Some Effects of the Larger Types of Aquatic Vegetation on Iron Content of Water

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CHEMISTRY OF IRON IN NATURAL WATER

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Investigation of factors affecting solution of iron in natural water

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SOME EFFECTS OF THE LARGER TYPES OF AQUATIC VEGETATION ON IRON CONTENT OF WATER

By EUGENE T. OBORN and JOHN D. HEM

ABSTRACT

Complex antagonistic factors affecting solution of iron in natural water were investigated by correlating data from field and laboratory studies of aquatic plants.

As blanketing type of water-plant growth increases, oxygen in the water is generally depleted, principally through respiratory processes; furthermore, the normal exchange of oxygen at the air-water interface is inhibited if vegetation forms a complete blanket at the water surface.

A gradual accumulation of iron in the bottom mud of the Federal Center Lake seems to result from additive effects of oxygen entry into lake water from the air and from photosynthesis of the water plants growing in the lake. In both greenhouse and lake, water with submerged soil-rooted plants had highest concentrations of iron in solution when growth was most conspicuous Water-emergent soil-rooted plants, such as parrotfeather and broad-leaved cattail permitted the additional blanketing effect by allowing the additional growth of duckweed or pond scum; this growth further decreased the exchange of oxygen at the air-water interface. Water-hyacinth leaves shade the water surface and do not permit the additional duckweed or pond-scum growth, but do permit exchange of oxygen at the air-water interface of the water body. As a result, dissolved oxygen and Eh remained high, and iron in water continued low throughout the growing season of water-hyacinth.

Pasteurization or sterilization of soil caused additional iron to go into water solution. Water percolating through soil may dissolve 10 or more times the amount of iron normally present in water at a lake bottom.

Water usage, particularly by the water-emergent soil-rooted plants, varies considerably with the morphologic differences of the different species. Transpiration by such plants seems in general to be proportional to leaf surface area exposed per unit of water or to soil area upon which the plants grow.

INTRODUCTION

The general relation of plant growth to the chemistry of iron in natural waters has been noted earlier (Oborn, 1960a). The plan of the present report is to correlate observations of changes in dissolved iron in a small lake with those in greenhouse tanks. The causative agents in both locations are common types of aquatic vegetation easily visible to the naked eye. Two small plants (duckweed and waterbloom) collectively have an effect equal to or exceeding that of larger plants and accordingly are included. Because the growth and normal development of larger plants is dependent on the presence and activity of a microflora, no attempt was made to separate the two; nevertheless, emphasis is here placed on the effects of the larger aquatic plants.

Seasonal fluctuation of plant growth in water has been known for thousands of years. Anyone acquainted with swamp or marsh areas has witnessed the sudden seasonal appearance and subsequent disappearance of waterblooms. Other planktonic and benthonic forms are less conspicuous but are nonetheless seasonally present. Microbiota and macrobiota usually exist in the same area. Some microspecies frequent areas that are almost devoid of direct light, but larger forms require sunlight and tend to concentrate in the quiet shallow and shoreward recesses of rivers, lakes, and reservoirs.

Major features of the environment control the forms of life that exist, but living organisms can modify their environments appreciably. After death of aquatic plants, the organic matter is consumed by animals or is decomposed by the action of micro-organisms. Decomposition of organic matter alters the structure of compounds in plant tissues that contain iron. As a result of partial decomposition, a soluble organic complex containing iron may be produced. Ultimately, however, if ample dissolved oxygen is available, organic matter and iron may be completely oxidized and the iron deposited as ferric hydroxide.

Iron in organic complexes derived from dead organisms may be available for plant metabolism even in alkaline solution. Shapiro (1957) described a complex of ferrous iron of high molecular weight (straight-chain organic acid) which he extracted from lake water. Hem (1960a) obtained a ferrous complex with tannic acid. Although both complexes were oxidized slowly in water that was in contact with air, both retained dissolved ferrous iron in appreciable quantity for more than a month at pH values considerably above neutrality. In the field and laboratory studies here described, both lake-bottom and canal-bank soils subjected to heat treatments, showed evidence of ferrous iron complex formation.

Iron solubility and concentration in water where vegetation is growing are evidently subject to many continually changing factors. These factors, which include vertical and horizontal currents, diffusion, stratification, and the diurnal variation of dissolved oxygen were recognized by Welch (1935), Ruttner (1953), and others.

Variations in concentration of iron in water as affected by the natural microbiota or macrobiota present were discussed by Moore and Maynard (1929) Baas-Becking and others (1957), Hutchinson (1957), Ruttner (1953) and Steinberg (1946).

MATERIALS AND METHODS

Thomas Carlyle years ago said, "A world * * * exists by the balance of antagonism." This statement is applicable to the interrelated factors that control the iron content of natural waters. A correlation of field and laboratory studies seemed the best approach to a better understanding of these complex and sometimes antagonistic factors.

FEDERAL CENTER LAKE STUDY

The Federal Center Lake is near the east-central edge of the Denver Federal Center; it has a surface area of about 3 acres. The small reservoir has been in existence for about 20 years and, with the exception of a few short intervals, has been kept full of water. It receives some water from the industrial-waste treatment plant of the Federal Center; objectionable matter, including organic wastes, are removed from this effluent and do not enter the lake.

In comparison to the crested wheatgrass soil surrounding the lake, the lake-bottom soil is relatively rich in organic matter (Oborn 1960b, p. 201), and the lake supports an abundant growth of a wide assortment of aquatic vegetation during the warm months of each year. The lake was selected as a convenient field location to study the relation of occurrence and behavior of native species of aquatic vegetation to presence of dissolved iron in natural water.

GREENHOUSE STUDY

Most lake phenomena are affected by variables that cannot be controlled; therefore, some of the same species of vegetation that were present in the lake were used in the laboratory studies. These studies were made in a greenhouse, where temperature was thermostatically controlled. Dormancy of some species was delayed and of others was eliminated by use of fluorescent lighting.

EXPERIMENTAL PROCEDURE

So far as practicable, sampling and sample analyses were performed in a similar manner for lake and greenhouse samples. Care was exercised to keep variables at a minimum. Technique differences peculiar to lake or to greenhouse studies are discussed on pages 240 and 243.

LAKE STUDY

Conditions in the Federal Center Lake were averaged on a monthly basis by using data collected weekly during the 1958 growing season. Water samples were collected near the inlet, near the outlet, and at one to five other locations in the lake. Sampling stations, numbered 1 to 7 in figure 23, were in areas of different kinds of actively growing vegetation and are described in the table below. The red waterbloom

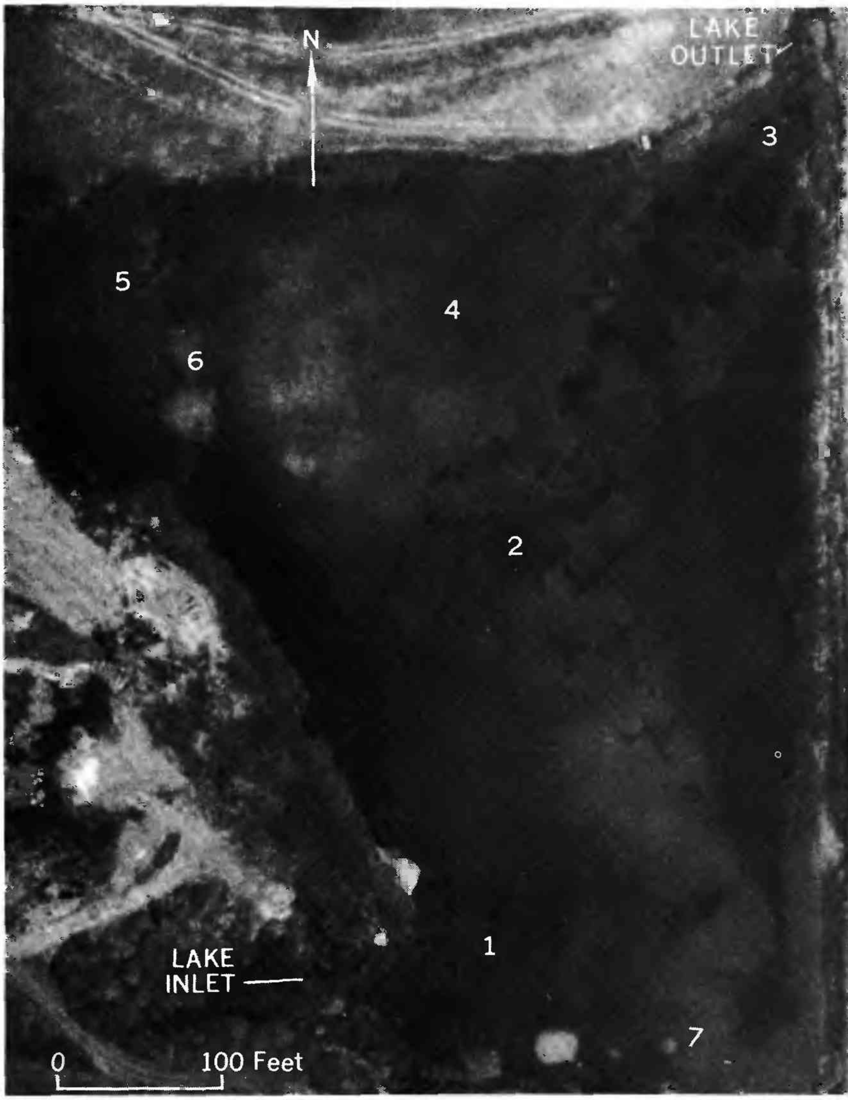

FIGURE 23.—Aerial photograph of Federal Center Lake showing sampling locations.

was identified by C. Norton, Colorado State University, the other plants by the senior author. The percent water-surface cover is not reported for lake stations because of the presence of inherently uncontrollable variables.

