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A Water Quality Study of Higgins Lake, Michigan

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Douglas Lake

A WATER QUALITY STUDY OF HIGGINS LAKE, MICHIGAN

by

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TABLE OF CONTENTS

I. INTRODUCTION

Higgins Lake has long been noted for its extremely high water quality, and is presently regarded as one of the cleanest lakes in Michigan. Recently, however, property owners and lake association members have reported decreases in water clarity, the appearance of lake bottom bands of detritus, and also a very noticeable increase in algal growth near the shoreline. These are all signs of cultural eutrophication, an increase in lake productivity, often to undesirable levels, stimulated by increases in nutrients supplied to the lake. Limnologists use the terms "oligotrophic", "mesotrophic" and "eutrophic" to roughly describe stages in the eutrophication process. Oligotrophic lakes tend to be clear, relatively deep lakes with low biological production and high dissolved oxygen concentrations throughout the year. Eutrophic lakes in contrast are turbid water bodies with high biological productivity and low dissolved oxygen levels in the deeper water during thermal stratification. Mesotrophic lakes show intermediate characteristics between oligotrophy and eutrophy, and often have productive warmwater fisheries (NEMCOG, 1979).

A growing concern that Higgins Lake may be experiencing eutrophication, thereby decreasing the lake's economic and recreational value, prompted the Township Boards of Lyon and Gerrish Townships to contact the University of Michigan Biological Station to initiate a comprehensive water quality survey of Higgins Lake. In January of 1983, Dr. G. Winfield Fairchild, at that time Professor of Limnology at the Station, began work on the project with the hiring of Richard Schultz, a graduate student in aquatic biology at Central Michigan University, as project coordinator.

A large portion of this report addresses the physical, chemical, and biological conditions which characterize the present trophic state of Higgins Lake (Sections IV-VI). The data are intended as a baseline for future studies, and have also been compared with previously collected information in order to examine changes in water quality during the past decade. Phosphorus is then identified as a major limiting nutrient in the lake, and an input-output nutrient budget model for phosphorus is summarized (Sections VII-VIII). A major concern of the research has been the impact of human recreation and development in supplying nutrients to nearshore areas of the lake, and water quality is described for 18 sites along the lakeshore (Sections IX-X). Finally, general recommendations are made for further long term study and water quality management (Section XI). Major results of the study are briefly summarized in Section II.

II. SUMMARY

Higgins Lake remains an oligotrophic lake of high water quality. Both deep basins studies have high year-round dissolved oxygen concentrations throughout the water column, deep light penetration, and low nutrient and chlorophyll-a concentrations. The plankton community also contains biological indicator species, such as the calanoid copepod *Senecella calanoides*, which are indicative of oligotrophy.

The North Basin of Higgins Lake has slightly higher water quality than the South Basin, which, because of its morphometry and location, may be particularly sensitive to eutrophication in the future. Analysis of nitrogen: phosphorus ratios indicates that both basins are phosphorus-limited during mid-summer.

In contrast to the deep basins, nearshore areas of Higgins Lake have consistently high concentrations of phosphorus, and heavy accumulations of both marl and the filamentous green alga *Cladophora glomerata* at many locations. Inorganic nitrogen (especially nitrate) is depleted to potentially limiting levels. An *in situ* biostimulation experiment, conducted at one of the 18 nearshore sampling locations, provides confirmation that the growth of algal periphyton nearshore is nitrogen-limited by mid-summer, apparently owing to high phosphorus loading.

It is suggested that water quality be managed by reducing human sources of phosphorus, particularly from riparian land, and that further development of the Higgins Lake watershed be considered carefully with regard to its impact upon nutrient loading to the lake.

III. HISTORICAL OVERVIEW

Prior to the initiation of this study, a literature search was conducted of work done previously on Higgins Lake. The following studies provide a basis for the present research.

Bosserman (1969) completed an inventory of present land use in the Higgins Lake Basin and examined the effects of these uses on the quality of the lake water. He walked the shoreline, taking note of all inflowing and outflowing surface waters, and compiled basic morphometric, biological, and chemical information for the lake. From these data, Bosserman concluded that there were four basic sources of pollution to Higgins Lake: (1) drains and outfalls, (2) ice-caused erosion, (3) erosion caused by wave action, and (4) erosion caused by road ends. He suggested a number of management measures, including the use of jetties, revetments, and sea walls to protect against erosion from wind and ice and also the use of vegetative cover to deal with problems of drainage and road end erosion.

During 1971, the Student Water Publications Club of Michigan State University conducted a survey of Higgins Lake dealing with two issues of importance to water quality. Their report discussed the drainage of Battin Swamp, from which large amounts of tannins enter the lake near Point Comfort. A number of attempts were made to fill in the drain, in part because of the fear that nutrients were being added to the lake with the tannins. It was finally decided that the County Road Commission had the legal right to maintain the drain as a means of regulating water levels in the swamp.

A second concern addressed by the study was the overuse of the two State Parks on Higgins Lake. A series of interviews with park employees revealed that the parks were frequently filled to capacity and that this overuse might lead to overloading of the parks' lagoon sewage systems, thereby causing increased sewage infiltration into groundwater feeding into the lake. As a means of combatting this problem, it was suggested that the parks restrict the number of sites available on a particular day.

The Student Water Publications Club of Michigan State University was contacted by the Higgins Lake Board in early 1972 and requested to collect water samples from a series of riparian wells, from within the lake itself, and from associated streams to determine bacterial densities and nutrient concentrations. Of the 20 wells tested, two were positive of coliform bacteria. Several areas of the lake and a number of surface inflows also showed positive tests for bacteria, indicating that sewage from septic tanks may be leaking into the lake.

The Michigan Department of Natural Resources (Ellis & Childs, 1973) has investigated nutrient movements from septic tanks and lawn fertilization to nearby Houghton Lake. The objectives of this study were two-fold: (1) to determine if nutrients (phosphorus and nitrates) were moving with the groundwater to Houghton Lake from septic tank systems and (2) to determine the effects of lawn fertilization on the concentration of phosphorus in overland runoff.

In determining nutrient movement from septic tanks, 38 test wells were drilled to a depth of 22-24 feet below the water table. Nutrient concentrations in all wells were then monitored.

The study concluded that: (1) phosphates and nitrates from household septic tanks migrated through the groundwater and eventually reached Houghton Lake, and (2) the movement of nutrients with the groundwater was traceable for distances exceeding one hundred feet at several sites.

The data for lawn fertilization were derived by use of a questionnaire and through personal interviews. From these data, it was apparent that about one-half of the sites studied had been over-fertilized. It was recommended that no phosphorus fertilizer be applied to lawns surrounding the lake without prior soil testing to verify the need.

In response to accelerated shoreline development, the Lyon, Markey, Gerrish, and Beaver Creek Township Boards contracted the Progressive Engineering Company to initiate an engineering study regarding hazards associated with wastewater discharge within the community. The firm developed a Facilities Plan in 1976 to determine the most cost-effective method for upgrading existing wastewater treatment facilities. In conjunction with the development of this plan, a series of studies were conducted in the lake area to determine soil types, depths to the water table, and the phosphorus adsorption capacity of the soils. The Facilities Plan concluded that: (1) due primarily to either high water tables or the density of development, some areas adjacent to Higgins Lake did not receive adequate sewage treatment from on-site treatment systems, and (2) unless corrective measures (e.g., installation of public sanitary sewer systems) were implemented, public health hazards would continue, and a gradual degradation of the quality of nearby surface and groundwater resources could be expected.

The National Eutrophication Survey released a water quality analysis of Higgins Lake (U.S. EPA, 1975), emphasizing limnological measurements of the deep basins. The following conclusions were reached: (1) Higgins Lake was an oligotrophic lake with low mean levels of dissolved and total phosphorus, inorganic nitrogen, chlorophyll-a, and a high Secchi disk transparency, (2) phosphorus limitation to algal growth occurred in September, whereas slight nitrogen limitation occurred in June and November, and (3) septic tanks contributed roughly 28% of the total phosphorus load, with 72% coming from other non-point sources (e.g., runoff, precipitation). The study concluded that, although the present phosphorus loading was quite low, every effort should be made to reduce all phosphorus inputs to ensure continued high water quality.

Finally, Dr. Kenneth Reckhow (1980, 1983) developed a nutrient budget model for predicting lake phosphorus concentrations from known physical data and used Higgins Lake as an example for this method. Reckhow predicted that Higgins Lake should have a low phosphorus concentration, and categorized the lake as being oligotrophic.

IX. PHYSICAL FEATURES OF THE LAKE AND ITS WATERSHED

Higgins Lake is located in Crawford and Roscommon Counties (T24-25N, R3-4W) in the north central portion of northern lower Michigan (Fig. 1), five miles west of the village Roscommon. The lake is a deep, coldwater lake of Pleistocene glacial ice block origin underlain by Mississippian Period bedrock (Dorr & Eschmann, 1970). Lakes of this nature are formed as a result of melting ice blocks left behind in an area scoured out by the glacier as it retreated (Goldman & Horne, 1983).

Higgins Lake has a maximum length of 6.33 miles, a breadth of 3.30 miles, a mean depth of 44.3 ft, and a maximum depth of 136.2 ft. The lake's surface area of 10,317 acres ranks tenth in size among Michigan's lakes and is large relative to its watershed area of 21,653 acres (Table 1).

About one-third of Higgins Lake is shoal (0-20 ft) and about one-half of the lake has depths exceeding 50 ft (Fig. 2). Figure 3, a hypsographic or depth-area curve, is a graphic representation of the relationship between the lake's surface area and its depth. The volume of Higgins Lake is 1.99×10^{10} ft^3 (5.64×10^8 m^3) and the lake's volume development factor (D_v) is 0.97. Lakes with D_v values greater than 1.0 are typically steep sided and possess large water volumes relative to their surface area. Examples are Burt Lake (D_v = 1.6) and Black Lake (D_v = 1.5) (Table 2) (Gannon & Paddock, 1974). Lakes with D_v values less than 1.0 frequently have extensive shoal areas, and less water volume relative to other lakes of similar surface area and depth. Examples are Crooked Lake (D_v = 0.5) and Pickerel Lake (D_v =0.5). Generally, the greater the D_v of a lake, the more resistant it is to eutrophication from increased nutrient loading.

The Higgins Lake shoreline measures 20.49 miles, and has a shoreline development factor (D_L) of 1.44. The shoreline development factor provides an index of the relative potential for inputs to the lake from points along the shoreline. Lakes with high D_L values have extensive shorelines for their size, and are often subject to rapid eutrophication because of the consequent opportunity for nutrient inputs from riparian development. Examples of high D_L values are seen in Lake Charlevoix ($D_L = 3.1$), Crooked Lake ($D_L = 3.0$) and Walloon Lake ($D_L = 3.0$) (Gannon & Paddock, 1974).

Higgins Lake has only two major surface inputs, Big Creek and Little Creek. The lake empties into Houghton Lake through the Cut River and has a flushing rate of 9.8% of the lake's volume per year.

The watershed area of Higgins Lake is situated in the central highland region of the Lower Peninsula on the surface divide between Lake Michigan and Lake Huron drainage basins. Landscape features of the area are intermorainic and probably originated some 11,000 years ago. The hills near the north and south shore are marginal moraines, deposits from the edge of a retreating glacier. Most of the Higgins Lake watershed is topographically flat, and represents a glacial outwash plain. Elevations within the watershed vary from 1154 to 1300 feet above sea level (Fig. 4: after U.S.G.S., 1963). The shoreline is generally surrounded by uplands. Large wetlands exist near the Cut River, in Battin Marsh, and in portions of the watershed drained by Big and Little Creeks. Groundwater flow is influenced by the marginal moraines and generally follows the surface contours (Fig. 5: after Mich. Water Resources Commission, 1974).

The soils in the Higgins Lake area are primarily glacial till, a mixture of gravel, sand, and clays. Soil permeability is generally high. Although five soil series are found in the watershed, three predominate and are discussed here (Fig. 6:after USDA, 1924, 1927). The soil type immediately adjacent to much of the shoreline is of the Grayling-Rubicon series. Soils of this type exhibit a slope of 0-6%, rapid soil permeability (6-20 in/hr) and high phosphorus adsorption capacity.

A second major soil type in the watershed is the Grayling-Montcalm series. The slope associated with this soil type is 6-25%, indicating often considerable relief and high erosion potential. This series also has high permeability (6-20 in/hr), but lower phosphorus adsorption capacity.

The Carbondale-Roscommon series exhibits a slope of 0-2% and is often found in swamps and lowlands. The soils are highly organic and have a high moisture holding capacity. The soils have moderately high permeability (2-6 in/hr) and a high phosphorus adsorption capacity.

Coniferous and deciduous forests comprise 95.3% of the watershed (Fig. 7:after Michigan DNR, 1970). Residential areas, which make up 4.4% of the total watershed, are chiefly clustered along the lakeshore. All units are presently serviced by septic systems. Agriculture accounts for only 0.20% of the watershed and consists chiefly of pastureland.

V. LIMNOLOGY OF THE NORTH AND SOUTH BASINS

METHODS

Physical, chemical and biological measurements were taken at two deepwater stations, termed the North and South basins (Fig. 8) on March 3 and July 19, 1983.

Temperature and dissolved oxygen profiles were obtained using a YSI Model 51B dissolved oxygen probe and thermistor at 5 m intervals during the March sampling and at 1 m intervals during the July sampling. Percent saturation of dissolved oxygen was determined by nomagraph. Light transparency was determined with a standard Secchi disk. Light penetration was further quantified using a LiCor submarine photometer fitted with Weston cells and color filters during the July sampling.

Water samples were obtained with a 3 liter Kemmerer bottle. Hardness was determined by titration (APHA, 1976). Conductivity was measured on an Industrial Instruments Model RC-16B2 Conductivity Bridge. Conductivity recordings were corrected to umhos/cm at 25^{o}.

Total alkalinity was measured by titration with a mixed indicator solution of bromcresol-green methyl-red (APHA, 1975). Determinations of pH were made using a Beckman Selectmeter. Free carbon dioxide was determined by nomagraph from the pH and alkalinity measurements. Ammonia, nitrate/nitrite, total nitrogen, orthophosphate, total phosphorus, silica, and chloride were determined colorimetrically on a Technicon Dual Channel Autoanalyzer (APHA, 1976).

Plankton samples were obtained during the July sampling by bottom-to-surface tows with a conical 1/4 m plankton net with 80 um nylon mesh. Phytoplankton samples were preserved in 1% Lugol's iodine and were examined qualitatively. Zooplankton samples were preserved in 5% buffered formalin for later enumeration. Chlorophyll-a values were determined with a Turner Model 111 fluorometer. Values were corrected for phaeopigments (Holm-Hansen, 1965). An Ekman grab (15 cm X 15 cm) was used to collect bottom samples, which were then dried and ignited to determine % organic matter using standard methods (APHA, 1976).

RESULTS

Light

The measurement of solar radiation is of fundamental importance to the study of freshwater ecosystems, because of its energy contribution to the lakewater and to photosynthesis, and because of its diagnostic value in interpreting lake water quality. Higgins Lake has clear, unstained water that allows good light penetration. The North and South basins had Secchi depth readings of 12 m and 10 m respectively (Fig. 9a,c). Readings of 10-20 m are characteristic of oligotrophic lakes, while more productive lakes often exhibit considerably less transparency.

The euphotic zone, the portion of the lake where light intensity is sufficiently high that photosynthesis exceeds respiration, is usually considered to extend to a depth where light intensity equals 1% of incident light. Higgins Lake has an extensive euphotic zone extending to approximately 24 m.

Total light is attenuated exponentially in the water column (Fig. 9a,c). Red light waves are absorbed readily by the water itself and reveal little about water quality. The comparatively deep penetration of blue light in both basins of Higgins Lake indicates relatively little algal biomass in the water column, and is thus consistent with the lake°s oligotrophic status. Green light, not used in photosynthesis, penetrates still deeper than blue light, as expected (Fig. 9b,d).

Temperature and Dissolved Oxygen

As solar radiation passes downward from the surface of a lake, much of its energy is absorbed as heat. Wind driven mixing causes the heated upper waters to redistribute downward. The result is a sigmoid curve of water temperature with depth (Fig. 10c,d). These curves show thermal stratification, with a zone of dense, cold water (the hypolimnion) beneath a zone of less dense, warmer water (the epilimnion). Separating the epilimnion from the hypolimnion is the thermocline, a zone in which water temperature drops more than 1°C with each meter increase in depth.

Both basins of Higgins Lake possess an extensive hypolimnion in comparison to the epilimnion. In the North basin, the epilimnion extends to 8 m, and the thermocline occurs between 9-14 m. The South basin's epilimnion is slightly shallower, extending only to 7 m, while the thermocline is located between 8-12 m. During winter, as is typical of lakes under ice cover, both basins display a slight inverse thermal stratification (Fig. 10a,b).

There are two major sources of oxygen to the water column: (1) atmospheric oxygen dissolves slowly into water at the lake surface, and (2) phytoplankton contribute oxygen as a by-product of photosynthesis in the euphotic zone. Decreases in oxygen, which may be particularly pronounced in the hypolimnion, are generally attributable to organismal respiration and the decomposition of organic matter which has settled to the bottom. In both basins of Higgins Lake, maximum oxygen levels are found in the thermocline (Fig. 10c,d). These curves represent "positive heterograde" oxygen profiles, and indicate high algal photosynthesis in the thermocline, with greater respiration in the hypolimnion. Summer oxygen values were generally lower in the hypolimnion of the South basin and declined to 52% saturation at the sediment-water interface.

The solubility of oxygen decreases as temperature increases. Cold water can thus hold more gas in solution at saturation than warm water, and both basins accordingly show greater dissolved oxygen levels during the winter than in summer. Percent saturation approaches 100% throughout the entire water column during winter in both basins with the exception of the lower reaches of the South basin, where it drops to 67% (Fig. 10a,b).

Hardness, Conductivity, Chloride and Silica

Hardness in lakewater is defined as the total concentration of calcium and magnesium ions expressed as mg Calcium carbonate ($CaCO_3$) per liter. The usual classification of hardness is that of Brown, Skougstad, and Fishman (1970): 0-60 = soft water, 61-120 = moderately hard water, 121-180 = hard water, and >180 = very hard water. Higgins Lake is thus a hardwater lake, the South basin being slightly harder than the North basin (Fig. 11c,d). Calcium carbonate levels in the North basin are nearly uniform throughout, ranging from 120-124 mg/1. The South basin profile is more irregular. A decrease in hardness at the thermocline is attributed to the increased photosynthetic activity and the precipitation of calcium carbonate from that portion of the water column.

Calcium carbonate is also precipitated in the lake on rocks, sediments, and plant surfaces in nearshore areas of the lake as marl. Marl production increases as lake productivity increases, and noticeable accumulations of marl along portions of the shoreline of Higgins Lake (Appendix B) provide an early warning of nutrient loading to those areas.

The specific conductance of lake water is a measure of the ability of a solution to allow electrical flow, and is increased with increasing ionic content (especially calcium, magnesium, sodium, potassium, carbonate and bicarbonate, sulfate, chloride). Conductance in the North and South basins of Higgins Lake ranged from 250-277 umhos/cm and 253-298 umhos/cm, respectively, during summer and from 231-241 umhos/cm and 210-230 umhos/cm during winter (Fig. 11). These relatively high conductance values are typical of hardwater lakes, but increases in conductance over time in a given lake can often signal changes in trophic state.

Chloride (Cl) is the major halide stored in most freshwater algal cells, but is usually not the dominant anion in lakes. Pollutional sources of chlorides can modify natural concentrations greatly and include atmospheric inputs, seepage from domestic sewage, and winter road salting. Generally, chloride is not considered harmful to living organisms in a lake until it reaches concentrations of 10^4 mg/l (Wetzel, 1983). Chloride levels in both basins during summer and winter showed little variation, ranging from 3.9-6.2 mg/l.

Silica (SiO_2) is an essential nutrient in lake systems dominated by diatom algae, and an inverse relationship between silica and diatom densities is a frequent consequence of algal uptake (Lund, 1964; Munawar & Munawar, 1975). Compared to the high levels of other growth-stimulating nutrients such as nitrogen and phosphorus in water from human sources (e.g., sewage), silica loading is minor. Excessive loading of nitrogen and phosphorus can thus cause rapid algal growth and the depletion of available silica to limiting levels. Under such conditions diatoms are frequently replaced by less desirable green and blue-green algae which do not require silica (Schelske & Stoermer, 1971).

During winter, silica in the North basin ranged from 7.8-8.9 mg/l, while the South basin had a slightly elevated range of 8.3-9.9 mg/l (Fig. 11a,b). Both basins display gradual increases in silica levels near the bottom, largely because of the resupply of silica to the hypolimnion from the sediments. Summer silica levels in both basins are slightly reduced below winter values in both basins, presumably by algal uptake (Fig. 11c,d). Silica levels are particularly depressed at 8 m and 12 m in the North basin and at 8 m in the South basin and, like the increased oxygen levels at those depths, indicate higher diatom densities at the thermocline.

Carbon dioxide, pH and Alkalinity

The pH of most natural waters falls in the range of 4.0 to

9.0. Deviation from a neutral pH of 7.0 is caused by the presence of acids or bases, either produced by organisms within the lake or by the entry of chemicals into the lake. Hardwater lakes usually have basic pH values (>7) owing to their high carbonate/bicarbonate content. Within a given lake, increases in pH often reflect increased photosynthesis, while declines often accompany increased respiration.

Carbon dioxide is an end product of respiration by living organisms. It is also added to the water by the action of added acids on bicarbonates. The saturation concentration of carbon dioxide is less than 1.1 mg/l at normal temperatures and atmospheric pressure (Lind, 1979). Waters are frequently supersaturated with carbon dioxide when respiration rates are high.

The alkalinity of water represents the quantity and kinds of compounds present that collectively increase the pH. Three kinds of ions contribute most to total alkalinity: carbonate ($CO_3^=$), bicarbonate (HCO_3^-), and hydroxide (OH^-). Carbonates and bicarbonates are common to most waters while contributions by hyroxides are usually minimal.

The vertical distribution of carbon dioxide, pH and alkalinity in the water column is strongly influenced by biologically mediated reactions. Most conspicuous is the uptake of CO_2 through photosynthesis in the euphotic zone, which reduces both CO_2 and alkalinity while increasing pH. In contrast, the release of CO_2 during respiration in deeper water decreases pH and increases alkalinity.

During the winter, CO_2, pH and alkalinity values in both basins are uniform throughout the water column (Fig. 12a,b). Values of CO_2 are low in both basins, with slight increases at the bottom caused by respiration in or near the sediments. The pH in both basins ranged from 8.7-8.8. Alkalinity values for both basins are also similar, ranging from 100-118 mg/l.

During summer, CO_2 was elevated in the hypolimnion, as was alkalinity (range: 110-118 mg/l), while pH values declined (Fig. 12c,d). Further increases in lake productivity can be expected to accentuate both the increase in CO_2 and the decline in pH in the hypolimnion, associated with the increased decomposition of organic matter utilized in respiration.

Nitrogen

The major forms of nitrogen usually measured in fresh water include dissolved and particulate organic nitrogen, and the inorganic nutrients ammonia and nitrate. The combined measurement of both inorganic and organic nitrogen is referred to as total nitrogen. Nitrogen is also abundant in water as the dissolved gas N_2, but this form can only be utilized through nitrogen fixation by a small number of blue-green algae and bacteria.

Nitrate (NO_3), although usually present in low concentrations in natural waters, is often the most abundant inorganic form of the element. The seasonal cycle of nitrate tends to be similar in most lakes. In winter, inflow usually exceeds algal uptake, and is supplemented by nitrogen release from the sediments. In summer, nitrate uptake is usually faster than combined inputs, and concentrations in the water column therefore decline. Major sources of nitrate for lakes are river inflows, direct precipitation and groundwater.

Ammonia (NH_3) is also taken up as a nutrient by phytoplankton and may also be converted to nitrate by bacterial oxidation. It persists, however, as a major excretory product of aquatic organisms and the end product of the breakdown of organic nitrogen. The amount of ammonia present thus depends largely on the relative rates of these processes.

Seasonal cycles of ammonia usually follow one of two patterns depending on the trophic state of the lake. In oligotrophic lakes, ammonia persists at low levels throughout the year, and varies little with depth. In eutrophic lakes, by contrast, summer values of ammonia are usually much lower in the epilimnion than in the hypolimnion owing to the decomposition of organic matter settling to the bottom, and during winter ammonia concentrations may increase to levels exceeding 1 mg/l. The major sources of ammonia to lakes are inflowing streams, precipitation, atmospheric dust and nitrogen fixation. Sewage inputs often contain much higher levels of ammonia than of nitrate.

Nitrate concentrations ranged from 36-95 ug/l and 23-393 ug/l for the North and South basins respectively during the winter (Fig. 13a,b), and declined slightly during summer as expected (Fig. 13c,d). Ammonia levels during winter ranged from 11-21 ug/l and 12-36 ug/l for the North and South basins, respectively (Fig. 13a,b). A slight increase in ammonia was noted near the bottom in both basins, produced largely by the decomposition of organic nitrogen.

Summer values for ammonia were 6-51 ug/l and 18-66 ug/l for the North and South basins (Fig. 13c,d), and show a slight increase over winter concentrations. Hypolimnetic values were elevated in comparison to those of the epilimnion in both basins (Fig. 13c,d).

Total nitrogen during winter averaged 163 ug/l and 214 ug/l for the North and South basins (Fig. 13a,b). The North basin profile shows a gradual increase toward the bottom sediments, and an even sharper increase in total nitrogen near the bottom is seen in the South basin. Total nitrogen values during summer varied from 85-245 ug/l for the North and South basins, respectively (Fig. 13c,d). Concentrations in both basins were relatively constant in the epilimnion, with gradual increases near the sediments. Fluctuations in total nitrogen coincided, as expected, with fluctuations in nitrate and ammonia levels.

Phosphorus

Phosphorus is a common limiting nutrient in many lakes owing to its frequent geochemical scarcity. Phosphorus in natural waters is present primarily as organically bound phosphorus, inorganic polyphosphates and as inorganic orthophosphates. Of these, the form most usable as a nutrient is inorganic orthophosphate (PO_4), which often constitutes a small fraction of total phosphorus.

The vertical distribution of phosphorus, much like that of nitrogen, varies according to lake trophic state. Oligotrophic lakes usually show little variation in phosphorus content with depth. More productive lakes, in contrast, accumulate large amounts of phosphorus in the hypolimnion during summer stratification.

Phosphorus is added to a lake primarily through precipitation, overland runoff, groundwater, and sediment regeneration. Most natural hydrological inputs have low phosphorus content. Residential development surrounding a lake, however, usually results in increases in phosphorus discharged to lakes in approximately direct proportion to population densities (Weibel, 1969). Inputs of phosphorus from heavy lawn fertilization, storm sewer drainage, and sewage can all significantly elevate overall phosphorus availability.

Winter orthophosphate values in both basins of Higgins Lake are very low, with mean values of 5.3 and 6.2 ug/l for the North and South basins, respectively (Fig. 14a,b). There was little variation with depth in the South basin, while showing a slight increase at the bottom of the North basin. Total phosphorus during winter was similarly low, with mean values of 18.7 and 15.2 ug/l for the North and South basins, respectively.

Summer orthophosphate values for both basins show more than two-fold increase over winter values at all depths (Fig. 14c,d), probably owing in part to the greatly increased riparian population during summer. In the North basin the mean orthophosphate concentration increased from 5.2 ug/l in winter to a summer value of 11.3 ug/l. Again, slight increases in the hypolimnion were apparent. The summer orthophosphate profile for the South basin showed pronounced increases in the hypolimnion. Total phosphorus values during summer in the South basin likewise show at least a two-fold increase over winter concentrations, and increase substantially with depth to a maximum of 183.1 ug/l at the sediment-water interface. Increases in both orthophosphate and total phosphorus in the hypolimnion can be expected if further nutrient enrichment of the lake occurs.

Phytoplankton

Phytoplankton are algae suspended in the water column. They are the most important primary producers in most lakes, and their growth provides the principal basis for the growth of invertebrates and fish (Fig. 15). Phytoplankton species are found varying quantities according to season and lake type. The dominant algal groups in lakes of northern Michigan are the green algae (Chlorophyta), blue-green algae (Cyanophyta), diatoms (Bacillariophyta), and golden-brown algae (Chrysophyta).

Several kinds of environmental factors interact to regulate spatial and temporal growth. As well as temperature and light, a number of organic and inorganic nutrients play critical roles in the success of algal populations. As the supply of limiting nutrients is increased, rates of algal production likewise increase. Increased phytoplankton densities progressively reduce light penetration and the depth of the euphotic zone. A point is eventually reached at which self-shading inhibits further increases in productivity in very eutrophic lakes, regardless of nutrient supply (Wetzel, 1983).

A distinct periodicity in the biomass of phytoplankton is observed in temperate lakes. Growth is greatly reduced during winter by low light and cold temperatures. Phytoplankton numbers normally peak during spring, supported by increasing temperatures and light, and by the mixing upward into the euphotic zone of nutrients from the bottom waters. The spring maximum of phytoplankton biomass is usually followed by a period of lower biomass during summer, as nutrient supplies are depleted by algal uptake, algal consumption by zooplankton increases, and many algae sink to the bottom.

In oligotrophic lakes, the phytoplankton community usually consists of cryptomonads and small green algae during winter, primarily of diatoms in spring, and of green algae during summer. Accumulations of algae at the thermocline are typical in summer, owing to the greater density (and thus buoyancy) of colder water.

Chlorophyll-a is the primary pigment used by phytoplankton for photosynthesis. The measurement of chlorophyll-a thus serves as a convenient index of total algal biomass, and by extension, of lake trophic status. The U.S. EPA National Eutrophication Survey (1975) has classified lakes according to the following summer chlorophyll-a concentrations: <7 ug/l = oligotrophic; 7-12 ug/l = mesotrophic; >12 ug/l = eutrophic.

