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THE EFFECTS OF LOW LEVEL TURBIDITY ON FISH AND THEIR HABITAT

by

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ABSTRACT

The effects of low level turbidity on fish habitat were investigated from July 1980 to September 1982 in a pond near Raleigh, NC. Three levels of turbidity were maintained in polyvinylchloride curtain enclosures with open bottoms each of which enclosed 260-400 m^2 and had a maximum depth of 2 m. Turbidity levels in the pond routinely ranged from 6 to 50 NTU turbidity units with peaks associated with blue-green algal blooms in excess of 120 NTU. The turbid enclosure was maintained between 7 and 45 NTU, the cleared enclosure was maintained between 2 and 12 NTU and the untreated control was between 4 and 18 NTU. Total suspended solids, TSS, explained 68% of the variability associated with turbidity: a 10 mg/l increase in TSS increased turbidity 6 NTU units. Turbidity affected light penetration as determined by secchi depth. In the pond and turbid enclosure the secchi depth represented the 30% light level whereas in the cleared enclosure the secchi depth was equivalent to the generally accepted 15% light level. A 10 NTU increase in turbidity resulted in a 0.6 m^{-1} increase in the light extinction coefficient. As light penetration decreases, the light energy is transformed into heat over a shorter distance and higher epilimnetic temperatures may result. This theory was tested using the above relationships to develop a model, which included the effects of backscatter, to predict epilimnetic temperature changes as a function of turbidity. It was found that as the turbidity increased and/or depth of the epilimnion decreased, the magnitude of the temperature change increased. This was validated by field observations for an epilimnion depth of 0.25 m. In this case, temperatures in the turbid enclosure (28 NTU) were 2-5°C higher than the cleared enclosure (14 NTU). However, at the 'normal' epilimnion depth of 1m, large increases in turbidity resulted in only small temperature increases. Turbidity also had a direct effect on the fish's physical

habitat: a reduction from 12 NTU to 6 NTU enabled submerged macrophytes, due to the increased available light, to colonize deeper waters. This increase in plant biomass would result in increased invertebrate prey and therefore higher fish production.

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SUMMARY AND CONCLUSIONS

An investigation of the effects of low levels of turbidities on fish habitat was conducted from June 1980 to September 1982 in Yates Pond, Wake County, NC. This study investigated the major parameters which were affected by turbidity and influenced fish habitat such as temperature, dissolved oxygen and plant biomass. A mathematical model of the effects of turbidity on temperature was also developed.

We observed in the field and predicted from the model that under low wind conditions, turbidity was responsible for increasing the water temperature by as much as $4^{o}C$ within two days. This increased temperature increases the metabolic cost of fish living in this zone and may exacerbate oxygen depletion in the hypolimnion which would then preclude its use by fish as well as their prey. High levels of turbidity were correlated to restricted development of submerged plants which in addition were probably responsible for reduced dissolved oxygen levels.

In Yates Pond, the sources of turbidity were clays and silts as well as blue-green algae. The highest turbidity levels observed were due to blue-greens algal blooms. These blooms lasted for two to three weeks during which time the water column was supersaturated with oxygen. After the algae died, though, the concentration of oxygen in the water was so low (3-4 mg O_2/l) as to be stressful to fish.

In summary, low level increases in turbidity negatively impact the fish's physical habitat through increases in temperature and decreases in submerged plants which would potentially reduce epiphytic prey as well as dissolved oxygen levels.

RECOMMENDATIONS

Ecological benefits of turbidity control to fish habitat must be considered on a case-by-case basis. Turbidity control should be dealt with as part of a total water management plan. In general, a decrease in turbidity will result in an increase in primary production due to the increased available light. This increased primary production results in an increase in invertebrate grazers which in turn are consumed by fish.

Whether the increase in primary production is due to phytoplankton or macrophytes depends primarily on water depth, which affects light penetration, 'seed' source for the plants, and nutrient availability. Under high nutrient loading conditions, phytoplankton biomass may increase to high levels which could result in low dissolved oxygen at night or anoxic conditions when the population dies. Such rapid changes in dissolved oxygen are not generally associated with macrophytes. In fact, if macrophytes are growing below the thermocline, anoxic bottom waters may not occur. Crowder (1982) showed that fish do well at intermediate macrophyte densities due to the increases in habitat structure and the associated prey, but do less well at either high or low densities. This is of concern in shallow ponds and lakes and on the margins of deeper reservoirs because macrophytes are generally found in waters less than 1 m deep.

When water temperatures are higher than 30°C, measures should be taken to ensure that rapid turbidity increases do not occur. Under certain environmental conditions, i. e. no wind, shallow epilimnion, anoxic bottom waters, and a turbidity increase of 60 NTU, fish are likely to die because they are unable to contend with the

oxygenated but lethal temperatures of the surface waters and the cooler but anoxic bottom waters. We have no estimates of the frequency of occurrence of this set of circumstances. However, we did observe a fish kill in Yates Pond for just such reasons in 1977.

In general a water management program for an area with high nutrient loading that deals with turbidity abatement alone is likely to lead to a decrease in environmental quality unless the nutrients are decreased as well.

INTRODUCTION

Effects of suspended solids or turbidity have been found on nearly every trophic level in aquatic ecosystems (Fig. 1). King and Ball's (1964) study of the effects of highway construction found a two-fold increase in inorganic sediment load reduced by half the primary production of streams (from 269 to 124 mg C $m^{-2}day^{-1}$). Strawn (1961) working in Florida, showed that turbidity was partly responsible for restricted zones of submerged macrophytes and suggested that an important food source for fishes had been reduced. Similarly, Hart and Fuller (1972) found that persistent high turbidity levels limited the development of macrophytes in the Patuxent River. Williams (1966) showed a reduction in zooplankton associated with increased suspended solids. Hubbs (1940) found evidence of reduced eye size, increases in other sensory organs, changes in body form, color and fin development among fishes inhabiting turbid waters.

Effects of suspended solids or turbidity on fishes can be categorized into direct and indirect effects. Examples of direct effects include the following: Green sunfish exhibited a stress response to turbidity (20,000 JTU) (Wallen 1951); green sunfish increased ventilation rates with bentonite suspension levels of about 7500 mg/l (Horkel and Pearson 1976); at much higher levels suspended solids levels also caused gill damage and suffocation in fishes (Ellis 1944); and Wallen also listed lethal suspended solids levels for 14 warm-water species of fish as ranging from 38,250 to 222,000 mg/l . With few exceptions fishes show little direct damage except by very high levels of suspended solids.

Indirect effects on behavior of fishes occur at considerably lower levels. The reactive distance of

bluegills to zooplankton prey was reduced at turbidities as low as 6.25 JTU (Vineyard and O'Brien 1976). Similarly, Gardner (1981) found the feeding rate of bluegill on Daphnia was inversely proportional to turbidity. At the highest turbidity tested (190 JTU) the feeding was 54% of the control.

Additional indirect effects include blockage of spawning migrations by striped bass which occurred at 300 mg/l suspended solids, ss, (Radtke and Turner 1967) and reduced feeding by trout at 35 mg/l ss (Bachmann 1959). The vertical distribution of larval lake herring changed when exposed to turbidity levels of 26-28 FTU (about 18 mg/l ss)(Swenson and Matson 1976). Activity was reduced and social hierarchies of largemouth bass and green sunfish were disturbed at turbidities of 4-16 JTU (Hemistra et al. 1969).

More general effects include reduced fish populations and reduced fishing success and effort (Buck 1956). In his study primary productivity was 12.8 times higher in clear than turbid (100 mg/l ss) ponds and the former supported 5.5 times more fish.

Any increase in turbidity, however, affects light penetration and therefore, can affect primary production, hence oxygen concentration, and temperature. These, in turn, can have sub-lethal effects on fishes.

Doudoroff and Shumway (1970) reviewed the literature on dissolved oxygen requirements of fishes. Among the more important findings pertinent to the discussion were those of Hoglund (1961) who showed increased fish activity in oxygen deficient water. Whitmore et al. (1960) found avoidance of oxygen concentrations of 3 mg/l and 4.5 mg/l by largemouth bass and bluegill, respectively. They further argued that, unlike Hoglund's suggestion of low oxygen as a "releasing

stimulus" to higher activity, fish in their experiments exhibited a "directed response" away from low oxygen. Dunst (1969) found largemouth bass could not survive in the low oxygen (<5.0 mg O_2/l) hypolimnion of many Wisconsin lakes in summer. Tolerance of low oxygen, and perhaps avoidance, is affected by thermal stress (Moss and Scott 1961). Hutchinson (1976) found the converse, that is, reduced temperature tolerance in oxygen-stressed fish.