Station	*Location in lake*	*Approximate water depth (feet)*	*Predominant vegetation*
1	Southwest near inlet.	2½–3	*Potamogeton nodosus* Poir (American pondweed).
2	Middle	12–14	*P.foliosus-P.pectinatus* (leafy pondweed and Sago pondweed in approximately equal parts).
3	Northeast near outlet.	2½–3	*Potamogeton foliosus* Raf. (leafy pondweed).
4	North	7–9	*Potamogeton pectinatus* L. (sago pondweed).
5	Northwest	2½	*Typha latifolia* L. (broad-leaved cattail)
6	Northwest	2½	*Lemna minor* L. (lesser duckweed).
7	South	2½	*Euglena rubra* Hardy (red waterbloom)

Some plant succession and variability in predominant lake-plant growth took place through the growing season. Ten to fifteen percent of the lake-water surface was covered by red waterbloom in July through August and by duckweed in August through October. All lake samples were obtained from a boat with an open-tube (Kemmerer) sampler. The sampler was fitted with stoppers that could be closed to entrap the sample at any desired depth below the water surface. A messenger weight, which was sent down the line suspending the sampling tube, triggered the closing mechanism. The samples were obtained from as near the lake-bottom mud-water interface as practical, and most were clear or only slightly turbid. Sampling operations on the lake are shown in figure 24. Temperature, pH, and Eh of each sample were immediately measured and recorded at the time of sampling.

Dissolved oxygen was determined in the laboratory within 2 hours after sample collection; the Rideal-Stewart modification of the Winkler procedure was used. .The iron content of each sample was analyzed after filtration through medium-porosity (Whatman) filter paper; the 2,2 bipyridine procedure was used. Ferrous iron and ferric iron were determined separately. In most samples, most of the iron was in the ferric form. At the pH of the samples, (between 7.1 and 9.1) oxidation of ferrous iron, unless organically complexed, is rapid; therefore, at time of sampling more ferrous iron may have been present.

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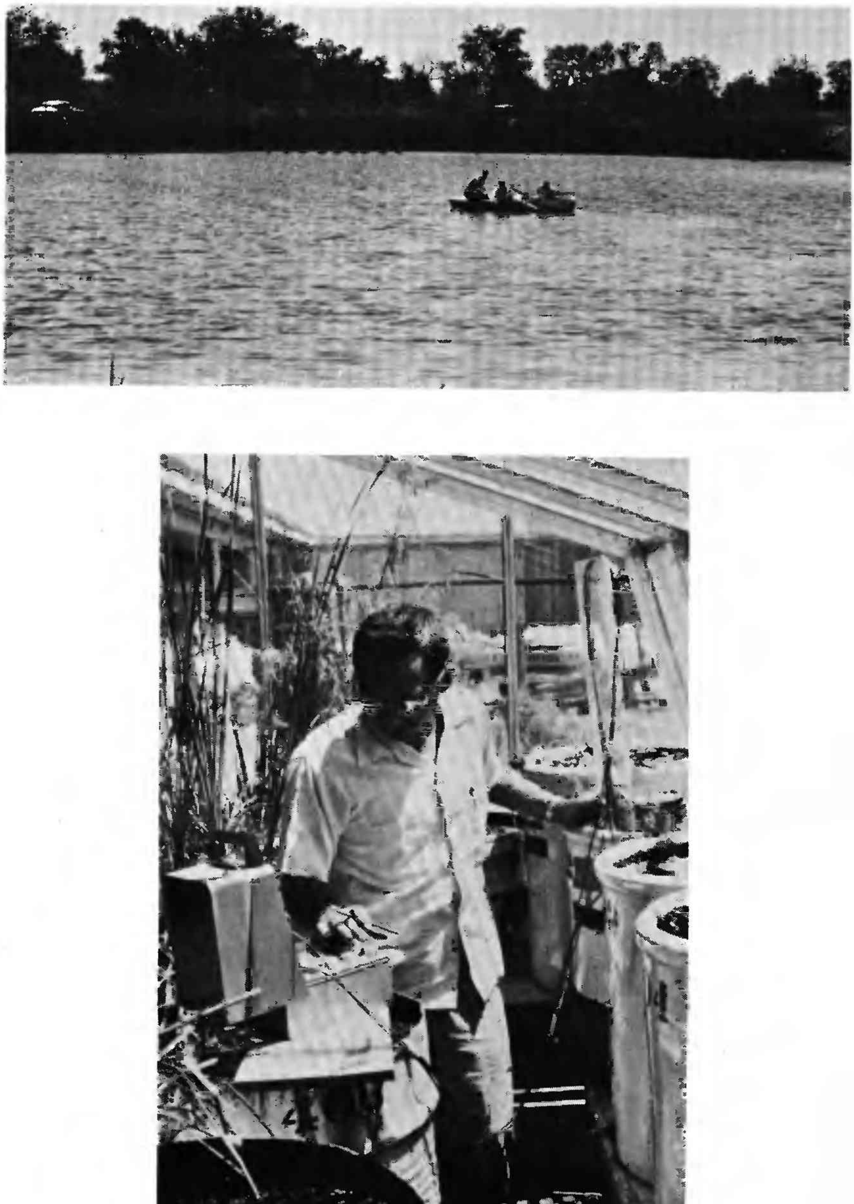

FIGURE 24.—Measuring pH and Eh of water. Top, on Federal Center Lake; bottom, in greenhouse tank.

Ferrous iron in small concentrations was usually present at the more shallow lake stations. At stations 1 and 3 it was definitely in higher concentrations during the period of most conspicuous plant growth. No ferrous iron was found in most of the samples from greenhouse tanks. Because oxidation after samples were collected may have influenced the results, separate ferrous and ferric iron concentrations are not reported.

Table 1 shows the chemical analyses of single lake inlet and outlet samples collected during the 1956 growing season, before the present study was begun. The loss of iron and silica and the gain in pH from the inlet to the outlet are probably due to influence of vegetation in the lake. Lake samples taken among vegetative growth in the immediate area of inflow and outflow indicate the overall gain or loss of iron in this lake water; observations at other sites indicate alterations caused by the other kinds of lake vegetation.

TABLE 1.—*Chemical analyses of water samples from inlet and outlet of Federal Center Lake, July 23, 1956*

[Results in parts per million, except as indicated]

	Inlet (12:30 p.m. slight turbidity)	*Outlet (12:45 p.m. clear)*
Silica (SiO_2)	11	1.0
Aluminum (Al)	1.1	.0
Iron (Fe)	.30	.00
Manganese (Mn)	.00	.00
Calcium (Ca)	16	16
Magnesium (Mg)	1.9	3.9
Sodium (Na)	83	39
Potassium (K)	2.8	1.2
Bicarbonate (HCO_3)	42	43
Carbonate (CO_3)	0	5
Sulfate (SO_4)	186	66
Chloride (Cl)	10	17
Fluoride (F)	.4	.4
Nitrate (NO_3)	.8	.4
Phosphate (PO_4)	2.2	1.8
Dissolved solids (residue on evaporation at 180°C)	365	198
Specific conductance (micromhos per cm at 25°C)	512	301
pH	6.6	9.0
Temperature (°F)	68	74

GREENHOUSE STUDY

A series of greenhouse tests provided a more detailed study of the effects of individual plant species on the dissolved iron of water in which the plants grew. A greenhouse adjacent to the laboratory was used for the study, and earthenware crocks were used as test tanks. Four inches of bottom soil from the Federal Center Lake was placed in each tank; the total iron content of this soil was 3.45 percent of its air-dry weight. A selected test species was planted to cover about 5 percent of the soil area, and the tank was filled with tapwater containing 0.01 to 0.05 ppm of iron. After weekly sampling, tapwater was added to restore the original water volumes.

One 30-gallon, one 15-gallon, and one 5-gallon container were used for each test plant species. Control tanks, containing the same types of water and soil but no vegetation, were maintained during the study.

Emergent and submerged aquatic plants having widely diverse physiological methods of growth were selected for the tests. Thus, information could be obtained on increase or decrease in dissolved iron caused by different growth habits of different vegetation.

