Limnological Features of Some Northwestern Iowa Lakes[1]

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Quantitative information on the morphology, watershed characteristics, water transparency, water chemistry and algal crops of six Iowa lakes is summarized. Lake West Okoboji had less oxygen present in the hypolimnion in 1950-1973 than in 1919-1928, indicating an increase in eutrophication. On the basis of increasing plant-nutrient concentrations, increasing summer algal standing crops and decreasing water transparency, the lakes can be ranked thus: Lake West Okoboji, Big Spirit Lake, Lake East Okoboji (including Upper Gar and Minnewashta) and Lower Gar Lake. These differences among lakes are related to the ratio of watershed area to lake volume, which controls the impact of annual nutrient inputs from the watersheds.
INDEX DESCRIPTORS: Iowa Lakes, Eutrophication, Water Quality, Limnology.

A water quality study of the Okoboji lakes was conducted from March, 1971, through August, 1973, to document present limnological conditions in each lake and the reasons for the differences in the degree of eutrophication among lakes. Indicators of recent trophic change also were noted.

The lakes are located in northwestern Iowa (Dickinson County), with a portion of the watershed extending into southwestern Minnesota (Jackson County) (Figure 1). The lakes are of glacial origin and are enclosed by morainal topography (Thomas, 1913; Carman, 1915; Tilton, 1916). Radiocarbon dating of lake sediments indicated a late Cary or postglacial age for the basin (Dodd et al., 1968).

Seven major lakes lie within the watershed; they are West Okoboji, Spirit, East Okoboji, Upper Gar, Minnewashta and Lower Gar in Iowa, and Loon in Minnesota. The entire watershed can be subdivided into separate drainage areas for each major lake (Figure 1). The lakes are interconnected, and drainage is southerly from Minnesota to Spirit Lake and over a spillway to Lake East Okoboji. Lakes East Okoboji, West Okoboji, Upper Gar, Minnewashta and Lower Gar have the same water level. The outflow for this drainage system is an ungated spillway on Lower Gar Lake, through which drainage passes to the Missouri River via the Little Sioux River. The region is served by a modern sewage collection and treatment system, which diverts human wastes out of the watershed.

These lakes are eutrophic to various degrees as indicated by the severity of the summer blue-green algal blooms occurring in each lake. Nuisance phytoplankton conditions develop each summer in lakes East Okoboji, Minnewashta, and Upper and Lower Gar. Conditions in Spirit Lake are less severe, depending upon the year, and Lake West Okoboji has localized algal problems of short duration.

The differences in the degree of eutrophication among these lakes are surprising within a lake region with a common watershed having relatively uniform land-use practices (Table 1). Most of the land within the region is devoted to row-crop agriculture or livestock production; nearly 20% of the watershed is covered by ponds, lakes or marshes.

