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INVESTIGATION OF ODOR PROBLEMS ASSOCIATED WITH WASTEWATER TREATMENT FACILITIES IN NORTH CAROLINA

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ABSTRACT

Odors from wastewater collection and treatment facilities are a common problem throughout the United States. However, relatively little research has focused on odor characterization and control, and standard approaches to studying and solving odor problems have not been well documented. This project involved a new approach to quantifying odors derived from a wastewater treatment plant, using the Elledge plant in Winston-Salem, N.C. as prototype. The study was set up to allow affected residents to serve as odor analyzers by recording odor strength in their neighborhoods, on a numerical scale from 1 to 5, three times a day for six months. Public involvement also was encouraged through the creation of an odor advisory board, and by holding community meetings at the start of the project to educate residents about wastewater treatment and to discuss the odor problem. Public participation and the sincerity of city personnel led to a generally cooperative relationship. Numerical data from the residents' evaluation forms were analyzed to correlate odors to practices at the treatment plant and other factors. Odors correlated strongly to waste strength and to wind direction, implicating the treatment plant as the major source of odors. Other information collected in conjunction with the odor data was used to identify major sources within the treatment plant. Recommendations to modify operating practices were made based on these findings, and the city also has initiated several projects aimed at further reducing the release of odors from the plant. (key words: wastewater, odor, public participation, quantification)

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INTRODUCTION

A number of cities in North Carolina have received complaints from residents about odors associated with wastewater collection and treatment facilities. This is a common problem throughout the United States, but relatively little research has been focused on odor characterization and control, and standard approaches to studying and solving the problem have not been well documented. In particular, methods of quantifying odors to evaluate long-term trends in specific neighborhoods have not been established. As a result, this project was initiated to investigate wastewater odor problems in North Carolina, using the City of Winston-Salem Archie Elledge wastewater treatment plant as a prototype. The study was conducted through the Department of Environmental Sciences and Engineering at the University of North Carolina at Chapel Hill, in cooperation with the City of Winston-Salem Department of Public Works and local residents. Findings of the study are presented in this report.

Background

Odors are associated with both the collection and treatment of wastewater. The extent to which these odors become a problem in a community depends on the extent to which odors are released from the collection or treatment facility, and on the proximity of the facility to the community. Although most wastewater treatment plants historically were sited in relatively remote areas, many communities expanded into these areas after the plants were built. As a result, wastewater odors have become a serious nuisance in municipalities across the United States and Canada (Henry and Gehr, 1980). The need to address wastewater odors and their control has been documented in publications by the U.S. Environmental Protection Agency (EPA, 1985) and the Water Pollution Control Federation (WPCF, 1979).

Many new treatment plants located in or near metropolitan areas are now built with odor control features, and many cities have retro-fitted plants with odor control systems. The cost of odor control can be significant, both in terms of capital investment and in terms of operating cost. For example, Orange County, California has recently initiated an odor control retro-fit for two treatment plants, with a combined estimated capital cost of $20 million (Malcolm Pirnie, Inc., 1990).

Odors are difficult to quantify because they are caused by a wide mixture of compounds which have interacting effects (WPCF, 1979; EPA, 1985), and because responses of individuals vary greatly for a given odorous mixture. Current methods for measuring odor rely on dilution of a sample to a non-odorous level, or threshold odor, which is a quantifiable parameter (EPA, 1985; Henry and Gehr, 1980). Frequently, odors are quantified with groups of people referred to as an odor panel, using an "olfactometer" or other means of obtaining reproducible dilution. However, if comparisons are to be made among different samples or at different time periods, then the panel members should remain as constant as possible. Furthermore, panel tests require that discrete samples be collected for analysis. Thus, to characterize a particular odor problem over an extended period of time and at various locations simultaneously would require an unwieldy number of samples and odor panels (Keddie, 1982). If odor problems in a particular neighborhood are intermittent, then discontinuous sampling becomes an even more impractical method of evaluating the problem.

Odors also can be measured using surrogate parameters, including individual chemical species. Although there is a wide range of chemical species found in odorous air associated with wastewater, hydrogen sulfide is a major constituent and has known odor characteristics (Keddie, 1982; Ando, 1980). Gaseous hydrogen sulfide concentration has been found to correlate well with direct odor measurement at wastewater treatment plants

(Koe and Brady, 1986). However, even with a suitable surrogate parameter for odor, sampling must still be conducted over an extended period of time to fully characterize an odor problem. This would require continuous or semi-continuous measurement of hydrogen sulfide at selected locations, involving expensive sulfide monitoring and data acquisition instrumentation. Since the odor detection threshold for hydrogen sulfide is in the low part per billion range (WPCF, 1979), very sensitive instruments would be required to correlate its presence to odor complaints at remote locations. Commercially available instruments normally are manufactured to measure hydrogen sulfide concentrations in the range of importance for personnel safety (low part per million range).