For comparisons, plants were physically removed from certain tanks for various periods of time. For further comparisons, soils of certain tanks were subjected to pasteurizing and ultimately to sterilizing temperatures. However, none of the heat-treated soils were sterile. Use of sterile soil would have defeated the purpose of the study.

In nature, water-sedge has more the growth habit of phreatophytes than of true aquatic plants. This common species was transplanted into a tank that was filled with the same soil in which the field plant had been growing. Another tank of similar soil from which water-sedge had been removed served as the control. Water additions to these two tanks was sufficient to keep the soil surface moist (but not water submerged) at all times.

For several months after the initial plantings were made in the tanks, growth was relatively slow. However, the rate of growth increased during the spring and summer and coincided with natural growing-season trends. Most of the plants were still growing vigorously at the end of the study in December, 1958.

All the species except the water-sedge were planted December 9, 1957; the water-sedge was planted November 19, 1957. As might be expected, through the year some plant succession and variability in predominant greenhouse plant growth took place. For example, sago pondweed, leafy pondweed, stonewort, and duckweed, not visible at first, appeared in some of the greenhouse tanks later in the year. Seeds and other materials capable of propagation were present in the lake-bottom soil.

Some algal plant and other microbiological species no doubt were introduced by waterborne and airborne spore reseeding in all the greenhouse tanks. This reseeding continued for the duration of the study.

Table 2 lists the plant species that were studied in the greenhouse and follows a classification based on growth habit (Oborn, 1960b).

The table indicates the months during which growth was most vigorous.

After plants were established, the tanks were sampled each week. Water temperature, pH, and Eh in each tank were measured at the time of sampling. The glass, calomel, and platinum electrodes required for the measurements were mounted in a rubber stopper, which in turn was fixed in the lower part of a 3-foot plastic tube. The leads were thus protected from contact with water when the tube was immersed in the tanks. Readings were made with a battery-operated pH meter (fig. 24). A sample of water was then withdrawn for dissolved-oxygen and iron analysis. Samples were taken from the mud-water interface of the tank bottom by siphoning through glass tubing. The amount of water lost from each tank, including organism metabolic and transpiration requirements as well as water lost through tank-surface evaporation, was measured. The percentage of water surface covered by vegetation was recorded, and pertinent growth changes and physical phenomena occurring both at lake stations and in greenhouse tanks were noted each week. Sampling was discontinued at the end of December 1958.

The weekly measurements for each set of tanks containing the same species were averaged for each month. The results were further averaged to contrast the effects of plants during periods of vigorous growth with effects during periods of relative dormancy. Most of the interpretation is based on the averaged measurements.

Thermograph records showed that some deviations from constant temperature occurred in the greenhouse. However, the effects of these deviations were minor compared with the effects of other factors.

The initial measurement of iron concentration was made 24 hours after planting was completed. The iron concentration at the mud-water interface at that time was uniformly very low (about 0.04 ppm); nevertheless, the iron content of water samples collected in the first month after planting was commonly considerably greater. The high reading for the first month following planting was attributed to the soil disturbance caused by the planting and accordingly was not included in any of the tabulated average values.

INTERPRETATION OF RESULTS

Any phenomenon affected by seasonal fluctuation of growth is itself subject to continuous change dependent on kind and amount of influencing factors present; thus, both the form and the amount of iron in water could be seasonally altered.

TABLE 2.—*Plant species grown in greenhouse*

[Higher (vascular) plant nomenclature according to Fernald (1950) with the exception of Eichhornia (Kobuski, written communication, 1958). Algal (nonvascular) plant nomenclature according to Smith (1950)]

Plant species	*Growth habit*	*Months of growth*	
		Sparse	*Abundant*
Carex aquatilis Wahlenb. (water-sedge)	Land-water		February–December.
Lemna minor L. (lesser duckweed)	Water emergent, water roots		September–December.
Eichhornia crassipes (Mart.) Solms (water-hyacinth).	Water emergent, soil roots	February–July	August–December.
Myriophyllum brasiliense Camb. (parrot-feather).	Water emergent, soil roots	February–April	May–December.
Cladophora sp. Kützing (pond scum)	Water submerged, water roots.		August–December.
Potamogeton nodosus Poir. (American pond-weed).	Water submerged, soil roots	February–April, August–December.	May–July.
Elodea nuttallii (Planch.) St. John (western waterweed).	Water submerged, soil roots	February–July	August–December.
Heteranthera dubia (Jacq.) MacM. (water-stargrass).	Water submerged, soil roots	February–July	August–December.
Eleocharis acicularis (L.) R. and S. (needle spikerush).	Water submerged, soil roots	February–July	

MONTH TO MONTH CHANGES IN GREENHOUSE TANKS

The four chemical variables measured in the lake and in the greenhouse tanks—dissolved iron, pH, Eh, and dissolved oxygen—are interrelated (Oborn, 1960a). For example, the amount of iron that can be retained in solution is directly related to pH, Eh, and dissolved oxygen in the absence of complexing and excessive amounts of certain anions (Hem, 1960a, 1960b). The Eh of water in contact with air is generally a function of the effects of oxygen in solution. The amount of oxygen dissolved is, in turn, affected by temperature, wind action, freedom of exchange between air and water at their interface, and the chemical or biologic oxidative processes going on in the water.

As plant metabolic-growth rates increase, the oxygen in the water is generally depleted, particularly at night when processes of respiration exceed those of photosynthesis. The exchange of oxygen at the air-water interface is inhibited if the vegetation forms a sufficiently dense blanket at the water surface. Depletion of oxygen lowers the Eh and makes iron more soluble. Hence, rapid respiration, coupled with a complete blanketing of leaves or other cover on the water surface, causes more iron to go into solution; furthermore, an apparent increase in soil solutes, of 1–3 ppm iron, frequently made available in the partial decomposition of plant materials, may be retained in solution indefinitely as an organic complex under anaerobic conditions.

Interrelations of dissolved iron, dissolved oxygen, and Eh are shown in figures 25–27 for greenhouse-grown water-stargrass, parrotfeather, and western waterweed, respectively. These three plants are all soil rooted. Water-stargrass and western waterweed have a water-submerged type of growth, and parrotfeather has a water-emergent type of growth. Figures 25–27 consistently show that preceding rapid plant growth, Eh and dissolved oxygen were high and dissolved iron was low. During the most vigorous growth, Eh and dissolved oxygen decreased and iron increased.

Most of the available iron supply in the tanks was in the soil. As previously mentioned, iron was dissolved from the soil when the plantings were made, but most of this iron was returned to the soil from solution during the initial 30-day period of growth adjustment. In another study (Oborn, 1960b) it was pointed out that direct extraction of water-dissolved iron by the commonly iron-rich aquatic plants depends mainly on whether the plants are water-rooted or soil-rooted species. The amounts of iron retained in solution during vigorous plant growth reflect the sum results of the several interrelated factors such as pH, Eh, temperature, dissolved oxygen, kind and amount of organic matter present, and method of iron extraction by the plants.

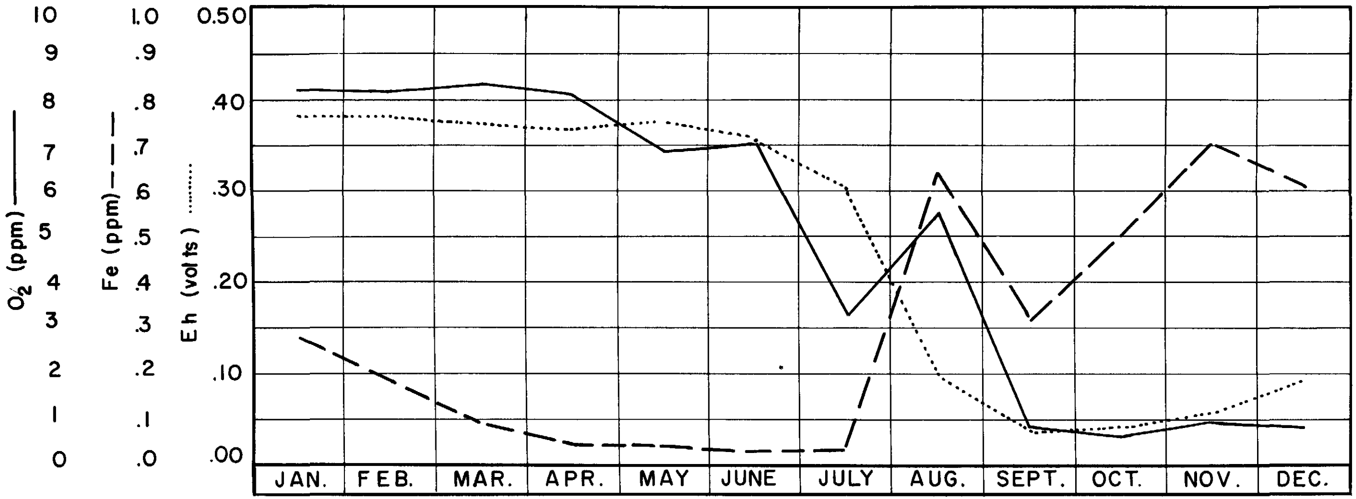

FIGURE 25.—Monthly average dissolved oxygen, iron content, and Eh of water in greenhouse tank 505 (water-stargrass).

