Relationships between Odor and Commonly Measured Water Quality Characteristics in Surface Water Supplies

by SHUNDAR LIN and RALPH L. EVANS
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Indexing Terms: Actinomycetes, algae, benthic macroinvertebrates, chemical analysis, chlorine demand, dissolved oxygen, finished water, Illinois, impoundments, manganese, nitrate nitrogen, odor, sulfate, taste, threshold odor number, water properties, water quality, water sampling, water treatment
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Relationships between Odor and Commonly Measured Water Quality Characteristics in Surface Water Supplies

by Shundar Lin and Ralph L. Evans

ABSTRACT

Weekly threshold odor numbers (TONs) were determined for the waters of three impoundments and the finished water produced by treatment at each impoundment site during a 2-year period. The correlation between the TONs and each of 20 commonly measured biological, chemical, and physical parameters was examined. The correlation coefficients were generally low, except those for nitrate-nitrogen, sulfate, manganese, and chlorine demand. The magnitude of taste and odor in the three impoundments was found to be a seasonal function. High TONs generally occurred during the period from May through October, the period of anoxic conditions in bottom waters of impoundments. Regardless of the magnitude of TONs for the raw waters, the TONs for the three finished waters ranged from 3 to 10 about 95 percent of the time. The probable causes of the excessive TONs are discussed, and predictions of the occurrences and magnitude of odor are presented, based on stepwise multiple regression analyses.

INTRODUCTION

It is an accepted rule in the water industry that drinking water shall contain no impurity which can reasonably be expected to cause offense to the senses of sight, taste, or smell. As part of an effort to achieve this goal, the Illinois Pollution Control Board (IPCB) recommends a maximum threshold odor number (TON) of 3 in finished water. Despite the acceptance of the rule and the assignment of TON limitations, taste and odor problems continue to frustrate the skills of management and the patience of consumers.

Taste and odor problems are encountered in almost all water works which use surface water as a source. Tastes and odors in water can be derived from natural or man-made sources or a combination of both. The problems experienced are often associated with such factors as season, reservoir stratification and turnover, rainfall, stream flow, spring thaw, odor-producing organisms, decaying vegetation, and industrial spills. Some odor episodes are predictable; others are not.

Lin (1976a, 1976b, 1977a, 1977b) reviewed the literature on tastes and odors in water. He found that although there is a long history of taste and odor problems, there is very little information available on long-term studies of threshold odor in reservoirs. The purpose of this report is to provide information on such a study.
Objectives and Report Plan

This study was performed on three central Illinois impoundments that serve as sources of public water supplies. The purposes of the study were:

1) To measure long-term TONs for raw and finished waters
2) To explore the relationships, if any, between TON and commonly measured water quality constituents
3) To identify the elements responsible for excessive TONS
4) To develop a procedure for predicting the occurrences of odor and its magnitude

This report describes the methods and procedures used in the study. It also presents the results and discussions related to the four objectives. The weekly TON values and odor types for the finished and raw lake waters are tabulated in appendices A, B, and C.

Acknowledgments

The writers extend their thanks to the following personnel who assisted in the study. The personnel of the water works at Canton, Decatur, and Eureka were most helpful in providing access to the lakes. Randy Rohman and Robert Grabel collected most of the samples and conducted the threshold odor number tests. Robert Sinclair assisted in the statistical analysis. Dave Hullinger, Gary Benker, Melbern E. Jannett, Wuncheng Wang, and Dana Shackleford performed chemical analyses. Dave B. Beuscher identified and enumerated algae samples. Tom Hill and Scott Bell examined benthic collections. The other personnel of the Water Quality Section also participated in the sample collections and odor tests. Linda Johnson typed the original manuscript, and Gail Taylor edited the manuscript. Illustrations were prepared by John Brother, Jr., and William Motherway. Marilyn J. Innes prepared the camera copy.

SAMPLES AND METHODS

Three man-made water supply impoundments were examined for a 2-year period extending from September 13, 1976, to October 16, 1978. They vary in size, water depth, drainage area, and water quality (table 1). Lake Decatur has a large surface area and a maximum depth of 5 m. Lake Eureka is a small body of water with a maximum depth of 6 m. Lake Canton has a mid-size surface area and a maximum depth of about 11 m.

The three impoundments were constructed principally as sources for public water supplies, and they also serve as recreation areas. Lake Canton started to fill in 1939, with the draining of Copperas Creek. Lake Decatur was formed by a dam on the Sangamon River, and storage began in April 1922. Lake Eureka was constructed in 1942 by the damming of a branch of Walnut Creek and was discontinued as a water supply source in October 1978. All three lakes have the typical serpentine shape of midwestern impoundments, as may be seen in figures 1, 2, and 3.
Table 1. Pertinent Physical Data for the Study Lakes

<table>
<thead>
<tr>
<th>Lake</th>
<th>Surface area (ba)</th>
<th>Watershed area (ba)</th>
<th>Maximum depth (m)</th>
<th>Water volume (10^6) (\text{Xm}^3)</th>
<th>Water withdraw (m(^3/d))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canton</td>
<td>88.2</td>
<td>3,845</td>
<td>11</td>
<td>3.73</td>
<td>7,600</td>
</tr>
<tr>
<td>Decatur</td>
<td>1166</td>
<td>23,470</td>
<td>5</td>
<td>26.50</td>
<td>60,600</td>
</tr>
<tr>
<td>Eureka</td>
<td>14.6</td>
<td>688</td>
<td>6</td>
<td>0.28</td>
<td>1,140</td>
</tr>
</tbody>
</table>

Note: 1 ha = 2.471 acres; 1 m = 3.28 ft; 1 m\(^3\) = 8.107 \(10^{-4}\) acre-ft; 1 m\(^3/d\) = 2.642 \(10^{-4}\) mgd

Figure 1. Configuration of Lake Canton and location of sampling station
Figure 2. Configuration of Lake Eureka and location of sampling station

Figure 3. Configuration of Lake Decatur and locations of sampling stations
The sampling stations were located near the deepest parts of the three lakes. In Lake Canton (figure 1) the sampling point was about 70 m north of the intake tower. The sampling point at Lake Eureka (figure 2) was near the intake, about 40 m away from the dam. Three water samples were collected from each of these two lakes with a Kemmerer sampler at weekly intervals. Waters at the surface, mid-depth, and near the bottom were obtained at each sampling location. The samples were usually collected by boat, except during the ice-cover periods (December to March). During severe cold weather, ice at depths of 30 to 40 cm was broken through to collect samples. During periods of thin ice-cover, when it was impossible to reach the sampling locations, raw water samples were collected from the intakes of the Canton and Eureka Water Works. These samples represented the mid-depth waters of the lakes.