Chlorophyll-a values for both basins of Higgins Lake are low, ranging from 0.90-3.78 ug/l with a mean of 2.3 ug/l and 2.4 in the North and South basins (Fig. 16c,f). These values are indicative of oligotrophic conditions. The continued presence of viable algae at considerable depth is a consequence of the good light penetration in Higgins Lake, and is again characteristic of oligotrophic waters. Although algal biomass is not unusually high at the thermocline, rates of photosynthesis and nutrient uptake appear to be maximal, accounting for the high dissolved oxygen and low nitrate, phosphate and silica concentrations between 8-12 m.

Also depicted in Figure 16 are phaeopigment values for both basins. Phaeopigments are produced by the decomposition of chlorophyll-a, and thus serve as a measure of the health of the phytoplankton community. High phaeopigment levels are often characteristic of the decline of the spring maximum, for example, or may indicate unusually heavy grazing by zooplankton. Phaeopigment levels in Higgins Lake are low in most of the water column, providing evidence of a relatively stable algal community in the days prior to sampling. Phaeopigment values increase, as expected, near the bottom, owing to the decomposition of algae which have sunk out of the water column during preceding weeks.

Zooplankton

Zooplankton are microscopic invertebrates which feed on algae or smaller zooplankton, and which in turn are utilized as food by most fish (Fig. 15). The chief components of zooplankton communities are protozoans, rotifers, and crustaceans (cladocerans and copepods). Most zooplankton are about 0.5 mm to 1.0 mm in length. Zooplankton abundances range from <10 individuals per liter in very oligotrophic waters to more than 10^4 individuals per liter in eutrophic lakes.

The species composition of the zooplankton community may also be a valuable indicator of lake trophic status (Gannon & Stemberger, 1978). Although most species exist under a wide range of environmental conditions, certain species are limited by temperature, dissolved oxygen, salinity, and other physicochemical factors. The species composition in a lake typically remains quite constant for many decades under natural conditions, but lakes undergoing cultural eutrophication often experience marked changes in zooplankton community composition over much shorter time intervals. Oligotrophic lakes generally display very diverse zooplankton communities with many species, and are often dominated by calanoid copepods. Eutrophic lakes usually have just a few very abundant species, especially smaller rotifers, Cladocera and protozoa (Gliwicz, 1969).

The calanoid copepod *Senecella calanoides*, found in Higgins Lake (Fig. 16) is an excellent indicator of classic oligotrophic conditions (Gannon & Stemberger, 1978). *Senecella* is a cold stenotherm, requiring cold, well oxygenated bottom waters (Dadswell, 1974).

Another zooplankton species of interest is *Kellicottia longispina*, an indicator of oligotrophic-to-mesotrophic water and abundant in both basins of Higgins Lake. Overall numbers of zooplankton were low in the lake, while species diversity was high, a further indication of good water quality. Declines in species such as *Senecella* and *Kellicottia*, and further increases in *Bosmina longirostris*, now present in the lake and usually associated with eutrophy (Deevey 1942), may be predicted if further eutrophication occurs in the lake.

Sediments

Deepwater (profundal) sediments consist of organic matter in various states of decomposition, particulate mineral matter, (especially quartz) and an inorganic component of biogenic origin (mostly diatom frustules and calcium carbonate). Two general types of sediments are usually distinguished in hardwater lakes: copropel and sapropel.

Copropel is derived primarily from settled plankton, modified extensively by bottom-dwelling invertebrates, which both consume it and contribute their feces to it. The sediments are usually grey or brown, with an organic content of less than 50% of total dry weight, as abundant oxygen in waters overlying the sediments favors the bacterial decomposition of organic materials. Grey copropels with less than 20% organic content are characteristic of oligotrophic lakes (Cole, 1979).

Sapropels in contrast are subjected to long periods of anoxia, as occurs in most deep eutrophic lakes. Sapropels are a glossy black, watery material of very high organic content, which may give off the rotten-egg odor of hydrogen sulfide and often contains the marsh gas methane.

The surficial sediments of Higgins Lake are grey copropels. Their organic content is 18.5% and 22.8% of total dry weight in the North and South basins, respectively. The most recently deposited profundal sediments are thus consistent with the current oligotrophic status of the lake.

VI. SUMMARY OF EVIDENCE FOR EUTROPHICATION IN HIGGINS LAKE

Most of the data presented in Section V indicate that Higgins Lake possesses water of very high quality. Most parameters (e.g., high hypolimnetic dissolved oxygen, deep light penetration, low chlorophyll-a values, the presence of the zooplankton species *Senecella calanoides*) are indicative of oligotrophic conditions. However, the lake has also begun to show human impacts. Eutrophication was much more evident in the South basin than in the North basin, on the basis of virtually all measurements taken (Table 3). The South basin is morphometrically smaller, with less water volume, than the North basin, and may also receive greater amounts of organic input, as both the prevalent wind direction and location of the surface outflow favor the collection of organic materials in deep portions of the southeast end of the lake. Continued monitoring of the South basin may thus be particularly valuable because of its sensitivity as a warning device of any further eutrophication in the future.

A comparison of these data with data taken less than a decade ago provide evidence of slowly deteriorating water quality. Particularly noticeable is a gradual decline in water quality in the South basin since 1974 and 1977, when data were collected by the EPA at approximately the same location and time of the season. For example, mean percent saturation of dissolved oxygen in the hypolimnion has declined from 86.8% in 1974 to 73.5% in 1983 (Fig. 17). The South basin is also experiencing a steady increase in the levels of nitrogen and phosphorus. Total nitrogen levels have nearly doubled from a mean of 110 ug/l in 1974 to the present value of 213 ug/l (Fig. 18). Mean total phosphorus levels are increasing at almost the same rate, from 33.8 ug/l in 1974 to the present value of 53.2 ug/l (Fig. 19). The depth profile for phosphorus in 1974 is typical of an oligotrophic lake, as concentrations remain low in the hypolimnion. During 1977 and 1983, however, phosphorus increases distinctly with depth, a pattern characteristic of more productive waters.

A number of indices have been developed in recent years to classify lakes according to trophic state. Carlson (1977) developed one such system, the Trophic State Index (TSI), based upon chlorophyll-a values, secchi depth readings, and total phosphorus concentrations. According to Carlson's system, chlorophyll-a values and Secchi disk measurements for the South basin still fall within the range of oligotrophic (O) waters while total phosphorus concentrations describe the basin as eutrophic (E) (Fig. 20). The seeming disparity in classification is due largely to the extremely high hypolimnetic total phosphorus levels found in the basin. Other northern Michigan lakes are also shown in Figure 20 for comparison with the South basin.

VII. N VS. P LIMITATION - THE NORTH AND SOUTH BASINS

A comparison of the nutrients nitrogen (N), phosphorus (P) and silica in Higgins Lake suggests that whereas both N and P reach potentially growth-limiting levels by mid-summer, silica remains sufficiently abundant that it probably does not influence overall algal productivity. A more detailed analysis of N vs. P limitation is therefore presented here.

Algal communities require approximately 15 times as much total Nitrogen (TN) as total phosphorus (TP) for normal growth, although nutritional needs are now known to vary considerably according to species (Rhee & Gotham, 1980). Whichever nutrient is in least supply relative to this 15TN:1TP average need may thus be identified as the growth limiting nutrient for most algal species.

Sakamoto (1966), who measured chlorophyll-a in Japanese lakes relative to both total phosphorus and total nitrogen concentrations, concluded that if the (weight-to-weight) TN:TP ratio was between 10:1 and 17:1, chlorophyll yield was controlled jointly by the two nutrients. Biomass was limited by TN at ratios less than 10:1, and limited by P when at ratios exceeding 17:1. Similar conclusions have been drawn by Forsberg et al. (1978) for the phytoplankton of Swedish lakes, and by Smith (1982) for North American lakes.

This relationship of algal growth to available Nitrogen vs. Phosphorus is shown graphically in Figure 21 (after Tilman 1980). Any parcel of lake water can be viewed as a point on the graph, consisting of a certain concentration of N (X-coordinate) and P

(Y-coordinate). The 15:1 ratio which is optimal for most algae is shown as an oblique line from the lower-left to upper-right portion of the Figure. The algae in water represented by any point below this optimal N:P ratio (darker, horizontal stripes) will be limited directly by phosphorus, and will experience no additional growth regardless of how much nitrogen is added to the water. Likewise, algae in water represented by any point above the optimal N:P ratio (lighter, vertical stripes), will experience N-limitation and cannot respond to further additions of P.

The concentrations of TN and TP in both basins of Higgins Lake show that phosphorus is likely to be the growth-limiting nutrient during mid-summer. The TN:TP ratio in the North basin is approximately 22:1, while that of the South basin is 17:1 (Fig. 22). These ratios are likely to vary considerably with time during mid-summer, however, as a consequence of the very low concentrations of both nutrients.

The occurrence of P-limitation in Higgins Lake is important in that (1) phytoplankton growth may be directly predicted by measuring available phosphorus concentrations, (2) sources of phosphorus (both natural and human) can be estimated with reasonable accuracy, and (3) unlike nitrogen, phosphorus can be "managed" by reducing human sources of phosphorus to the lake. The first step in such a management effort is the preparation of a nutrient budget for phosphorus, described in the next Section.

VIII. A PHOSPHORUS BUDGET FOR HIGGINS LAKE

The input of phosphorus to Higgins Lake depends both upon (1) rates of water (hydrologic) flow from various sources to the lake, and (2) phosphorus concentrations of the water supplied from each source. Many of the conclusions which follow are documented in greater detail in Reckhow's earlier study of the lake (Reckhow, 1980, 1983), and summarized as a mathematical model in Appendix A. Reckhow's estimates are supplemented with measurements of discharge and stream nutrient content, obtained for the Cut River, Big Creek and Little Creek on March 3, May 25, June 22, and July 19, 1983. Stream velocities were measured using a General Oceanics flowmeter and were multiplied by stream cross-sectional area to obtain discharge estimates.

1. Only a small portion of the water that leaves Higgins Lake via the Cut River actually reaches the lake as surface inflows through Big and Little Creeks. The two influent streams accounted for only 6-7% of total hydrologic inputs during both winter and summer 1983 (Table 4). Inputs from smaller streams, non-stream runoff, and groundwater thus constitute the bulk of the water supply, and groundwater is assumed to be the principal contributor of water to the lake.

2. Roughly 95% of the Higgins Lake watershed is forested land, which tends to retain P well compared to other land uses and contributes 43% of the total yearly loading of phosphorus to the lake. Agriculture in contrast is rare in the area and provides only 0.01% of the total phosphorus budget (Reckhow, 1980).

3. Measurements of the phosphorus content of Big and Little Creeks during 1983 suggest that they not only supply a small portion of the lake's water each year, but contribute a relatively small portion of the phosphorus which enters the lake from the watershed as well (about 1-2%)(Table 4).

4. Numerous residential developments ring the shoreline. Residential land contributes approximately 9% of the total phosphorus budget to Higgins Lake, primarily through lawn fertilization, increased shoreline erosion and the removal of natural vegetation which might otherwise intercept phosphorus inputs.

Domestic sewage is handled through either on-site septic systems or sewage lagoons within the watershed. Domestic sewage contributions have been estimated to be approximately 17% of the total phosphorus budget, a conservative estimate in that public facilities are not included in the calculations. The U.S. EPA (1975) suggested that as much as 28% of the phosphorus budget was attributable to domestic sewage. The combined potential for human influence from riparian land is thus judged to be at least 26%, and may be considerably higher.

5. Direct precipitation may be extremely variable both in the amounts of water supplied and in its nutrient content. Reckhow has estimated that as much as 32% of the total phosphorus budget of Higgins Lake (=1253 kg/yr) may be supplied directly by precipitation (Reckhow, 1980). Based upon P content measured in rainfall in the Higgins Lake area during 1982 (NADP, 1983), a more conservative estimate of 496 kg/yr may be more reasonable, at least in drier years.

Rain gauges were established at three sites (Alameda Beach, Higgins Lake Shores, and Lakeside), and monitored for daily rainfall volume during June-July 1983. Mean precipitation was 1.04" and 1.24" for June and July, respectively, well below expected summer averages (Williams & Works, 1976). Phosphorus inputs through precipitation may therefore have been proportionally lower than usual during summer 1983.

6. Of the phosphorus which enters Higgins Lake (=3933 kg/yr; Reckhow, 1980), only a small portion actually leaves the lake via the Cut River. Roughly 354 kg/yr, or approximately 9% of total yearly inputs, was estimated to have left the lake during 1983. The remainder of the phosphorus supplied to the lake is presumably precipitated to the sediments, either in organically bound form (e.g., algae, zooplankton feces, detritus) or adsorbed to inorganic particles (e.g., $CaCO_3$). This result is not unexpected, particularly for a deep lake with a relatively low flushing rate. As long as the bottom waters of Higgins Lake remain well oxygenated year round, most of the phosphorus which enters the sediments can be expected to remain there, and be gradually buried with time. However, if the lake continues to experience increases in nutrient enrichment and hypolimnetic oxygen levels are depleted seasonally to very low values (e.g., <1 mg/1), the nature of the chemical bonding of phosphorus to the sediments can be expected to change, and the sediments will then become an additional, substantial contributor to yearly phosphorus loading.

In summary, although the above estimates are subject to considerable year-to-year variation, several conclusions of importance to phosphorus management are apparent. First, phosphorus from non-residential land enters Higgins Lake largely as groundwater. More easily controlled surface sources of phosphorus (e.g., influent streams) are insignificant in their phosphorus contributions by comparison. Secondly, phosphorus inputs via direct precipitation, which may be of major importance to Higgins Lake, are impossible to control using watershed management methods, but should be monitored closely in the future using information supplied by the National Atmospheric Deposition Program. Finally, riparian dwellings, which contribute more than 1/4 of the phosphorus budget for Higgins Lake, collectively constitute a source of nutrients over which some control may be exerted. Impacts of riparian development upon lake water quality are also likely to be most apparent along the lakeshore, and are considered in the next Section.

IX. SOURCES OF NUTRIENTS ALONG THE LAKESHORE

Nearshore sources of nutrients most likely to affect Higgins Lake include a) contributions to surface runoff and groundwater from riparian land from the many access roads which lead to the lake, and b) domestic sewage from public and private on-site treatment systems:

a. Nutrient inputs through surface runoff from undisturbed watersheds are determined largely by the volume of precipitation, and by the slope and composition of soils near the lakeshore. Bluffs along portions of the Higgins Lake shoreline are examples of a watershed feature with high potential for nutrient input regardless of human activity. Both the nutrient content and the flow rate of overland runoff are increased, however, by the removal of natural riparian vegetation, for example by the numerous public accesses to Higgins Lake and properties with uninterrupted views of the water. The concentrations of certain nutrients are often further increased by activities such as lawn fertilization, which typically contains large amounts of phosphate and ammonia or nitrate. Water from riparian lands may also percolate to the groundwater, and eventually reach the lake in that manner (Hasler, 1947).

b. Lakeside septic systems are likely to be major sources of nutrients to the Higgins Lake shoreline (Fig. 24). Depending on soil conditions, groundwater level and flow, septic system age and proximity of a system to the lake, and the degree of use, as much as 85% of the nitrogen and 75% of the phosphorus that enters each septic system may eventually reach the lake (NEMCOG, 1979).

Septic systems located directly adjacent to the lakeshore may not be the only sources of sewage input, as septic drainfields anywhere within the watershed are capable of enriching groundwater which may eventually reach the lake (Ellis & Childs, 1973). Septic systems may contribute as much as 60% of the total nutrient load to lakes when surrounding soils are poor and densities of nearshore dwellings are high (Wetzel, 1983).

In order to identify nutrient loading from such sources, 18 sites along the Higgins Lake shoreline were selected for the analysis of 1) nutrient concentrations in the water and 2) algal periphyton accumulations on substrates collected at each site. Some of the sites were selected as representative of areas with varying residential densities. Other sites were placed directly out from public access roads with varying potential for erosional runoff based upon their slope, surface type and distance to the shoreline (Table 5).

Periphyton communities, like the phytoplankton, consist of a diverse assemblage of algal species, but are found in association with rocks, sediments, pilings or other surfaces in nearshore areas of lakes. Because of their attached habit and ability to integrate short-term fluctuations in nutrient supply, periphyton have received considerable attention as biological indicators of water quality nearshore (Eminson, 1978: Collins & Weber, 1978). Indeed, point sources of limiting nutrients are often first detected by the rich growths of algae on nearby substrates. One algal species which dominates the periphyton in Higgins Lake was given particular consideration. *Cladophora glomerata* is an attached filamentous green alga which has been used extensively as an indicator of nutrient loading (Neil, 1975).

Nutrients critical to periphyton growth are the same as those responsible for phytoplankton productivity: nitrate +/or ammonia, orthophosphate, silica, and occasionally micronutrients or carbon (Raschke & Weber, 1970; Goldman, 1972; Cooper & Wilhm, 1975; Collins & Weber, 1978; Weitzel, 1979). Measures of periphyton biomass and species composition may thus be used to validate nutrient measurements taken concurrently at a given site.

METHODS

A total of 72 artificial substrates were constructed from 3" clay flower pots as shown in Figure 25 (Fairchild & Lowe, 1984). Each substrate was filled with lakewater, and four substrates were then placed at each of 18 locations around the lake (Fig. 23) during late May, 1983. Each substrate was secured at approximately 0.5 m depth by inserting its wooden dowel into the sandy lake bottom.

In addition to the 4 flower pot substrates, 4 pre-cleaned flat-surfaced rocks were placed closer to shore at each site, at a depth of 0.2 m. Water samples were also obtained (at 0.5 m depth) at each of the 18 sites on May 25, 1983 at the time of substrate installation, again when the substrates were retrieved on June 22, and a third time (at both 0.2 m and 0.5 m depths) on July 22. Finally, one natural substrate (usually a representative rock) was collected at each site on July 19 for comparison with the artificial (flower pot and pre-cleaned rock) substrates (Silver, 1977).

The artificial substrates were retrieved after 28 days. Known areas of substrate surface were carefully scraped into a sample jar, which was then adjusted to uniform volume with filtered lake water. Three 20 ml subsamples were then removed for the analysis of 1) chlorophyll-a and phaeopigment densities, expressed as mg/m^2 of substrate surface (Holm-Hansen, 1965), 2) Ash-free dry weight (AFDW), a measure of total accumulated organic matter and also expressed per unit surface area of substrate (APHA, 1976), and 3) algal periphyton species densities (Schultz, in prep.).

In order to determine whether the data obtained for the 18 sampling sites were representative of the lake as a whole, the entire shoreline was walked during the first week of June, 1983. Observations included a) total numbers and locations of residences within 100 m of the shoreline, b) locations of road ends providing public access to the lake, c) sediment types nearshore, d) presence or absence of *Cladophora* on solid surfaces near the water's edge, e) marl accumulations on rocks and sediments, and f) locations of influent streams and drains. These data are summarized in Appendix B, organized as mile-long segments of the shoreline.

RESULTS

Nutrient data from the sampling sites are presented in Table 6 and are analyzed in three ways. First, mean concentrations for all sites are compared by sampling date to determine seasonal trends in nutrient input. Secondly, mean nutrient levels for all nearshore sites at 20 cm depth are compared to values for the same sites at 50 cm depth further from shore, and with data from the North and South basins to determine spatial differences in nutrient availability nearshore vs. offshore. Finally, nutrient concentrations are compared by site. Algal periphyton biomass is likewise compared by site in Tables 7 and 8.

Seasonal Trends in Nutrient Supply

Mean nitrate concentrations were highest during the first (May) sampling, at 184.9 (S.E. 26.9) ug/l. Nitrate availability subsequently declined rapidly (Fig. 26). The June mean was 62.8 (S.E. 11.9) ug/l, and the July means at 20 cm and 50 cm were 4.6 (S.E. 0.7) ug/l and 4.8 (S.E. 0.9) ug/l, respectively.

Ammonia concentrations followed the same trend. The highest mean value occurred during May, at 65.7 (S.E. 8.4) ug/l, followed by a decline to 58.1 (S.E. 15.2) ug/l during June and to 40.1 (S.E. 7.1) ug/l and 16.0 (S.E. 4.1) ug/l at 20 cm and 50 cm during July.

In contrast, mean orthophosphate concentrations increased steadily (Fig. 26), from 5.5 (S.E. 0.4) ug/l during May to 17.5 (S.E. 4.1) during June and finally to 37.8 (S.E. 12.5) ug/l and 25.7 (S.E. 6.5) in July at 20 cm and 50 cm depth.

No trends in silica concentrations were observed during the study. Mean concentrations were 7.3 (S.E. 0.3) mg/l during May, 6.2 (S.E. 0.2) mg/l during June, and 7.9 (S.E. 0.1) mg/l and 7.9 (S.E. 0.1) at 20 cm and 50 cm during July.

The declines in both forms of inorganic nitrogen are characteristic of algal uptake, and are expected during summer. The concurrent increases in available phosphorus, however, indicate that phosphorus is being added to nearshore areas of Higgins Lake in high enough quantities to exceed phosphorus removal (e.g., through algal growth or adsorption to inorganic surfaces). This has important consequences in that the form of nutrient limitation may be shifted to a nitrogen requirement for periphyton nearshore (see Section X).

Nearshore vs. Offshore Differences

Evidence of nutrient loading from riparian land is also provided by a comparison of mean nutrient concentrations nearshore (at both 20 cm and 50 cm depths for all 18 sites) vs. mean concentrations offshore (in the euphotic zone of the North and South basins) (Table 9).

Nitrate concentrations are depleted to limiting levels nearshore compared to concentrations offshore, presumably owing to algal uptake. Ammonia concentrations are in fact higher than nitrate values at both 20 cm and 50 cm depth. In contrast, phosphate is most abundant nearshore, and is gradually taken up by phytoplankton/diluted/precipitated in deeper water. The more conservative chloride ion shows a similar trend. Silica is notable by the absence of nearshore vs. offshore differences.

Human sources of nutrients, which are typically high in nitrate, ammonia, phosphate and chloride, but usually low in silica, may be viewed as the most probable contributors to the nearshore vs. offshore gradients observed.

Comparison of Nutrients and Periphyton by Site

Physical features, nutrient concentrations, periphyton accumulations and ancillary measurements are summarized here for each of the 18 sites.

1. St. Louis Avenue: The site was chosen as an example of the Southwest portion of the lakeshore, surrounded by high residential densities. Heavy Cladophora and marl accumulations were apparent in the general area (Appendix B: Mile #2). Nutrient concentrations from May-July, however, were similar to the mean for all 18 stations (Table 10) and periphyton biomass was lower than average. Overall water quality was rated as moderate.

2. Minto Pointe Avenue: Artificial substrates and water samples were collected directly out from the public access provided by the road end as a location with high potential for erosional runoff. Nitrate values at the site were indeed slightly higher than average (Table 10), but other nutrient estimates were moderate. Periphyton growth was minimal on artificial substrates collected, and moderate on the natural substrate collected at the site as well (Tables 7,8). Heavy growths of Cladophora were evident just South of the access, in an area characterized by high residential densities (Appendix B: Mile #3).

3. Maple Avenue: Maple Avenue is subject to high erosional potential because of its considerable slope and direct access to the lakeshore (Table 5). Water samples and artificial substrates were collected directly out from the road end. Growth of Cladophora was only moderate, perhaps owing to the low summer rainfall. Periphyton accumulations on artificial substrates were also moderate, as were mean nutrient concentrations.

4. Lone Pine Avenue: Water and artificial substrate samples

were collected directly out from the road end, at a location selected for its low potential for erosional run-off. All 4 flower pot substrates at the location were vandalized, but periphyton growth on precleaned rocks and on natural substrates at the location was moderate. Mean concentrations of ammonia and particularly phosphate were unusually high. Cladophora and marl accumulations were moderate (Appendix B: Mile #4,5).

5. Battin Marsh Drain: Water samples and artificial substrates were retrieved from a location close to the Battin Drain outfall, in an area of obviously high tannin-stained water. As expected, ammonia concentrations were high, owing to the decomposition of organically bound nitrogen introduced by the outfall. Other nutrient concentrations were moderate to low. Because of the large discharge of water to the lake, Battin Drain may nonetheless be a greater source of nutrients, particularly during Spring, than is indicated by the low summer nutrient concentrations shown here. Artificial flower pot substrates at the site experienced greater than average periphyton growth, but periphyton accumulations natural surfaces were light to moderate.

6. West Avenue: Like Lone Pine Avenue, West Avenue was selected as a road end with relatively low erosional potential. Both nitrate and chloride concentrations were higher than average, whereas ammonia and phosphate concentrations were moderate. Periphyton growth on the flower pot substrates was low, but accumulations of algae on natural surfaces nearer shore were much higher (Table 7). Cladophora was not abundant in the area, perhaps owing to a general absence of solid surfaces for attachment (Appendix B: Mile #8).

7. Newman Avenue: The road-end at Newman Avenue, like Maple Road, has a relatively high potential for nutrient runoff. Concentrations of nitrate, phosphate and chloride were in fact much higher than average, as were accumulations of periphyton on natural substrates nearshore. Growth of Cladophora (Appendix B: Mile #9) was similarly very high at and just South of Newman Avenue. The site was judged to have the poorest overall water quality of the 18 sites studied.

8. Big Creek: Rates of dishcarge to Higgins Lake by Big Creek, and nutrient concentrations of the stream water have both been described already in this study. A sampling site was established approximately 30 m directly out into the lake from the stream to measure effects of the stream discharge in the lake itself. Like Battin Drain, the water from Big Creek is tannically stained, and ammonia concentrations were the highest of any of the 18 sampling sites as a consequence. Other nutrients were found at low concentrations, however. Periphyton accumulations on both types of artificial substrates were very high, as were periphyton densities on natural surfaces nearer the stream inflow.

9. Little Creek: The water of Little Creek not only contains fewer nutrients than that of Big Creek, but discharge is also considerably less as well (Table 5). The effect of Little Creek on water quality in Higgins Lake is therefore much less than that of Big Creek. Water samples collected approximately 40 m from the stream inflow showed lower than average nutrient levels and low to moderate periphyton growth.

10. Stuckey Avenue: Located in an area at the Northwest end of the lake, water quality at the Stuckey Avenue site is representative of effects of high riparian densities in that area. Concentrations of both nitrate and chloride were slightly higher than average, but the concentrations of other nutrients, and periphyton growth were moderate. Cladophora was not found in the area (Appendix B: Mile #10), presumably in part because of the uniformly sandy sediments and paucity of suitable attachment sites.

11. Conference Center Creek: The tiny stream which flows into Higgins Lake through the Department of Natural Resources Conference Center property appears to have little effect upon water quality in the lake. Nutrient values were low, and periphyton levels low to moderate, both on artificial and natural surfaces (Table 10, Appendix B: Mile #12).

12. Cedar Avenue: The Cedar Avenue site was chosen as an area with relatively few riparian dwellings. Nitrate concentrations were slightly higher than average, but the concentrations of other nutrients were generally moderate. Artificial flower pot substrates were vandalized at the site, but periphyton growth on other surfaces was moderate. Accumulations of Cladophora were quite noticeable all along the shoreline near Cedar Avenue, providing evidence of perhaps seasonally higher nutrient inputs not detected on the three water collection dates (Appendix B: Mile #12).

13. Lansing Avenue: Both the nutrient data and periphyton growth data indicate minimal effects of the road end at Lansing Avenue during Summer 1983. Evidence for seasonally higher

nutrient concentrations closer to shore, however, is provided by both the growth of Cladophora and accumulations of marl along the shoreline on both sides of the road end (Appendix B: Mile #12).

14. Cottage Grove Association: Access was provided through the Association property to obtain water samples and place artificial substrates at a site approximately 40 m from the shoreline. The steep bluff overlooking the lakeshore at the site undoubtedly contributes nutrients through erosion and rapid groundwater flow, but human effects are presumed to be minimal. The site was also used for a separate study of the form of algal growth limitation nearshore (see Section X). Concentrations of phosphorus, nitrogen and chloride were slightly lower than average, while periphyton growth was low to moderate. Both Cladophora and marl accumulations were quite evident nearer shore, however (Appendix B: Mile #14).

15. Henry Avenue: The site at Henry Avenue was chosen to represent an area of the shoreline with high residential densities. All artificial flower pot substrates were vandalized at the site, but other substrates indicated moderate to high growth close to shore (Appendix B: Mile #14). Nutrient concentrations did not differ greatly from average values for the 18 sites.

16. Hitchcock Avenue: Both because of its use as a public access site and the relatively high density of adjacent riparian dwellings, the sampling site at Hitchcock Avenue was expected to have an higher than average potential for nutrient loading. Mean nitrate concentrations were indeed the highest of the 18 sites,

though concentrations of other nutrients were moderate. Although all flower pot substrates were vandalized, periphyton growth on other surfaces was moderate, and accumulations of Cladophora were minimal (Appendix B: Mile #16).

17. Gallagher Avenue: Despite relatively high residential densities near Gallagher Avenue, the concentrations of all nutrients were slightly below mean values for the 18 sites. Periphyton biomass was similarly low, and neither Cladophora nor heavy marl accumulations were apparent (Appendix B: Mile #17).

18. Second Avenue: Chosen as a section of lakeshore with lower densities of surrounding houses, Second Avenue showed approximately average nutrient concentrations and minimal periphyton growth on artificial substrates placed at the site. Heavy accumulations of both marl and Cladophora were evident closer to shore, however (Appendix B: Mile #19).

Of the nutrients summarized in Table 10, the highly "conservative" ion chloride (which experiences little biological uptake) showed the least variation between sites (Coefficient of Variation = 16.7%). High chloride levels may indicate runoff from salted roads, domestic sewage inputs or rapid groundwater inflow. Chloride levels were highest at Newman and Stuckey Avenues.

In contrast, orthophosphate concentrations showed considerable site-to-site variation (Coefficient of Variation = 98.4%), indicative primarily of differences in supply rates. Phosphorus concentrations are especially high in sewage and commercial fertilizers. Highest phosphorus values were noted at

Lone Pine and Newman Avenues.