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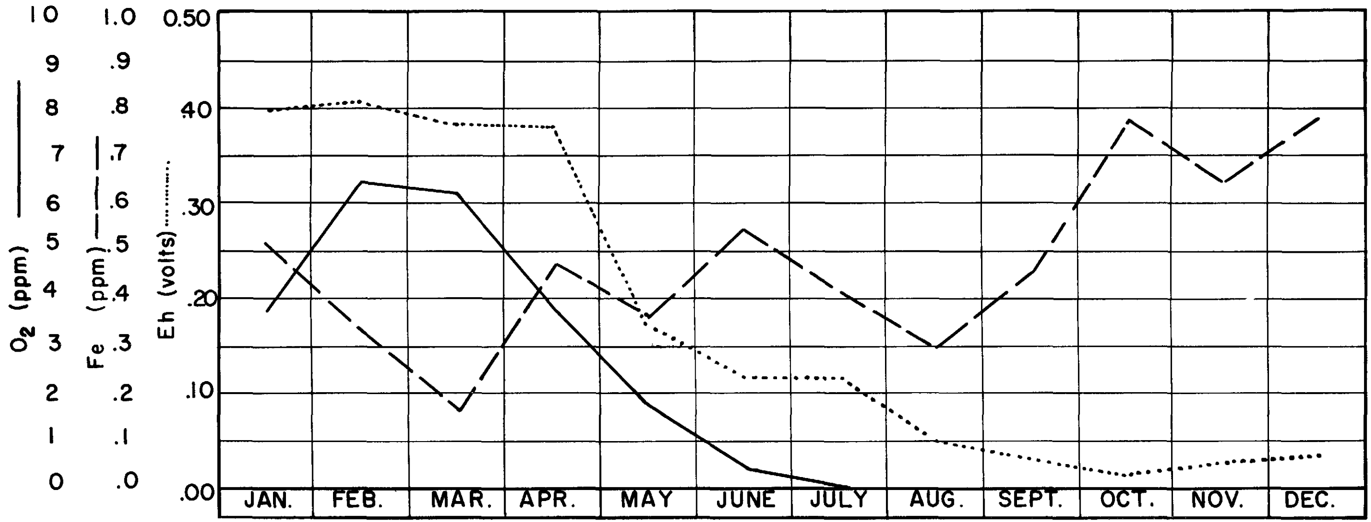

FIGURE 26.—Monthly average dissolved oxygen, iron content, and Eh of water in greenhouse tank 202 (parrotfeather).

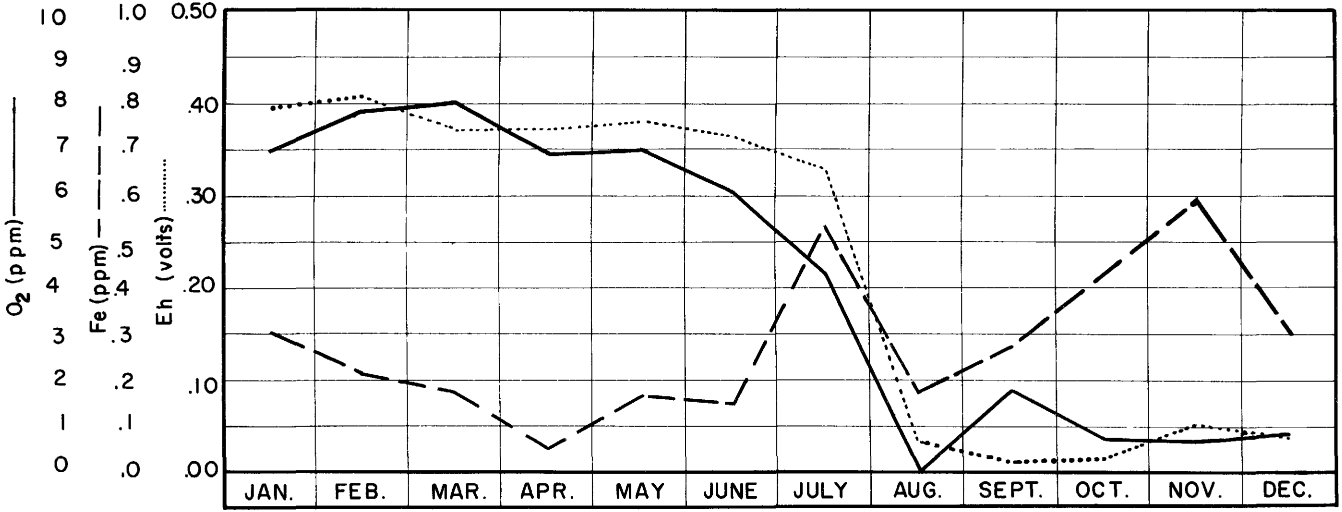

FIGURE 27.—Monthly average dissolved oxygen, iron content, and Eh of water in greenhouse tank 204 (western waterweed).

Data shown in figures 25–27 suggest that the supply of iron made available for solution by aquatic plants fluctuates seasonally. During and immediately after the growing season, iron in water solution is in excess of the amount that will be present in solution during other months of the year. The low Eh, its associated oxygen depletion, and available complexing organic matter probably are the principal controlling factors. The high iron values generally occur in conjunction with low Eh and low dissolved oxygen.

Figure 28 is a graph, similar to figures 25–27, for a tank containing water-hyacinth. The water in this tank did not have sufficiently low Eh and dissolved-oxygen values to permit much iron to go into solution.

The great importance of water-blanketing effect has been brought out in this study and is shown in figures 26 and 28. Both plants (parrotfeather and water-hyacinth) are water emergent and soil rooted. Even when growing at maximum density, parrotfeather (fig. 33) did not exclude light from the water surface and so duckweed or pond scum developed and coexisted as a heavy blanketing growth on the water surface of the tanks. The dense, thick (nonincised) leafage of water-hyacinth (fig. 33) does not allow adequate light for duckweed or pond scum to develop and coexist on the water surface of the tanks. Throughout the growing season, the additional blanketing effect of the growth of duckweed or pond scum (as in the parrotfeather tanks) and lack of it (as in the water hyacinth tanks) brought about the differences between low and high dissolved oxygen and Eh and between high and low iron in water at the soil-water interface in the tanks. The dissolved oxygen and Eh in the water-hyacinth tank decreased slowly during the summer, but never became as low as the dissolved oxygen and Eh in water in the parrotfeather tank (fig. 26). Water-hyacinth, for the reasons stated, did not exert any pronounced effect on iron content of the water.

Actual total quantities of iron circulated from the soil into the plants and thence into the water and back to the soil cannot be readily determined from the data obtained. The experiments were stopped before the greenhouse plants had run a full cycle of growth and dormancy; nevertheless, the mechanisms of iron extraction from and return to submerged soils are clearly indicated.

LAKE STUDY OBSERVATIONS

Average composition of the water samples from the lake stations are presented in tables 3–7. The averages for iron, pH, Eh, and dissolved oxygen represent seasonal periods of growth and dormancy for the different and predominant plant species present at the seven

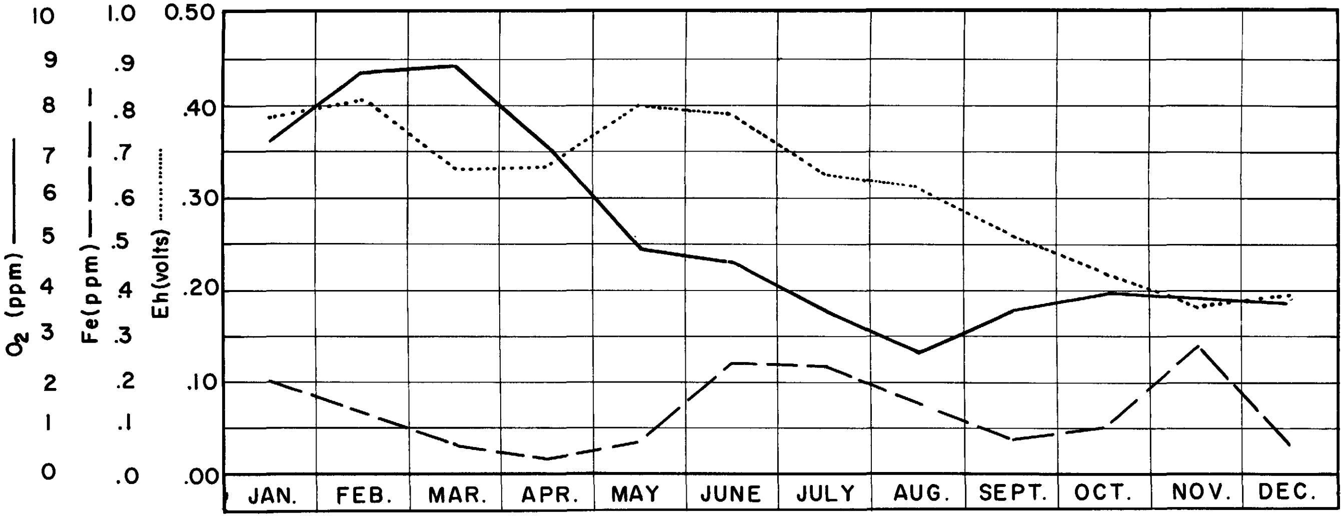

FIGURE 28.—Monthly average dissolved oxygen, iron content, and Eh in greenhouse tank 201 (water-hyacinth).

sampling points. Data in the tables show a pronounced tendency for iron in solution to be highest in late summer or early fall (August through October). This same tendency was observed in the greenhouse experiments.