For Lake Decatur (figure 3), weekly samples were taken from either Station A or B. Samples at three depths were obtained from Station A by boat. During the thin ice-cover periods, three depth samples were taken from the sidewalk of the pumping house, at Station B near the intake. During the thick ice-cover periods, the ice was broken and water samples were taken about 20 m from the intake.

Water samples for chemical analyses were collected in 3.8-liter glass bottles. The finished waters were dechlorinated immediately after collection. Samples for total organic carbon were collected in 60-ml brown glass bottles and were preserved with HCl to a pH of 2 or less. Bacteria samples were collected in 200-ml sterile glass bottles and were placed on ice immediately upon collection. The algae samples were taken in small-necked 480-ml glass bottles preserved with a formaldehyde solution.

Sediment samples for benthic macroinvertebrate examination were collected by three grabs with an Ekman dredge (15 x 15 cm). The mud samples were then washed in a 30-mesh screen bucket, placed in quart jars, and preserved with 25 ml of formalin. In the laboratory, the samples were again washed in a 30-mesh sieve. The organisms were then picked from the bottom detritus, identified, counted, and preserved in 70 percent ethyl alcohol.

Field measurements were made for water and air temperatures, dissolved oxygen (DO), and water transparency. Water temperature and DO measurements were made at 30 cm intervals by a YSI model 51B DO meter. Table 2 lists the analytical methods used for physical, chemical, and biological determinations. Analyses as shown in table 2 were performed in accordance with Standard Methods for the Examination of Water and Wastewater (1975). The TONs were determined by the modified dilution method (Standard Methods, 1975; USEPA, 1976). A series of at least eight flasks was used. The first flask was always a blank, and from one to three additional blanks were inserted in the series. The series of flasks was kept at a room temperature of 60°C and was sniffed by a panel of four to eight persons. The water sample judged to be odor-bearing was diluted with odor-free water to a volume of 200 ml. The number of times this water had to be diluted until it reached an odor barely perceptible to the tester determined the TON. The type of odor for each sample was also recorded by the test panel.
Table 2. Analytical Procedures

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Analytical procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold odor number</td>
<td>NTU</td>
<td>Dilution method (modified), 60 °C</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>Nephelometric method</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>pH meter</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg/l as CaCO₃</td>
<td>Titration with 0.02N H₂SO₄ to a pH of 4.5</td>
</tr>
<tr>
<td>Hardness</td>
<td>mg/l as CaCO₃</td>
<td>EDTA titration</td>
</tr>
<tr>
<td>Ammonia-N</td>
<td>mg/l</td>
<td>Phenate method</td>
</tr>
<tr>
<td>Nitrate-N</td>
<td>mg/l</td>
<td>Chromotropc acid method</td>
</tr>
<tr>
<td>Silica (total)</td>
<td>mg/l SiO₂</td>
<td>Heteropoly blue (colorimetric)</td>
</tr>
<tr>
<td>Iron (total)</td>
<td>mg/l</td>
<td>Phenanthroline (colorimetric)</td>
</tr>
<tr>
<td>Manganese (total)</td>
<td>mg/l</td>
<td>Periodate method (colorimetric)</td>
</tr>
<tr>
<td>Chemical oxygen demand</td>
<td>mg/l</td>
<td>Re flux with K₂Cr₂O₇ + H₂SO₄</td>
</tr>
<tr>
<td>Phosphorus (total)</td>
<td>mg/l</td>
<td>Ascorbic acid method, H₂SO₄ + NH₄O₃ digestion</td>
</tr>
<tr>
<td>Phosphorus (dissolved)</td>
<td>mg/l</td>
<td>Ascorbic acid method, H₂SO₄ + NH₄O₃ digestion</td>
</tr>
<tr>
<td>Sulfate (dissolved)</td>
<td>mg/l</td>
<td>Turbidimetric method</td>
</tr>
<tr>
<td>Chlorine demand</td>
<td>mg/l</td>
<td>Iodometric method, 30 min contact</td>
</tr>
<tr>
<td>Total organic carbon</td>
<td>mg/l</td>
<td>TOC analyzer</td>
</tr>
<tr>
<td>Standard plate count</td>
<td>counts/ml</td>
<td>Trypton glucose yeast agar, 35°C, 48 hrs</td>
</tr>
<tr>
<td>Actinomycetes</td>
<td>counts/ml</td>
<td>Actinomycetes isolation agar, 28°C, 7 days</td>
</tr>
<tr>
<td>Algae</td>
<td>counts/ml</td>
<td>Filtered (modified)</td>
</tr>
<tr>
<td>Water transparency</td>
<td>cm</td>
<td>Secchi disc, 24cm diameter</td>
</tr>
</tbody>
</table>

RESULTS AND ANALYSIS

Threshold Odor Number

The measurements of threshold odor numbers for the nine lake samples were made at weekly intervals throughout the study period. TON determinations for the three finished waters were performed weekly beginning January 3, 1977. The TON results are depicted in figures 4, 5, and 6. High TONs for the lake waters occurred at about the same time of year for each lake. The periods were October-November 1976; June through October 1977; and August-September 1978. The uncharacteristic odor episodes in Lake Eureka (figure 6) during the months of February and March 1977 will be discussed later.

Figures 4, 5, and 6 show that the TONs for the water near the bottom were generally greater than those for the other two depths. This is especially true for Lake Canton, the deepest of the lakes. Surface waters resulted in the lowest TONs. Similar conditions have been reported for reservoirs in Israel (Leventer and Eren, 1970).

