WATER QUALITY ISSUES IN RESERVOIRS: SOME CONSIDERATIONS FROM A STUDY OF A LARGE RESERVOIR IN KANSAS

Frank deNoyelles
Associate Director and Professor
Kansas Biological Survey
University of Kansas
Lawrence, Kansas

Shih H. Wang, Justin O. Meyer,
Donald G. Huggins, Jay T. Lennon,
Kansas Biological Survey
University of Kansas
Lawrence, Kansas

Werner S. Kolln
Department of Chemistry and Physics
Simpson College
Indianola, IA 50125

Stephen J. Randtke
Department of Civil and Environmental Engineering
University of Kansas
Lawrence, Kansas 66045

INTRODUCTION

In May of 1997 a detailed study began of the water quality of Clinton Lake, a 7000 acre (2833 ha, multipurpose pool) federal reservoir constructed in the late 1970's near Lawrence, Kansas (Figure 1). With the rapid growth in population in the vicinity of this reservoir, at the time of this study it was providing drinking water for more than 100,000 customers, one of the largest customer bases for reservoirs in Kansas. The findings of this study reported on here are based, for the most part, on data gathered through November of 1998. For this study water quality conditions are considered to be the characteristics of materials either dissolved or suspended in the water column. Other conditions of the reservoir basin such as depth and bottom configuration, including sediment accumulation and habitat structure, are not directly water quality but are affected by and affect water quality and will only be considered here secondarily in this context.

The geographic region for this consideration of the water quality of reservoirs includes most places where reservoirs have been constructed in areas where there are few natural lakes due

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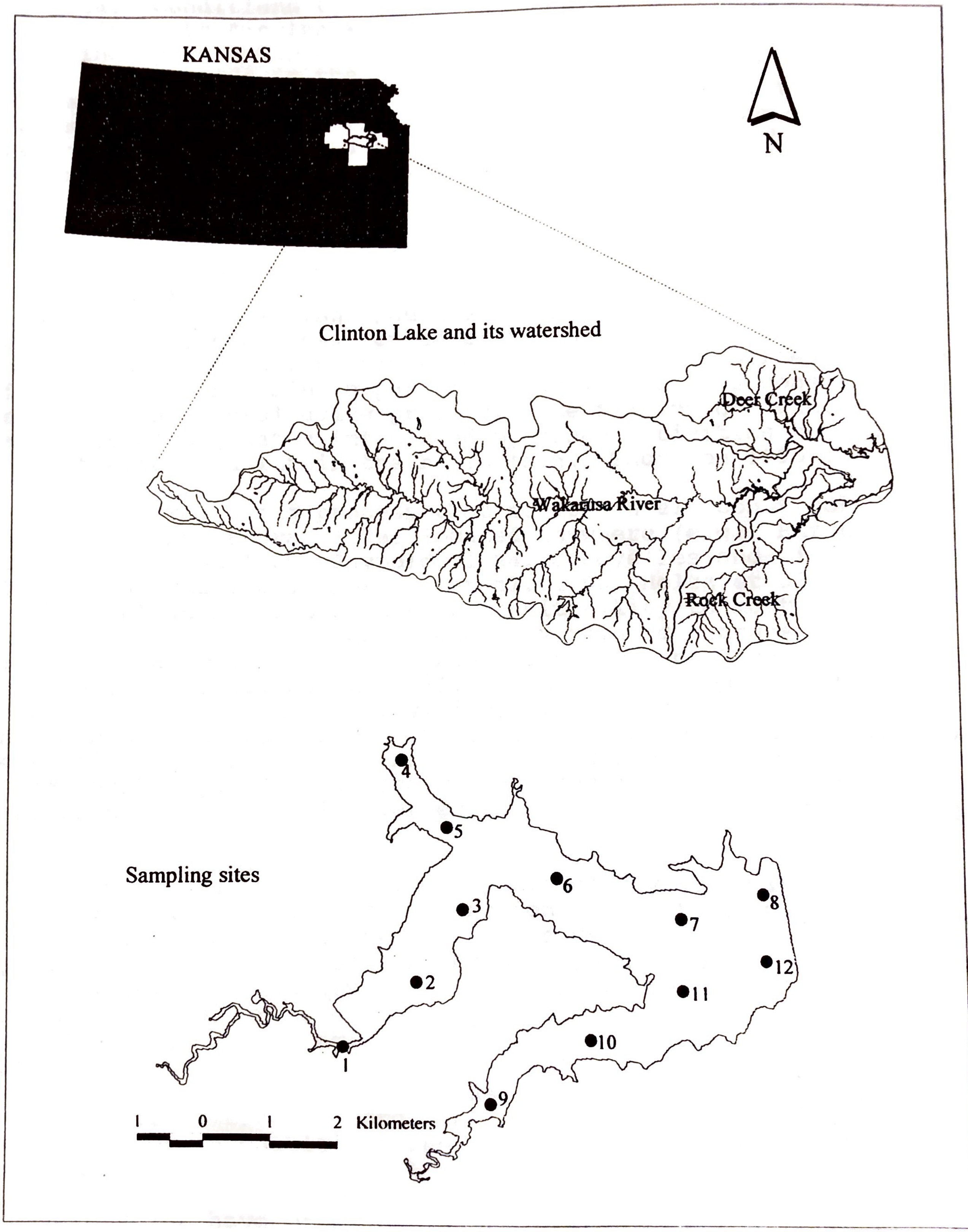

Figure 1. Clinton Lake and the positioning of 12 sampling stations as described in the text.

to certain conditions to be discussed below. As a more defined region in North America we relate this work most to the region extending between the Rocky Mountain uplift in the west to the Appalachian uplift in the east and the Great Lakes in the north to the Gulf Coastal Plain in the south. Again, within this broad region we are more specifically considering areas where natural processes have formed and maintained very few lakes that have remained to the present and reservoirs have been constructed.

Most reservoirs in North America were constructed from the 1920s to the 1980s along major stream courses and thus share a common feature of being highly impacted by their watersheds as they act as settling basins receiving particulate materials. These basins are filling from the settling of fine particulate materials by the process termed siltation. Materials accumulate in reservoirs at varying rates and selectively in different parts of the reservoir basin in part by natural processes considered to be part of a natural aging process. The filling of reservoir basins is also greatly influenced by human activities both within the watershed and within the basin (e.g., Thornton 1990).

The natural aging process that occurs in all constructed reservoirs and natural lakes located anywhere (e.g., Hutchinson 1967, Hutchinson 1969, Reynolds 1984, deNoyelles and Likens 1985a,b, Wetzel 1985, Thornton et al. 1990, Holtz et al. 1997, Smith 1998) introduces a certain inevitability to most of the water quality problems and secondarily related changes such as habitat alteration that are encountered. The critical questions then become: 1) how rapidly will these problems appear and accelerate due to human activities beyond what is natural; 2) what can be done to slow or temporarily reverse the process. For reservoirs the human influence begins with reservoirs typically being located and constructed where natural lakes are not prevalent, thus not being formed or maintained by natural processes.

There are few natural lakes, particularly large ones, in Kansas and in most areas of the region of the US defined above, which delivers an important message as we try to manage these systems. Even where basins might have been naturally formed in this region, particularly by glaciation and other more ancient processes 10,000 or more years ago, most would have long since filled by the natural aging process. This is due to the naturally mobile deep soils and the naturally erodable surface rock of much of this region. Thus, the regional and local locations of reservoirs force them to be settling basins in naturally more erodable watersheds compared to other regions of North America.

Reservoirs have been constructed and located to serve as important human resources. Reservoirs provide flood control, hydroelectric power generation, water quality protection for flowing waters, water for human and livestock consumption and for irrigation, and recreation of many types. Serving these functions brings reservoirs even further under the influence of human activities as they are purposely manipulated in various ways to serve these purposes. For example water levels are routinely manipulated to prepare for seasonal rainfall and flood control or to manage wildlife habitat to improve the resource for recreation.

It is well known that human activities in watersheds and basins of reservoirs and lakes can greatly effect their ecology and how they serve as human resources (e.g., Duttweiler and Nicholson 1983, Thornton et al. 1990, Levich 1996, Clark et al. 1997, Smith 1999). Some human activities can accelerate processes that are naturally occurring leading to more rapidly declining water quality. Other human activities can attempt to protect water quality by controlling what is naturally occurring and what other human activities are causing.

The most frequently studied disturbances of reservoirs and lakes related to water quality are the processes of eutrophication and siltation. Both are natural processes which are also greatly influenced by human activities. Both processes occur naturally, at varying rates, in the aging of all reservoirs and lakes. Eventually, even without human disturbances, reservoirs and lakes will fill and cease to exist. It is the rate at which this occurs, e.g., 100,000 years for lakes verses less than only 200 years for reservoirs, that is of particular concern in this region. Of more immediate concern is that, along the way to this ultimate loss of the basin, perhaps even very early on, it is natural and inevitable for eutrophication and siltation to significantly impair water quality from a human use standpoint and to interfere with some or all of the purposes the reservoir was originally intended to serve.

Recognizing a natural aging process, and how human activities can affect it, helps to better identify the critical cause-and-effect relationships behind present and future water quality and related problems in reservoirs. Only by clearly recognizing what is naturally happening, inevitably happening, can we best protect the water quality, habitat quality, and every other condition of these valuable resources.

Using data gathered during a detailed study of the water quality conditions in Clinton Lake, the natural aging process of reservoirs and human influences are herein related to various water quality conditions. For this study, the water quality conditions viewed as most often threatening their uses include: 1) elevated plant nutrient levels, which accelerate eutrophication, and increase plant biomass, and alter habitat; (2) elevated suspended solids levels (silt), which accelerate siltation process, resulting in loss of basin depth and area and alteration of habitat; (3) elevated toxic chemical levels, particularly pesticides here in this region; and (4) objectionable taste and odor conditions when using water for human consumption. All of these conditions are interrelated and will be shown to occur in the comparatively young (22-year-old) Clinton Lake to varying degrees as revealed by the data gathered from May 1997 through November 1998.

There have been occasions of taste and odor problems in the drinking water drawn from Clinton Lake so severe that alternate sources had to be used for weeks at a time. This particular water quality problem (e.g., Zisette et al. 1994, Jones and Korth 1995, Suffet et al. 1995, Barrett et al. 1996, Young et al. 1996, Clark et al. 1997) in reservoirs and lakes appears to be more commonly reported by the public today, requiring managers and water treatment plant operators to respond. These conditions are evident in this young reservoir despite the fact that its watershed (67% grassland and forest) is less impacted by human activity than many other federal reservoirs in Kansas (personal communication, Natural Resources Council, Lawrence, KS).

MATERIALS AND METHODS

Clinton Lake, located near Lawrence, Kansas located in east central Kansas (Figure 1), is a multipurpose US Army Corps of Engineers reservoir with a 7000 acre (2833 ha) multipurpose pool and a 236,000 acre (95,000 ha) watershed (Figure 2) extending about 40 miles (64 km) to the west from the more forested Lawrence area out into the tallgrass prairie. It is one of 17 large federal reservoirs located in Kansas. The watershed of Clinton Lake is approximately 58% grassland, 30% cropland, 9% forest, and 2% residential/industrial. Construction was completed and filling began in 1977 with the multipurpose pool being reached in 1980. The Wakarusa River, draining approximately 71%, of the watershed was dammed just below two main tributaries, Deer Creek and Rock Creek, draining 10% and 14% of the watershed respectively.

Twelve sampling sites were established to characterize the main body of the reservoir and its three shallower upper branches. These sites (Figure 1, Table 1) are distinguished as the three upper shallowest riverine sites closest to the inflowing streams, the five deeper transitional sites extending down the arms, and the deepest four main basin sites. Water samples were collected with a 2 liter Van Dorn sampler at a series of depths (Table 1) representative of the total depth of each site. Considering the number of sites and depths at each site, a total of 37 samples were analyzed for each sampling date (Table 3). Routinely for each sampling date two sample locations (site and depth) were chosen at random and a replicate sample was taken and then analyzed for all of the parameters. Parameter values for these two additional samples were not included in the analyzed data set but were retained to judge the precision of the analyses.

