2(1.0)	0.4(0.2)	7.4(1.1)	11.6(5.9)	0.3(0.1)	1.3(0.8)	0.1(0.0)	1.3(0.0)	673(228)
1975										
June	13(9)	19.5(0.8)	0.6(0.2)	0.3(0.9)	0.7(0.1)	0.0(0.0)	0.6(0.2)	1.3(0.2)	0.1(0.0)	585(40)
July	11(18)	38.3(25.1)	0.9(0.5)	4.7(9.4)	2.4(2.1)	0.4(0.5)	1.0(0.5)	2.3(0.6)	4.2(6.3)	483(445)
Aug.	7(8)	111.4(11.1)	0.4(0.3)	23.7(8.7)	8.5(0.2)	0.2(0.1)	0.4(0.3)	0.8(0.5)	41.7(1.1)	3488(470)
Sept.	22(14)	28.2(11.3)	0.5(0.7)	9.5(8.0)	4.4(4.0)	0.1(0.1)	0.5(0.7)	0.6(0.2)	2.1(0.7)	1905(1009)
Oct.	6(3)	66.9(1.7)	0.1(0.2)	0.5(0.4)	5.5(1.5)	0.0(0.1)	0.1(0.2)	0.8(0.1)	1.0(1.7)	2127(150)
Nov.	4(2)	1.8(0.9)	0.2(0.4)	0.1(4.7)	0.4(0.1)	0.1(0.0)	0.2(0.4)	0.0(0.1)	0.2(0.2)	117(314)
1976										
June	26(6)	4.3(1.8)	0.3(0.4)	1.3(1.8)	0.2(0.0)	0.0(0.0)	0.5(0.4)	0.2(0.2)	0.2(0.2)	126(121)
July	22(11)	90.9(33.4)	0.7(0.2)	4.0(0.6)	4.8(10.9)	0.8(0.6)	0.7(0.3)	0.5(0.2)	0.7(0.5)	1520(975)
Aug.	18(4)	45.3(24.3)	0.3(0.1)	7.3(2.8)	7.3(3.5)	3.5(1.4)	0.5(0.6)	0.2(0.2)	3.6(0.6)	1930(1046)
Sept.	28(3)	45.6(3.2)	0.1(0.2)	4.4(27.3)	5.8(0.0)	2.3(0.5)	1.2(0.3)	1.6(0.2)	4.6(0.2)	2678(1826)
Oct.	12(5)	31.6(1.6)	0.2(0.2)	0.7(10.7)	1.1(3.6)	2.3(1.8)	0.3(1.0)	0.0(0.6)	0.1(0.4)	1549(1091)

*Etheostoma nigrum, Percina caprodes, Pomoxis nigromaculatus, Ambloplites rupestris, Lopomis macrochirus, Micropterus dolomieui, Catostomus commersoni, Coregonus artedii, Ictalurus melas, Noturus gyrinus, Lota lota and Osmerus mordax.

ABUNDANCE AND DISTRIBUTION OF AGE II AND OLDER FISH

Walleye and yellow perch catch per gill net set (CPE) for the 1974-1976 period was lower than during the 1959, 1966 and 1969 Department of Natural Resources lake surveys (Table 4). Comparison of CPE for 1974-1976 with the catches made in earlier years suggests abundance of northern pike, lake herring and white suckers has not changed significantly (Table 4).

Distribution of walleye appeared to be correlated with changes in distribution and abundance of the smaller fish which they preyed upon. Trawl catches showed walleye concentrated in shallow water (<5 m) where age 0 yellow perch density was high during July and August. Abundance of walleye was higher in deeper water during early June and late September when abundance of small fish increased offshore. Gill net catches demonstrated that walleye occupy the near surface and midwater depths where pelagic age 0 yellow perch concentrate in addition to areas near the bottom (Table 5). Gill net catches show lake herring are abundant at all depths (Table 5).

WALLEYE POPULATION STUDIES

Population Structure and Survival

Age structure of the walleye population was estimated from length frequency distribution and aged samples following the method of Ketchen (1950). The analysis showed that the population was dominated by the 1972 year-class which was followed by a weak 1973 year-class (Table 6). Abundance of age 0 walleye in the 1975 catches and age I walleye in 1976 catches suggests the formation of a second strong year-class in 1975. Strength of the 1975 walleye year-class appears to be related to high food availability during 1975, when age 0 yellow perch densities were high. Abundance of walleye and age 0 yellow perch during 1975 may result from favorable temperatures. Higher than normal spring water temperatures occurred during 1975. A similar situation occurred during 1972 (Appendix Table 1).

A catch curve was constructed by plotting log·e of frequency (ages I-XI) on age (Figure 2). Instantaneous mortality (i) (Ricker, 1975) was estimated as the slope of a line describing changes in frequency (log·e) with age, for age groups V-XI. Frequencies of younger age groups were influenced by the unusually large 1972 year-class and were omitted to avoid bias. The instantaneous mortality rate of 0.58 is equivalent to an annual mortality of 44% and a survival rate of 56%. The survival rate compares favorably with estimates by Heyerdahl and Smith (1972) for Lake of the Woods, Minnesota (31%), and by Smith and Pycha (1961) for Red Lakes, Minnesota (30%). Survival of Shagawa Lake walleye was similar to the rate estimated by Johnson (1975) for Wilson Lake, Minnesota (62%).

Growth

Shagawa Lake walleye average 132 mm at the end of their first year, 395 mm at age V, and 555 mm at age IX (Table 7). Comparison with other Minnesota lakes suggests first year growth in Shagawa Lake is slower (Table 8).

TABLE 4. CATCH PER BOTTOM SET OF EXPERIMENTAL GILL NETS IN SHAGAWA LAKE

Sampling Year	Number of Sets	*Stizostedion vitreum v.*	*Coregonus artedii*	*Esox lucius*	*Catostomus commersoni*	*Perca flavescens*
1959[a]	15	38.6	10.9	0.9	17.1	19.4
1966[a]	7	37.9	36.5	3.7	11.0	33.7
1967[a]	11	22.4	26.5	2.4	10.4	16.0
1974	8	5.6	6.6	6.6	4.5	11.0
1975	7	15.0	22.7	3.3	18.6	9.1
1976	6	10.5	15.8	1.7	7.3	9.0

[a]Data from Minnesota Department of Natural Resources, Shagawa Lake Survey Reports.

TABLE 5. CATCH PER SET OF EXPERIMENTAL GILL NETS SET NEAR THE SURFACE (Upper 3 m) MIDWATER (3 to 9 m) AND ON THE BOTTOM IN SHAGAWA LAKE

Year	Set		Catch				
	Type	(No.)	*Stizostedion vitreum v.*	*Coregonus artedii*	*Esox lucius*	*Catostomus commersoni*	*Perca flavescens*
1974	Bottom	(8)	5.6	6.6	6.6	4.5	11.0
	Surface	(4)	5.3	18.5	2.0	5.0	10.5
1975	Midwater	(4)	7.3	30.8	2.8	8.0	7.3
	Bottom	(7)	15.0	22.7	3.3	18.6	9.1
	Surface	(5)	7.2	10.0	0.4	0.6	1.8
1976	Midwater	(3)	7.7	1.7	2.0	5.3	2.3
	Bottom	(6)	10.5	15.8	1.7	7.3	9.0
	Surface	(9)	6.3	14.2	1.2	2.8	6.2
1974-1976	Midwater	(7)	7.5	16.3	2.4	6.7	4.8
	Bottom	(21)	10.4	15.0	3.9	10.1	9.7

TABLE 6. AGE FREQUENCY DISTRIBUTION OF SHAGAWA LAKE WALLEYE CAPTURED BY SEINE, TRAWL AND GILL NETS DURING 1974, 1975 AND 1976

Age	Year Class	Number in Age Group	Length Range in Millimeters
1974			
0	1974	85	60 - 150
I	1973	5	136 - 181
II	1972	540	167 - 300
III	1971	2	281 - 310
IV	1970	14	282 - 488
V	1969	8	355 - 437
VI	1968	7	409 - 485
VII	1967	4	421 - 560
VIII	1966	1	480
IX	1965	2	593 - 663
X	1964	1	529
		Total: 669	
1975			
0	1975	526	48 - 165
I	1974	163	100 - 228
II	1973	11	160 - 239
III	1972	818	212 - 367
IV	1971	15	268 - 388
V	1970	35	324 - 445
VI	1969	8	431 - 518
VII	1968	7	450 - 503
VIII	1967	8	442 - 538
IX	1966	2	556 - 660
X	1965	4	489 - 605
XI	1964	1	692
XII	1963	1	700
XIII	1962	1	759
		Total: 1600	
1976			
0	1976	3453	61 - 187
I	1975	289	130 - 268
II	1974	62	197 - 297
III	1973	5	225 - 339
IV	1972	528	244 - 454
V	1971	10	380 - 500
VI	1970	6	425 - 512
VII	1969	4	437 - 572
		Total: 4357	

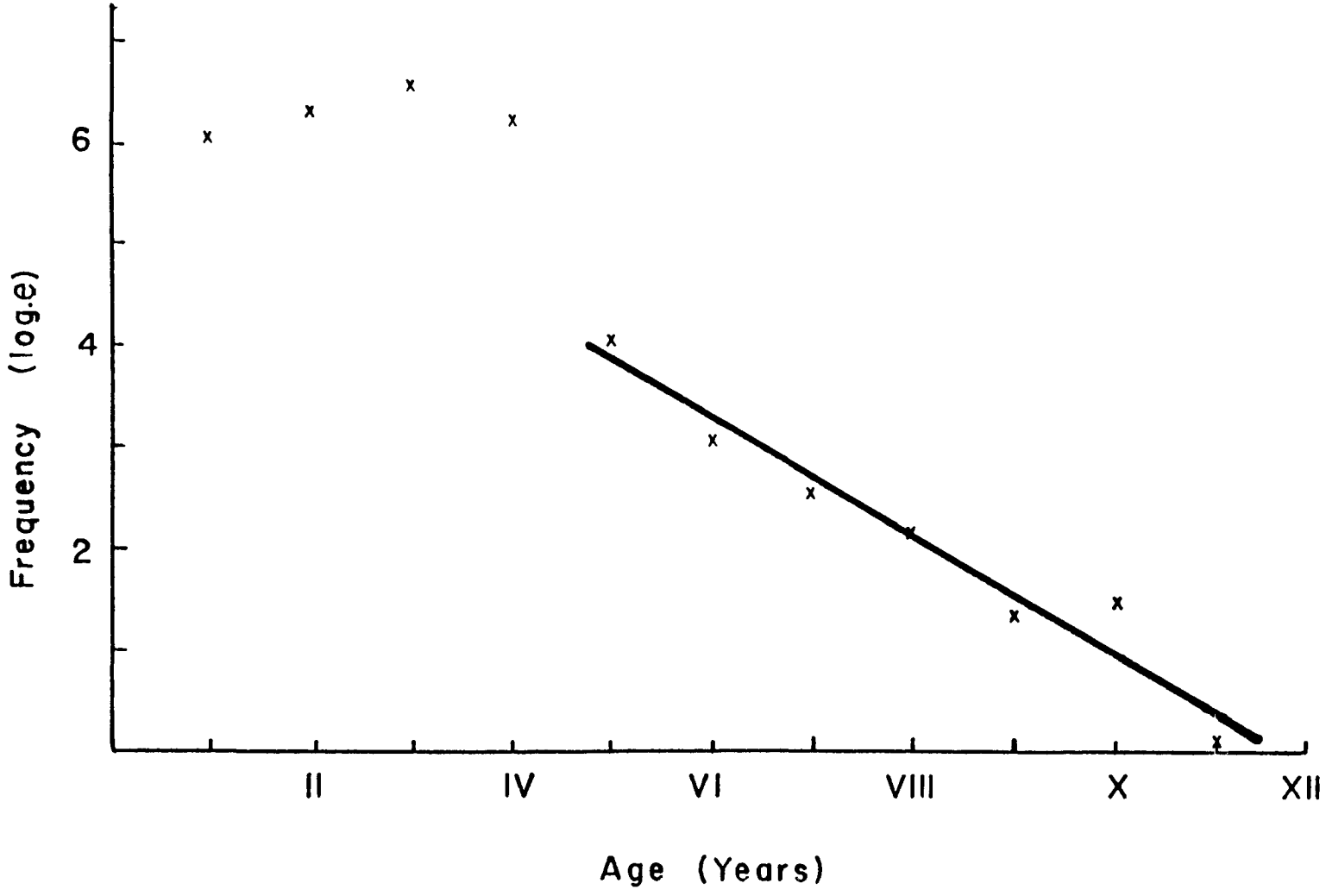

Figure 2. Shagawa Lake walleye catch curve. The line was fitted to the plotted points by the formula: $y = 6.73 + (-0.58X)$.

TABLE 7. CALCULATED TOTAL LENGTH OF THE 1965 THROUGH 1975 WALLEYE YEAR-CLASSES EXPRESSED IN MILLIMETERS

Year Class	No. in Sample	Age Group									
		I	II	III	IV	V	VI	VII	VIII	IX	X
1965	5	129	205	269	333	383	422	453	485	514	534
1966	3	134	239	312	391	434	463	495	524	596	--
1967	12	128	203	280	341	385	429	458	477	--	--
1968	13	116	186	269	334	390	430	450	--	--	--
1969	18	129	216	286	353	400	445	478	--	--	--
1970	40	130	185	264	312	361	432	--	--	--	--
1971	12	132	211	280	328	414	--	--	--	--	--
1972	165	145	199	242	340	--	--	--	--	--	--
1973	14	138	194	258	--	--	--	--	--	--	--
1974	50	124	192	--	--	--	--	--	--	--	--
1975	34	141	--	--	--	--	--	--	--	--	--
Grand Average	366	132	203	273	343	395	437	467	495	555	534

TABLE 8. CALCULATED TOTAL LENGTH IN MILLIMETERS AT SUCCEEDING ANNULI FOR WALLEYES FROM VARIOUS MINNESOTA WATERS

Water	No. in Sample	Length at Age								
		I	II	III	IV	V	VI	VII	VIII	IX
Shagawa Lake (1976)	366	132	203	273	343	395	437	467	495	555
Shagawa Lake (1967)	86	159	208	281	353	413	455	476	523	608
Lower Red Lakes (Smith and Pycha, 1961)	5152	141	212	266	309	344	371	392	410	431
Lake of the Woods (Heyerdahl and Smith, 1972)	391	155	227	289	348	392	433	466	497	522
Lake Vermilion (Carlander and Hiner, 1943)	--	148	213	260	302	342	378	411	451	498

However, size attained by age III exceeded that of the Lake Vermilion and Lower Red Lake, Minnesota, populations. Calculations based on samples collected during 1967 indicate growth in Shagawa Lake has declined. These differences may reflect actual changes in growth; however, precision of estimates based on the 1967 samples is limited due to variability in the body-scale relationship and small sample size.

Calculated deviations from mean annual growth (Hile, 1941) indicated growth declined during 1973 and 1974 and then increased during 1975 (Figure 3). Deviations in growth followed a pattern similar to chlorophyll α concentrations (CERL, 1977). The coefficient of correlation between average annual chlorophyll α concentration and annual growth deviations was not significant ($r = +0.69$; $P > 0.1$). Annual increments of age groups I through VI (Table 9) accrued during the pretreatment period (1965-1972) were compared with those accrued during years after operation of the tertiary treatment plant had resulted in reduced nutrient levels in Shagawa Lake (1974-1975). Two way analysis of variance demonstrated that growth during 1974 was significantly lower ($P < 0.01$) than the average for the pretreatment period (1965-1972). However, increments accrued during 1975 and the average for the 1974-1975 post treatment period did not differ significantly from the average for the pretreatment period ($P > 0.1$; Table 9).

Comparison of age 0 walleye growth during 1974, 1975 and 1976 showed the highest rates occurred during 1975 (Figure 4). Growth differences appear to be related to abundance of age 0 yellow perch during the three growing seasons (Table 3). Morsell (1970) showed that the availability of yellow perch is a factor controlling growth in age 0 walleye.

Feeding

Age 0 Walleye--

Relative length of age 0 walleye and yellow perch had a major influence on the percentage occurrence of yellow perch in the diet of age 0 walleye (Figure 5; Appendix Table 2). Occurrence was highest (60 to 80%) when length of age 0 yellow perch did not exceed 45% of age 0 walleye length. Occurrence was low (0 to 55%) when age 0 yellow perch length exceeded 50% of age 0 walleye length. Changes in relative length were associated with changes in age 0 walleye growth. During September 1975 when growth of age 0 walleye was rapid, age 0 yellow perch length was less than 45% of age 0 walleye length. During September 1974 and 1976 yellow perch length exceeded 45% of age 0 walleye length and both occurrence of perch and growth of age 0 walleye were relatively low. During periods of reduced age 0 yellow perch availability, occurrence of johnny darters (*Etheostoma nigrum*) and invertebrates increased in age 0 walleye diets (Appendix Table 2).

Food Consumption--

Daily food consumption of walleye exceeding 200 mm TL was estimated for 30 sampling days and for five prey species or major food groups (Table 10). Total daily food consumption in terms of body weight ($mg \cdot g^{-1} \cdot day^{-1}$) was highest during 1975 whereas consumption expressed independent of walleye weight ($g \cdot individual^{-1}$) was highest during 1976. Differences between the two years may reflect the larger average size of walleye in 1976 samples (Table 10).