Ammonia concentrations were highest at the two tannically stained sites near Big Creek and Battin Drain as a consequence of the breakdown of organically bound nitrogen. Nitrate, usually the more abundant form of inorganic nitrogen in oxygenated waters and characteristic of both groundwater and surface inputs, was highest at Hitchcock and Newman Avenues.

Overall differences in water quality between sites during summer 1983 were not extreme, and were probably reduced considerably by the virtual absence of precipitation during the study (see Section VIII). Surface runoff particularly was probably greatly reduced. Our estimates of the effects of nearshore sources of nutrients may therefore be judged conservative relative to most years.

X. N VS. P LIMITATION - NEARSHORE

Human sources of nutrients to a lake are typically very high in phosphorus (Wetzel 1983) and may thus not only increase lake productivity by adding a limiting nutrient, but may also reduce the N:P ratio and shift the form of nutrient limitation from phosphorous to nitrogen. In a large lake, such effects are most likely to be observed first in littoral (nearshore) areas. The possibility of nitrogen limitation nearshore was tested experimentally using an in situ nutrient stimulation bioassay.

METHODS

An additional 16 flower pots substrates were filled according to the following specifications: 4 pots with lakewater, 4 pots with 2% agar + 0.05M Na_2PO_4, 4 pots with 2% agar + 0.5M $NaNO_3$, and 4 pots with 2% agar + 0.05M Na_2PO_4 + 0.5M $NaNO_3$. These substrates were placed in a grid on the Northeastern shore of Higgins Lake in front of the Cottage Grove Association property during the last week of May as shown in Figure 27. The nitrogen and phosphorus contained in the pots slowly diffused to their outer surfaces, supplementing nutrient supplies provided by the lakewater (Fairchild et al., 1984). Examination of periphyton growth on substrates containing the different nutrient treatments thus permitted the assessment of N vs. P limitation in nearshore waters. More specifically, algal growth stimulation on substrates with added P would indicate P limitation. Likewise, growth stimulation with added N would indicate N limitation. Finally, joint limitation by both nutrients is indicated if algal growth is enhanced only by a combination of the two nutrients.

The substrates were collected after 28 days, as described previously, and analyzed for chlorophyll-a, AFDW and periphyton species densities.

RESULTS

Mean chlorophyll-a values for the (control) substrates without added nutrients were 1.1 mg/m^2 of flower pot surface (Fig 28a), a value quite typical of much of the littoral zone of Higgins Lake (Table 7). Chlorophyll-a on substrates with added P was 1.3 (S.E. 0.1) mg/m^2, a slight but not significant increase over control substrate values. In contrast, nitrogen-releasing substrates had 36.8 (S.E. 2.8) mg/m^2 chlorophyll-a, a significant ($p<.05$) 33-fold increase in algal biomass over control values.

Analysis of total accumulated organic matter as AFDW revealed similar trends. Again the control substrates showed the least organic matter, with a mean value of 73.9 (S.E. 2.0) mg/m^2 (Fig. 28b). The effect of phosphorus addition was again minimal, while the mean for nitrogen-releasing substrates was 347.4 (S.E. 17.7) mg/m^2, a roughly 5-fold increase over control levels.

Results of the nutrient addition experiment at Cottage Grove Association are thus consistent with the changes in the relative abundances of nitrogen vs. phosphorus observed at all 18 nearshore sites in showing that phosphorus concentrations become sufficiently high by mid-summer to cause a shift to nitrogen limitation. Continued nitrogen limitation during summer can have significant consequences in its effect upon organisms in the lake, often causing excessive growth of nitrogen fixing blue-green algae, for example. The maintenance of low levels of phosphorus in nearshore waters is thus desirable.

XI. RECOMMENDATIONS

Further Study

It is important that Higgins Lake be monitored frequently as a means of detecting further changes in water quality. The following kinds of measurements are suggested:

1. The entire shoreline of the lake should be walked once each summer in order to assess the abundance of *Cladophora* and identify areas of potential nutrient loading. Both the timing and form of data collection should be standardized.

2. Basic limnological data should be collected once each summer and winter, at 4 m intervals in both the North and South basins. Recommended measurements are temperature, dissolved oxygen and Secchi depth.

3. A more complete limnological survey, similar to the present study, is recommended roughly every 5-10 years. Such a study should not only include a limnological description of the lake itself, but also include the assessment of changes in land use within the Higgins Lake watershed.

Water Quality Management Alternatives

Several generalizations concerning future water quality management appear warranted on the basis of present data:

1. Changes in the lake are most evident nearshore and attributable largely to very localized nutrient sources. Corrective measures of relatively low cost might include: (a) a ban on the use of fertilizers containing phosphorus within 100 yards of the lakeshore, (b) the increased use of natural vegetation (Greenbelts) between riparian residences and the lake

to absorb nutrient inputs from overland runoff and reduce shoreline erosion, and (c) the elimination of public access roads with particularly high potential for erosional runoff.

Phosphorus loading from residential land use is estimated to be approximately 9% of the total phosphorus budget. Such corrective measures would thus have minimal effect upon overall water quality in the lake, but should reduce algal and macrophyte growth nearby along the shoreline.

2. On-site sewage treatment presently contributes approximately 17% (Reckhow, 1980) to 28% (U.S.EPA, 1975) of the total P budget of Higgins Lake. As septic systems age and surrounding soils lose their capacity of phosphorus retention, and as new systems are built, contributions from domestic sewage can be expected to increase. Alternatives to present septic systems are expensive, but deserve consideration.

3. Higgins Lake has historically been protected by its small, largely forested watershed. Replacement of forested land with agricultural or residential land can be expected to increase phosphorus loading to the groundwater, eventually leading to increased inputs to the lake itself. Population densities in the Higgins Lake area are expected to increase from present levels of about 16,000 people (Williams & Works, 1976) to as many as 21,000 by the turn of the century (Fig. 29). Without careful consideration of ways to minimize their impact, such population increases can be expected to lead to further deterioration of water quality in the lake.

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Forest Cover Map, Crawford Co., T.25N. - R.3W.
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Table 1. Physical Features of Higgins Lake, Michigan and its watershed.

(Lake Morphometry)

Maximum Length:	10.10 km (6.33 mi)
Breadth:	5.32 km (3.30 mi)
Surface Area (A_o):	41.75 km^2 (16.10 mi^2)
Shoreline Length (L):	32.99 km (20.49 mi)
Lake Volume (V):	$5.64 X 10^8 m^3$ ($1.99 X 10^{10} ft^3$)
Maximum Depth (Z_m):	41.5 m (136.2 ft)
Mean Depth ($Z V/A_o$):	13.5 m (44.3 ft)
Shoreline Development Factor ($D_L L/2 A_o$):	1.44
Volume Development Factor ($D_V 3V/A_o.Z_m$):	0.97

(Watershed Characteristics)

Watershed Area (A_{ow}):	87.63 km^2 (33.82 mi^2)
Length of Watershed Perimeter (L_w):	57.21 km (35.53 mi)
Watershed Development Factor ($D_{LW} L_W/2 A_{ow}$):	1.72
Ratio of Lake Area to Watershed Area (A_o/A_{ow}):	1: 2.10
Flushing Rate:	0.098 yr^{-1}

Table 2. Higgins Lake, Michigan morphometric data as compared to that of several other Northern Michigan Lakes.

Lake Name	Maximum Depth (m)	Mean Depth (m)	Shoreline Length (km)/ Shoreline Development Factor	Surface Area (ha)	Watershed Area (ha)/ Area Ratio	Volume (m^3 X 10^8)/ Volume Development Factor
Higgins	41.5	13.5	32.9/1.44	4175	8763/ 2.10	5.64/0.97
Black	15.2	7.7	28.7/1.30	4052	136554/33.70	3.13/1.50
Burt	22.2	12.0	52.3/1.80	6848	101388/14.81	8.26/1.60
Charlevoix	37.2	17.0	90.2/3.10	6800	73541/10.81	----/1.37
Crooked	18.6	3.0	29.7/2.96	960	11194/11.66	0.29/0.50
Douglas	27.1	5.5	25.1/1.82	1510	5651/ 3.74	0.83/0.61
Mullett	42.7	11.2	45.1/1.60	6652	64767/ 9.74	7.56/0.80
Munro	4.6	1.0	7.2/1.20	277	925/ 3.33	0.03/0.70
Pickeral	21.3	3.9	10.6/1.40	427	13664/31.98	0.17/0.50
Walloon	30.5	8.8	44.3/3.00	1728	9170/ 5.31	1.54/0.90

Table 3. Summary comparison of water quality parameters indicating differences between the North and South basins of Higgins Lake, Michigan.

Parameter	North	South
Secchi Depth (m)	12.0	10.0
Mean Winter Hypolimnetic % Saturation (%)	100.3	88.5
Mean Summer O-Phosphate (ug/l)	11.3	37.7
Mean Summer Total Phosphorus (ug/l)	19.6	53.8
Mean Summer Nitrate (ug/l)	32.3	48.1
Mean Summer Total Nitrogen (ug/l)	165.3	213.7
Chlorophyll-a (ug/l)	2.3	2.4

Table 4. Major inflow and outflow streams of Higgins Lake, Michigan and their approximate nutrient loads.

Stream Name	Streamflow (m^3/day)	SiO_2 (kg/day)	NO_3-N (kg/day)	PO_4-P (kg/day)
Big Creek				
Winter	8.14×10^3	28.49	4.05	0.07
Summer	4.85×10^3	18.08	0.08	0.04
Little Creek				
Winter	2.55×10^3	11.18	1.35	0.01
Summer	4.32×10^2	3.97	0.06	0.01
Cut River				
Winter	1.56×10^5	1249.32	35.34	1.03
Summer	1.47×10^5	1109.59	5.23	0.91
Total Inflow				
Winter	1.07×10^4	39.67	5.40	0.08
Summer	5.42×10^3	22.05	0.14	0.04
Total Outflow				
Winter	1.56×10^5	1249.32	35.34	1.03
Summer	1.47×10^5	1109.59	5.23	0.91

Table 5. Metric features of some of the road-ends which terminate at Higgins Lake.

Location	Road Type	% Slope	Width (m)	Length (m)
Hyslip Ave	Sand-Gravel	4-5	8.4	33
Chicago	Sand-Gravel	4-6	8.0	33
St. Lawrence	Sand-Gravel	7-8	9.0	7
Minto Pointe	Sand-Gravel	9-10	7.0	100
Maple	Macadem-Gravel	5-6	9.5	33
Lone Pine	Macadem-Sand	2-3	8.0	30
Magnolia	Gravel	1-2	10.0	50
Lincoln	Gravel	1-2	10.0	52
Bismark	Gravel	2-3	9.0	35
Lyon	Gravel	0-1	7.0	70
East	Gravel-Sand	1-2	7.0	61
West	Organic-Sand	1-2	9.0	40
Access Site	Gravel-Cement	2-3	16.0	9
Newman	Sand-Gravel	8-9	9.5	73
Hallie	Sand-Gravel	4-5	7.0	22
Phoenix	Gravel-Sand	5-6	9.0	60
Wilson	Gravel-Grass	4-5	6.5	21
Funston	Gravel-Grass	3-4	7.0	34
Des Moines	Macadem	2-4	6.5	20
Cooke	Sand	3-4	6.0	70
Taylor	Gravel	3-4	7.5	84
Thorpe	Gravel-Grass	7-8	4.5	110
Hickory	Sand-Gravel	3-4	7.0	132
N. Park	Macadem	2-3	6.0	37
Forest	Gravel	3-4	20.0	17
Jackson	Gravel	2-3	6.0	101
Lansing	Sand-Gravel	2-3	6.5	41
Earl	Gravel	4-5	6.0	110
Forest-Reeves	Sand-Gravel	1-2	13.0	17
West	Gravel	2-3	8.0	81
Maplehurst	Macadem	7-8	16.0	112
Hitchcock	Cement-Macadem	8-9	8.0	62
Hoffman	Gravel	2-3	8.0	93
Kelly	Macadem	4-5	6.0	22
2nd	Gravel	5-6	8.0	121
Lincoln	Gravel-Sand	8-9	12.0	141

Table 6. Nearshore nutrient concentrations in Higgins Lake, Michigan

	Cl^-			SiO_2		
Site	5-83 (mg/l)	6-83 (mg/l)	7-83(20cm/50cm) (mg/l)	5-83 (mg/l)	6-83 (mg/l)	7-83(20cm/50cm) (mg/l)
1	6.46	6.16	6.01/5.00	7.33	5.87	8.19/8.03
2	6.57	5.96	6.11/5.82	7.07	5.66	7.49/7.94
3	6.98	5.98	5.70/5.80	7.04	6.36	9.13/8.33
4	6.57	6.16	5.18/5.03	7.34	5.86	7.56/8.64
5	6.78	5.86	5.37/5.80	----	5.95	7.94/8.31
6	8.56	8.56	5.88/5.72	7.77	6.27	7.53/7.34
7	11.60	8.53	7.34/5.82	7.64	6.23	7.83/7.32
8	5.27	8.38	6.00/5.35	3.53	3.96	7.48/7.82
9	----	8.28	6.58/6.35	6.38	6.57	7.23/7.17
10	9.03	10.98	7.31/6.99	7.40	5.75	7.99/7.45
11	5.29	5.89	5.61/5.65	----	6.85	7.92/7.88
12	6.78	5.19	6.47/6.27	8.29	6.69	7.45/8.32
13	7.69	6.68	7.64/7.46	8.71	5.98	8.11/7.56
14	6.53	5.66	5.24/5.18	7.44	6.37	7.96/8.34
15	6.22	3.19	6.17/5.95	8.19	7.20	7.66/8.86
16	7.04	6.40	6.49/5.95	8.28	6.81	8.38/7.97
17	7.47	6.40	6.78/6.36	7.53	6.58	8.32/7.61
18	7.33	5.14	5.94/6.01	7.18	6.92	8.21/8.24

Table 6. (cont.)

	NO_3-N			NH_3-N		
Site	5-83 (ug/l)	6-83 (ug/l)	7-83(20cm/50cm) (ug/l)	5-83 (ug/l)	6-83 (ug/l)	7-83(20cm/50cm) (ug/l)
1	64.99	17.42	5.03/ 3.73	60.71	144.71	27.03/15.22
2	263.61	81.35	3.73/ 3.73	68.70	61.69	23.09/ 9.73
3	129.97	62.22	3.63/ 3.10	69.43	25.29	49.81/ 9.03
4	35.12	12.07	3.42/ 2.16	76.11	113.54	89.61/81.88
5	-----	15.55	1.12/ 1.12	78.87	190.90	56.14/18.87
6	282.42	54.12	3.73/ 1.12	23.38	19.56	13.25/27.77
7	325.44	61.47	2.42/ 1.90	61.03	9.53	112.53/ 6.22
8	-----	20.01	1.12/ 1.12	147.92	192.33	20.28/ 8.33
9	122.63	42.61	5.31/ 3.21	49.36	31.88	13.67/ 5.52
10	236.35	70.42	3.73/ 3.73	45.31	22.42	11.41/11.00
11	-----	56.13	2.68/10.25	4.20	-----	17.05/ 8.33
12	217.49	100.42	2.68/ 2.16	56.50	34.46	84.27/13.39
13	175.04	98.71	9.40/ 5.83	126.23	4.37	13.32/ 7.62
14	118.71	46.18	5.83/11.39	29.72	63.42	33.57/13.39
15	67.71	17.81	9.72/11.60	60.42	13.83	49.81/15.08
16	408.25	232.95	11.18/12.86	105.17	14.33	54.73/11.70
17	156.70	72.81	5.52/ 5.83	87.43	22.14	37.50/16.43
18	169.80	68.43	2.16/ 1.12	32.53	23.57	15.36/ 9.03

Table 6. (cont.)

		PO_4-P	
Site	5-83 (ug/l)	6-83 (ug/l)	7-83(20cm/50cm) (ug/l)
1	5.25	21.33	----/41.32
2	3.99	23.43	47.66/31.53
3	4.43	4.06	10.56/ 5.82
4	6.35	72.31	196.28/98.60
5	10.23	15.43	19.44/27.48
6	4.98	19.18	24.31/16.88
7	6.18	41.33	99.81/68.05
8	6.78	6.10	7.48/ 6.06
9	2.78	2.91	4.52/ 4.52
10	4.32	9.31	-----------
11	6.54	11.32	19.64/20.28
12	9.09	8.15	7.48/ 8.31
13	5.80	4.55	3.69/ 3.69
14	5.75	6.63	5.47/11.39
15	3.61	12.04	58.49/57.49
16	3.44	17.77	31.76/ 5.94
17	4.98	5.81	6.89/ 5.11
18	4.98	32.62	60.62/24.31

Table 7. Periphyton growth on artificial substrates as represented by chlorophyll-a and phaeopigment values for the period of May-June,1983 in Higgins Lake, Michigan at 18 sites.

Site	Natural Substrate (mg/m^2)		Artificial Substrate-Pot (mg/m^2)		Artificial Substrate-Rock (mg/m^2)	
	Chl-a	Phaeo	Chl-a	Phaeo	Chl-a	Phaeo
1	0.10	0.06	0.29	0.00	--	--
2	12.86	3.60	0.18	0.00	--	--
3	14.55	1.32	0.62	0.00	--	--
4	23.65	18.77	--	--	3.15	0.38
5	4.34	0.00	3.52	0.26	--	--
6	38.34	3.40	0.58	0.05	--	--
7	46.41	5.77	--	--	4.57	0.55
8	44.15	27.77	9.96	1.81	30.75	8.11
9	6.37	0.00	1.12	0.00	4.46	0.32
10	4.11	1.36	0.25	0.02	--	--
11	5.02	8.91	--	--	3.67	0.00
12	13.43	7.91	--	--	2.41	0.00
13	8.41	1.41	--	--	1.56	0.16
14	15.87	2.34	1.12	0.03	--	--
15	25.21	12.84	--	--	5.05	0.00
16	6.40	0.15	--	--	5.12	0.00
17	0.39	0.19	--	--	2.25	0.00
18	26.03	5.21	0.79	0.00	2.12	0.00

Table 8. Periphyton growth on artificial substrates as represented by ash-free dry weight values for the of May-June, 1983 in Higgins Lake, Michigan at 18 sites.

Site	Artificial Substrate-Pot (gm/m^2)	Artificial Substrate-Rock (gm/m^2)
1	74.181	---
2	76.379	---
3	70.819	---
4	---	67.119
5	79.828	---
6	63.276	---
7	---	88.597
8	78.276	79.015
9	76.552	78.666
10	75.776	---
11	---	97.013
12	---	54.485
13	---	51.955
14	73.879	---
15	---	81.016
16	---	85.432
17	---	61.600
18	76.293	75.741

Table 9. Comparison of nutrient concentrations very close to shore (20 cm depth) and further from shore (50 cm depth) on July 22, 1983 with concentrations in the euphotic zone of the North and South basins on July 19, 1983: $\bar{x}$(S.E.)

	NO_3-N (ug/l)	NH_3-N (ug/l)	PO_4-P (ug/l)	SiO_2 (mg/l)	Cl (mg/l)
20 cm:	4.6(0.7)	40.1(7.1)	37.8(12.5)	7.9(0.1)	6.2(0.2)
50 cm:	4.8(0.9)	16.0(4.1)	25.7(6.5)	7.9(0.1)	5.9(0.2)
N. & S. Basins	39.7(6.0)	31.9(4.1)	12.5(1.3)	7.9(0.2)	4.9(0.2)

Table 10. Mean nutrient concentrations, based upon all 3 sampling dates, for 18 nearshore sites, Higgins Lake, Michigan.

Site	NO_3-N	NH_3-N	PO_4-P	Cl^-
1.	28.9	75.5	22.6	6.0
2.	116.2	48.9	22.3	6.2
3.	65.2	41.3	5.6	6.2
4.	16.6	91.6	75.4	5.9
5.	-	102.4	16.3	6.1
6.	113.0	21.1	14.9	7.6
7.	129.7	43.3	43.8	8.9
8.	-	118.2	6.5	6.4
9.	56.4	30.3	3.4	-
10.	103.4	26.2	-	9.0
11.	-	-	12.6	5.6
12.	106.7	46.6	8.4	6.1
13.	93.8	47.0	4.7	7.3
14.	57.8	38.9	6.9	5.8
15.	32.0	35.6	24.5	5.1
16.	217.7	50.9	13.3	6.6
17.	78.4	45.5	5.6	6.8
18.	79.9	22.8	26.7	6.1
$\bar{x}$:	86.4	52.1	18.4	6.6
s:	49.0	28.2	18.1	1.1
CV(%):	57.8	54.1	98.4	16.7

Figure 1. An outline of the State of Michigan indicating the location of Higgins Lake, Michigan.

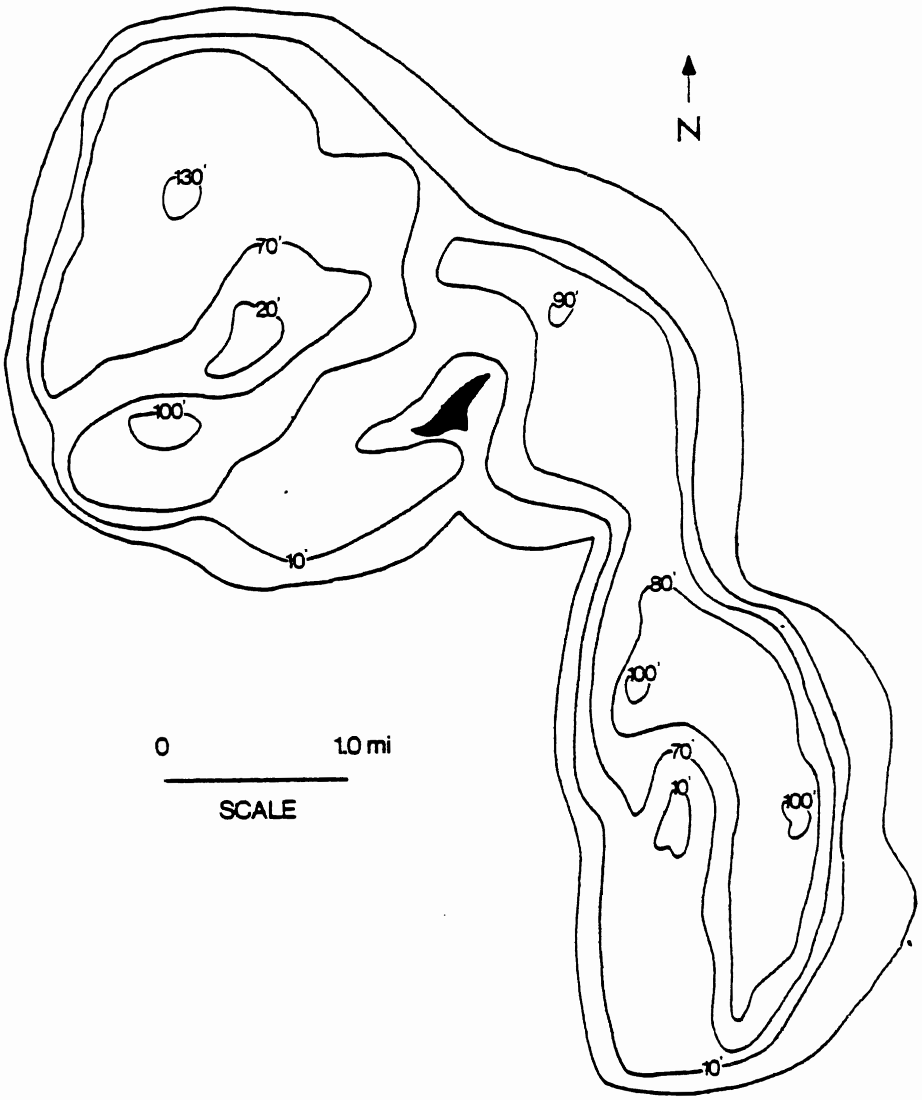


Figure 2. Bathymetric map of Higgins Lake, Michigan.

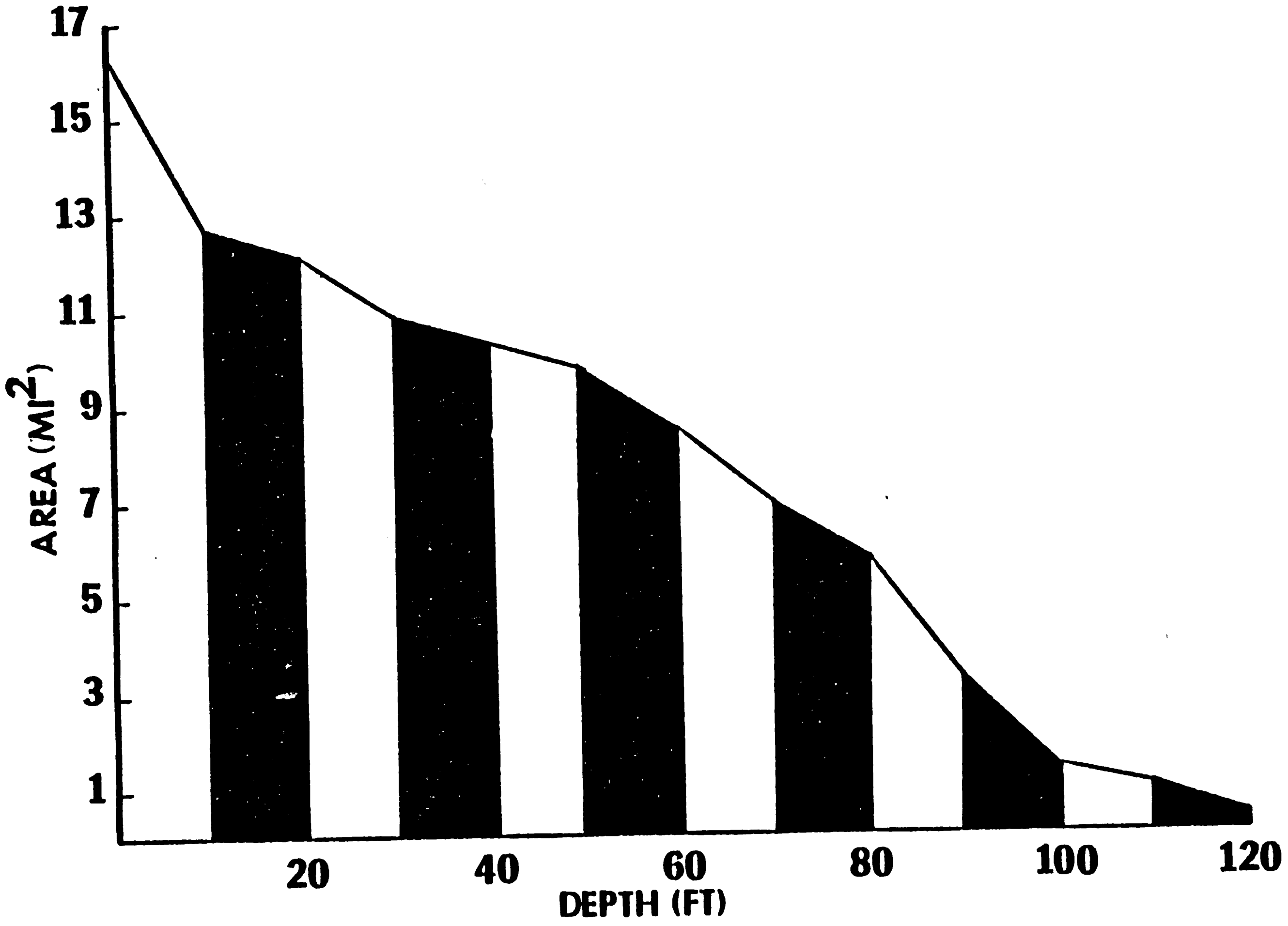


Fig. 3. Hypsographic curve of Higgins Lake, Michigan depicting lake surface area vs. depth.

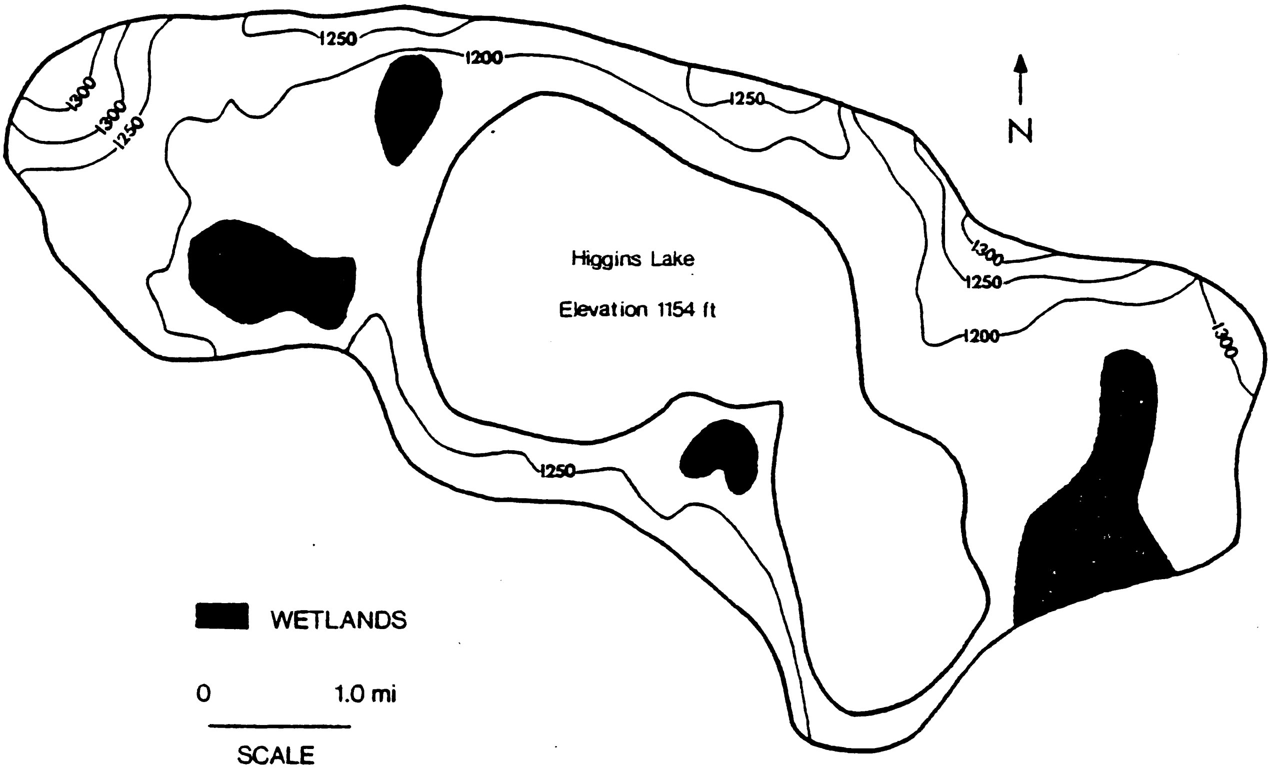


Figure 4. Topographic map of the Higgins Lake, Michigan watershed.