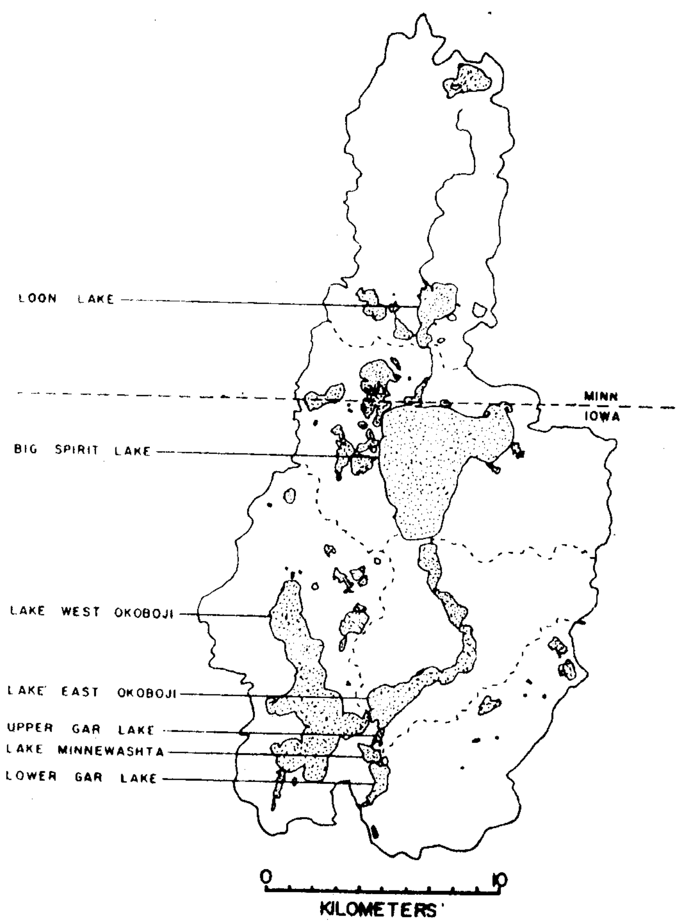

Figure 1. Map of the watershed. Dashed lines indicate watershed boundaries.

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TABLE 1. BREAKDOWN OF LAND-USE PRACTICES WITHIN INDIVIDUAL LAKE WATERSHEDS AS A PERCENTAGE OF WATERSHED AREA (MAJOR LAKE EXCLUDED)

	West Okoboji	*East Okoboji*	*Big Spirit*	*Lower Gar*
Row Crops	65	74	76	79
Pasture and Grassland	18	13	9	11
Urban (Includes Summer Homes)	11	10	2	1
Marsh	2	1	3	7
Permanent Water	4	–	9	2
Woodland	–	2	1	–

METHODS AND MATERIALS

The watershed area and individual lake watersheds were delineated from U.S.G.S. topographic maps (7.5-minute series).

The following chemical analyses were made on unfiltered lake samples taken within the upper 0.5 m. Ammonia nitrogen concentration was determined by using the direct Nesselerization method. Nitrate nitrogen concentration was determined by using the cadmium reduction method. Prepared reagents for these analyses were purchased from Hach Chemical Co., Ames, Iowa. Total phosphorus was determined by using the procedures of Murphy and Riley (1962) with a persulfate oxidation described by Menzel and Corwin (1965). An Industrial Instruments Conductivity Bridge, Model RC 16B1, was used to measure specific conductance in micromhos/cm at 25 C. Chemical oxygen demand was measured in lake samples by using the dichromate oxidation method (A.P.H.A., 1965), with a one-hour reflux time and 0.025N potassium dichromate and 0.01N ferrous sulfate.

Dissolved oxygen samples were collected and processed by standard procedures (A.P.H.A., 1965). The samples were titrated with 0.025N phenylarsine oxide. Total alkalinity was determined by use of brom cresol green-methyl red indicator and titrating with 0.02N sulfuric acid.

Water transparency was determined by using a 20-cm Secchi disk.

A measured volume of lake water was filtered through a Type A Gelman glass fiber filter for chlorophyll *a* analysis. Chlorophyll concentration was determined by use of the methods of Richards and Thompson (1952) and Yentsch and Menzel (1963). Values were calculated from the equations of Parsons and Strickland (1963).

RESULTS

Morphological and Hydrological Features

Morphological and hydrological characteristics of the lakes are given in Table 2. Lake West Okoboji is the deepest lake and the only one with thermal stratification. Because of its large volume and small watershed, it has the lowest ratio of watershed area to lake volume (m^2/m^3) and longest hydrologic turnover time. The Spirit Lake basin is saucer-shaped, with a large surface area and a moderate mean depth. Lake East Okoboji is long and narrow, composed of several contiguous shallow basins. It has a moderate watershed area and small volume. Lakes Upper Gar and Minnewashta do not have surface watershed drainages separate from Lake East