Concentrations of geosmin, a chemical associated with taste and odor problems, were determined in selected samples and especially in samples collected at the reservoir surface near the

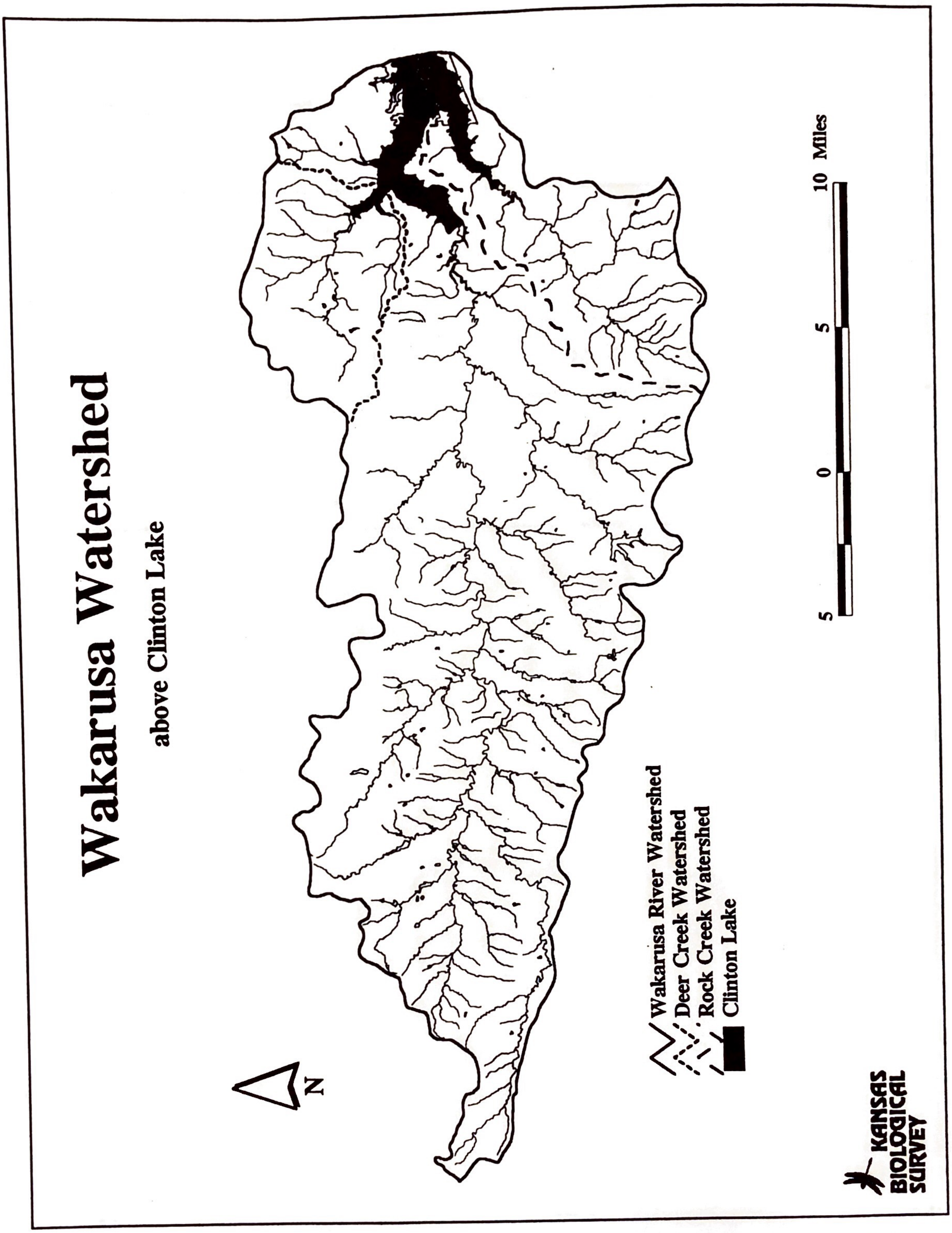

Figure 2. Clinton Lake watershed with the Wakarusa River main basin and the Deer Creek and Rock Creek sub-basins.

Table 1. **Sampling site classification for the Clinton Lake water quality study.**

Site type	Site number	Approximate site depth (m)	Depths sampled (m)
Riverine	1, 4, 9	1.5	0.25
Transitional	2	2.5	0.25, 1.5
	3, 5, 6, 10	3.5 - 5	0.25, 1.5, 3.0
Lacustrine (Main Basin)	7, 11	7.5	0.25, 1.5, 3.0, 6.0
	8, 12	12	0.25, 1.5, 3.0, 6.0, 9.0, 10.0

Table 2. Water quality and biological parameters assessed in Clinton Lake.

Parameter	Instrument/Method	Method Citation	Method Detection Limit
Total Dissolved Phosphate	Lachat QuikChem 4200 (flow injection automated analyzer)	19th ed. Standard Methods 4500 P	1 µg L^{-1}
Chemical Oxygen Demand	Hach COD Reactor, Milton Roy 501 spectrophotometer	19th ed. Standard Methods 5220 C	1.0 mg L^{-1}
Total & Dissolved Organic Carbon	Beckman 915A carbon analyzer	19th ed. Standard Methods 5310 B	1.0 mg L^{-1}
Total Phosphorus	Lachat 48 place digester, Lachat QuikChem 4200 (flow injection automated analyzer)	Ebina et al., 1983	5 µg L^{-1}
Total Nitrogen	Lachat 48 place digester, Lachat QuikChem 4200 (flow injection automated analyzer)	Ebina et al., 1983	0.01 mg L^{-1}
Ammonia (NH_3-N)	Lachat QuikChem 4200 (flow injection automated analyzer)	19th ed. Standard Methods 4500NH3-G	1 µg L^{-1}
Sulfate	Dionex DX-300 Gradient Chromatography System	19th ed. Standard Methods 4110 B	0.1 mg L^{-1}
Chloride	Dionex DX-300 Gradient Chromatography System	19th ed. Standard Methods 4110 B	0.1 mg L^{-1}
Nitrate (NO_3-N)	Lachat QuikChem 4200 (flow injection automated analyzer)	19th ed. Standard Methods 4500NO3-G	0.01 mg L^{-1}
Total Dissolved Solids	Myron TDS meter, Model DP4	19th ed. Standard Methods 2540 C	1.0 mg L^{-1}
Total Hardness	Titrimetric; EDTA	19th ed. Standard Methods 2340 C	1 mg L^{-1}
Total Alkalinity	Titrimetric; pH meter	19th ed. Standard Methods 2320 B	1 mg L^{-1}
Total Suspended & Total Volatile Solids	Gravimetric; volatile solids ignited at 500 °C	19th ed. Standard Methods 2540 D and E	1 mg L^{-1}
pH	Horiba U-10 Water Quality Checker (measured *in situ)*	19th ed. Standard Methods 4500-H A	0.1
Conductivity	Horiba U-10 Water Quality Checker (measured *in situ)*	19th ed. Standard Methods 2510 A-B	1 µS cm^{-1}
Dissolved Oxygen	Horiba U-10 Water Quality Checker (measured *in situ)*	19th ed. Standard Methods 4500-0 G	0.1 mg L^{-1}
Turbidity	Horiba U-10 Water Quality Checker (measured *in situ)*	19th ed. Standard Methods 2130 B	1.0 NTU
Air and Water Temperature	Horiba U-10 Water Quality Checker (measured *in situ)*	19th ed. Standard Methods 2550 B	0.1 °C
Transparency	Secchi Disk (measured *in situ)*	Wetzel and Likens, 1991	-

Table 2. continued

Oxidation/Reduction Potential	silver:silver chloride electrode, Hach ISE meter, Model 45400	19th ed. Standard Methods 2580 B	1 mV
Chlorophyll *a*	Optical Tech. Devices, Ratio-2 System Filter Fluorometer	19th ed. Standard Methods 10200 H	1.0 µg L^{-1}
Atrazine + metabolites	Gas Chromatography/Mass Spectrometry	Thurman and others, 1990	0.05 µg L^{-1}
Cyanazine	Gas Chromatography/Mass Spectrometry	Thurman and others, 1990	0.1 µg L^{-1}
Alachlor	Gas Chromatography/Mass Spectrometry	Thurman and others, 1990	0.05 µg L^{-1}
Metolachlor	Gas Chromatography/Mass Spectrometry	Thurman and others, 1990	0.05 µg L^{-1}
Metributzin	Gas Chromatography/Mass Spectrometry	Thurman and others, 1990	0.05 µg L^{-1}
Geosmin	SPE/GC-MS	Unpublished method	1 ng L
Total Coliform Bacteria	M-FC Broth with rosolic acid	19th ed. Standard Methods 9222 B	-
Phytoplankton	cell counts	19th ed. Standard Methods 10200 F	-

Table 3. Sampling dates for the Clinton Lake study during the period from 1997 through 1998.

Month	Day
1997	
May	28, 29
June	12, 13
July	15, 16
August	26, 27
September	16, 19
October	15, 17
November	11, 12
December	16, 17
1998	
Early April	2, 7
Late April	21, 23
Early May	5, 7
Late May	20, 21
June	16, 17
July	13, 14
August	17, 18

dam where water was being withdrawn for the water treatment plant. At times samples were instead collected at the pump house just after water had left the reservoir at a depth of about three meters and passed through the dam. This area of the reservoir is well mixed by the prevailing southwesterly winds, thus both types of samples were considered to be equivalent.

All of the parameters included in this study are listed in Table 2 along with the methods used and their detection limits. Parameters chosen for this study are primarily those characterizing the conditions in the water column that most specifically relate to the four water quality conditions cited in the introduction as of primary concern in this study. Of these parameters the following are considered in greater detail here: total phosphorus, total nitrogen, transparency, turbidity, total suspended solids, total organic carbon, geosmin, atrazine, chlorophyll *a*, and phytoplankton species counts.

The method for enumerating surface water phytoplankton differs in some ways from the general method cited in Table 2. From 100-ml raw water samples taken from 0.25 m in the reservoir and preserved with Lugol's solution, one subsample of 10 ml from each was settled for 24 hours in a chamber that could then be counted using a Wild inverted microscope. Twenty-five fields were counted at each of two magnifications and measures of the dimensions of a representative number of the individuals of each species were also taken for biovolume calculations. Unidentified taxa were counted in three size categories so that an accurate estimate of the total biovolume of phytoplankton could be made. For the October 1997 sampling date, samples from each depth (Table 1) from eight sites (sites 2,3,4,5,8,9,10,12) were also counted for phytoplankton as described above.

A nutrient and light bioassay was performed four times during the study, in October and November, 1997 and in June and July, 1998. For each bioassay, water was collected from a depth of 0 to 1 m in the reservoir and, in the laboratory on the same day, was randomly subdivided into 1-liter Pyrex glass bottles. Five served as controls and there were five replicates for each of five treatments that produced elevated concentrations of phosphorus, nitrogen, and nitrogen plus phosphorus, and 150 and 220 percent increases (1.5x and 2.2x) in light intensity. The 30 bottles were incubated in a growth chamber for 14 days on a twelve-hour light/dark cycle. The ambient light intensity for incubation was approximately the same as the intensity at 1 m in the reservoir and for the elevated light levels was about that at 0.5 m and 0.25 m. Algal biomass was estimated for each bottle every 48 hours by measuring the relative chlorophyll fluorescence of a 25 ml subsample using a Turner Model 10 fluorometer. The October and June bioassays were performed on water from the main basin and the November and July bioassays on water from a riverine site in the Wakarusa arm of the reservoir. Further details describing this bioassay method are reported by Meyer (1998).

RESULTS AND DISCUSSION

Nutrient conditions in Clinton Lake

Eutrophication is driven by available plant nutrients in the reservoir or lake. The nutrient phosphorus is most often identified as causing the accelerated plant growth of eutrophication (e.g., Schindler 1977, deNoyelles and O'Brien 1978, Reckhow and Chapra 1983, Heyman and Lundgren 1988, Foy et al. 1996, Smith 1998). The literature on eutrophication provides many accounts of water quality conditions, such as the total phosphorus (TP) levels, that most often accompany and are involved with this process in reservoirs and lakes. The following relationships (Smith 1998), all in ug liter^{-1}, are widely accepted.

	TP	TN	chl *a*
oligotrophic	<10	<350	<3.5
mesotrophic	10-30	350-650	3.5-9.0
eutrophic	30-100	650-1200	9.0-25
hypertrophic	>100	>1200	>25

Analyzed total phosphorus (Figure 3) was found to be in relatively high concentrations in the Clinton Lake water column when considering levels commonly associated with eutrophication. Concentrations of TP in excess of 30 ug liter^{-1} are considered to be evidence of eutrophication and the average TP for Clinton Lake throughout the study generally ranged between 30 and 100 ug liter^{-1} (Figure 3). In Figure 3 and in similar summary graphs presented here, the value plotted for each particular date is the average for all samples from all 12 sites, including those collected from multiple depths (see Figure 1). One to six depths were sampled at each site (Table 1) depending on the maximum depth. Thus each point on the graph is the mean of 37 measurements throughout the reservoir and water column for that date.