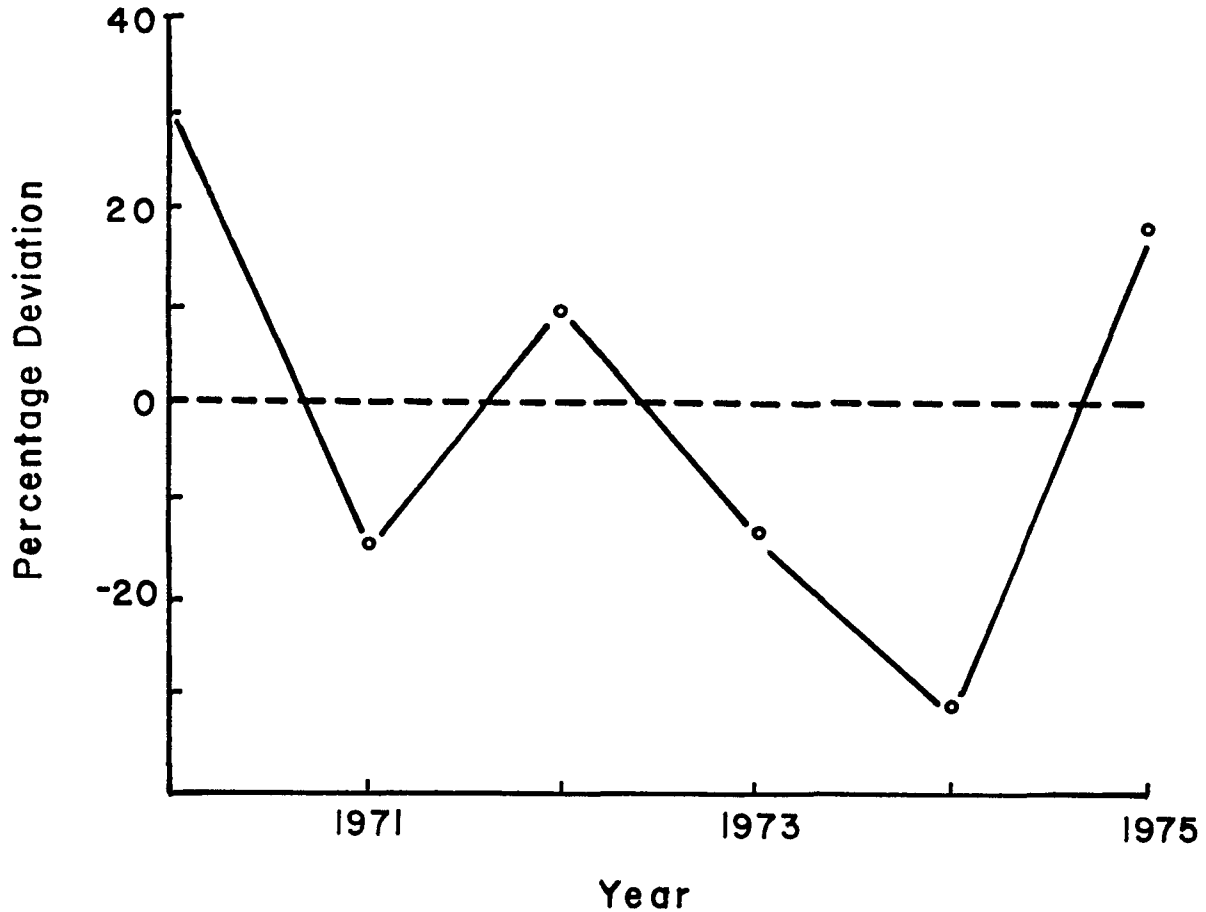

Figure 3. Percentage annual deviation from mean growth of Shagawa Lake walleye for the period 1970 through 1975.

TABLE 9. ANNUAL WALLEYE GROWTH INCREMENTS (mm) FOR EACH AGE GROUP BY CALENDAR YEAR WITH STANDARD ERRORS GIVEN IN PARENTHESIS

	AGE					
Year	I	II	III	IV	V	VI
1965	129 (8.7)	75 (14)				
1966	134 (19.5)	76 (14.7)	75 (12.5)			
1967	128 (7.2)	105 (8.2)	64 (15.9)	66 (6.5)		
1968	115 (21.9)	71 (13.1)	73 (15.4)	64 (10.7)	46 (24.5)	
1969	129 (21.1)	78 (14.8)	76 (12.8)	79 (18.9)	51 (8.9)	34 (16)
1970	132 (18.2)	87 (29.2)	83 (19.5)	63 (20.4)	43 (9.7)	38 (5.5)
1971	132 (14.7)	57 (24.9)	70 (20.1)	65 (16.2)	44 (14.1)	30 (8.1)
1972	146 (18.1)	79 (24.4)	79 (17)	68 (14.7)	57 (11.9)	43 (12.7)
1973	139 (11.6)	53 (11.9)	68 (21.9)	56 (12.6)	46 (18.9)	39 (15.3)
1974	124 (14.1)	52 (16.9)	43 (13.3)	48 (20.4)	43 (9.2)	34 (13)
1975	141 (12.3)	75 (15.6)	65 (12.7)	63 (15.4)	59 (20.6)	46 (12.3)
1965-72 mean	131	79	74	68	48	36
1974-75 mean	133	64	54	56	51	40

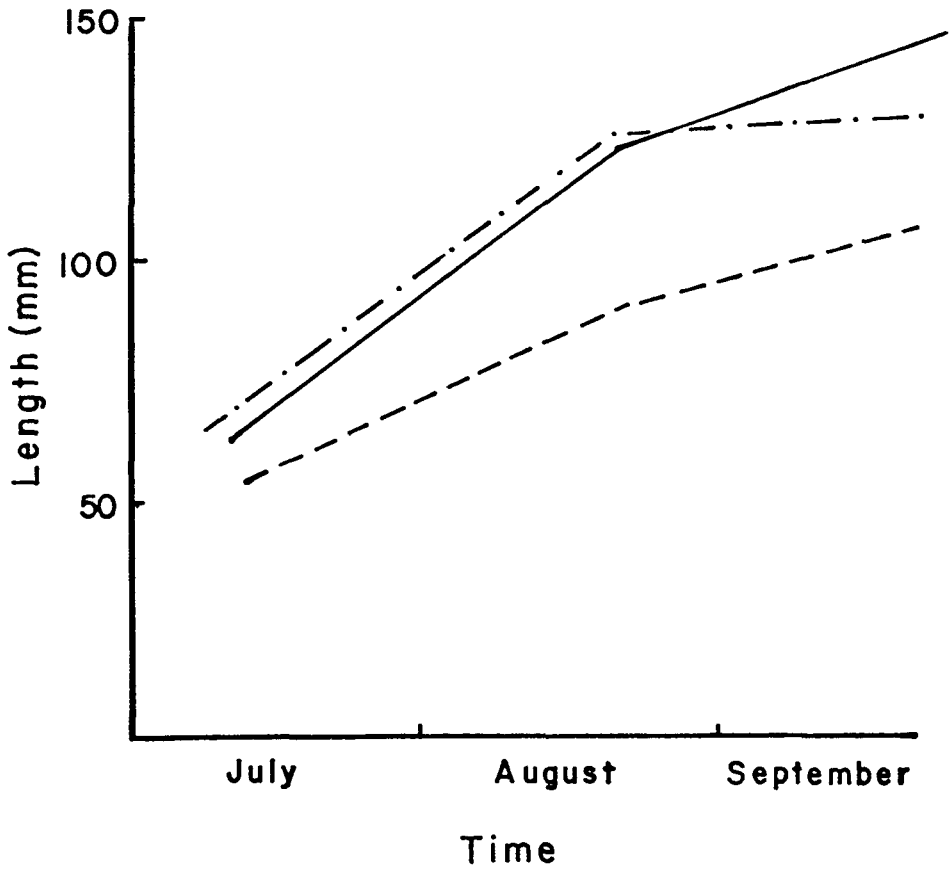

Figure 4. Growth of young-of-the-year walleye in Shagawa Lake during 1974 (---), 1975 (——) and 1976 (-·-).

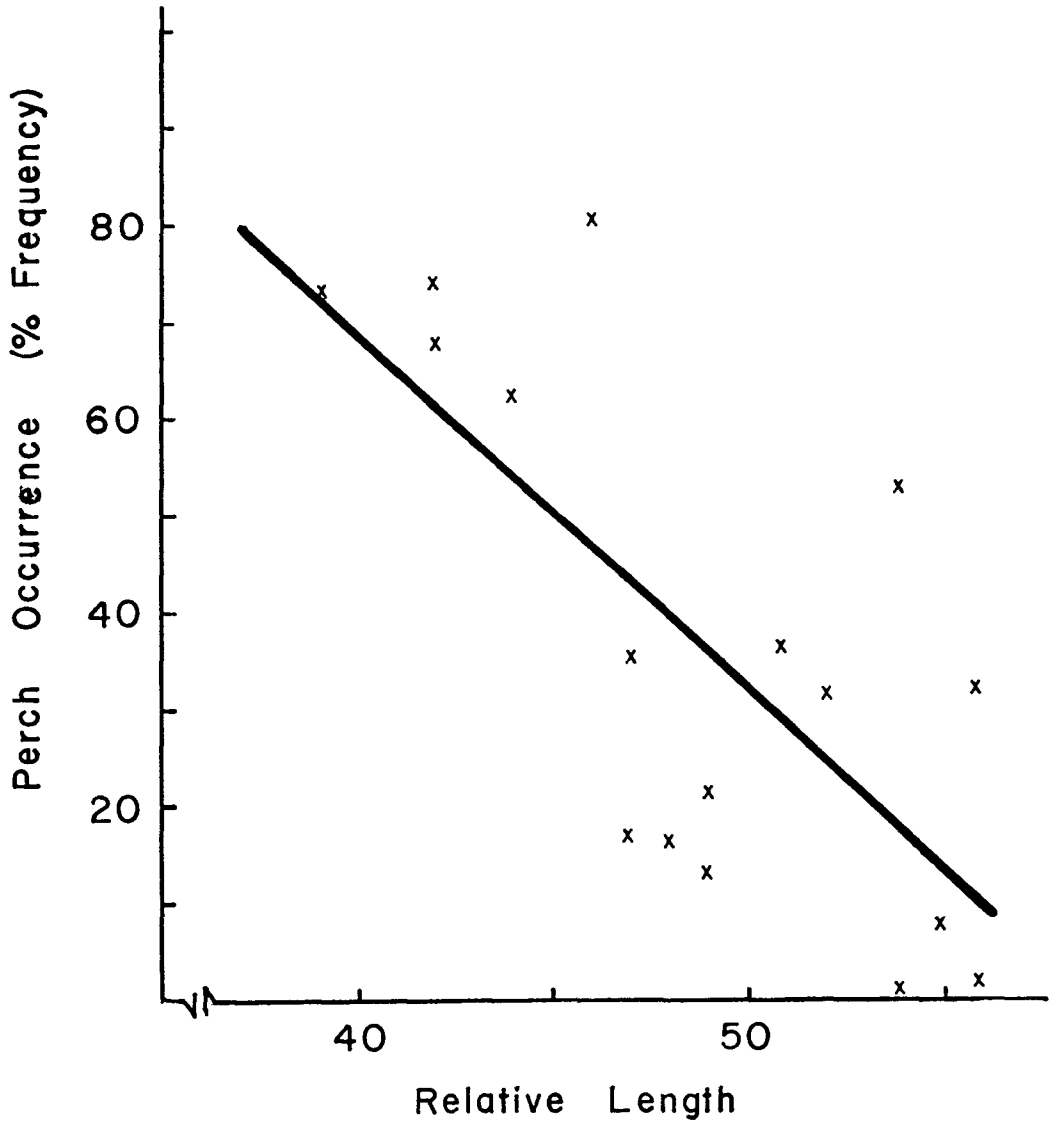

Figure 5. Relationship between relative length of age 0 yellow perch and walleye and the frequency of occurrence of age 0 yellow perch in walleye diets. Relative length is modal length of age 0 perch divided by modal length of age 0 walleye, multiplied by 100.

TABLE 10. TOTAL DAILY FOOD CONSUMPTION (gm·individual^{-1} and mg·g^{-1}) AND CONSUMPTION OF MAJOR FOOD FORMS (number of prey consumed daily·100 m^{-3}) BY WALLEYE EXCEEDING 200 mm TL WITH THE PERCENTAGE OF THE MEAL COMPRISED OF THE FOOD FORM GIVEN IN PARENTHESIS

Date	Sample Size (No.)	Mean Wt. (g)	Consumption						
			Total		Perch	Trout-perch	Shiners	Other Fish	Invert.
			g·ind^{-1}	mg·g^{-1}					
1974									
June 5	60	107	1.4	13.3	0(0)	0(1)	0.28(37)	(26)	(36)
June 6	71	102	1.8	16.6	0(0)	0(5)	0.44(22)	(12)	(61)
Ave.			1.6	15.0	0(0)	0(3)	0.36(30)	(19)	(49)
July 12	80	145	5.6	38.9	12.10(96)	0(0)	0.17(2)	(<1)	(2)
Aug. 21	68	98	2.7	28.0	1.07(65)	0(0)	0.18(10)	(5)	(20)
Aug. 22	43	97	3.5	36.3	1.37(85)	0(0)	0.12(7)	(1)	(7)
Ave.			3.1	32.2	1.22(75)	0(0)	0.15(9)	(3)	(14)
Sept. 20	23	135	3.5	26.1	0.96(57)	0(0)	0.83(38)	(0)	(4)
1975									
May 29	53	151	4.0	26.3	0.81(92)	0(2)	0(0)	(1)	(7)
June 10	48	129	2.9	22.6	0.08(20)	0.04(5)	0(0)	(19)†	(55)
Ave.			3.4	24.5	0.45(56)	0.02(3)	0(0)	(10)	(31)
June 27	25	106	3.5	33.2	25.90(81)	0(0)	0(0)	(8)	(11)
July 11	44	163	12.2	74.0	4.04(98)	0(0)	0.21(<1)	(<1)	(1)
July 29a*	22	169	4.4	26.3	6.96(86)	0(0)	0(0)	(0)	(12)
July 29b	49	268	6.4	23.9	10.88(94)	0(0)	0.06(4)	(0)	(1)
Ave.			6.6	39.5	11.94(90)	0(0)	0.07(1)	(2)	(6)

(continued)

TABLE 10 (continued)

Date	Sample Size (No.)	Mean Wt. (g)	Consumption: Total g.ind^{-1}	Total mg.g^{-1}	Perch	Trout-perch	Shiners	Other Fish	Invert.
Aug. 20	43	178	6.6	36.8	1.19(86)	0.01(1)	0.05(5)	(4)	(<1)
Aug. 21	35	181	5.7	31.8	1.07(89)	0.01(2)	0.94(1)	(8)	(<1)
Ave.			6.2	34.3	1.18(88)	0.01(2)	0.50(3)	(6)	(<1)
Sept. 12	50	254	6.7	26.5	0.62(67)	0.05(3)	0.05(4)	(16)†	(9)
Sept. 13	35	249	8.8	35.5	0.60(70)	0(0)	0.05(5)	(20)	(5)
Ave.			7.8	31.0	0.61(69)	0.03(2)	0.05(5)	(18)	(7)
Sept. 26	28	229	4.0	17.4	0.05(86)	0(0)	0.01(4)	(9)	(1)
Sept. 27	63	300	3.0	10.0	0.27(79)	0(0)	0.03(5)	(8)	(7)
Ave.			3.5	13.7	0.16(83)	0(0)	0.02(5)	(9)	(4)
1976									
June 2	26	215	4.4	20.3	0(0)	0.07(5)	0(0)	(5)	(90)
June 3	37	242	5.4	22.4	0.53(45)	0(0)	0(0)	(0)	(55)
June 18	33	328	8.3	24.7	2.09(76)	0(0)	0.21(8)	(10)	(6)
Ave.			6.0	22.5	0.87(40)	0.02(2)	0.07(3)	(5)	(50)
July 9	30	300	7.2	24.0	7.55(97)	0(0)	0(0)	(2)	(<1)
July 22	31	346	13.4	38.7	5.47(85)	0(0)	0.06(2)	(1)	(12)
Ave.			10.3	31.4	6.51(91)	0(0)	0.03(1)	(<2)	(<6)
Aug. 4	30	326	8.0	24.4	4.13(87)	0(0)	0.15(11)	(<1)	(<1)
Aug. 5	33	339	8.6	25.3	2.88(97)	0(0)	0.03(2)	(1)	(0)
Aug. 19	43	281	5.5	19.5	1.55(84)	0.03(2)	0.07(6)	(8)†	(0)
Ave.			7.4	23.1	2.85(89)	0.01(1)	0.08(6)	(3)	(0)

(continued)

TABLE 10 (continued)

Date	Sample Size (No.)	Mean Wt. (g)	Consumption: Total $g.ind^{-1}$	Total $mg.g^{-1}$	Perch	Trout-perch	Shiners	Other Fish	Invert.
Sept. 1	48	317	7.1	22.4	1.32(83)	0(0)	0.04(3)	(3)	(10)
Sept. 2	32	279	7.0	25.1	1.97(89)	0(0)	0.05(5)	(0)	(6)
Ave. (Early Sept.)			7.1	23.8	1.65(86)	0(0)	0.05(4)	(2)	(8)
Sept. 17	36	311	4.5	14.9	1.05(82)	0(0)	0(0)	(16)†	(2)
Oct. 6	24	372	4.8	12.9	0.26(75)	0(0)	0(0)	(25)	(<1)
Oct. 7	27	461	6.8	14.7	1.40(75)	0(0)	0(0)	(24)	(0)
Ave.			5.8	13.8	0.83(75)	0(0)	0(0)	(25)	(<1)

*Separate estimates were derived from samples collected on 29 July 1975 from Station III (a) and Station II (b).

