Application of the OECD eutrophication modeling approach to Lake Ray Hubbard, Texas

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By using the OECD eutrophication model, it was determined that significant improvements in Lake Ray Hubbard water quality could be achieved as a result of initiation of advanced wastewater treatment for phosphorus removal from adjacent communities' domestic wastewater discharges.

A large number of reservoirs have been constructed in north-central Texas to minimize the impact of extended drought periods on domestic water supplies. These reservoirs also serve as recreation areas and are used for swimming, boating and fishing. The excessive growth of algae in these reservoirs adversely affects beneficial uses. As a result of the comparative recent construction of many of these reservoirs in north-central Texas, limited information is available on the amounts of aquatic plant nutrients entering these water bodies, the factors controlling algal growth, and the relationship between algal growth and water quality. As part of the North Central Texas Council of Governments' 208 planning process, a fifteen-month study (June 1976 to August I977) was initiated by the Dallas Water Utilities (DWU) and University of Texas at Dallas (UTD) to examine nutrient load-eutrophication response relationships for Lake Ray Hubbard, one of the primary water supplies for the city of Dallas, Texas.

The impairment of beneficial uses in Lake Ray Hubbard is manifested by tastes and odors in the treated drinking water and reduced use of parts of the lake for recreational purposes. During the mid-1970s the apparent algal-related taste and odor problems were such that DWU did not use Lake Ray Hubbard as a source of water for part of each summer.

Lake Ray Hubbard is located on the East Fork of the Trinity River approximately 16 km northeast of Dallas. The city of Dallas began construction of Lake Ray Hubbard in 1964. The lake was completed and put into use as a water supply in 1972. Lake Ray Hubbard has a volume of 5.5 x10^8 m^3 and a surface area of 8.8 x 10^7 m^2 at the normal pool elevation of 132.4 m. The mean depth is 6.3 m and the maximum depth is 13 m. As shown in Figure 1, highway and railroad bridges divide the lake into four main areas, the Main Body and three arms. (Table 1 contains an explanation of the symbols used in this paper). The Main Body is the largest and deepest area of the lake. The East Fork Arm is a large, shallow section of the lake fed by the East Fork of the Trinity River and several small tributaries. The Rockwall sewage treatment plant discharges treated wastewater into one of these tributaries. Most of the water would enter Lake Ray Hubbard from the East Fork of the Trinity River under normal flow conditions. However, the U. S Army Corps of Engineers was raising the normal pool elevation of the upstream reservoir, Lake Lavon, during the study period; essentially no water was discharged to Lake Ray Hubbard. Rowlett Arm, which is fed by Rowlett Creek, is the small, narrow area northwest of the U.S. Highway 67 bridge. This principal tributary receives treated domestic wastewaters from the cities of Garland and Plano. The remaining small arm north of U.S. Highway 67 bridge is Muddy Creek Arm, fed by Muddy Creek, which receives treated domestic wastewaters from Wylie.

Methodology

As shown in Figure 1, several sampling stations were located in the Main Body and in the three arms of the lake to characterize each area with respect to pertinent nutrient load-lake response parameters. Samples were collected weekly during the recreational season and every two to four weeks during the remainder of the year. Dissolved oxygen (DO) and temperature measurements were made at 1-m intervals with a DO meter.* Surface light penetration was measured at 1-m intervals with a submarine photometer.** The Secchi depth was determined with a 20-cm Secchi disc. Samples for chemical analyses (total phosphorus, soluble orthophosphate, ammonia, nitrate, nitrite, organic nitrogen, pH, specific conductance, turbidity, total alkalinity, chlorophyll *a* and pheophytin *a*) were collected with a submersible pump or Van Dorn sampler at the surface (1 m) and bottom (0.5 m from the sediments), and at the mid-depth at the five stations that had a total depth greater than 5 m. Algae and

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actinomycetes samples were collected at 1 m, and a threshold odor sample was collected at 2 m below the surface.

Samples were collected from each of the ten tributaries and the two outlets (the spillway and the water treatment plant intake) at weekly intervals during the summer of 1976; every two to four weeks during the fall, winter, and spring of 1976-1977; and every two weeks during the summer of 1977. Temperature and DO were measured at the surface at each tributary station and at 1 m intervals throughout the water column at the water treatment plant intake. Samples for chemical analysis were collected with a Van Dorn sampler at the intake and spillway. A surface sample was collected with a bucket at each of the tributary streams and at the effluent pipe at the Garland-Rowlett sewage treatment plant. The samples were analyzed for total phosphorus, soluble orthophosphate, ammonia nitrate, nitrite, pH, and specific conductance.

All lake and tributary samples were stored on ice from the time of collection until they were delivered to the laboratories. The samples were stored in the dark at 4ºC at the laboratories until the analyses were performed. The DWU research laboratory conducted all lake water sample analyses except for chlorophyll *a* and pheophytin. The UTD laboratory analyzed all tributary samples and the lake chlorophyll and pheophytin samples. Samples were analyzed by procedures outlined in *Standard Methods* fourteenth edition[1] and the USEPA's *Methods for Chemical Analysis of Water and Wastes*[2].