An alternative method of collecting data on odors was developed for this project. The method involved selecting residents from neighborhoods in which a large number of complaints had been received, and asking them to complete odor evaluation forms three times a day for six months. In essence, the residents themselves were asked to serve as analytical tools for quantifying odors. The evaluation forms were designed to be convenient to fill out, so that the respondent only had to circle a number from one to five for a given time period. In this way, a large database was generated for evaluation of trends in odor complaints. Preliminary trends evaluated included correlation of odor levels to wastewater characteristics (influent strength and loading rate), time of day, day of week, seasonal patterns, practices at the treatment plant (e.g., use of certain treatment processes) and wind direction and speed. An effort is in progress to correlate odor data to a more comprehensive set of atmospheric conditions using an EPA atmospheric dispersion model; this modeling effort is beyond the scope of the study described in this report.

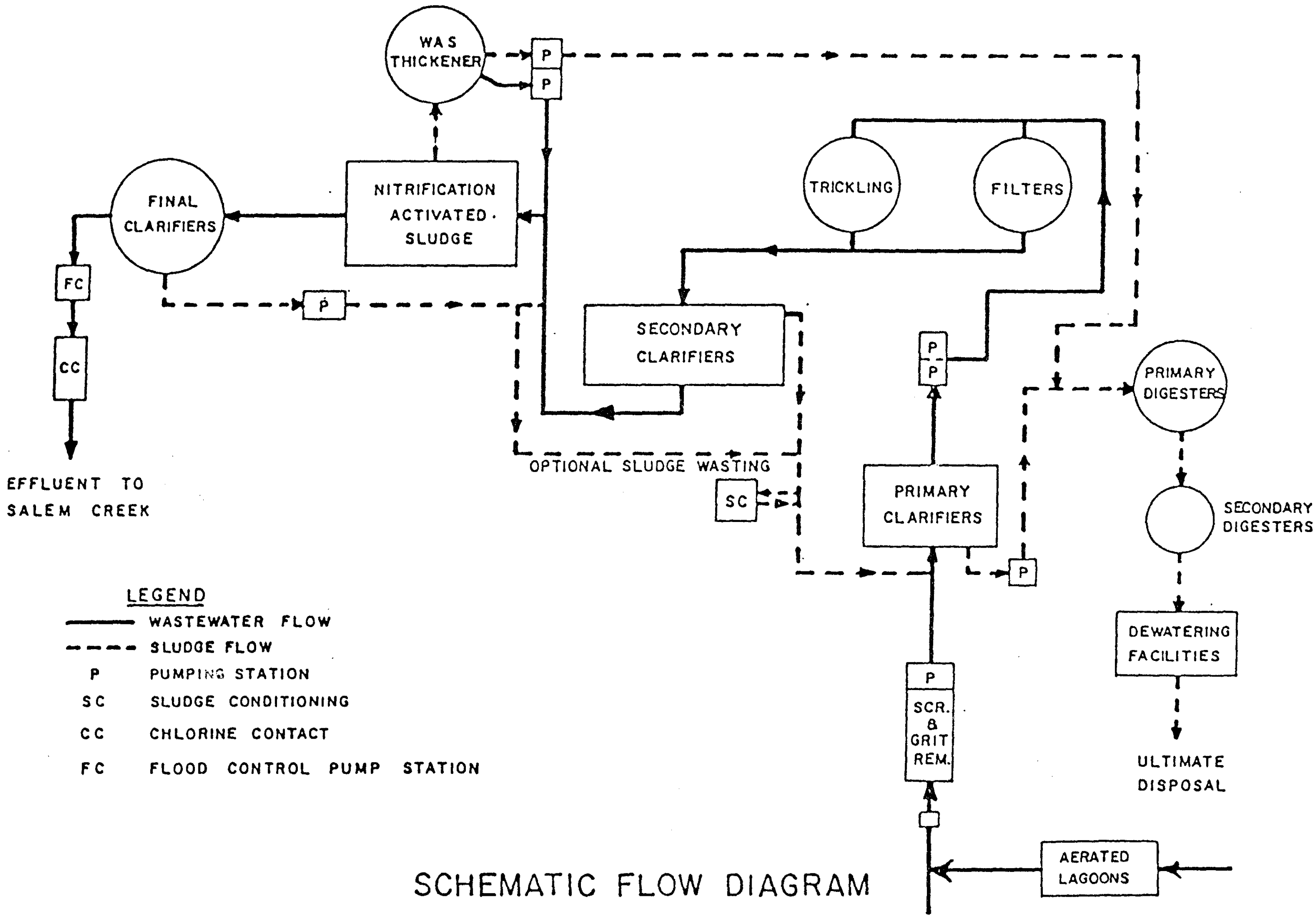
Background on the Elledge treatment plant, which was the focus of this study, is provided below. Although it is believed that the methods used in this project are applicable to virtually any odor study, any such study must take into consideration site-specific factors if odor data are to be used to help solve the problem.