A statistical summary of the observed TONs for each sampling location is given in table 3. Samples taken from deep stations gave greater TON ranges as well as higher geometric means and geometric standard deviations. A smaller TON gradient with depth occurred at Lake Decatur, presumably because of the high ratio of surface area to depth. The water column of Lake Decatur is not subject to the degree of thermal stratification experienced by the other lakes. The geometric means were 130 and 100 at Lakes Canton and Eureka, respectively, while at Lake Decatur the geometric mean was 67.
Figure 4. Temporal variations in threshold odor number (TON) in lake waters and finished water at Lake Canton.
Figure 5. Temporal variations in threshold odor number (TON) in lake waters and finished water at Lake Decatur.
Figure 6. Temporal variations in threshold odor number (TON) in lake waters and finished water at Lake Eureka.
Table 3. Statistical Summary of Threshold Odor Numbers

<table>
<thead>
<tr>
<th>Water sample</th>
<th>Number of samples</th>
<th>Range</th>
<th>Geometric mean</th>
<th>Geometric standard deviation</th>
<th>95% confidence values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Canton</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>94</td>
<td>13-160</td>
<td>43</td>
<td>1.66</td>
<td>18-100</td>
</tr>
<tr>
<td>Mid-depth</td>
<td>110</td>
<td>13-200</td>
<td>49</td>
<td>1.75</td>
<td>19-130</td>
</tr>
<tr>
<td>Deep</td>
<td>94</td>
<td>13-5600</td>
<td>130</td>
<td>3.92</td>
<td>13-1200</td>
</tr>
<tr>
<td>Finished water</td>
<td>93</td>
<td>2.2-13</td>
<td>5.2</td>
<td>1.42</td>
<td>2.9-9.3</td>
</tr>
<tr>
<td>Lake Decatur</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>106</td>
<td>13-200</td>
<td>45</td>
<td>1.91</td>
<td>15-130</td>
</tr>
<tr>
<td>Mid-depth</td>
<td>106</td>
<td>12-280</td>
<td>52</td>
<td>1.62</td>
<td>17-160</td>
</tr>
<tr>
<td>Deep</td>
<td>106</td>
<td>12-670</td>
<td>67</td>
<td>2.17</td>
<td>18-250</td>
</tr>
<tr>
<td>Finished water</td>
<td>90</td>
<td>1.9-10</td>
<td>5.0</td>
<td>1.47</td>
<td>2.6-9.4</td>
</tr>
<tr>
<td>Lake Eureka</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>91</td>
<td>12-670</td>
<td>59</td>
<td>2.29</td>
<td>15-240</td>
</tr>
<tr>
<td>Mid-depth</td>
<td>107</td>
<td>12-740</td>
<td>68</td>
<td>2.27</td>
<td>17-270</td>
</tr>
<tr>
<td>Deep</td>
<td>91</td>
<td>12-780</td>
<td>100</td>
<td>2.45</td>
<td>23-390</td>
</tr>
<tr>
<td>Finished water</td>
<td>89</td>
<td>2.0-54</td>
<td>6.3</td>
<td>1.87</td>
<td>2.2-18</td>
</tr>
<tr>
<td>Finished water</td>
<td>80*</td>
<td>2.0-13</td>
<td>5.4</td>
<td>1.45</td>
<td>2.9-10</td>
</tr>
</tbody>
</table>

*Excludes samples collected from January 3 through March 7, 1977 (dynamite used to break ice)*

Figures 4, 5, and 6 show the TON limits stipulated by the IPCB (i.e., the threshold odor number should not exceed 3 in finished water) and the temporal variation in finished water at the three treatment plants. A TON of 3 or less is rarely achieved. Compliance with the IPCB TON standard was achieved in 8 of 93 samples at Canton, 12 of 90 samples at Decatur, and 5 of 89 samples at Eureka. With the exclusion of the 1977 winter samples for Eureka's finished water, the geometric means for the three finished waters were 5.0 (Decatur), 5.2 (Canton), and 5.4 (Eureka), as shown in table 3. This means that about 50 percent of finished water samples would be in compliance with the standard if the TON limit were 5 instead of 3. There is not a great deal of difference between TONs of 3 and 5.

The treatment processes at the three water plants are practically the same, i.e., the addition of lime, alum, powder-activated carbon, and chlorine prior to clarification, followed by rapid sand filtration and post-chlorination. Although (as can be seen in figures 4, 5, and 6) the processes substantially reduce the TON as introduced to the treatment system, nevertheless a finished water with a TON of 3 or less is not produced.

With the data assembled, the following equation (Steel and Torrie, 1960) was used to determine likely TON values at a 95 percent confidence level:

\[
 P \left[ \bar{x} - t_{0.05} \left( s^2 \frac{(n + 1) / n}{n} \right)^{1/2} \leq X \leq \bar{x} + t_{0.05} \left( s^2 \frac{(n + 1) / n}{n} \right)^{1/2} \right] = 0.95 \quad (1)
\]

where \( \bar{x} \) represents the mean, \( s^2 \) is the variance, \( n \) is the number of observations, \( t_{0.05} \) is a tabular value for Student's t distribution at the 5 percent probability level for \( n-1 \) observations, and \( X \) is the predicted TON.

The TON values recorded during the study were first transformed to logarithmic values. The TON values at a 95 percent confidence level were determined by applying the transformed values to equation 1 and taking the antilog. The results for each sampling...
location are shown in column 6 of table 3. For example, 95 percent of the TONs for Lake Canton at the water surface will lie between 18 and 100. It is apparent that the 95 percent confidence values for the three finished waters are practically identical: 2.9-9.3 (Canton), 2.6-9.4 (Decatur), and 2.9-10 (Eureka, excluding January-March 1977 samples). It is also apparent that despite the wide range of TONs for the raw water the TONs for the finished water are quite consistent.

**Correlations**

It would be desirable if a simple chemical analysis could be used instead of the TON test. This would be possible if a strong correlation exists between TONs and some water quality characteristics.