The highest TP levels for a given sampling date were consistently higher in the upper arms (Figure 4), sometimes by more than two fold, indicating that inflow from the watershed was a major source. As will be discussed later, this does not preclude the possibility that certain conditions in the arms of the reservoir independently contribute to this and other water quality conditions. In Figure 4 and similar graphs herein, average values are plotted only for surface samples from the 12 sites (see Figure 1) grouped into the three riverine sites (1,4,9), the five transitional sites (2,3,5,6,10), and the four main basin sites (7,8,11,12) as described in Table 1.

Nitrogen is generally the second most important nutrient driving eutrophication in reservoirs and lakes as considered by the references cited above for phosphorus. Concentrations of total nitrogen (TN) above 650 ug liter^{-1} generally indicate eutrophication as noted above. Lower concentrations down to 350

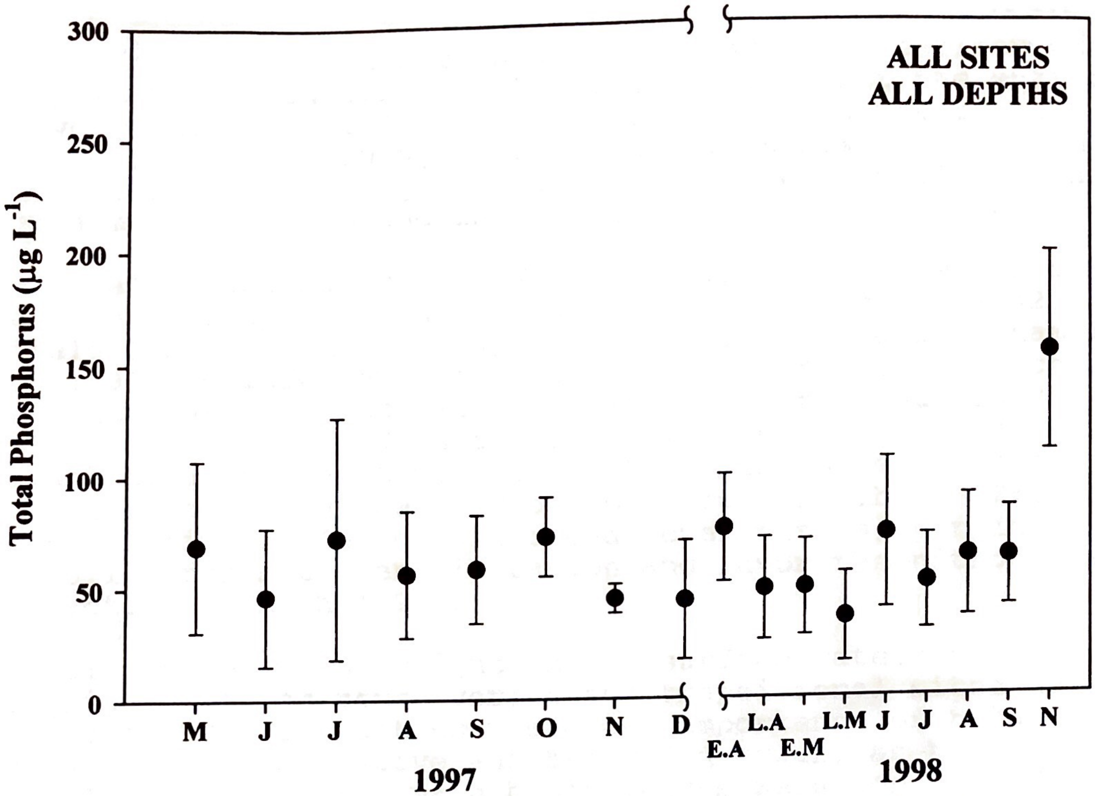

Figure 3. Total phosphorus from all sites and depths for each date. Error bars represent one standard deviation.

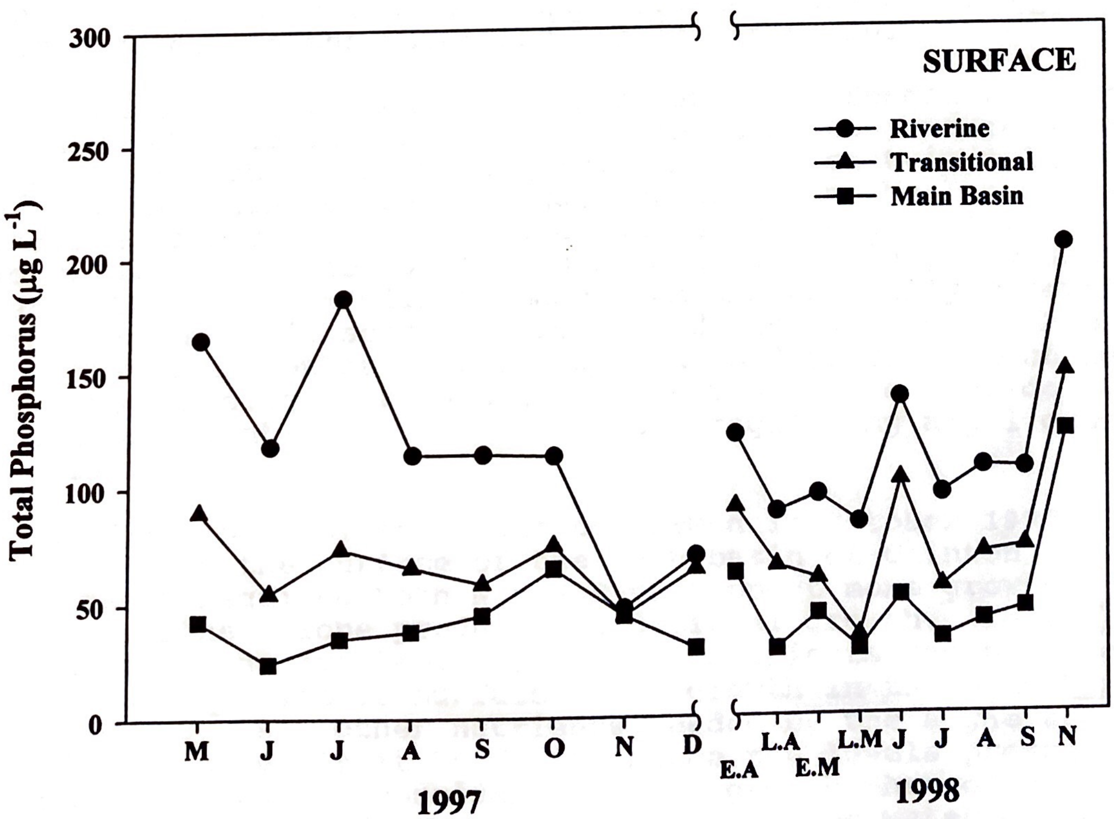

Figure 4. Total phosphorus for surface samples from stations grouped as described in the text.

ug liter^{-1} indicate mesotrophic conditions or an earlier stage of eutrophication. TN concentrations summarized for the entire reservoir and water column (Figure 5) show concentrations consistently above 350 ug liter^{-1} and about 50% of the time above 600 ug liter^{-1}. The highest levels were consistently in the upper arms closest to the inflowing streams as shown in Figure 6.

The elemental ratios of TN and TP (TN:TP) from water samples have been used by some investigators (e.g., Pearsall 1932, Redfield 1958, Sakamoto 1966, Smith 1982, Hecky and Kilham 1988, Smith 1998) to infer nutrient limitation in terms of which of these nutrients is most likely limiting plant growth in the water sampled. This is based on the relative requirement for each nutrient by different types of plants which for algae tends to be 10N:1P by weight. Higher ratios, particularly above 17:1, infer phosphorus limitation for algae and lower ratios, particularly below 5:1 infer nitrogen limitation and favor the nitrogen fixing cyanobacteria (Smith 1998).

Ratios of TN:TP by weight in the surface waters of Clinton Lake (Figure 7) for the riverine and transitional sites tended to be close to 10:1 indicating the equal importance of both nutrients but values above and below did occur, as high as 17:1 and as low as 5:1. The main basin values were consistently higher, though only occasionally above 25:1, suggesting more likely phosphorus limitation at times. For the reservoir as a whole, based on this nutrient ratio consideration, there is not a consistent importance of one nutrient over the other; thus it is concluded that both must be considered in nutrient management practices both in the watershed and in the basin.

There are additional tests that can be performed to help determine whether one or both of these nutrients are regulating the algal growth in the reservoir. One such test is a laboratory bioassay in which reservoir algae are grown in the lab under various nutrient conditions (O'Brien and deNoyelles 1976, deNoyelles and Kettle 1985). As described earlier, raw surface water collected from Clinton Lake with the naturally occurring algae was placed in some bottles spiked with various combinations of nutrients and other bottles exposed to differing light levels. Conditions causing increased growth in the bottle provide some support for identifying the conditions regulating algal growth in the reservoir.

The first such bioassay was performed in October 1997 with raw water from the surface of the main basin of Clinton Lake. At this time it required both N and P to support more growth (Figure 8), with neither alone producing additional growth. This suggests that the availability of both nutrients was necessary for any acceleration of surface algal growth in the main basin of the reservoir. All other nutrients needed by the algae appeared to be in ample supply at this time since the levels present in the bottles supported considerable more growth when only N and P were increased. The TN:TP ratio in the surface water of the main

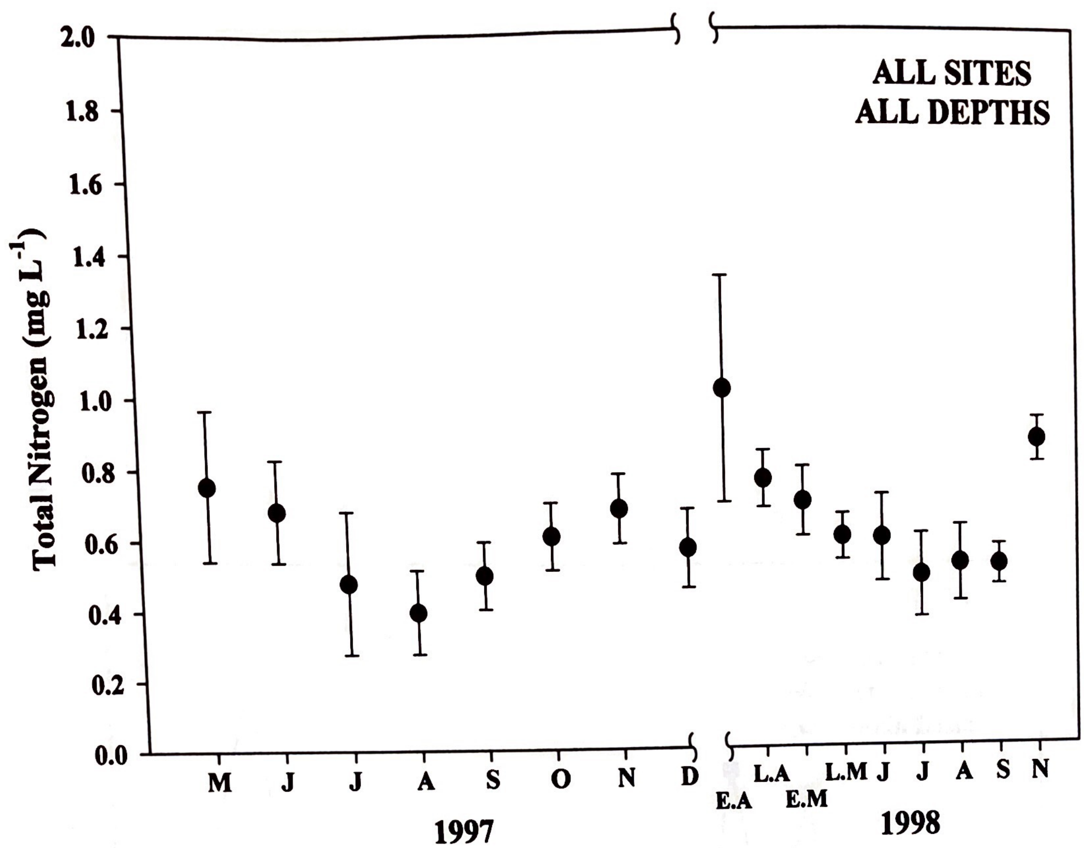

Figure 5. Total nitrogen from all sites and depths for each date. Error bars represent one standard deviation.