†Age 0 walleye comprised 2.4% of 10 June 1975, 1.2% of 12 September 1975, 4% of 19 August 1976 and 14% of 17 September 1976 meals.

Comparison of 1975-1976 consumption estimates with those for 1974 supports the conclusion that feeding and growth conditions improved during 1975 and 1976. Differences in daily consumption were greatest during June. Yearling yellow perch were not available or eaten during June 1974 but comprised 56 and 45% of the 1975 and 1976 daily meals (Table 10).

The highest consumption occurred during July of all three years when over 90% of walleye daily meals were comprised of age 0 yellow perch under 40 mm. During July most of the meal was consumed at night or under low light conditions of dawn and dusk (Figure 6). The high ration size and feeding time demonstrates availability is highest at night when age 0 yellow perch under 40 mm are pelagic (Noble, 1975). Daily consumption was greatly reduced during late September 1975 and 1976 when yellow perch disperse into deep water or concentrated near aquatic macrophytes, indicating that food availability is reduced under these conditions. Low late September feeding rates were not associated with reduced temperatures. Temperatures during late September were similar to those of early September (Table 1) when walleye feeding rates were higher (Table 10).

Prey Quality and Feeding--

Electivity indices (Table 11) were calculated from the percentage of yellow perch, shiners (Notropis sp.), troutperch and young black crappie in walleye meals and the percentages of these prey in trawl catches. Electivity indices suggested yellow perch were relatively more available or were preferred by walleye in both Shagawa Lake and Lake of the Woods, Minnesota (Swenson and Smith, 1976). Although troutperch were the second most abundant prey in both waters (Table 3; Swenson and Smith, 1976) they comprised a very small part of the walleye daily meal (Table 10; Swenson and Smith, 1976). For both Lake of the Woods and Shagawa Lake, electivity of troutperch was strongly negative during all sampling months suggesting that troutperch are avoided or are not available (Table 11). Electivity indices for Notropis sp. were positive or zero during periods of reduced age 0 yellow perch abundance but became negative during periods of high yellow perch abundance (Table 11). Variability in electivity indices for age 0 black crappie may be attributed to small sample size and the fact that young black crappie congregate near vegetation making sampling difficult. The results suggest relatively high availability or some preference for this species by walleye. The relatively low electivity for troutperch, a species associated with the bottom and high electivity of species which locate away from the bottom suggests that pelagic prey are more available to walleye and are required to maintain high feeding and growth rates.

The number of yellow perch consumed daily by walleye occupying a standard volume of 100 m^3 was estimated as the product of: the average walleye biomass captured $g \cdot 100\ m^{-3}$, multiplied by an estimate of yellow perch consumed per gram of walleye, divided by the average weight of young (age 0-I) yellow perch in trawl catches. A similar procedure was used in estimating the number of troutperch and spottail shiner eaten by walleye. The analysis showed large numbers of yellow perch are consumed in July when night feeding is most pronounced and perch are small (Table 10). Predation rates were lower during August and September when age 0 yellow perch are larger and total walleye food consumption was slightly lower. The data shows the

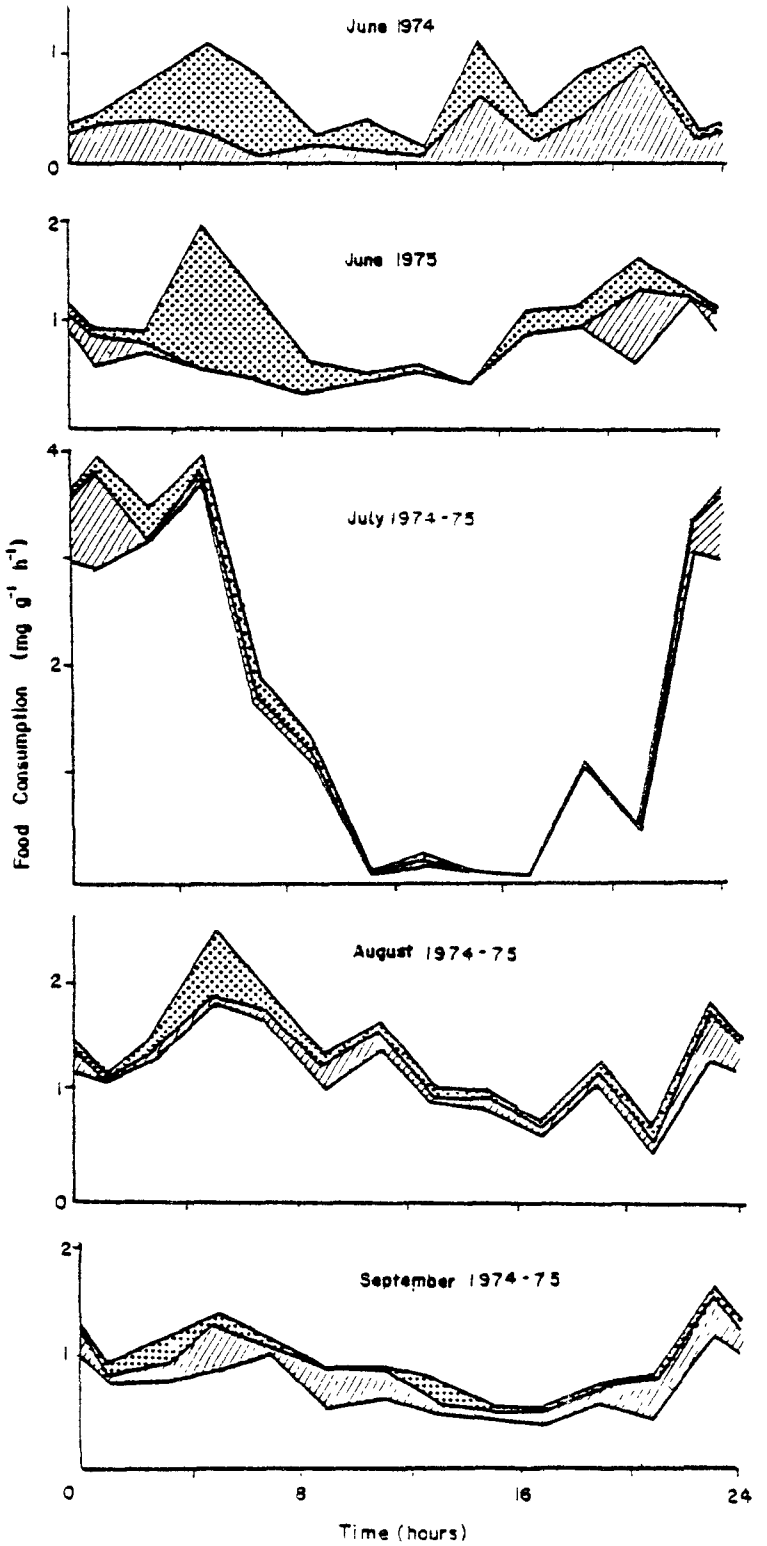

Figure 6. Hourly food consumption of invertebrates (stippled), age 0 yellow perch (open) and other fish (barred) by walleye.

(continued)

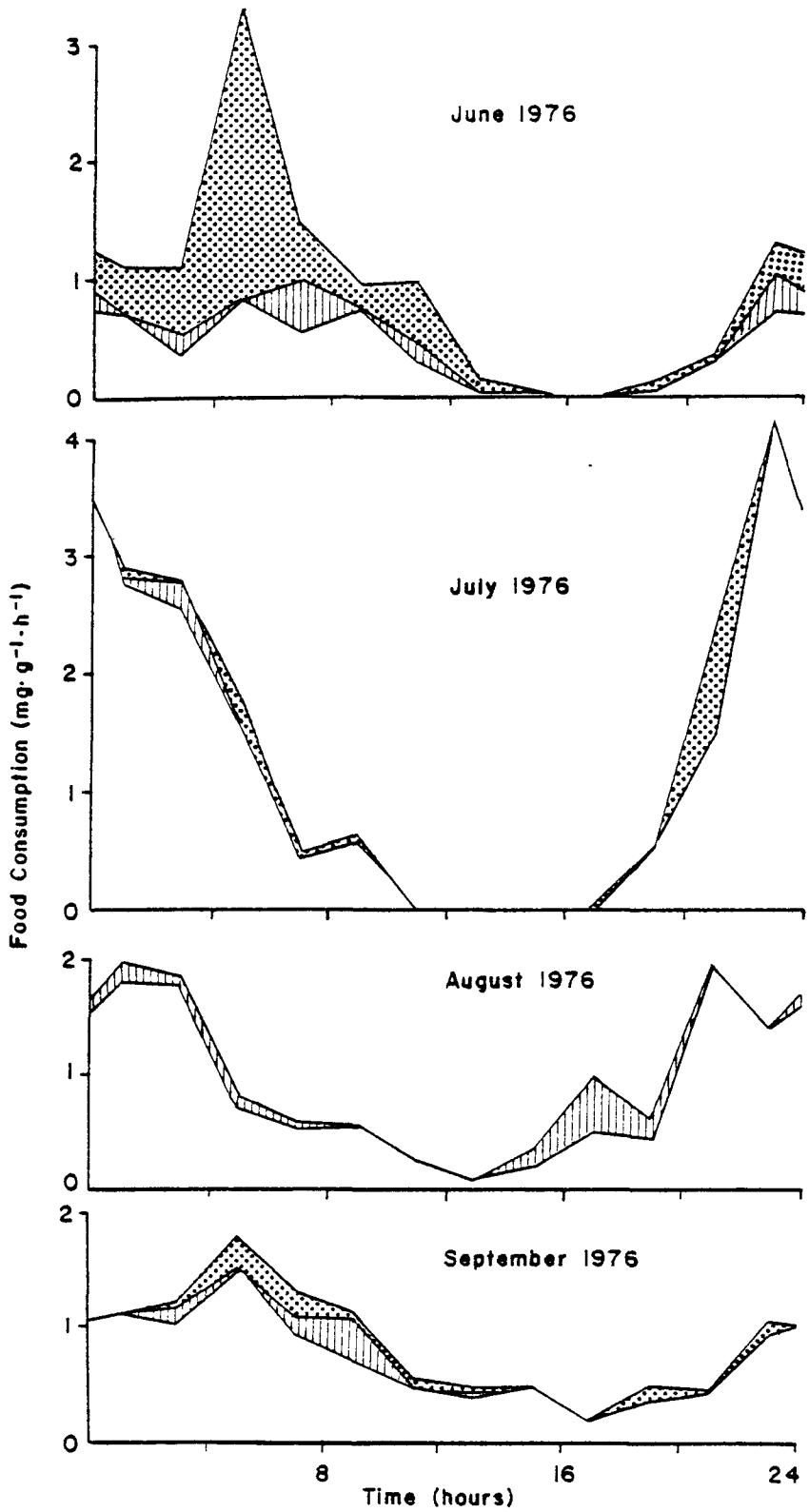

Figure 6. (continued)

TABLE 11. ELECTIVITY INDICES (Ivlev 1961)[a] OF MAJOR PREY CONSUMED BY WALLEYE OVER 200 mm IN SHAGAWA LAKE AND LAKE OF THE WOODS, MINNESOTA

Month	*Perca flavescens*	*Percopsis omiscomaycus*	*Notropis* sp.	*Pomoxis nigromaculatus*
		Shagawa Lake, Minnesota		
June	0.0	-0.7	0.0	--
July	+0.3	-0.8	-0.9	+1.0
Aug.	+0.3	-0.9	-0.4	-0.6
Sept.	+0.3	-1.0	-0.2	+0.7
		Lake of the Woods, Minnesota		
June	0.0	-0.6	+0.6	
July	+0.2	-1.0	+0.2	
Aug.	+0.3	-1.0	-0.1	
Sept.	+0.2	-1.0	-0.7	

[a]The electivity index is a convenient method for estimating the availability of, or preference for, specific prey species and is calculated by the formula:

$$E = \frac{r_1 - P_1}{r_1 + P_1}$$

where: r_1 = is the relative importance of a prey species in the predator's daily meal and;

P_1 = is the relative abundance of the prey species in the environment.

Values may range from +1, indicating the prey species is selected or highly available to -1, indicating the prey species is avoided or unavailable.

greatest pressure on age 0 yellow perch occurs during July when a small reduction in age 0 yellow perch growth could result in a large increase in the percentage of the total number consumed.

Comparison of the average concentration of yellow perch in trawl catches (Table 3) with estimates of daily consumption (Table 10) suggests the average available stock is consumed over a several day period during July. Because yellow perch are pelagic during early July, prey density was underestimated by bottom trawl catches. A better estimate of young (age 0-I) perch abundance for July sampling days was calculated from the average number of age 0 yellow perch captured during the first two sampling days in August (when they are demersal) and the total number consumed by walleye·100 m^{-3} for the period from the July sampling date to the August sampling period.

Prey Density and Feeding--

To determine the influence of food availability on walleye production the relationship between prey density and food consumption was estimated by comparing average daily consumption for each month of sampling with density of small fish (<10 g) using data from Shagawa Lake gathered during this study and information from Lake of the Woods, Minnesota, and western Lake Superior presented by Swenson (1977). Estimates of prey density and consumption were based on catches from water less than 5 m deep except during late September 1975-1976 when abundance of walleye and prey in Shagawa Lake was higher offshore (Table 3) and estimates for water exceeding 3 m were used. Troutperch abundance was not included in estimating prey density due to low utilization by walleye. The analysis demonstrated a single relationship exists between walleye food consumption and prey density in the three waters and that both prey density and food consumption are highest in Shagawa Lake (Figure 7). Consumption in all three waters increased rapidly with prey densities from 10 to 400 $mg \cdot m^{-3}$. At higher prey densities consumption appeared to increase at a slow rate or to vary independent of prey density. Multiple regression analysis demonstrated the relationship was significant and curvilinear ($P < 0.01$). The analysis showed that during most months prey density in Shagawa Lake greatly exceeds 400 $mg \cdot m^{-3}$ and major reduction in prey abundance would be required to significantly limit walleye food consumption and growth.

Low prey abundance or availability during June and after mid-September appears to be responsible for increased walleye cannibalism. Cannibalism was found to occur during June and September 1975 and August, September and November 1976. Analysis of walleye food habits (Appendix Table 3) shows the number of prey species in the diet increases during autumn when yellow perch availability declines, due to lower abundance, offshore movement and their association with aquatic macrophytes in shallow water (<5 m). Comparison of rates of cannibalism (Table 10) with abundance of age 0 walleye (Table 3) indicates that cannibalism may be a significant source of mortality. Swenson and Smith (1976) showed that walleye cannibalism did not occur in the Lake of the Woods, Minnesota, where abundance of yellow perch and troutperch was higher during late September in water exceeding 5 m deep.

Physical Conditions and Feeding--

Walleye consumption of age 0 yellow perch was greatly restricted during late September 1975 (Table 10, Figure 6) when density of small yellow perch

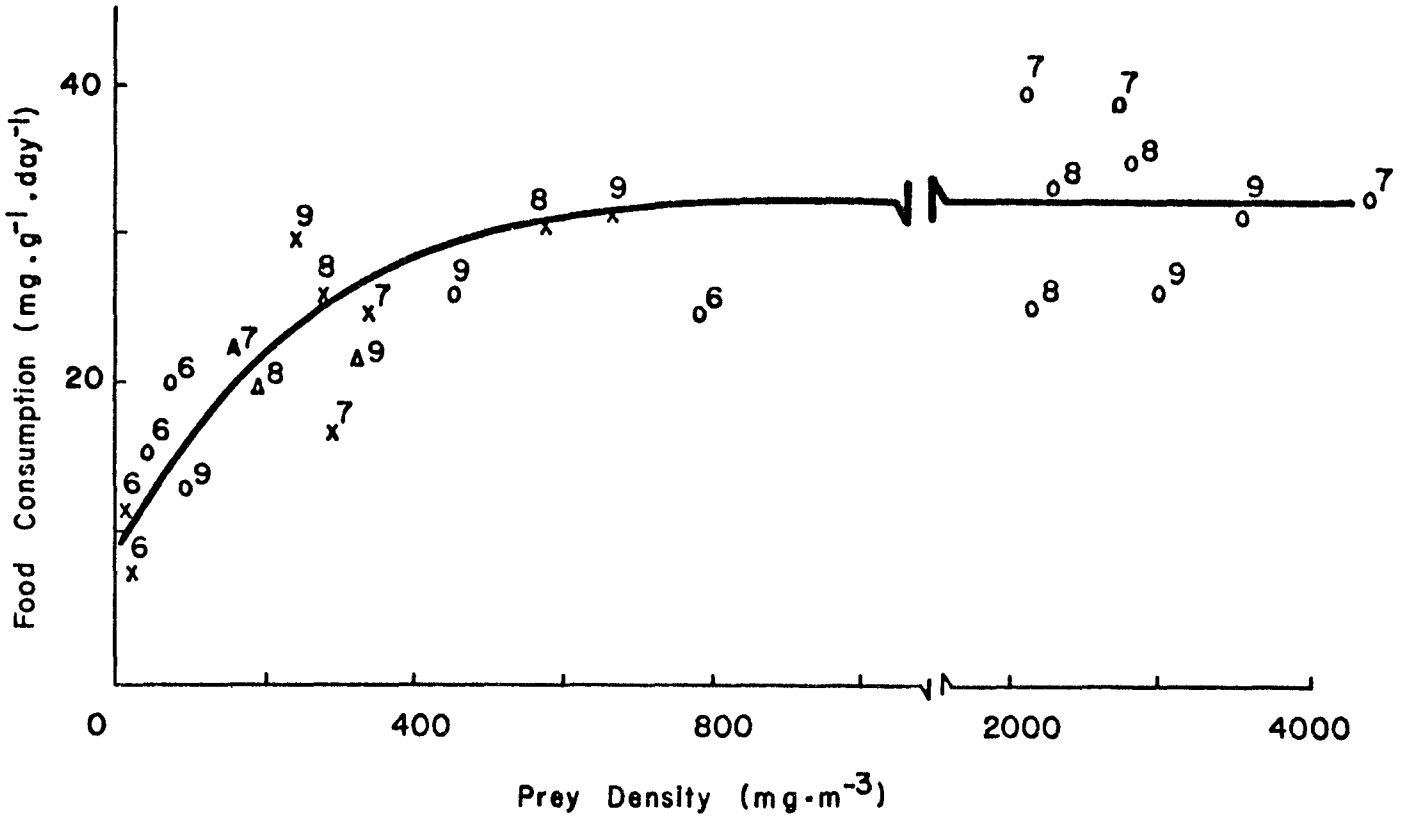

Figure 7. Relationship between monthly averages of walleye daily food consumption rates and prey density for Shagawa Lake (O), Lake of the Woods, Minnesota (X) and western Lake Superior (Δ). Numerals indicate calendar month.

in open water was less than 200 $mg \cdot m^{-3}$ but exceeded 1000 $mg \cdot m^{-3}$ in areas of aquatic macrophytes. Macrophyte growths appear to reduce food availability to walleye by providing cover for prey. Walleye catches in areas with aquatic macrophytes were low, but catches of age 0 Centrarchidae (primarily black crappie) were highest in these areas throughout most of the growing season.