TABLE 2. TOTAL AREA OF INDIVIDUAL LAKE WATERSHEDS, MORPHOMETRIC CHARACTERISTICS AND RATIOS OF WATERSHED AREAS TO LAKE VOLUMES FOR LAKES WEST OKOBOJI, BIG SPIRIT, EAST OKOBOJI, LOON AND LOWER GAR

	West Okoboji	*Big Spirit*	*East Okoboji*	*Loon*	*Lower Gar*
Watershed Area (ha)	7,698	9,962	5,903	7,935	4,720
Lake Area (ha)	1,540	2,168	764	291	98
Lake Volume ($1 \times 10^6 m^3$)	184.0	111.9	21.2	4.5	1.1
Mean Depth (m)	11.9	5.2	2.8	1.5	1.1
Ratio of Watershed Area to Lake Volume (m^2/m^3)	0.33	0.69	2.42	16.9	42.0
Turnover Time (Years)	20	5.5	1.2	0.5	0.3

Okoboji; therefore we considered them as a southern expansion of the larger lake. The watershed area:lake volume ratio of these lakes is such that the turnover time is one year. Lower Gar Lake is shallow and receives drainage from a land area 43 times that of the lake surface area. Because of the large watershed area:lake volume ratio, the waters of Lower Gar Lake are more directly influenced by the watershed runoff than those of any other lake in the watershed.

The watershed areas and surface area of lakes East and West Okoboji influence the interchange of water between them. Because the surface outlet for the watershed is on Lower Gar Lake, it is natural to assume that water flows from Lake West Okoboji into Lake East Okoboji. Field observations, however, indicate that the waters of Smith's Bay, West Okoboji (connected to Lake East Okoboji), had characteristics similar to waters of Lake East Okoboji, indicating mixing between these lakes. We collected water samples during the summers of 1971-73 to determine water chemistry characteristics within this interchange (Figure 2).

The mixing pattern between these lakes can be inferred from the specific conductance values (Figure 2), a conservative characteristic of a given water mass. Lake East Okoboji has higher specific conductance values than does Lake West Okoboji. If the outflow was from Lake West Okoboji to Lake East Okoboji, lower conductance values would persist to the interchange (Station 5, Figure 2) and increase into Lake East Okoboji. This was not found; rather, there was a gradient across this connection.

The ratio of watershed area:lake area is greater in Lake East Okoboji (6:1) than in Lake West Okoboji (3.8:1). During periods of rising water levels, Lake East Okoboji would rise at a more rapid rate than Lake West Okoboji (if runoff volumes per unit area were the same in the two watersheds), and water would tend to flow from Lake East Okoboji toward Lake West Okoboji. During periods of falling water levels due to outflows through the Lower Gar Lake outlet, the flow would be in the other direction. During stable water levels, wind action and waves would cause an interchange of water between these lakes.

Water Quality and Trophic Conditions of the Lakes

All the lakes studied are eutrophic or biologically productive, but some lakes are more eutrophic than others. Water quality parameters of the lakes are summarized in Table 3.