The subject of temperature tolerance of fishes has received considerably more attention than oxygen tolerance. Recently, most research has been directed at sub-lethal effects of temperature on fishes. Doudoroff (1969) found the maintenance ration of largemouth bass increased from 0.5% of body weight day to 2.0% with an increase in temperature from 10 to 15°C. Sylvester (1972) found that thermally stressed sockeye salmon were more vulnerable to predation. Coutant et al. (1974) reported similar findings for young largemouth bass and channel catfish. Coutant and Cox (1976) found the temperature for maximum growth to be 26 and 27°C for small and large largemouth bass, respectively. Growth was thus depressed well before the incipient lethal temperature (about 36.5^{o}C) was reached. They suggested 31.3^{o}C as an upper limiting temperature. Plumb (1973) found heat-stressed channel catfish to be more susceptible to disease, and Swallow (1968) found increased mortality among fish embryos exposed to higher incubation temperatures.

The preferred temperature and temperature avoidance behavior of fishes generally reflects these sub-lethal temperatures. Peterson and Schutsky (1976) found bluegill acclimated to 27.0^{o}C preferred a temperature of 31.7^{o}C and avoided 33.5^{o}C which is below their upper lethal limit. Neill and Magnuson (1974) investigated the preferred temperature of 11 species of fish in Wisconsin and also

found that these fish avoided temperatures well above and below their lower and upper lethal limits, respectively.

Conclusions possible from the literature are: 1) fish generally avoid conditions well inside their lethal limits of both temperature and oxygen; and 2) sub-optimal growth (or health) probably occurs when fish are forced to live outside their preferred ranges of oxygen and temperature.

In nature, and especially in stratified small turbid lakes, it is likely that the habitat (living space) of fishes in summer is restricted to an intermediate stratum between avoided high temperature above and avoided low oxygen below.

In eutrophic lakes, fish are often excluded from the hypolimnion by the low oxygen levels in summer (Dunst 1969). In turbid lakes, fish may also be thermally excluded from surface layers. An extreme example occurred in Yates Pond, NC, during fall 1977. Defining the living space of fish as water below $31_{o}C$ and having more than 4.5 mg/l O_2, this was a layer between 0.2 and 1.5 m on 29 July. During the ensuing 14 days, this living space shrunk; on 8 August it was between 0.6 and 0.8 m. On 12 August the two boundaries converged and on the same day, a fish kill of an estimated 500 kg occurred.

This study documents the indirect effects of low levels of turbidity on factors that influence fish habitat such as temperature and dissolved oxygen as well as chlorophyll a and macrophyte distribution. A companion report is currently in preparation that will describe the direct effects of turbidity on fish feeding and their prey.

METHODS

Site description

The study site was located in Wake county, N.C. at Yates Research Facility owned by North Carolina State University. Based on surveys of other lakes in the region, Yates Pond is a typical shallow turbid impoundment. Yates Pond has an area of 8.7 hectares and an average depth of 1.5 m. Fifty nine percent of the total volume was less than 1 m deep. Nuphar and Polygonum were the principle emergent vegetation that occupied most of the margin of the lake. Sediments were soft mud with varying amounts of plant detritus. The main feeder stream entered at the north end of the pond where the water was less than 0.5 m deep and there were extensive dense beds of Nuphar. The pond gradually deepened to 3 m near the dam at the south end. Experiments were conducted on the eastern shore in water 0.2 to 2 m deep.

Experimental units

Turbidity was manipulated in three large enclosures that encompassed both the littoral zone and open water. One side of the enclosure was the shore, the other three sides were made of 16 mil clear polyvinylchloride, PVC. This curtain was 2 m wide in the open water and tapered down to 30 cm on the shore. The bottom of the curtain was held down by a lead weighted line that was pressed into the bottom. The entire top of the curtain was supported by sealed 10 cm diameter PVC pipes. In 1981 the enclosures were approximately 400 m^2. In 1982 the area of the enclosures was reduced to 260 m^2. During each experiment one enclosure was enriched with suspended sediments, one had the

suspended material removed by a chemical flocculating agent and one served as a control. Between experimental runs, then enclosures were pulled onto shore and scrubbed in order to remove periphyton growth.

Turbidity manipulations

Suspended sediments were removed from the enclosures using alum (aluminum sulfate) and calcium hydroxide (Boyd 1979). In 1981 approximately 22 kg of alum to 3 kg of $Ca(OH)_2$ per enclosure was added in the following manner: 4.4 kg alum was mixed with pond water in a 100 l plastic container. In a second container, 600 g $Ca(OH)_2$ was mixed with pond water. Contents of both were added simultaneously from a boat. This procedure was repeated five times. Settling of suspended solids began almost immediately with equilibrium levels reached within 24 hours. In 1982, because of the reduced size of the enclosures, 9 kg alum and 1.2 kg of $Ca(OH)_2$ were used per enclosure. The diluted chemicals were sprayed from shore from the containers using a submersible pump. If during the experiment, turbidity increased, an additional 4.5 kg alum and 600 g $Ca(OH)_2$ were added.

In 1981 turbidity in enclosures was enhanced by the addition of benthic mud sieved through 335 micrometer plankton nets. Approximately 90 l of mud were added in early morning three times per week. In 1982, we used commercially available bentonite. On day one 18 kg of bentonite was mixed with well water in a 100 l container and sprayed out over the enclosure using a submersible pump. Then on every other day an additional 4.5 to 9.0 kg were added in a similar manner.

Field sampling

Yates pond was sampled weekly during 1980 and 1981. After late 1981 samples were taken monthly through early 1982. The subponds were sampled intensively, sometimes as often as twice a day for several days in a row.

Water samples were taken from surface to bottom at 0.5m intervals using a Van Dorn sampler. Three replicates were taken at 0.5m depth, single samples at other depths. The samples were placed in plastic bottles and processed in the lab within 3 hours.

Temperature, dissolved oxygen and light

Water temperatures were measured at depths 0 m (surface), 0.02 m, 0.03 m, and 0.25 m to the bottom at 0.25m intervals using a digital thermometer (Bailey Instruments BAT-8) equipped with thermocouple probes. In 1982 temperatures were taken with a YSI Model 54M Oxygen Meter equipped with a thermistor.

Dissolved oxygen was measured in the field with a YSI oxygen meter from the surface (0 m) to the bottom at 0.25 m intervals.

Underwater intensities of photosynthetically active radiation (PAR) in the 400-700 nanometer waveband was measured using a Li-Cor LI-192S Underwater Quantum Sensor and the Li-Cor LI-185A Quantum meter/ Radiometer/ Photometer. Omnidirectional PAR in the same range was measured using a Li-Cor LI-193S Spherical Quantum Sensor.

Turbidity measurement

Turbidity was measured with a Turner Model III fluorometer (Turner Instruments, Inc.) adapted for nephelometry. In 1980-81, the instrument was equipped with Turner filter # 5-60 (430-450 nm) in the primary slot and neutral density filters equivalent to 0.5% transmittance in the secondary slot. All readings were made with the sensitivity scale set to '3x'. Calibration curves were produced using standard formazin mixtures (APHA et. al.,1975) and measuring their turbidities in a square cuvette.

In March, 1982 the filters were changed because the fluorometer had been modified to measure chlorophyll. The filters used were Turner filter # 10-053 (or Kodak Wratten color specification 16) in the primary slot and 3% transmittance Neutral Density filters in the secondary slot. The machine required frequent rezeroing after this modification.

Determination of total suspended solids and organic fraction

In the lab, the water samples were shaken and 50 ml - 1,000 ml were filtered through prewashed, preweighed Whatman glass fiber filter (GF/C) with a 1.2 micrometer pore size. Filters were dried for 20-24 hours at 55°C to determine total suspended solids, TSS. They were then weighed, combusted for 1 hour combustion at 550°C, and reweighed to determine the percent organic fraction.

Determination of chlorophyll a

Water samples were shaken and 25 ml to 100 ml were filtered with 22 cm of Hg vacuum through a 47 mm diameter,

0.45 micrometer pore, Millipore acetate filter. When approximately 10-15 ml of the sample remained to be filtered, 1-2 ml of a saturated magnesium carbonate ($MgCO_3$) solution was added to prevent chlorophyll deterioration. Two to three replicate filters were prepared from each field sample. The filters were folded, placed in vials, enclosed in light-tight boxes and frozen. Chlorophyll was extracted in the freezer with 10 ml of 90% acetone for 20-24 hours. The contents of the vial were centrifuged, diluted and measured in a Turner Model III fluorometer equipped as in Lorenzen (1966). Phaeo-pigments were determined by acidification.

Net ecosystem production

Daily changes in oxygen in free water were used to calculate net ecosystem production, NEP:

NEP=(O_2 change in epilimnion)*(depth of epilmnion) *(proportion of solar day)

where the proportion of the solar day is a factor that adjusts for change in solar energy throughout the day.

Changes in planktonic oxygen production were measured using 300 ml glass bottles.

RESULTS

Turbidity and suspended solids

In Yates pond, turbidity fluctuated from highs during the fall in excess of 100 NTU to summer lows of 5 NTU with winter values around 50 NTU (Fig. 1). The total suspended solids, TSS, associated with the fall peaks (Fig. 2) was 100% organic matter where as for the winter it was only 30% organic matter. For all of the winter values combined, total suspended solids averaged 19 mg/l and were 30% organic material. During the summer and fall seasonal averages ranged from 14 to 40 mg/l TSS and 33 to 70% organic matter (Table 1).