A lake normally accumulates iron because of oxidation of the iron in the incoming water. Data in table 1 and a comparison of data for station 1 (table 3) with those for station 3 (table 6) show these results to occur at the Federal Center Lake. An additional indication is the fact that the iron content of the organically rich lake-bottom soil is greater than that of the soil of the surrounding area (Oborn, 1960b).

COMPARISONS OF DATA FROM GREENHOUSE AND LAKE STUDIES

Averaged measurements for the greenhouse-lake study were compiled from weekly readings. They show amounts of iron present in the water during the season of maximum growth as contrasted with amounts present at other times. The data also permit comparisons of changes of iron in water caused by plants of similar growth habit, regardless of whether growth takes place in lake or greenhouse. These data are presented in tables 4–8.

Vegetative surface cover for greenhouse tanks is reported to the nearest 5 percent. Figure 29 illustrates two plants that have dense leafy or leaflike growth at the surface of the water. Both in lake and in tanks, these plants tend to increase dissolved iron when water-surface cover is complete or nearly so. Table 3 summarizes the effect of American pondweed on iron content of water supporting the growth of this species and clearly indicates a seasonal trend. In greenhouse and lake, high dissolved iron content (accompanied by dense surface-water leaf growth) was both preceded and followed by lower iron concentrations (and pronounced decrease in amount of surface-water leaf growth).

Iron in the greenhouse tank water reached a maximum earlier in the season than did iron in the lake water, probably because a higher temperature was maintained in the greenhouse. Iron content of water in the tanks did not increase significantly until about 85 percent of the surface area of the water was covered by plants. The cover in the tanks with American pondweed and with some other plants used in the greenhouse experiments was not always a pure stand of the initial planting. Plant competition and to some extent plant succession resulted in the establishment of mixtures of species and sometimes of genera.

Table 3 does not show the usual relation of iron content of water to pH and Eh; however, dissolved oxygen was lower in both greenhouse and lake when iron was high.

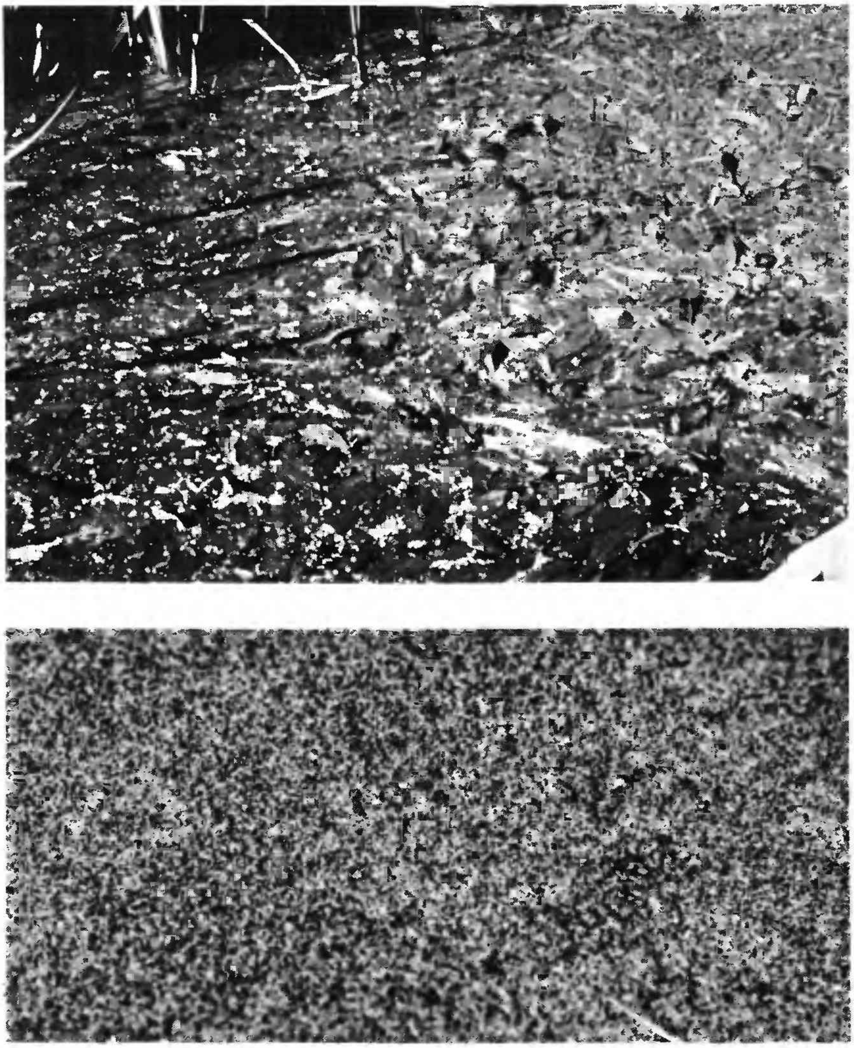

FIGURE 29.—Plants whose floating leaves or leaflike parts completely cover the water surface. Top, American pondweed; bottom, duckweed.

Lesser duckweed growth in the greenhouse was all volunteer. Data for this species are presented in table 4. This water-rooted plant frequently forms a dense cover on organically rich, quiet waters during the late summer and fall (fig. 29). In contrast to American pondweed, duckweed was conspicuous in greenhouse tanks several weeks after its natural disappearance from the lake. Cooler temperatures combined with effects of wind on the lake likely were important contributing factors in the disappearance of duckweed from the lake.

TABLE 3.—*Characteristics of water affected by American pondweed in greenhouse tanks and in the lake*

Sampling points	Period of average (1958)	Temp. °C	pH	Eh (volts)	Iron (ppm)	O_2 (ppm)	Plant species	Water surface covered (percent)
Greenhouse tanks 103,203,503.	February–April and August–December.	20.4	8.0	0.19	0.17	4.8	American pondweed.	10
							Stonewort [1]	15
							Algal scum	15
							Duckweed	10
							Total cover	50
Do	May–July	21.8	7.5	.23	.30	1.8	American pondweed.	80
							Sago pondweed	10
							Algal scum	5
							Total cover	95
Lake station 1	March–August and November.	17.4	7.2	.29	.74	3.1	American pondweed.	(2)
Do	September–October	18.5	8.1	.30	1.15	2.4	do	(2)

[1] *Chara* sp.
[2] Percent water-surface cover not reported for lake stations because of presence of inherently uncontrollable variables.

TABLE 4.—*Characteristics of water affected by lesser duckweed in greenhouse tanks and in the lake*

Sampling points	Period of average (1958)	Temp. °C	pH	Eh (volts)	Iron (ppm)	O_2 (ppm)	Plant species	Water surface covered (percent)
Greenhouse tanks 103, 504 (without vegetation).	September–December	20.5	8.0	0.07	0.29	3.7	Vascular plants continuously removed.	------
Greenhouse tanks 104, 205 (containing Duckweed).	September–October	21.9	7.9	.02	.39	.6	Lesser duckweed	100
Do	November–December	21.1	8.1	.05	.26	2.4	do	90
Lake station 6	July–August	24.0	7.3	.05	.32	1.2	do	(1)
Do	September–October	16.4	7.8	.02	.42	1.7	do	(1)

[1] Percent water-surface cover not reported for lake stations because of presence of inherently uncontrollable variables.

Duckweed growth caused increase in iron in both greenhouse and lake water during the months of September and October. Iron in water in the greenhouse tanks was highest when the water surfaces were most nearly covered with vegetation.

A total cover of algal scum would probably have an effect on dissolved iron similar to that produced by a total cover of duckweed: A blanketing effect would result and upon disintegration of the plants, organic iron would be released. Data from a greenhouse tank that contained only a partial cover of algal scum showed no significant variation, and so the data are not included here. Algal scum, illustrated in the upper left area of figure 30, top, is primarily *Cladophora* sp.