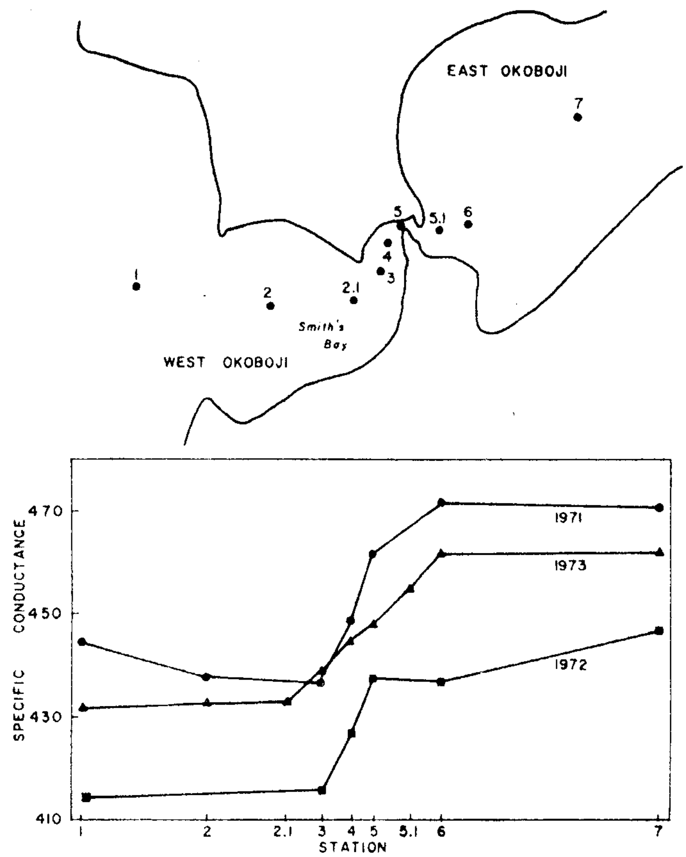

Figure 2. Map of stations along a transect extending from the deep hole of Lake West Okoboji to the open waters of Lake East Okoboji. Also, the distribution of mean specific conductance values across the transect in 1971, 1972 and 1973 is plotted for the respective stations.

The concentrations of nitrogen and phosphorus compounds are indicative of the potential growth of plant materials in these lakes, and chemical oxygen demand and chlorophyll *a* measurements indicate the amount of growth achieved. Secchi disk transparencies are inversely related to chlorophyll *a* concentrations. Each of these lakes has summer algal problems ranging from mild to nuisance conditions, as indicated by the chlorophyll *a* values in Table 3.

TABLE 3. SUMMARY COMPARISON FOR LAKE WEST OKOBOJI, BIG SPIRIT LAKE, LAKE EAST OKOBOJI (INCLUDING UPPER GAR LAKE AND LAKE MINNEWASHTA) AND LOWER GAR LAKE OF MEAN SUMMER VALUES FOR TOTAL PHOSPHORUS, NITRATE NITROGEN, AMMONIA NITROGEN, CHLOROPHYLL *a*, CHEMICAL OXYGEN DEMAND AND SECCHI DISK TRANSPARENCY (1971, 1972, 1973)

	West Okoboji	*Big Spirit*	*East Okoboji*	*Lower Gar*
Total P mg/l	0.033	0.041	0.165	0.222
NO_3–N mg/l	0.009	0.017	0.085	0.145
NH_3–N mg/l	0.110	0.239	0.468	0.644
Chlorophyll *a* mg/m³	4.3	27.5	122.2	226.8
Chemical Oxygen Demand mg/l	20.5	24.9	46.5	56.5
Secchi Disk Transparency (m)	3.2	1.7	0.9	0.4

Thomas (1953) used the difference between winter and summer alkalinity in epilimnion waters as a lake eutrophication index. The greater this difference, the more eutrophic is the lake. From seasonal alkalinity differences, Lake West Okoboji is the least eutrophic lake, with a winter-to-summer difference in alkalinity of less than 10 mg/l. In Spirit Lake, this difference is about 50 mg/l, and lakes East Okoboji and Lower Gar have alkalinity differences from 80-165 mg/l.