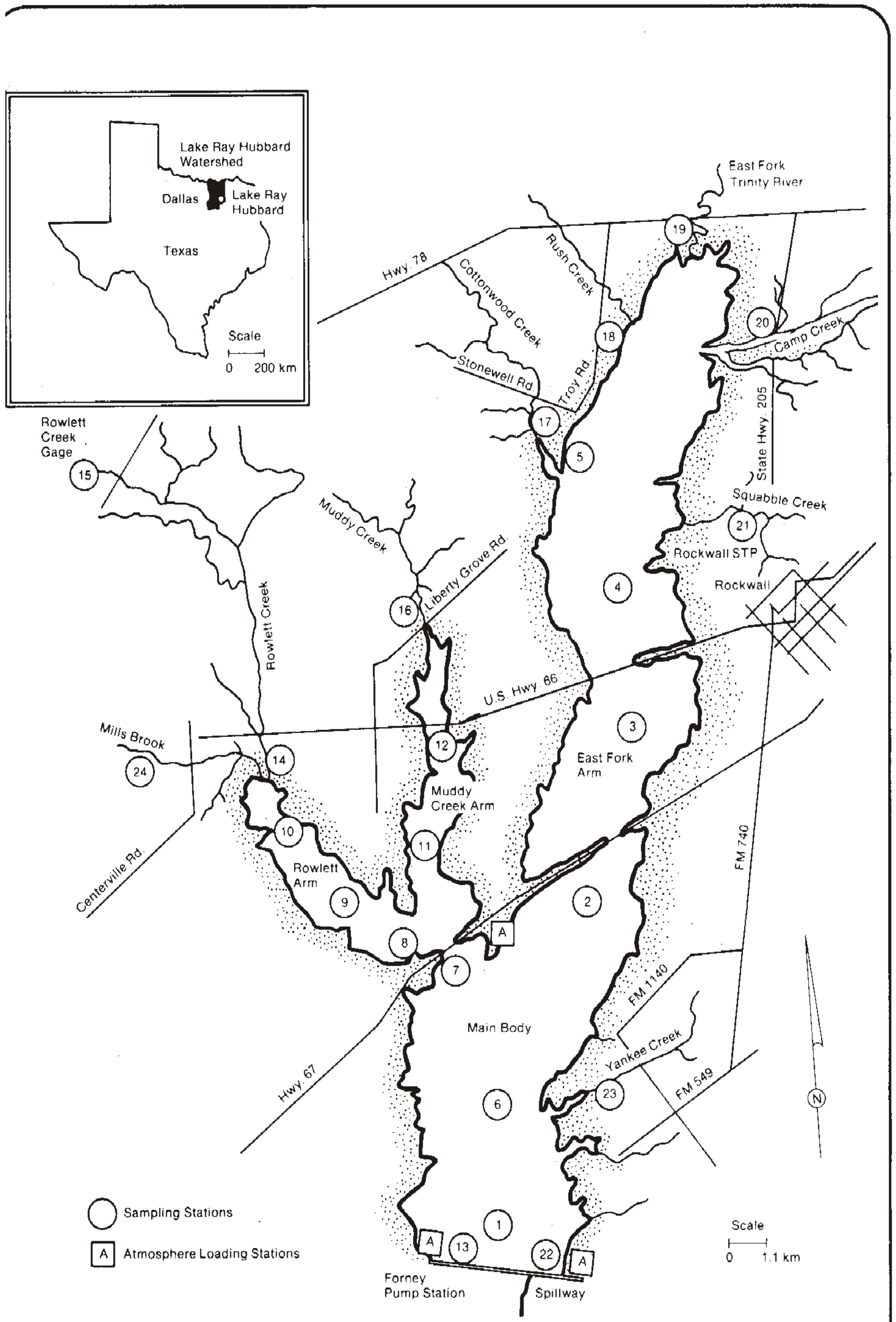

Figure 1. Lake Ray Hubbard sampling stations

Results and discussion

This paper presents a general discussion of the water quality characteristics of the Main Body and Rowlett Arm of Lake Ray Hubbard. Information is also provided on the nutrient loads to this lake and the estimated impact of altering these loads on the lake's water quality. The complete data obtained in this study and a more extensive discussion of these data, with particular reference to their implications for water quality, are presented in the report by Lee et al[3].

Physical characteristics. Lake Ray Hubbard is a warm-water impoundment that does not retain a permanent ice cover during the winter months. The summer surface water temperatures are generally about 10ºC higher then the temperatures of northern US lakes and impoundments. They ranged from 23ºC in May to 32ºC in August. Figure 2 presents the surface water temperatures for each of the four major areas of the lake during the study period. A thermocline started to develop in the deeper areas of the Main Body during May and became permanently established near 10 m during the summer months of 1976 and 1977. Figure 3 is a depth-time diagram of isotherms at station 1. The figure shows that this part of the Main Body was isothermal from mid-September to May, indicating that the water was well mixed during this period of time. A depth-time diagram of isopleths of dissolved oxygen at station 1 is shown in Figure 4. During the summer months, the DO was completely depleted below 10 m because of the sediment oxygen demand and the decomposition of organic matter (predominantly algae) sinking from the surface waters through the thermocline. The thermocline served as an effective barrier to mixing of the hypolimnetic waters with oxygen-rich epilimnetic waters during the summer months. The thermocline disappeared in mid-September; the water column became completely mixed and the DO concentration became constant from surface to bottom. This pattern persisted throughout the winter and spring months until the thermocline became established again in May.

Rowlett Arm was usually completely mixed with relatively constant temperatures throughout the water column. No permanent thermal stratification of the water column was observed during the summer months. There was normally a decrease in the DO concentration near the bottom, most likely caused by the sediment oxygen demand and the bacterial decomposition of the large quantity of organic matter settling from the surface waters. The surface waters were normally saturated or supersaturated with DO, because of the photosynthetic production of oxygen by the algal population and because of surface reaeration.

Nutrient dynamics. The average tota1 phosphorus concentrations in the Main Body and Rowlett Arm are shown in Figure 5. During the summer of 1976 the total P concentration in the Main Body was generally near 0.03 mg/L P with a peak of 0.28 mg/L P in June and a peak of 0.09 mg/L Pin August. Those peaks were likely attributable to algal-incorporated phosphorus, since the algal populations were high at these times. The concentrations were generally low during the winter months. In March a large amount of phosphorus entered the lake from the tributaries resulting in high concentrations (0.12 mg/L P) in the Main Body.

The total P concentrations in Rowlett Arm were always much higher than the Main Body concentrations. The high concentrations were caused by effluent from the Garland and Plano sewage treatment plants, which is discharged into Rowlett Creek, the tributary to Rowlett Arm. During the summer of 1976 the total P concentration was generally near 0.2 mg/L P with a peak of 0.8 mg/L P in June. The concentrations fluctuated erratically and did not appear to be related to the algal population. Since this arm of the lake had a maximum depth of 5 m and a large section less than 2 m deep, suspension of the sediments and release and uptake of phosphorus by the suspended particles could explain the highly erratic concentrations of phosphorus.

The soluble ortho P concentration in the Main Body was variable over time, decreasing to less than the detection limit (a few µg/L P) at times, and reaching peaks of 0.014 mg/L P in October 1976 and 0.02 mg/L P in May 1977. The highest soluble ortho P concentrations were found during the periods of low algal numbers, and the low concentrations were found during the algal blooms when essentially all of the soluble ortho P had been incorporated into algal cells and was limiting algal growth. An inverse relationship between the soluble ortho P concentration and the algal numbers would be expected in a lake where phosphorus is the algal growth-limiting nutrient.

The soluble ortho P concentration in Rowlett Arm was highly erratic. There was no indication of algal growth being limited by phosphorus in this arm of the lake, since the soluble ortho P concentration was generally between 0.01 and 0.05 mg/L P.

TABLE 1

Symbols used in nutrient load-lake response figures

Symbol	Explanation
A	Main Body 1976-1977
B	Main Body 1976-1977 with 85 percent P removal at STPs*
C	Main Body 1976-1977 with 35 percent P removal at STPs
D	Main Body with Lake Lavon P loading and flow
E	Main Body with Lake Lavon P loading and flow and 85 percent P removal at STPs
F	Main Body with Lake Lavon loading and flow with 35 percent P removal at STPs
G	Main Body with 1990 estimated load and Lake Lavon P loading and flow
H	Main Body with 1990 estimated load and Lake Lavon P loading and flow and 85 percent P removal at STPs
I	Rowlett Arm 1976-1977
J	Rowlett Arm 1976-1977 with 85 percent P removal at STPs
K	Rowlett Arm 1976-1977 with 35 percent P removal at STPs
L	Rowlett Arm with estimated 1990 P loads
M	Rowlett Arm with estimated 1990 P loads and 85 percent P removal at STPs

STP—sewage treatment plants

TABLE 2

OECD eutrophication modeling characteristics of the Main Body and Rowlett Arm of Lake Ray Hubbard

Characteristic	Main Body	Rowlett Arm
Phosphorus load—*g/year* P × 10^6		
Atmosphere	3.7	0.7
Tributaries		
1976-77	11.9	181.8
with 35 percent removal at STPs	10.0	150.0
with 85 percent removal at STPs	7.2	94.9
1976-77 load and Lake Lavon load	12.9	
with 35 percent removal at STPs	11.0	
with 85 percent removal at STPs	8.2	
1990 estimated loads including	18.4	290.7
Lake Lavon		
with 85 percent removal at STPs	9.1	111.2
Inflow—*L/year*		
1976-77	1.0×10^{11}	7.0×10^{10}
With Lake Lavon flow	2.9×10^{11}	7.0×10^{10}
Surface area—m^2	3.8×10^{7}	6.8×10^{6}
Volume—*L*	3.5×10^{11}	1.9×10^{10}
Hydraulic residence timer (τ_ω)—*(years)*		
1976-77	3.5	0.27
With Lake Lavon flow	1.2	0.27
Mean depth ($\bar{Z}$)—m	9.2	2.8
Mean summer epilimnetic chlorophyll *a* for 1976—$\mu g/L$	11.5	47.0
Mean summer Secchi depth for 1976—m	1.3	0.3

The average total nitrogen (ammonia, nitrite, nitrate, and organic nitrogen) concentrations in the Main Body and Rowlett Arm are shown in Figure 6. The total N concentration was generally between 0.5 and 1.0 mg/L N in the Main Body and between 1.0 and 1.5 mg/L N in Rowlett Arm. There were peaks in June and November of 1976 and in the spring of 1977 in both arms areas of the lake. The June 1976 peak was most likely attributable to the large influx of nutrients from the tributaries and the nitrogen incorporated into algal cells. The peak during November 1976 occurred when the lake was isothermal and was likely attributable to release of N from the sediments, since there was a corresponding increase in the inorganic N concentration at this time. The high concentrations of total N found during March and April 1977 reflect the large influx of nutrients from the tributaries during the spring.