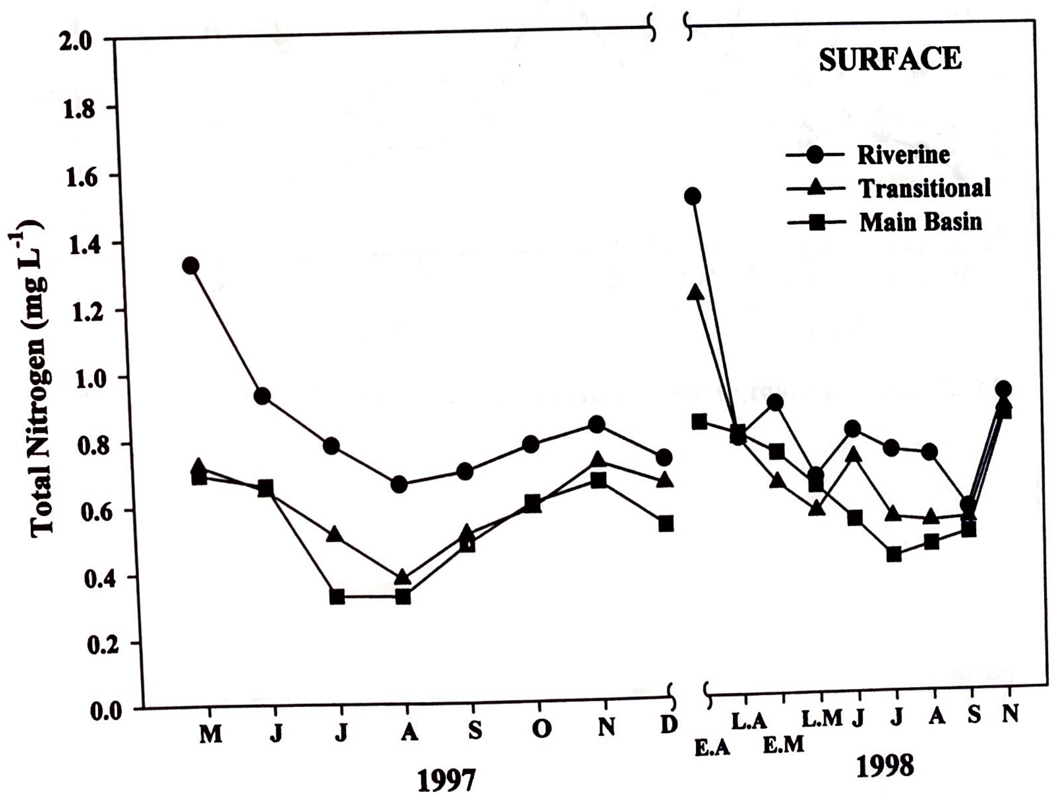

Figure 6. Total nitrogen for surface samples from stations grouped as described in the text.

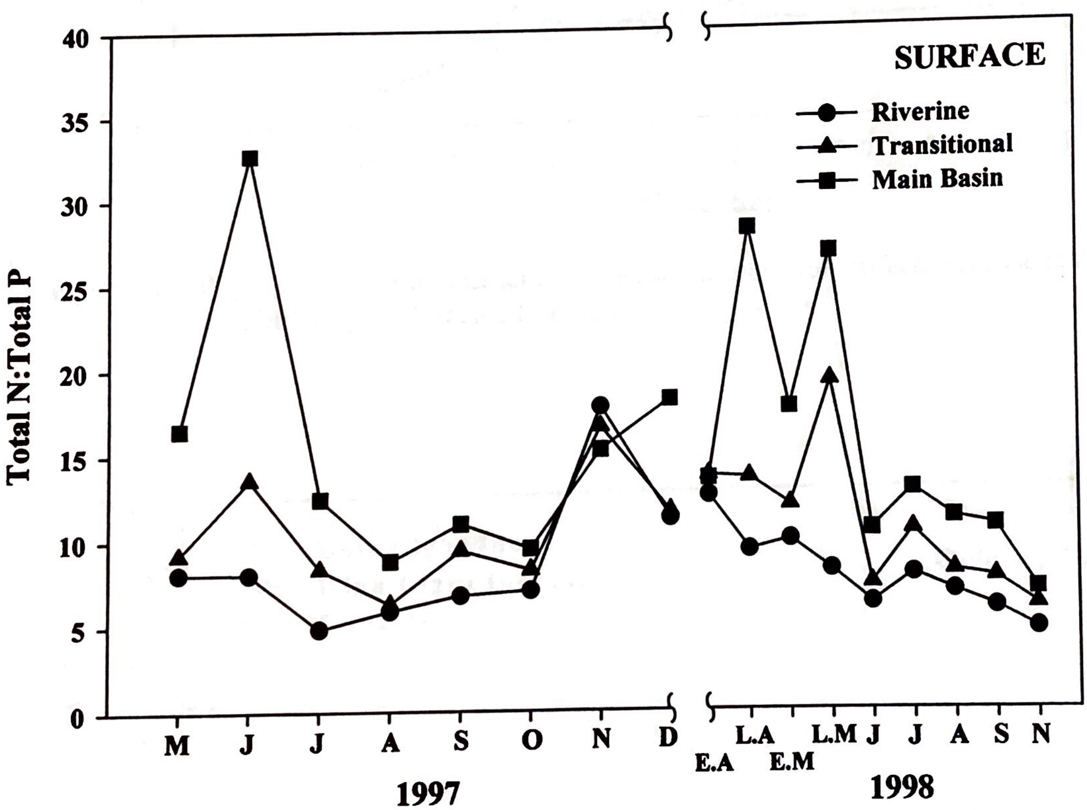

Figure 7. Total N: total P for surface samples from stations grouped as described in the text.

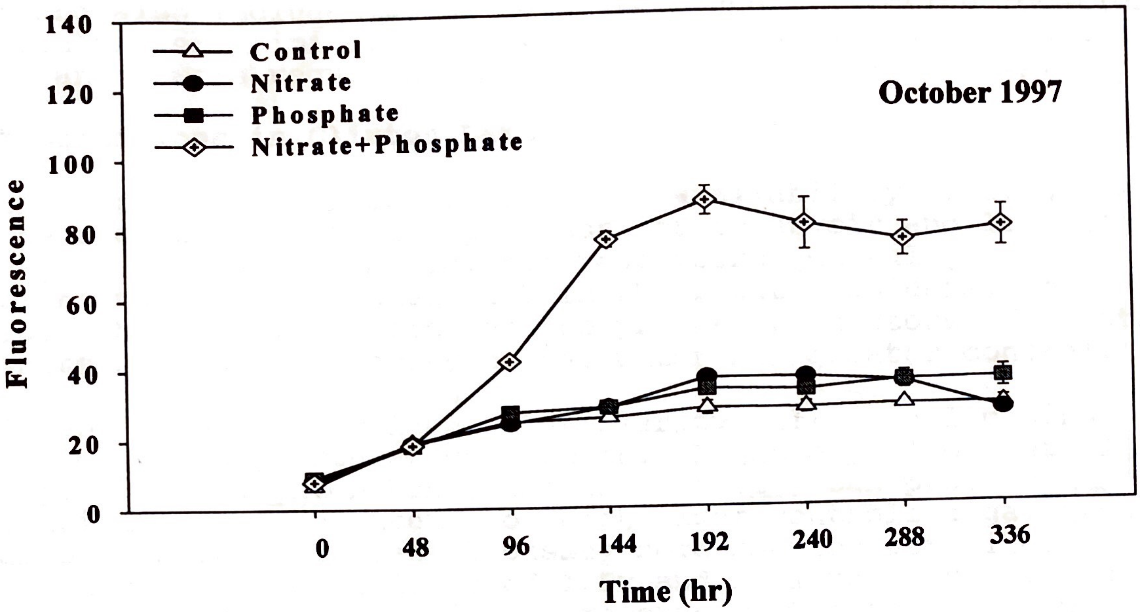

Figure 8. Phytoplankton biomass as relative fluorescence for different nutrient treatments in a bioassay as described in the text.

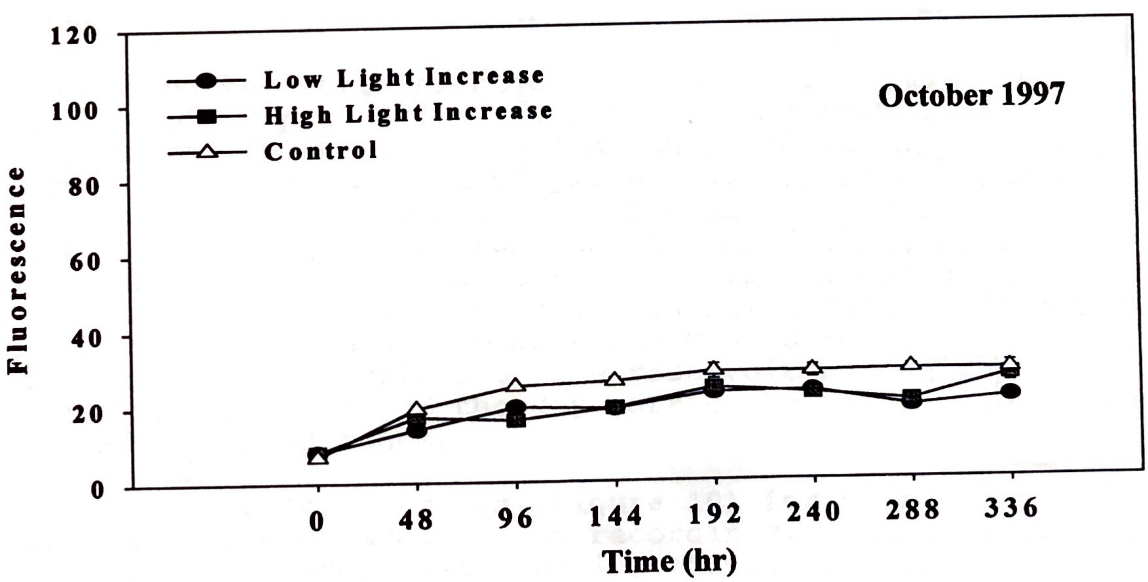

Figure 9. Phytoplankton biomass as relative fluorescence for different light treatments in a bioassay as described in the text.

basin at this time was 10:1. Three more bioassays of this type were performed at other times (November 1997, and June and July 1998) and also included water collected from a riverine location. The results were similar in that on each occasion increases in both N and P were required for maximum growth (Meyer 1998).

Light conditions in Clinton Lake

Apart from N and P conditions, the availability of light may also be a critical regulating factor for reservoir and lake algae and higher plants. With regional reservoirs generally experiencing much suspended silt in their water columns, it is possible that nutrients are not the primary regulators of growth but instead that the clarity of the water has greater control.

In any reservoir or lake water clarity will be a limiting factor for plant growth at some depth. Light may also control algal growth in Clinton Lake, and the bioassay can provide information as to the extent to which light controls algal growth at various depths. In each bioassay some samples were incubated with higher light intensities of 1.5x and 2.2x the intensity of ambient light at one meter in the reservoir, the intensity used for the bottles receiving nutrients. This produced no additional growth without added N and P (Figure 9) for the October 1997 bioassay and the other bioassays yielded the same results. Though light is certainly regulating growth at some depth, in the upper most productive zone of the water column, the nutrients N and P, rather than light, were both consistently important regulators and thus should both be managed in the watershed and in the basin.

Considering the eutrophication of a reservoir and the increases in plant production, it might appear that more suspended matter in the water column would effectively control plant growth. It is not that simple because there are other consequences of this material, even some that could be expected to accelerate plant growth. For example, as filling of a reservoir basin proceeds by siltation, shallow zones of the reservoir increase in area, actually providing more habitat for rooted vegetation. The phytoplankton may also increase in abundance because as portions of the reservoir become shallower phytoplankton spend less of the day carried by water movements to deeper, light-limited zones.

Water transparency measures (Figure 10) for Clinton Lake were obtained using lowered secchi disc recordings. The greater the Secchi depth the clearer (less turbid) the water. The lowest transparency occurred in the upper arms closest to the inflow, with levels generally less than half those in the transitional zones and much less than those in the main basin. The same pattern is supported by the turbidity (Figure 11) and the total suspended solids data (Figure 12). This indicates that a source of this condition is, once again, the watershed and that much of this material settles out before reaching the main basin.