Daily food consumption rate did not change with water temperature during periods when food abundance exceeded 400 $mg \cdot m^{-3}$ in Shagawa Lake or Lake of the Woods, Minnesota (Swenson and Smith, 1976). Daily food consumption at 14-15.5°C (11 days during June and late September) and at 20-22°C (10 days during August and early September) averaged 30.0 and 29.1 $mg \cdot g^{-1}$ day^{-1}, respectively. Higher stomach volumes occurred during the lower temperature periods (t-test; $P < 0.01$) and promoted more efficient digestion (Swenson, 1977).

Predominance of night and twilight feeding by Shagawa Lake and Lake of the Woods, Minnesota, walleye (Swenson and Smith, 1976) indicates high light intensity may be a significant factor influencing daily food consumption. Midday feeding was greatest during June and September when walleye ate more demersal prey (Figure 6). Light intensity and the percentage of the total meal consumed between 08:00-18:00 CST by Shagawa Lake walleye were ranked for six periods during which a minimum of two estimates of food consumption were available for days characterized by similar prey densities. The ranks were negatively correlated ($r_c = -0.89$; $P < 0.05$) demonstrating walleye food consumption during daylight hours is limited by high light intensity.

PERCH POPULATION STUDIES

Growth

Modal lengths of age 0 yellow perch captured by trawl during each sampling period were used to calculate growth during 1974 through 1976 in Shagawa Lake and during 1969 and 1970 for Lake of the Woods, Minnesota. Data for Lake of the Woods were taken from Swenson (1972). Relationships between length and time show growth is faster in Shagawa Lake (Figure 8) and was highest during 1976 among the five years compared. Growth in Shagawa Lake during 1974 was slower in comparison with 1975 and 1976 (Figure 8).

Analysis of 669 scale samples showed Shagawa Lake yellow perch average 63 mm TL at age I and reach 216 mm at age IV (Table 12). Comparison with yellow perch in Wilson Lake (Johnson, 1975) and Red Lakes (Heyerdahl and Smith, 1971) shows growth is similar in the three waters (Table 12).

Calculation of percentage deviation from mean annual growth for the eight year 1968-1975 period indicated growth was slowest during 1974 and 1975, the two years following initiation of advanced wastewater treatment (Figure 9). Growth during 1974 and 1975 was more than 10% below the eight year average. Deviations in yellow perch growth were positively correlated with chlorophyll α concentrations (CERL, 1977) during the 1971-1975 period ($r = +0.85$; $P < 0.05$). Mean length increments of age groups I-VI for the 1967-1972 pretreatment period and for the 1974-1975 period, when tertiary

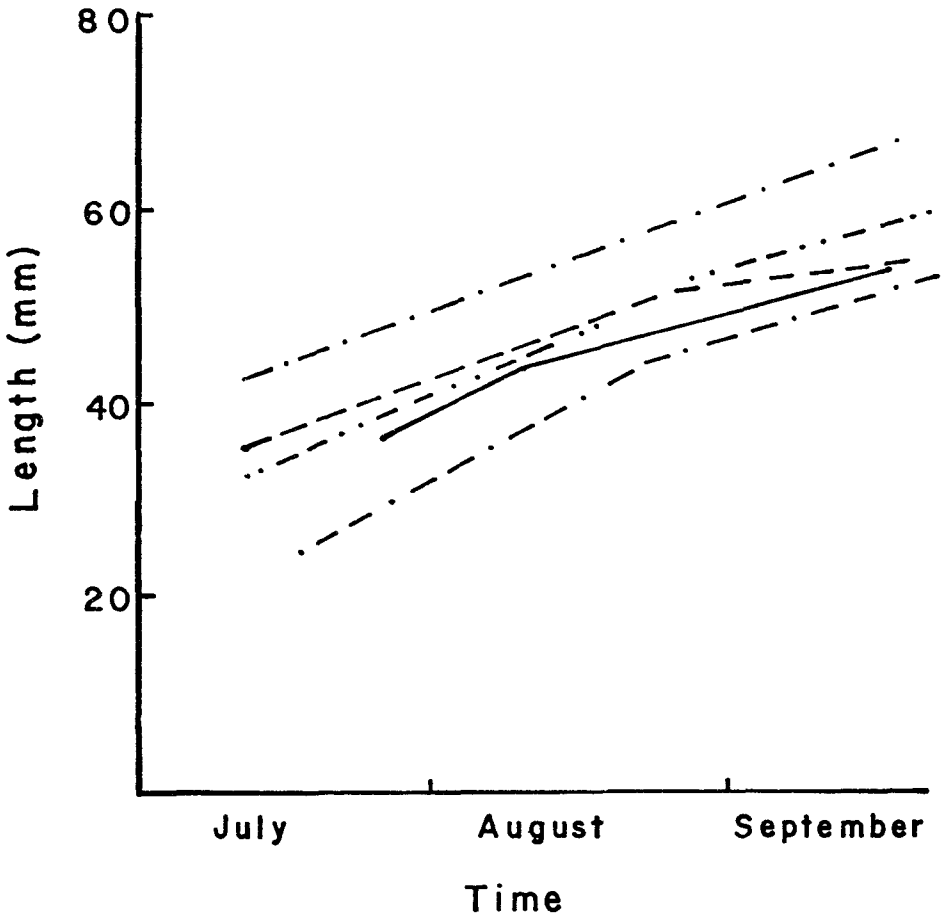

Figure 8. Growth of young-of-the-year yellow perch in Shagawa Lake during 1974 (— —), 1975 (• • — —) and 1976 (— • —) and in Lake of the Woods, Minnesota, during 1969 (• — — •) and 1970 (——).

TABLE 12. CALCULATED TL (mm) OF THE 1967 THROUGH 1975 YELLOW PERCH YEAR-CLASSES IN SHAGAWA LAKE WITH GRAND AVERAGE LENGTH FOR SHAGAWA LAKE AND OTHER WATERS

Year Class	No. in Sample	Age Group							
		I	II	III	IV	V	VI	VII	VIII
1967	7	65	115	169	221	248	268	282	--
1968	11	62	109	168	214	246	269	290	309
1969	13	65	116	179	228	255	273	286	--
1970	76	66	108	170	215	237	251	--	--
1971	53	66	121	175	213	238	--	--	--
1972	239	65	118	166	206	--	--	--	--
1973	54	61	107	157	--	--	--	--	--
1974	161	59	103	--	--	--	--	--	--
1975	55	61	--	--	--	--	--	--	--
Shagawa Lake Grand Average	669	63	112	169	216	245	265	286	309
Wilson Lake, Minn. (Johnson, 1975)		67	116	155	176	240	268	--	--
Red Lakes, Minn. (Heyerdahl and Smith, 1971)		74	132	173	201	221	234	--	--
Mill Lake, Minn. (Schneider, 1971)		76	119	150	170	196	226	241	--
Red Deer Lake, Ontario (Chadwick, 1976)		53	85	112	144	176	178	--	--
West Okoboji Lake, Iowa (Moen, 1964)		53	127	183	216	244	264	--	--

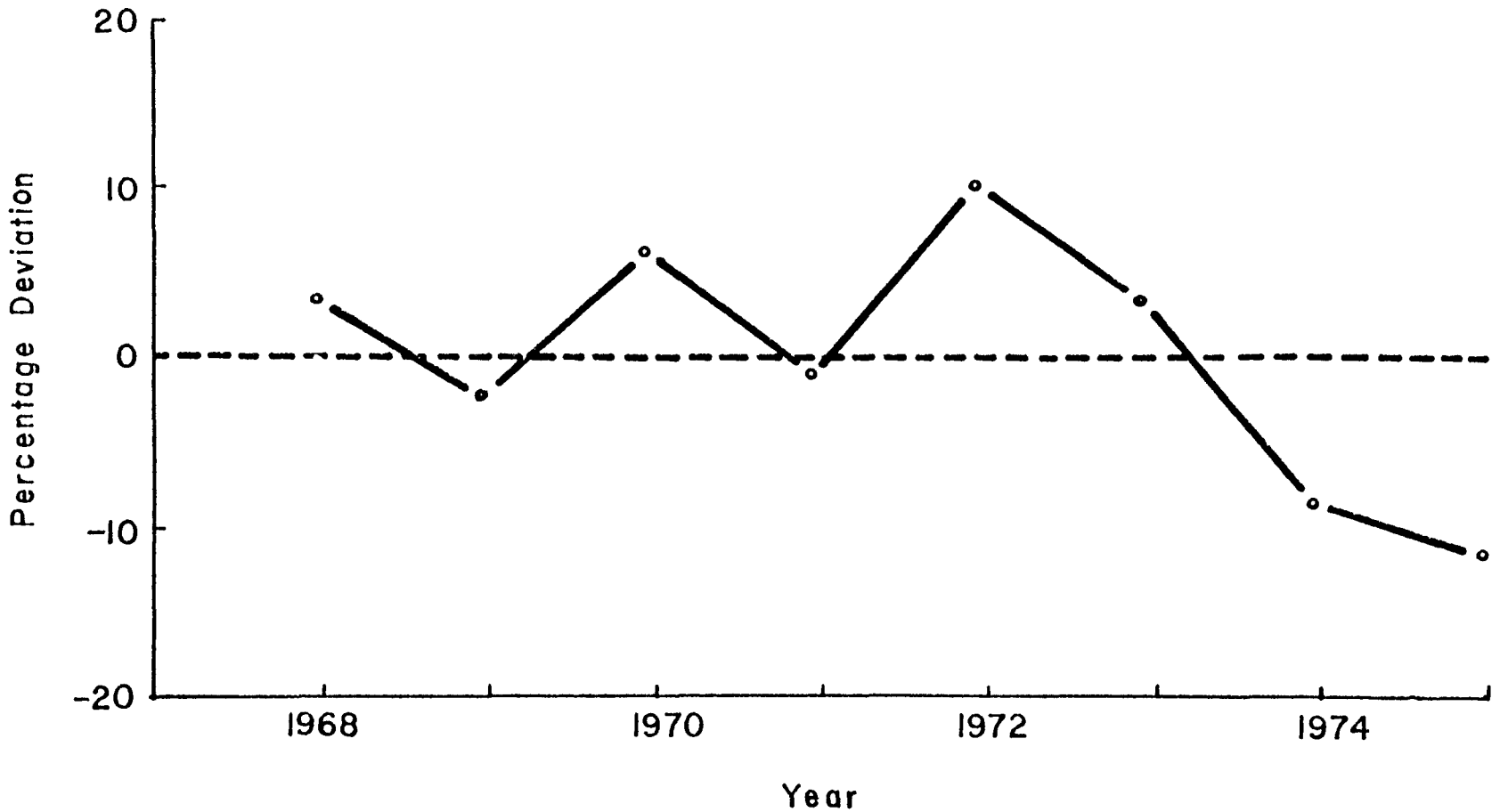

Figure 9. Percentage annual deviation from average perch growth for the period 1968 through 1975.

wastewater treatment had resulted in reduced primary production, were calculated. Comparison of pretreatment and post-treatment mean growth increments, for age groups I-VI, by two-way analysis of variance showed growth was significantly lower during the 1974-1975 post-treatment period (Table 13; $P < 0.01$).

Food Habits

Analysis of perch food habits showed dependence on zooplankton and macroinvertebrates during the first year of life (<70 mm TL; Table 14) and on macroinvertebrates and fish thereafter (Table 15). Young perch diets were more diverse during 1976 and included a number of items not encountered in stomachs collected during 1975 (Table 14). Higher diversity was accompanied by increased food volumes. Faster growth, increased food diversity and larger stomach volumes during 1976 suggest that prey population densities were higher or that the larger size of age 0 yellow perch permitted feeding on more food types. Mouth size has been found to be a major factor limiting predation by age 0 yellow perch (Wong and Ward, 1972).

Food volumes found in yellow perch exceeding 71 mm TL were highest during 1976. Yellow perch contained a higher percentage of age 0 yellow perch in their diet during 1976. Increased cannibalism during 1976 does not appear related to differences in age 0 yellow perch densities which were similar during 1975 and 1976 (Table 3).

LAKE HERRING POPULATION STUDIES

Population Structure

Information on age from 331 herring was applied to measurements of 567 fish to describe population structure (Table 16). Low abundance of age 0 and age I herring may indicate failure of recent year-classes. However, relatively high abundance of age II fish in 1975 and 1976 catches indicates the sampling methods were not efficient in capturing small herring.

Growth

Accessory growth checks were found on scales of all year-classes but could not be positively attributed to environmental conditions such as high mid-summer temperatures or spawning activity. The accessory checks made accurate aging of samples extremely difficult. Although the scales were read three times by two experienced project staff, age assignments may not be completely valid. However, because potential errors resulting from inaccurate age assignment should be distributed between pre- and post-treatment periods, comparisons of growth between these periods should be valid.

Growth estimates show herring average 174 mm at age I, 290 mm at age III and 408 mm at age VI (Table 17). Comparison with other waters indicates growth is excellent in Shagawa Lake (Table 17). However, comparison of deviations in mean annual growth during the 1967-1975 period suggests growth is declining (Figure 10). Growth has been below average since 1973 (Figure 10). Herring growth was not correlated with chlorophyll α concentration ($r = -0.29$;

TABLE 13. ANNUAL GROWTH INCREMENTS (mm) OF SHAGAWA LAKE YELLOW PERCH FOR EACH YEAR OF LIFE BY CALENDAR YEAR WITH STANDARD DEVIATIONS GIVEN IN PARENTHESIS

Calendar Year	Increment for Growth Period						
	I	II	III	IV	V	VI	VII
1967	65.4(4.5)	--	--	--	--	--	--
1968	62.5(6.6)	49.3(11.2)	--	--	--	--	--
1969	64.9(5.8)	46.5(9.9)	54.4(10.6)	--	--	--	--
1970	65.7(5.5)	51.2(10.2)	59.3(8.8)	51.7(4.6)	--	--	--
1971	65.5(5.3)	42.1(10.1)	62.7(10.1)	45.5(10.7)	27.1(7.8)	--	--
1972	64.5(5.9)	55.2(12.9)	62.3(8.1)	48.9(9.5)	32.2(6.9)	20.7(4.3)	--
1973	61.4(4.7)	53.1(9.9)	54.8(10.5)	45.0(7.6)	27.8(5.0)	22.7(3.4)	13.6(2.1)
1974	58.8(4.6)	46.1(7.5)	48.2(9.1)	38.0(10.8)	23.2(5.7)	17.8(4.3)	14.7(5.1)
1975	60.5(5.1)	44.9(7.5)	51.0(6.7)	40.7(7.1)	23.5(4.2)	17.7(2.8)	11.6(1.3)
1967-1972 Mean	64.8	48.9	59.7	48.7	29.7	20.7	
1974-1975 Mean	59.7	45.5	49.6	39.4	23.4	17.8	13.2

TABLE 14. FOOD OF SHAGAWA LAKE YELLOW PERCH <71 mm TL, EXPRESSED AS PERCENTAGE FREQUENCY OF OCCURRENCE FOR STOMACHS CONTAINING FOOD, WITH PERCENTAGE OF TOTAL FOOD VOLUME IN PARENTHESIS