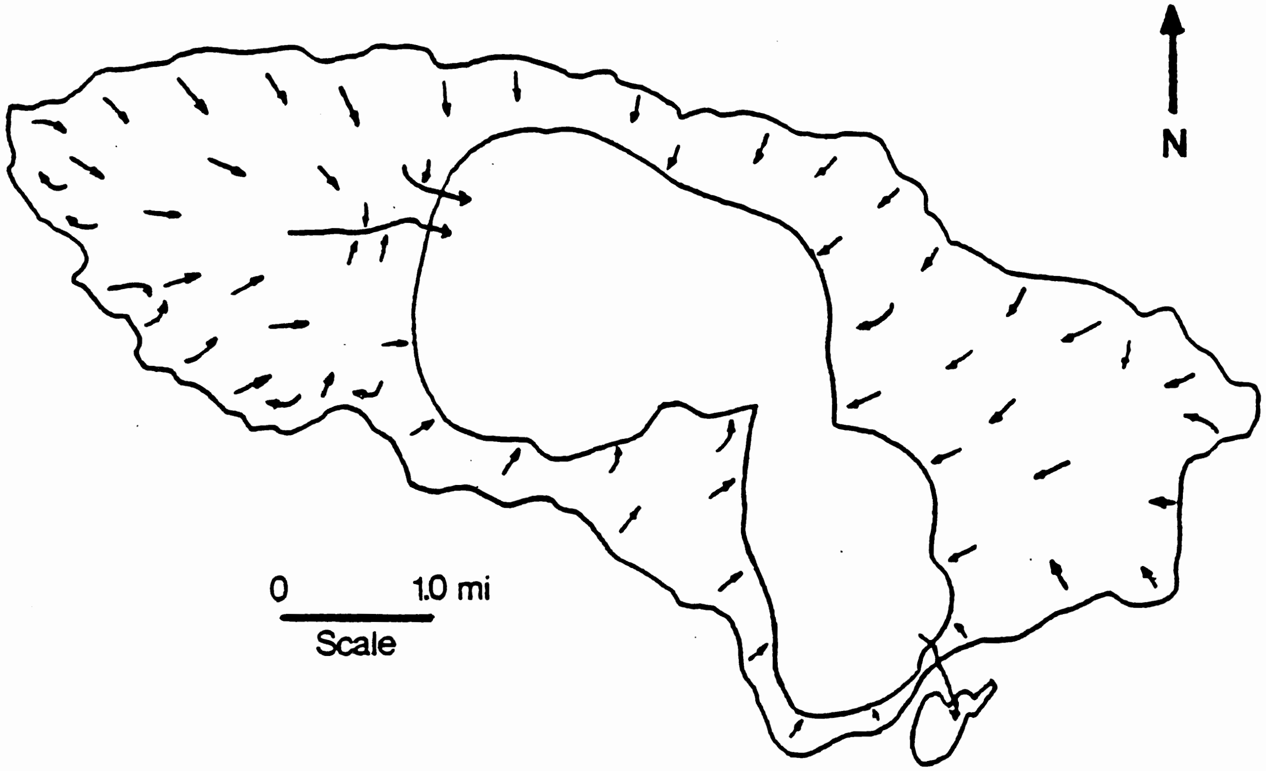


Figure 5. Drainage patterns within the Higgins Lake, Michigan watershed. The arrows indicate the direction of net groundwater flow.

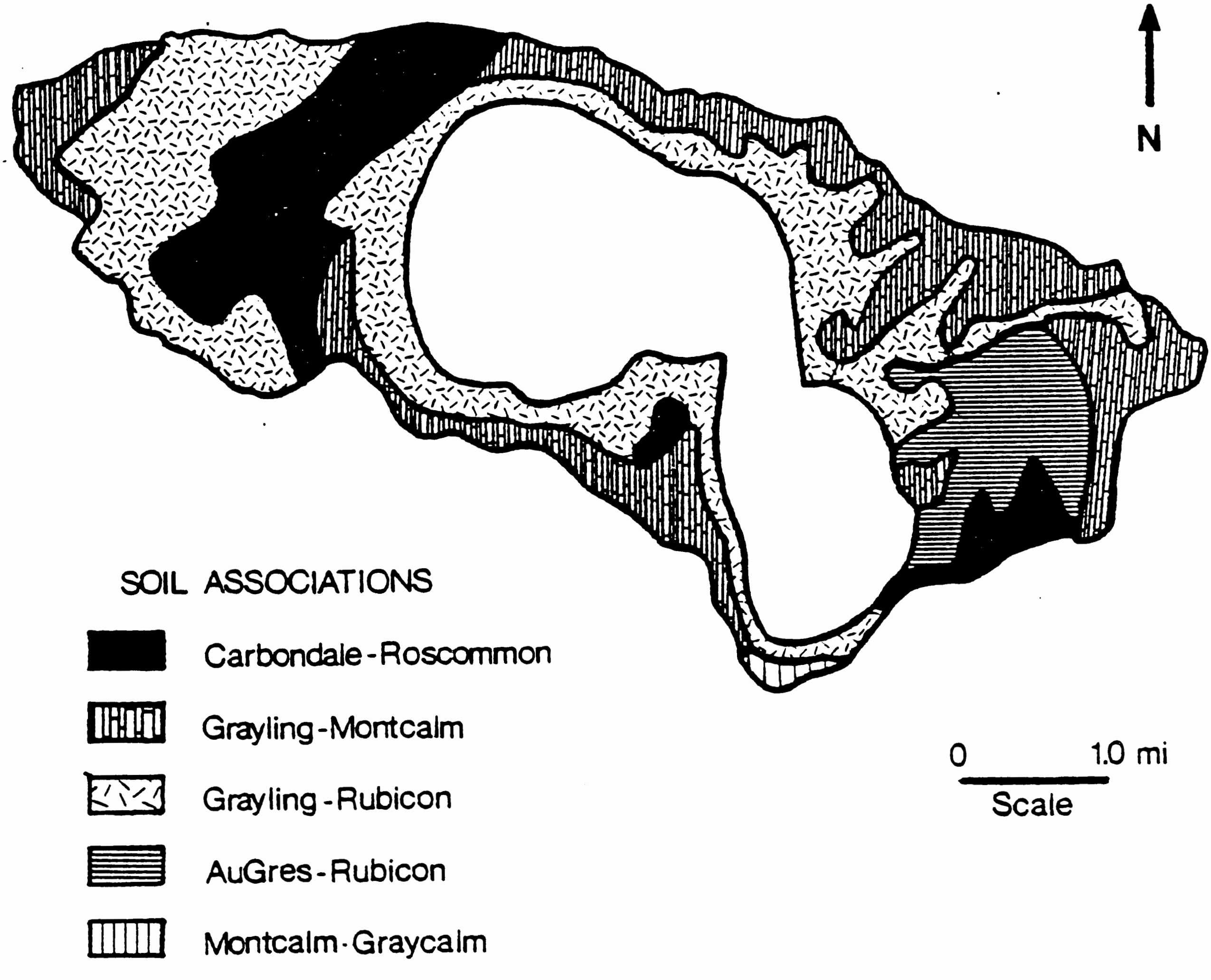


Figure 6. Soil associations of the Higgins Lake, Michigan watershed.

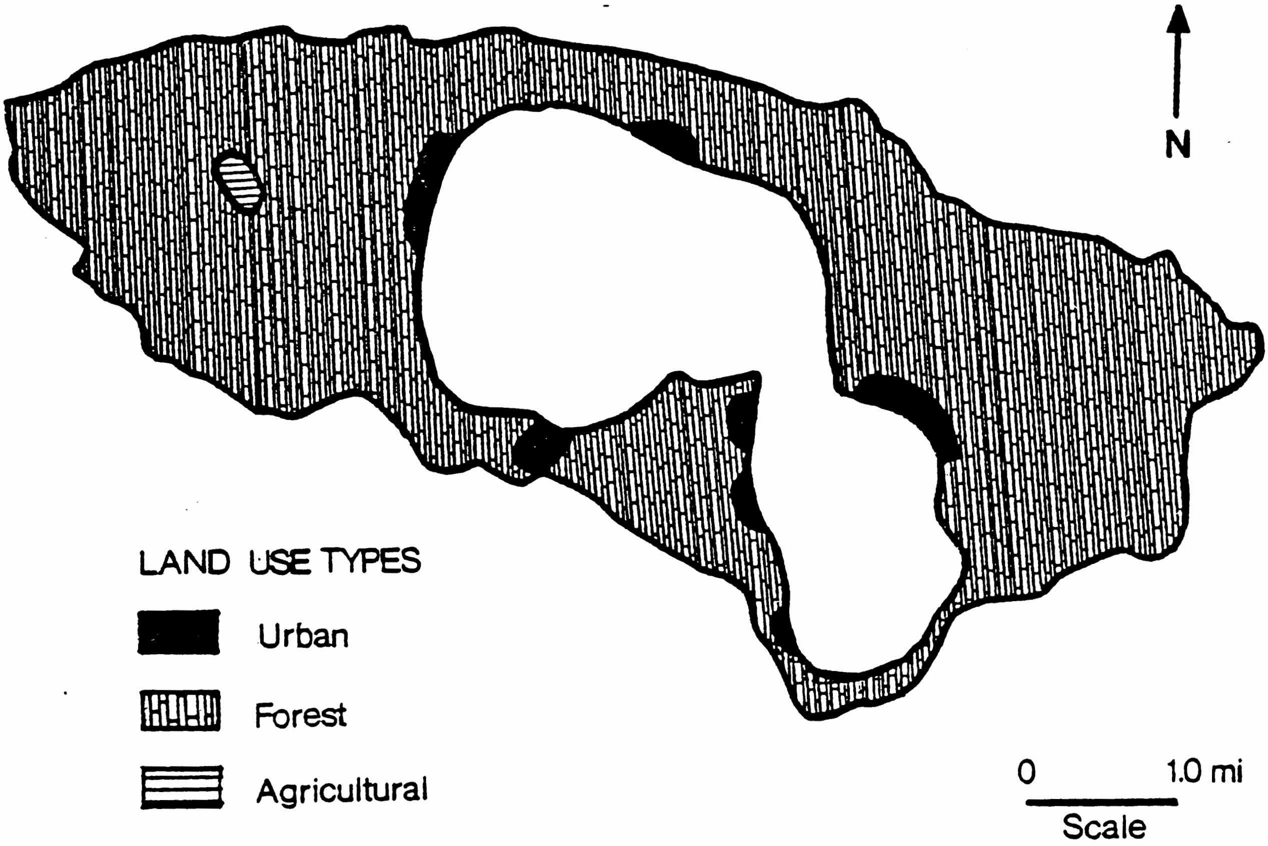
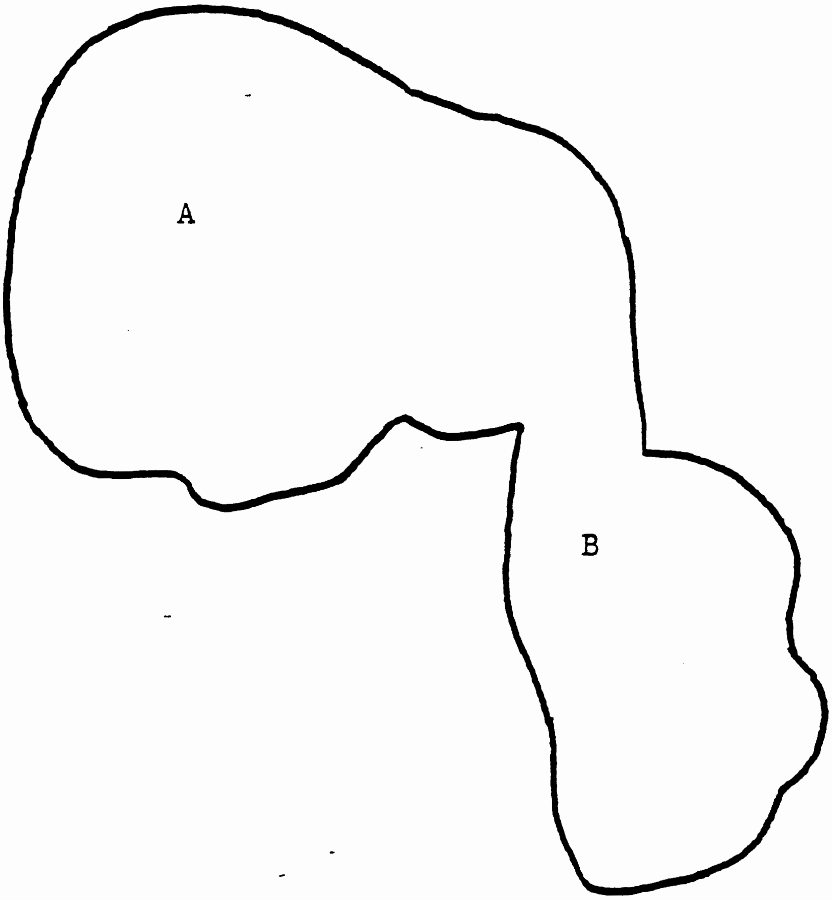


Figure 7. Land use types within the Higgins Lake, Michigan watershed.



A - North Hole Sampling Site

B - South Hole Sampling Site

Figure 8. An outline of Higgins Lake, Michigan indicating the location of the deepwater sampling stations utilized for this study.

NORTH BASIN

Figure A

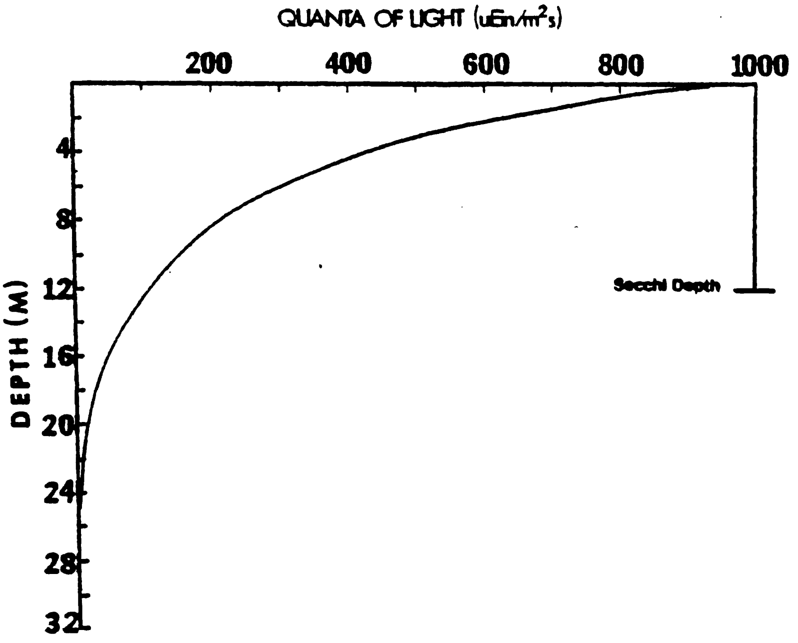


Figure B

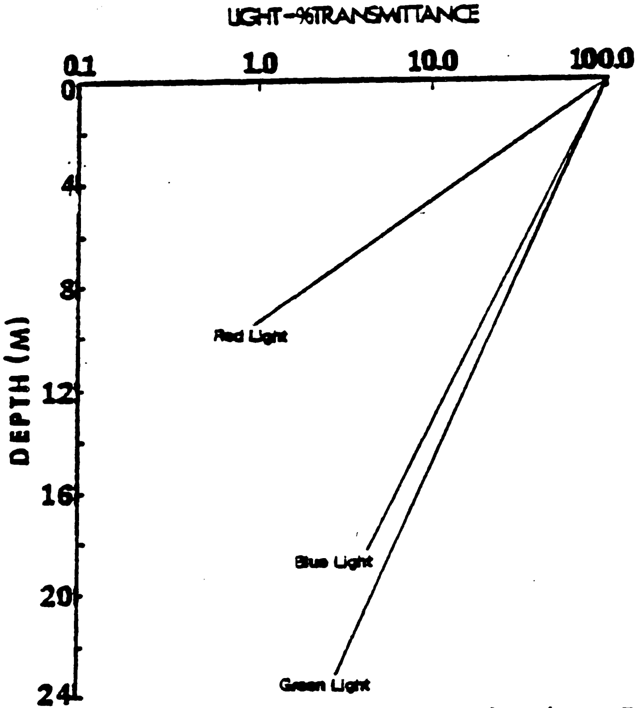


Figure 9. Light profiles for Higgins Lake, Michigan. Figures A & C depict Secchi depth and light attenuation, Figures B & D depict light penetration.

SOUTH BASIN

Figure C

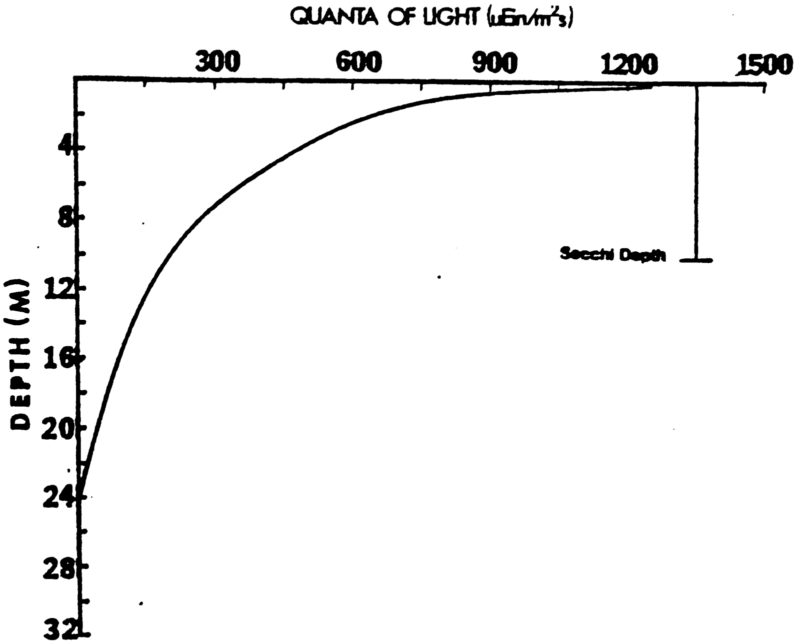


Figure D

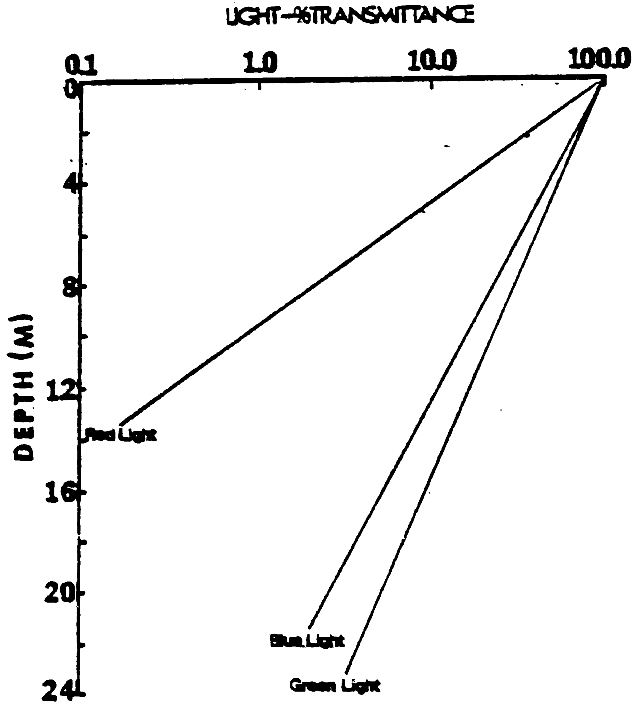


Figure 9. Light profiles for Higgins Lake, Michigan.

Figure A

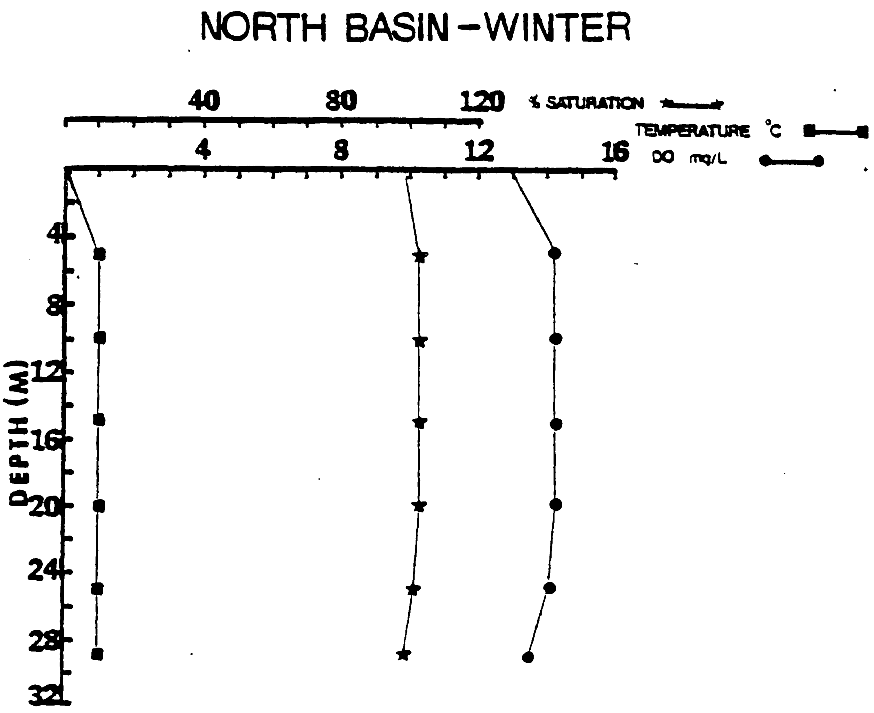


Figure B

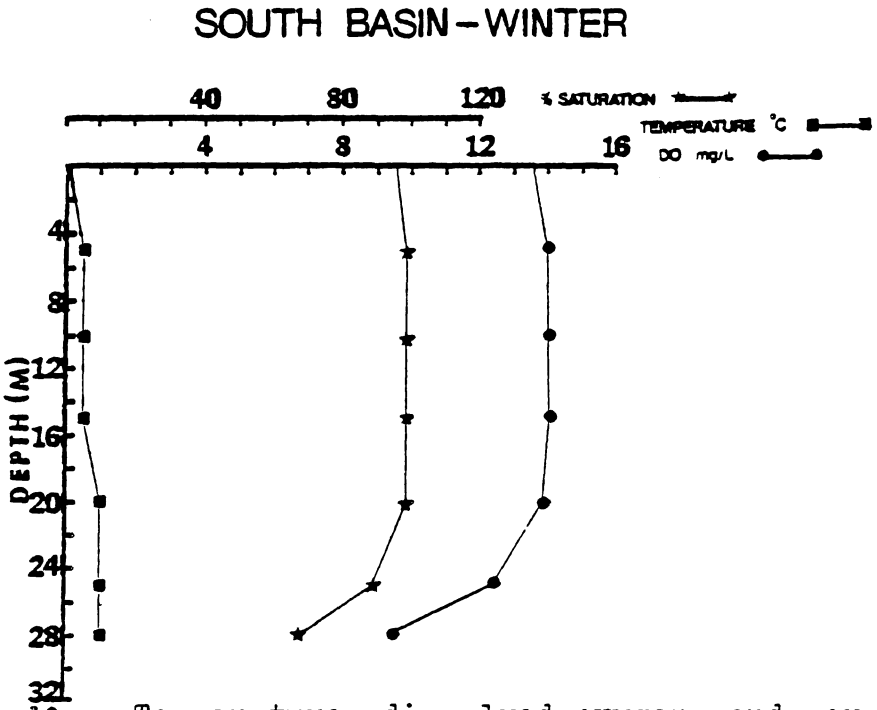


Figure 10. Temperature, dissolved oxygen, and per cent saturation depth profiles for Higgins Lake, Michigan.

Figure C

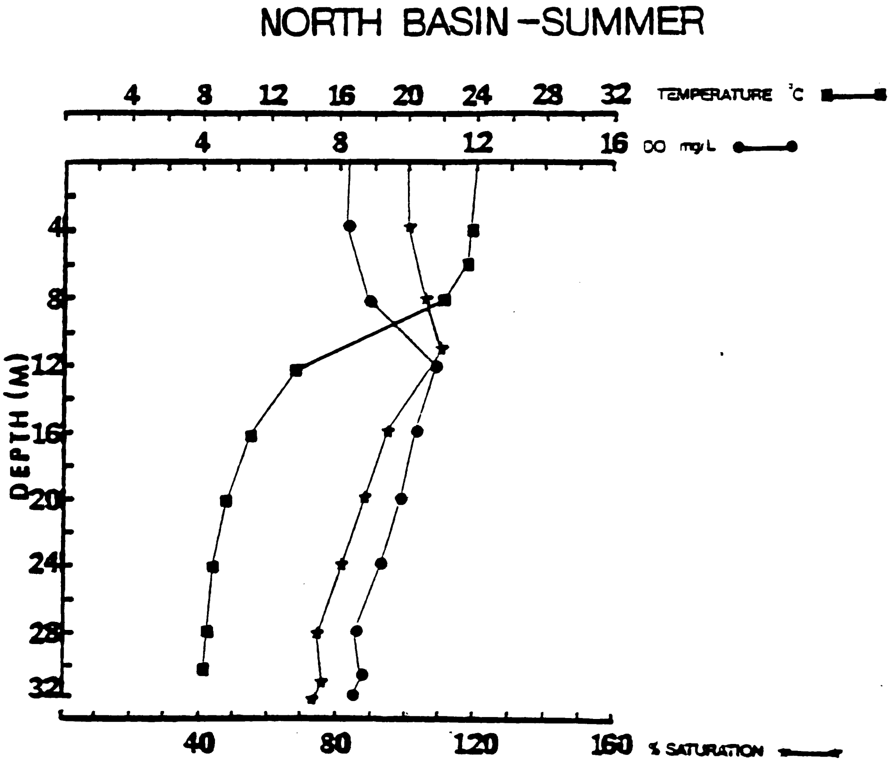


Figure D

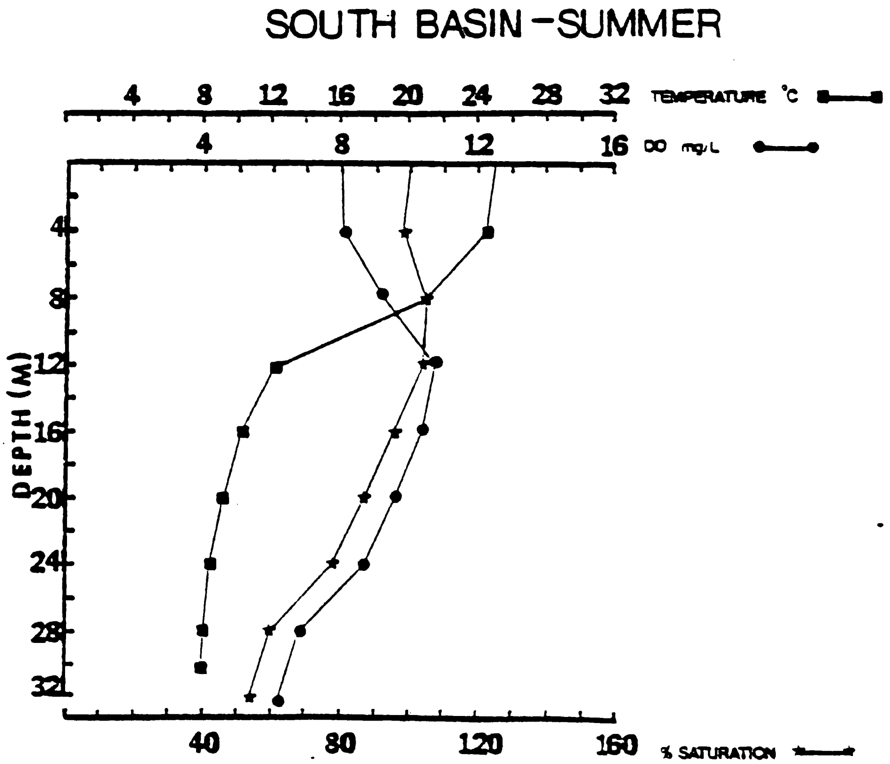


Figure 10. Temperature, dissolved oxygen, and per cent saturation depth profiles for Higgins Lake, Michigan.