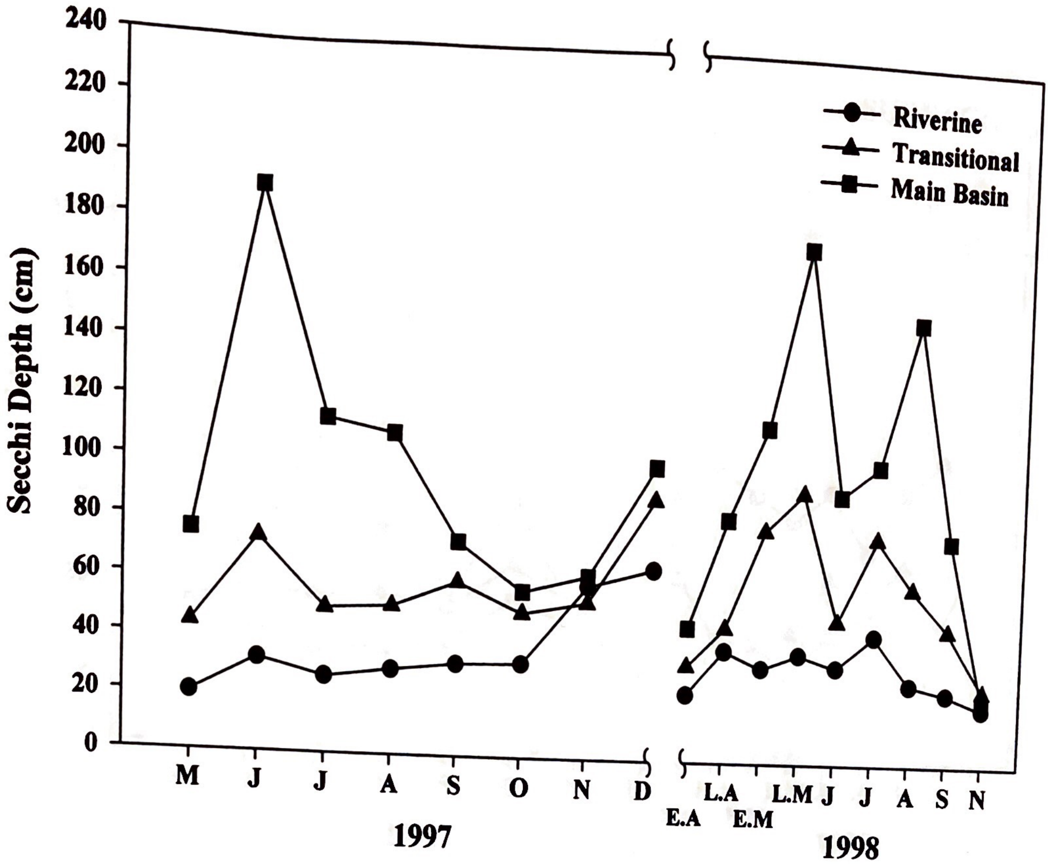

Figure 10. Secchi depth from stations grouped as described in the text.

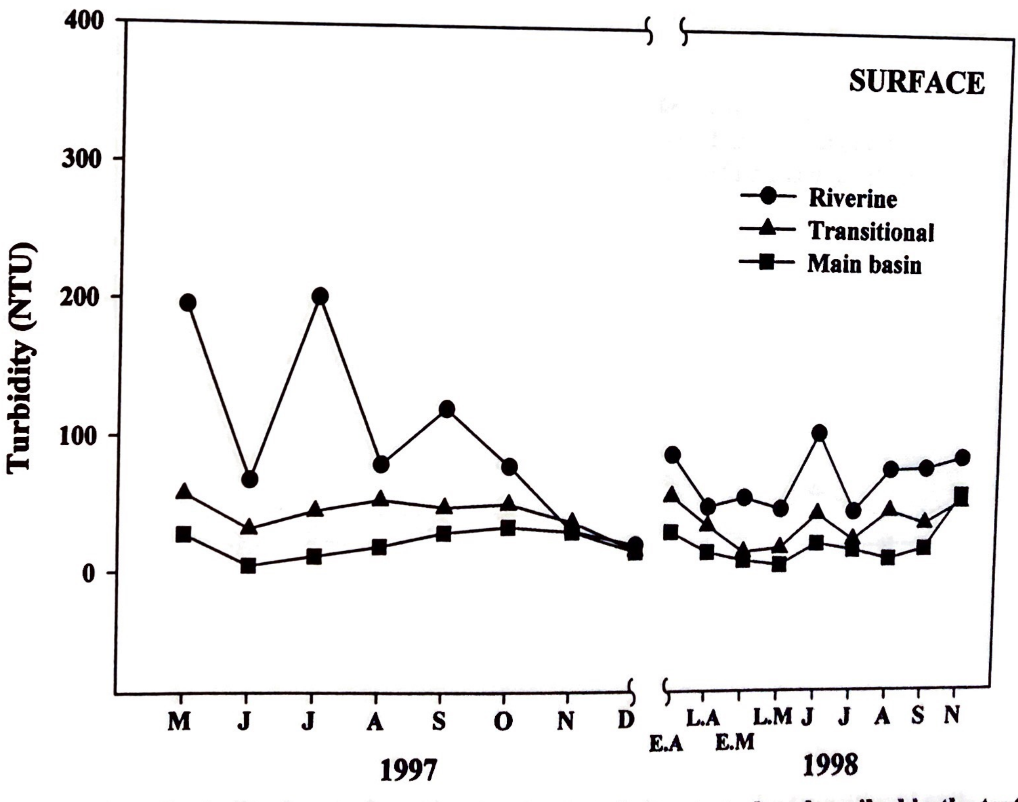

Figure 11. Turbidity for surface samples from stations grouped as described in the text.

To better support the suggestion from the above data that much of the silt was settling in the upper arms, the turbidity

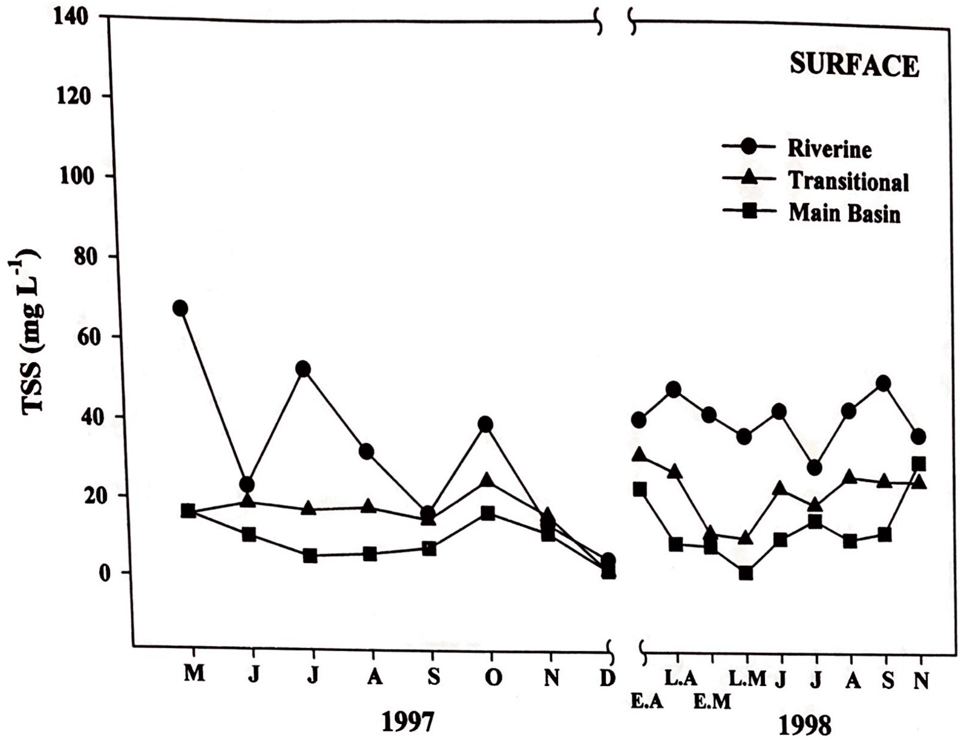

Figure 12. Total suspended solids for surface samples from stations grouped as described in the text.

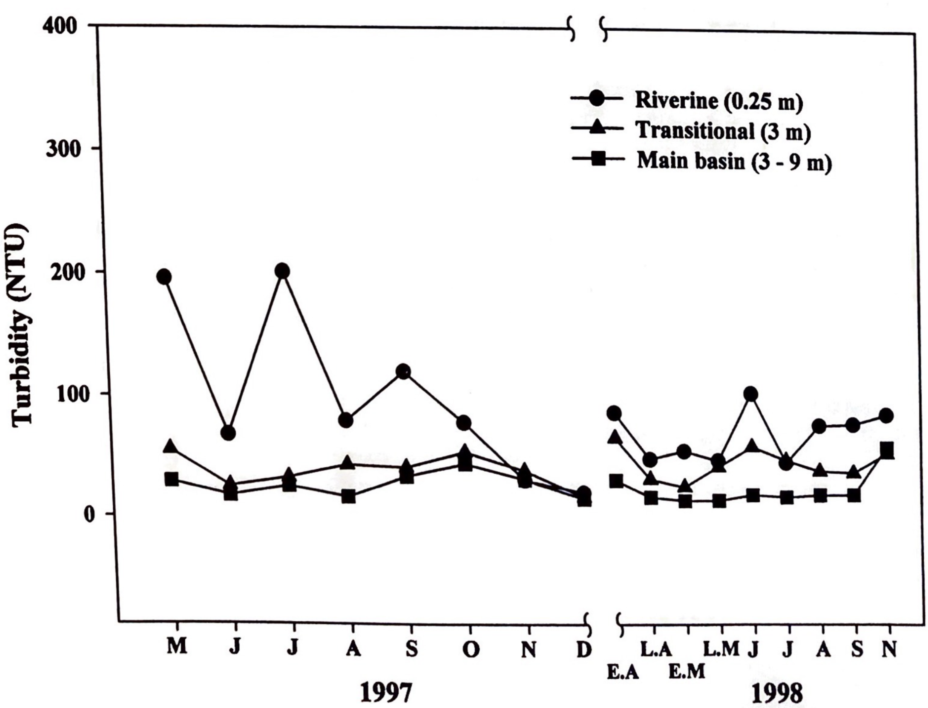

Figure 13. Turbidity for all sites with just the lower depths in the transitional and main basin areas.

To better support the suggestion from the above data that much of the silt was settling in the upper arms, the turbidity (Figure 13) and TSS (Figure 14) data was examined for deeper depths which could show that much silt was actually leaving the water column. The same lower values in transition and main basin sites are evident here, further supporting that much of the silt was leaving the entire water column soon after entering the upper arms of the reservoir. Available data for sedimentation rates across basins for other large reservoirs in eastern Kansas indicate that the rate is at least 3x to 5x greater in the arms (Juracek 1997, Pope 1998).

The shallowest conditions of the upper arms of a reservoir are also be expected to affect the transparency of the water since wind driven waters across shallow zones will cause more uplift of the sediments (Carper and Bachmann 1984, Bloesch 1995, Effler et al. 1998). However, given the orientation of the arms (Figure 1) and the prevailing winds from the southwest for Clinton Lake, the most turbid or least transparent riverine zone is often the most protected from these winds, indicating the often greater importance of watershed inputs and calmer waters promoting more rapid settling of suspended silt.

Transparency of the main basin of Clinton Lake is similar to or greater than many other large reservoirs in the area but is still relatively low compared to most natural lakes to the north and in the mountain ranges of North America. If a watershed is being very successfully managed for soil erosion but dissolved N and P are still elevated in the runoff water, plant growth could be accelerated even more with more light available to the water column and sediments. Management must involve controls over both soil erosion and nutrients.

Other physical and chemical conditions in Clinton Lake

Of the other physical and chemical parameters monitored in Clinton Lake (Table 2) not yet discussed, TOC, DOC, COD, VSS, NVSS, TDS, SO_4, Cl, conductivity, and alkalinity showed the same strong relationship to position in the basin described above, with the highest values recorded in the riverine sites, the lowest values in the main basin sites, and the transitional sites intermediate. Dissolved oxygen and pH showed the reverse relationship, with the lowest values consistently in the riverine sites and the highest values in the main basin sites. Thermal stratification did not develop during the summer to the extent that anaerobic conditions developed in deeper waters. The levels of geosmin concentration in the water column will be discussed separately below as its role in the taste and odor water quality problem is considered.