The nature of the distribution of the data obtained for each parameter was determined by tests for skewness and kurtosis. If skewness values were equal to or less than 1.0, the data were considered normally distributed; for values greater than 1.0, the data were considered geometrically distributed. The range, mean or geometric mean, and standard deviation or geometric standard deviation for each parameter are listed in tables 4, 5, and 6.

As can be seen in these tables, the data for some parameters were normally distributed, the data for some parameters were geometrically distributed, and the data for some parameters were handled both ways. If the distribution was geometrical, the observed data were logarithmically transformed. A simple correlation was made between log-TON and each of the other 20 measured parameters. A tabulation of correlation coefficients (R) is shown in table 7. For most cases, the correlation coefficients were low. However, nitrate-N was reasonably correlated, though negatively, with TONs for Lakes Canton and Decatur. There was fair correlation between TON and Cl$_2$ demand, iron, manganese, total phosphorus, and organic carbon for some stations.

Other investigators (Hansen, 1976; Hendricks and Silvey, 1977; Roseboom et al., 1979; Weete et al., 1977) have reported on the lack of correlation between the number of actinomycetes and TONs and between algae and TONs. This was the case here, as shown in table 7. The metabolites produced by actinomycetes and some blue-green algae, not the densities of these microorganisms, are responsible for taste and odor. The metabolites exist even when the organisms do not. Unfortunately, the equipment required for detecting these metabolites (geosmin, mucidone, and 2-methylisoborneol) are not available at most water works. Nevertheless, algal enumeration and species identification may provide some information regarding odor episodes.

Weete et al. (1977) reported that there was correlation between odor episodes in Lake Ogletree, Alabama, and temperature (> 15°C) and rainfall. For this study, however, water temperature, dissolved oxygen, and bacterial density (standard plate count) did not correlate with TONs (table 7). Nevertheless, they are important factors indirectly. During the periods of summer stagnation and increasing water temperatures, the bacterial decomposition of the bottom organic sediment exerts a high rate of oxygen demand on the overlying waters. When the oxygen up-take by bacteria and their by-products exceeds the oxygen replenishment by molecular diffusion or by algae, an anaerobic condition is created. Under these conditions, the bacteria use nitrate and then
### Table 4. Summary of Observed Parameters for Lake Canton

*(Concentrations in milligrams per liter unless otherwise indicated)*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Surface</th>
<th>Mid-depth</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of samples</td>
<td>Range</td>
<td>Mean*</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>94</td>
<td>0-28.8</td>
<td>15.2</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>93</td>
<td>3.0-15.5</td>
<td>9.5</td>
</tr>
<tr>
<td>pH (units)</td>
<td>94</td>
<td>7.3-9.7</td>
<td></td>
</tr>
<tr>
<td>Alkalinity, as CaCO₃</td>
<td>94</td>
<td>61-202</td>
<td>135</td>
</tr>
<tr>
<td>Hardness, as CaCO₃</td>
<td>93</td>
<td>99-380</td>
<td>220</td>
</tr>
<tr>
<td>Nitrate-N</td>
<td>93</td>
<td>0-2.25</td>
<td>0.79</td>
</tr>
<tr>
<td>Log silica</td>
<td>93</td>
<td>0.2-13.5</td>
<td>2.73</td>
</tr>
<tr>
<td>COD</td>
<td>93</td>
<td>0.1-33.2</td>
<td>10.4</td>
</tr>
<tr>
<td>Dissolved phosphorus</td>
<td>94</td>
<td>0-0.33</td>
<td>0.018</td>
</tr>
<tr>
<td>Log dissolved phosphorus</td>
<td>83</td>
<td>38.6-75.4</td>
<td>52.0</td>
</tr>
<tr>
<td>Sulfate</td>
<td>93</td>
<td>0-12.4</td>
<td>5.2</td>
</tr>
<tr>
<td>Chlorine demand</td>
<td>94</td>
<td>0-19.0</td>
<td>2.8</td>
</tr>
<tr>
<td>Log turbidity (NTU)</td>
<td>94</td>
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<tr>
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<td>0.17</td>
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<tr>
<td>Log iron</td>
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</tr>
<tr>
<td>Log manganese</td>
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<td>Log total phosphorus</td>
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<td></td>
</tr>
<tr>
<td>Log standard plate count (c/ml)</td>
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<td>14-7200</td>
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<tr>
<td>Log actinomycetes (c/ml)</td>
<td>87</td>
<td>1-1100</td>
<td>44</td>
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<tr>
<td>Log algae (c/ml)</td>
<td>93</td>
<td>15-4000</td>
<td>340</td>
</tr>
<tr>
<td>Log TON (unitless)</td>
<td>94</td>
<td>13-160</td>
<td>43</td>
</tr>
</tbody>
</table>

*In the case of log parameters, the geometric means are given

**In the case of log parameters, the geometric standard deviations are given
Table 5. Summary of Observed Parameters for Lake Decatur

*(Concentrations in milligrams per liter unless otherwise indicated)*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Surface</th>
<th>Mid-depth</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of samples</td>
<td>Range</td>
<td>Mean*</td>
</tr>
<tr>
<td>Temperature (°C)</td>
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<td>0.2-31.0</td>
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<tr>
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<td>4.7-18.7</td>
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</tr>
<tr>
<td>pH (units)</td>
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<td>7.5-8.9</td>
<td>7.2</td>
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<tr>
<td>Alkalinity, as CaCO₃</td>
<td>106</td>
<td>83-298</td>
<td>195</td>
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<tr>
<td>Hardness, as CaCO₃</td>
<td>106</td>
<td>146-481</td>
<td>298</td>
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<tr>
<td>Nitrate-N</td>
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<td>0.2-12.3</td>
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</tr>
<tr>
<td>Silica</td>
<td>102</td>
<td>0-37.0</td>
<td>5.7</td>
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<tr>
<td>COD</td>
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<td>0-72.4</td>
<td>6.8</td>
</tr>
<tr>
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<td>Log turbidity (NTU)</td>
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<td>Log iron</td>
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<tr>
<td>Log manganese</td>
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<tr>
<td>Log total organic carbon</td>
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<td>1.3-110.0</td>
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<td>400</td>
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<tr>
<td>Log actinomycetes (c/ml)</td>
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<td>100</td>
</tr>
<tr>
<td>Log algae (c/ml)</td>
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<td>4-3300</td>
<td>220</td>
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<td>Log TON (unitless)</td>
<td>106</td>
<td>13-200</td>
<td>45</td>
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</tbody>
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*In the case of log parameters, the geometric means are given