The inorganic N concentration in the Main Body generally ranged from 0.04 to 0.12 mg/L N with two major peaks during the study period in June 1976 and in April to mid-June 1977. Since soluble ortho P was generally present in lower concentrations relative to the stoichiometric requirements of algae, inorganic N was most likely not limiting algal growth through most of the study period in this part of the lake. The inorganic N concentration

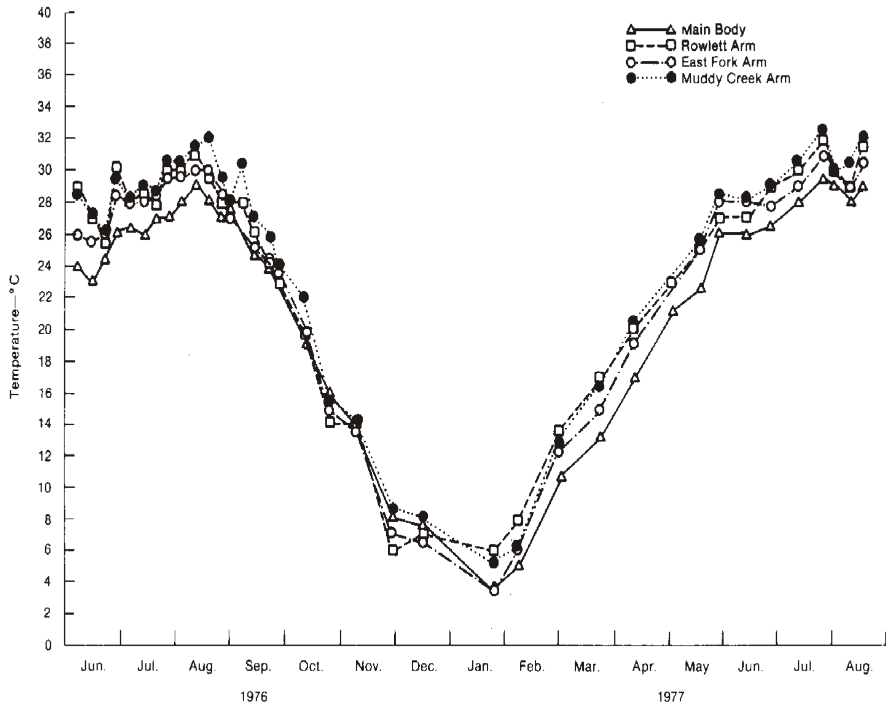

Figure 2. Lake Ray Hubbard surface water temperatures

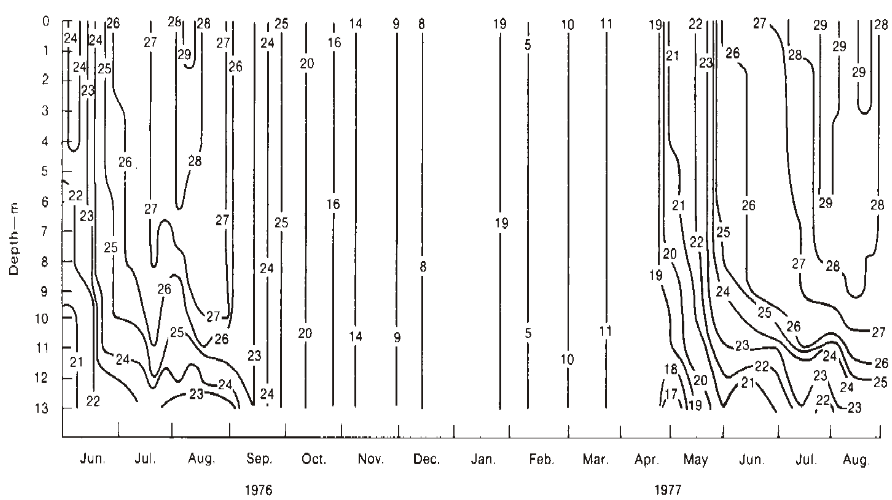

Figure 3. Isotherms at station 1 in the Main Body of Lake Ray Hubbard

Data reported in °C

was generally less than 0.1 mg/L during most of the summer of 1976 and 1977. The low inorganic N concentrations and high soluble ortho P concentrations indicate that nitrogen may have been limiting algal growth in this lake.

Most algae take up phosphorus in the form of soluble ortho P and nitrogen in the form of nitrate or ammonium. The inorganic nitrogen ($NO_3 + NO_2 + NH_4$) concentration measures the nitrogen readily available for use by algae. Algae use approximately 7.5 g inorganic nitrogen for every 1.0 g of phosphorus. The ratio of inorganic N to soluble ortho P is indicative of algal growth-limiting nutrient[4]. An N:P ratio greater than about 7.5 indicates excess phosphorus, whereas a ratio less then 7 5 indicates excess nitrogen relative to the normal stoichiometric requirements of algae.

As discussed by Lee & Jones[5], the concentrations of soluble ortho P or inorganic N in the water must be relatively low before the nutrient limits algal growth. The critical level is generally accepted to be a few µg/L P and less than 0.05 mg/L N. If both of these elements are present in concentrations somewhat greater than these amounts, neither of these elements will limit algal growth independent of the N:P ratio.

As shown in Figure 7, the N:P ratios in the Main Body were typically greater than 7.5, indicating that phosphorus may have been limiting algal growth in this part of the lake. The soluble ortho P concentrations in the Main Body were generally less than 0.005 µg/L P, which suggests that phosphorus was the growth-limiting nutrient. The N:P ratios in Rowlett Arm were typically less than 7.5, indicating that nitrogen was the nutrient that limited algal growth in this pert of the Lake.

Water quality response characteristics. The concentration of chlorophyll *a* in a water body is generally indicative of the algal biomass. Samples from each lake station were analyzed for chlorophyll *a* and its degradation product, pheophvtin *a*. The sum of chlorophyll *a* and pheophylin *a* is referred to as uncorrected chlorophyll *a*.

Figure 8 is a map of Lake Ray Hubbard showing the uncorrected chlorophyll concentration throughout the lake on September 14, 1976. From this figure it can be seen that the Main Body had the lowest chlorophyll *a* concentrations. Rowlett Arm had the highest, and the concentrations in Muddy Creek Arm and the East Fork Arm were generally intermediate between the Main Body and the Rowlett Arm. The large concentrations in the arms of the lake would be expected, since most nutrients enter the lake from tributaries that empty into the arms. The few small tributaries that discharge into the Main Body contribute little to the total nutrient load.

The average concentrations of chlorophyll *a* and uncorrected chlorophyll *a* in the Main Body during the study period are shown in Figure 9. During the periods of thermal stratification, the mean of :the surface and mid-depth concentrations at each station was plotted. However, during the isothermal period, the mean concentration in the water column was plotted. The uncorrected chlorophyll *a* ranged from 4 to 20 µg/L during the study period. The concentrations increased during the summer months with peaks of 16 µg/L in October 1976 and 20 µg/L during June 1977. Since the study ended in mid-August 1977, no data are available for the end of the 1977 summer; there appeared to be an upward trend in August, indicating that the concentrations found during late summer of that year would also be high. There was also an increase in uncorrected chlorophyll *a* concentration during January 1977 with a peak of l5 µg/L.

Rowlett Arm had the highest uncorrected and corrected chlorophyll *a* in the lake throughout the study. The average concentration of uncorrected chlorophyll *a* fluctuated from week to week from 13 µg/L to 118 µg/L, as shown in Figure 10. The two highest concentrations, found in January (118 µg/L) and August (110 µg/L) corresponded to large algal blooms.

Generally, chlorophyll *a* concentrations above 10 µg/L are indicative of eutrophic waters. Using this criterion, the Main Body would be classified as eutrophic and Rowlett Arm would be hypereutrophic. Normally, waters with chlorophyll concentrations exceeding 10 µg/L have excessive growths of algae that significantly impair the use of the water for domestic water supplies and recreation.