Figure A

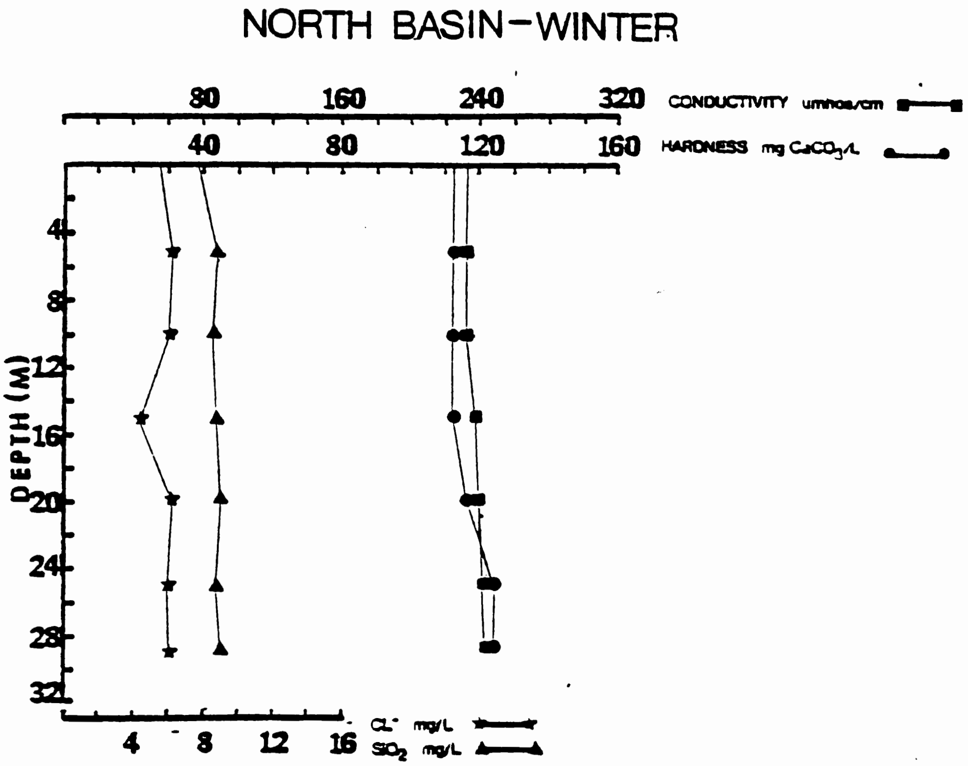


Figure B

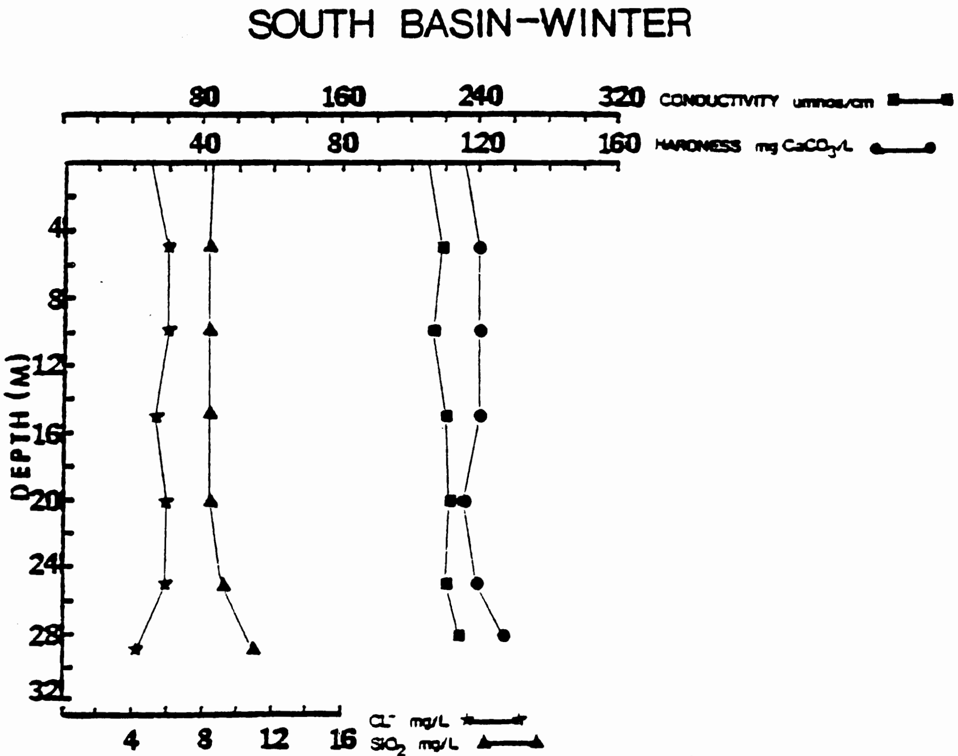


Figure 11. Hardness, conductivity, silica, and chloride depth profiles for Higgins Lake, Michigan.

Figure C

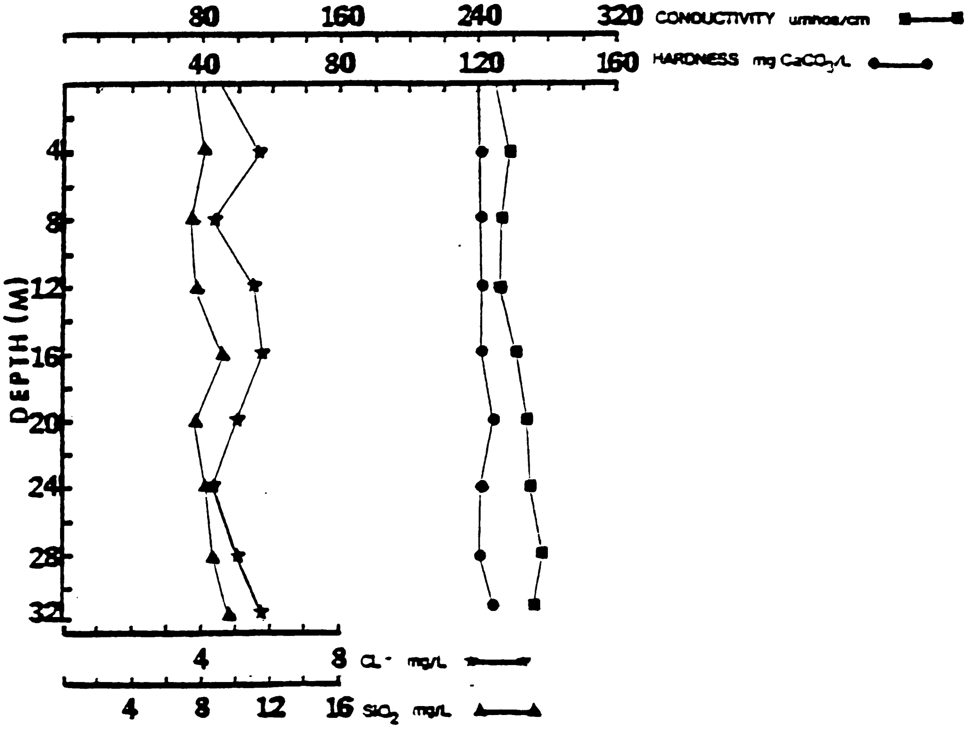

NORTH BASIN-SUMMER

Figure D

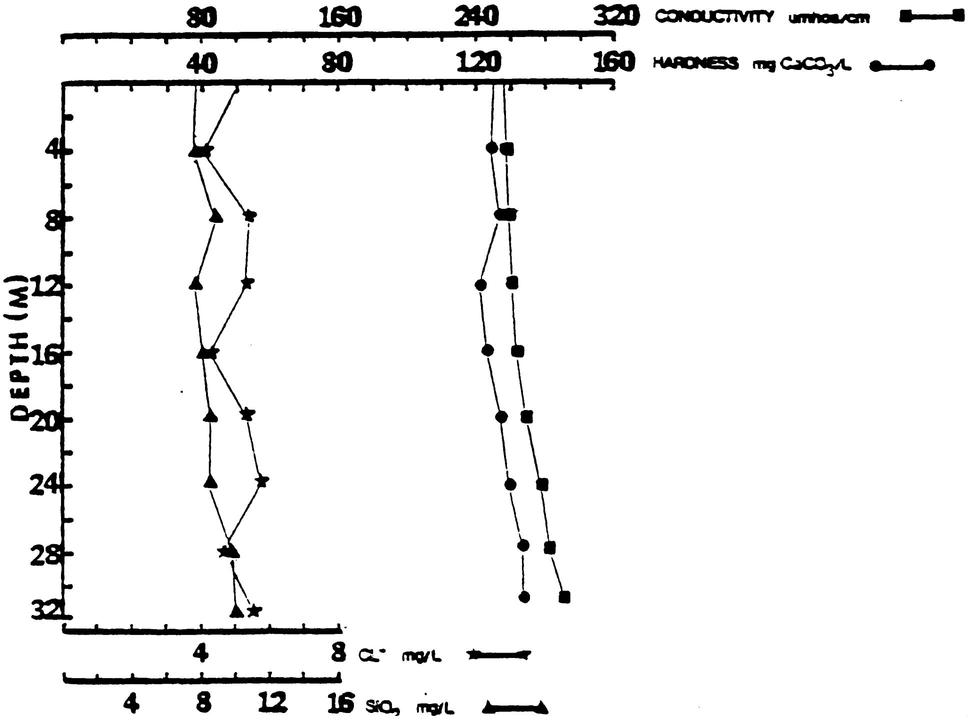

SOUTH BASIN-SUMMER

Figure 11. Hardness, conductivity, silica, and chloride depth profiles for Higgins Lake, Michigan.

Figure A

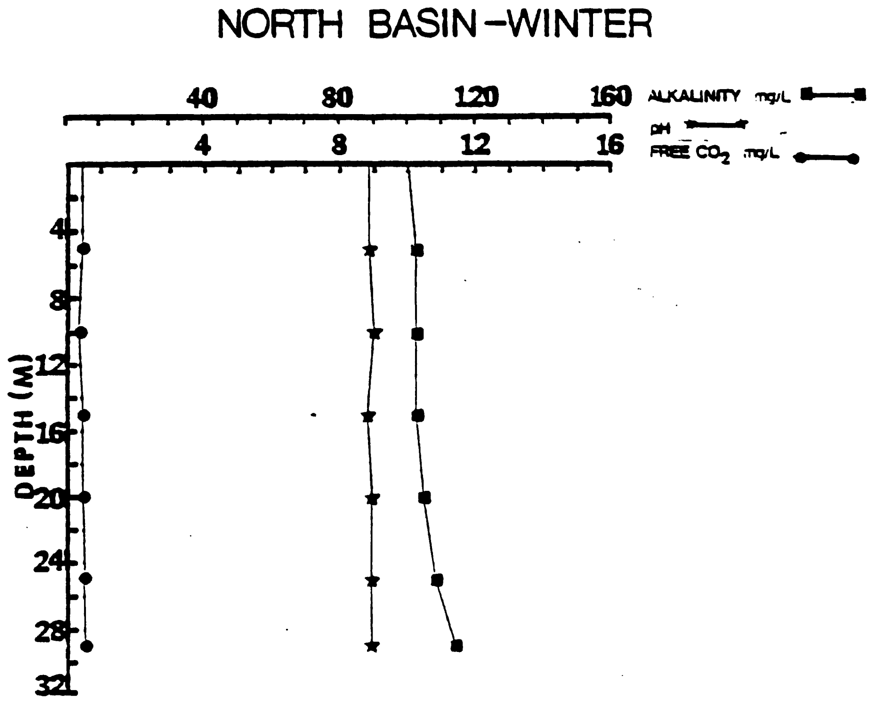


Figure B

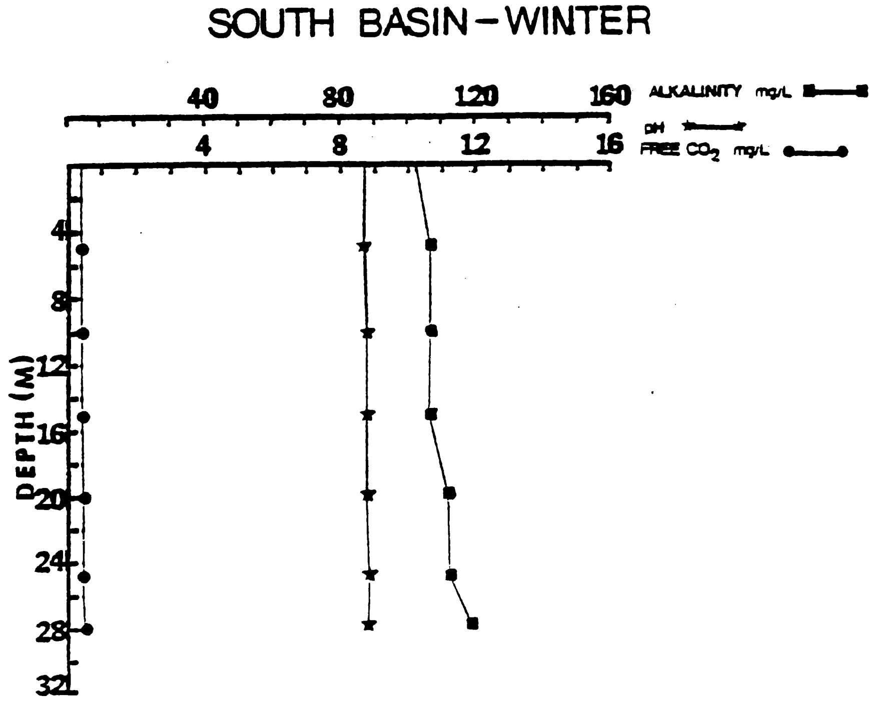
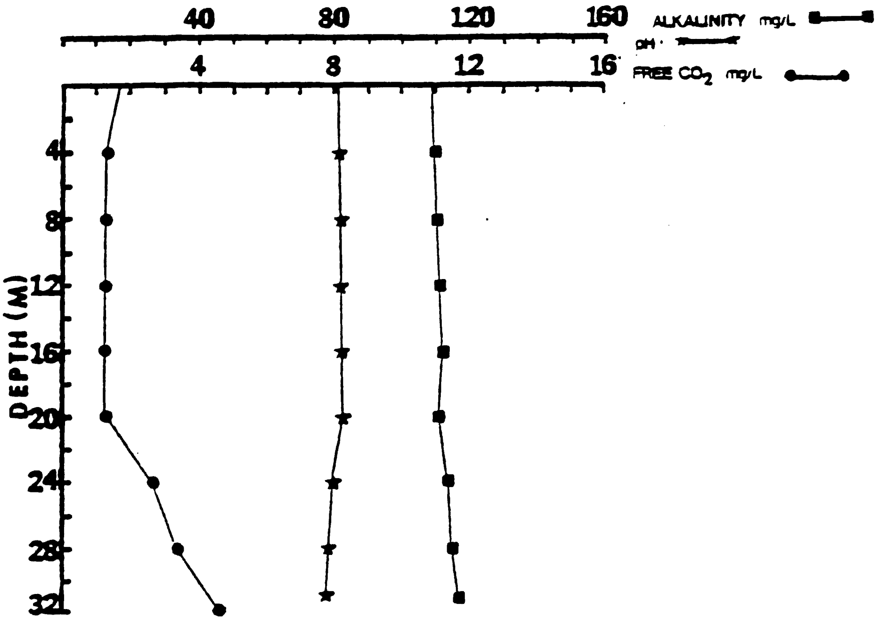


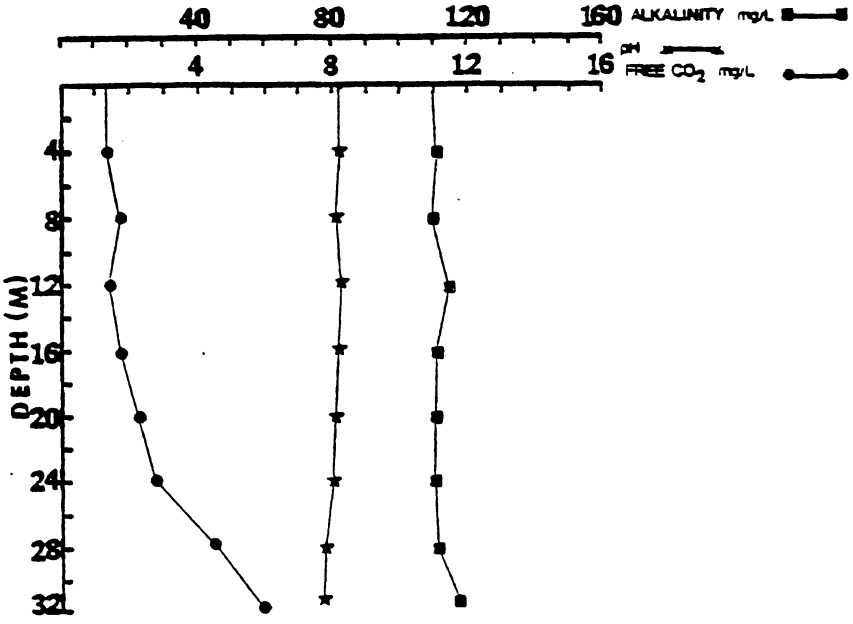
Figure 12. pH, alkalinity, and free carbon dioxide depth profiles for Higgins Lake, Michigan.

Figure C



NORTH BASIN–SUMMER

Figure D



SOUTH BASIN–SUMMER

Figure 12. pH, alkalinity, and free carbon dioxide depth profiles for Higgins Lake, Michigan.

Figure A

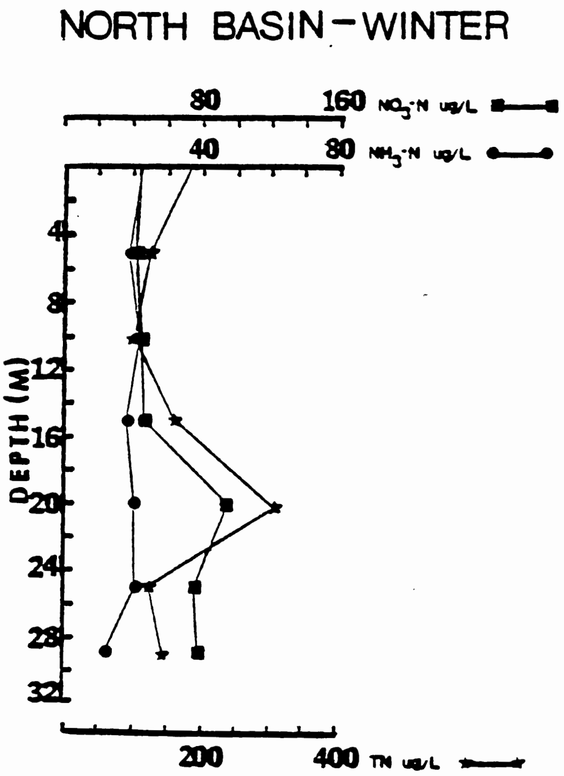


Figure B

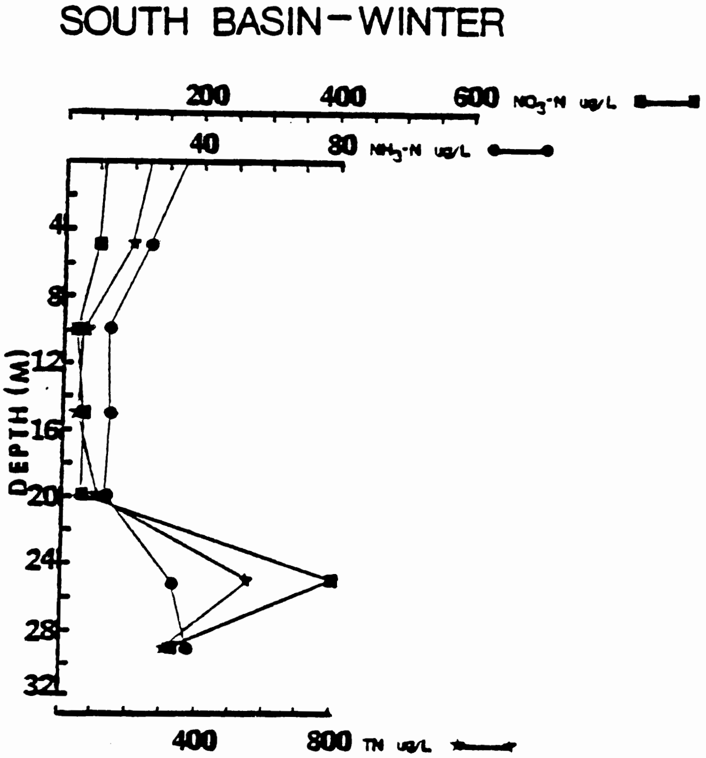


Figure 13. Ammonia, nitrate, and total nitrogen depth profiles for Higgins Lake, Michigan.

Figure C

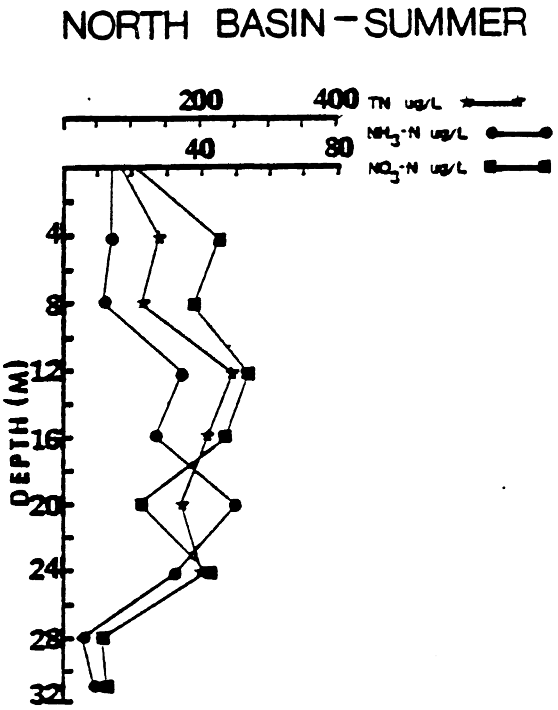

NORTH BASIN-SUMMER

Figure D

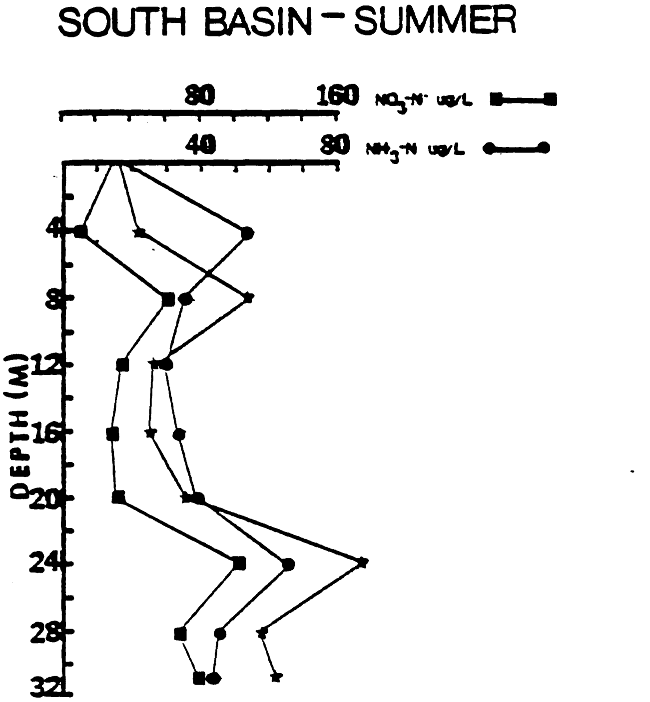

SOUTH BASIN-SUMMER

Figure 13. Ammonia, nitrate, and total nitrogen depth profiles for Higgins Lake, Michigan.

Figure A

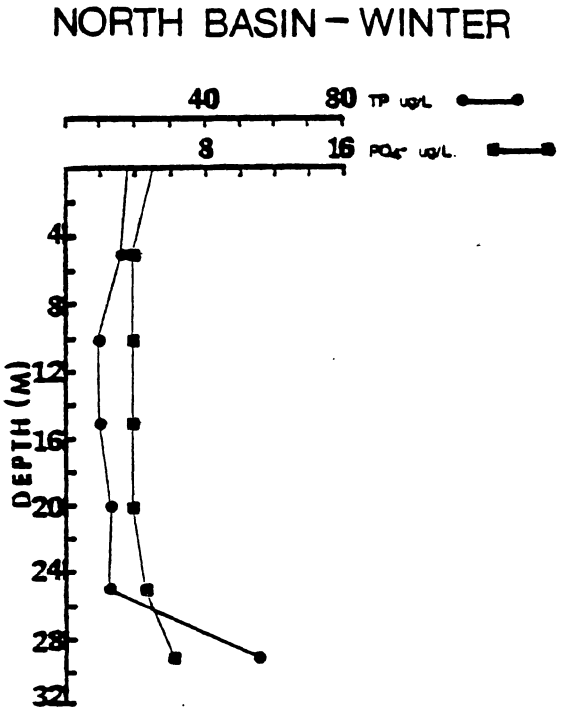

NORTH BASIN - WINTER

Figure B

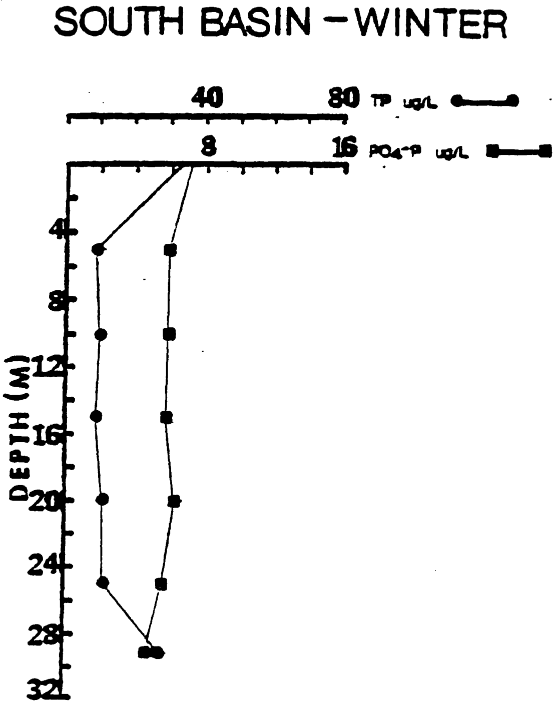

SOUTH BASIN - WINTER

Figure 14. Orthophosphate and total phosphorus depth profiles for Higgins Lake, Michigan.

Figure C

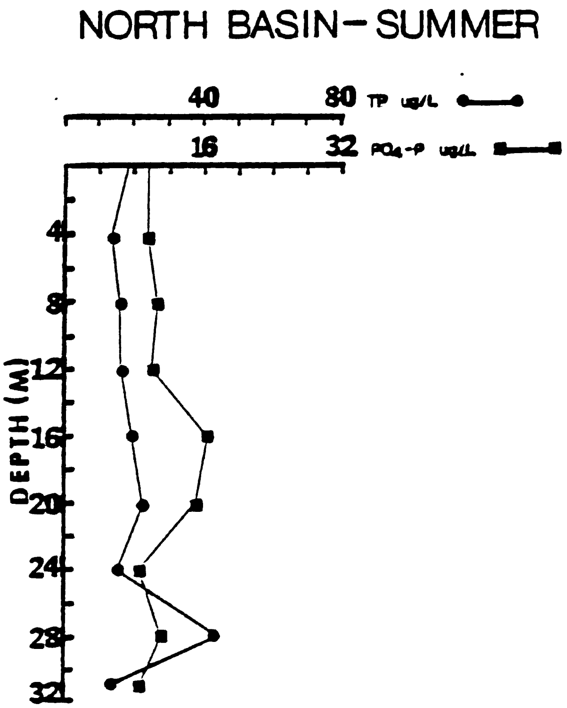


Figure D

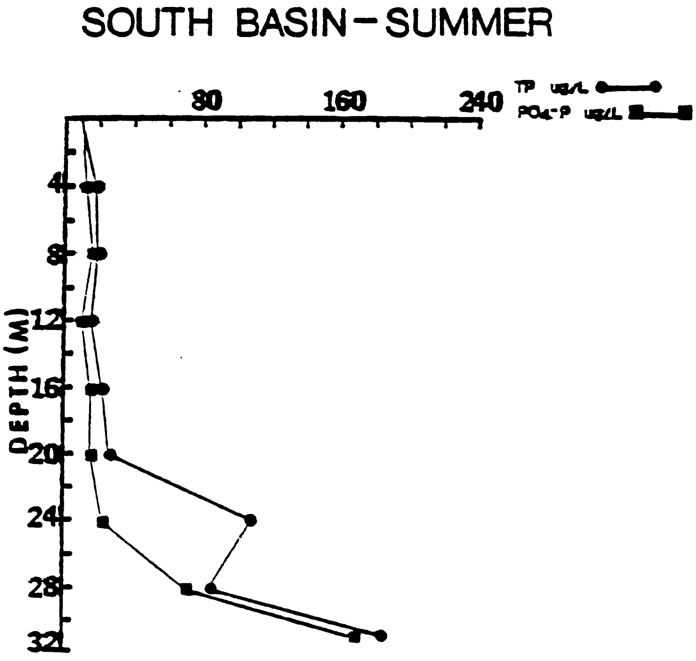


Figure 14. Orthophosphate and total phosphorus depth profiles for Higgins Lake, Michigan.