Another clear threat to the water quality of reservoirs and lakes is the synthetic (unnatural) chemicals that can also be introduced. Most commonly observed, for reservoirs in Kansas and neighboring states where there is much agriculture, is the

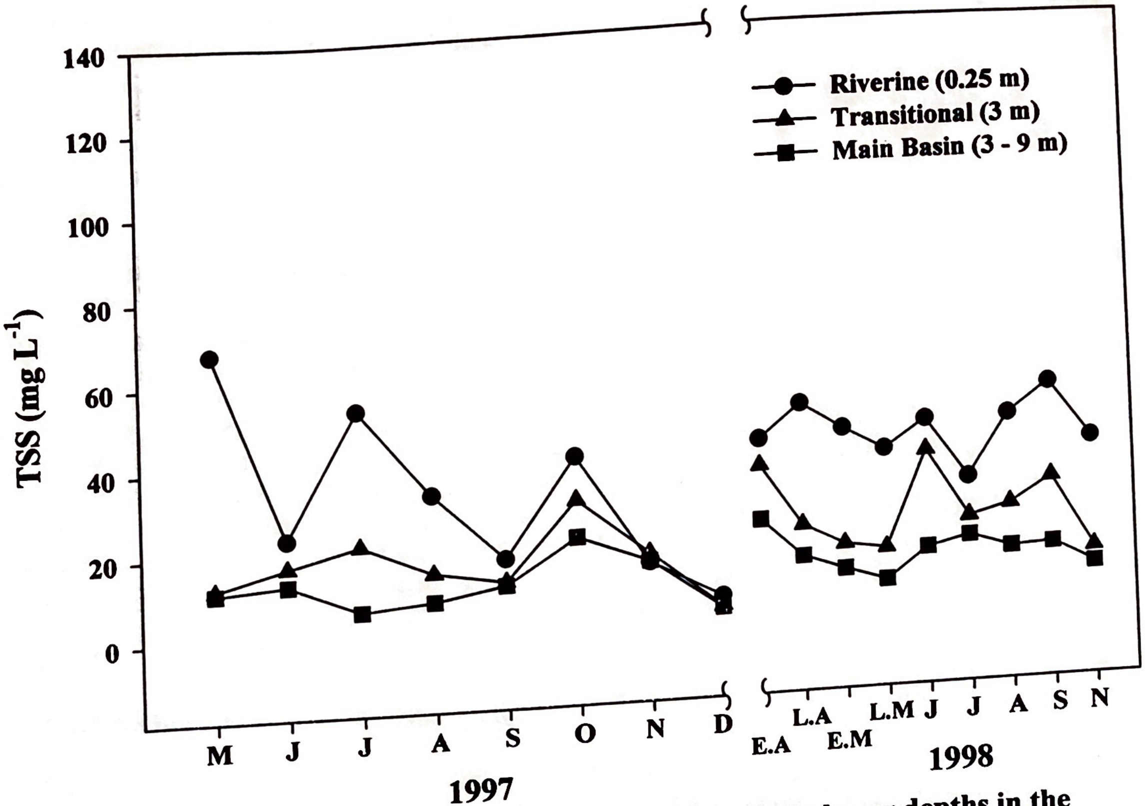

Figure 14. Total suspended solids for all sites with just the lower depths in the transitional and main basin areas.

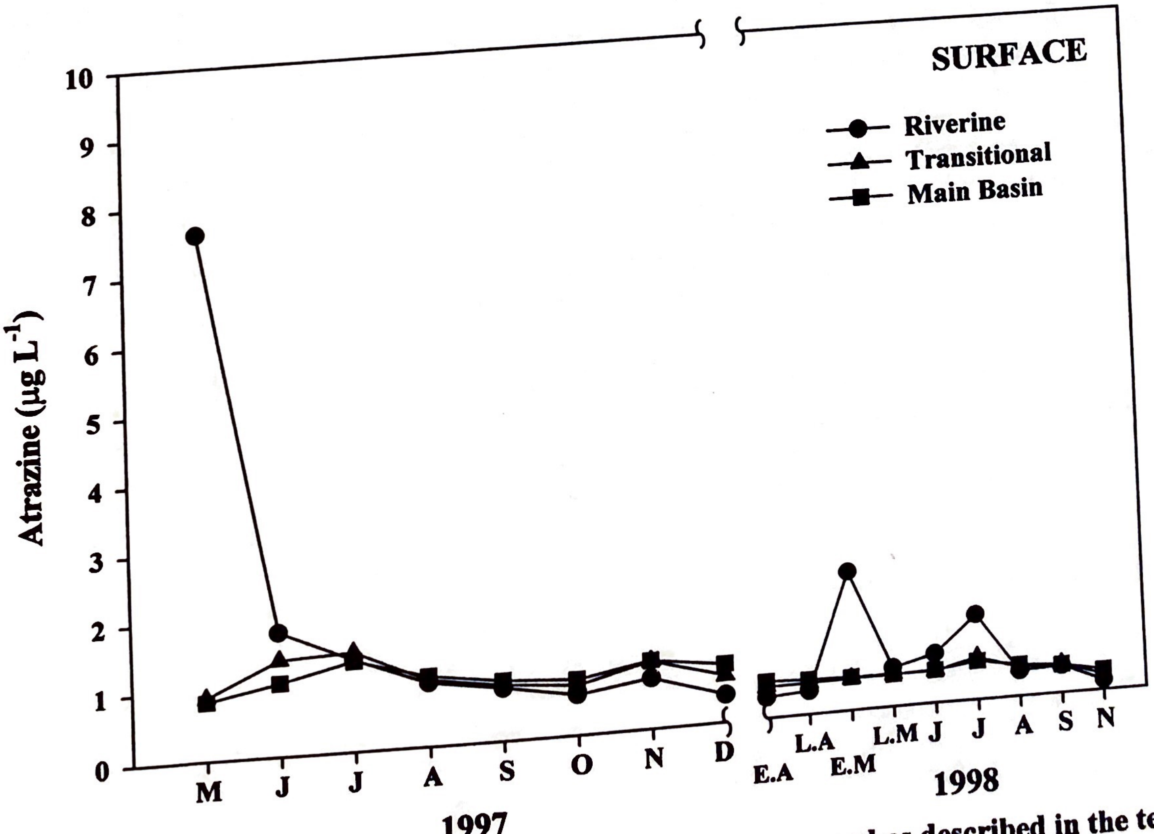

Figure 15. Atrazine for surface samples from stations grouped as described in the text.

appearance of pesticides. One of the most widely used and most slowly degrading herbicides applied in this area is atrazine (deNoyelles et al. 1982, 1994) and this chemical does reach the water column in Clinton Lake (Figure 15). The highest concentrations were in the spring and early summer in the upper arms, soon after the observed time of application in the watershed.

Three samples collected during the study had levels (14.5, 6.5, 4 ug liter^{-1}) exceeding State and federal drinking water standard of 3 ug liter^{-1}. However, it should be noted that the standard is based on an annual average and atrazine is partially removed during treatment by the water utilities using Clinton Lake as a source of supply. Although the levels of atrazine observed during this study were not high enough to cause a violation of the drinking water standard, they were high enough to warrant continued vigilance to insure against such an occurrence. Furthermore, the levels were high enough to raise concerns regarding effects on aquatic ecosystems (deNoyelles et al. 1994), since some states have established limits as low as 1 ug liter^{-1} on atrazine for protection of aquatic ecosystems.

Phytoplankton in Clinton Lake

Turning to the measures of phytoplankton in the reservoir water column, consistently high biomass was recorded as measured by chlorophyll *a* extracted from filtered water samples (Figure 16). These biomass concentrations were higher than those normally found in oligotrophic natural lakes in North America. Concentrations above 9 ug liter^{-1} as chlorophyll *a* indicate eutrophication (Smith 1998), as stated earlier. For the surface waters across the entire reservoir values were generally above 10 ug liter^{-1}. Concentrations were consistently highest in the riverine sites often double those in the other sites. Concentrations in the transitional sites were consistently higher than those in the main basin. Total organic carbon values (Figure 17), also providing some indication of the total suspended microbial community, including the phytoplankton, also displayed this pattern of distribution.

The biovolume of total phytoplankton and the dominant species were determined from May 1997 through May 1998 (June through November 1998 data were not yet available at the time this manuscript was prepared) from samples taken at 0.25 m. At times species that have come to be routinely recognized as indicating eutrophication were abundant. These were species of cyanobacteria, particularly species of *Anabaena*, *Aphanizomenon*, *Microcystis*, and *Aphanocapsa* and species of diatoms, particularly species of *Melosira* and *Cyclotella*. The biovolume of total cyanobacteria (Figure 18) was recorded in the greatest abundance for the year in October 1997 with the highest concentrations for the year also recorded for each genus of the cyanobacteria, except *Aphanizomenon* (highest in June). All of these biovolumes in October were highest in the transitional sites and lowest in

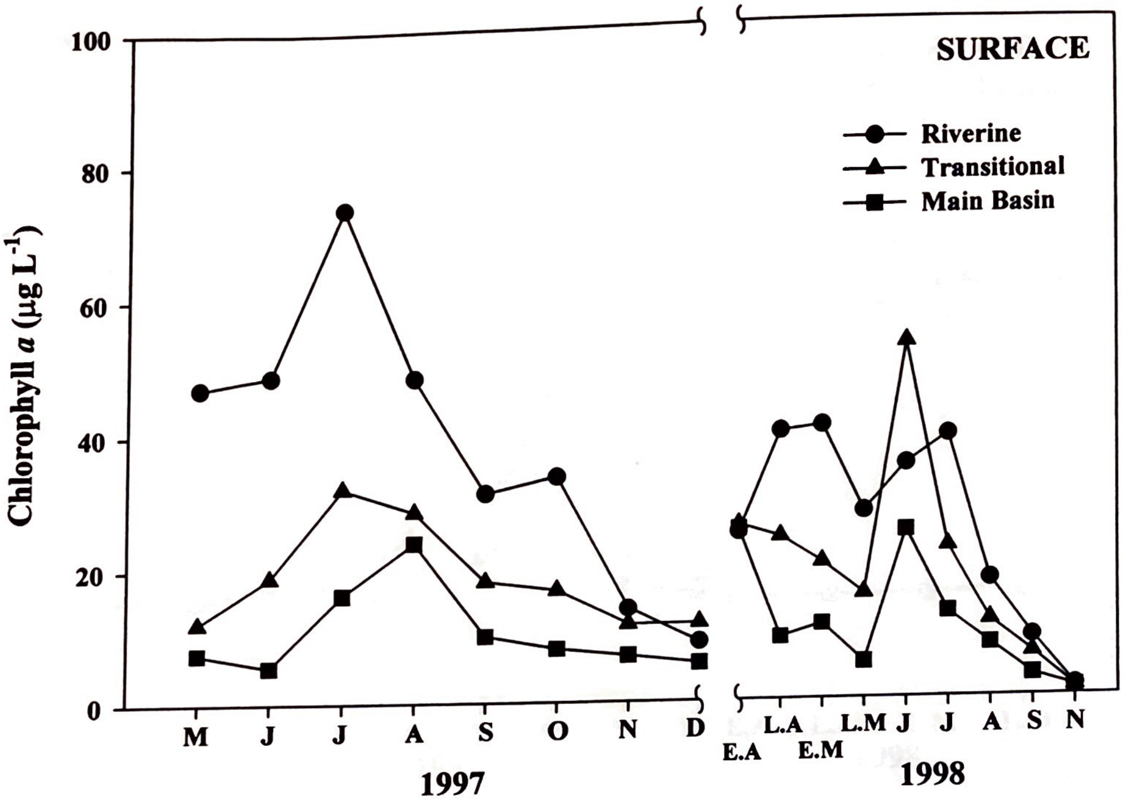

Figure 16. Chlorophyll *a* for surface samples from stations grouped as described in the text.

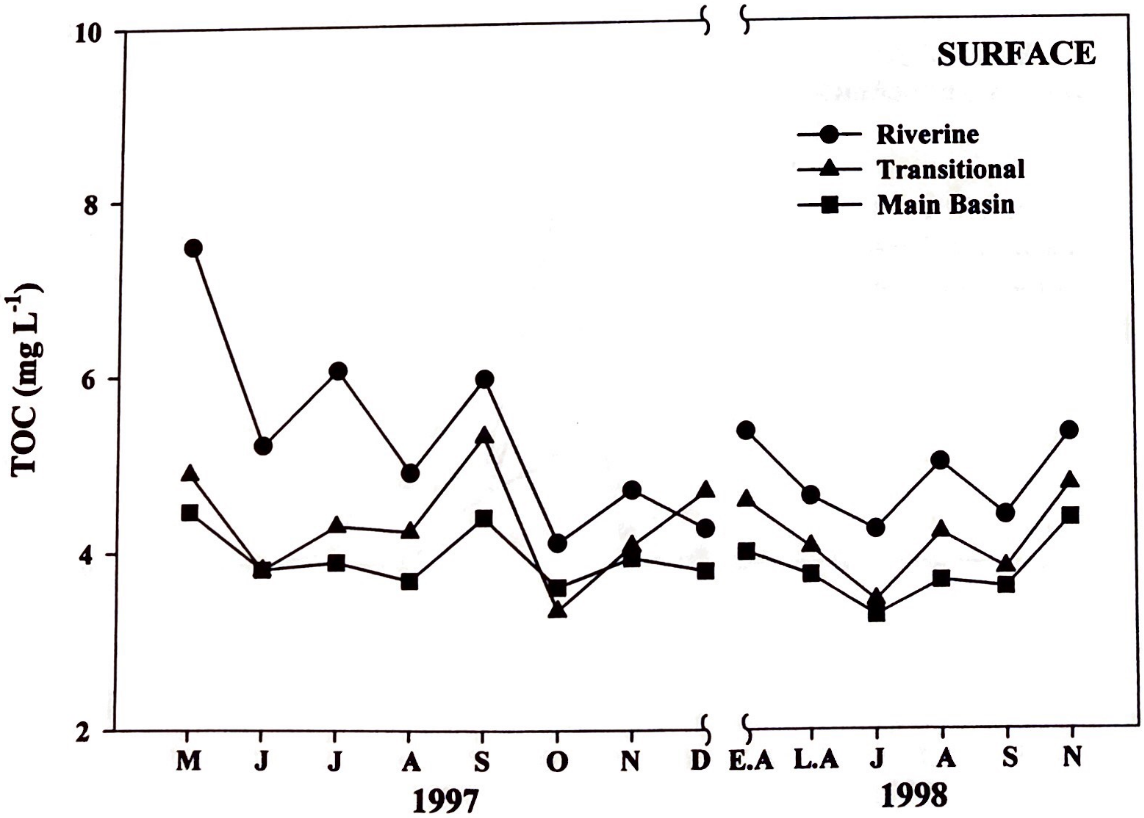

Figure 17. Total organic carbon for surface samples from stations grouped as described in the text.