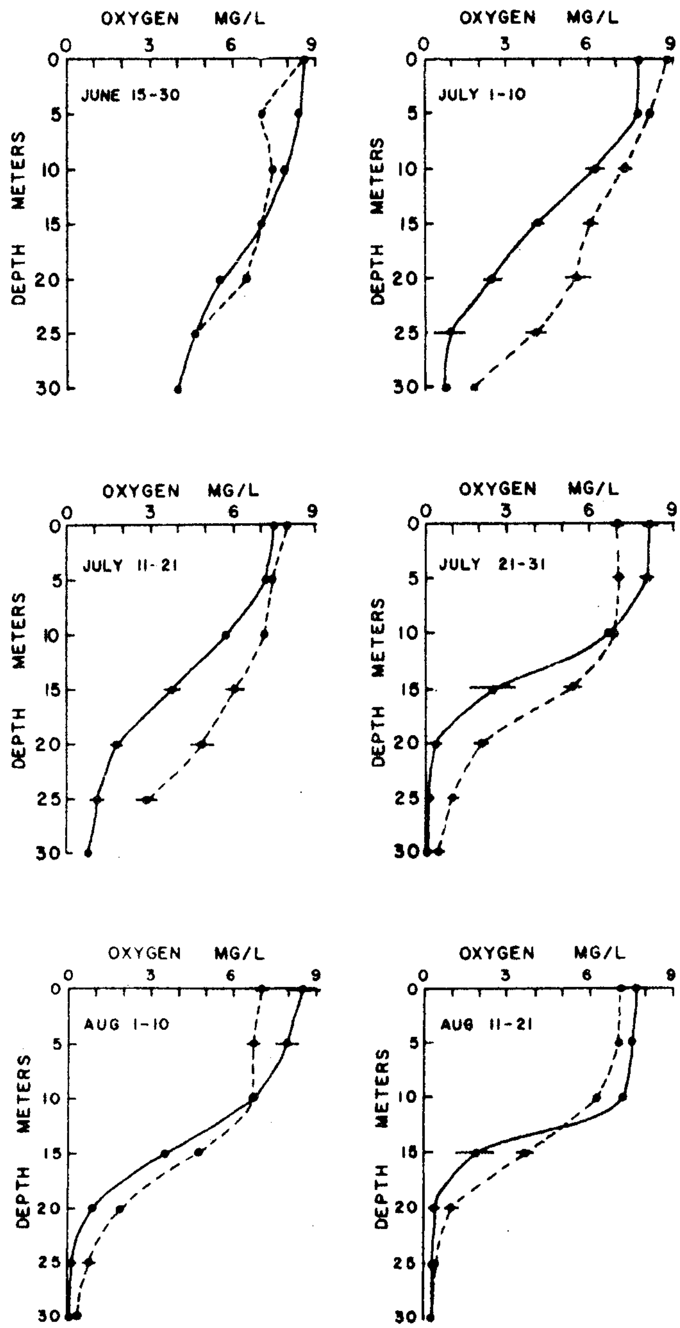

Figure 3. Average dissolved oxygen concentrations at 5-m depth intervals in Lake West Okoboji during June-August, 1919-1928 (dashed line) and 1950-1973 (solid line). Standard-error bars indicate means are significantly different at a given depth.

Hypolimnetic Oxygen Change in Lake West Okoboji

Oxygen data from Lake West Okoboji were examined to determine possible changes that would indicate increased eutrophication (Edmondson, 1966; Bazin and Saunders, 1971). Available oxygen profiles are in separate time periods, 1919-1928 (past data) and 1950-1973 (recent data). The original data from various sources (many unpublished) are given in Bachmann and Jones (1974a). For comparative purposes, summer oxygen profiles were separated into six periods of 10 to 15 days beginning June 15 and ending August 21. Mean oxygen profiles within these periods are plotted in Figure 3. Because of insufficient data, oxygen concentrations below 30 m were excluded.

Comparing recent with past oxygen profiles, less oxygen currently is present at various depths below the thermocline (10 m). A t-test was used to determine significant differences between mean past and recent oxygen concentrations from the various profile depths. Corresponding means that differ significantly are indicated by standard-error ranges in Figure 3. In July, recent oxygen concentrations below the thermocline are significantly less than past values at all depths but one (30 m, July 1-10). In August, recent oxygen concentrations at the upper hypolimnetic depths of 15, 20 and 25 m are significantly less than past concentrations. By late summer, oxygen depletion is almost complete at 30 m in both past and recent profiles.