	1975					
Collection Date	July	Aug.	Sept.	Oct.	Nov.	All Dates
Stomachs with Food	30	14	28	12	10	94
Stomachs Empty	1	0	0	2	4	7
CRUSTACEA						
Cladocera						
Daphnia	83(29)	79(46)	86(25)	100(60)	80(47)	85(33)
Leptodora	20(8)	50(22)	75(25)	50(9)	10(1)	44(15)
Copepoda	53(5)	64(19)	82(33)	58(6)	70(34)	66(19)
Amphipoda						
Hyalella	13(12)	--	4(1)	--	--	5(5)
Gammarus	--	--	--	--	--	--
Ostracoda	27(2)	36(3)	36(1)	--	--	24(1)
Decapoda	--	--	--	--	--	--
INSECTA						
Diptera						
Chironomidae						
larvae	17(11)	7(7)	21(11)	8(5)	--	14(9)
pupae	7(2)	--	--	--	--	2(1)
Chaoboridae						
larvae	3(<1)	--	--	25(20)	20(13)	6(3)
pupae	--	--	4(1)	--	--	1(<1)
Ephemeroptera						
Hexagenia	10(16)	--	4(2)	--	--	4(7)
Other	7(14)	--	--	--	--	2(5)
Trichoptera	--	--	--	--	--	--
Odonata	--	--	--	--	--	--
Hemiptera	--	--	--	--	--	--
OTHER						
Hydracarina	--	--	--	--	--	--
Nematoda	--	--	--	--	--	--
Pelecypoda	--	--	--	--	--	--
Annelida						
Hirudinea	--	--	--	--	--	--
Gastropoda	--	--	--	--	--	--
Unidentified	3(1)	21(2)	4(1)	--	10(5)	6(2)
FISH						
Yellow Perch	--	--	--	--	--	--
White Sucker	--	--	--	--	--	--
Johnny Darter	--	--	--	--	--	--
Spottail Shiner	--	--	--	--	--	--
Troutperch	--	--	--	--	--	--
Unidentified	--	--	--	--	--	--
PLANT	--	7(1)	--	--	--	1(<1)
Average Volume	.021	.010	.022	.015	.015	0.018

(continued)

TABLE 14 (continued)

	1976					
Collection Date	June	July	Aug.	Sept.	Oct.	All Dates
Stomachs with Food	30	18	17	19	12	94
Stomachs Empty	0	3	3	2	1	9
CRUSTACEA						
Cladocera						
Daphnia	57(18)	100(50)	59(15)	53(28)	83(62)	68(24)
Leptodora	20(1)	33(10)	65(20)	47(23)	17(6)	35(7)
Copepoda	20(4)	89(26)	53(12)	32(9)	42(2)	44(7)
Amphipoda						
Hyalella	27(4)	6(2)	6(1)	--	--	10(3)
Gammarus	--	--	--	--	--	--
Ostracoda	3(<1)	28(3)	24(3)	5(1)	8(<1)	13(1)
Decapoda	--	--	--	--	--	--
INSECTA						
Diptera						
Chironomidae						
larvae	37(6)	6(2)	29(9)	74(27)	50(27)	39(11)
pupae	37(51)	6(2)	24(26)	11(2)	8(3)	20(34)
Chaoboridae						
larvae	7(1)	17(5)	12(1)	16(3)	--	10(2)
pupae	3(1)	--	--	--	--	1(<1)
Ephemeroptera						
Hexagenia	3(1)	--	12(13)	5(5)	--	4(3)
Other	17(8)	--	--	5(1)	--	6(5)
Trichoptera	3(<1)	--	--	--	--	1(<1)
Odonata	--	--	--	5(1)	--	1(<1)
Hemiptera	3(<1)	--	--	--	--	1(<1)
OTHER						
Hydracarina	7(<1)	--	--	--	--	2(<1)
Nematoda	3(<1)	--	--	--	--	1(<1)
Pelecypoda	--	--	--	--	--	--
Annelida						
Hirudinea	--	--	--	--	--	--
Gastropoda	--	--	--	--	--	--
Unidentified	--	--	--	--	--	--
FISH						
Yellow Perch	3(3)	--	--	--	--	1(2)
White Sucker	--	--	--	--	--	--
Johnny Darter	--	--	--	--	--	--
Spottail Shiner	--	--	--	--	--	--
Troutperch	--	--	--	--	--	--
Unidentified	--	--	--	--	--	--
PLANT	--	--	--	--	--	--
Average Volume	0.101	.014	.014	.042	.032	.055

TABLE 15. FOOD OF SHAGAWA LAKE YELLOW PERCH >70 mm TL, EXPRESSED AS PERCENTAGE FREQUENCY OF OCCURRENCE FOR STOMACHS CONTAINING FOOD, WITH PERCENTAGE OF TOTAL FOOD VOLUME IN PARENTHESIS

	1975						
Collection Date	May	July	Aug.	Sept.	Oct.	Nov.	All Dates
Stomachs with Food	3	8	22	64	7	12	116
Stomachs Empty	1	0	4	9	1	2	17
CRUSTACEA							
Cladocera							
Daphnia	--	13(<1)	14(1)	3(1)	29(1)	--	7(<1)
Leptodora	--	--	14(<1)	20(2)	29(3)	--	16(1)
Copepoda	--	--	--	--	--	--	--
Amphipoda							
Hyalella	100(56)	38(2)	5(<1)	--	14(2)	8(<1)	8(2)
Gammarus	--	--	--	--	--	8(<1)	2(<1)
Ostracoda	--	--	--	--	--	--	--
Decapoda	--	--	--	2(<1)	--	--	1(<1)
INSECTA							
Diptera							
Chironomidae							
larvae	67(2)	63(28)	59(17)	47(26)	57(40)	75(9)	54(22)
pupae	--	13(1)	55(16)	9(1)	14(2)	--	17(3)
Chaoboridae							
larvae	33(3)	13(<1)	23(<1)	9(1)	43(2)	17(<1)	16(<1)
pupae	33(3)	--	5(<1)	--	14(2)	--	3(<1)
Ephemeroptera							
Hexagenia	100(36)	63(23)	32(36)	56(40)	29(33)	50(89)	51(46)
Other	--	38(9)	--	--	--	--	3(1)
Trichoptera	--	25(15)	18(2)	5(<1)	14(15)	--	9(2)
Odonata	--	--	--	2(<1)	--	8(1)	2(<1)
Hemiptera	--	--	--	--	--	--	--
OTHER							
Hydracarina	--	13(<1)	--	--	--	--	1(<1)
Nematoda	--	13(<1)	--	8(1)	--	--	5(<1)
Pelecypoda	--	--	--	--	--	--	--
Annelida							
Hirudinea	--	13(1)	--	--	--	--	1(<1)
Gastropoda	--	--	--	2(<1)	--	--	1(<1)
Unidentified	--	--	--	2(<1)	--	--	1(<1)
FISH							
Yellow Perch	--	25(19)	9(13)	5(11)	--	--	6(10)
White Sucker	--	--	5(15)	2(10)	--	--	2(8)
Johnny Darter	--	--	--	5(3)	--	--	4(2)
Spottail Shiner	--	--	--	3(2)	--	--	2(1)
Troutperch	--	--	--	2(1)	--	--	1(<1)
Unidentified	--	--	--	3(1)	--	--	2(<1)
PLANT	--	--	--	--	--	--	--
Average Volume	1.01	0.89	0.75	0.78	0.38	1.25	0.81

(continued)

TABLE 15 (continued)

	1975					
Collection Date	June	July	Aug.	Sept.	Oct.	All Dates
Stomachs with Food	65	48	48	58	36	255
Stomachs Empty	5	13	16	6	8	48
CRUSTACEA						
Cladocera						
Daphnia	17(3)	--	--	--	8(1)	6(1)
Leptodora	2(<1)	2(<1)	6(<1)	21(<1)	42(5)	13(<1)
Copepoda	6(<1)	--	--	2(<1)	--	2(<1)
Amphipoda						
Hyalella	48(6)	6(1)	6(<1)	7(<1)	3(<1)	17(2)
Gammarus	--	--	--	--	--	--
Ostracoda	--	2(<1)	--	--	--	1(<1)
Decapoda	9(20)	2(<1)	2(1)	3(5)	--	4(8)
INSECTA						
Diptera						
Chironomidae						
larvae	65(8)	33(3)	31(7)	90(41)	58(16)	57(16)
pupae	45(2)	15(14)	27(2)	41(4)	8(1)	30(5)
Chaoboridae						
larvae	17(1)	4(<1)	2(<1)	3(<1)	11(<1)	8(<1)
pupae	15(1)	6(<1)	--	--	--	5(<1)
Ephemeroptera						
Hexagenia	62(50)	23(3)	65(60)	55(27)	56(54)	53(37)
Other	11(<1)	2(<1)	--	--	--	3(<1)
Trichoptera	28(3)	4(<1)	15(2)	5(<1)	22(5)	15(2)
Odonata	8(<1)	--	--	2(<1)	3(1)	3(<1)
Hemiptera	5(<1)	4(<1)	--	--	--	2(<1)
OTHER						
Hydracarina	14(<1)	4(<1)	--	--	--	4(<1)
Nematoda	11(<1)	2(<1)	10(<1)	3(<1)	3(1)	6(<1)
Pelecypoda	5(<1)	--	--	--	--	1(<1)
Annelida						
Hirudinea	6(<1)	2(1)	--	--	--	2(<1)
Gastropoda	6(<1)	--	--	--	--	2(<1)
Unidentified	5(<1)	4(<1)	2(<1)	--	--	2(<1)
FISH						
Yellow Perch	3(1)	58(68)	23(23)	10(22)	3(10)	19(25)
White Sucker	--	2(5)	--	--	--	1(1)
Johnny Darter	--	--	2(4)	--	6(5)	1(1)
Spottail Shiner	--	--	--	--	--	--
Troutperch	--	2(2)	--	--	--	1(<1)
Unidentified	2(<1)	2(<1)	--	2(<1)	3(1)	2(<1)
PLANT	3(<1)	2(<1)	12(<1)	2(<1)	--	4(<1)
Average Volume (ml)	1.03	0.90	0.72	0.92	0.47	0.84

TABLE 16. AGE FREQUENCY DISTRIBUTION OF SHAGAWA LAKE HERRING CAPTURED BY GILL NET AND TRAWL DURING 1974, 1975 AND 1976

Age	Year Class	Number in Age Group	Length Range in Millimeters
1974			
0	1974	0	---
I	1973	0	---
II	1972	17	221 - 240
III	1971	0	---
IV	1970	10	317 - 402
V	1969	24	376 - 435
VI	1968	12	405 - 464
	Total:	63	
1975			
0	1975	3	147 - 160
I	1974	0	---
II	1973	213	160 - 281
III	1972	18	310 - 360
IV	1971	56	316 - 401
V	1970	74	361 - 453
VI	1969	74	365 - 479
VII	1968	23	405 - 480
VIII	1967	3	457 - 464
	Total:	464	
1976			
0	1976	21	---
I	1975	0	---
II	1974	6	221 - 337
III	1973	33	290 - 360
IV	1972	7	388 - 420
V	1971	12	420 - 464
VI	1970	13	410 - 457
VII	1969	10	448 - 490
VIII	1968	1	457
	Total:	103	

TABLE 17. CALCULATED TOTAL LENGTH (mm) OF THE 1966 THROUGH 1974 LAKE HERRING YEAR-CLASSES IN SHAGAWA LAKE WITH GRAND AVERAGE LENGTH FOR SHAGAWA LAKE, LAKE OF THE WOODS, MINNESOTA, AND WESTERN LAKE SUPERIOR

Year Classes	No. in Sample	Age Groups								
		I	II	III	IV	V	VI	VII	VIII	IX
1966	1	188	227	276	387	422	437	447	451	455
1967	1	173	214	238	355	396	422	432	436	--
1968	20	178	246	319	396	419	436	433	--	--
1969	56	168	257	329	382	411	428	--	--	--
1970	72	160	238	296	352	393	--	--	--	--
1971	31	174	238	284	339	--	--	--	--	--
1972	9	177	214	289	--	--	--	--	--	--
1973	134	157	202	--	--	--	--	--	--	--
1974	7	193	--	--	--	--	--	--	--	--
Shagawa Lake Grand Average	331	174	230	290	369	408	431	441	444	455
Lake of the Woods[a] (Heyerdahl and Smith, 1972)	664	129	210	289	305	328	345	356	361	--
Western Lake Superior (Dryer and Beil, 1964)	536	117	180	224	267	285	302	323	--	--

[a]Fork lengths were converted to total lengths by multiplying by 1.103.

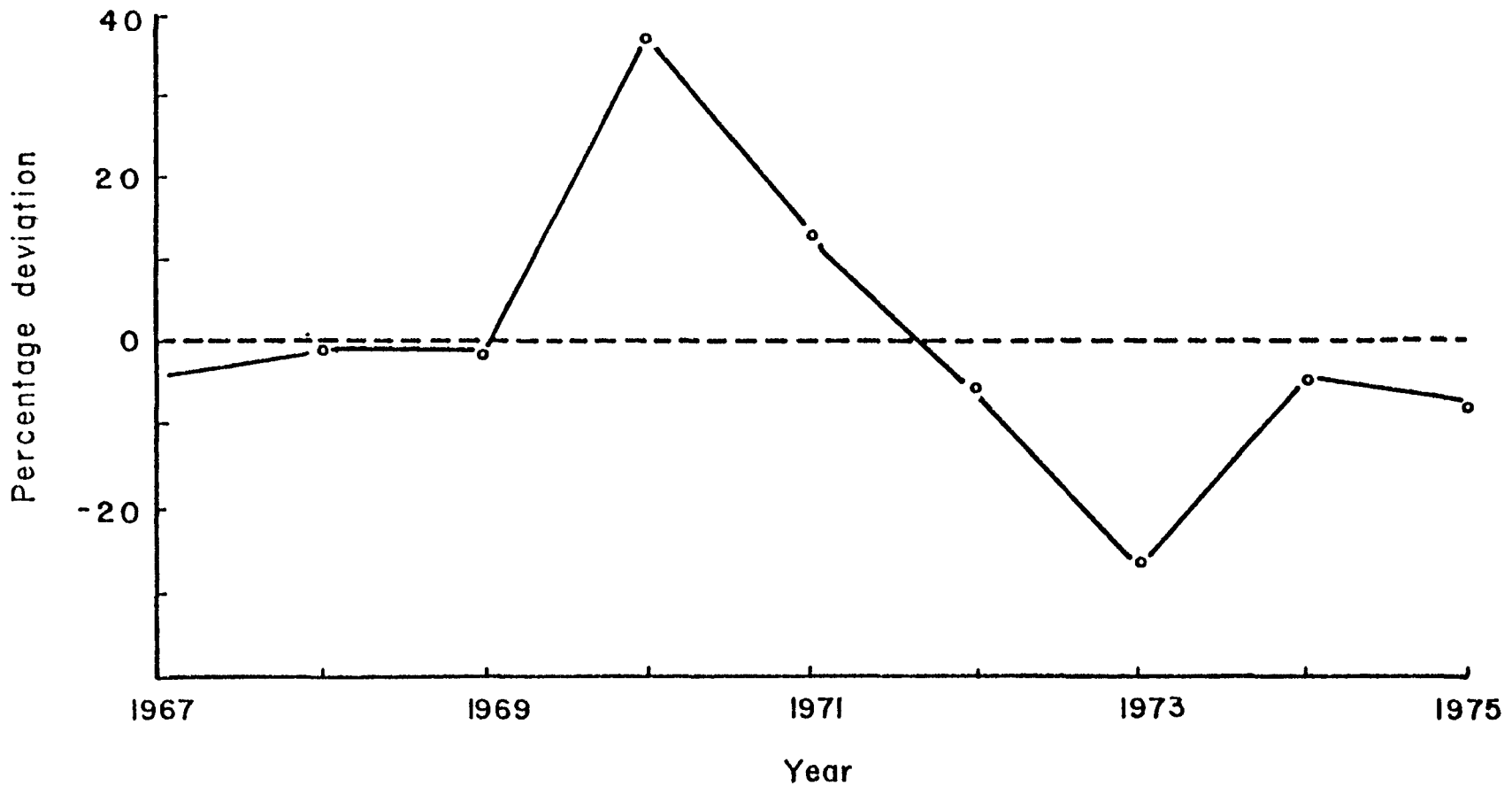

Figure 10. Percentage annual deviation from average lake herring growth for the period 1967 through 1975.

P = >0.1). Mean length increments of age groups I-VII were calculated for the 1968-1972 pretreatment period and 1974-1975 period when nutrient levels and primary production were reduced as a result of advanced wastewater treatment (Table 18). Comparison of pretreatment and post-treatment means for age groups I-V showed growth did not change significantly (P > 0.1).

Food Habits

The percentage of stomachs containing food was highest (>85.5%) during May-June and October-November of 1975 and 1976. Empty stomachs were most frequent (32.0-74.1%) during July-September of both years (Table 19).

Dipteran larvae (Chironomids and *Chaoborus* sp.) represented a higher percentage of the diet early in the spring (Table 19) and declined later in the sampling season. Cladocerans, principally *Daphnia* sp. and *Leptodora kindtii*, increased in importance in the diet during the sampling season. Copepods and related organisms were found in many stomachs and usually comprised between 10 and 30% of the total volume.

Zooplankton abundance during the ice-free seasons of 1974 and 1975 was studied by Richter (1975) and Piragis (1976) and was not correlated with the food habits of lake herring. Cladocerans (*Daphnia* sp. and *Leptodora kindtii*) showed progressive importance in the diet of lake herring through each sampling season while their abundance (Richter, 1975; Piragis, 1976) remained high through the summer and early autumn. Abundance of *Leptodora kindtii* peaked during early July and late August in Shagawa Lake and during mid-September in lake herring stomachs. Copepods constituted 6% or less of the stomach volume which did not reflect fluctuations in their populations. Copepoda exhibited population maximas during mid-June through early July, the month of August and again in late September.

Occurrence of Chironomids and *Chaoborus* sp. in the diet of lake herring suggests an association with the bottom during spring and early summer months. A shift to pelagic feeding during the summer and autumn is suggested by the increased occurrence of zooplankton. This change in distribution may be associated with hypolimnetic oxygen depletion during the summer.