The algal population experienced a summer and a winter peak in the Main Body. In August 1976 the total number of algae reached 18,000 organisms/mL. During the summer of 1977 the total number reached 19, 000 organisms.mL (in July). The summer peaks were mainly caused by an increase in the blue-green algal population, particularly *Oscillatoria*. *Anabeana*, and *Aphanizomenon* were also found. Even though the blue-green algae were present in relatively large numbers during late summer, the blue-green algal surface scum frequently associated with nutrient-rich waters did not develop. The winter peak of 23,000 organisms/mL occurred in January and resulted from large numbers of the green alga *Chlorella*. The diatoms *Fragillaria* and *Cyclotella* were present but were not as abundant as *Chlorella*. The algal population in the Main Body was smaller than in the arms of the lake. During the nonpeak periods the total number of algae fluctuated around 6,000 organisms/mL.

The algal population was larger in Rowlett Arm than in the Main Body because of the large amounts of nutrients entering Rowlett Creek. The average total number of algae ranged from 5,500 to 60,000 organisms/mL. Unlike the pattern of algal numbers found in the Main Body, the total number of algae in Rowlett Arm fluctuated from week to week without a definite cycle. The diatoms (mainly *Cyclotella*) dominated the population in Rowlett Arm, whereas, in the Main Body, the green and blue-green algae were dominant. There was no significant increase in the blue-green algal population during the summer in Rowlett Arm as there was in the Main Body. However, the blue-green population did reach a few thousand organisms/mL in late summer.

Secchi depth is a measure of water clarity that is related to the amount of organic and inorganic turbidity in the water. Figure 11 shows the average Secchi depth and average surface turbidity in the Main Body during the study period. The Secchi depth and the surface turbidity were inversely related. The Secchi depth of the Main Body ranged from 0.5 to 2.2 m, with the greatest Secchi depths during the summer months and the lowest Secchi depths during the winter months. This indicates that both organic and inorganic turbidity control water clarity.

Rowlett Arm had the most turbid water in the lake, with the Secchi depth ranging from 0.2 to 0.6 m and the turbidity ranging from 6 to 70 ftu. The Secchi depth was, in general, inversely related to the turbidity. In Rowlett Arm the fluctuations in the turbidity were much greater than in the Main Body. The Secchi depth fluctuated from week to week with no apparent trend over the annual cycle. As discussed above, this is to be expected because of the shallow nature of this part of the lake.

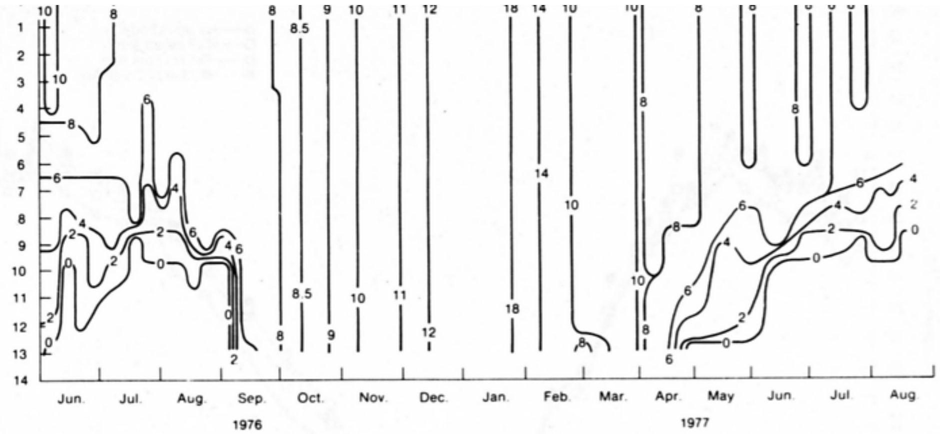

Figure 4. Isopleths of dissolved oxygen at station 1 in the Main Body of Lake Ray Hubbard

Data reported in mg/L

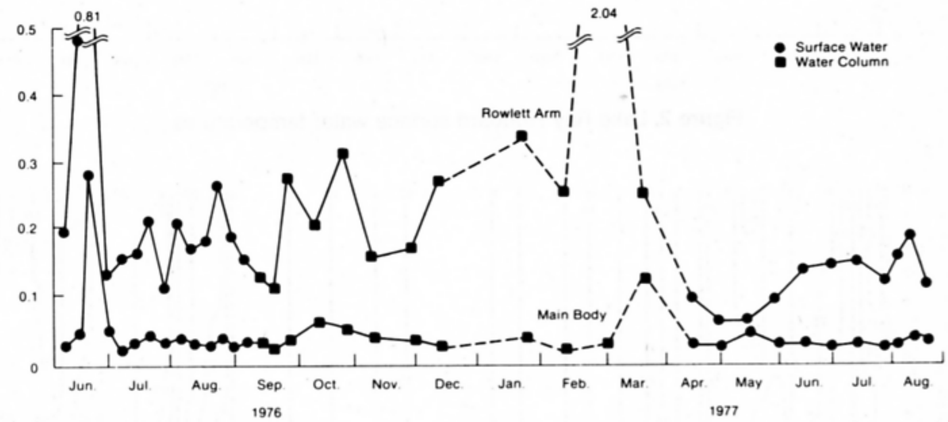

Figure 5. Average total phosphorus concentrations in the Main Body and Rowlett Arm

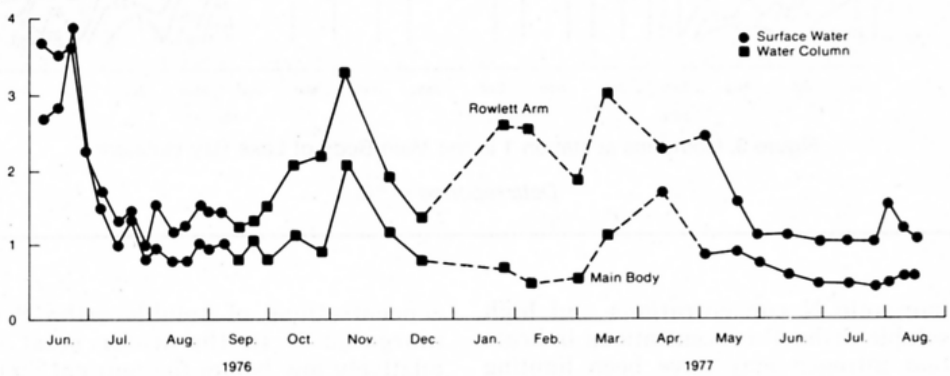

Figure 6. Average total nitrogen concentrations in the Main Body and Rowlett Arm

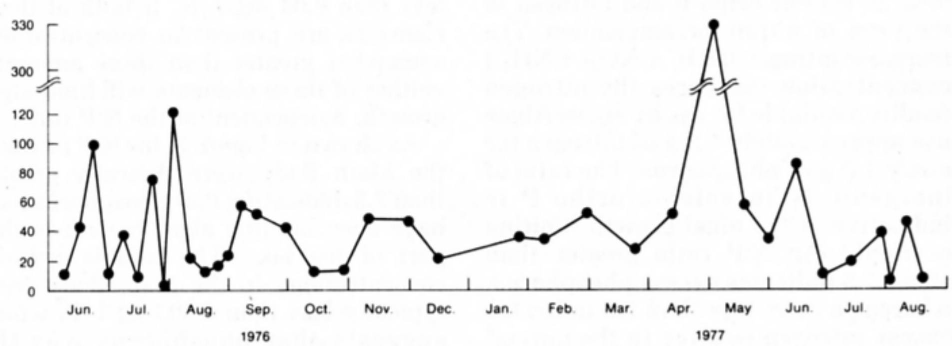

Figure 7. Inorganic nitrogen: soluble orthophosphate ratios in the Main Body

Odor samples were collected to determine the average threshold odor number (TON) and the' characteristic odor of the water. The average TON in the Main Body ranged from 6.5 to 13 during the summer of 1976 and 6 to 10 during the summer of 1977. During the winter months, the TON was typically near 7. The characteristic odors commonly found were musty, grassy, rooty, fishy, and vegetable. The TON in Rowlett Arm ranged from 7 to 18 with large fluctuations from week to week. The odor characteristics most commonly found were musty, earthy, grassy, and rooty, with an occasional septic odor.