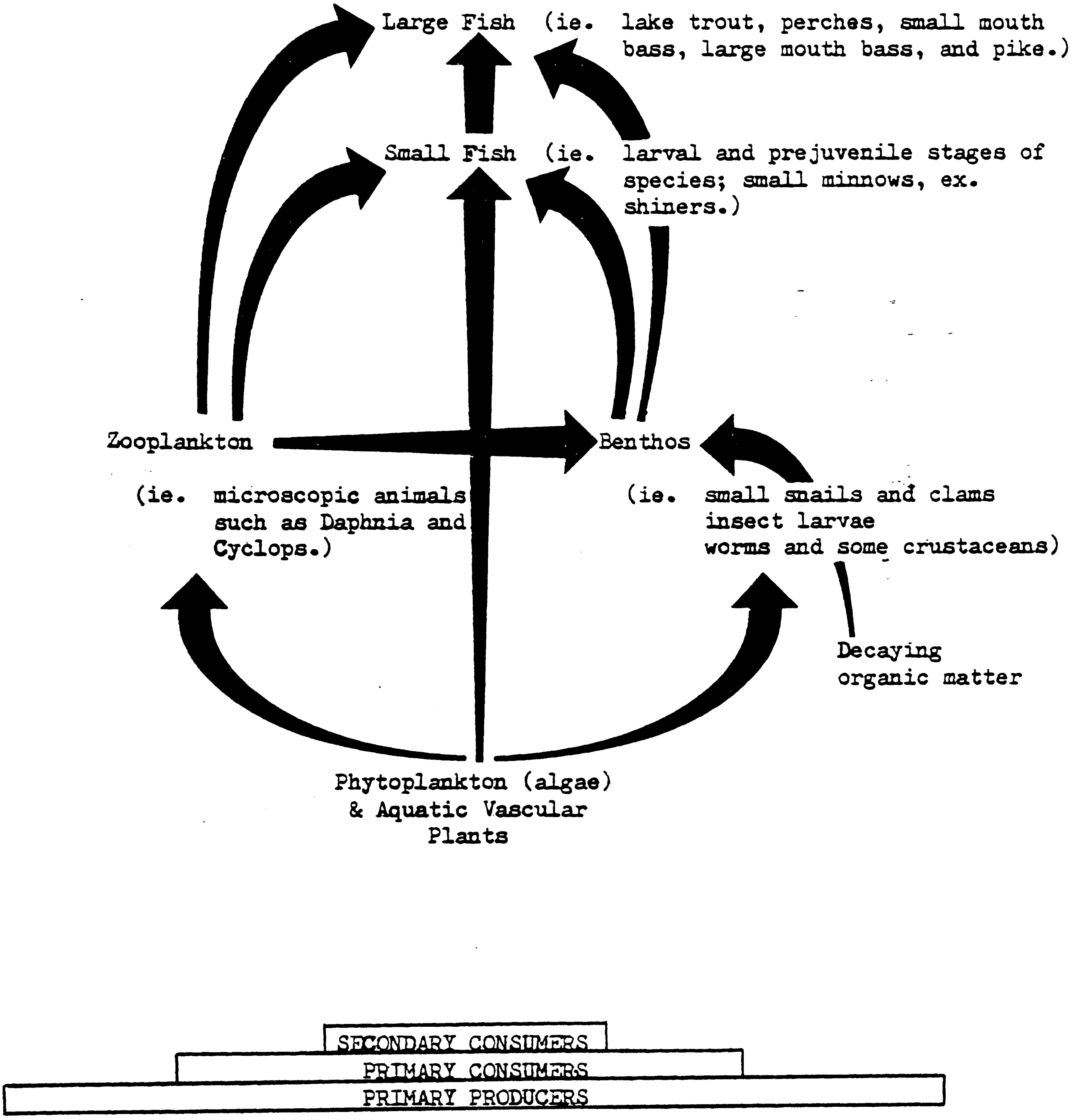


Figure 15. Generalized food web and energy pyramid for Higgins Lake, Michigan depicting phytoplankton as primary producers for the system.

NORTH BASIN

Figure A

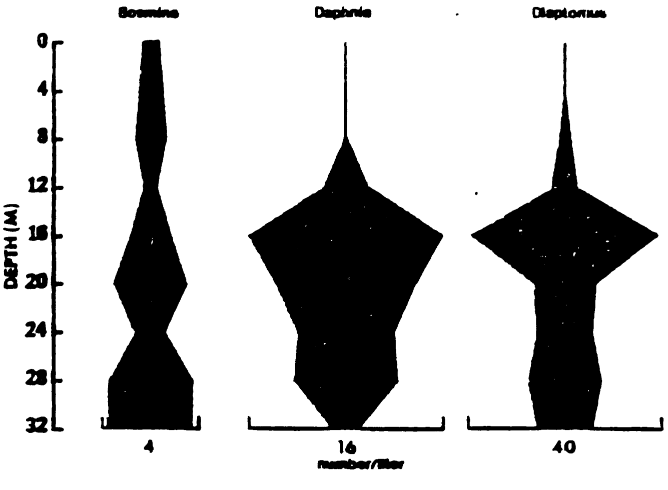


Figure B

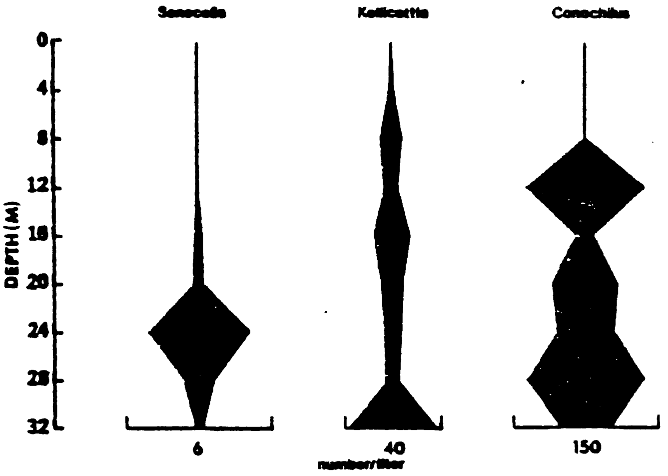


Figure C

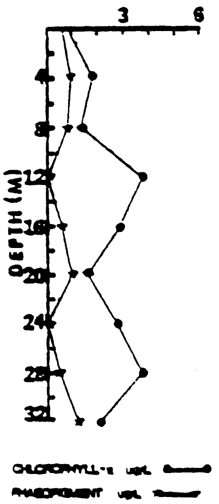


Figure 16. Zooplankton and phytoplankton depth profiles for Higgins Lake, Michigan.

SOUTH BASIN

Figure D

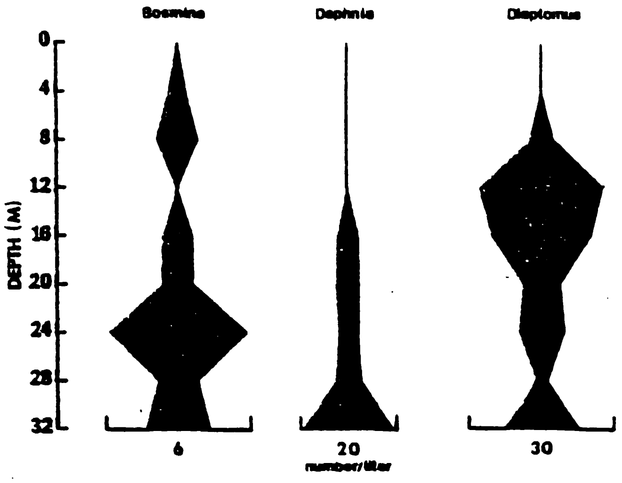


Figure E

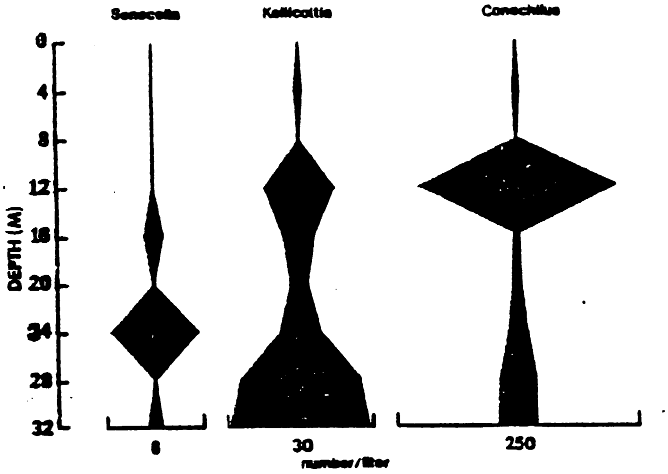


Figure F

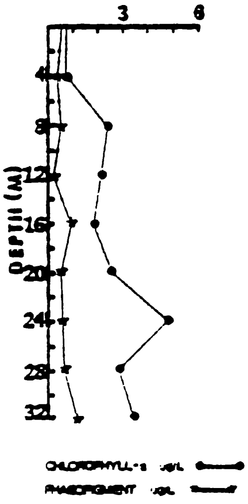
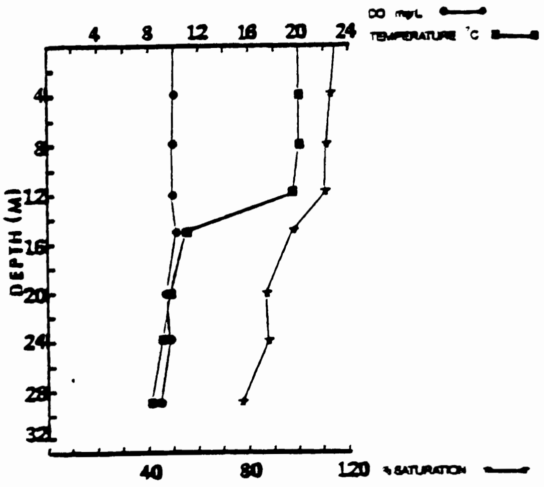


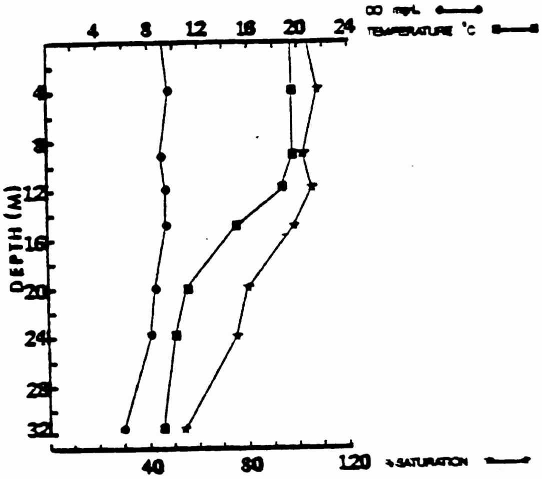
Figure 16. Zooplankton and phytoplankton depth profiles for Higgins Lake, Michigan.

Figure A



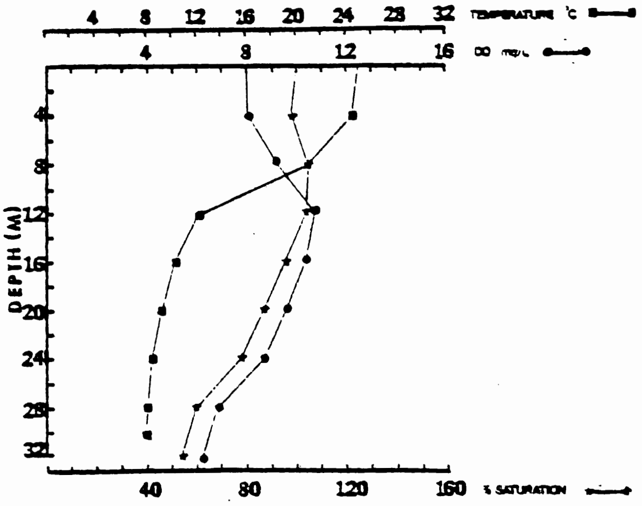
1974

Figure B



1977

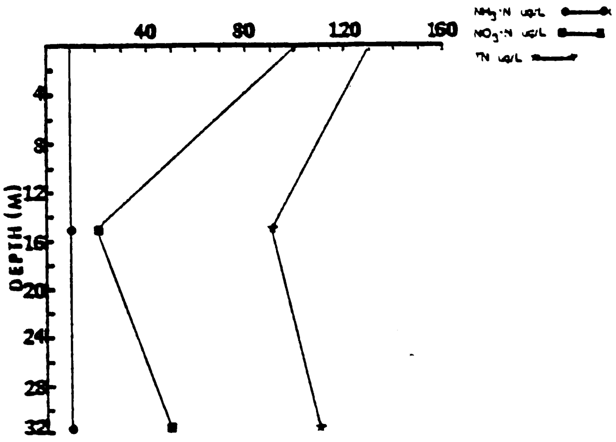
Figure C



1983

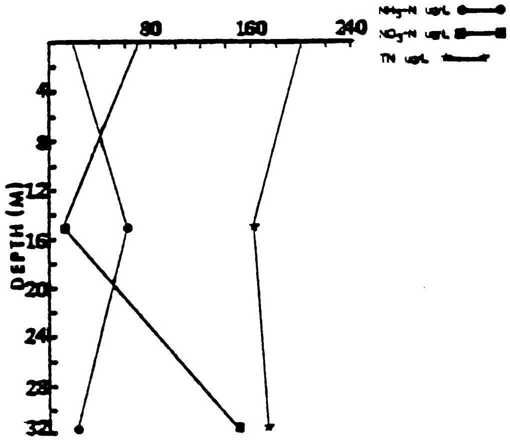
Figure 17. Temperature, dissolved oxygen, and per cent saturation depth profiles for Higgins Lake since 1974.

Figure A



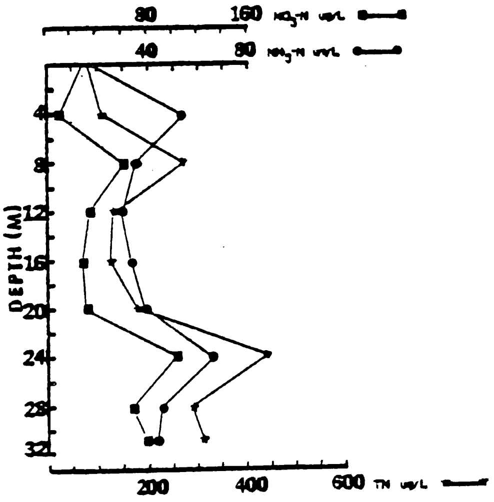
1974

Figure B



1977

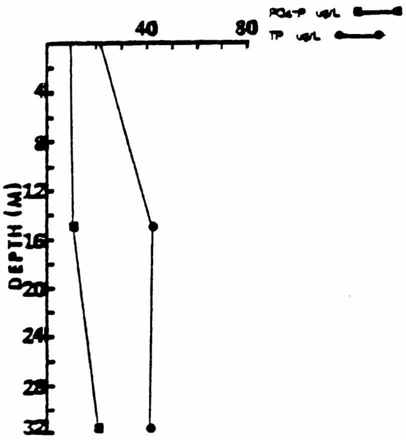
Figure C



1983

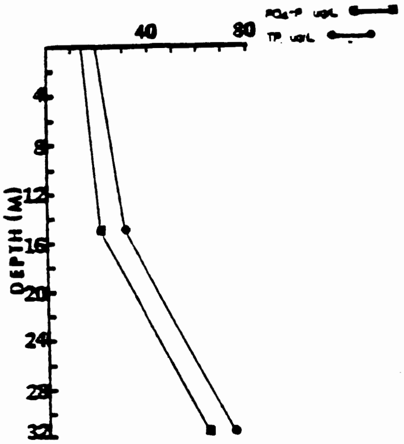
Figure 18. Ammonia, nitrate, and total nitrogen depth profiles for Higgins Lake since 1974.

Figure A



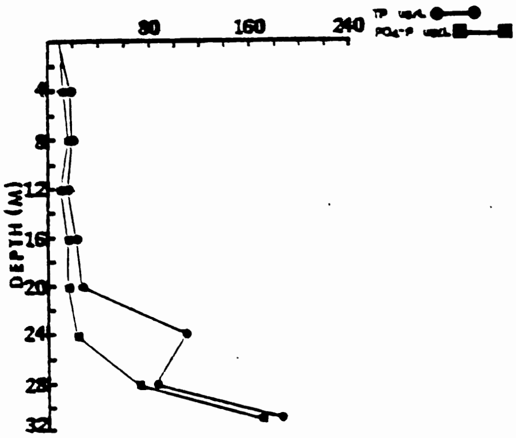
1974

Figure B



1977

Figure C



1983

Figure 19. Orthophosphate and total phosphorus depth profiles for Higgins Lake, Michigan since 1974.

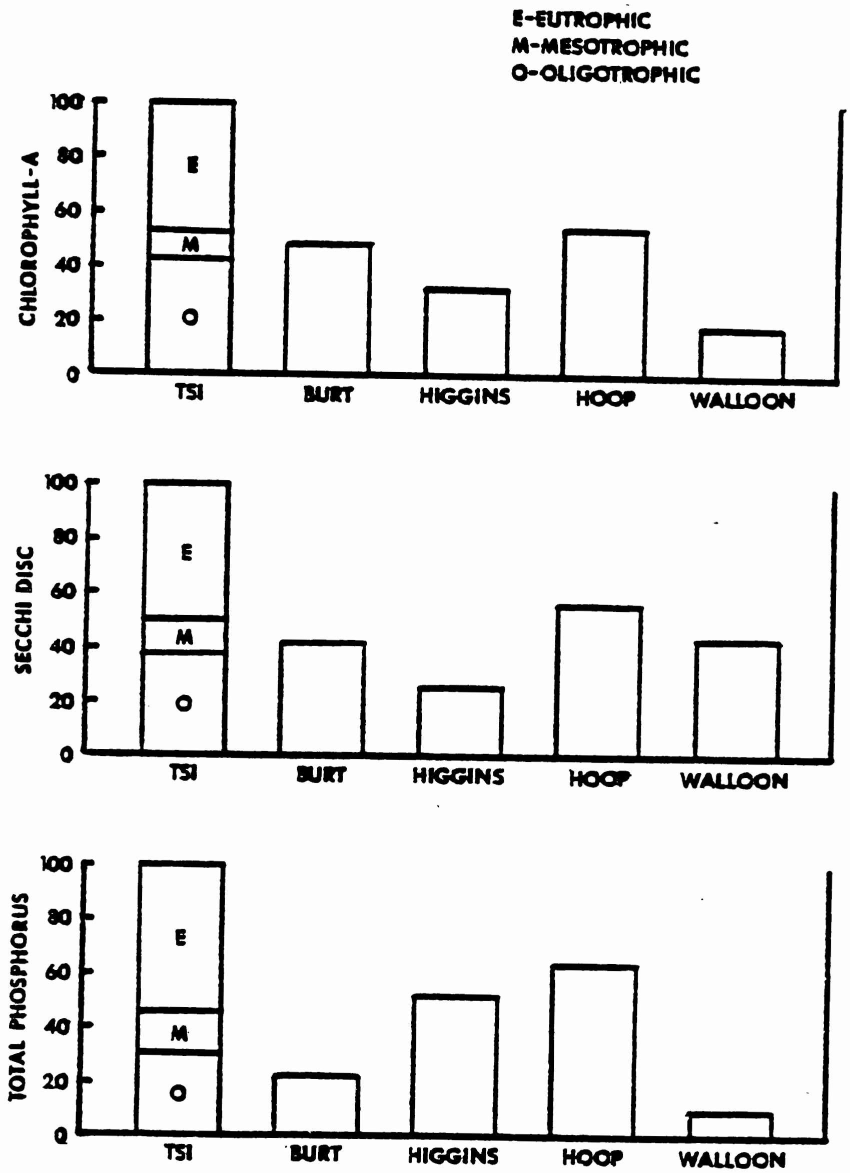


Figure 20. Predicted trophic status of Higgins Lake and several other Northern Michigan lakes based upon Carlson's index.

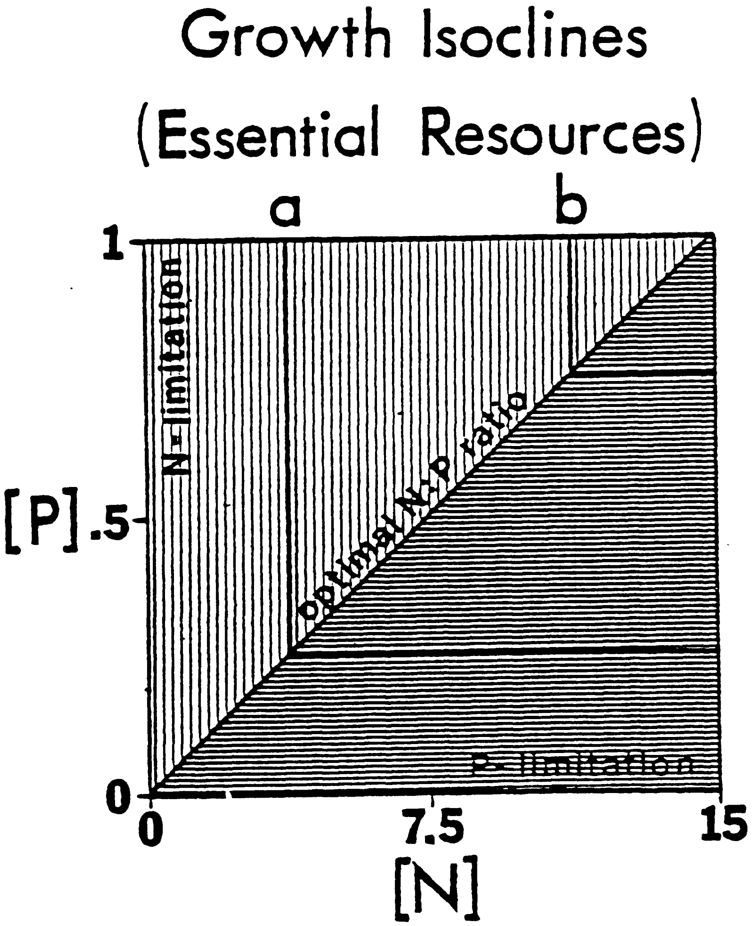


Figure 21. Growth isoclines associated with the nutrients nitrogen and phosphorus indicating optimal algal growth at a ratio of 15:1.

NORTH BASIN

Figure A

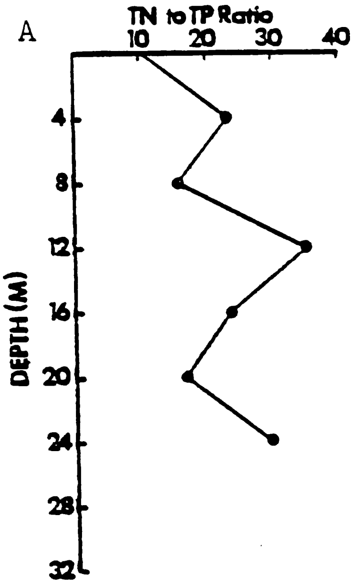
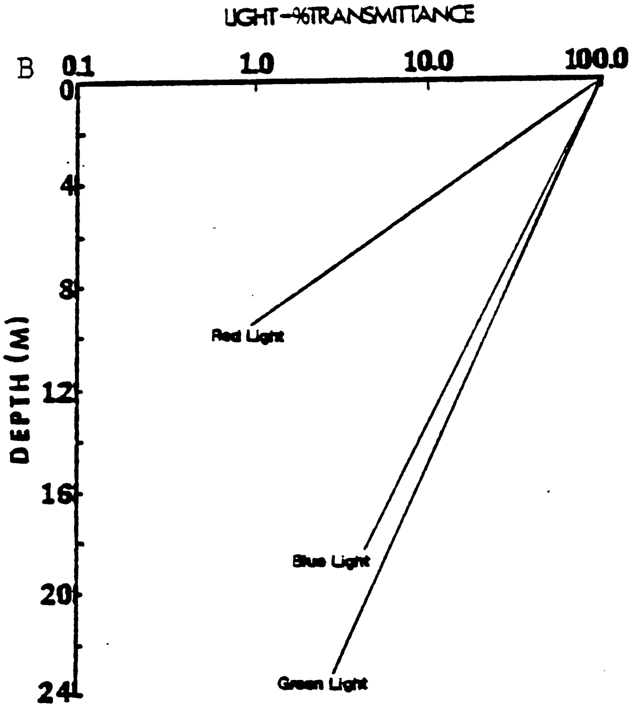


Figure B



SOUTH BASIN

Figure C

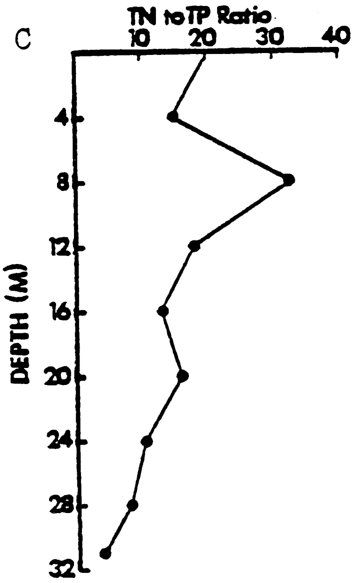


Figure D

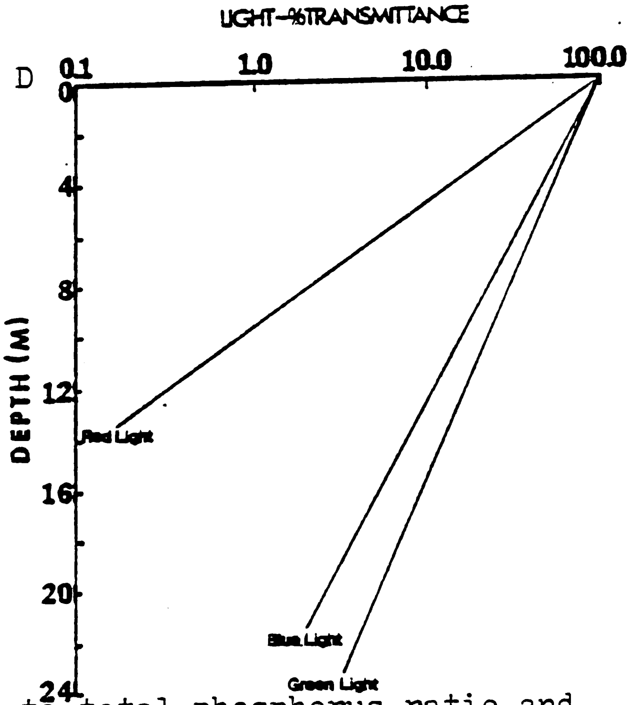
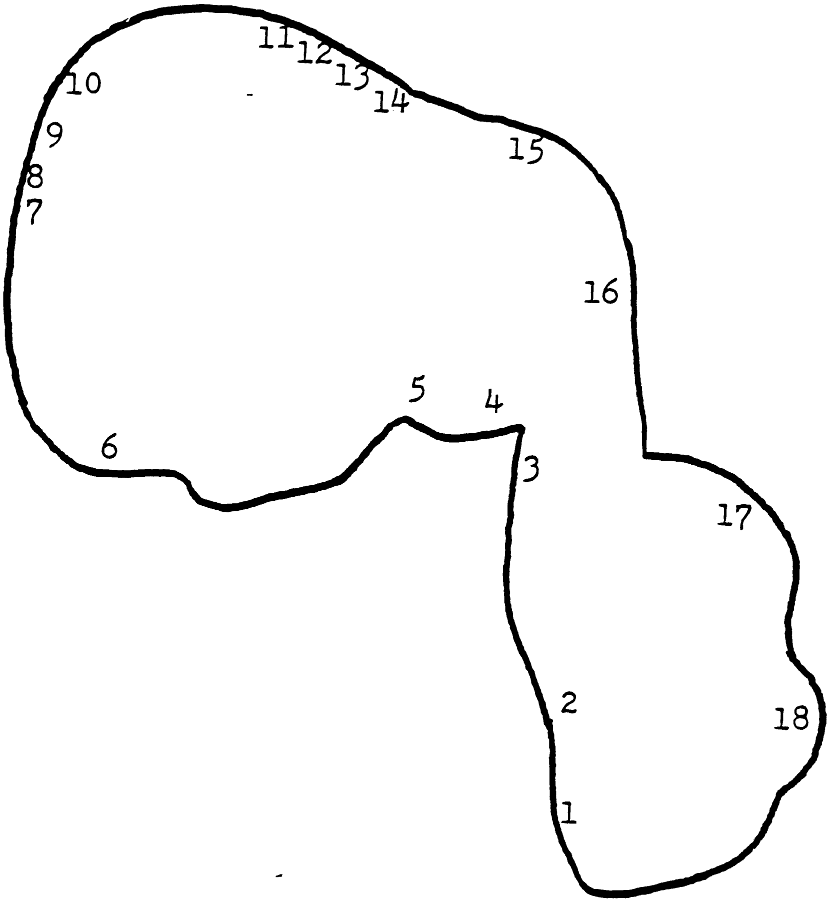


Figure 22. Total nitrogen to total phosphorus ratio and light penetration depth profiles for Higgins Lake, Michigan.



1-St. Louis
2-Minto Pointe
3-Maple
4-Lone Pine
5-Battin Marsh
6-West
7-Newman
8-Big Creek
9-Little Creek

10-Stuckey
11-Conference Center Crk.
12-Cedar
13-Lansing
14-Cottage Grove Assoc.
15-Henry
16-Hitchcock
17-Gallagher
18-2nd

Figure 23. An outline of Higgins Lake, Michigan indicating the location of the 18 nearshore sampling sites utilized for the study.

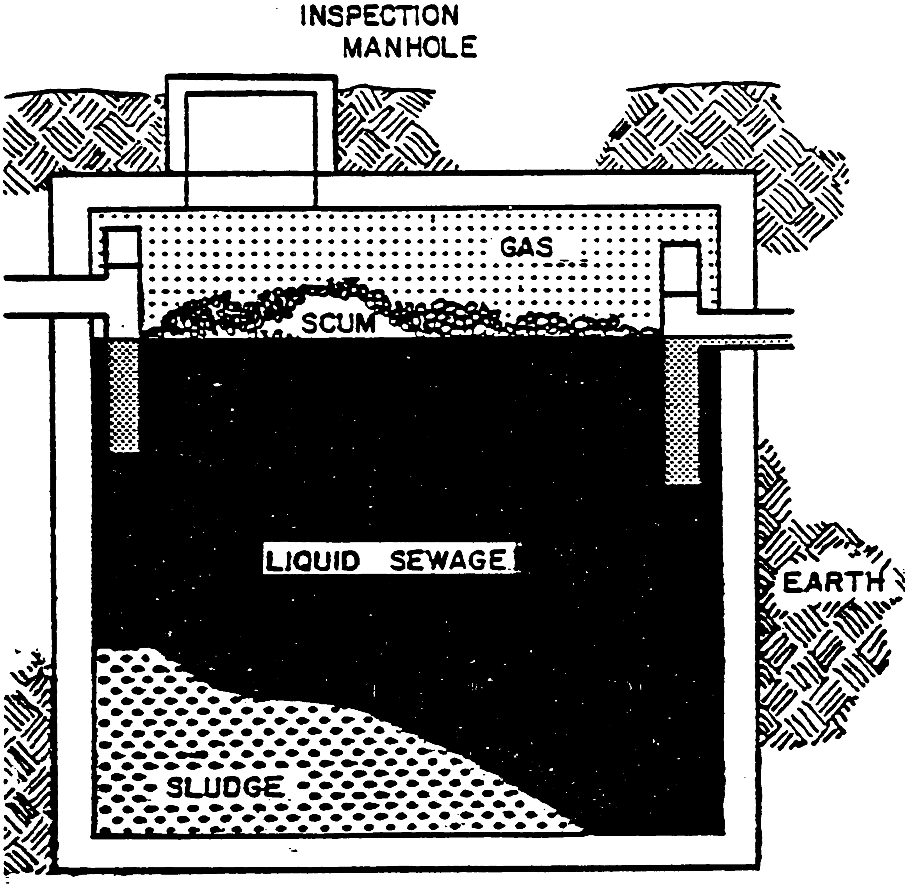


Figure 24. An example of a functioning septic system.