Table 1 : Seasonal averages of turbidity (NTU), chlorophyll a (CHL), phaeo-pigments (PHAEO), total suspended solids (TSS), percent organic matter (%OM), secchi depth, the one percent light level and extinction coefficient (Nt).

YEAR	SEASON	NTU	CHL	PHAEO	TSS	%OM	SECCHI	1%LIGHT	Nt_{-1}
			---ug/l--		mg/l		m	m	m^{-1}
1980	FALL	43	12	8	40	33	0.25	1.1	4.3
1981	WINTER	27	7	5	22	31	0.64	1.9	2.5
1981	SPRING	13	5	4	10	27	1.1	3.6	1.4
1981	SUMMER	16	25	5	14	70	0.6	2.7	2.0
1981	FALL	20	113	11	19	64	0.7	1.6	4.3
1982	WINTER	38	10	3	17	29	0.5	1.1	4.5
1982	SUMMER	19					0.7	1.1	4.5

Relationships between turbidity and chlorophyll, phaeo-pigments, total suspended solids and percent organic matter were examined. Only total suspended solids was significantly correlated with turbidity ($p<0.0001$) and it accounted for only 24% of the variation in turbidity ($n=239$). However, a significant portion of the turbidity was caused by particles that passed through the 1 micrometer

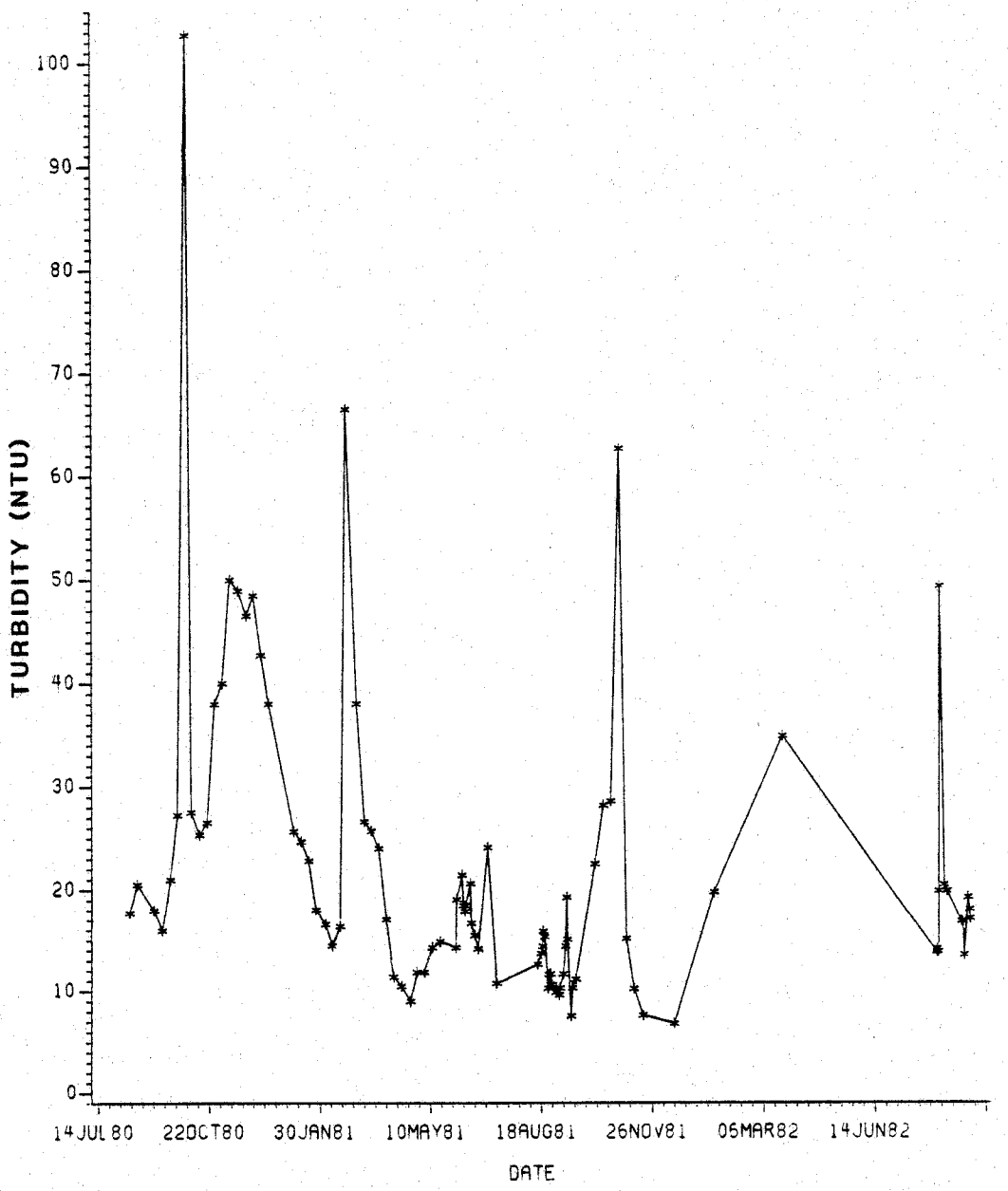

FIGURE 1 · AVERAGE NTU IN THE UPPER 0.5M OF YATES

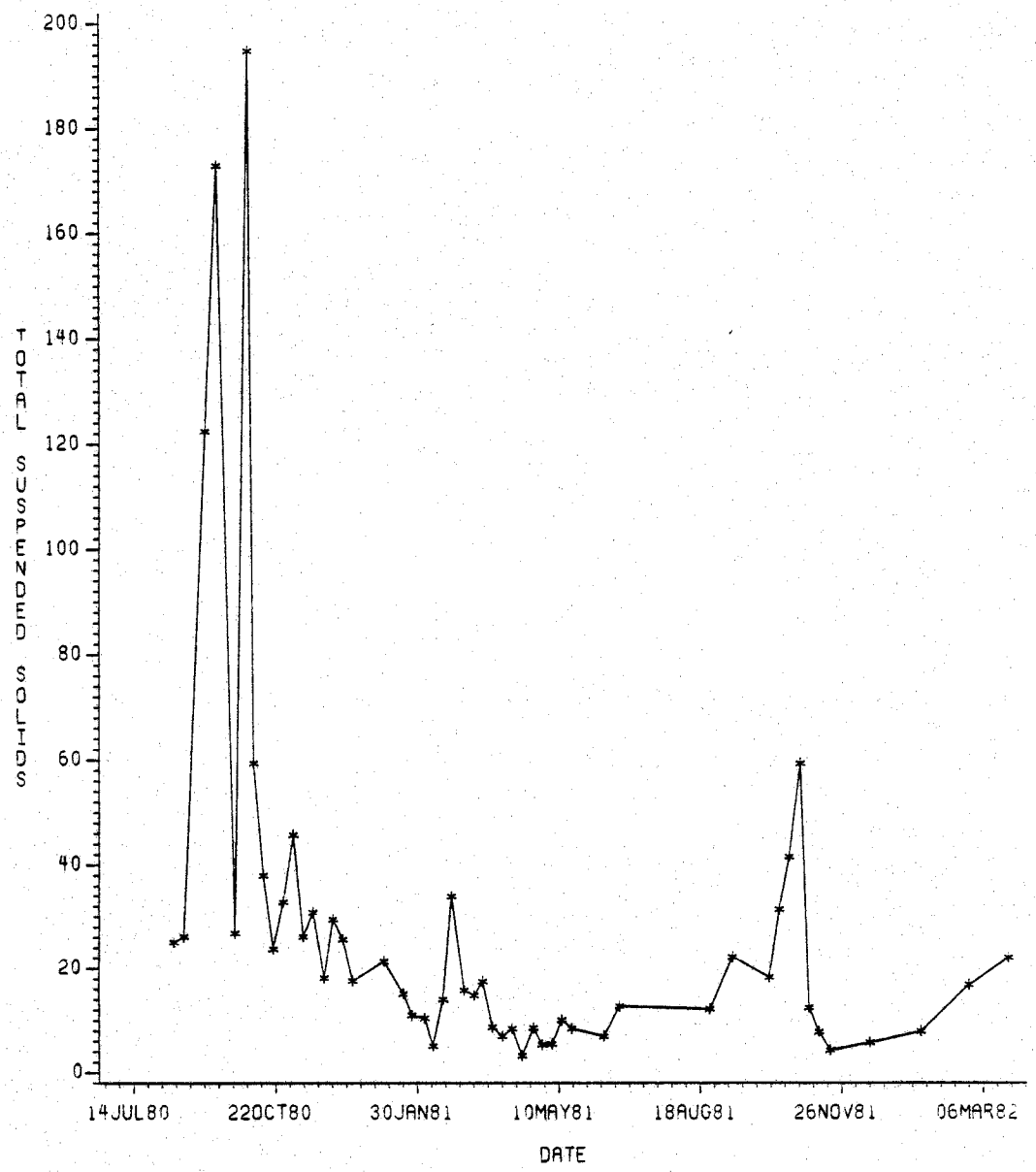

FIGURE 2 AVERAGE SUSPENDED SOLIDS (MG/L) IN THE UPPER 0.5M OF YATES POND

glass fiber filters used for determining TSS. When the NTU of the filtrate was subtracted from the initial NTU, TSS accounted for 68% of the variability (n=112). There were seasonal differences as well. During the fall, TSS accounted for 54% of the variability in NTU, whereas in the summer no correlation was found (Table 2).