It is generally thought that high TONs are related to large populations of blue-green algae; however, in the Main Body major peaks in the TON were found in early summer when the blue-green algal population was small. Peaks in the TON in Jun e and July of 1976 and in May and June of 1977 corresponded to algal populations that were dominated by the green alga, *Chlorella*. There was no apparent relationship between the TON and the number of algae in Rowlett Arm.

Phosphorus loads to the Main Body and Rowlett Arm. The phosphorus load to Rowlett Arm was calculated by adding the tributary load to the atmospheric load. The tributary load was calculated by multiplying measured phosphorus concentrations by USGS flow data for Rowlett Creek upstream of the Garland-Rowlett sewage treatment plant. The treatment plant phosphorus load was added to the Rowlett Creek load to determine the total tributary load of 182,000 kg/year P. The atmospheric load was determined by multiplying the atmospheric loading coefficient of 0.1g/m^2/year by the surface area of Rowlett Arm. This resulted in an atmospheric load of 700 kg/year P and total phosphorus load to Rowlett Arm of approximately 183,000 kg/ year P.

The calculation of the total P load to the Main Body was more complex. It would not be technically valid to assume that the total tributary load to the lake reached the Main Body, since a significant amount of phosphorus is removed in the arms of the lake. The Main Body tributary phosphorus load was based on the concentrations of total P at the stations in each arm closest to the Main Body (stations 3, 8 and 11) multiplied by the flows of the nearby tributaries, Squabble Creek, Rowlett Creek, and Muddy Creek, respectively. This resulted in a tributary load of 11,900 kg/year P. The atmospheric load calculated with the atmospheric loading coefficient was determined to be 3,700 kg/year P. The total phosphorus load to the Main Body was 15,600 kg/year P. Further information on the N and P loads is available in Lee *el al*[3]. Additional discussion of procedures used to measure and estimate nutrient loads to lakes and impoundments are discussed by Lee and Jones[6] and Lee *et al*[7].

OECD Modeling Approach. The Organization for Economic Cooperation and Development (OECD) has conducted an international study to define the relationship between the nutrient load in a water body and the water quality of the water body. This recently completed five-year study included approximately 200 water bodies (lakes and impoundments) throughout Western Europe, North America, Japan and Australia. A critical review and synthesis of the US OECD eutrophication water bodies data were prepared by Rast and Lee[8] and Lee et al[9]. This has recently been updated by Jones and Lee[10]: The OECD eutrophication modeling approach was originally developed by Vollenweider[11] and used by the USEPA in its National Eutrophication Survey. Vollenweider[12] developed a simple relationship relating the phosphorus load in a phosphorus-limited water body to the planktonic algal chlorophyll produced in the water body. The key factor in the Vollenweider modeling approach is that the phosphorus loads must be normalized among water bodies based on the mean depth and hydraulic residence time (filling time) of the water body. Lakes grouped according to similar phosphorus loads, mean depths, and hydraulic residence times are found to have similar chlorophyll concentrations. Several researchers[8-10] have shown that the Vollenweider approach is applicable to the US OECD eutrophication study water bodies.

Rast and Lee[8] and Lee et al.[9] have expanded Vollenweider's basic relationship to include an estimate of the Secchi depth of a water body based on the phosphorus load and mean depth-hydraulic residence time characteristics. Their model assumes that the Secchi depth is controlled by phytoplankton growth and not by color or sediment derived turbidity. Rast and Lee[8] and Lee et al.[9] were also able to derive a relationship between the phosphorus load in a water body and its hypolimnetic oxygen depletion.

The OECD modeling approach was applied to the Main Body and Rowlett Arm of Lake Ray Hubbard. Table 2 presents the characteristics of these two parts of the lake that are necessary for application of the model to Lake Ray Hubbard.

Vollenweider phosphorus loading diagram. Figure 12 presents a plot of the phosphorus loads to the Main Body and Rowlett Arm of Lake Ray Hubbard as a function of the mean depth-hydraulic residence time of these areas of the lake. The actual 1976-77 conditions are shown as (A) for the Main Body and (I) for Rowlett Arm. The phosphorus load of 0.41 g/m^2/year P during the study period places the Main Body near the excessive loading curve. The Rowlett Arm phosphorus load of 26.8 g/m^2/year P places this area of the lake well above the excessive loading curve. As discussed by Rast and Lee[8] and Lee *et al*.[9] this excessive loading line is based on impairment of recreational use as derived from studies in southern Wisconsin lakes in the mid 1940s. It bas been found that, in general, the excessive loading zone in Figure 12 represents the trophic zone where an impairment of the use of the lake has occurred because of the excessive growth of algae. There would also likely be an adverse impact on the use of the water for domestic water-supply purposes.

In addition to the 1976-1977 study period, various hypothetical phosphorus management scenarios were considered.

- Phosphorus removal at all sewage treatment plants in the watershed—85 percent removal was assumed.
- Detergent phosphate ban in the watershed – it was assumed that this would reduce the load from the domestic sewage treatment plants by 35 percent.
- 1990 population in the watershed—the 1990 treatment plant phosphorus load was calculated by multiplying the projected 1990 population by the average 1.1 kg/capita/year P. The nonpoint source load in 1990 was assumed to be equal to the 1976-77 load.
- Normal flow and phosphorus load from Lake Lavon—as discussed previously, the US Army Corps of Engineers was raising the level of Lake Lavon Dam, the upstream reservoir, during the study period. Under normal conditions the average flow from Lake Lavon would be 1.9 x 10^{11} L/'year and the phosphorus load would be about 20,000 kg/year P.

These hypothetical conditions are plotted in Figure 12, which shows that the Main Body would fall below the excessive loading line with normal flows from Lake Lavon and removal of phosphorus at the sewage treatment plants located in the watershed. Rowlett Arm remains in the eutrophic zone of the Vollenweider plot under all hypothetical l conditions. However, it is important to emphasize that, as discussed by several researchers[8-10], water quality of a water body does not change significantly as a result of the phosphorus load being reduced from just above to just below the excessive loading line. Water quality must be judged according to changes in such response parameters as chlorophyll, taste, and odors. In should not be judged on changes in phosphorus loads.

Phosphorus load-chlorophyll relationship. Figure 13 presents the relationship between the phosphorus loads, as normalized by mean depth and hydraulic residence times, and the mean summer epilimnetic chlorophyll concentrations within the Main Body and Rowlett Arm of Lake Ray Hubbard. One of the most significant findings of this study is that the average summer epilimnetic chlorophyll concentration of the Main Body is only slightly lower than the concentration predicted by the model based an the phosphorus load (point A). These results indicate that the OECD phosphorus loading relationship is applicable to lake Ray Hubbard. This is evidence that the southern warm water bodies show the same nutrient load-eutrophication response relationship as north temperate water bodies that have been extensively studied. To predict the mean chlorophyll concentration for each hypothetical loading scheme, it was assumed that the line for the Main Body would be parallel to the OECD line and the same distance below the line as the 1976-77 point (A) is..

As shown in Figure 13, the average epilimnetic chlorophyll *a* concentration per growing season in the Main Body during the study period (A) was 11.5 µg/L. This could be reduced to 7.5 µg/L with 85 percent removal of phosphorus from domestic wastewaters (B), and 10 µg/L with 35 percent removal (C). The adoption of a detergent phosphate ban in the Lake Ray Hubbard watershed would not likely produce a detectable change in the planktonic algal chlorophyll. On the other hand, the removal of 85 percent of the phosphorus discharged to tributaries from the domestic wastewater treatment plants in the Lake Ray Hubbard watershed would produce a readily measurable change in the planktonic algal chlorophyll during years with flows typical of the study period.