**In the case of log parameters, the geometric standard deviations are given*
Table 6. Summary of Observed Parameters for Lake Eureka

(Concentrations in milligrams per liter unless otherwise indicated)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Surface</th>
<th>Mid-depth</th>
<th>Deep</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of samples</td>
<td>Range</td>
<td>Mean*</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>90 0-30.2</td>
<td>16.1</td>
<td>10.0</td>
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<tr>
<td>Dissolved oxygen</td>
<td>91 0.2-22.1</td>
<td>9.6</td>
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<tr>
<td>pH (units)</td>
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<td></td>
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<tr>
<td>Alkalinity, as CaCO₃</td>
<td>91 110-419</td>
<td>233</td>
<td>73</td>
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<td>Hardness, as CaCO₃</td>
<td>91 132-479</td>
<td>278</td>
<td>73</td>
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<tr>
<td>Nitrate-N</td>
<td>90 0.05-8.74</td>
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<tr>
<td>Silica</td>
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<td>3.6</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Log dissolved phosphorus</td>
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<td>0.018</td>
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<tr>
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<td>Chlorine demand</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>5.07</td>
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<td>7.58</td>
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<td>Log ammonia-N</td>
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<td>2.21</td>
</tr>
<tr>
<td>Log iron</td>
<td>91 0-1.34</td>
<td>0.31</td>
<td>2.21</td>
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<tr>
<td>Log manganese</td>
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<td>0.092</td>
<td>4.26</td>
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<tr>
<td>Log total phosphorus</td>
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<tr>
<td>Log total organic carbon</td>
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<td>2.18</td>
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<tr>
<td>Log standard plate count (c/ml)</td>
<td>91 10-4300</td>
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<td>3.47</td>
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<tr>
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<td>88 1-1300</td>
<td>59</td>
<td>3.52</td>
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<tr>
<td>Log algae (c/ml)</td>
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</tr>
<tr>
<td>Log TON (unitless)</td>
<td>91 12-670</td>
<td>59</td>
<td>2.29</td>
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</table>

*In the case of log parameters, the geometric means are given
**In the case of log parameters, the geometric standard deviations are given
Table 7. Correlation Coefficients for Log TONs with other Measured Water Quality Parameters

(Concentrations in milligrams per liter unless otherwise indicated)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lake Canton</th>
<th></th>
<th></th>
<th>Lake Decatur</th>
<th></th>
<th></th>
<th>Lake Eureka</th>
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<td>Deep</td>
<td>Surface</td>
<td>Mid-depth</td>
<td>Deep</td>
<td>Surface</td>
<td>Mid-depth</td>
<td>Deep</td>
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<td>.03</td>
<td>.15</td>
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<td>-.24</td>
<td>-.29</td>
<td>-.40</td>
<td>-.09</td>
<td>-.46</td>
<td>-.42</td>
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<td>-.06</td>
<td>-.02</td>
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<td>-.46</td>
<td>-.13</td>
<td>.21</td>
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<td>-.22</td>
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<td>-.24</td>
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<td>.57</td>
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<td>-.28</td>
<td>.32</td>
<td>.19</td>
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<td>-.49</td>
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<tr>
<td>Sulfate</td>
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<td>.38</td>
<td>-.70</td>
<td>.09</td>
<td>-.25</td>
<td>-.30</td>
<td>.49</td>
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<tr>
<td>Log sulfate</td>
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<td>.34</td>
<td>.34</td>
<td>.32</td>
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<td>.32</td>
<td>.46</td>
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<td>.64</td>
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<tr>
<td>Log Cl₂ demand</td>
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<td>.32</td>
<td>.46</td>
<td>.56</td>
<td>.64</td>
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</tr>
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<td>.14</td>
<td>.20</td>
<td>.28</td>
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<td>.33</td>
<td>-.09</td>
<td>.01</td>
<td>.07</td>
<td>.20</td>
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<td>.54</td>
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<td>.62</td>
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<td>.55</td>
<td>.47</td>
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<tr>
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<td>.51</td>
<td>.44</td>
<td>.49</td>
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<tr>
<td>Log standard plate count (c/ml)</td>
<td>-.08</td>
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<td>-.20</td>
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<td>-.18</td>
<td>.03</td>
<td>.15</td>
<td>.04</td>
<td>-.22</td>
</tr>
<tr>
<td>Log actinomycetes (c/ml)</td>
<td>.22</td>
<td>.003</td>
<td>.12</td>
<td>-.47</td>
<td>-.20</td>
<td>-.25</td>
<td>-.14</td>
<td>-.19</td>
<td>-.27</td>
</tr>
<tr>
<td>Log algae (c/ml)</td>
<td>.34</td>
<td>.38</td>
<td>.52</td>
<td>.35</td>
<td>.29</td>
<td>.28</td>
<td>.05</td>
<td>.08</td>
<td>.03</td>
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</tbody>
</table>
sulfate as oxygen sources. Iron, manganese, phosphorus, hydrogen sulfide, ammonia, and methane will be released from the muds. These are common occurrences for most Illinois impoundments.

Discussion

Finished Water

A comparison of the temporal variations in TONs for lake bottom water and finished water at Lake Canton (figure 4) shows that extremely high TONs developed for the bottom water during June through October 1977 and late July to October 1978, while taste and odor problems in the finished waters were observed from July through October 1977 and from August to October 1978. It appears that high TONs occur in the finished waters about 3 to 4 weeks after high TON pulses in the deep waters of Lake Canton. The odor types for the finished waters were generally characterized as chemical (chlorinous) and musty for the 1977 and 1978 episodes, respectively (appendix A).

The temporal variations of TONs in Lake Decatur's finished waters (figure 5) followed a similar pattern. The high TONs in the finished waters generally occurred about 1 to 2 weeks after high TONs occurred in the deep water of Lake Decatur. The odor types of the finished waters were usually described as musty and moldy during winter 1977-1978 and most of 1978 and as chlorinous during the summer and fall of 1977 (appendix B).