Table 2. Relationships between turbidity, NTU, and total suspended solids, TSS (mg/l).

		n	R^2	data base
NTU (total)	= 21.8 + 0.22*TSS	239	.24	all seasons
NTU (total)	= 21.8 + 0.42*TSS	92	.54	fall
NTU (total)	= 10.2 + 0.32*TSS	38	.42	spring
NTU (total)	= 24.5 + 0.18*TSS	75	.23	winter
NTU(filterable)	= 1.65 + 0.62*TSS	112	.68	all seasons
TSS	= 2.68 + 1.08*NTU(filt)	112	.68	all seasons

Turbidity and light

Light extinction coefficients, Nt, were derived from photometer data based on the following equation:

$$Iz = Io * e^{(-Nt*z)} \qquad (1)$$

where Iz is the light at depth z, and Io is the light at the surface.

Extinction coefficients varied from a seasonal average low of 1.4/m in the spring of 1981 to a high of 4.3/m in the winter of 1982 (Table 1, Fig 3). From the extinction coefficients, the depth of 1% light intensity and the light intensity that corresponds to the secchi depth were estimated. The average depth of the 1% light level ranged

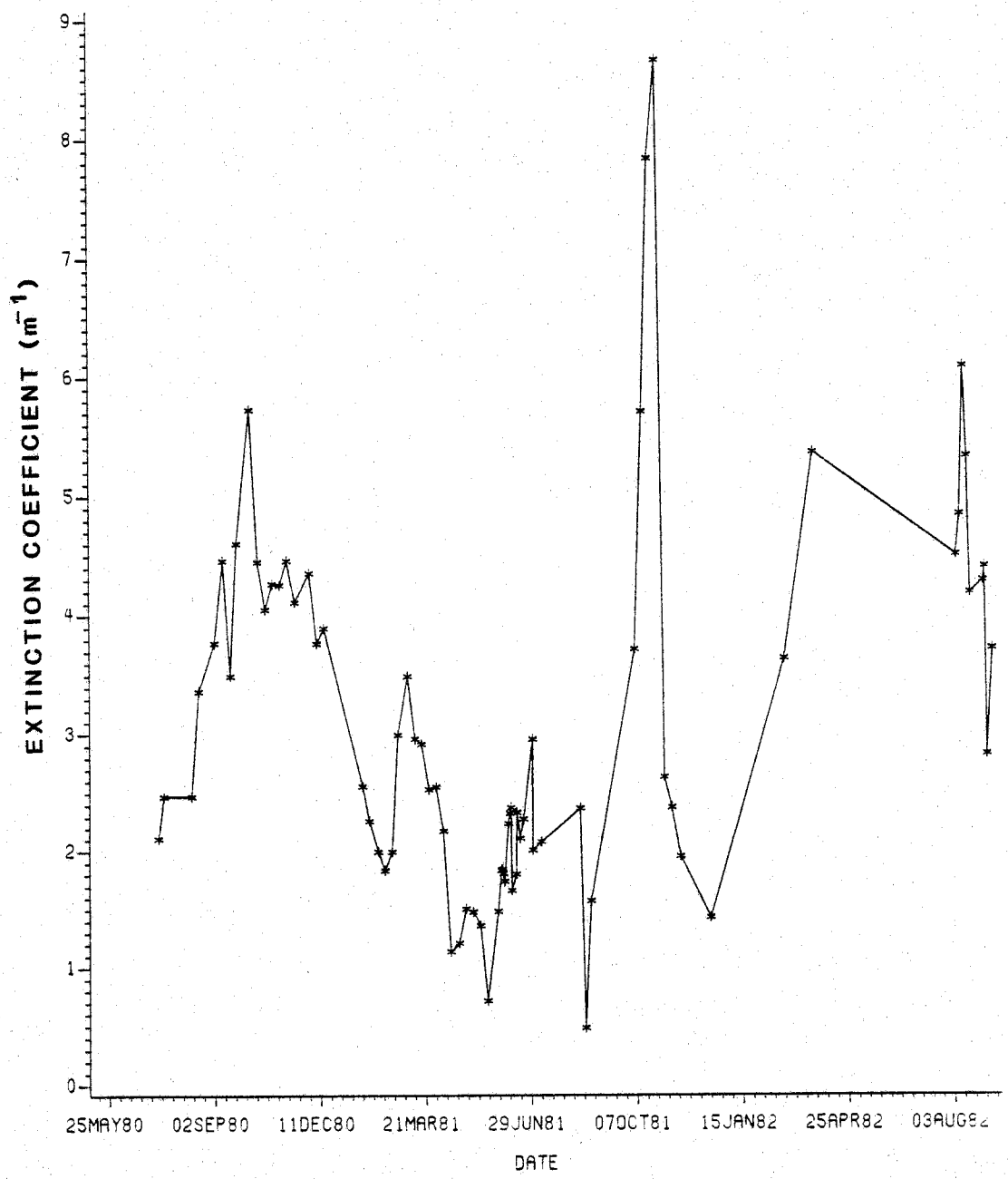

FIGURE 3 : EXTINCTION COEFFICIENT FOR YATES POND VS TIME

from 1.1 m to 3.6 m. Based on 66 observations that spanned two years, we estimated that the depth at which the secchi disk disappears corresponds to the 30% light level.

The extinction coefficient was significantly correlated to both turbidity and TSS. Based on 224 observations over all seasons, the regression on TSS was significant but explained only 11% of the variation. When only fall data were used 58% of the variation was explained. Spring, summer and winter data produced nonsignificant relationships between TSS and Nt. Turbidity was significantly related to Nt for all seasons combined; seasonally only the spring data was nonsignificant (Table 3).

Table 3. Relationships between TSS (mg/l), NTU and extinction coefficients, Nt.

Nt = No + f(TSS or NTU)	n	R^2	SE*	data base
Nt = 2.7 + 0.014TSS	224	.11	.003	all seasons
Nt = 2.1 + 0.07TSS	80	.58	.007	fall only
Nt = 1.4 + 0.06NTU	250	.34	.006	all seasons
Nt = 2.4 + 0.06NTU	81	.30	.009	fall
Nt = 1.2 + 0.08NTU	63	.11	.029	summer
Nt = 2.0 + 0.03NTU	68	.27	.005	winter

* SE = standard error of the regression coefficient.

Seasonal variation in temperature

Yates was generally isothermal during fall and winter and was stratified during the spring and summer. During 1981 the pond was well mixed until March 24, within a week the surface layer had increased 8°C from the previously isothermal 6°C. The difference between top and bottom water temperature was 6°C. The pond remained stratified until late June with a temperature differential between top

and bottom, a 2 m distance, of 8-9°C. The epilimnion was 0.75 m deep. It restratified and remained that way until mid-August. During the summers of 1980 and 1981 the average temperature of the upper 0.5 m of the water column exceeded 31°C (Fig. 4) while the surface layer itself was hotter than 33°C. Minimum surface temperatures of 1-2°C were measured in January of both 1981 and 1982.

Effects of turbidity manipulations on temperature

The subponds, maintained at three different turbidity levels, only exhibited differences in temperature under the certain environmental conditions. In early September 1982 temperature differences of 2 to 4°C were maintained for one or two days before the wind would completely mix the water column (Fig. 5). On 9/7/82 all subponds and Yates were well mixed: control and alum-treated subponds had a temperature of 22.9 °C, turbid was 22.1°C and Yates was 23.5 for an average temperature of 22.8°C. By the next day the turbid subpond had an 0.25 m epilimnion, a temperature of 28.7 and a 3.5 degree difference between 0.25 m and 0.5 m. The control subpond also had 0.25 m epilimnion but was 2.3°C cooler at 26.4°C. The alum-treated subpond was still well mixed with an average temperature of 23.5°C. By 9/9/82 temperature differences were even greater. The turbid subpond had a 29.2°C, 0.25 m thick epilimnion and a 4.5°C temperature differential between 0.25 m and 0.5 m. The control subpond had a 26.8°C, 0.25 m thick epilimnion and a 1.2°C differential between the epilimnion and the hypolimnion. The alum-treated subpond had developed a temperature gradient to 0.75 m with an average temperature of 25°C. The differential between the turbid and alum-treated enclosures then was 4.2°C. During this time the turbid enclosure had an average extinction coefficient 7.83/m, a 1% light level of 0.6 m and a turbidity level of 28 NTU. The alum-treated enclosure on