Triaenophorus sp. Infestation Rates

Occurrence of *Triaenophorus* sp. plerocercoids in the flesh of lake herring represents a major factor influencing economic value of lake herring stocks in northern lakes. The adult cestodian parasite occurs in the intestine of northern pike. The mature tapeworm lays eggs when northern pike spawn. The eggs hatch into coracidium larvae which exist for one to two days unless injested by a Cyclops, primarily *Cyclops bicuspidatus thomasi* (Miller, 1945). A few procercoids have been observed in *C. vernalis brevispinosus* (Watson and Lawler, 1965) and *C. strenuus* (Lawler and Watson, 1963). After a 10- to 14-day development period the procercoid will infect lake herring or other fish (Table 20) if infected Cyclops are ingested. The pleurocercoids usually are located in the muscles around the back and are enclosed by a cyst formed by the irritated tissues of the infected fish.

TABLE 18. ANNUAL LAKE HERRING GROWTH INCREMENTS FOR EACH YEAR OF LIFE BY CALENDAR YEAR WITH STANDARD DEVIATIONS GIVEN IN PARENTHESIS

	AGE						
Year	I	II	III	IV	V	VI	VII
1968	186(13.1)						
1969	177(16.9)	69(35.1)					
1970	170(22.9)	91(42.4)	65(47.0)				
1971	183(20.0)	75(34.1)	73(38.4)	62(15.3)			
1972	183(10.2)	67(54.5)	66(37.8)	45(24.2)	22(14.0)		
1973	166(15.4)	35(7.9)	57(32.2)	51(24.9)	25(16.9)	12(8.4)	
1974	199(19.5)	41(10.5)	85(32.3)	51(22.2)	34(16.1)	14(9.6)	12(4.0)
1975	---	47(17.8)	80(25.2)	81(17.5)	15(9.0)	10(4.3)	5(2.6)
1968-1972 mean	180	76	68	54	22	--	--
1974-1975 mean	199	44	83	66	25	12	9

TABLE 19. FOOD HABITS OF SHAGAWA LAKE LAKE HERRING DESCRIBED AS PERCENTAGE FREQUENCY OF OCCURRENCE WITH MEAN PERCENTAGE OF FOOD VOLUME IN PARENTHESIS

	1975						
	May	June	July	Aug.	Sept.	Oct.	Nov.
Number of Stomachs	1	36	13	25	37	15	35
Percentage Empty	0	14	69	32	35	13	6
Insecta							
Chaoborus sp.	100(2)	50(14)	--	28(7)	16(1)	7(<1)	9(<1)
Chironomidae	100(93)	44(15)	23(50)	44(33)	30(8)	7(8)	6(<1)
Ephemera sp.	100(1)	--	--	--	--	--	--
Hexagenia sp.	--	--	--	--	13(6)	--	--
Megaloptera	--	3(<1)	--	--	--	--	--
Zygoptera	--	--	--	--	--	--	--
Tricoptera	--	--	--	--	--	--	--
Arachnidae							
Hydracarina sp.	100(<1)	36(<1)	8(6)	16(2)	8(<1)	--	--
Crustacea							
Copepoda	100(<1)	25(4)	8(6)	12(3)	22(9)	--	31(6)
Daphnia sp.	--	83(60)	15(31)	36(25)	49(41)	87(62)	86(50)
Leptodora sp.	--	19(6)	15(7)	44(23)	46(32)	--	3(<1)
Daphnia ephippium	--	--	--	--	--	46(27)	71(43)
Ostracoda	--	14(<1)	--	--	--	--	--
Hyalella	100(<1)	--	--	--	--	--	--
Annelida							
Oligochaeta	--	8(<1)	--	4(<1)	5(<1)	--	--
Nematoda	--	--	--	--	5(2)	--	--
Fish							
Etheostoma nigrum	--	--	--	--	3(1)	--	--
Unidentified	100(3)	3(<1)	--	8(7)	--	20(3)	--

(continued)

TABLE 19 (continued)

	1976				
	June	July	Aug.	Sept.	Oct.
Number of Stomachs	16	7	18	27	3
Percentage Empty	6	57	39	74	0
Insecta					
Chaoborus sp.	50(2)	14(2)	44(15)	11(13)	33(4)
Chironomidae	56(21)	43(98)	39(22)	4(7)	--
Ephemera sp.	--	--	6(<1)	--	--
Hexagenia sp.	12(8)	--	--	--	--
Megaloptera	--	--	--	--	--
Zygoptera	--	--	--	--	--
Tricoptera	--	--	--	--	--
Arachnidae					
Hydracarina sp.	44(1)	--	17(<1)	15(12)	--
Crustacea					
Copepoda	38(4)	--	44(2)	--	100(2)
Daphnia sp.	75(45)	--	56(58)	7(3)	100(81)
Leptodora sp.	--	--	44(2)	22(60)	100(3)
Daphnia ephippium	6(<1)	--	--	--	100(10)
Ostracoda	--	--	--	--	--
Hyalella	6(<1)	--	--	--	--
Annelida					
Oligochaeta	19(<1)	--	--	--	--
Nematoda	6(7)	--	--	--	--
Fish					
Etheostoma nigrum	--	--	--	--	--
Unidentified	38(12)	--	--	4(5)	--

TABLE 20. SPECIES OF INTERMEDIATE HOST FISH FOUND IN SHAGAWA LAKE FROM WHICH VARIOUS SPECIES OF TRIAENOPHORUS HAVE BEEN REPORTED IN NORTH AMERICA (modified from Lawler and Scott, 1954)

		T. crassus	*T. nodulosus*	*T. stizostedionis*
Lake herring	(*Coregonus artedii*)	X	X	
White sucker	(*Catostomus commersoni*)		X	
Bullhead	(*Ictalurus* sp.)		X	
Troutperch	(*Percopsis omiscomaycus*)	X		X
Yellow perch	(*Perca flavescens*)		X	
Smallmouth bass	(*Micropterus dolomieui*)		X	
Black crappie	(*Pomoxis nigromaculatus*)		X	
Slimy sculpin	(*Cottus cognatus*)		X	
Brook stickleback	(*Culaea inconstans*)		X	
Burbot	(*Lota lota*)	X	X	
Walleye	(*Stizostedion vitreum vitreum*)		X	

The grubby appearance of fish flesh infected with numerous cysts reduces acceptability. Shagawa Lake herring are particularly desirable because of low levels of parasite infestation and large size whereas herring from many lakes of the region carry numerous cysts.

Changes in Shagawa Lake zooplankton populations suggest lake restoration is creating conditions favoring the parasite. Available EPA project data suggest Cyclops and related genera (Copepoda) have doubled (Table 21) since initiation of advanced wastewater treatment. Cyst counts on 156 fish show the level of infestation has remained low (Table 22). Failure to identify cysts in fish captured during 1974 or June 1975 and their occurrence thereafter suggests infestation rates may be increasing.

NORTHERN PIKE POPULATION STUDIES

Population Structure

Information on age from 192 northern pike samples was applied to measurements of 251 fish to describe population structure (Table 23). Low abundance of age 0 and I fish in catches for all three sampling seasons could indicate failure of recent year-classes. However, abundance of age II fish in 1976 catches demonstrates that the 1974 year-class was abundant during 1974 and 1975 and low occurrence resulted from sampling bias.

Growth

Estimates of growth in length of northern pike suggest growth of the 1962-1966 year-classes exceeded that for the 1970-1975 year-classes (Table 24). However, data for both periods are limited and variable and provide little assurance that differences are real. Growth of northern pike in Shagawa Lake was comparable or slower than growth in other waters (Table 24).

Growth of Shagawa Lake northern pike during 1973-1975 was above the average for the 1970-1975 period (Figure 11). Deviations in growth appeared inversely related to chlorophyll α concentration ($r = -0.24$; $P > 0.1$). Mean length increments of age groups I-IV were calculated for the 1969-1972 pretreatment period and the 1974-1975 period when nutrient levels and primary production were reduced as a result of advanced wastewater treatment (Table 25). Comparison of pretreatment and post-treatment means for age groups I-IV by two-way analysis of variance showed growth of northern did not change significantly ($P > 0.1$).

Food Habits

Analysis of northern pike food habits was limited to 44 samples collected during 1976 (Table 26). Few of the 1974 and 1975 samples, which were collected primarily by gill net, contained food. More intensive trawling in areas with macrophytes during 1976 provided a better sample for use in food habit analysis. The limited sample showed yellow perch were the primary food of northern pike. High occurrence of age 0 walleye in northern stomachs (Table 26) suggests that predation by nortnern pike may be a major factor limiting walleye survival and production.

TABLE 21. DENSITY (no.·liter^{-1}) OF CYCLOPS AND RELATED GENERA IN THE CENTRAL BASIN OF SHAGAWA LAKE

YEAR	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	June-Sept. Ave.	Annual Ave.
1971*	--	--	--	--	--	57.0	--	12.3	13.5	15.5	26.7	10.5	27.6	--
1972	7.3	5.0	4.0	5.0	10.2	38.0	6.8	14.6	18.0	35.8	26.0	28.5	19.4	16.6
1973	20.4	17.5	8.2	41.0	28.8	84.2	18.4	23.2	29.2	73.6	34.5	25.0	38.8	33.7
1974	16.4	8.0	3.5	12.8	9.0	61.0	31.2	21.8	49.5	74.6	44.3	74.5	40.9	33.9
1975	25.8	14.0	11.0	9.7	18.2	48.2	29.0	18.8	50.8	77.3	55.7	95.4	36.7	40.9
1976**	--	--	--	--	--	31.5	69.0	91.1	60.5	--	--	--	68.8	--

*Data for the 1971-1975 period were provided by EPA project staff and represent counts from net catches.

**Piragis (1976).

TABLE 22. COUNTS OF TRIAENOPHORUS SP. CYSTS IN LAKE HERRING FROM SHAGAWA LAKE

Date	Number of Fish Examined	Mean Total Length (m) of All Fish	No. of Infected Fish	Mean Total Length (mm) of Infected Fish	Mean No. of Cysts Per Infected Fish	Mean No. of Cysts Per Fish >400 mm
1974	12	408	0	---	---	---
6/12/75	13	417	0	---	---	---
9/12/75	27	372	2	445	1.0	0.2
9/27/75	5	375	2	471	1.0	0.1
10/28/75	19	335	1	429	2.0	2.0
11/14/75	31	379	7	442	1.6	0.6
7/23/76	8	395	0	---	---	---
9/18/76	18	382	5	442	1.2	1.0
9/16/77	23	420	4	442	1.0	0.3
	156					

TABLE 23. AGE FREQUENCY DISTRIBUTION OF SHAGAWA LAKE NORTHERN PIKE CAPTURED BY SEINE, TRAWL AND GILL NET DURING 1974, 1975 AND 1976

Age	Year Class	Number in Age Group	Length Range in Millimeters
1974			
0	1974	0	---
I	1973	11	240 - 312
II	1972	30	405 - 555
III	1971	32	464 - 669
IV	1970	15	548 - 734
	Total:	88	
1975			
0	1975	-	---
I	1974	2	246 - 267
II	1973	16	330 - 450
III	1972	23	418 - 562
IV	1971	33	433 - 721
V	1970	16	590 - 718
VI	1969	7	667 - 800
	Total:	97	
1976			
0	1976	1	119
I	1975	4	292 - 335
II	1974	30	320 - 546
III	1973	28	416 - 636
IV	1972	2	607 - 620
V	1971	1	696
	Total:	66	

TABLE 24. CALCULATED TOTAL LENGTH OF NORTHERN PIKE YEAR-CLASSES EXPRESSED IN MILLIMETERS

Year Class	No. in Sample	Age Group I	II	III	IV	V	VI
1961	2	205	258	383	535	653	748
1962	3	227	235	536	680	754	--
1963	9	228	308	462	580	--	--
1964	20	235	345	470	--	--	--
1965	28	249	390	--	--	--	--
1966	7	268	--	--	--	--	--
1969	7	196	256	370	471	568	639
1970	22	191	240	355	468	577	--
1971	47	197	285	419	512	660	--
1972	37	204	299	427	571	--	--
1973	44	217	330	430	--	--	--
1974	31	222	363	--	--	--	--
1975	4	249	--	--	--	--	--
1961-1966 Grand Average	69	235	307	463	598	704	748
1969-1975 Grand Average	192	211	296	400	506	602	639
Gilbert and Big Cedar Lake, Wis. (Priegel and Krohn, 1975)†	173	256	455	551	629	662	680
Eight Wisconsin Lakes (Ave.)† (Snow, 1969)		216	351	452	503	561	612

†Values are averages for female and male.

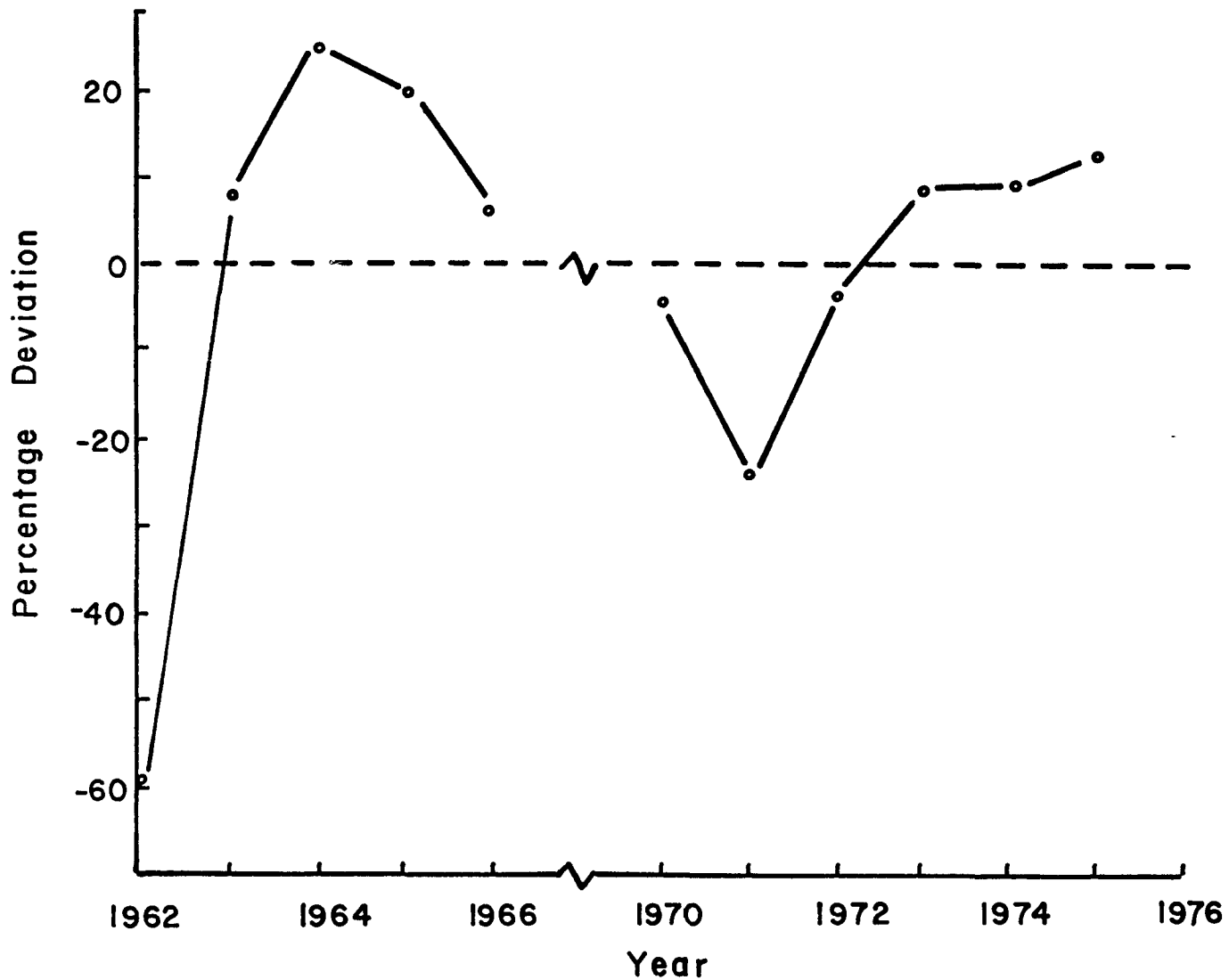

Figure 11. Percentage annual deviation of northern pike growth from average growth during 1962-1966 and 1970-1975.