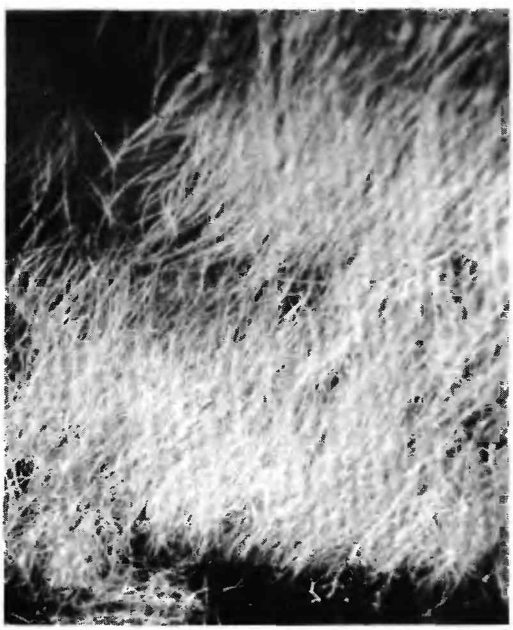

FIGURE 30.—Submerged aquatic plants present in lake and greenhouse tanks. Top, leafy pondweed; bottom, sago pondweed (aerial view of water surface).

During July and August, a blood-red algal bloom, consisting of many unicellular organisms, appeared in the lake (fig. 31). Each cell of the bloom consists almost entirely of protoplasm and conducts its own independent iron metabolism. The blood-red algal bloom probably is very active in altering iron content of water because each plant cell is alive and metabolically very active.

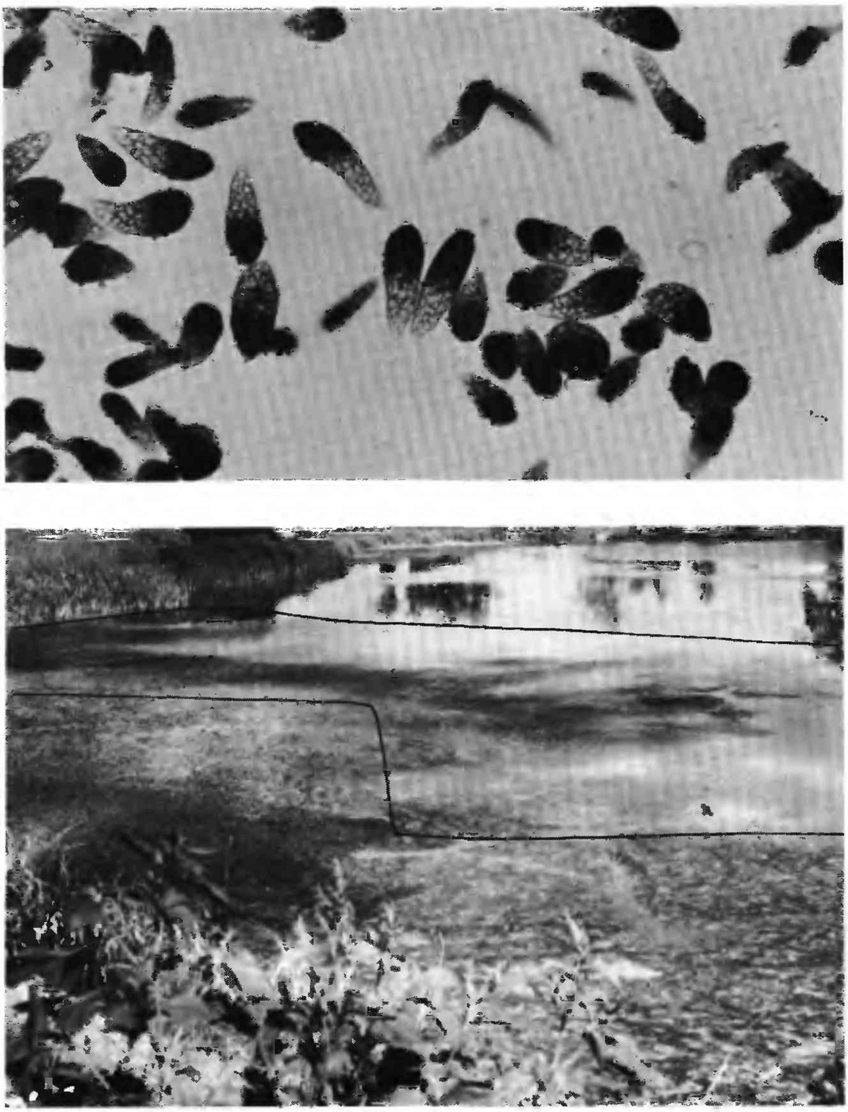

FIGURE 31.—Unicellular organism producing blood-red bloom on lake. Top, microscopic view; bottom, habitat view (organism is concentrated within the lined area).

Euglena polymorpha Dangeard (Johnson, 1944) commonly produces a pea-green waterbloom in the greenhouse. Denver laboratory analysis showed this plant to have 4.08 milligrams of iron per gram of blotter-dry plant material. *Euglena rubra* Hardy, the organism responsible for red waterbloom, is a different species but closely related in morphology and physiology.

TABLE 5.—*Characteristics of lake water during and after period in which red waterbloom was present*

Sampling points	Period of average (1958)	Temp. (° C)	pH	Eh (volts)	Iron (ppm)	O_2 (ppm)	Plant species
Lake station 7	July–August (bloom)	23.2	7.8	0.28	0.48	1.9	Red waterbloom.
Do	September (postbloom)	20.8	7.4	.34	1.0	.5	Do. [1]

[1] Note this is actually the postbloom period.

Waterblooms make considerable amounts of iron available suddenly when their individual cells disintegrate. Data in table 5 shows that the iron content of the water during the postbloom period was about double the iron content during the most flourishing growth of the organism. After cessation of the bloom, the plant decays rapidly, and organic iron is released to the water.

DATA CLASSIFIED BY PLANT GROWTH HABIT

Aquatic vegetation has been classified for this study into water-rooted and soil-rooted, submerged and emergent types. Comparisons of data from greenhouse and lake studies of similar aquatic plants having submerged soil-rooted habits of growth are presented in table 6.

Submerged plants growing at lake stations 2, 3, and 4 (fig. 23) are illustrated in figure 30. Both kinds of plants also grew in small volunteer amounts in several of the greenhouse tanks. Submerged plants, observed in the greenhouse but not present in the lake in appreciable amount, are illustrated in figure 32. Iron concentrations of about 0.3 ppm were measured for most of the water-submerged soil-rooted plants summarized in table 6. At the three lake stations, more iron was present in the water during August through October than during June, July, and November. Thus, the pondweeds had the same effect on the iron content of the water as the waterblooms; decaying vegetation made iron available for solution during and after periods of vigorous growth. At the three lake stations, the higher concentrations of iron in August through October were accompanied by lower pH, Eh, and dissolved oxygen.