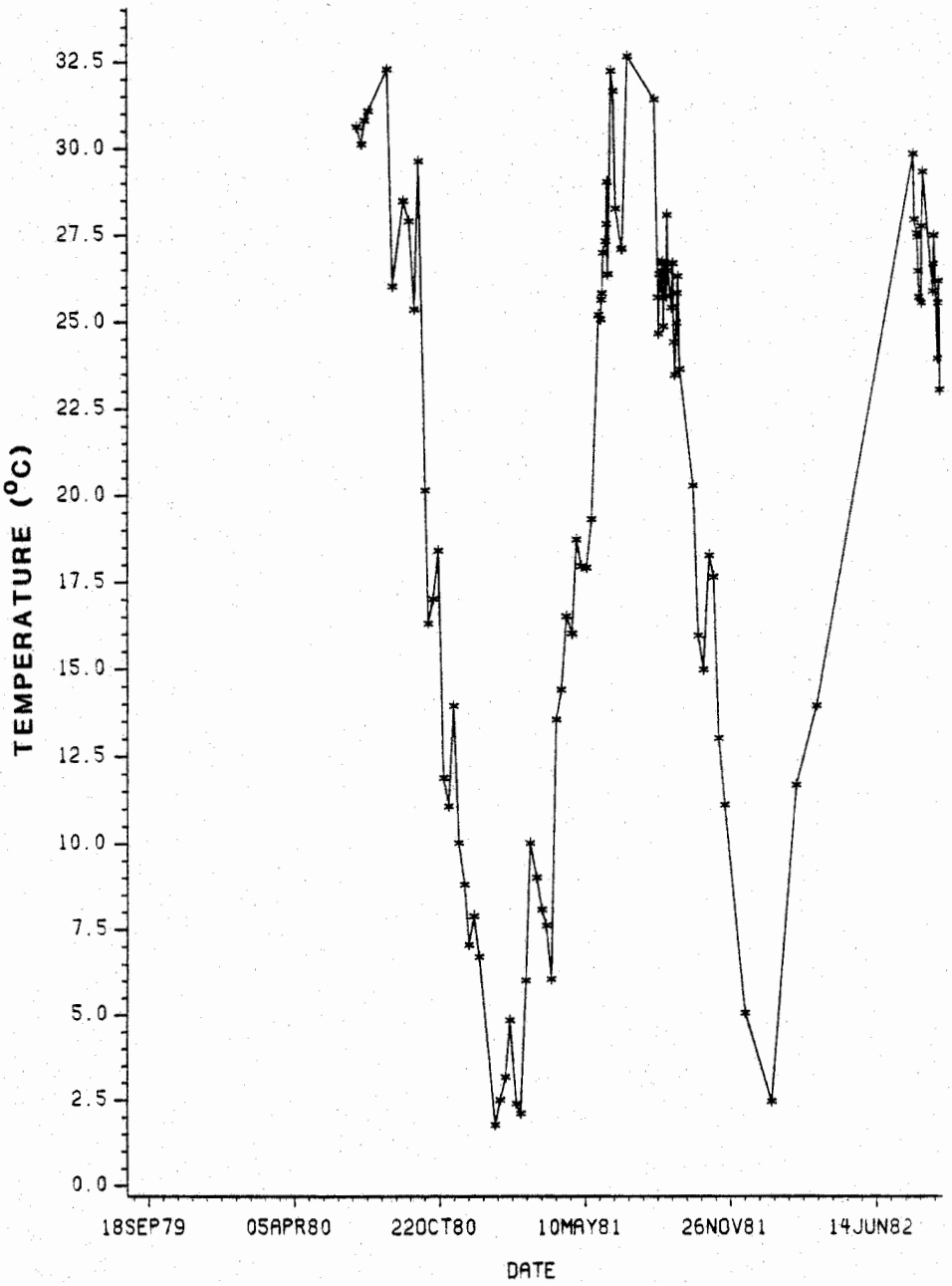

FIGURE 4 : AVERAGE TEMPERATURE IN THE UPPER 0.5M OF YATES POND FOR 1980 -

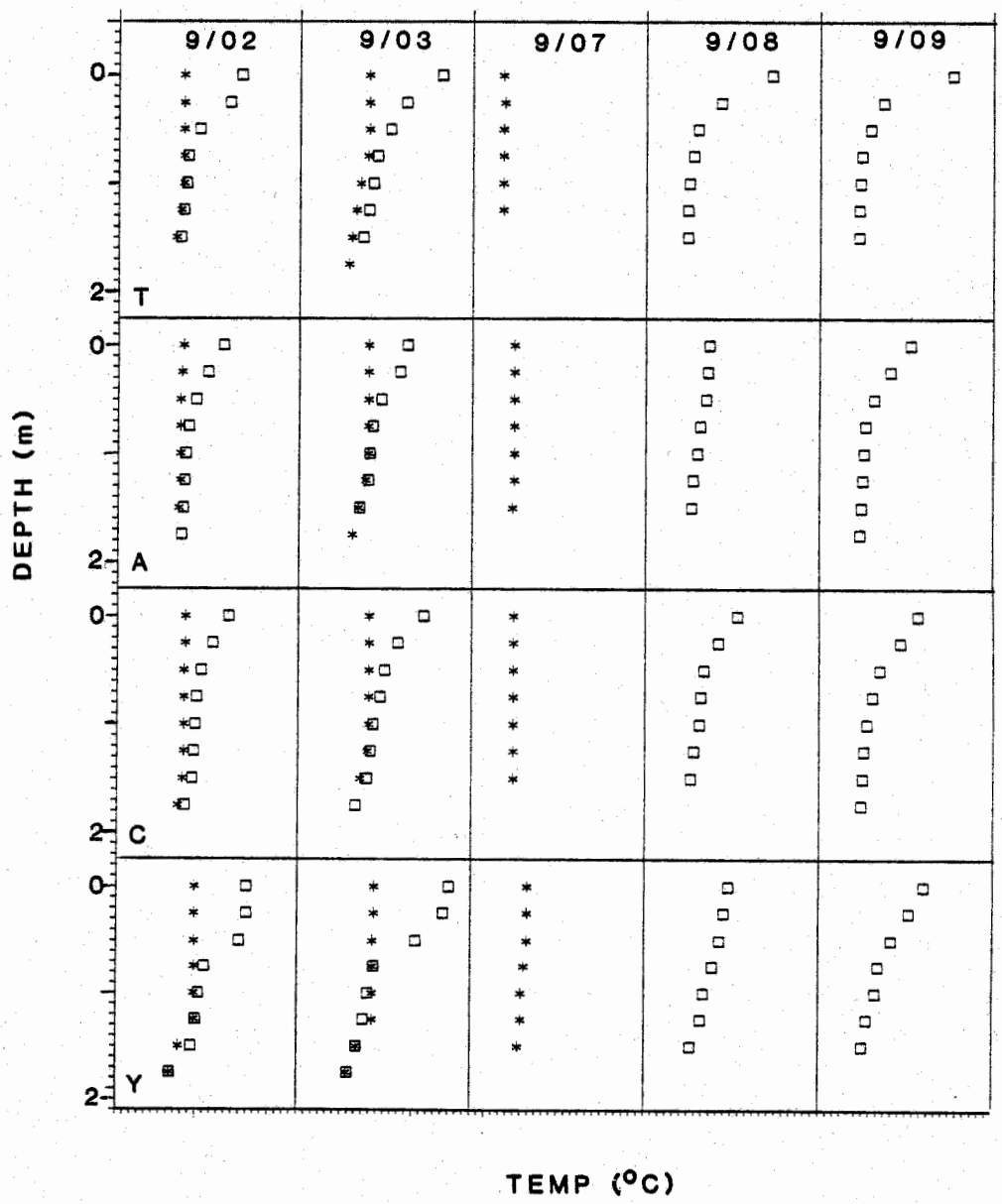

FIG. 5 TEMPERATURE VS DEPTH THROUGH TIME FOR SEPTEMBER 1982
EACH BOX WIDTH IS A TEMPERATURE RANGE FROM 20 TO 32 DEGREES
LEGEND: Y=YATES, T=TURBID, A= ALUM TREATMENT, C=CONTROL
SYMBOLS : * = MORNING SAMPLING, □ = AFTERNOON SAMPLING

the other hand had an extinction coefficient of 3.1/m, a 1% light level of 1.5 m and a turbidity level of 13.5 NTU.

During 1981 and August 1982 (Fig.6), however, thermoclines were much deeper than in September 1982 and these extremes in temperature were not observed. For example, between 8/7/81 and 8/17/81 the turbid enclosure had an average thermocline depth of 1.4 m, an average extinction coefficient of 5.76/m and the 1% light level at 0.8 m but there was no difference in temperature between the subponds.

Plants and oxygen

Plant biomass varied greatly both between and within years. In August 1981 the density and 95% confidence intervals of the submerged macrophyte, Chara, for all 3 subponds was 257 $\pm$70 g dry weight m^{-2}. In September 1981 alum was added to the turbid enclosure and turbidity was added to the alum enclosure. At the end of the experiments, the enclosure with increased light penetration also had an increase in bottom coverage of the plants. The enclosure that received increased turbidity showed no change in plant coverage over the 21 day treatment period (Table 4). In the summer of 1982, no Chara was observed. With the higher water levels in 1982, the emergent plant Polygonum and the floating leaved plant Nuphar were inundated. During 1981 because of the low water, the beds of most of these plants were out of the water.