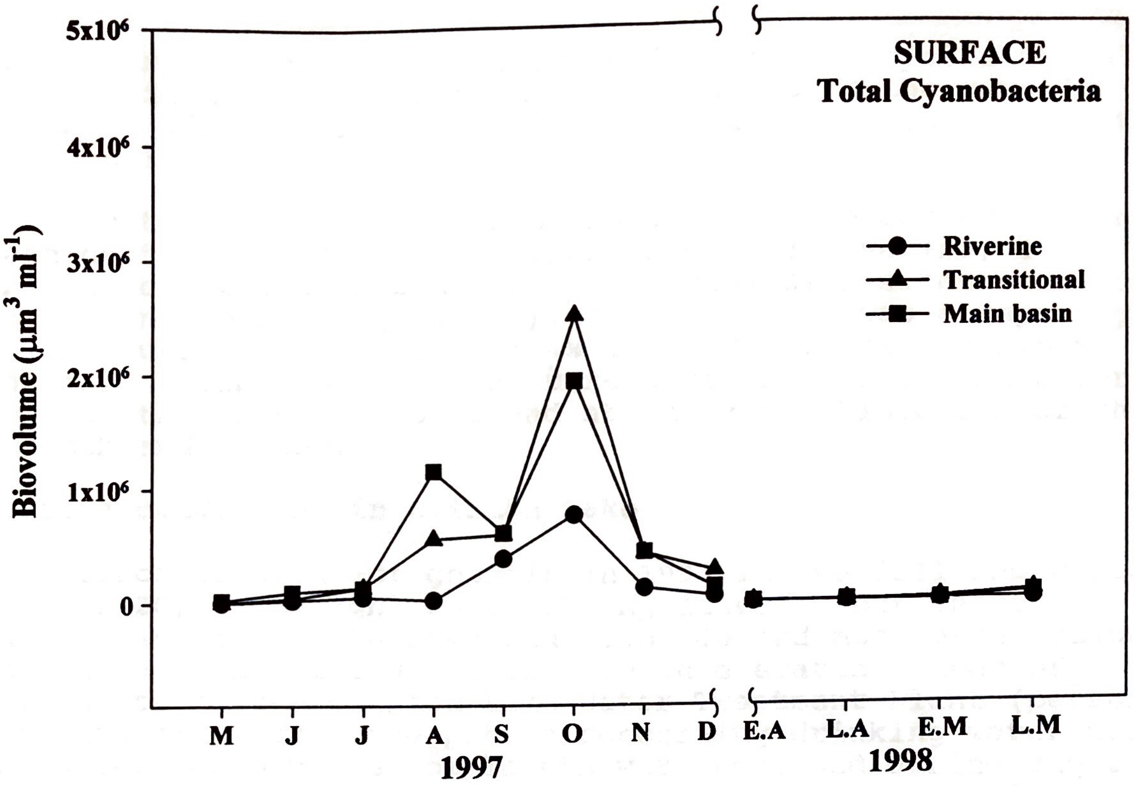

Figure 18. Biovolume of total cyanobacteria for surface samples from stations grouped as described in the text.

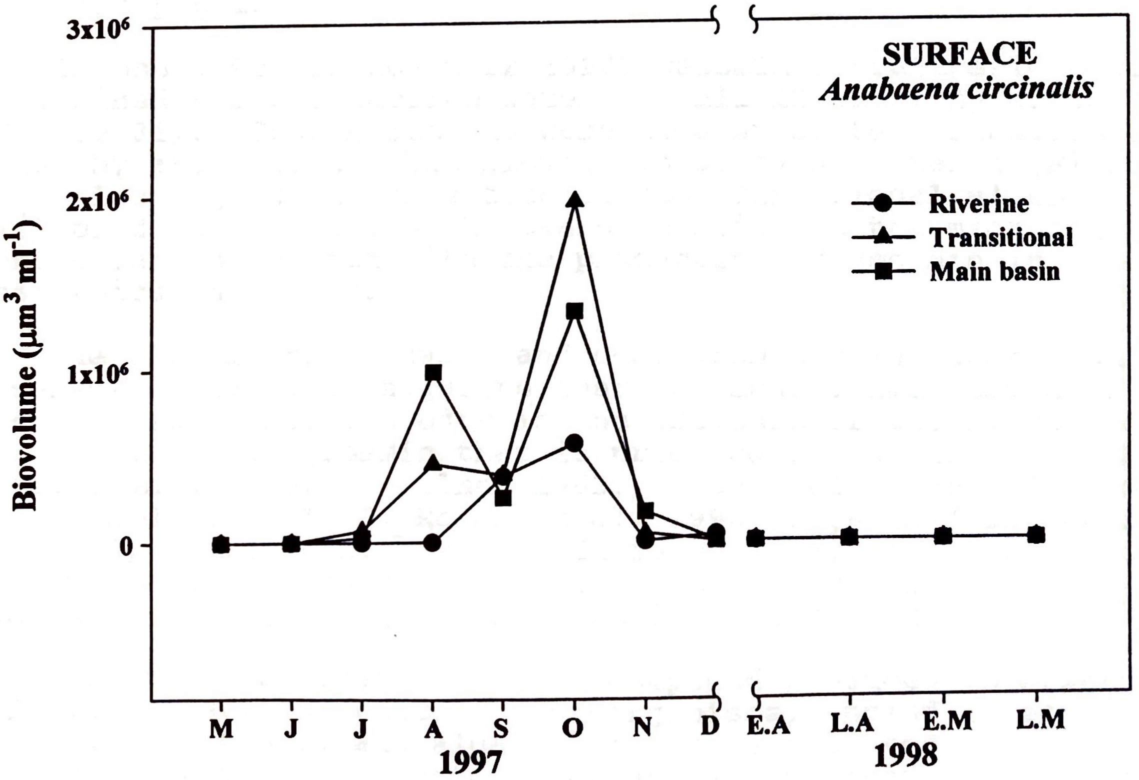

Figure 19. Biovolume of *Anabaena circinalis* for surface samples from stations grouped as described in the text.

the riverine sites with the exception of *Microcystis* which was highest in the main basin sites and lowest in the riverine sites. *Anabaena circinalis* was the most abundant species at this time (Figure 19).

For the October 1997 sampling date phytoplankton samples from each depth were counted for eight sites, 2 riverine, 4 transition, 2 main basin. For the transition sites sampled at more than one depth (Table 1), the biovolume was always highest at the surface (0.25 m) by 1.4x to 1.8x compared to 1.5 m. In the main basin biovolume was more similar between the upper two depths, though both depths had about 3x the biovolume of the 3.0 m depth and deeper.

Geosmin conditions in Clinton Lake

Concentrations of geosmin in 1997 in the fall and winter (Figure 20) were high, up to 170 ng liter^{-1}, but thereafter through November 1998 remained below 40 and most often below 10. During the fall of 1997 there were an elevated number of complaints to the Clinton Lake Water Treatment Plant (personal communication) from the public concerning drinking water taste and odor. Comparable complaints were recorded during the fall and winter 1995/96 when geosmin concentrations were similarly high at about 200 ng liter^{-1} causing plant operation to be suspended for eight weeks in December 1995 and January 1996. Plant operation was not suspended in 1997. In the fall of 1998, with very low geosmin concentrations, there were few complaints from the public.

On one date (11 November 1997) geosmin concentrations were determined for the surface waters of all 12 sampling sites (Figure 21). Concentrations were highest in the transitional sites by about 1.3x. The biovolumes of cyanobacteria (Figure 18) were also highest at this time in the transitional sites. As will be discussed below the cyanobacteria are the microorganisms most often associated with the production of geosmin in reservoirs and lakes.

The literature on taste and odor problems in water from reservoirs and lakes suggests that the most common cause of earthy/musty taste and odor is the presence of the dissolved organic chemical geosmin that is produced by certain microorganisms (e.g., Palmer 1962, Gerber and LeChevalier 1965, Silvey and Roach 1975, Rosen et al. 1992, Persson 1995, Suffet et al. 1995, Clark et al. 1997). In recent years more accurate and more frequent analyses of geosmin from reservoirs and lakes has continued to suggest geosmin as an important contributor.

Geosmin is a natural alcohol compound produced in reservoirs and lakes mostly by certain microorganisms, including some types of bacteria, fungi, and algae. It can be detected as an earthy/musty odor and taste by humans at concentrations as low as about 5 ng liter^{-1}. Geosmin is not known to be toxic to humans