TABLE 25. ANNUAL NORTHERN PIKE GROWTH INCREMENTS FOR EACH YEAR OF LIFE, BY CALENDAR YEAR, WITH STANDARD DEVIATIONS GIVEN IN PARENTHESIS

	Age					
Year	I	II	III	IV	V	VI
1969	196(9.0)					
1970	198(14.4)	60(16.8)				
1971	200(16.3)	83(61.5)	114(57.5)			
1972	211(26.0)	87(42.7)	113(36.3)	102(37.2)		
1973	211(17.7)	109(65.7)	141(43.0)	109(28.5)	96(29.3)	
1974	222(22.3)	95(42.1)	113(43.4)	94(28.3)	109(23.2)	71(10.0)
1975	247(15.7)	141(41.1)	118(43.2)	77(20.5)		
1967-1972 Mean	201	77	114	102	---	--
1974-1975 Mean	235	118	116	86	109	71

TABLE 26. FOOD OF NORTHERN PIKE IN SHAGAWA LAKE (1976) EXPRESSED AS PERCENTAGE FREQUENCY OF OCCURRENCE WITH PERCENTAGE OF TOTAL WEIGHT IN PARENTHESIS

	June	July	August	September	October
Number of Stomachs	7	5	10	14	8
Percentage Empty	57.1	20.0	40.0	28.6	37.5
Fish (Total)	66.7(93.1)	100.0(100.0)	100.0(100.0)	100.0(100.0)	100.0(100.0)
Perca flavescens	33.3(81.9)	100.0(68.2)	50.0(53.5)	100.0(98.2)	60.0(13.8)
Notropis sp.	33.3(10.5)	25.0(13.4)	--	--	--
Stizostedion vitreum	--	25.0(15.9)	33.3(44.5)	--	--
Catostomus commersoni	--	--	--	10.0(0.8)	20.0(85.6)
Etheostoma nigrum	--	--	--	--	20.0(0.4)
Unidentified	33.3(0.7)	25.0(2.5)	33.3(2.0)	30.0(1.0)	20.0(0.3)
Invertebrate (Total)	33.3(6.9)	--	--	--	--
Hirudinea	33.3(5.4)	--	--	--	--
Ephemeroptera	33.3(1.4)	--	--	--	--

DISCUSSION

The tertiary waste treatment facility constructed by the U.S. Environmental Protection Agency has operated successfully since 1973, reducing the estimated external total phosphorus (TP) supply to Shagawa Lake by 70-80% (CERL, 1977). Measurement of TP and soluble reactive phosphorus (SRP) from 1971 to 1976 indicates that both forms were significantly reduced during 1974-1976. Annual average TP and SRP were reduced from approximately 50 and 20 $\mu g \cdot \ell^{-1}$ during 1971-1973 to 30 and 6.6 $\mu g \cdot \ell^{-1}$ respectively during 1974-1976. Although the change was significant, earlier estimates indicated TP would be reduced to less than 15 $\mu g \cdot \ell^{-1}$ within the 1974-1976 period and would result in a major response in the trophic character of the system (Larsen *et al.*, 1973). Internal cycling of TP resulted in a less dramatic response (Larsen *et al.*, MS).

LAKE RESTORATION AND FISH HABITAT

Phosphate reduction was expected to stimulate changes in production of major fish species populations and the fish species complex through its influence on the following general habitat conditions:

1. Prey Populations
2. Light
3. Macrophyte Abundance
4. Hypolimnetic Oxygen Concentration

Information from this and cooperating projects suggests that minor changes in prey populations, light penetration and macrophyte production have occurred; however, available evidence fails to show improvement in hypolimnetic oxygen concentration.

Reduction in primary production and increased light penetration were demonstrated by a 29% drop in annual average chlorophyll α concentration and a 22% increase in secchi disc readings between the pretreatment (1971-1973) and post-treatment (1974-1976) study periods (CERL, 1977). The lowest annual average chlorophyll α concentrations (6.2 $\mu g \cdot \ell^{-1}$) and the highest secchi disc readings (3.2 m) occurred during 1974. During 1976 chlorophyll α was 96% of the pretreatment period average and secchi disc readings declined from 3.2 m (1974) to 2.6 m (1976).

Although not verified by direct observation during pre- and post-treatment years, core analysis shows diatom diversity will increase as the lake progresses to a mesotrophic state and abundance of pollution intolerant

zooplankton such as Bosmina longirostris and Cyclops bicuspidatus will also increase (Bradbury and Megard, 1972). Response of bacteria and rotifer populations was not studied in Shagawa Lake; however, increased transparency and other studies (Lynch and Smith, 1931) suggest their production probably declined.

Growth and abundance of age 0 yellow perch were reduced during 1974 when light penetration increased (CERL, 1977) and May Copepoda abundance was low (Table 21). These observations indicate that Shagawa Lake reached its lowest trophic level during 1974 and changes in primary production indirectly restricted the amount of energy, in the form of small fish, which was available to major predator populations.

Increased light transmission appears to have caused a shift from phytoplankton to macrophyte production. Although not substantiated by critical mapping, abundance of aquatic vegetation in the trawl indicated distribution of macrophytes was extended from a maximum depth of 2 to 3 m during 1974, the first year of increased transparency (CERL, 1977), to 4 m during 1975 and 1976. The trawl data are supported by other observations showing macrophyte distribution is influenced by transparency (Forney, 1977; Hurley and Christie, 1977). Because trawling was restricted to fairly protected areas with substrates conducive to macrophyte development, changes in macrophyte production may have been less extensive than suggested by the observations.

Anoxic conditions continued to occur in the hypolimnion when the lake stratified during post-treatment years. Oxygen concentration fell below 1 ppm at depths exceeding 5 m during all three post-treatment years (unpublished EPA data). Improvement in hypolimnetic oxygen was not suggested by either increased oxygen concentrations or reduced oxygen demand. Experience with other waters, however, indicates that hypolimnetic oxygen will increase as lake recovery progresses (Edmondson, 1977).

THE NICHE MODEL

Kerr and Ryder (1977) demonstrated that the "niche concept" has practical application in assessing the influence of habitat change on individual stocks and the fish species complex of lakes. By adopting Hutchinson's (1965) abstract hypervolume concept of a "niche" and the "zone of tolerance" of Fry (1947), they redefine "niche" as a hypervolume consisting of multiple measurable dimensions. Under this definition, any condition which has a measurable influence on the dynamics of a species and can be measured qualifies as a niche dimension. Provided the capacity to measure changes in significant niche dimensions and the response of populations to changes in these dimensions, Kerr and Ryder (1977) show the concept could have broad application in measuring the effects of habitat changes on individual populations and the total fish species complex in lakes. Precision of predictions from models employing the concept is dependent upon the number of niche dimensions and population responses which can be accurately measured.

The limited and variable response of Shagawa Lake to reduced nutrient loading and the scope of the total Shagawa Lake research program make it

impractical to quantitatively define the influence of lake restoration on production of any species population. However, the available data and the "niche concept" were applied in developing a conceptual model which describes whether production of major stocks is being negatively or positively influenced and the mechanism through which the effects are induced.

In developing the model it was concluded that primary production, transparency, macrophyte production and hypolimnetic oxygen concentration should not be directly identified as "niche dimensions" as their influence on fish populations are induced through their effects on spawning, space and predator-prey relationships. Therefore, the influence of each habitat condition on spawning, space and predator-prey relationships were analyzed. The number of niche dimensions negatively and positively affected for each species population was considered in describing changes in relative niche size. Predator-prey relationships were considered on the basis of changes in seven separate variables (dimensions) including prey distribution, prey species, prey size, prey density, walleye predation, yellow perch predation and northern pike predation.

Changes in the size of each niche dimension were described on the basis of information developed through this and other studies. Changes in the dimensions were identified by interpreting the effects of changes in prey populations, transparency, macrophyte distribution and oxygen concentration on niche size of walleye, yellow perch, northern pike, lake herring, trout-perch and the Centrarchidae (sunfish) group. Age 0 walleye and yellow perch were considered separately from older age classes.

INFLUENCE OF LAKE RESTORATION ON NICHE SIZE

Changes in the niche dimensions were identified, organized and summarized using a niche dimension response matrix (Table 27) which consists of a listing of the nine niche dimensions with each general habitat condition on the vertical axis. The fish species and groups are identified on the horizontal axis. A positive sign was entered where changes in general habitat conditions were interpreted from existing data to result in an increase in the size of a specific niche dimension for a given species or group. Negative signs signify reduction in the size of a given dimension. Zeroes were entered where no meaningful data were available or no change was suggested. Effects of change in general habitat conditions on niche size of individual species or groups were interpreted by summation (Table 27). Relative change in niche size was used to interpret gross changes in the species complex. Accuracy of the analysis is based on the assumption that effects on each dimension were correctly interpreted and that changes in the size of each dimension have an equal influence on niche size and production of a species or group. The first assumption which concerns the qualitative aspects of the study is supported by considerable information. Due to the constraints alluded to previously, quantitative information was limited and, therefore, the assumption of equal effects was adopted.

TABLE 27. NICHE DIMENSION-RESPONSE MATRIX: THREE PRIMARY DIMENSIONS ARE LISTED WITH EACH CHANGE IN THE LAKE AND SEVEN SEPARATE PREDATOR-PREY DIMENSIONS ARE CONSIDERED. CHANGES IN THE SIZE OF EACH DIMENSION ARE IDENTIFIED AS INCREASING (+), DECREASING (-) AND UNALTERED OR NOT MEASURED (0)

Environmental Change Niche Dimensions	SPECIES OR GROUP							
	Walleye		Perch		Northern Pike	Lake Herring	Trout-perch	Centrarchidae
	Age 0	Older	Age 0	Older				
Prey Populations (A)								
Space	0	0	0	0	0	0	0	0
Spawning	0	0	0	0	0	0	0	0
Pred.-Prey								
Prey Distribution	0	0	0	0	0	0	0	0
Prey Species	+	0	-	0	0	-	0	0
Prey Size	+	0	0	0	0	0	0	0
Prey Density	-	-	-	-	0	-	0	0
Walleye Predation	-	-	-	-	0	0	0	0
Perch Predation	0	0	0	0	0	0	0	0
N. Pike Predation	0	0	0	0	0	0	0	0
Total	0	-2	-3	-2	0	-2	0	0
Transparency (B)								
Space	0	-	0	+	+	0	-	+
Spawning	0	0	0	0	0	0	0	0
Pred.-Prey								
Prey Distribution	0	-	0	+	+	+	0	0
Prey Species	0	0	0	0	0	0	0	0
Prey Size	0	0	0	0	0	0	0	0
Prey Density	0	0	0	0	0	0	0	0
Walleye Predation	0	0	+	+	0	0	-	+
Perch Predation	0	0	0	0	0	0	0	0
N. Pike Predation	-	-	-	-	+	0	0	0
Total	-1	-3	0	+2	+3	+1	-2	+2

(continued)

TABLE 27 (continued)

Environmental Change Niche Dimensions	SPECIES OR GROUP							
	Walleye		Perch		Northern Pike	Lake Herring	Trout-perch	Centrarchidae
	Age 0	Older	Age 0	Older				
Macrophyte Distribution (C)								
Space	0	-	0	0	0	0	-	+
Spawning	0	0	+	0	+	0	0	+
Pred.-Prey								
Prey Distribution	0	-	0	0	+	0	0	0
Prey Species	0	-	0	0	0	0	0	0
Prey Size	0	-	0	0	0	0	0	0
Prey Density	0	-	0	0	+	0	0	0
Walleye Predation	-	-	+	+	0	+	-	+
Perch Predation	0	0	0	0	0	0	0	0
N. Pike Predation	-	-	-	-	+	-	-	0
Total	-2	-7	+1	0	+4	0	-3	+3
Oxygen Concentration (D)								
Space	0	+	0	+	0	+	+	0
Spawning	0	0	0	0	0	0	0	0
Pred.-Prey								
Prey Distribution	0	+	0	+	0	+	+	0
Prey Species	0	+	0	+	0	+	+	0
Prey Size	0	+	0	+	0	+	+	0
Prey Density	0	+	0	+	0	+	+	0
Walleye Predation	+	+	+	0	0	0	+	0
Perch Predation	0	0	0	+	0	0	0	0
N. Pike Predation	0	0	+	+	0	0	+	0
Total	+1	+6	+2	+7	0	+5	+7	0
Total A-C	-3	-12	-2	0	+7	-1	-5	+5
Total A-D	-2	-6	0	+7	+7	+4	+2	+5

Prey Populations

Available data on prey populations and fish feeding suggest that lower primary production has had limited influence on the niche of most fish species. In lakes where extensive spawning gravel or stream spawning habitat are less available, reduced plankton production and related decomposition in the system may promote spawning of walleye and lake herring. However, the available data did not indicate that lower plankton production would influence space or spawning in Shagawa Lake (Table 27).

Reduction in plankton populations resulting from reduced phosphorus loading should result in reduction in the size of some predator-prey dimensions in the niche of walleye, yellow perch and lake herring (Table 27). The limiting effects on walleye and yellow perch identified in Table 27 are based on the assumption that zooplankton density will decline. Under reduced zooplankton densities, growth of age 0 yellow perch will be slower and mortality will increase because walleye will require larger numbers of smaller perch to reach preferred feeding levels. Because yellow perch year-class strength is dependent on walleye predation (Forney, 1974) abundance of yellow perch will decline. Production of adult yellow perch may also be limited as a result of reduced density of benthic macroinvertebrates (Stewart and Rohlich, 1967; Eggers et al., 1978). Growth of adult yellow perch was significantly slower during post-treatment years, and growth of age 0 yellow perch was slow during 1974, supporting a conclusion that yellow perch production is declining as a result of reduced food availability. Growth of age 0 and older yellow perch was equal to or exceeded growth rates of populations in other waters suggesting that effects of reduced prey production on the niche of yellow perch are limited to date. The yellow perch niche may also be restricted by species shifts in zooplankton which result in lower rotifer densities. Rotifers should be favored in systems sponsoring high bacteria production (Lynch and Smith, 1931) and represent the first food of young yellow perch (Siefert, 1972).

Zooplankton shifts should favor survival of young walleye which are dependent on larger zooplankton than yellow perch. Increased availability of zooplankton for walleye and lower availability of small zooplankton utilized by yellow perch could result in larger size differences and higher availability of age 0 yellow perch as food for age 0 walleye. However, expansions of the walleye niche accrued through zooplankton species changes may be offset by lower yellow perch densities resulting from walleye predation. Actually, lower walleye survival could occur as a result of increased cannibalism at lower prey densities (Table 27). This study and others (Swenson and Smith, 1976; Forney, 1976) indicate prey density is limited by walleye predation and is a primary factor controlling cannibalism in the species. Cannibalism did increase when yellow perch availability was low in Shagawa Lake and represents a mechanism which limits production of the species. Because yellow perch density greatly exceeded the level limiting to walleye feeding (Figure 7) during most of the open water period, reductions in walleye food availability and effects on growth, cannibalism and abundance (Table 27) should be minor and are dependent on continued reduction in the trophic status of Shagawa Lake.

Prey species and prey density dimensions of the lake herring niche are probably being reduced. Food habit analysis shows lake herring are dependent on zooplankton in open water as an energy source. Reduced growth of lake herring during post-treatment years was suggested and supports a conclusion that the food density dimension of their niche is being restricted. Abundance of cyclops (Table 21) and the number of Triaenophorus crassus in lake herring appears to be increasing slightly. Although the apparent changes are minor and fail to demonstrate significant trends, they support the hypothesis that changes in the prey species component of the lake herring niche are having a minor negative impact on the population and on the fishery by resulting in increased parasite burdens. Distribution of Triaenophorus indicates occurrence is higher in clear water lakes (Lawler and Scott, 1954).

Transparency

Increased transparency decreases the space dimension of walleye and troutperch niches but increases the space dimensions of yellow perch, northern pike and Centrarchidae niches (Table 27). Data from this study show walleye exceeding 200 ml TL are crepuscular and night active predators, and Ryder (1977) found cover and offshore movement are used to reduce light intensity in clear water. Ryder (1977) and Swenson (1977) found activity of age II and older walleye increases under reduced light. Swenson (1978) and Ryder (1977) found distribution of age 0 walleye is not limited by high light intensity in shallow (1-5 m) depths of clear lakes. Distribution (Swenson and Smith, 1976) and movements of troutperch (McPhail and Lindsay, 1970) indicate a preference for low light intensity. Distribution and information on feeding behavior of yellow perch, northern pike and some Centrarchidae (Keast, 1970) indicate an affinity for high light intensities typical of the littoral areas in clear water lakes. On the basis of the above it was concluded that increased transparency limited the niche of walleye through reductions in suitable feeding space. The time of maximum prey availability was also restricted (Figure 6) as a result of distributional shifts. Increased transparency has the opposite effect on yellow perch, northern pike and Centrarchidae (Table 27). Lower walleye feeding success should result in lower predation related mortality in yellow perch; however, mortality associated with increased northern pike predation could take the place of that imposed by walleye. The effect of increased light therefore appears to be a transfer of more energy from the less light-tolerant walleye to the more tolerant northern pike. Increased northern pike feeding success and related production could stimulate higher mortality in age 0 walleye as a result of increased predation by northern, further limiting walleye abundance (Table 27). Movement of walleye into deeper water increases the niche of the Centrarchidae group by limiting walleye predation but could result in a reduction of the troutperch niche because walleye and troutperch are placed in the same zone increasing the probability of walleye predation on troutperch.

Macrophyte Distribution

Increased macrophyte production and distribution appear to be resulting in a reduction of several walleye niche dimensions and increased size of several northern pike niche dimensions (Table 27). Macrophytes limit space availability for walleye which trawl catches indicate avoid areas near

macrophytes. Macrophytes reduce six feeding related dimensions of the walleye niche (Table 27). The results of this study suggest age 0 yellow perch may congregate near macrophytes reducing their availability to walleye and prey density in open water. This results in reduced walleye feeding rates. Some evidence was developed by this study and Forney (1976) to show that cannibalism increases when alternate prey is less available. Because macrophytes are distributed over a larger area resulting in more space for northern pike (Makowecki, 1973), northern pike-induced mortality on age 0 walleye probably has increased during the July through mid-September period when age 0 walleye concentrate in the littoral area. The first evidence of substantial predation on walleye by northern pike in Shagawa Lake was provided during 1976. Changes in macrophyte distribution and northern pike abundance should result in increased predation by northern pike on yellow perch. The influence of northern pike predation on yellow perch mortality should replace that imposed by walleye predation. Thus, the effect of increased macrophyte abundance as well as transparency would appear to be a transfer of available energy away from walleye to northern pike with the total effect on yellow perch being limited. A similar change in energy transfer is identified for relationships between walleye and northern pike predation on lake herring. Increased walleye predation on troutperch would be stimulated by offshore movements of walleye. Change in macrophyte abundance should improve space, spawning and walleye predation dimensions of the Centrarchidae "niche."