At Lake Eureka, unlike at the other two lakes, the odors of the finished waters were immediately responsive to odor episodes in the lake's waters. The TONs in the lake were about 100 from October 1976 to January 1977 (figure 6). The water level of the lake was low during this period. In an effort to improve the raw water quality that had been degraded because of low dissolved oxygen content, the covering ice was partially removed by two dynamite blasts — one on January 21 and the other on January 28, 1977. The inadvisability of such procedures is indicated by figure 6. On January 24, a strong hydrogen sulfide smell was detected immediately after 40 cm of ice was broken to enable the taking of water samples. The blasting had done a good job of mixing up the bottom muds in this shallow lake. High intensity taste and odor episodes continued through March 1977. As expected, it was very difficult for the water plant to produce acceptable finished waters using a septic water source. From late January to mid-March 1977, strong odors were emitted by the finished water. The odor types were classified as fishy and septic. They were musty and grassy during the summer and fall of 1977 and were usually musty during August and September 1978 (appendix C).

The identification of the constituents contributing to high TONs in the finished waters at the three lakes is beyond the scope of the study. However, an effort is made here to relate high TONs for the lakes' waters with the data assembled.

Lake Canton

Very high TONs were observed for samples taken from the deep water at Lake Canton during September through November 1976 (figure 4). A maximum of 5600 occurred on October 4, 1976. Figure 7 shows that the lower water strata of Lake Canton
Figure 7. Isolets of dissolved oxygen in Lake Canton
were void of dissolved oxygen during the summer and fall months, i.e., for a 5-month period extending from May through September 1977 and from mid-May to mid-October 1978. It is probable that oxygen depletion occurred during a similar 5-month period in 1976. The water temperatures of Lake Canton — surface, mid-depth, and deep — for the months from June through September were 20-28°C, 18-21°C, and 10-13°C, respectively. The anoxic zone in Lake Canton extended 4 to 6 m from the bottom. About 30 percent of the water volume of Lake Canton was void of oxygen during the 1978 stagnation period (Roseboom et al., 1979).

Table 4 shows that the concentrations of ammonia-N, iron, manganese, and phosphorus in the deep waters are significantly higher than those for the surface and mid-depth waters. These were more profound during the stagnation periods. Nitrate-N and sulfate contents in the deep waters decreased to very low levels under anoxic conditions. Sulfate, manganese, and alkalinity were found to be correlated to 1976 high TONs in the deep waters. The high TONs for the surface and mid-depth waters of Lake Canton during November 1976 (figure 4) were undoubtedly caused by the deep waters after the mid-October fall turnover (figure 7).

During the period of stagnation in 1977, nitrate-nitrogen decreased from 0.8 mg/l in April to below 0.1 mg/l in June through September. Sporadic high TONs in the summer were related to the increase of manganese and alkalinity. *Aphanizomenon flos-aquae*, an odor-producing blue-green alga, persisted in the surface water with densities of 1,700 to 4,000 counts/ml during late June to mid-September. This species of algae occurred in the mid-depth water at densities of 1,000 to 2,000 counts/ml in August and September. Usually the bottom samples contain low algae counts. Increases of *A. flos-aquae* (150-460) were observed from late August through September. The dying and sinking algae were correlated to the high TONs in the deep waters in August and September 1977. *Aphanizomenon flos-aquae* was also responsible for the taste and odor problems in the surface and mid-depth waters during 1977 episodes. As mentioned previously, the metabolic products, rather than algal densities, influence taste and odor conditions.

In 1978, the taste and odor problems in Lake Canton started late, beginning in mid-July (figure 4) six weeks after anoxic conditions developed in the lake bottom (figure 7). High TONs persisted for 2½ months. The causes of 1978 odor problems were the same as those for 1977.

Nineteen benthos samples were taken from the bottom muds of Lake Canton during April to mid-November in both 1977 and 1978. Only four taxa were recovered from the samples for benthic macroinvertebrates. The phantom midgefly larvae (*Chaoborus* spp.) frequently made up 100 percent of the total benthos population (table 8). This organism has the capability to survive in anaerobic conditions because of its ability to migrate to the upper aerobic layers for occasional replenishment of oxygen. This organism is the most common in Illinois lake bottoms.

The densities of *Chaoborus* spp. in the Lake Canton bottom increased in the spring, then decreased in the summer, and increased again in the fall (table 8). Comparison of the TONs plot in figure 4 showed no correlation between TONs and *Chaoborus*. Thus, *Chaoborus* is not a good indicator of taste and odor conditions.
Table 8. Benthic Macroinvertebrates in Muds of Lakes at Maximum Water Depths
(Number of individuals per square meter)

<table>
<thead>
<tr>
<th>Lake</th>
<th>Date</th>
<th>Chao bonis</th>
<th>Chironomidae</th>
<th>Tubificidae</th>
<th>Oligochaeta</th>
<th>Total</th>
</tr>
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<td></td>
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<td>947</td>
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<td></td>
<td>8/1</td>
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<td>14</td>
<td>14</td>
<td>559</td>
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High TONs persisted in the lake station of Lake Decatur during October and November 1976 (figure 5). The odor problems continued until late December 1976 at the intake station (B). The causes of these episodes are not clear-cut. The lake waters were never void of oxygen during that time (figure 8). The minimum DO concentration near the lake bottom was from 1 to 2 mg/l. As mentioned previously, Lake Decatur is shallow (maximum depth 5 m) with a large water surface. Because of the large expanse of water unsheltered to prevailing winds, thermal gradients are insignificant because of mixing.

There was no correlation between TONs and any measured parameter. The total organic carbon concentrations of the deep waters were high (32 to 38 mg/l) during the first half of October 1976. It is possible that residual metabolic products of algae and actinomycetes were responsible for 1976 episodes, but that is conjecture.