The chlorophyll *a* concentration is reduced by several µg/L when the Lake Lavon flow and loading are considered. The chlorophyll *a* concentration is predicted to be 6.5 µg/L with no phosphorus removal from domestic wastewaters (D), 5.5 µg/L with 35 percent removal (F), and 4.5 µg/L with 85 percent removal (E). Reductions of this magnitude would result in noticeable improvements in water quality in the Main Body. The Main Body chlorophyll *a* concentration in 1990 is predicted to be 7.5 µg/L with no phosphorus removal from domestic wastewaters and normal flows from Lake Lavon, and 5 µg/L with 85 percent phosphorus removal and normal Lake Lavon flows. The influence of the Lake Lavon flows on water quality in Lake Ray Hubbard is illustrator! by the fact that the model predicts lower chlorophyll *a* concentrations in 1990 than the 1976-77 study period concentrations.

As shown in Figure 13, the actual mean chlorophyll *a* concentration in Rowlett Arm (I) is lower than the predicted concentration. The model predicts a mean summer epilimnetic concentration of 200 µg/L; however, the actual concentration was 47 µg/L during the study period. Two factors help to explain this anomaly: Phosphorus does not always limit algal growth in this part of the lake, and the high turbidity of this area reduces the rate of photosynthesis and, therefore, the rate of algal growth. Both of these factors should result in lower chlorophyll concentrations than predicted by the phosphorus load into Rowlett Arm, as found in this study.

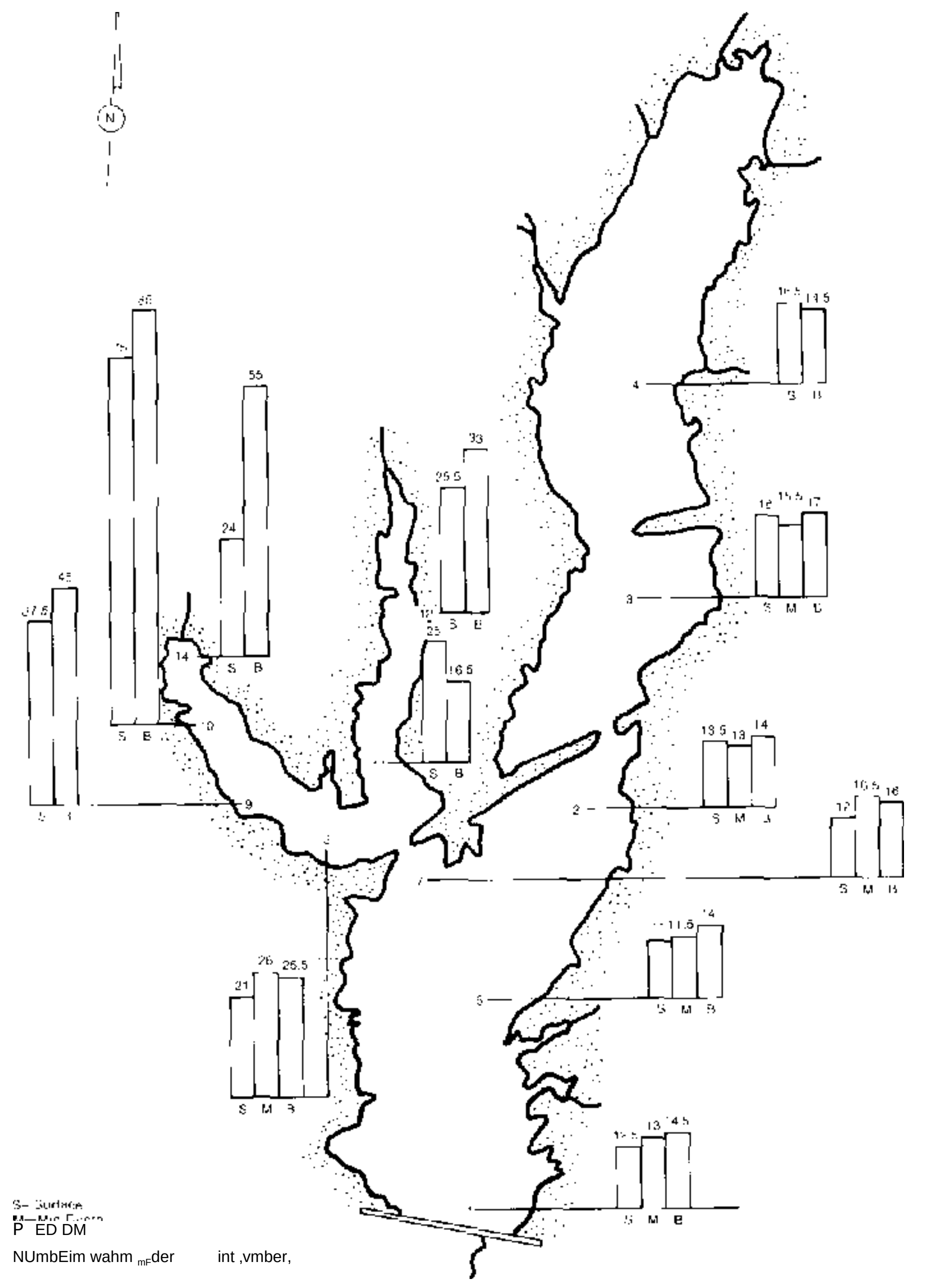

Figure 11. Uncorrected chlorophyll a concentrations tor September 14, 1976

Numbers atop *bars are chlorophyll concentraltues (o9,1); numbers within water bodies refer* to sampling *stations.*