Oxygen Concentration

The influence of lower plankton production, increased transparency and macrophyte distribution all appear to be resulting in a shift from walleye to northern pike production because they reduce important dimensions of the walleye niche and increase or do not influence the dimensions of the northern pike niche (Table 27). No improvements in hypolimnetic oxygen concentration occurred as a result of the first three years of nutrient removal. However, continued treatment should eventually result in higher hypolimnetic oxygen concentrations. Change in oxygen supplies could dramatically increase the niche size of walleye, yellow perch, lake herring and troutperch but would not greatly alter the niche of northern pike. Space and food in deep water could substantially add to the space and predator-prey dimensions of the walleye niche (Table 27) promoting increased production. Higher and stable hypolimnion oxygen concentrations should stimulate increased availability of invertebrates to walleye, yellow perch, troutperch and herring and result in offshore distribution of age 0 yellow perch, increasing their availability to walleye. Higher prey density in offshore areas associated with the buildup of troutperch populations could result in reduced cannibalism and increased feeding success of walleye. Although walleye may eat more troutperch, the percentage consumed would continue to be low. Swenson and Smith (1976) found that predation on troutperch in Lake of the Woods, Minnesota, did not control troutperch population size because of their large size and low availability.

SUMMATION OF EFFECTS

Application of available data and the niche concept in measuring the influence of nutrient removal on the Shagawa Lake fishery resource indicates

that impacts are generally limited to minor shifts in production of existing populations stimulated through changes in the space and predator-prey dimensions of the niche of each species. Changes in the space dimension of a niche influenced distribution directly. Additional indirect effects of changes in the space dimension were activated through the influence of distributional change on predator-prey dimensions of the niche.

To date, changes in prey populations, transparency and macrophyte abundance have resulted in minor reductions in the production and niche size of walleye, yellow perch, lake herring and troutperch. The model and available data suggest niche size and production of northern pike and the Centrarchidae are increasing (Table 27). Changes in light intensity and macrophyte populations appear to play an important role in determining the availability of energy to piscivorous predators and in controlling survival and abundance of several species. The mechanisms identified require further study but would appear to be responsible for the dominance of northern pike in clear water systems and of walleye in more eutrophic dark water lakes.

Low abundance of fish in water exceeding 5 m, positive correlations between abundance and oxygen concentrations and comparisons with abundance in Lake of the Woods, Minnesota, show that the space- and feeding-related dimensions of walleye, yellow perch, lake herring and troutperch would be expanded if nutrient removal is continued beyond the point at which hypolimnetic oxygen concentration is maintained above 5 ppm. Although information developed within the limited time frame of this study is inconclusive, it supports the hypothesis that higher production of the major species in the Shagawa Lake community is promoted under mesotrophic conditions.

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APPENDIX TABLE 1. AVERAGE MONTHLY TEMPERATURES (°C) FOR THE UPPER 6 M OF WATER NEAR BRISSONS POINT SHAGAWA LAKE (EPA unpublished data)

	Year								
Month	1968	1969	1970	1971	1972	1973	1974	1975	1976
January	--	--	--	1.6	2.2	3.0	1.5	2.1	3.2
February	--	--	--	1.5	2.3	2.5	1.7	2.1	3.3
March	--	--	--	1.5	2.3	3.1	1.7	2.3	3.1
April	2.1	--	--	1.9	2.6	5.4	1.8	2.6	6.5
May	9.5	12.0	5.7	8.3	10.3	10.2	6.8	10.3	11.0
June	14.3	15.4	15.9	16.9	15.9	18.0	14.4	16.0	19.5
July	--	20.0	21.1	20.2	18.8	21.3	20.3	21.2	22.2
August	--	22.1	20.1	19.5	19.7	21.8	19.0	20.7	21.4
September	--	18.7	14.6	17.5	15.7	17.4	13.1	15.7	16.9
October	--	7.6	9.5	12.2	7.3	10.4	6.7	10.2	9.9
November	--	--	4.6	4.4	3.0	3.1	6.5	6.9	3.0
December	--	1.3	1.8	1.8	2.4	1.5	1.5	--	--

APPENDIX TABLE 2. FOOD HABITS OF YOUNG-OF-THE-YEAR WALLEYES EXPRESSED AS PERCENTAGE FREQUENCY OF OCCURRENCE FOR STOMACHS CONTAINING FOOD WITH PERCENTAGE OF TOTAL INGESTED FOOD WEIGHT IN PARENTHESIS

Collection Date	1974	
	Aug.	Sept.
Number of Stomachs	24	15
Percentage Empty	33.3	20
Invertebrates		
Annelida		
Fluke	--	--
Amphipoda		
Hyalella azteca	--	--
Arachnida		
Hydracarina sp.	--	--
Cladocera	56.3(15.3)	16.1(2.6)
Copepoda		
Cyclops sp.	--	--
Diaptomus sp.	--	--
Diptera		
Chironomidae	6.3(0.2)	--
Chaoboridae	--	8.3(0.3)
Emphemeroptera	12.5(4.0)	--
Nematomorpha	--	--
Platyhelmenthes	--	--
Tricoptera	--	--
Unidentified	--	16.6(5.9)
Fish		
Catostomus commersoni	--	--
Etheostoma nigrum	18.7(14.3)	25.0(14.0)
Notropis hudsonius	12.5(33.0)	33.3(54.3)
Perca flavescens	6.3(33.2)	16.6(22.8)
Pomoxis nigromaculatus	--	--
Unidentified	--	--

(continued)

APPENDIX TABLE 2 (Continued)

Collection Date	1975				
	July	Aug.	Sept.	Oct.	Nov.
Number of Stomachs	82	53	59	11	17
Percentage Empty	46.4	39.4	28.4	10	21.4
Invertebrates					
Annelida					
Fluke	3.3(0.7)	--	--	--	--
Amphipoda					
Hyalella azteca	--	--	--	11.1(0.1)	--
Arachnida					
Hydracarina sp.	3.3(0.2)	--	--	--	--
Cladocera	3.5(0.5)	21.6(1.8)	28.4(0.8)	61.6(3.3)	78.7(7.0)
Copepoda					
Cyclops sp.	--	4.3(0.7)	3.0(<.1)	--	--
Diaptomus sp.	--	--	--	--	--
Diptera					
Chironomidae	6.7(0.4)	8.7(0.8)	9.1(0.2)	11.1(2.8)	27.2(5.2)
Chaoboridae	--	--	12.1(0.6)	22.2(0.1)	45.4(1.8)
Ephemeroptera	6.7(3.6)	--	3.0(0.4)	--	--
Nematomorpha	--	--	--	--	--
Platyhelmenthes	--	--	--	--	--
Tricoptera	--	--	--	--	--
Unidentified	--	--	--	--	--
Fish					
Catostomus commersoni	3.3(3.7)	--	3.0(2.3)	--	--
Etheostoma nigrum	6.7(2.2)	--	9.1(10.5)	--	--
Notropis hudsonius	--	--	3.0(2.3)	--	--
Perca flavescens	80.0(88.7)	73.9(81.8)	69.7(82.8)	44.4(93.5)	27.2(85.9)
Pomoxis nigromaculatus	--	13.0(15.2)	--	--	--
Unidentified	--	--	--	--	--

(continued)

APPENDIX TABLE 2 (Continued)

Collection Date	1976		
	July	Aug.	Sept.
Number of Stomachs	66	57	42
Percentage Empty	41	34.4	25
Invertebrates			
Annelida			
Fluke	--	14.0(0.2)	7.1(1.6)
Amphipoda			
Hyalella azteca	--	--	--
Arachnida			
Hydracarina sp.	--	1.8(<.1)	--
Cladocera	46.7(14.1)	55.6(6.6)	23.5(2.7)
Copepoda			
Cyclops sp.	6.1(<.1)	--	--
Diaptomus sp.	3.0(0.2)	--	--
Diptera			
Chironomidae	7.6(0.9)	19.3(1.9)	33.3(12.5)
Chaoboridae	7.6(4.5)	8.8(3.3)	11.9(3.9)
Ephemeroptera	4.5(7.9)	5.2(0.9)	14.2(1.4)
Nematomorpha	--	--	2.4(<.1)
Platyhelmenthes	--	1.8(<.1)	--
Tricoptera	--	1.8(0.2)	--
Unidentified	3.0(1.3)	--	--
Fish			
Catostomus commersoni	--	--	--
Etheostoma nigrum	12.1(9.9)	21.0(21.8)	21.4(19.3)
Notropis hudsonius	--	--	--
Perca flavescens	43.9(60.9)	29.0(64.9)	26.1(58.1)
Pomoxis nigromaculatus	--	--	--
Unidentified	1.5(0.2)	--	--

APPENDIX TABLE 3. FOOD HABITS OF SHAGAWA LAKE WALLEYE BEYOND THE FIRST YEAR OF LIFE EXPRESSED AS PERCENTAGE FREQUENCY OF OCCURRENCE WITH PERCENTAGE BY WEIGHT IN PARENTHESIS

Collection Date	1974			
	June	July	Aug.	Sept.
Number of Stomachs	131	80	111	39
Percentage Empty	21.4	42.5	18.0	28.2
Invertebrates				
Amphipoda				
Hyalella azteca	19.4(0.8)	--	--	--
Cladocera	2.0(0.4)	--	--	--
Coleoptera	--	--	1.1(0.1)	--
Copepoda	--	--	--	--
Decapoda				
Astasidae	--	--	--	--
Diptera				
Chaoboridae	28.2(12.9)	2.0(0.1)	2.2(0.9)	--
Chironomidae	53.4(5.0)	10.9(0.1)	26.4(2.8)	21.4(2.8)
Ephemeroptera	41.8(26.1)	9.8(0.8)	14.4(5.8)	10.7(2.3)
Hirudinea	--	--	--	--
Megaloptera (*Sialis*)	--	--	--	--
Notostraca	--	--	--	--
Odonata	--	--	--	--
Pelecypoda	--	--	1.1(0.3)	--
Plecoptera	--	--	--	--
Tricoptera	--	11.4(0.1)	2.2(0.1)	3.6(0.2)
Fish				
Ambloplites rupestris	--	--	--	--
Catostomus commersoni	--	--	--	--
Coregonus artedii	--	--	--	--
Etheostoma nigrum	10.7(9.6)	4.3(0.1)	3.3(1.2)	--
Ictalurus melas	1.0(0.5)	--	--	--
Lota lota	--	--	--	--
Micropterus dolomieu	--	--	--	--
Notropis hudsonius	13.6(36.8)	8.7(3.3)	14.3(5.8)	35.7(22.4)
Noturus gyrinus	--	--	--	--
Perca flavenscens	--	89.0(94.8)	64.8(82.5)	57.1(72.5)
Percina caprodes	--	--	--	--
Percopsis omiscomaycus	2.9(7.6)	--	--	--
Pomoxis nigromaculatus	--	--	1.1(0.3)	--
Stizostedion vitreum	--	--	--	--
Unidentified	1.0(0.1)	4.3(0.6)	4.4(0.3)	3.6(0.8)

(continued)

APPENDIX TABLE 3 (Continued)

Collection Date	1975				
	May	June	July	Aug.	Sept.
Number of Stomachs	74	104	139	83	176
Percentage Empty	21.6	20.2	34.5	15.7	17.6
Invertebrates					
Amphipoda					
Hyalella azteca	27.6(0.8)	18.1(5.2)	--	--	2.1(<.1)
Cladocera	8.1(0.1)	25.9(13.9)	2.1(2.1)	--	5.1(0.1)
Coleoptera	--	--	--	--	--
Copepoda	1.7(0.1)	6.0(0.1)	1.1(<.1)	--	--
Decapoda					
Astasidae	--	--	2.3(0.3)	--	--
Diptera					
Chaoboridae	17.2(0.1)	16.9(0.3)	2.3(<.1)	--	0.7(<.1)
Chironomidae	37.9(0.3)	47.0(2.2)	14.1(0.4)	10.0(1.5)	13.1(1.5)
Ephemeroptera	22.9(3.6)	20.2(9.5)	9.3(1.0)	2.4(<.1)	9.1(0.4)
Hirudinea	3.4(0.5)	3.6(3.8)	2.3(<.1)	--	0.7(0.2)
Megaloptera (*Sialis*)	--	--	--	--	--
Notostraca	--	1.2(<.1)	--	--	--
Odonata	--	1.2(<.1)	--	--	--
Pelecypoda	--	--	--	--	--
Plecoptera	--	--	--	--	--
Tricoptera	3.4(<.1)	1.2(<.1)	2.3(<.1)	--	--
Fish					
Ambloplites rupestris	--	--	--	--	1.4(0.9)
Catostomus commersoni	--	--	4.5(1.5)	--	4.8(5.9)
Coregonus artedii	--	--	--	--	--
Etheostoma nigrum	5.2(1.3)	2.4(2.2)	--	1.4(0.2)	2.1(0.3)
Ictalurus melas	--	1.2(0.4)	--	--	--
Lota lota	--	--	1.1(1.4)	--	--
Micropterus dolomieu	--	--	--	--	0.7(0.8)
Notropis hudsonius	1.7(0.2)	--	2.2(2.1)	2.9(5.8)	8.3(5.1)
Noturus gyrinus	--	--	--	--	--
Perca flavescens	53.4(88.6)	38.6(43.0)	87.6(91.4)	87.1(85.8)	75.9(71.0)
Percina caprodes	--	--	--	--	0.7(0.1)
Percopsis omiscomaycus	10.3(4.4)	2.4(5.0)	3.4(<.1)	2.9(1.0)	1.4(1.5)
Pomoxis nigromaculatus	--	1.2(0.2)	--	8.6(5.2)	9.7(9.6)
Stizostedion vitreum	--	2.4(14.1)	--	--	0.7(2.3)
Unidentified	--	--	--	1.4(<.1)	--

(continued)

APPENDIX TABLE 3 (Continued)

Collection Date	1976				
	June	July	Aug.	Sept.	Oct.
Number of Stomachs	97	73	115	116	69
Percentage Empty	35.1	41.1	37.4	30.2	27.5
Invertebrates					
Amphipoda					
Hyalella azteca	20.6(0.6)	--	--	--	--
Cladocera	--	--	--	--	--
Coleoptera	--	--	--	--	--
Copepoda	--	--	--	--	--
Decapoda					
Astasidae	--	--	--	--	--
Diptera					
Chaoboridae	11.1(1.2)	--	--	--	--
Chironomidae	38.1(0.8)	18.6(5.9)	4.2(<.1)	30.9(5.0)	8.0(<.1)
Ephemeroptera	38.1(28.2)	7.0(0.4)	1.4(0.2)	4.3(0.4)	2.0(<.1)
Hirudinea	6.4(0.2)	--	--	2.5(0.2)	--
Megaloptera (*Sialis*)	9.5(0.2)	--	--	--	--
Notostraca	--	--	--	--	--
Odonata	1.6(<.1)	--	--	--	--
Pelecypoda	--	--	--	--	--
Plecoptera	1.6(0.1)	--	--	--	--
Tricoptera	1.6(0.1)	--	--	--	--
Fish					
Ambloplites rupestris	--	--	--	--	--
Catostomus commersoni	--	--	--	1.2(0.5)	2.0(2.9)
Coregonus artedii	3.2(1.8)	--	1.4(0.7)	--	4.0(33.3)
Etheostoma nigrum	1.6(0.3)	2.3(1.6)	2.8(0.3)	--	2.0(0.4)
Ictalurus melas	--	2.3(0.7)	--	--	--
Lota lota	--	--	--	--	--
Micropterus dolomieu	--	--	--	--	--
Notropis hudsonius	1.6(8.5)	4.7(3.2)	6.9(5.1)	3.7(4.6)	4.0(1.4)
Noturus gyrinus	1.6(1.0)	--	--	--	--
Perca flavescens	47.6(56.6)	88.4(88.2)	88.9(88.6)	77.8(81.9)	76.0(56.3)
Percina caprodes	--	--	--	--	--
Percopsis omiscomaycus	1.6(0.6)	--	2.8(2.1)	--	--
Pomoxis nigromaculatus	--	--	--	--	--
Stizostedion vitreum	--	--	1.4(2.7)	1.2(7.1)	2.0(5.1)
Unidentified	--	--	2.8(0.4)	2.5(0.3)	6.0(0.6)

TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/3-80-036	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Influence of Advanced Wastewater Treatment on the Fishery Resource of Shagawa Lake, Minnesota		5. REPORT DATE March 1980 issuing date 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) William A. Swenson		8. PERFORMING ORGANIZATION REPORT NO.
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15. SUPPLEMENTARY NOTES

16. ABSTRACT

This project was conducted to measure the response of the warmwater fish populations in Shagawa Lake, Minnesota, to altered trophic conditions brought about by phosphate removal from sewage discharges entering the lake. The project also served to provide basic information on the mechanisms through which a lake's trophic status controls its fish species complex.

Abundance, distribution, growth, and feeding interrelationships of walleye (Stizostedion vitreum vitreum), northern pike (Esox lucius), yellow perch (Perca flavenscens), and lake herring (Coregonus artedii) were described in relation to changes in prey density and other environmental factors. A conceptual model based on the "niche concept" was developed to identify the influence of changes in various parts of the system on individual fish populations and on the total fish species complex.

The field data and model suggest that production of walleye, yellow perch and lake herring is being reduced while the "niche" and production of the northern pike population is expanding in response to changes in several feeding-related "niche dimensions"

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
water pollution	Shagawa Lake	13B
freshwater fishes	Minnesota	8H
sewage treatment	Stizostedion vitreum vitreum	6F
models		
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