Further t-tests were run of the mean differences between past and recent temperature values for June 15-30 to test the possibility that temperature differences in the early summer may have caused hypolimnetic oxygen differences. These were not significant. It is concluded that increased biological activity in the epilimnion is responsible for the oxygen difference.

The hypothesis that increased algal productivity in the epilimnion is responsible for this change is supported by the finding that epilimnetic oxygen concentrations were greater in 1950-1973 than they were in 1919-1928 (July 21 through August 10). Again, water temperatures could not account for this difference because recent average temperatures for this period are slightly higher (22.9 C) than those measured in 1919-1928 (21.2 C). This difference is statistically significant and would tend to make the recent oxygen concentrations lower, rather than higher, on the basis of solubility laws. Higher rates of photosynthetic oxygen production in the epilimnion in recent years could account for these higher values.

Oxygen deficits (mg/cm^2) were calculated for periods during the summer by determining the oxygen saturation value between the thermocline (10 m) and 30 m from the mean temperature curves for June 15-30, 1923-1928 and 1950-1973. By using saturation values for these temperatures and the volume-depth curve for the lake, the calculated hypolimnetic oxygen content at the onset of saturation was 685,500 kg in 1919-1928 compared with 684,000 kg in 1950-1973. Hypolimnetic oxygen content was then calculated for past and recent mean oxygen profiles within each of the six time blocks between June 15 and August 21. These values were subtracted from their respective initial saturation value and divided by the surface area of the 10-m contour (716 ha) to yield areal oxygen deficit values (mg/cm^2) (Figure 4). Comparing summer oxygen deficits within the six time blocks, initial values are similar, but by July the 1950-1973 deficits are 50% greater than 1919-1928 values. The August oxygen deficit values converge as hypolimnetic oxygen is exhausted, and no further oxygen consumption is possible.

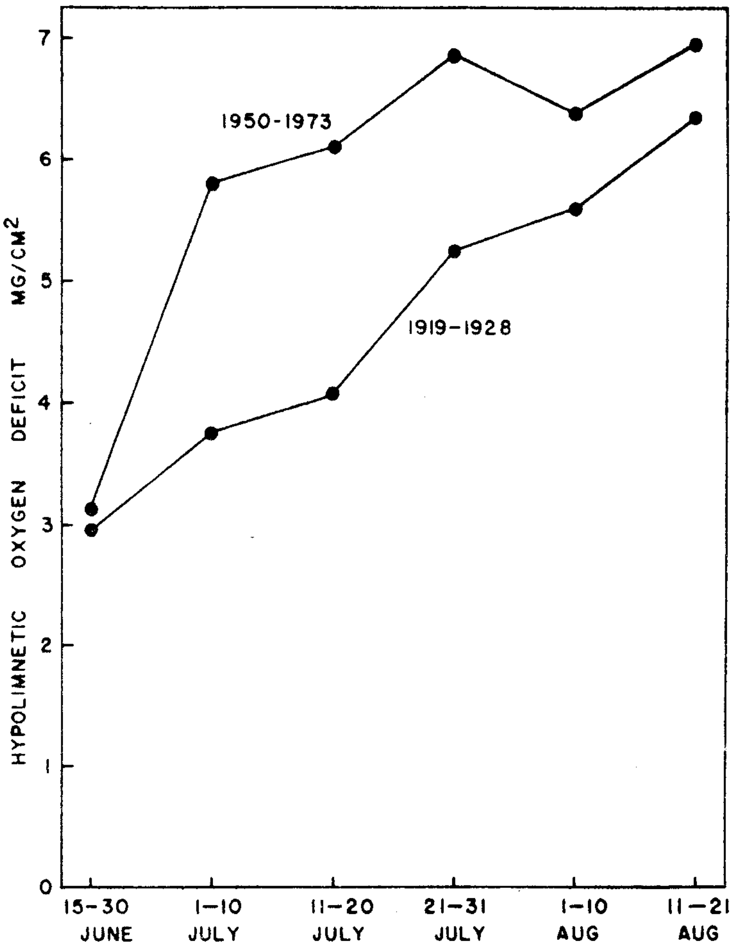

Figure 4. Oxygen deficit values (mg/cm^2) from Lake West Okoboji for periods between June and August, 1919-1928 and 1950-1973.