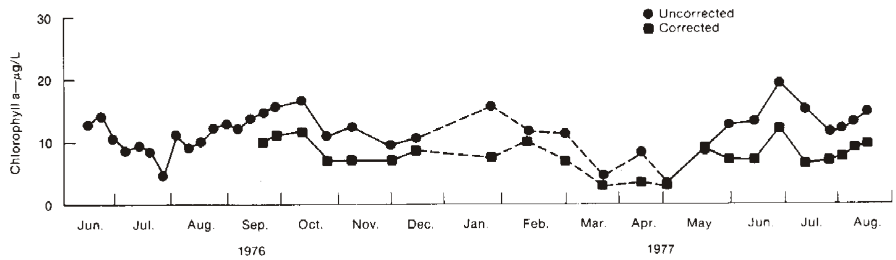

Figure 9. Chlorophyll *a* concentrations in the Main Body

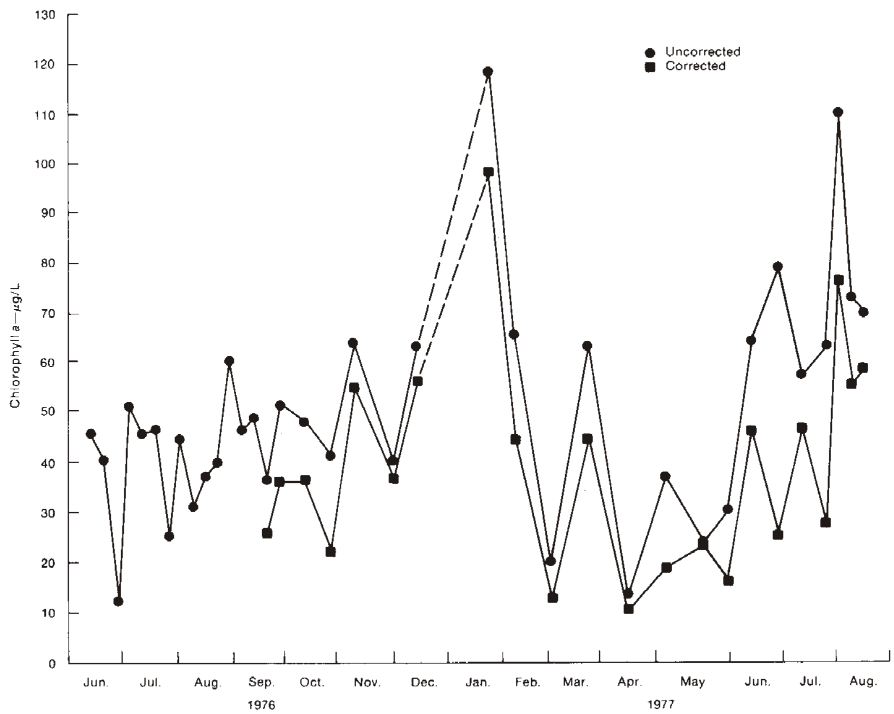

Figure 10. Chlorophyll *a* concentrations in Rowlett Arm

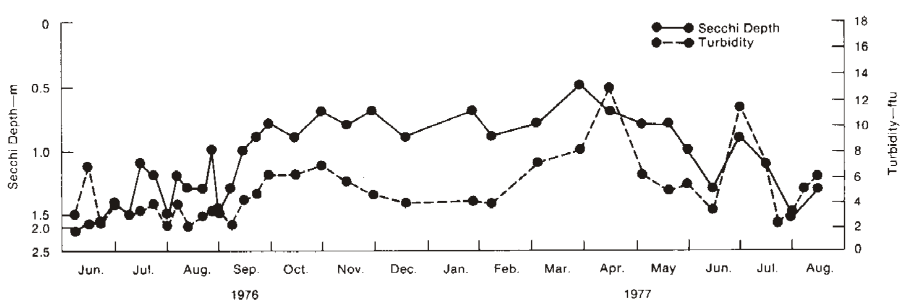

Figure 11. Average Secchi depth and turbidity in the Main Body

To predict the mean chlorophyll *a* concentration for each hypothetical loading scheme, it was assumed that the phosphorus load-chlorophyll line for Rowlett Arm would be parallel to the OECD eutrophication study line of line of best fit (that is, the relationship expressed by the line of best fit also occurs in Lake Ray Hubbard) and that the light limitation that exists now would continue to exist in the future. Since algal growth in Rowlett Arm was nitrogen-limited during some months of the study, it is likely that reductions in the phosphorus load would drive this part of the lake to phosphorus limitation during the summer months, which is the crucial time in terms of algal blooms and their associated water quality problems.

Phosphorus load-Secchi depth relationship. The Secchi depths of both the Main Body and Rowlett Arm fall below those predicted from the normalized phosphorus loads based on the relationship developed by Rast and Lee[8]. The low Secchi depths in Lake Ray Hubbard are likely produced by the significant stirring of the sediments into the water column. This reduces the light penetration and the resultant Secchi depth. If it is assumed that the turbidity derived from the bottom sediments is constant and independent of the chlorophyll content, the expected changes in Secchi depth can be predicted, if there is a constant proportion between the US OECD eutrophication study line of best fit and the line of existing and predicted values for Secchi depth.

The average Secchi depth of the Main Body during the study period was 1.3 m. The US OECD model predicts a mean summer Secchi depth of about 2 m. If the approach described earlier is used, the Secchi depth would be expected to increase to 1.4 m as a result of 35 percent removal of phosphorus from domestic wastewaters. There would be little additional increase in the Secchi depth if 85 percent of the phosphorus were removed from domestic wastewaters.

If the normal Lake Lavon flow and phosphorus loads are considered, the Secchi depth is predicted to be 1.6 m with no phosphorus removal, 1.75 m with 35 percent removal, and 1.9 m with 85 percent removal. The Main Body Secchi depth in 1990 is predicted to be about 1.5 m with no phosphorus removal from domestic wastewaters and normal flows from Lake Lavon, and 1.8 m with 85 percent phosphorus removal and normal Lake Lavon flows.

During the study period, the average Secchi depth in Rowlett Arm was 0.3 m. However, the OECD eutrophication model predicts a mean summer Secchi depth of 0.6 m. As in the Main Body the difference is likely attributable to turbidity from suspended sediments. The model predicts no detectable change in the Secchi depth with 35 percent phosphorus removed from domestic wastewaters, and 0.4 m with 85 percent phosphorus removal. When the 1990 phosphorus loads are considered, the Secchi depth decreases to 0.25 m with no phosphorus removal, and increases slightly to 0.35 m if 85 percent of the phosphorus in domestic waste waters is removed. This shows that reducing the phosphorus load will have a minimal impact on the water clarity of Rowlett Arm.

Phosphorus load-hypolimnetic oxygen depletion relationship. Rast and Lee[8], have shown that there is a relationship between the phosphorus load of a water body, normalized for mean depth and hydraulic residence time, rate. The depletion rate is defined as the rate at which oxygen is depleted during the stratification period. To calculate the rate of depletion in Lake Ray Hubbard, the mass of oxygen in the hypolimnion on the last day that the water column was isothermal (May 1, 1977) was calculated. It was assumed that the hypolimnion was the area of the lake below 10 m and has a volume of 1.8×10^{11} L. Based on an average DO concentration of 6 mg/L, the mass of oxygen in the hypolimnion was determined to be 8.8×10^{8} g. In the Main Body, the DO was completely depleted below 10 m on June 14, 1977, so it took approximately 35 days to deplete the DO completely in the hypolimnion.

Based on the 1976-77 phosphorus loads, Lake Ray Hubbard has a greater depletion rate than predicted by the OECD line of best fit developed by Rast and Lee[8] This greater depletion may be a result of the small volume of the hypolimnion of this lake. Oxygen is depleted in the hypolimnion by the decomposition of organic matter raining down from the surface waters and by the sediment oxygen demand. The oxygen depletion rate is related to the phosphorus load because the amount of organic matter entering the hypolimnion from the surface water is related to the phosphorus load. The sediment oxygen demand of a water body like Lake Ray Hubbard is made up of two components: residual decomposable organics that did not decompose in their descent from the surface waters and oxidation of the reduced forms of iron and sulfur. Ferrous iron and sulfide present in sediments create the major oxygen demand in many lakes and impoundments.[13] Since the hypolimnion in the Main Body of Lake Ray Hubbard has a maximum depth of 3.5 m, the sediment oxygen demand would be expected to play a more important role and result in a greater depletion rate than predicted by the OECD line of best fit.

The depletion rate in the Main Body of Lake Ray Hubbard was 1.2 $g/m^2/d$ O_2 during the summer of 1977. It is predicted[3] that there would be no perceptible change in the rate of oxygen depletion with 35 percent phosphorus removal from domestic wastewaters. If 85 percent of the phosphorus were removed from domestic. wastewaters, the rate of depletion would be reduced to 1.15 $g/m^2/d$ O_2. The oxygen depletion rate is reduced slightly when the Lake Lavon flow and loading are considered. The depletion rate is predicted to be 1 $g/m^2/d$ O_2 with no phosphorus removal from domestic wastewater, 0.9 $g/rn^2/d$ with 35 percent phosphorus removal, and 0.8 g O_2/m^2/day with 85 percent phosphorus removal.