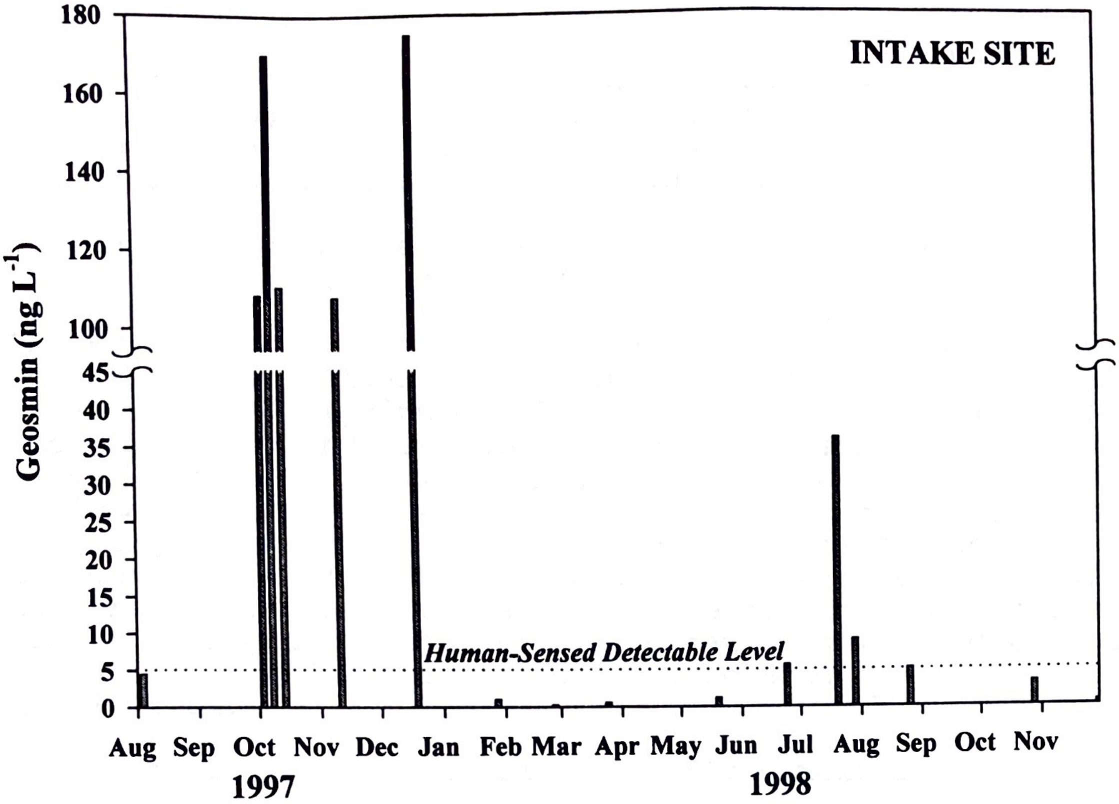

Figure 20. **Geosmin for samples from Lawrence water intake site.**

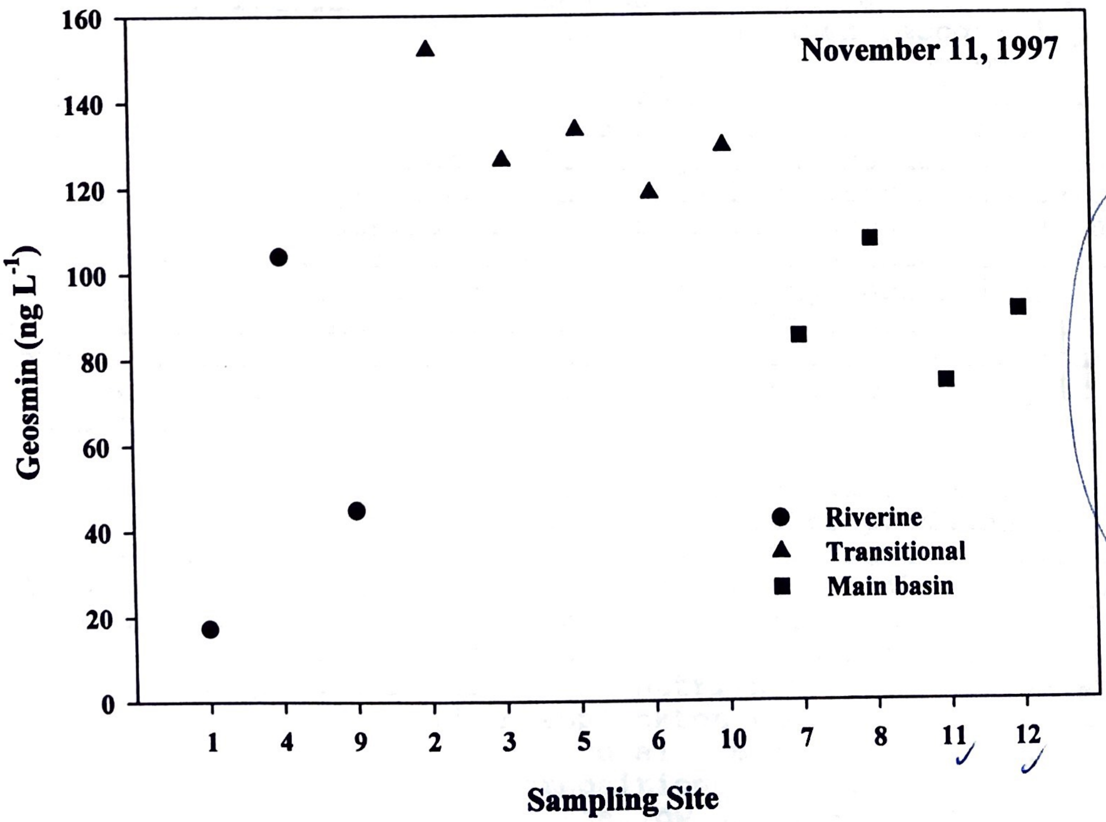

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Figure 21. **Geosmin for surface samples from stations grouped as described in the text.**

or wildlife at even the highest concentrations detected in reservoirs and lakes. However, when geosmin is present in the water drawn from either, it is very difficult and costly to remove enough of it at the treatment plant so that taste and odor problems are not passed on to the consumer (Suffet et al. 1995).

From the literature on geosmin cited above and from other studies, the cyanobacteria (e.g., Safferman et al. 1967, Henly 1970, Barnett 1984, Utkilen and Froshaug 1992, van Breeman et al. 1992, Evans 1994, Hu and Chiang 1996) and actinomycetes (eg., Gaines and Collins 1963, Gerber and Lechevalier 1965, Bentley and Meganathan 1981, Blevins et al. 1995, Stahl and Parkin 1996) as common reservoir and lake microorganisms have been studied in the greatest detail for their abilities to produce geosmin. From this literature it appears that some geosmin is released from the living organisms but most appears to be released into the water with the death and decomposition of these organisms. As will be considered next, the abundance of these organisms and their production of geosmin appear to be greatly influenced by other water quality conditions particularly related to eutrophication and siltation.

Some relationships between water quality conditions

In reservoirs and lakes there appears to be a strong relationship between the processes of eutrophication, siltation, and taste and odor development. The water quality conditions reported on here for Clinton Lake support this as well. Relationships become particularly apparent when recognizing certain conditions in the reservoir greatly affected by eutrophication and siltation are also known to accelerate the growth and ultimately also the death of the microorganisms most often cited as being responsible for geosmin production. These conditions include (1) expansion of shallow water zones overlying silt deposits, (2) periodically exposed silt deposits, (3) high nutrient levels in shallow waters, and (4) a greater fraction of the total volume of reservoir water occupying increasingly shallower areas. These relationships are less often considered together in the literature, particularly related to the taste and odor problem and to the expression of other problems requiring management.

Expanding shallow zones, more driven by siltation but contributed to by the increased organic matter produced as a result of eutrophication, provide more bottom surface covered by shallow water for attached microorganisms most likely involved in geosmin production to grow. For the bacteria and fungi this means more well aerated warmer surfaces containing more organic matter to decompose for energy and nutrients. For the growth of floating cyanobacteria and phytoplankton there is more warm shallow water with ample light and also more surrounding nutrients released by the decomposition processes provided by the bacteria and fungi. Even when shallow areas are very turbid, the cyanobacteria may be particularly favored over other phytoplankton (Cuker et al. 1990, Burkholder et al. 1998) because of their unusual buoyancy. With periodic exposure of more of the bottom sediments to bright light, heat, and desiccation, microorganisms would likely die and decompose at a higher rate, resulting in the release of greater amounts of geosmin. Such periodic exposure can result from natural weather conditions but can also be due to lowering reservoir levels for such purposes as preparing to capture flood waters and manipulating wildlife habitat.

Deeper water columns in reservoirs tend to reduce the growth of microorganisms, particularly the suspended algae, which can be circulated to deeper zones of insufficient light. Deeper waters also tend to be colder and less oxygenated, thereby reducing microbial growth. Algae growing on bottom surfaces are also unable to grow in deep water due to insufficient light. With siltation of a reservoir or lake the average water depths decline throughout the entire basin and microbial growth increases everywhere. Such growth is expected to be greatest in the upper arms where loss of depth is greater due to a comparatively thicker layer of silt being deposited.

All areas of a reservoir do not fill, particularly from siltation, at the same rate. The originally more shallow zones at the time of construction are most often located in the upper arms extending into the incoming stream systems. More rapid siltation will occur at these locations, and in the lower arms, than in the main body of the reservoir due to their proximity to the watershed source of the silt and the hydromechanics of the siltation process. From some recent data for Clinton Lake (unpublished) and two other large Kansas reservoirs (Juracek 1997, Pope 1998) the rate of silt accumulation in terms of its bottom thickness is at least 3x to 5x greater in the upper arms compared to the lower arms and main basin.

To further appreciate the possible role of siltation in the water quality issues discussed above consider, along with Clinton Lake, three other of the larger federal reservoirs in Kansas (Kansas Water Office Yield Analysis Reports, 1997). The 9,400 acre (multipurpose pool) John Redman Reservoir was placed in operation in 1964 and since then has lost 30% of its multipurpose pool, or normally maintained volume. Over the next 38 years it is projected that by the age of 73 it will decrease to only half of the original 1964 volume. The 12,200 acre Perry Lake placed in operation in 1966 is projected to decrease to 41% of its original volume at the same time. Clinton Lake is projected to lose 14% of its original volume and the 15,700 acre Milford Lake about 24%. These are figures for the entire basin and do not reveal the disproportionate filling that will occur in the upper arms as described above.

Additional parameters are still being analyzed in an attempt to determine the causes for the very high geosmin levels in 1997 compared to those in 1998. For the parameters presented here that might be related to geosmin production, only chlorophyll biomass was higher in the fall of 1997, by about 2x. The abundance of cyanobacteria in the summer and fall of 1998 is still being determined. Other parameters still being analyzed include reservoir water level, water residence time, precipitation, air temperature, and wind direction and velocity. The dramatic differences in geosmin concentrations observed in this study over the two successive years provide an excellent opportunity to isolate causal factors that we believe are related in some way to the shallow upper arms of the reservoir. In this area of the reservoir the general conditions expected to influence geosmin production as discussed above may have been exacerbated somehow in the summer and fall of 1997 in contrast to the same period in 1998. Finding relationships here could reveal other important relationships between the whole array of water quality conditions that seem to be so interrelated as suggested throughout this consideration of Clinton Lake.

Concluding remarks

In the US it is estimated (van der Leeden et al. 1990) that more than 50,000 reservoirs greater than 50 acre-feet in size have been constructed this century. For the 300 larger reservoirs built principally for flood control but also providing other uses, nearly half are more than 40 years old. For the 55 largest reservoirs, ones larger than 500,000 acre-feet and built principally for water storage but also providing other uses, two-thirds are more than 40 years old. Before a reservoir entirely fills with silt, its role as a resource becomes greatly diminished. Many reservoirs will reach this obsolescence at about the same time since most were built between 1920 and 1980.

We have already built our reservoirs in all the "best" places and surely over the next 100 years we will witness the growth of development nearly everywhere nearby most of these reservoirs. Yet, since we will still have all of the same needs for flood control, water consumption, and recreation, it will be necessary to either reclaim or replace our reservoirs. Excavating the silt-filled basins, whether full or nearly so, and finding a place for so much material is beyond any current perception of our means considering the following. Most dams when originally built have a predetermined ratio between the volume of earth moved for dam construction and the volume of water to be impounded. This ratio is generally one cubic meter of earth to 15 to 30 cubic meters of water impounded. The problem with a silted reservoir is all of the costs to remove fifteen to thirty times as much sediment as the earth that was moved in the original dam construction.

Some of the impacts on water quality of a reservoir becoming shallower, particularly in the upper arms, are evident from the data gathered from this study of Clinton Lake. Compared to other reservoirs in Kansas, this is a young reservoir, 22 years old, with a more intact watershed as indicated by the comparatively slower rate of siltation described above. However, all of the water quality problems most common in reservoirs today, as described in the introduction, are clearly present in Clinton Lake as the data presented have shown. Nutrient conditions, particularly N and P, and phytoplankton biomass (measured as chlorophyll *a* are elevated to the levels typical of eutrophic reservoirs and lakes. Other conditions expected to accompany these conditions in eutrophic waters are evident and include levels of turbidity, pH, dissolved organic carbon, total organic carbon, and other conditions. All of these conditions are now more apparent in the shallow upper arms, thus adversely impacted water quality seems to be developing there first; but these conditions can be expected to migrate into the main basin.

The upper, shallow portions of the basin will inevitably increase in area as they become filled with silt, the source of which is the watershed. In the increasingly larger shallow areas the bottom sediments, along with any contaminants they may contain, are also more likely at times to be resuspended by wind action and inflowing currents. Shallow portions of the basin, even when the reservoir is still comparatively young like Clinton Lake, may soon have considerable impact on water quality in the lower arms and main basin. The changes in the deeper areas of the reservoir may then be less under the direct control of the watershed, as is normally expected, and more affected by conditions in the upper, shallower areas of the reservoir. Under such circumstances, just managing the watershed may not solve all of the water quality problems in the main basin, which is also the most utilized portion of the reservoir as a human resource. Upper shallow zones, long before the deeper portions of the basin, may require direct management by such measures as water level manipulations and removal of some of the materials by dredging.

Water level manipulations should be reexamined for reservoirs, including Clinton Lake. Such manipulations have become routine over the years for preparing for rainy season flood control and to promote certain types of wildlife habitat. It is possible that deteriorating water quality conditions in the upper arms are exacerbated at certain times by these routine manipulations or could be reduced by this type of manipulation. With respect to the more extreme measure of sediment removal, it is inevitable that someday, sooner or later, this will be necessary in most reservoirs. We should develop methods and machinery specialized for the task of dredging reservoirs, not necessarily entire basins but at least the upper arms. By dredging the upper arms of reservoirs soon, we will remove silt from where it is most rapidly accumulating and from where it is already affecting the quality of the rest of the reservoir. By excavating such areas even deeper than they were originally, basins can be formed to serve as silt traps that can be conveniently and carefully excavated again every 20 or 30 years as a long-term maintenance strategy.

The dredging of entire reservoir basins, or portions of them, as we now perceive this, based on years of experience dredging rivers, is a costly and time consuming operation. Such actions are also potentially very disruptive to the surrounding aquatic and terrestrial environment typical of reservoirs. Methods to remove sediments from reservoirs, while at the same time not interrupting their function as a resource, are yet to be well developed and tested. We would be well advised to study and better develop these methods sooner rather than later.

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