Hypolimnetic oxygen utilization results from decompositional consumption of materials produced within and washed to the lake from its basin. These materials settle into the hypolimnion, resulting in an oxygen deficit. If recent delivery of organic material to Lake West Okoboji is unchanged from the 1919-1928 period, the increased oxygen deficit would result from an increased productivity of the surface waters during the past 50 years. The magnitude of this increased oxygen deficit could be as much as 50%.

DISCUSSION

Cultural eutrophication has had an alarming effect on the limnological conditions of many water bodies in recent years. Many lakes have changed from oligotrophic to eutrophic in a matter of decades. Such a rapid change usually is associated with domestic or industrial effluents. In the lakes studied, sewage presently has a minimal influence on water quality because most areas are sewered and the effluent is transported outside the watershed.

Although the watershed lakes are presently eutrophic, there is reason to believe that they have been eutrophic for several thousand years. There are no physical or floristic changes in the sediments of Lake West Okoboji indicative of severe changes in the sedimentation rate or trophic level of the lake, even in recent deposits, which would reflect changes due to the activities of man (Stoermer, 1963; Collins, 1968; Dodd, 1971). The diatom flora of the sediment of Lake West Okoboji is characterized by taxa normally associated with eutrophic waters, indicating a long-term eutrophication. Because Lake West Okoboji is the deepest lake, it probably was the last lake within the watershed to undergo a trophic advance. Thus, it is reasonable that the other watershed lakes were eutrophic before Lake West Okoboji.

Limnological changes have taken place within these lakes since the turn of the century. The increased hypolimnetic oxygen deficit in Lake West Okoboji during the past 50 years probably reflects a greater productivity in the surface waters, indicating accelerated eutrophication. The rich molluscan fauna of Lake West Okoboji described by Shimek (1913, 1915a) decreased by the 1930s (Shimek, 1935). Bovbjerg and Ulmer (1960) concluded from snails collected between 1954 and 1959 that from 25 to 40 additional species were found in the lake during the first quarter of this century. The marsh-like emergent and submerged vegetation so abundant in Lake East Okoboji and the Gar lakes at the beginning of this century (Shimek, 1915b; Iowa State Highway Commission, 1917) has almost disappeared. Recent studies (Volker and Smith, 1965; Crum and Bachmann, 1973) show that the plants have subsequently been replaced by blue-green algae. It is estimated that the blue-green algae problem developed between 1920 and 1930 (Gale et al., 1972). Without documentation it is impossible to determine what brought about these changes. Whatever the cause, the rate of change is not comparable to lakes Washington, Erie and Zurich, lakes noteworthy for accelerated eutrophication.

An obvious correlation exists between the algal standing crops in each of the lakes and the ratio of the watershed area to lake volume. This relationship also can be extended to include mean depth (Tables 2 and 3). The lakes can be ranked by decreasing mean depth, increasing ratio of watershed area to lake volume, and increasing algal biomass. This order is Lake West Okoboji, Spirit Lake, Lake East Okoboji (including Upper Gar and Minnewashta) and Lower Gar Lake.

We have shown elsewhere (Jones and Bachmann, in press) that the summer algal crops in these lakes are correlated with the annual phosphorus inputs per unit volume of water. This relationship holds for many other lakes as well (Bachmann and Jones, 1974b). This offers an explanation for differences among the lakes. If phosphorus loss per unit area of watershed is the same for each lake, then the ratio of watershed area to lake volume is directly proportional to the potential annual phosphorus input per unit volume of water. Thus Lake West Okoboji is least eutrophic because of its small watershed and large volume, and Lower Gar Lake is the most eutrophic because of its large watershed and small volume.

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