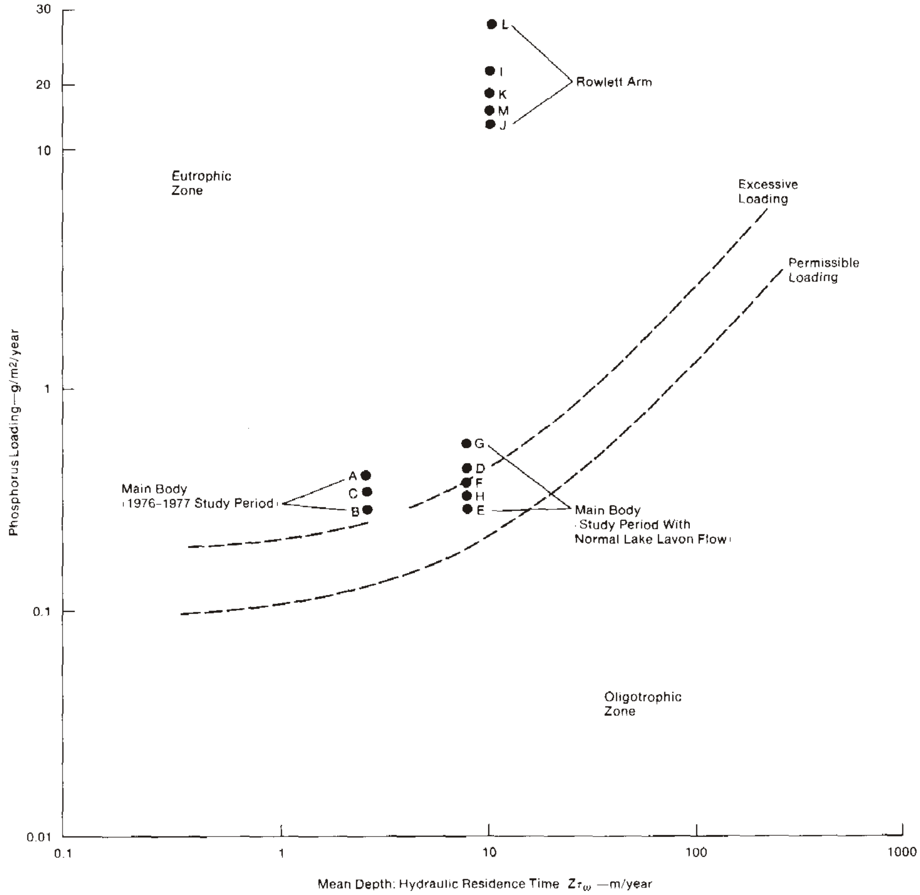

Figure 12. Phosphorus loading to the Main Body and Rowlett Arm of Lake Ray Hubbard

During this study Dallas Water Utility withdrew epilimnetic waters from Lake Ray Hubbard for domestic water supply during the stratified period. As discussed by Lee and Harlin[14] there may be significant advantages to using water from the hypolimnion since it often contains less algae and has fewer associated taste and odor problems. The presence of iron, manganese, and sulfide in the hypolimnetic water of many eutrophic lakes prevents the utilization of these waters for domestic water supply purposes. These chemical species do not form if dissolved oxygen is present in the hypolimnion. In order to maintain 1 mg/L O_2 in the hypolimnion of Lake Ray Hubbard throughout the summer stratification period, an oxygen depletion rate of 0.32 $g/m^2/d$ O_2 must be achieved This number is based on a period of stratification of 135 days (May 1 to September 15), an average concentration of 6 mg/L at the beginning of the stratification period and a hypolimnetic volume of 1.5×10^{11}L. A depletion rate of 0.32 $g/m^2/d$ is obtained with a phosphorus load to the Main Body of 870 kg/year P by using the 1976-77 hydraulic residence time of 3.5 years. If the normal flow from Lake Lavon is included in the calculations, the hydraulic residence time is decreased to 1.2 years. The decreased hydraulic residence time allows 1mg/L O_2 in the hypolimnion at the end of summer with a phosphorus load of 1843 kg/year P. It would be impossible to obtain a phosphorous load of 870 or 1843 kg/year P by simply controlling the phosphorus load from the sewage treatment plants present in the watershed. It would be necessary to control both point and nonpoint sources of phosphorus. Therefore, it appears unlikely that the phosphorus load will ever be sufficiently reduced to maintain oxygen in the hypolimnion of Lake Ray Hubbard during the summer period of thermal stratification.

Conclusions

The US OECD eutrophication models developed hy Vollenweider for predicting the trophic status and average chlorophyll *a* concentration, based on the phosphorus load and morphometric and hydrologic characteristics of the water body, and the sh

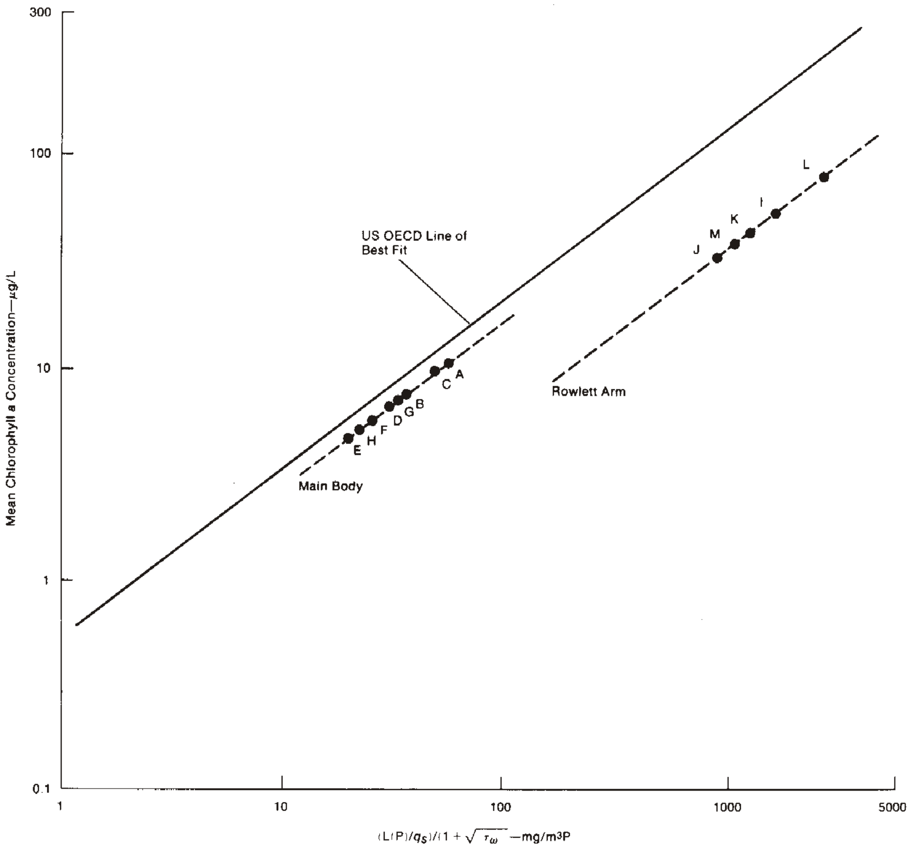

Figure 13. Relationship between phosphorus loading and chlorophyll *a* in the Main Body and Rowlett Arm of Lake Ray Hubbard

models developed by Rast & Lee for predicting the average Secchi depth and hypolimnetic oxygen depletion rate, based on these same characteristics, appear to be applicable to the Main Body and Rowlett Arm of Lake Ray Hubbard. These results indicate that Lake Ray Hubbard, a southern warm-water body, shows the same nutrient load-eutrophication response relationship as northern temperate water bodies.

The application of the OECD models to Lake Ray Hubbard revealed the importance to the Main Body of normal flows from Lake Lavon. If the Lake Lavon flow had been normal during the 1976-77 study period, the average chlorophyll *a* concentration in the Main Body would have been 6.5 µg/L rather than 11.5 µg/L.

The models predicted that a detergent phosphate ban in the watershed would have no significant impact on water quality in the lake. If 85 percent of the phosphorus were removed from domestic wastewaters from the cities of Plano, Garland-Rowlett, and Rockwall by advanced wastewater treatment, there would be a significant improvement in eutrophication-related water quality in Lake Ray Hubbard. As the population of the Lake Ray Hubbard watershed increases, there will be increased .deterioration of Lake Ray Hubbard water quality because of increased phosphorus input from domestic wastewaters. Failure to adopt phosphorus removal from the domestic wastewaters by the communities discharging domestic wastewaters in the Lake Ray Hubbard watershed will likely result in even more severe taste and odor problems, shortened filter runs, and possibly increased trihalomethane precursors in the raw water derived by the Dallas Water Utilities from Lake Ray Hubbard. It is now well established that 85 to 95 percent phosphorus removal can be readily achieved from domestic wastewaters by iron or aluminum hydrous oxide coprecipitation at a cost of less than a quarter of a cent per day per person tor the population served by the wastewater treatment plant.

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