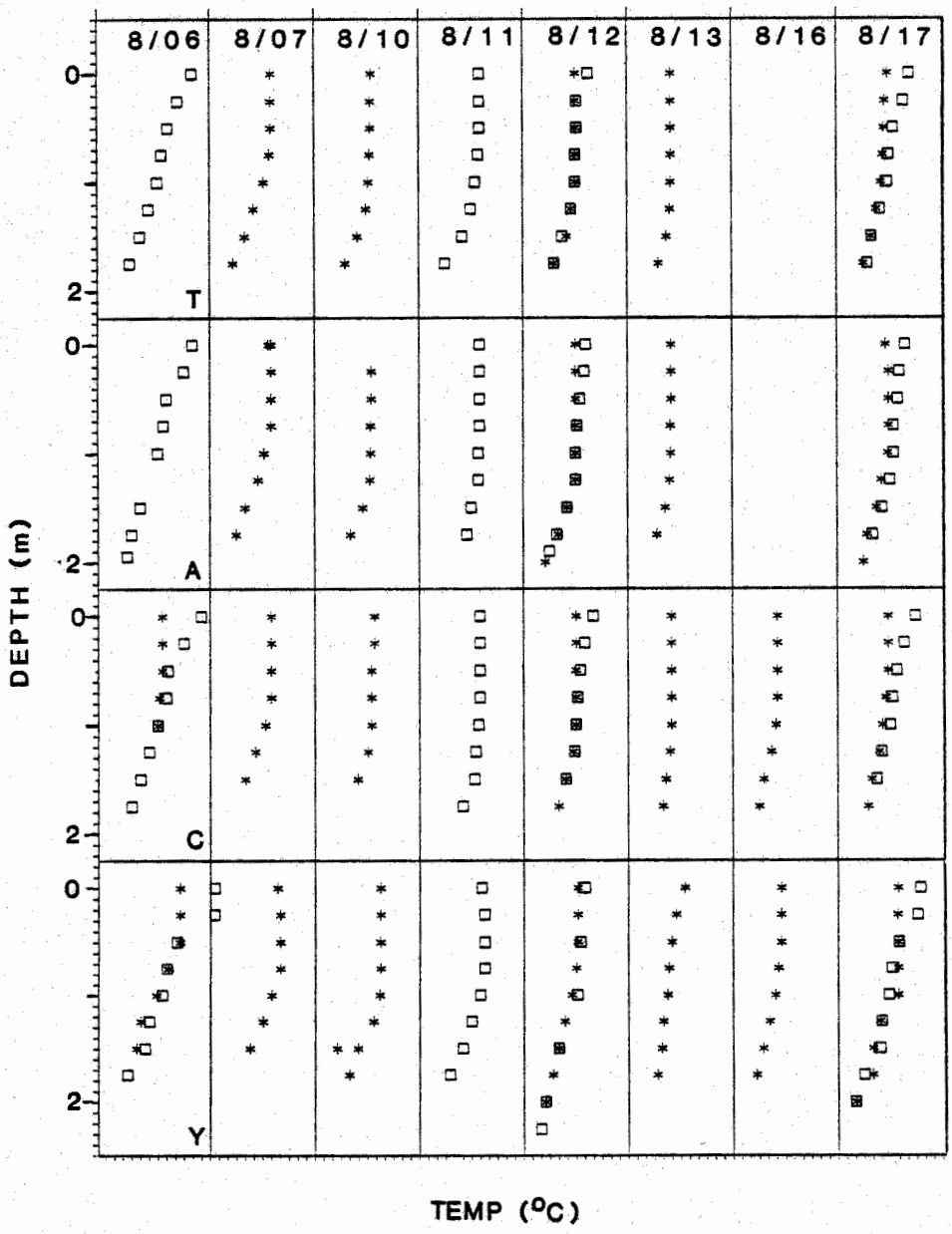

FIG. 6 TEMPERATURE VS DEPTH THROUGH TIME FOR AUGUST 1982
EACH BOX WIDTH IS A TEMPERATURE RANGE FROM 20 TO 32 DEGREES
LEGEND: Y=YATES, T=TURBID, A= ALUM TREATMENT, C=CONTROL
SYMBOLS : * = MORNING SAMPLING, □ = AFTERNOON SAMPLING

Table 4: Change in bottom area coverage of Chara beds in relation to changes in turbidity in 1981.

POND	AUGUST TRT	AUGUST AREA(m^2)	SEPTEMBER TRT	SEPTEMBER AREA (m^2)
I	TURBID	102	ALUM	164
II	CONTROL	nd*	CONTROL	196
III	ALUM	148	TURBID	154

* nd=no data.

Community production as measured by change in oxygen concentration in Yates pond was very high. In July 1981 net ecosystem production, NEP, which included phytoplankton and macrophytes was 3 g O_2 m^{-2} day^{-1}. For the isolated planktonic population, NEP was 0.6 g O_2 m^{-2} day^{-1} based on morning values. During the afternoon, however, oxygen production equaled respiration so NEP was zero. In late summer of 1981 NEP ranged from 0 to 3.8 g O_2 m^{-2} day^{-1}. In 1982 NEP ranged from -0.5 to 3.0 (Table 5).

Table 5 : Net ecosystem production values for Yates and subponds in 1981 and 1982 (g O_2 m^{-2} day^{-1}).

DATE	YATES	TURBID	ALUM	CONTROL
8/28/81	3.4	2.1	3.1	3.3
9/1/81	3.8	2.5	2.5	2.4
9/3/81	2.9	1.3	2.2	2.2
9/9/81	-	0	0	0
8/6/82	3.0	-	0.9	-
8/12/82	2.6	-	1.4	-
8/17/82	-0.4	0.5	-0.5	0
9/2/82	1.5	1.2	0.5	1.2
9/3/82	0.7	1.0	0.5	1.5

In 1981 plant production was of such magnitude that during the day the water was often supersaturated with oxygen. The hypolimnion though after stratification often experienced very low levels of oxygen, from 3 to less than 1 mg O_2/l (Fig. 7). Following the die off of large