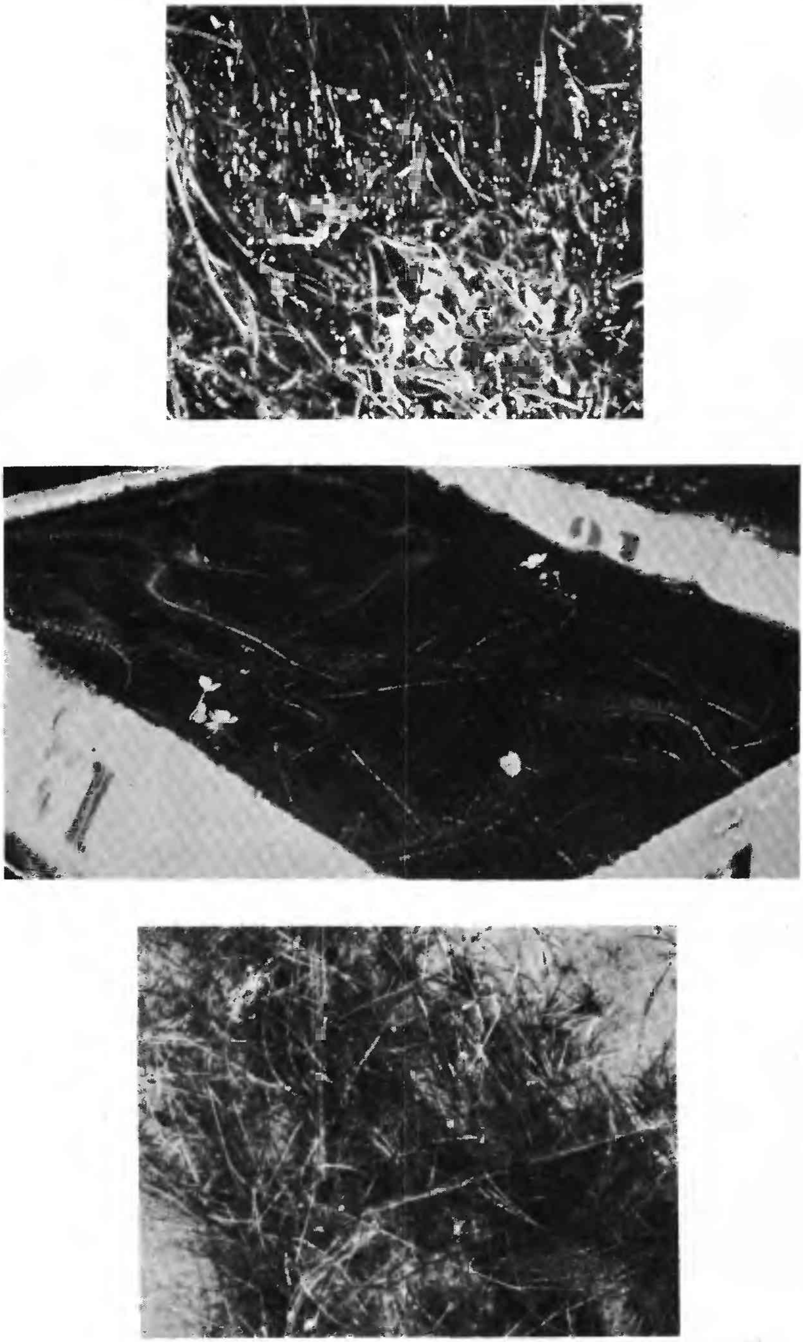

FIGURE 32.—Aerial views of submerged aquatic plants grown in greenhouse. Top, needle spikerush (usually completely submerged); middle, waterweed (breaks the water surface occasionally); bottom, water stargrass (breaks the water surface frequently).

TABLE 6.—*Characteristics of water affected by submerged soil-rooted plants in greenhouse tanks and in lakes*

Sampling points	Period of average (1958)	Temp. ° C	pH	Eh (volts)	Iron (ppm)	O_2 (ppm)	Plant species	Water surface covered (percent)
Greenhouse tanks 104, 204, 504.	February–July	20.6	7.9	0.36	0.15	6.8	Western waterweed.	30
							Algal scum	5
							Total cover	35
Do	August–December	22.2	7.8	.03	.32	.5	Western waterweed.	0
							Algal scum	10
							Lesser duckweed	85
							Total cover	95
Greenhouse tanks 105, 205, 505.	February–July	20.2	8.0	.36	.06	7.1	Water-stargrass	40
Do	August–December	20.9	8.1	.08	.32	2.5	Water-starrgrass	65
							Algal scum	5
							Lesser duckweed	10
							Sago pondweed	5
							Total cover	85
Lake station 3	March–July and November.	15.6	9.0	.29	.18	7.4	Leafy pondweed	[1]
Do	August–October	19.3	7.8	.24	.39	3.3	do	[1]
Lake station 4	June–July and November.	17.7	9.1	.28	.23	7.8	Sago pondweed	[1]
Do	August–October	19.2	8.0	.25	.33	6.3	do	[1]
Lake station 2	March–July and November.	14.9	8.4	.28	.30	6.0	Leafy pondweed and Sago pondweed equal parts.	[1]
Do	August–October	18.9	7.9	.27	.39	4.6	do	[1]

[1] Percent water-surface cover not reported for lake stations because of presence of inherently uncontrollable variables.

The averages of the iron content in the tank water during the growing season were comparable to the averages observed in the lake; however, decreases of the oxygen content and Eh during the growing season were more noticeable in the tank water than in the lake.

Emergent aquatic plants used in the water-iron study are illustrated in figure 33. Table 7 shows average characteristics of water affected by three emergent species—two that grew in the greenhouse tanks and one that grew only in the lake.

Presence or absence of duckweed growth depends, among other things, on availability of adequate light at the water-surface growth site. Cattail and parrotfeather growth sites permit such suitable light conditions for duckweed to grow and coexist (figs. 33 and 34, respectively); the water-surface area may thus seasonally be completely covered by coexisting plant growths. Conversely, water-hyacinth growth sites do not permit suitable light conditions for duckweed growth, and water-surface areas are open between plants; thus, oxygen can more readily interchange between atmosphere and hydrosphere. This fact is demonstrated by the higher dissolved-oxygen

FIGURE 33.—Emergent aquatic plants. Top, water-hyacinth, in greenhouse; middle, parrot-feather, in greenhouse; bottom, broad-leaved cattail, in lake.

FIGURE 34.—Coexistence of duckweed and cattail growth at Federal Center Lake.

and lower dissolved-iron content of the water affected by water-hyacinth compared with the oxygen and iron content of the water affected by parrotfeather.

Dense root growth and nearly complete covering of the water surface by parrotfeather, as well as by lesser duckweed and (or) pond scum, interfered with absorption of oxygen by the water and promoted a low Eh in the tanks. The data in figure 26 show more clearly than the seasonal averages that the iron concentration in the tanks where parrotfeather was growing increased as oxygen and Eh decreased.

In the shallow lake water where broad-leaved cattail was growing, Eh and dissolved oxygen were low from July to October. Although Eh and dissolved oxygen increased considerably during November, iron in the organically rich shallow area remained high. Growth of lesser duckweed among the cattails during July through October indirectly increased iron by interfering with oxygen interchange at the air-water interface and by oxygen usage in respiration. Disintegration of the duckweed during November also contributed organic iron to the water.

TABLE 7.—*Characteristics of water in greenhouse tanks and in lake affected by emergent aquatic plants*

Sampling points	Period of average (1958)	Temp. (°C)	pH	Eh (volts)	Iron (ppm)	O_2 (ppm)	Plant species	Water surface covered (percent)
Greenhouse tanks 101, 201, 501.	February–July	20.9	7.3	.38	0.15	5.6	Water hyacinth	55
Do	August–December	21.7	7.6	.22	.11	3.8	do	100
Greenhouse tanks 102, 202, 502.	February–April	19.3	7.6	.37	.31	4.9	Parrotfeather (pond scum also present).	40
Do	May–December	22.3	7.5	.06	.34	.2	Parrotfeather (duckweed and scum also present).	90
Lake station 5	July–August	24.1	7.2	.04	.42	.2	Broad-leaved cattail.	(1)
Do	September–October	16.6	7.1	.14	.60	.5	Broad-leaved cattail (duckweed also present).	(1)
Do.	November	7.1	7.7	.31	.48	6.8	Broad-leaved cattail.	(1)

[1] Percent water-surface cover not reported for lake stations because of presence of inherently uncontrollable variables.

IRON CONTENT OF WATER IN TANKS CONTAINING SOIL AND WATER-SEDGE

Figure 35 shows the growth of a common ditch-bank phreatophyte, water-sedge, in a greenhouse tank. Data obtained from this study are presented in table 8.

Table 8 shows that water percolating through soil may pick up 10 or more times the amount of iron normally present in water at the lake bottom. Soil in the bare tank was kept saturated. After 2 months of operation, the soil in the bare tank was removed and subjected to pasteurization heat treatment (65°C for 30 minutes) and then returned to the tank. Two months later the soil was again removed from the bare tank and subjected to sterilization heat (127°C for 15 minutes). The soil then was returned to the tank, and the study continued.

TABLE 8.—*Characteristics of water percolating through tank containing bare canal-bank soil and tank containing similar soil and water-sedge*

Tank containing—	Period of average (1958)	Temp. (° C)	pH	Eh (volts)	Iron (ppm)	O_2 (ppm)
Bare soil untreated	February–March	19.6	7.0	0.16	6.5	0.2
Water-sedge	do	20.2	7.0	.16	4.5	.2
Bare soil pastuerized	April–June	19.4			11	
Water-sedge	do	22.4	6.8	.08	7.8	.0
Bare soil sterilized	July–December	23.0	7.2	.11	3.2	.0
Water-sedge	do	22.3	7.3	.07	3.4	.0

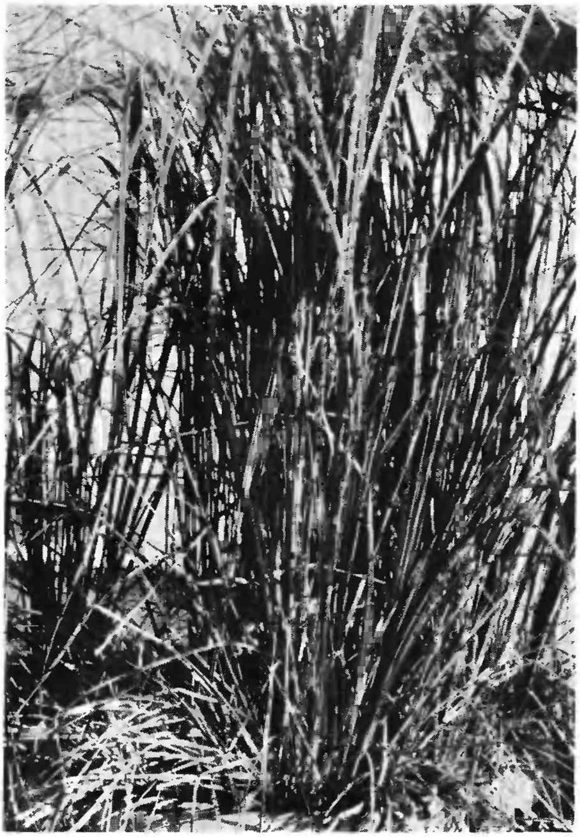

FIGURE 35.—Common canal-bank water-sedge growth in greenhouse tank.