During the last half of February 1977, there was a short period of DO stratification (figure 8). After this, the rises of TONs for the deep waters near the intake occurred from mid-February to mid-March 1977 (figure 5). From early May to mid-August of 1977, with the exception of the first half of June 1977, the waters of Lake Decatur stratified in terms of DO (figure 8). During these periods, nitrate-N concentration in lake waters reduced from 13 to 0.84 mg/l. Algal densities in the lake waters increased, with *Aphanizomenon flos-aquae* the predominant species. Both *A. flos-aquae* and the enriched lake bottom created high TONs in the summer of 1977 (figure 5).

For a period from late May through September 1978, the waters of Lake Decatur stratified in terms of DO; nitrate-N concentrations decreased from 7 to 0.4 mg/l. Algal populations increased from about 400 counts/ml to a maximum of 3300 counts/ml on August 8 and then gradually decreased to 400 counts/ml at the end of September. *Aphanizomenon flos-aquae*, a taste and odor producer, also was the dominant species at all locations. Algal densities at each sampling location in 1978 were significantly higher than those in 1977. However, the odor problems in the lake water in 1978 occurred only in August and September (figure 5). The causes were the same as those in 1977: DO stratification, lower nitrate-N contents, algae, and organic sediments in the lake bottom. There were two taxa of benthos, *Chaoborus* spp. and Chironomidae spp., of importance in the lake bottom (table 8).

Abnormally high concentrations of total organic carbon, 60 and 250 mg/l, were present in the bottom of Lake Eureka on October 4 and 14, 1976, respectively. This could be the cause for high TONs during October and November 1976 (figure 6). The fall turnover occurred around mid-October (figure 9). This permitted the bottom waters to mix with the upper water strata, causing high TONs for the entire water column from mid-October through November 1976. The odor episodes in February 1976 have been discussed earlier.

In both 1977 and 1978, the waters of Lake Eureka thermally stratified for a 6-month period from mid-April to mid-September. During the period of thermal stratification, the bottom water temperature varied from 9 to 19°C. As shown in figure 9, the lower water stratum was void of DO during summer months (May through
Figure 8. Isopleths of dissolved oxygen in Lake Decatur
Figure 9. Isopleths of dissolved oxygen in Lake Eureka
September 1977 and June through September 1978). The volume of water completely void of DO in the summer of 1978 was 14 percent (Roseboom et al., 1979).

Unlike what was observed for Lakes Canton and Decatur, the water quality characteristics of Lake Eureka varied greatly from year to year. Nitrate-nitrogen contents for all three depth samples were very low (0.1 mg/l) during the first study year but were above 5 mg/l for a period from October 1977 to September 1978. This was also the case for sulfate concentrations. In contrast, dissolved and total phosphates in the bottom waters increased ten-fold in the summer of 1977 but were constantly low in 1978.

Manganese and chlorine demand of the bottom waters showed good correlations with TONs. Sporadic increases of total organic carbon were also observed during 1977 and 1978 summer stagnation periods.

For the periods of June through October 1977 and late May to late July 1978, two algal species related to taste and odor, *Ceratium birundinella* (a flagellate) and *Stephanodiscus niagarae* (a diatom), predominated and were present in almost all samples taken from the surface and at mid-depth. The TONs for the surface and mid-depth waters increased and persisted from late July to mid-October 1977. *Anacystis cyanea*, a blue-green alga, became dominant in the upper half of Lake Eureka for a period from August to mid-October 1978. During the period, *C. hirundinella* also prevailed and high TONs occurred for the lake waters. The odor types of the summer episodes in 1977 and 1978 were characterized as fishy and septic. The maximum density of *A. cyanea* was 2300/ml on August 7 and 11, 1978.

As shown in table 8, benthic macroinvertebrate populations at Lake Eureka were much less than those at Lakes Canton and Decatur. Again, the density of benthic organisms is not an indicator of taste and odor conditions.

**Prediction of TONs**

The data were subjected to stepwise multiple linear regression analyses to develop mathematical relationships that might be useful for predicting TONs. A pre-written SOUPAC program at the University of Illinois Computer Center was employed for analyses. Log values were used for any parameter which had a geometric population distribution. The standard multiple linear regression equation is in the form:

\[ Y = a + a_1 X_1 + a_2 X_2 + \ldots + a_n X_n + e \]  \hspace{1cm} (2)

where \( Y \) is the dependent variable, log TON; \( a \) is the intercept; \( a_1, a_2, \text{ etc.} \) are constants; \( X \)'s are independent variables, i.e., the 20 water quality constituents listed in table 7; and \( e \) is the probable error. Two separate analyses were performed. In one case all the data were used with corresponding TONs; in the other case only those data assembled during periods of high TONs were examined. The use of all data produced the better results.

The results of stepwise regression analyses with all data for each station are shown in table 9. All the equations show a fair degree of multiple correlation (\( R > 0.70 \)). The \( R^2 \) values are also presented. The importance of any independent variable to the dependent variable is shown in the order of its appearance in the equation. For example,
nitrate-nitrogen concentrations in the waters of Lake Decatur have the best correlation (negatively) with log TONs. Log algae is the next important factor for the surface waters of Lake Decatur.

Nevertheless, they may be useful in alerting the operators of the water treatment plants to those parameters important to taste and odor conditions in their impoundments.

**CONCLUSIONS**

The magnitude of taste and odor in the waters of the three impoundments is a seasonal function. High TONs generally occur during the period from May through October, the period of dissolved oxygen depletion in bottom waters. The time interval between high TONs in the bottom water and high TONs in the finished water varies from about 3 to 4 weeks to zero depending upon the relative size and depth of the impoundment. However, regardless of the magnitude of TONs in the raw water, the intensity of TONs in finished water ranges from 3 to 10 about 95 percent of the time. In this study the required TON of 3 in finished water was achieved only 6 to 13 percent of the time.