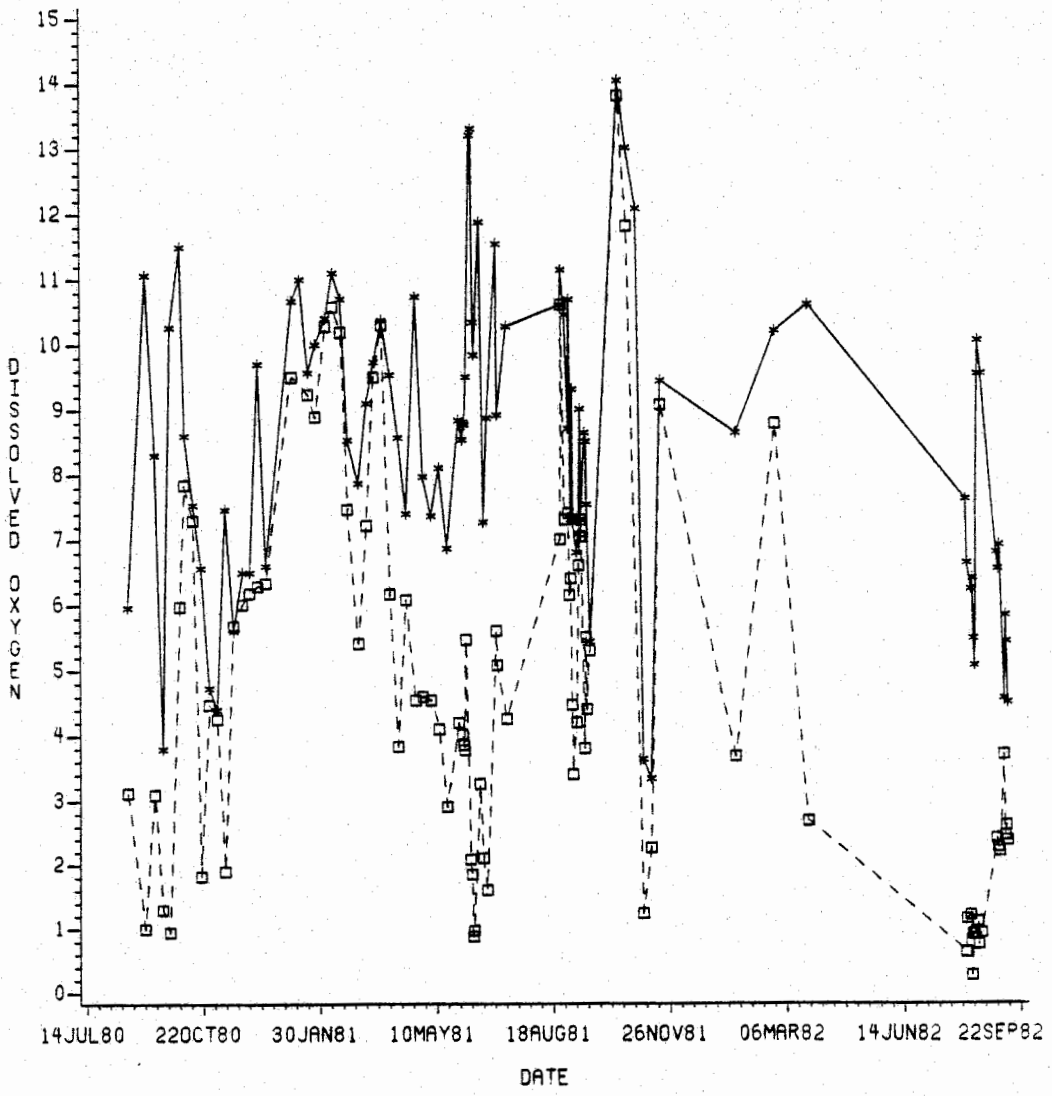

FIGURE 7 : DISSOLVED OXYGEN (MG/L) VS TIME - YATES POND
AVERAGE CONCENTRATION FOR 0-0.5M (-*-) AND 1.25-2.0M (-

blue-green algal blooms in both 1980 and 1981 the entire water column experienced low levels of oxygen, less than 3 mg/l, In 1982 oxygen concentrations in the epilimnion during the summer were generally below saturation. In the alum-treated subpond the entire water column was often near 3 mg/l O_2.

Phytoplankton biomass as measured by chlorophyll a concentration fluctuated from summer lows of 5 ug/l to fall peaks 100 and 300 ug/l for 1980 and 1981, respectively (Fig. 8). The peaks were due to blue-green algae. Accompaning these periods of intense algal production were increases in light extinction coefficient, Nt, decreases in secchi depth, increases in chlorophyll a, CHL, suspended solids, TSS, and dissolved oxygen concentration, DO (Table 6).

Table 6 : Water quality parameters before, during and after a blue-green algal bloom in 1981. Measured during mid-day.

DATE	CHL	NTU	TSS	DO surface	DO bottom	SECCHI	Nt
9/10	27	19	24	9.0	7.0	0.5	-
9/18	-	12	-	5.4	5.3	0.5	-
10/6	113	22	18	-	-	0.5	3.7
10/13	197	28	-	14	14	0.4	5.7
10/20	284	28	42	13	12	0.3	7.8
10/28	282	63	59	12	-	0.3	8.7
11/3	39	15	12	4	1.2	-	2.6
11/10	8	-	-	3	2	1.0	2.4
11/18	25	-	-	9.4	9.1	1.1	1.9

Chlorophyll a : phaeo-pigment ratios were correlated to fall values for NTU, R^2=18% n=49:

$$\text{chl-a/phaeo} = 10.2 - 0.17\ \text{NTU} \quad .$$

Regressions of this ratio against TSS and Nt, yearly as well as seasonally, were not significant.

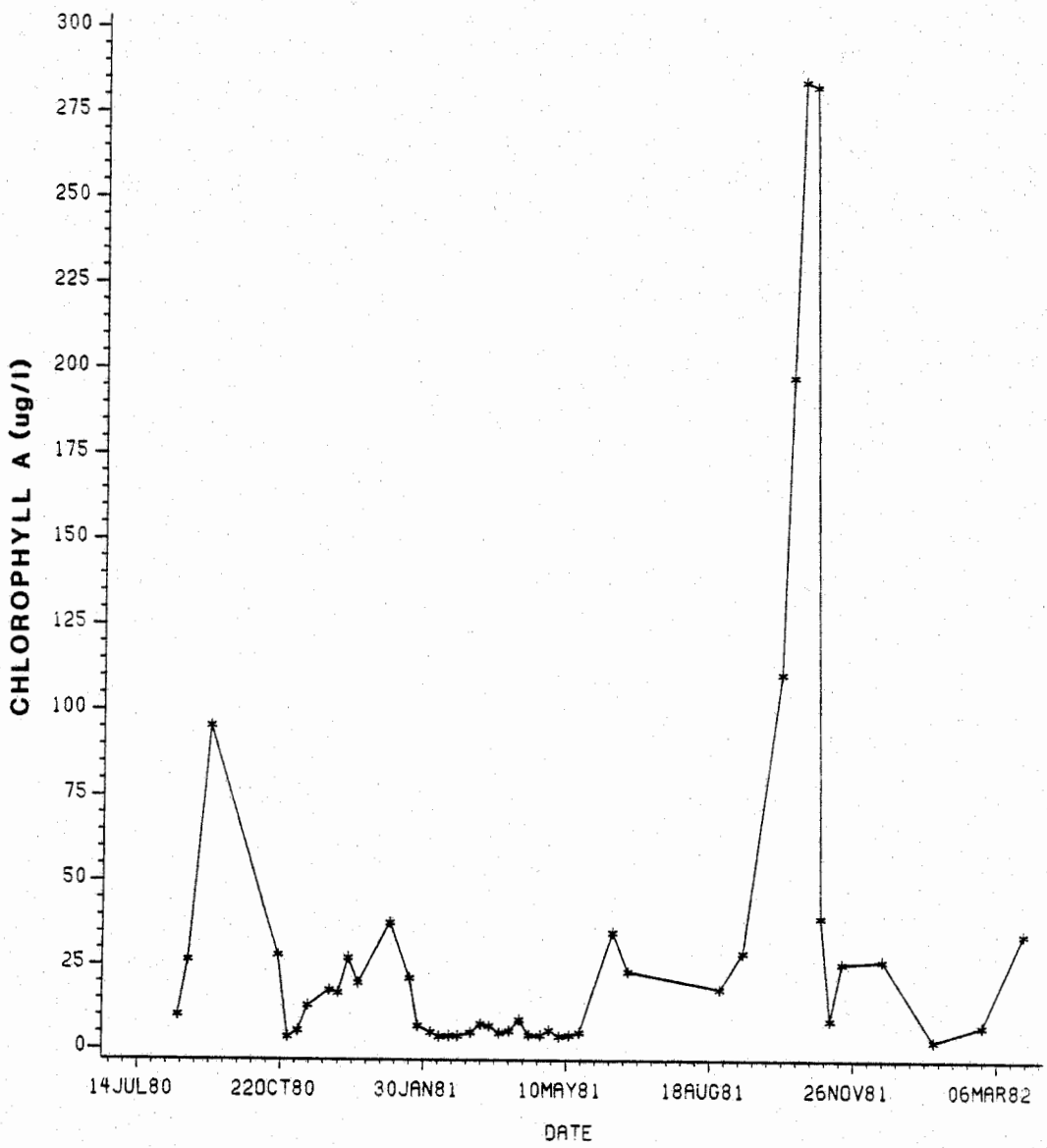

FIGURE 8 : AVERAGE CHLOROPHYLL IN THE UPPER 0.5M OF YATES

Mathematical model of the effects of turbidity and backscattering on epilimnetic temperature change

In addition to absorbing light and converting that energy into heat, particles may reflect light out of the water and into the air (backscatter) and thereby decrease the total amount of radiant energy in the water. The discussion that follows demonstrates that under certain environmental conditions, temperature will increase as turbidity increases until at high levels of turbidity backscattering becomes significant and there is no further increase in temperature.

The change in temperature is directly proportional to the amount of radiation absorbed within the mixed layer and inversely proportional to the depth of the mixed layer:

$$CTEMP = xIo' / z \qquad (2)$$

where: CTEMP is the change in temperature,
Io' is the effective incoming radiation,
x is the percent of the light absorbed in the mixed layer,
z is the depth of the mixed layer.
It is assumed that each 1 cal/cc increase in radiation will raise the temperature $1^{o}C$.

Using equation 1, we can solve for depth, z, by knowing that if x is the proportion of light absorbed in the upper layer then the depth at which (1-x) of the light remains will be bottom of the mixed layer:

$$z = \frac{\ln(1-x)}{-Nt} \qquad (3)$$

Further, Io', the effective radiation remaining after backscattering, can be defined as :

$$Io' = Io\ (1 - Backscatter), \qquad (4)$$

where: Io is the amount of incoming radiation and

$$Backscatter = 0.05 + 0.00036TSS \text{ (Stefan et al. 1982)} \qquad (5)$$

From Table 2 we know $TSS = 2.7 + 1.1NTU$ (6)

From Table 3, using the data for all seasons,

$$Nt = 1.4 + 0.06NTU\ . \qquad (7)$$

We can then answer the question : "How does the change in temperature in the mixed layer vary as a function of turbidity?" by substituting equations (3) through (7) into equation (2) :

$$CTEMP = -xIo(0.95 - 0.0004NTU)(1.4+0.06NTU)/\ln(1-x).$$

We can see that change in temperature will increase until very high levels of turbidity are reached. We can also see that at 25 NTU, backscatter will decrease the temperature change by about 1%, but the increased temperature change due to enhanced absorption will be nearly doubled compared to 0 NTU. This requires though that the mixed layer decrease as turbidity increases.