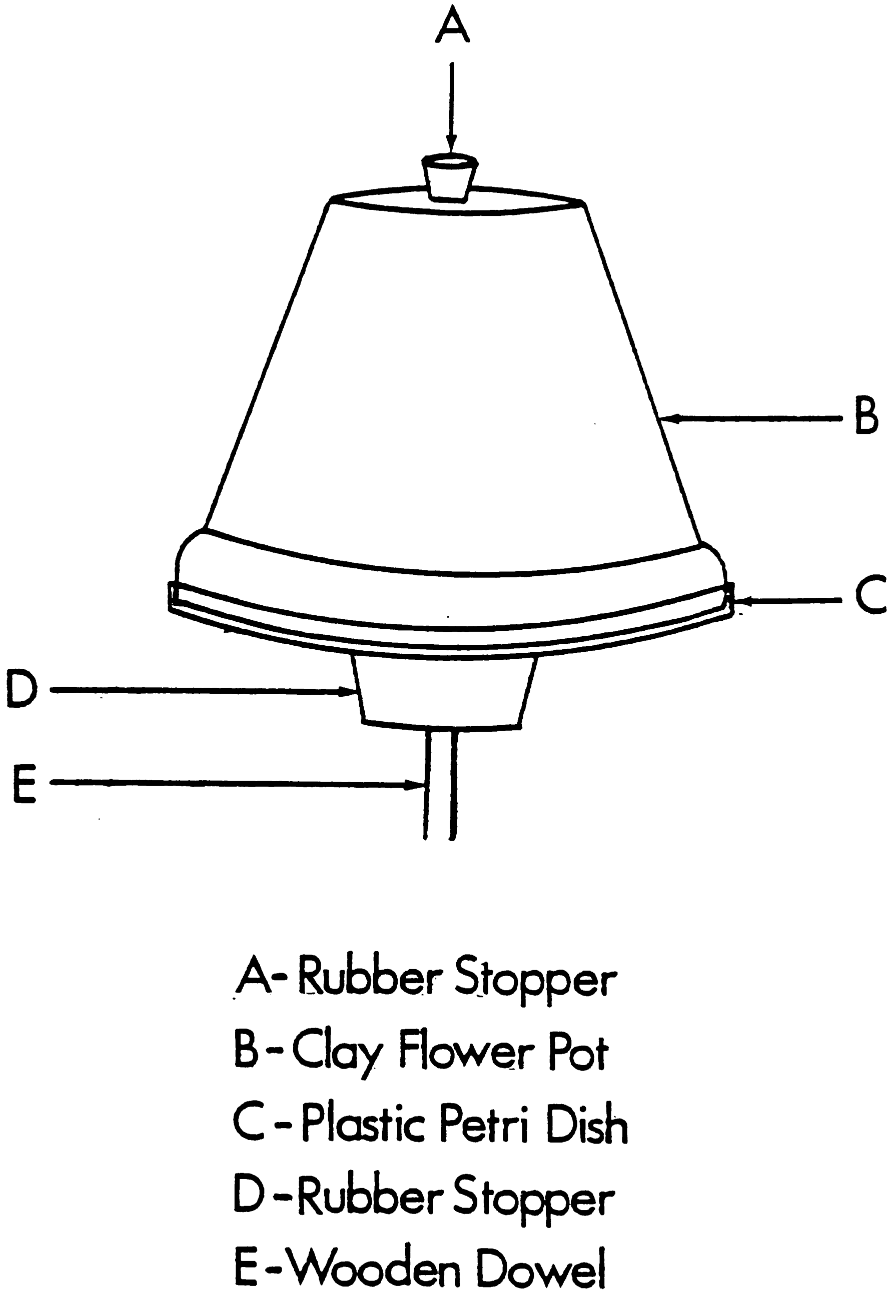


Figure 25. Artificial substrates used at 18 sites, including road ends, residential locations, and influent streams.

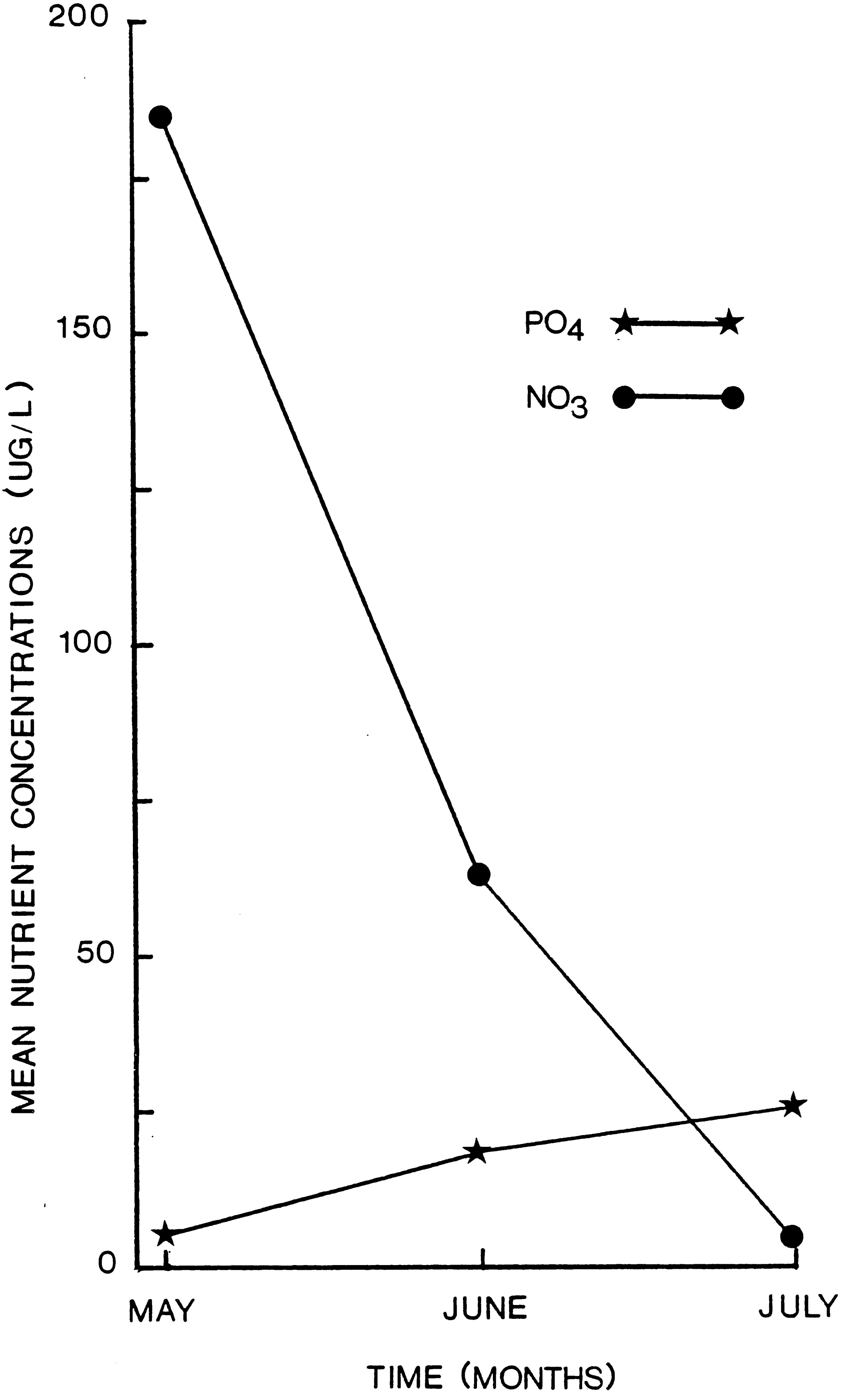
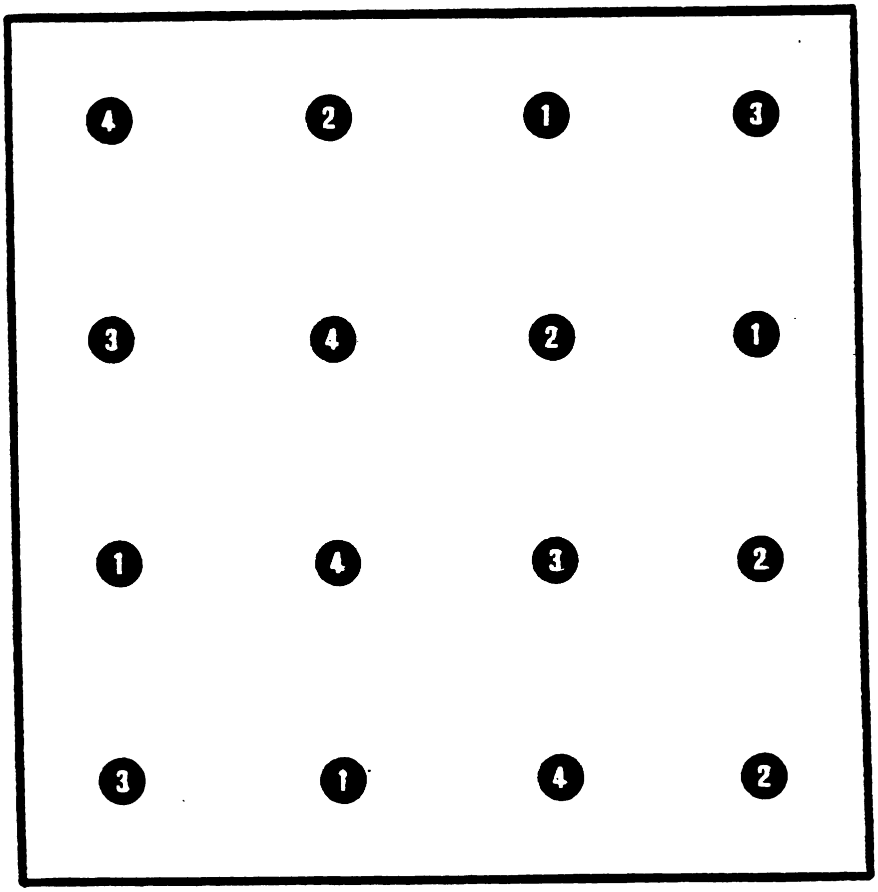


Figure 26. Changes in nearshore mean phosphate and nitrate concentrations during the Summer of 1983 in Higgins Lake, Michigan.



❹	❷	❶	❸
❸	❹	❷	❶
❶	❹	❸	❷
❸	❶	❹	❷

❶ - 0.05 PO_4
❷ - 0.5 NO_3
❸ - 0.05 PO_4 + 0.5 NO_3
❹ - LAKE WATER

Figure 27. Control grid pot placement utilized for the nearshore nutrient limitation study at the Cottage Grove Association location.

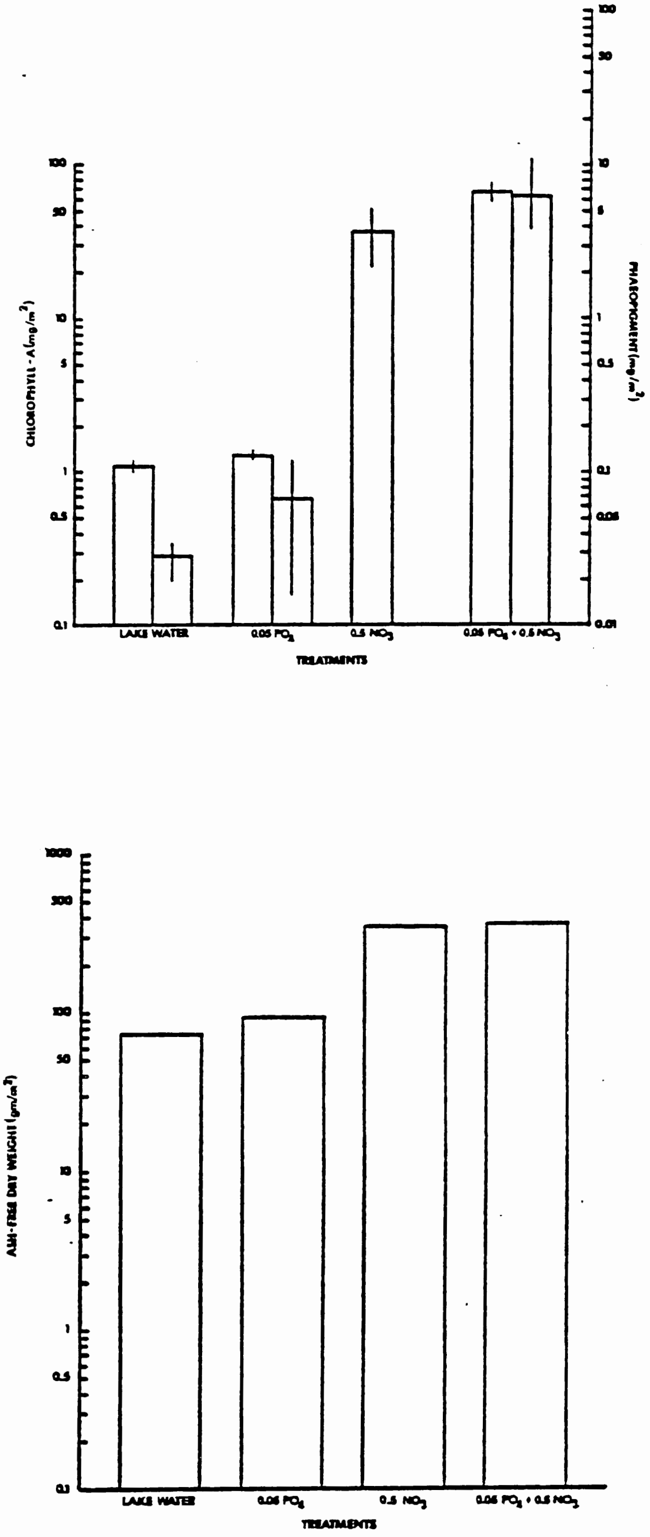


Fig. 28. Chlorophyll-a and ash-free dry weight of periphyton accumulations on Flower Pot Substrates, Cottage Grove Site.

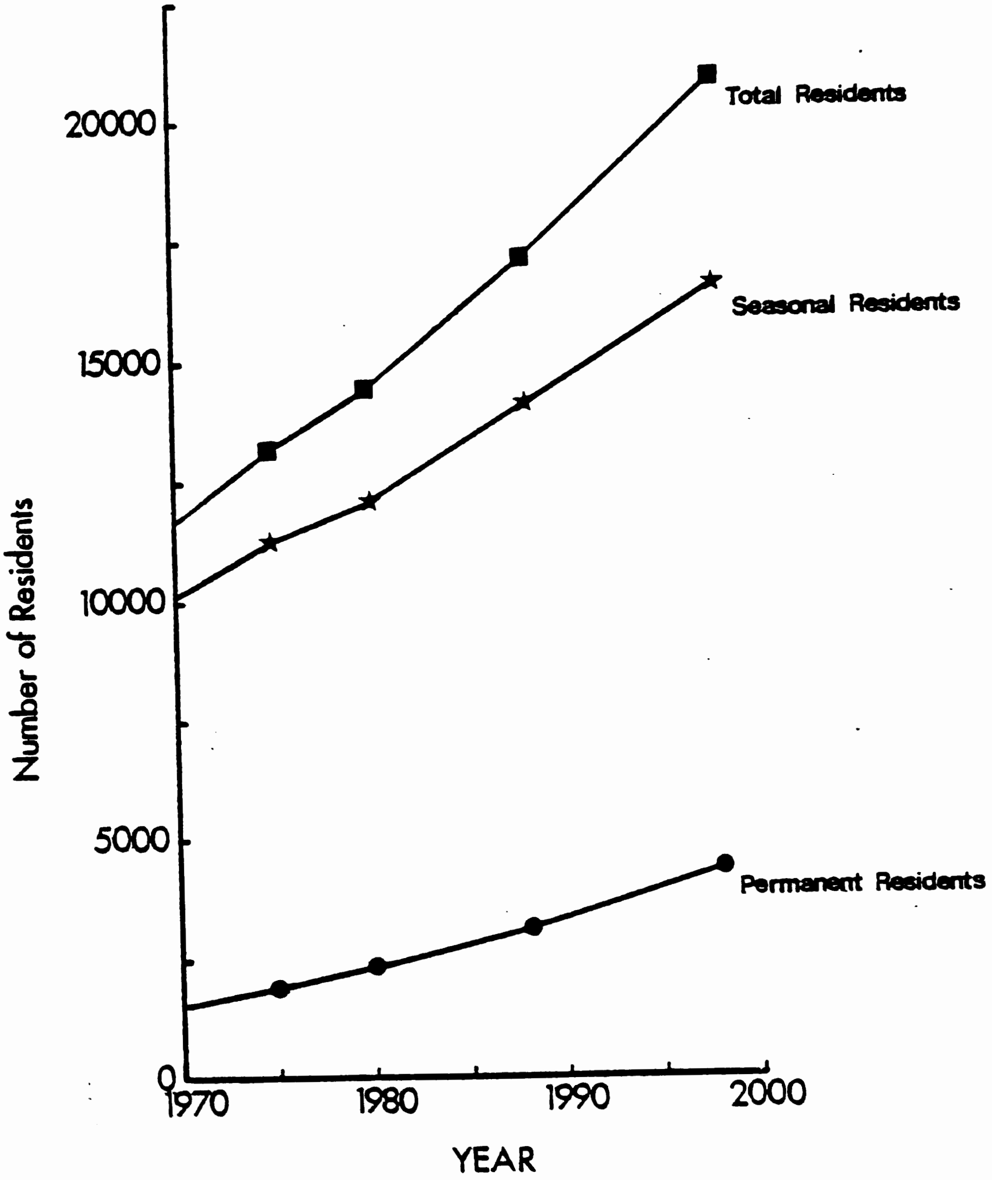


Figure 29. Past and projected population trends for the Higgins Lake, Michigan watershed.

APPENDIX A

Summary of Reckhow's (1980) Phosphorus Budget Model for Higgins Lake.

1) The model predicts ambient concentrations of phosphorus (P) as ug/l in the lake, based upon the mathematical formulation:

$$P \simeq L/(V_s+q_s)$$

where q_s is water loading (m/yr)
L is P-loading ($gm/m^2/yr$)
V_s is P settling velocity
$\simeq$ 11.6 m/yr

2) In order to calculate L, it is necessary to obtain estimates of areal dimensions of Forested, Agricultural, and Urban land within the watershed, and multiply these values by appropriate P-loading coefficients. For Higgins Lake these were:

Land Use Type	Area(ha)	"Most Likely" Export Coeff. (kg/ha/yr)	Total Yearly Loading (kg/yr)(%)
Agriculture	20	.40	8.0 (0.01%)
Forest	8354	.20	1671.2 (42.49%)
Urban	389	.90	350.7 (8.89%)

Phosphorus inputs via precipitation were estimated from rainfall valoume and concentration. Inputs from septic tanks assumed a P-loading value of o.6 kg/capita. An estimated 1447 residents in houses along the shoreline, expressed on a yearly basis, and a soil retention capacity of 25% were used in the computations:

Source	Input Calculations	Total Yearly Loading (kg/yr) (%)
Precipitation	(.30 kg/ha/yr)(4175 ha)	1253 (31.86%)
Septic Tanks	(.60 kg/capita/yr) (1447 capita/yr) (1 - .25)	651 (16.55%)
	TOTAL	3933 (100.00%)

3) The total phosphorus loading estimate, when divided by lake surface area, resulted in an areal loading estimate (L) of 0.97 $gm/m^2/yr$. This in turn allowed a prediction of 7.8 ug/l PO_4-P ambient concentration in the water column.

APPENDIX B

A SHORELINE SURVEY OF HIGGINS LAKE, MICHIGAN

The shoreline of Higgins Lake, Michigan was divided into a series of one mile segments and surveyed for the following:

1) Densities and locations of residences along the shoreline

2) Type of substrate(s)

3) Presence and relative abundance of <u>Cladophora</u>

4) Presence of marl

The maps in this appendix may be interpreted using the following information:

1) Densities and locations of residences along the shoreline are denoted as dots along the shoreline in the appendix.

2) Substrate types are denoted by the following symbols:

   Sand ● ● ●

   Gravel (0-5 cm) ■ ■ ■

   Cobble (5-20 cm) ★ ★ ★

   Rocks (greater than 20 cm) ▲ ▲ ▲

3) Presence and abundance of <u>Cladophora</u> is denoted by the following symbols:

   I (Slight growth on few rocks) △ △ △

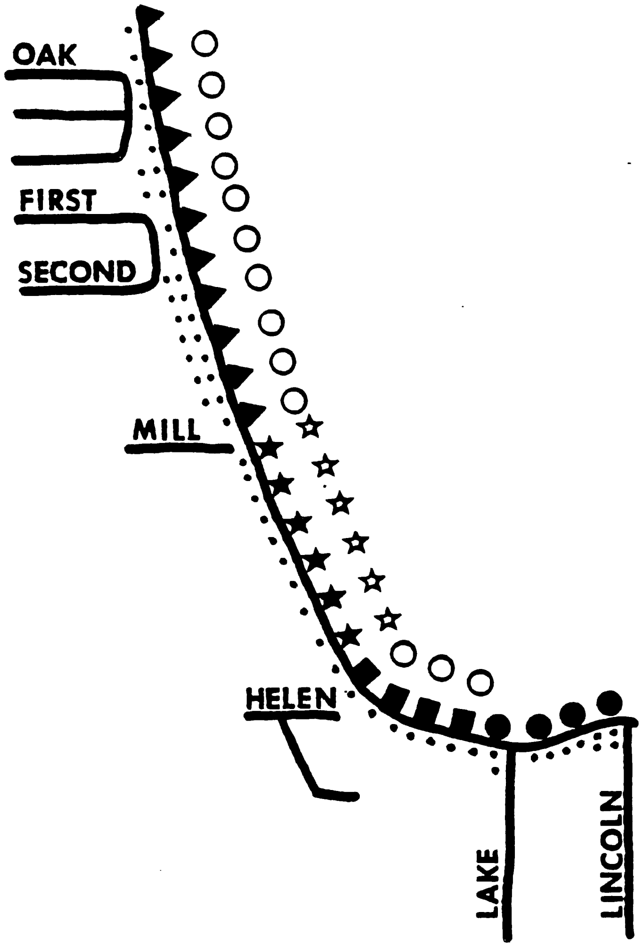
   II (Slight growth on many rocks) □ □ □

   III (Nonfilamentous green bands) ○ ○ ○

   IV (Filamentous green bands) ☆ ☆ ☆

4) The presence of marl is noted in the Comments section for each segment.

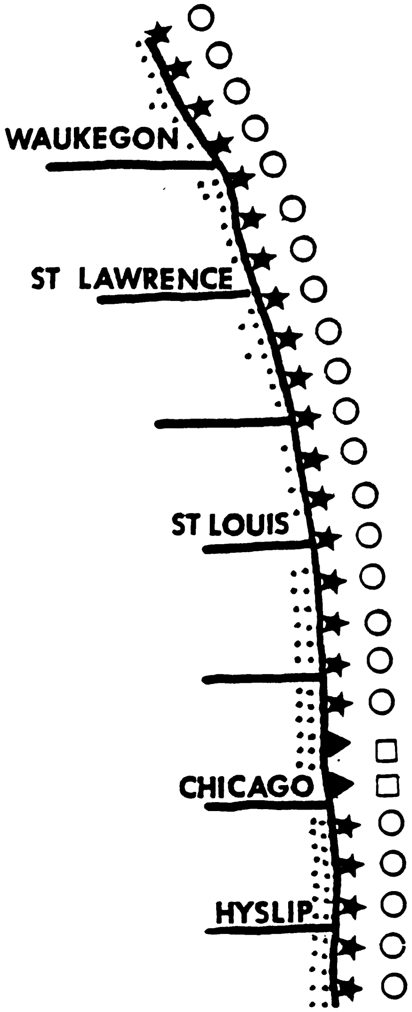
Also noted in the Comments section for each segment are study sites utilized, presence and general location of surface water inflows, and the presence of detritus.



MILE NUMBER 1

COMMENTS

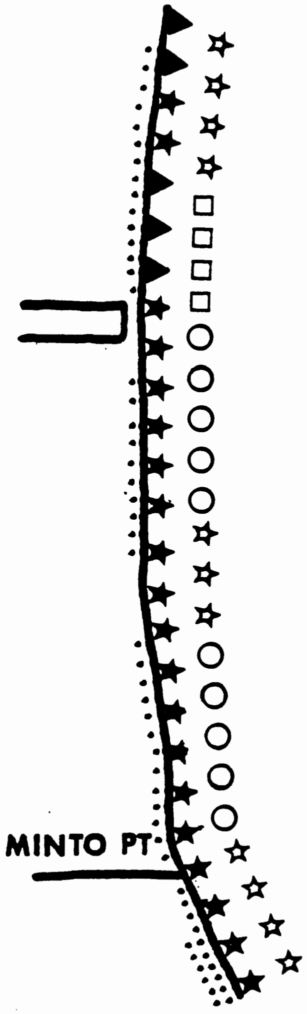
1) Much floating dead <u>Cladophora</u> between Lincoln and Helen Avenues.
2) Heavy marl deposits between Helen and Dunlop Avenues.



MILE NUMBER 2

COMMENTS

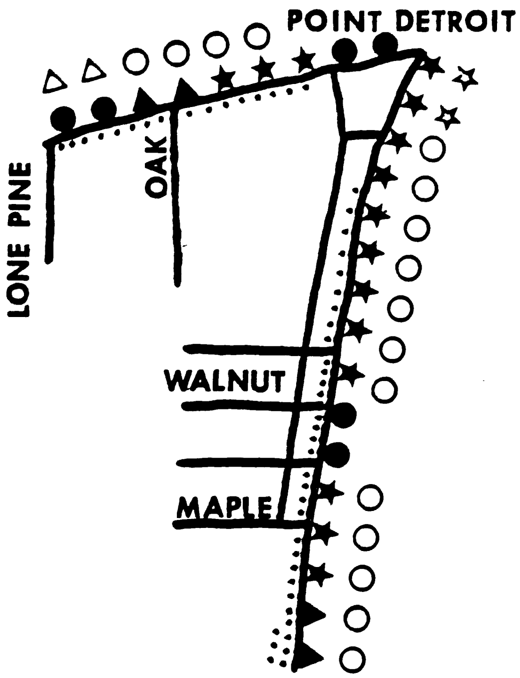
1) Some floating dead <u>Cladophora</u> between St. Louis and Waukegon Avenues.
2) Heavy marl deposits between Washington and Waukegon Avenues.
3) Septic tank site - St. Louis Avenue



MILE NUMBER 3

COMMENTS

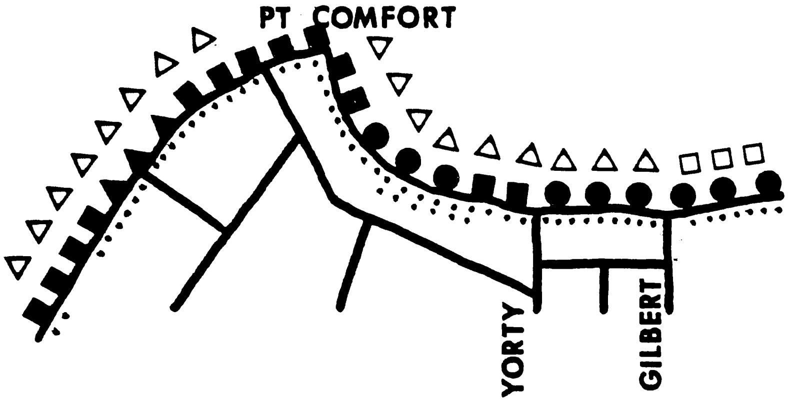
1) Intermediate marl deposits throughout entire segment.
2) Road end site - Minto Pt. Road



MILE NUMBER 4

COMMENTS

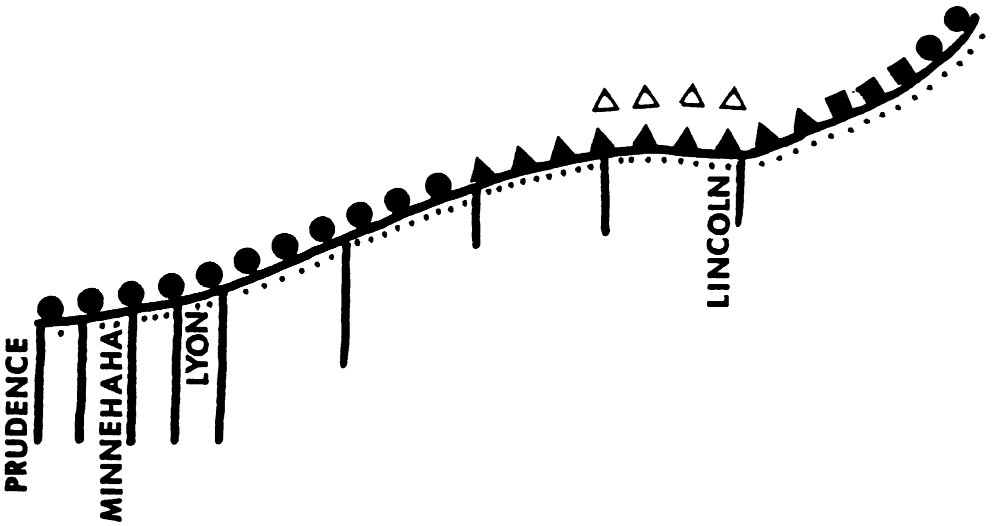
1) Heavy marl deposits between Maple Avenue and Pt. Detroit.
2) Road end site - Maple Avenue
3) Road end site - Lone Pine Avenue



MILE NUMBER 5

COMMENTS

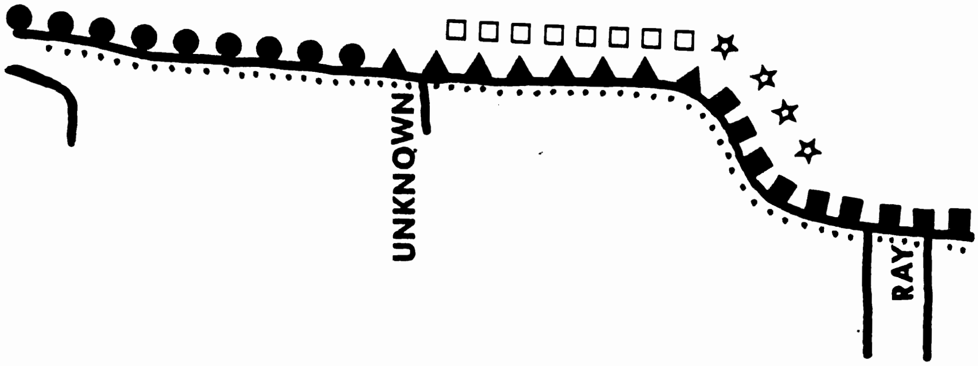
1) Surface water inflow site - Battin Drain
2) Water greatly discolored near Battin Drain



MILE NUMBER 6

COMMENTS

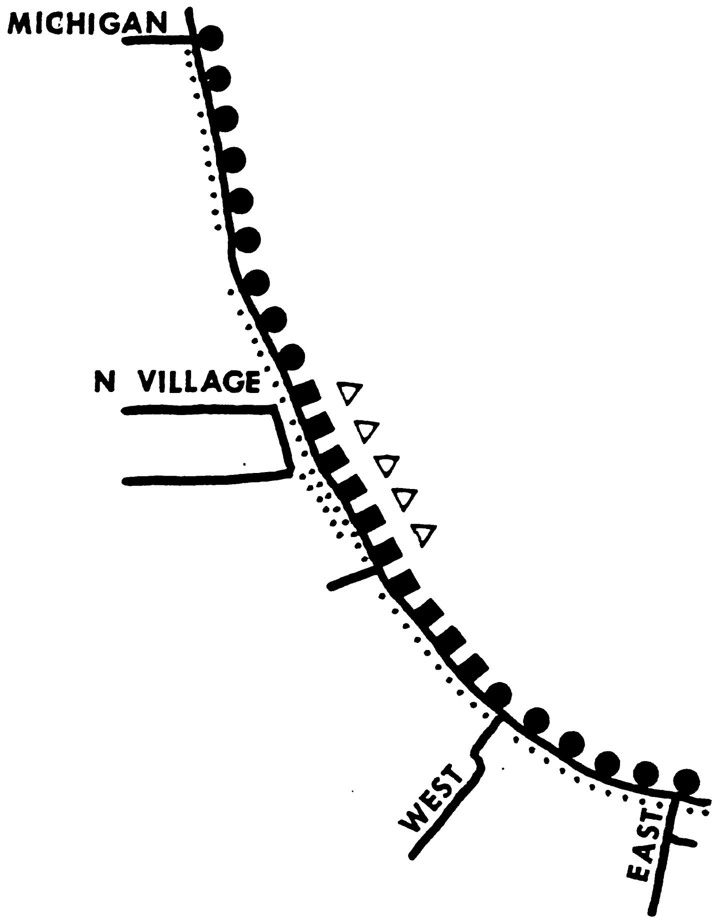
1) Heavy shoreline erosion from wave action throughout entire segment.