Pasteurization temperatures were not adequate to oxidize soil organic matter but did decrease particularly the non-spore-forming soil-microbe population. Sterilization temperatures had a greater killing effect on the soil microbiota. After soils were subjected to the pasturization and sterilization temperatures, no attempt was made to maintain sterile conditions; nevertheless, the heat treatments undoubtedly decreased the soil microbe population.

The iron in the protoplasm of microbes killed by heat treatment probably was released to the soil solutes as an organic complex. An important difference was noted in the amounts of iron released by lake-botom and by canal-bank soils when subjected to the same sterilization temperatures. The effect of sterilization on lake-bottom soil was to increase soil solute iron tenfold. The same treatment on canal-bank soil decreased soil solute iron by about half. Difference in results seems to be due to a more complete disintegration of organic matter in the lake-bottom soil. In both the bare pasteurized and water-sedge unpasteurized canal-bank soils, iron release by soil microbes during April-June was about double what it was for other months of the year.

AMOUNTS OF WATER USED BY PLANTS

Records were kept of the amounts of water that were added to the tanks in the greenhouse. This was done mainly to know the amount of iron introduced in the weekly tap water additions. The influence of the iron in the added water was minor. Figures 25–28 show no tendency for iron content of the water in the tanks to increase until the time when plant growth became vigorous, although water was evaporated from all but two tanks at a uniform rate through the year.

The rates of water use in the tanks for the period July-December were as follows:

Type of vegetation	*Average water use (gal per week per sq ft of water or soil surface)*
None (open water)	0.93
Do	1.0 (August–December)
Algal scum (mostly *Cladophora* sp.)	.86 (August–October)
Lesser duckweed	.86 (September–December)
Water-stargrass	.94
Western waterweed	.88
American pondweed	.90
Parrotfeather	1.0
Water-hyacinth	2.0
None (wetted canal-bank soil)	.56
Water-sedge in wetted canal-bank soil	3.0

The submerged types of aquatic vegetation reduced evaporation slightly when a thick growth was present. Emergent types, however, permitted at least as much water loss as open-water surfaces. Water-hyacinth, which has broad thick leaves, transpired twice as much water as was lost by evaporation alone from an equivalent open-water area.

Use of a surprisingly large amount of water by water-sedge agrees with observations made by investigators of other phreatophytes. Water-sedge plants consumed three times as much water per unit of soil surface area as was evaporated from open-water and six times as much water as was evaporated from wetted surfaces of similar soil but which had no plant growth.

SUMMARY AND CONCLUSIONS

The average values of iron concentration observed in the lake and in the greenhouse tanks lead to some important conclusions regarding the effects of aquatic vegetation on the transport and deposition of iron in water. Even though amounts of iron entering the Federal Center Lake are not large, iron accumulates in the lake-bottom soil. Contact of lake-bottom accumulated iron with ground water having a low Eh likely would cause the ground water to become iron bearing. Geologic terranes formed under conditions where lakes commonly existed likely would have iron-bearing ground water.

Vegetation growing in water bodies recirculates iron from both water and the bottom deposits by absorbing iron into plant tissues during the growing season and releasing iron both in water solution and as bottom deposits when the season's growth decays. Iron bacteria, notoriously involved in this process, can produce major deposits of iron ore.

Observations in this study emphasize the fact that the amounts of iron recirculated by aquatic vegetation vary with the species and combination of species.

For comparable plant species, iron concentration in lake water was greater than in the greenhouse tanks. The water in tanks that supported plant growth averaged two times more iron content than the water in similar tanks that supported no vegetation. The water-emergent soil-rooted plant parrotfeather brought iron into the water in a quantity comparable to that of the water-submerged soil-rooted and the water-emergent water-rooted groups. All these plants produce a dense and frequently solid cover of vegetation over the water surface during optimum growth conditions. In contrast, water-hyacinth, although it grows thickly, does not produce an asphyxiating cover over the water surface. Even when the water surface was fully covered by water-hyacinth, the pH, Eh, and dissolved oxygen and iron content of the water were nearly the same as for water in which no vegetation was growing. Thick asphyxiating cover of other species resulted in a low Eh and low dissolved-oxygen content in the tanks and favored solution of iron from the water-submerged tank mud.

Water of highest iron content noted in this study was obtained when water was allowed to percolate through the soil in tanks containing canal-bank soil either bare or with a vigorous growth of water-sedge. Soil microbiota activity is known to be extremely effective in bringing soil iron into water solution (Oborn and Hem, 1961) and is most likely the major factor involved in the high iron concentrations observed in the samples from the soil-water drainage tanks.

STATUS OF KNOWLEDGE OF THE CHEMISTRY OF IRON

The research described in this chapter and in chapters A through H of Water-Supply Paper 1459 does not completely cover all possible aspects of iron chemistry in natural water. Work on some aspects has been done by others and much additional research still is desirable. As an example, Eh values observed in some ground waters are higher than expected considering the amount of iron the waters contain; several explanations have been suggested for this anomaly. One of the several possibilities worth exploring is the complexing of ferrous iron with bicarbonate or carbonate ions. Such complexes have not been reported for ferrous iron.

Kinetics of the oxidation of inorganic ferrous iron by atmospheric oxygen were not extensively studied in this research. Recent work by Stumm and Lee (1960, 1961), has added to existing knowledge of this subject. Stumm and Lee found the oxidation to be a first-order reaction with respect to inorganic ferrous iron at a constant partial pressure of oxygen. The rate is highly dependent on pH; at pH levels between 6 and 7, the rate of inorganic iron oxidation is increased by a factor of 100 when the pH is raised by one unit. These experiments were done in water containing bicarbonate.

Before the problems involving iron or other impurities in water supplies can be effectively minimized, a more complete understanding of the chemical behavior of both organic and inorganic materials involved is needed. The research that has been summarized in this report and in the others of the series on iron chemistry are a step toward this understanding.

LITERATURE CITED

Baas-Becking, L. G. M., Wood, E. J. F., and Kaplan, I. R., 1957, Biological processes in the estuarine environment, Xa–Xb. The place of the estuarine environment within the aqueous milieu: Koninkl. Nederlandse Akad. Wetensch. Proc., ser. B, Phys. Sci., v. 60, no. 2, p. 88–95, 96–102.

Fernald, M. L., 1950, Gray's manual of botany: 8th ed., New York, Am. Book Co., 1632 p.

Hem, J. D., 1960a, Complexes of ferrous iron with tannic acid: U.S. Geol. Survey Water-Supply Paper 1459–D.

——— 1960b, Restraints on dissolved ferrous iron imposed by bicarbonate, redox potential, and pH: U.S. Geol. Survey Water-Supply Paper 1459–B.

Hutchinson, G. E., 1957, A treatise on limnology, v. 1, Geography, physics and chemistry: New York, John Wiley and Sons, Inc., 1015 p.

Johnson, L. P., 1944, Euglenae of Iowa: Am. Microscopical Soc. Trans., v. 63, no. 2, p. 97–135.

Moore, E. S., and Maynard, J. E., 1929, Solution, transportation, and precipitation of iron and silica: Econ. Geology, v. 24, 896 p.

Oborn, E. T., 1960a, A survey of pertinent biochemical literature: U.S. Geol. Survey Water-Supply Paper 1459–F.

——— 1960b, Iron content of selected water and land plants: U.S. Geol. Survey Water-Supply Paper 1459–G.

Oborn, E. T., and Hem, J. D., 1961, Microbiologic factors in the solution and transport of iron: U.S. Geol. Survey Water-Supply Paper 1459–H.

Ruttner, F., 1953, Fundamentals of limnology, *translated by* D. G. Frey and F. E. J. Fry: Toronto Univ. Press, 242 p.

Shapiro, Joseph, 1957, Chemical and biological studies on the yellow organic acids of lake water: Limnology and Oceanog., v. 2, no. 3, p. 161–179.

Smith, G. M., 1950, Fresh-water algae of the United States: 2d ed., New York, McGraw-Hill Book Co., 719p.

Steinberg, R. A., 1946, Mineral requirements of Lemna minor: Plant Physiol., v. 21, p. 42–48.

Stumm, Werner, and Lee, G. F., 1960, The chemistry of aqueous iron: Schweiz. Zeitschr. für Hydrologie v. 22, p. 295–319.

——— 1961, Oxygenation of ferrous iron: Ind. and Engr. Chem. v. 53, p. 143–146.

Welch, P. S., 1935, Limnology, New York, McGraw-Hill Book Co., 471 p.

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