If the mixing depth is greater than the effective light penetration depth, then the change in temperature is no longer dependant on the (1-x) light depth. The temperature

is a function only of the incoming radiation minus the amount backscattered divided by the mixing depth. Therefore turbidity does not increase the rate of temperature change when the mixed depth is greater than the effective light penetration depth.

From these equations we can estimate the magnitude of the effect that turbidity has on temperature. Assume that backscattering is insignificant, as justified above; Nt =1.4 +0.06NTU ; mixing depth = 1% light level and Io=500 cal cm^{-2} day^{-1}:

CTEMP=-Io/ln(0.01)*(1.4+0.06NTU)

or

CTEMP= 1.5^{o}C + 0.06NTU.

We conclude that for an increase in turbidity of 30 NTU we can expect approximately a 2°C increase in temperature in the epilimnion on a bright summer day.

DISCUSSION

Turbidity was caused by inorganic particles in the winter and by blue-green algae during late summer and fall. During winter, turbidity was controlled by storms. The sheet flow of rain water washes soil off unvegetated land and into creeks where along with resuspended bottom sediment it is carried into the pond. The amount of time these particles stay suspended is a function of the density and size of the particle, density of the water and strength of wind-generated water currents.

In the fall blue-green algal blooms were responsible for increases in turbidity and for many changes in habitat values. In October of 1980 a surface turbidity reading of 162 NTU was obtained which was twice as high as any other observed reading for that year. Total suspended solids were as high as 59 mg/l and the extinction coefficient peaked at 8.6/m. During the growth phase oxygen concentrations were generally high during the day, but after they died, decomposition of the algae resulted in low oxygen conditions. In 1981 the concentration of oxygen was 3-4 mg/l at the surface and less than 1 mg/l near the bottom. Oxygen levels this low have been shown to be stressful to fish (Doudoroff and Shumway 1970).

Summer turbidities were low, 10-20 NTU, due to decreased runoff, decreased input of suspended solids and the settling out of suspended particle in the epilimnion.

Turbidity was seasonally correlated with total suspended solids. But the correlations were low due to the variability associated with dissolved solids. A much higher correlation was obtained between the change in NTU associated only with particles, i. e. before and after

filtration, and TSS. We found a 6 NTU increase in turbidity for each 10 mg/l increase in TSS.

Light penetration was directly influenced by turbidity. Each unit increase in NTU produced a 0.06 unit increase in the extinction coefficient. A 1 mg/l increase in suspended solids produced a 0.07 unit increase in Nt during the fall. The intercept was 2.1. This is similar to the relationship found by Stefan et al. (1982) for Lake Chicot in Arkansas: Nt=1.9 + 0.045 TSS. Stefan et al. (1982) also analyzed laboratory data reported by Witte et al. (1982) and found Nt= 2.0 + 0.06 TSS. Stefan et al. 's equations though were derived from secchi depth data where they assumed the secchi depth represented the 15% light level. According to our measures of secchi depths and direct underwater photometer readings, secchi depth in the turbid enclosures and in the pond itself represented the depth at which 30% of the subsurface, 0 m, light remained. However, in the alum-treated enclosures, the secchi depth was equivalent to the 15% light level. This latter value is similar to Vollenweider's (1974) 15% light level and Wetzel's (1975) range of 1-15%. The difference between the two turbidity levels was due to the uniform absorption of wavelengths by the suspended particles as in the turbid enclosures and the selective absorption of wavelengths by the water and dissolved material in the alum-treated enclosures. For Yates pond, the average depth of the 1% light level, considered to be the limit of the euphotic zone, ranged from 1.1 m to 3.6 m.

Light absorption by suspended particles was shown to influence the temperature of the water. Water temperatures affect organisms directly by influencing biochemical reaction rates. Temperature also structures the environment the organisms live in through the development of vertical thermal gradients in the water column. The surface water is

generally well mixed by the wind, is generally well oxygenated, and has a uniform temperature that is warmer than the bottom. As summer progresses, the surface waters heat up and the bottom waters become anoxic through biological and chemical activity. These conditions compress the space in which organisms can live. Fish, for example, may be trapped in a zone between excessively high temperatures at the surface with adequate oxygen and adequate temperatures at the bottom but no oxygen.

As the number of particles in the water increases, the depth to which the light is absorbed and converted into heat decreases thereby concentrating heat in the upper layers. We observed this phenomena in the subponds only in September 1982. During this period there was a 3°C increase in the epilimnion over the alum-treated enclosure. Analysis of the model also showed that increased turbidity resulted in increased temperature. Backscatter was important only at high turbidity levels. A 25 NTU increase in turbidity resulted in less than a 2% decrease in light energy due to backscatter but the temperature increase per day increased from 3.8°C/day at 10 NTU to 5.9°C/day at 35 NTU for light = 2500 kcal m^{-2} d^{-1} and a mixed depth of 0.25 m. The final water temperature depends on environmental conditions including air temperature, wind and evaporative cooling. During September 1982, the stratification that formed during the day was eliminated during the night and then reformed the next day. To put this in perspective, the turbid enclosure had an NTU reading of 28 and extinction coefficient of 7.8/m, the alum-treated enclosure values were 13 NTU and 3.1/m. This compares to turbidity levels for Yates pond that range from 15 to 120 NTU. So Yates has the potential to show temperature increases due to turbidity fluctuations. The time when temperature increases may have a detrimental effect, i.e. when the fish are close to their

upper lethal limit, occurs during the June, July and August when the surface temperatures can be in excess of 30°C.

Our turbidity enrichment experiments in August of both 1981 and 1982 showed no temperature increase. During these experiments, the depth of mixed layer was 0.75 m to 1.4 m which was greater than the effective heating depth. As discussed in the theoretical section on turbidity and temperature, no increase in temperature would be detected if the mixed layer was greater than the effective light penetration level, the 1% light level, due to the redistribution of heat. In fact the temperature may decrease as cooler bottom waters are mixed with surface waters. On the other hand as the depth of the mixed layer approaches zero, the temperature increases and approaches the value of Nt*Io'. This can be shown using equation 4. The 'x' in eq. 4 is the proportion of the light absorbed within the layer of depth z. Because e^{-Nt*z} is the proportion at depth z, 1 minus this is the proportion absorbed above depth z. Equation 4 then becomes :

$$CTEMP = Io'(1-e^{-Nt*z})/z \quad .$$

As z approaches zero we see CTEMP approaches Nt*Io'. The final temperature then is determined by incoming radiation, mixing depth and the extinction coefficient which is a function of turbidity. The depth of the mixed layer is determined by wind, fetch and depth of the lake (Ragotzkie 1978). This leads us to conclude that for a given mixed layer depth which is less than or equal to the effective heating depth, increases in turbidity will result in an increase in temperature.

Turbidity influences the amount of light that penetrates through the water and thereby influences plant production. We measured chlorophyll and phaeo-pigments,

degraded chlorophyll, in order to determine the effect of turbidity on algae suspended in the water column. One would expect that as turbidity increased, algal production would decrease and therefore the quantity of chlorophyll would decrease. Algae though have the capability to increase the total amount of chlorophyll per cell as the amount of light decreases. Under conditions of prolonged low light levels, the algae should die off and there should be a decrease in the ratio of chlorophyll to phaeopigments. We found this only in the fall.

Submerged macrophytes also appeared to be influenced by light levels. Environmental conditions were not as conducive to Chara growth in 1982 as they were in 1981. In 1981 water level in the pond was nearly 0.75m lower than pool stage, the turbidities averaged 16 NTU and the extinction coefficient averaged 2.0/m. These conditions enabled light to reach the bottom, the 1% light level was 2.7 m, and promoted extensive development of Chara and a filamentous green algae. This in contrast to the summer of 1982 where extinction coefficient averaged 4.5/m, the 1% light level was at 1 m and the water level was near normal pool stage. As a result, sufficient light could not reach the bottom and submerged macrophytes were not observed.

Under extremely high turbidity levels, submerged plants may be killed. If the turbidity levels do not kill the plants, they may be sufficiently high to cause the plants in deep water to die back to a point where the light is adequate. In 1981 Chara was growing in the alum-treated subpond in August. In September suspended matter was added to the alum subpond. At the end of the treatments (21 days) no significant change in the horizontal extent of the plant bed was found. But we did find a 60% increase in areal coverage when then turbidity was reduced.

The macrophytic production in Yates pond was of such magnitude that during 1981 the water was often supersaturated with oxygen. In July 1981 we found that planktonic production equaled respiration and was insignificant relative to the macrophytic release of oxygen. During August 1982 production was lower than August 1981 and the waters were often undersaturated. The main difference between these two years was the development of submerged plants. It appeared that increased turbidity may have restricted the development of Chara. The luxuriuos stands we found in 1981 were not present in 1982. There were other aquatic plants in the pond but their gas exchange surfaces are usually out of the water, e. g. Nuphar and Polygonum.

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