MILE NUMBER 7

COMMENTS

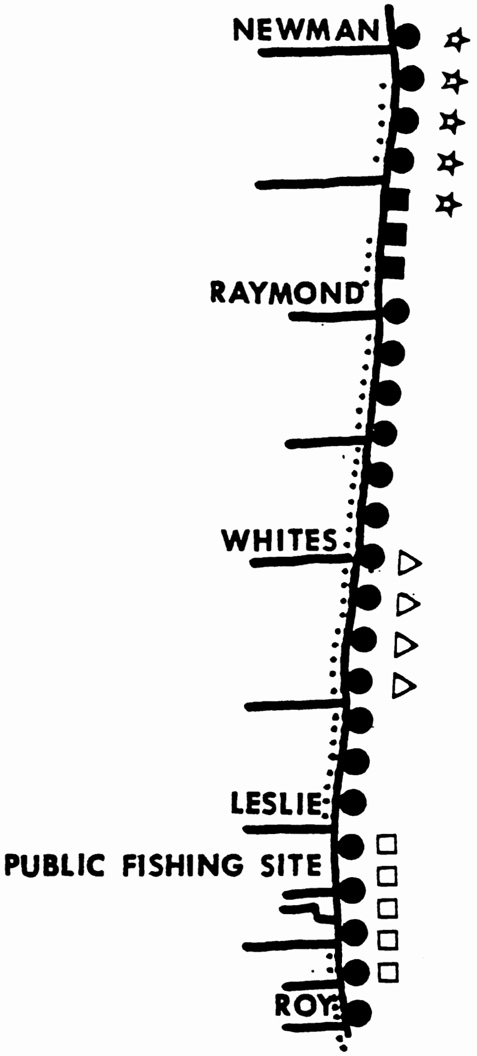
1) Light marl deposits throughout entire segment.



MILE NUMBER 8

COMMENTS

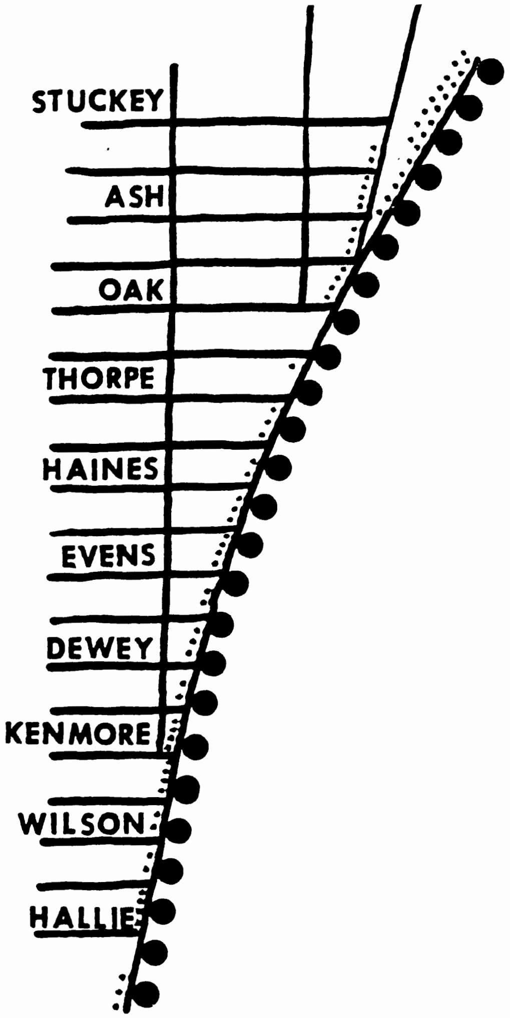
1) Light marl deposits throughout entire segment.
2) Heavy shoreline detritus band between Tie and Michigan Avenues.
3) Road end site - West Avenue



MILE NUMBER 9

COMMENTS

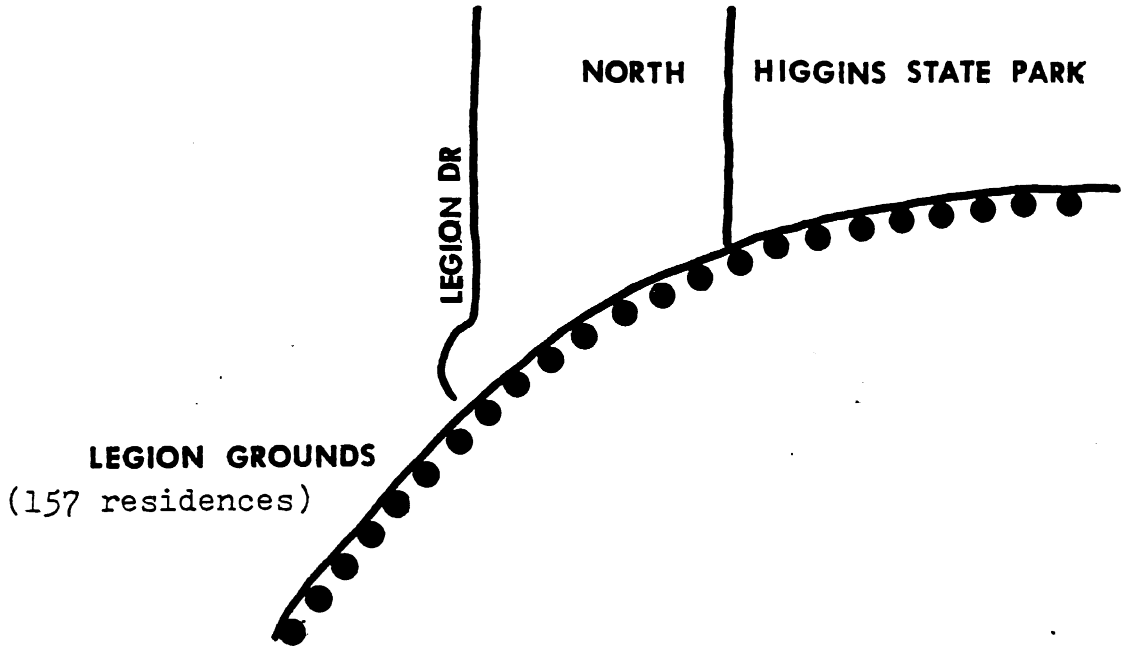
1) Many heavily wooded lots throughout segment.
2) Heavy shoreline detritus band throughout segment.
3) Intermediate marl deposits throughout segment.
4) Road end site - Newman Avenue



MILE NUMBER 10

COMMENTS

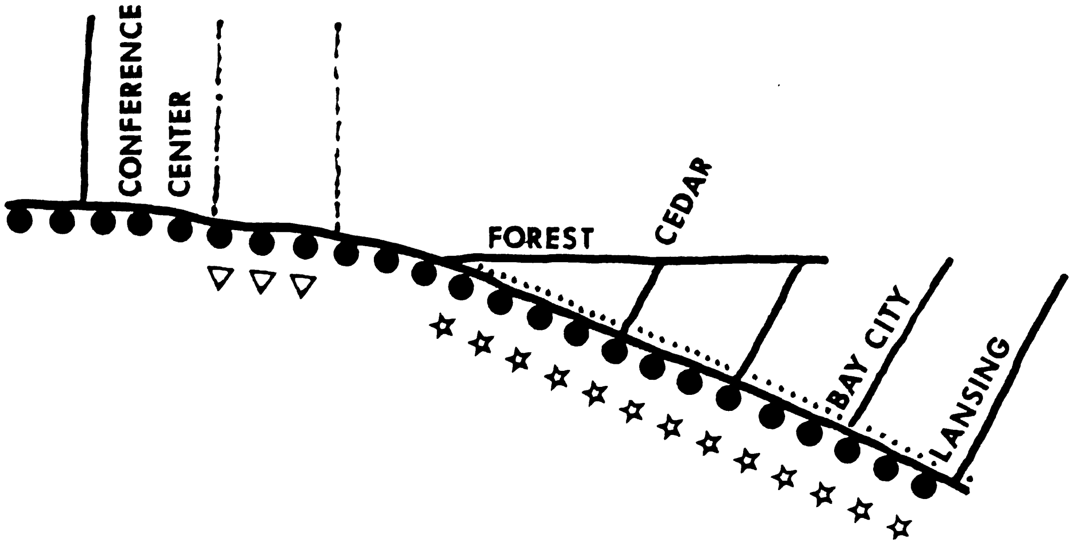
1) Light shoreline band of detritus throughout segment.
2) Septic tank site - Stuckey Avenue
3) Surface water inflow sites - Big and Little Creeks



MILE NUMBER 11

COMMENTS

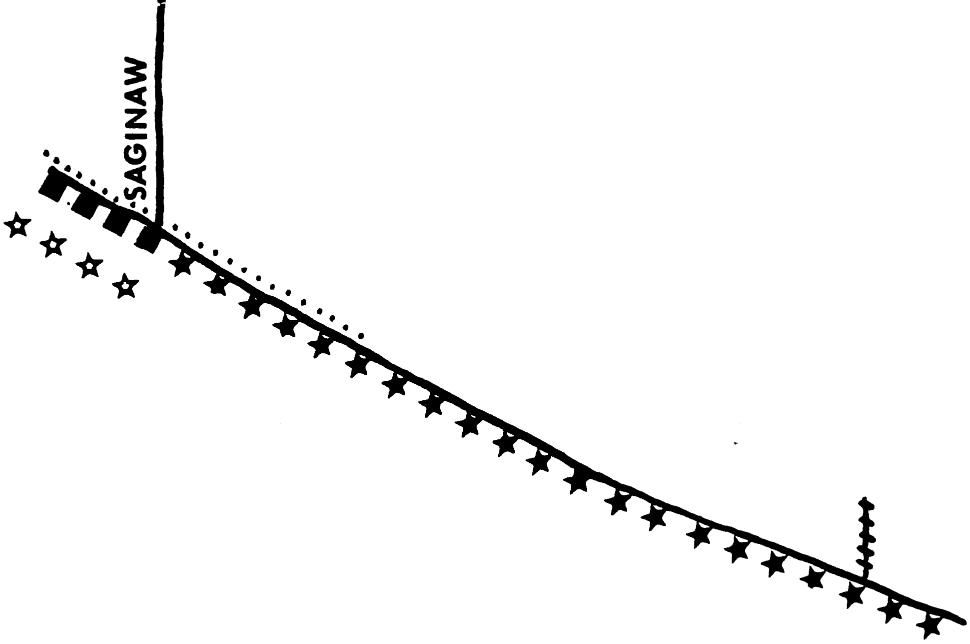
1) Light detritus band throughout entire segment.
2) Eight surface water outflows located along segment.



MILE NUMBER 12

COMMENTS

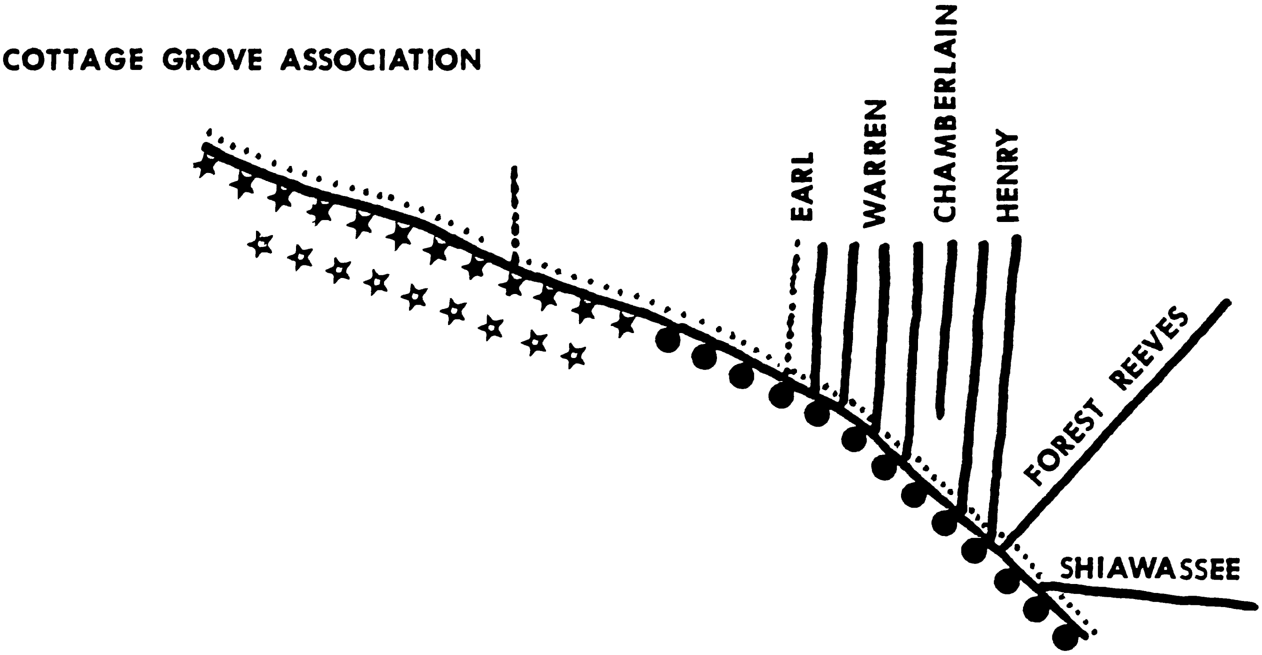
1) Intermediate marl deposits throughout entire segment.
2) Light detritus band throughout entire segment.
3) Surface water inflow site - Conference Center Creek
4) Septic tank site - Cedar Avenue
5) Road end site - Lansing Avenue



MILE NUMBER 13

COMMENTS

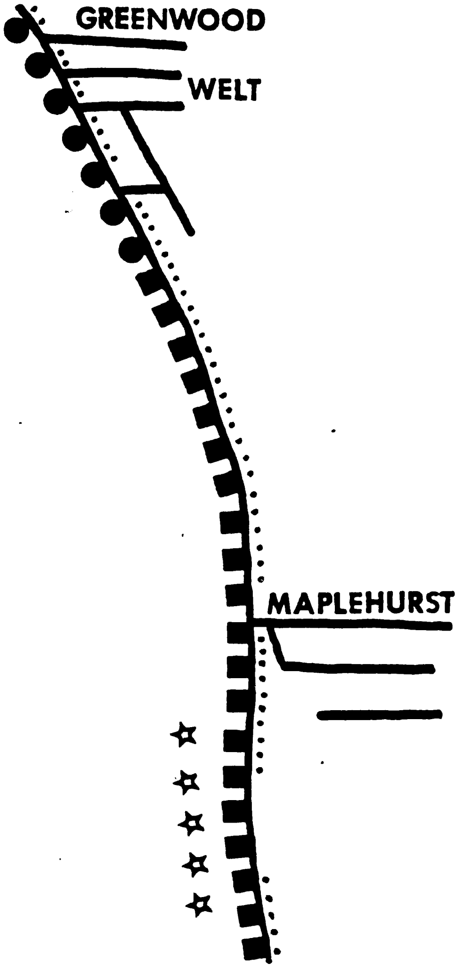
1) Heavy marl deposits throughout entire segment.
2) Heavily wooded area.
3) Shoreline area has extremely steep grade.



MILE NUMBER 14

COMMENTS

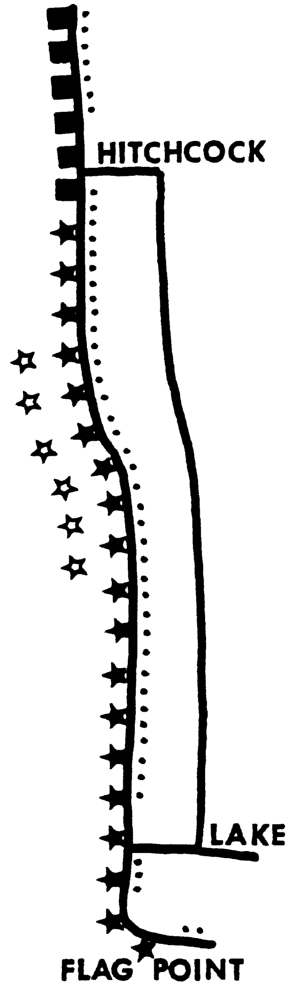
1) Heavy marl deposits throughout entire segment.
2) Control site - Cottage Grove Association
3) Septic tank site - Henry Avenue



MILE NUMBER 15

COMMENTS

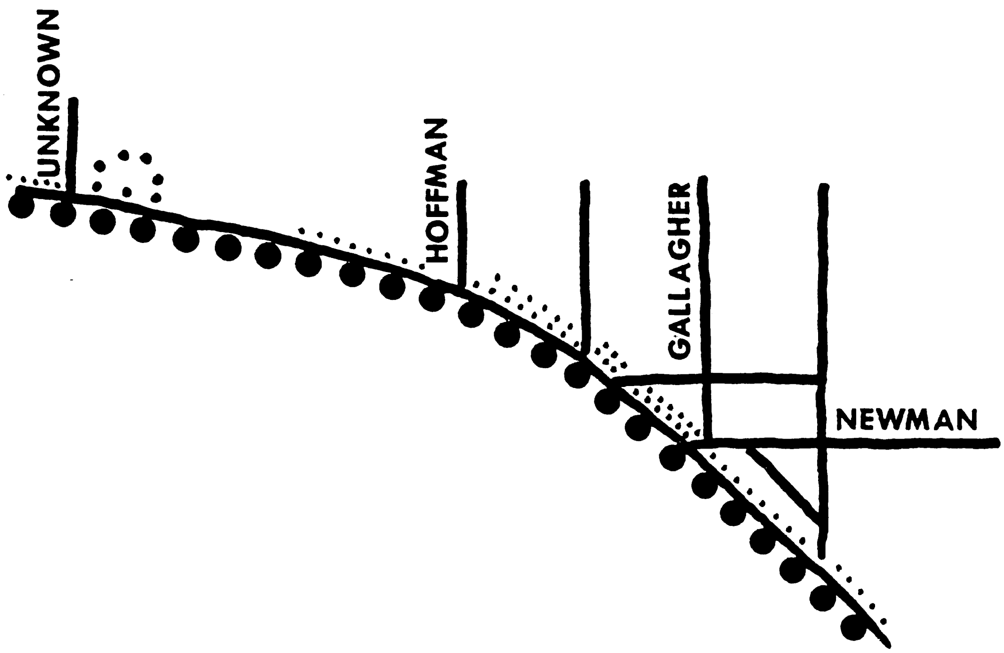
1) Light detritus band throughout entire segment.



MILE NUMBER 16

COMMENTS

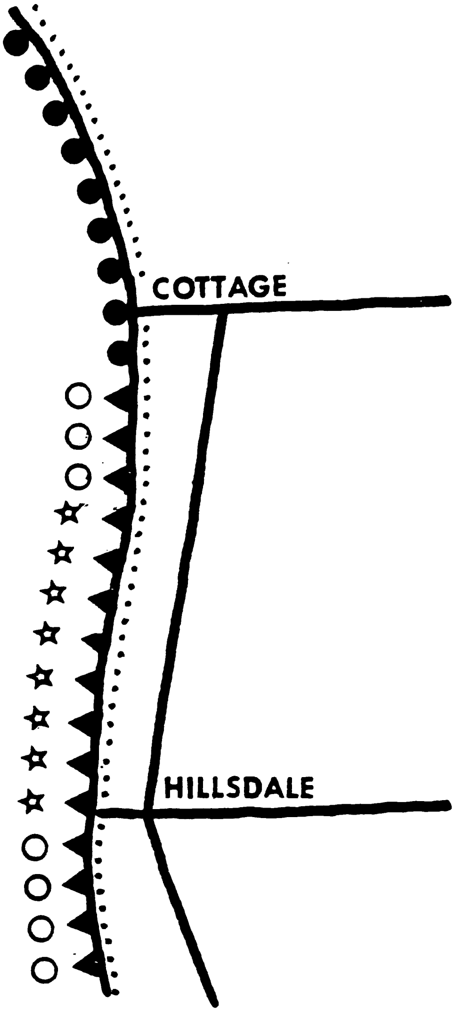
1) Light detritus band near Flag Point.
2) Road end site - Hitchcock Avenue



MILE NUMBER 17

COMMENTS

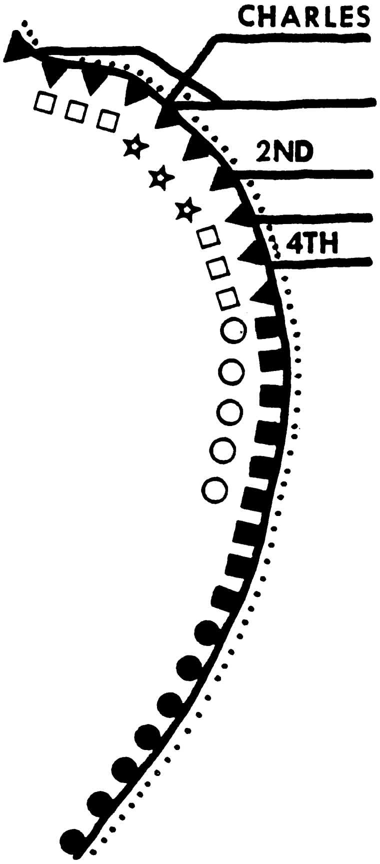
1) Large condominium near northwest end of segment.
2) Septic tank site - Gallagher Avenue



MILE NUMBER 18

COMMENTS

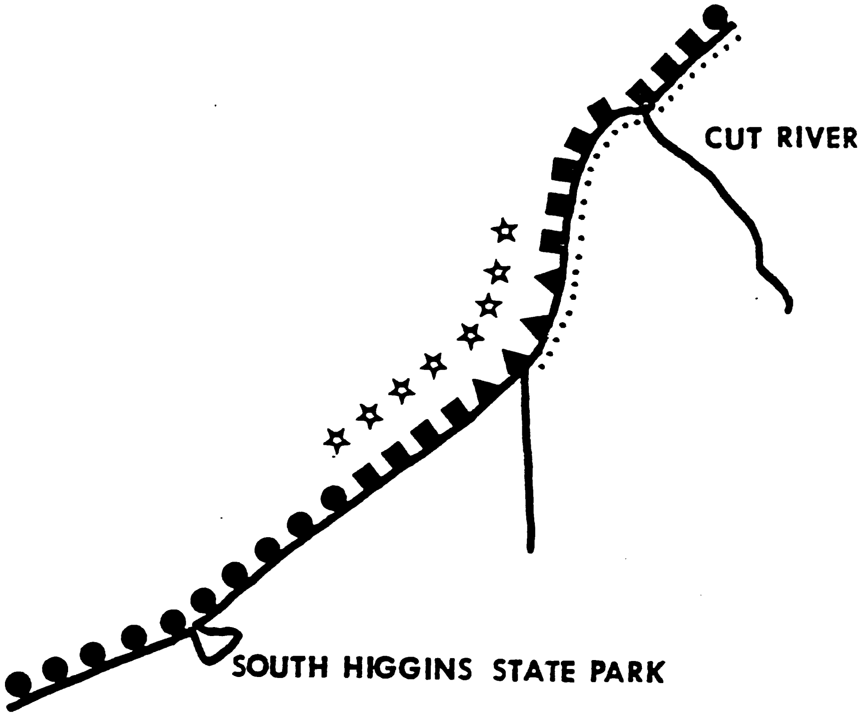
1) Light detritus band throughout entire segment.
2) Intermediate marl deposits throughout entire segment.



MILE NUMBER 19

COMMENTS

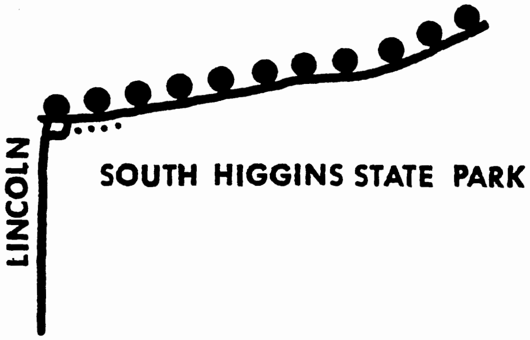
1) Heavy marl deposits throughout entire segment.
2) Septic tank site - 2nd Avenue



MILE NUMBER 20

COMMENTS

1) Heavy marl deposits throughout entire segment.



MILE NUMBER 21

COMMENTS

1) Light marl deposits throughout entire segment.

VEGETATION OF SOUTH MANITOU ISLAND,
Leelanau Co., Michigan

by
BRIAN T. HAZLETT
University of Michigan Biological Station
1983

1. NORTHERN HARDWOODS
    - a. Beech-Maple
    - b. Beech-Maple-Yellow Birch-Hemlock
    - c. Beech-Maple-Oak
    - d. Beech-Maple-Ash
    - e. Maple-Ash-Basswood

2. NORTHERN CONIFERS

3. COASTAL FOREST
    - a. Mixed Pines
        - 1) coniferous
        - 2) coniferous/deciduous
    - b. Cedar-Fir-Aspen
    - c. Hemlock-Hardwoods

4. DUNES AND SHORES

5. BLUFFS

6. FIELDS
    - a. Dense Juniper
    - b. Medium Juniper
    - c. Low Juniper
    - d. Past Juniper

7. WETLANDS

8. LAKE FLORENCE

9. SOUTH MANITOU VILLAGE

10. VALLEY OF THE GIANTS

==== roads
---- trails
♣ orchards

0 1
Miles

THE VEGETATION OF NORTH MANITOU ISLAND
Leelanau Co., Michigan

by
BRIAN T. HAZLETT
University of Michigan Biological Station
1983

1. NORTHERN HARDWOODS
    - a. Beech-Maple-Yellow Birch-Cherry
    - b. Beech
    - c. Maple
    - d. Beech-Maple
    - e. Beech-Maple-Aspen
    - f. Beech-Maple-Yellow Birch-Cherry-Aspen-Ash
    - g. Beech-Maple-Yellow Birch-Cherry-Ash-Basswood
    - h. Oak
    - i. Cut areas

2. NORTHERN CONIFERS

3. LAKE PLAIN WOODS

4. FIELDS

5. DUNES AND SHORES

6. BLUFFS

7. BLACK ASH SWAMPS

8. WETLANDS

9. LAKES
    - a. Lake Manitou
    - b. Tamarack Lake

=== roads
--- trails
♣ orchards

0 1
Miles