Most of the 20 measured biological, chemical, and physical characteristics of the lake water could not be significantly correlated with corresponding TONs. Those for which a reasonable correlation exists are as follows:

Table 9. Regression Equations for Threshold Odor Number

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<th>Sample</th>
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<tr>
<td>Surface</td>
<td>( Y = -0.081 X_5 + 0.316 X_2 + 0.089 X_{11} + 0.284 X_{13} + 0.0013 X_4 - 0.717 )</td>
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<td>Mid-depth</td>
<td>( Y = -0.198 X_5 + 0.11 X_3 + 0.054 X_{11} + 1.862 )</td>
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<td>( Y = -0.097 X_7 + 0.143 X_{11} + 0.205 X_{15} + 0.244 X_3 + 1.537 )</td>
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<td>( Y = -0.074 X_5 + 0.152 X_{13} - 0.10 X_{11} + 1.438 )</td>
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<td>Mid-depth</td>
<td>( Y = -0.562 X_7 - 0.014 X_3 + 2.199 )</td>
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<td>( Y = -0.053 X_5 - 0.01 X_4 - 0.016 X_1 + 2.445 )</td>
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<td>Surface</td>
<td>( Y = 0.152 X_{11} + 0.617 X_{13} + 0.0022 X_3 + 0.413 X_{12} + 2.477 )</td>
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<td>Mid-depth</td>
<td>( Y = 0.329 X_{13} + 0.144 X_{11} + 0.008 X_4 - 0.017 X_4 + 1.693 )</td>
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<td>( Y = 0.154 X_{11} + 0.0016 X_3 - 0.24 X_2 + 0.22 X_{10} + 0.3971 )</td>
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Note: \( Y = \log \text{TON}; X_1 = \text{dissolved oxygen}; X_2 = \text{pH}; X_3 = \text{alkalinity}; X_4 = \text{hardness}; X_5 = \text{nitrate-nitrogen}; X_6 = \text{COD}; X_7 = \text{sulfate}; X_9 = \log \text{turbidity}; X_{11} = \log \text{ammonia nitrogen}; X_{13} = \log \text{manganese}; X_{12} = \log \text{total phosphorus}; X_{13} = \log \text{chlorine demand}; X_3 = \log \text{algae} \)
All changes in the concentrations of these in-lake constituents are likely to occur because of bottom-mediated conditions and especially during periods of oxygen depletion.

There was no simple correlation between TONs and algal densities, actinomycetes, standard plate count, or benthos organisms. This does not mean that the by-products of these organisms do not contribute to TONs. The identification of these by-products was not within the scope of the study.

From the stepwise multiple regression analyses, nitrate and sulfate were determined to be the most important constituents affecting Lake Canton waters, and these are negatively correlated to TONs. At Lake Decatur, nitrate was a major governor of TON magnitude (negatively correlated). And at Eureka manganese and chlorine demand were the most important factors (positively correlated). This suggests that monitoring the depletion rate of sulfate and nitrate concentrations at Canton and Decatur would be a worthwhile endeavor to predict the likely occurrences of impending high TONs. Similarly, at Eureka tests for manganese and Cl\textsubscript{2} demand increases would be desirable.

For long-term control of TONs, the benefits to be derived from in-lake treatment designed to minimize the dissolved oxygen depletion of bottom waters should be a major consideration.
REFERENCES


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| 1/16 | 26      | 18        | 20   | 4.6    | Df      | M         | Mm   | M        |         |           |      |          |
| 1/23 | 27      | 29        | 32   | 3.5    | Df      | M         | Dp   | M        |         |           |      |          |
| 1/30 | 20      | 24        | 53   | 4.9    | G       | Mm        | Dp   | Cm       |         |           |      |          |
| 2/6  | 24      | 22        | 29   | 3.8    | M       | G         | Dp   | G        |         |           |      |          |
| 2/14 | 35      | 49        | 70   | 3.8    | G       | G         | Dp   | Cm       |         |           |      |          |
| 2/20 | 27      | 34        | 40   | 3.4    | V       | G         | M    | M        |         |           |      |          |
| 2/27 | 42      | 46        | 59   | 4.1    | G       | G         | Dp   | M        |         |           |      |          |
| 3/6  | 26      | 35        | 37   | 4.4    | G       | G         | E    | M        |         |           |      |          |
| 3/13 | 47      | 46        | 46   | 4.3    | Mm      | M         | M    | M        |         |           |      |          |
| 3/20 | 29      |           |      | 2.4    | M       |           |      | M        |         |           |      |          |
| 3/27 | 31      |           |      | 2.6    | Df      | M         |      |          |         |           |      |          |
| 4/3  | 31      | 35        | 50   | 3.7    | Mm      | M         | E    | M        |         |           |      |          |
| 4/10 | 46      | 50        | 54   | 3.1    | Df      | Mm        | Mm   | Mm       |         |           |      |          |
| 4/17 | 53      | 54        | 59   | 3.5    | Mm      | M         | Dp   | Mm       |         |           |      |          |
| 4/24 | 29      | 32        | 49   | 4.0    | Df      | Df        | Df   | G        |         |           |      |          |
| 5/1  | 32      | 46        | 53   | 4.4    | Df      | Df        | E    | M        |         |           |      |          |
| 5/8  | 43      | 41        | 50   | 3.7    | G       | Df        | E    | Bs       |         |           |      |          |
| 5/15 | 39      | 41        | 53   | 5.4    | M       | E         | Df   | G        |         |           |      |          |
| 5/22 | 35      | 46        | 50   | 4.7    | G       | M         | E    | Cc       |         |           |      |          |
| 5/29 | 35      | 47        | 54   | 4.8    | G       | Df        | E    | Cc       |         |           |      |          |
| 6/5  | 39      | 49        | 53   | 5.0    | G       | Df        | E    | M        |         |           |      |          |
| 6/12 | 42      | 51        | 57   | 4.6    | G       | E         | G    | Cc       |         |           |      |          |
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* A - Aromatic
  B - Balasamic (flowery)
  Bs - Sweetish
  C - Chemical
  Cc - Chlorinous
  Ch - Hydrocarbon
  Cm - Medicinal
  Cs - Sulfuretted

D - Disagreeable
  Df - Fishy
  Dp - Pigpen
  Ds - Septic
  E - Earthy
  Ep - Peaty
  G - Grassy
  M - Musty
  Mm - Moldy
  V - Vegetable
Appendix B. Threshold Odor Number and Odor Type of Lake Decatur and of Its Finished Water

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