Background on Elledge Treatment Plant

The Elledge wastewater treatment plant was originally built in the 1950's. At the time it was built, it was located in a rural area southwest of downtown Winston-Salem. The city has expanded with time and now several residential neighborhoods are located near the plant. The plant itself has undergone expansion since it was first built and currently provides secondary treatment, with seasonal removal of ammonium nitrogen. A schematic diagram of the treatment processes used in the plant is shown in Figure 1.

Raw wastewater flows to the plant through three major outfall sewers, known as the South Fork, Salem and Kimel outfalls. Flow from the South Fork outfall can be diverted to aerated basins ("aerated lagoons" in Figure 1) for pretreatment before being combined with flow from the Salem and Kimel outfalls. These pretreatment basins are used to reduce the organic load sent to the remainder of the plant when influent loadings are deemed to be high. It is important to note that they are not used all the time.

Combined wastewater flows to preliminary treatment consisting of screening and grit removal. It is then pumped to primary clarifiers for solids removal, and pumped again to trickling filters for partial removal of dissolved organic material. Effluent from the trickling filters flows through a set of intermediate or secondary clarifiers, which served as final clarifiers before the plant was expanded. These intermediate clarifiers serve little purpose at present. From the intermediate clarifiers, the wastewater flows to activated sludge treatment for biological removal of the remaining organic matter and, during warmer months, conversion of ammonium nitrogen to less polluting forms of nitrogen. The contents of the activated sludge basin flow to final clarifiers for solids separation, and the treated effluent is disinfected with chlorine before being discharged to Salem Creek.



SCHEMATIC FLOW DIAGRAM

FIGURE 1

Solids removed in the primary clarifiers and those wasted from the activated sludge process are treated in anaerobic digesters, which convert much of the solid material to methane gas and carbon dioxide. The methane gas is burned in generators that provide a substantial amount of the electricity required to operate the plant. Digested sludge is stored in on-site holding basins (sludge lagoons) before being transferred off-site for application to agricultural land.

A large fraction of the wastewater entering the treatment plant is of industrial origin, so that raw waste has an unusually high organic content when compared to typical domestic wastewater. Major industrial contributors include the Stroh brewery, CPC International, Hanes and R.J. Reynolds plants.

The City of Winston-Salem has for many years received numerous complaints regarding odors in the vicinity of the treatment plant. These complaints became particularly acute in the last two years; at least part of the increase in odor complaints can be attributed to new residential developments built near the plant. The city responded to complaints by keeping a log of phone calls to the treatment plant, by mailing survey forms to callers, and in many cases by sending plant personnel to the affected neighborhood to assess the problem. Survey forms provided space for a resident to identify the dates, times of day and duration of odors, weather conditions, wind direction, odor strength and general comments. There was, however, no formal followup on the surveys and the information could not be organized in a manner allowing a comprehensive understanding of the problem. The city has made a number of attempts to control the problem, including the use of chemicals in the South Fork outfall to help remove odor-causing substances. Chemical addition appears to help partially but the problem has persisted.

Project Objectives

The primary research objective of the project was to determine whether long-term trends in odor could be quantified through consistent, long-term public response to odor evaluation forms. Specific objectives of the project included:

(1) Determine whether the Elledge wastewater treatment plant is the primary source of odor complaints in affected neighborhoods;

(2) Evaluate the time variability of odors detected in residential areas near the plant, to possibly correlate odors with events or practices at the plant;

(3) Identify the major sources of odor, including individual sources at the treatment plant; and

(4) Make recommendations for interim and long-term solutions to the problem.

The principal objective of any study of this sort is to understand the problem to an extent that permits rational approaches to solving it. Inadequate approaches to addressing odor problems can result in continual public pressure, which can lead to ill-conceived, ineffective and costly solutions. In the worst cases, hasty attempts to solve odor problems may affect plant performance. The approach conducted in this project represented a relatively low-cost method of comprehensively studying an odor problem.

Public participation activities are described in the next section, followed by a description of methods used in the study, the study results, and finally conclusions and recommendations.

STUDY METHODS

Public Participation

The affected public played a key role in this project. Preliminary community meetings helped in designing the data collection effort by identifying key neighborhoods and by indicating that the problem was intermittent, varying not only from day to day but over the course of a day as well. Public involvement has been cited as critical in developing rational odor control strategies and in restraining public over-reaction (Harris and Lauria, 1984; Pope and Lauria, 1989).

Public participation in the project was encouraged through several activities:

(1) Creation of an Odor Advisory Board, comprising representatives of the city, the UNC study group, and affected neighborhoods;

(2) Public meetings to educate residents about wastewater treatment in general and practices at the Elledge plant in particular, and to discuss the odor problem; and

(3) Involvement of residents in daily odor evaluations, which served as a principal source of data for the study.

Advisory Board

Local citizens were solicited through telephone interviews to serve as respondents to odor evaluation forms ("data collectors") and to participate on the odor advisory board. These citizens were selected from the list of people who had called the plant or city offices to complain about odors. A total of fifteen people made up the advisory board, including the plants engineer from the city Department of Utilities, a member of the Winston-Salem Utilities Commission, the plant superintendent for the Elledge treatment plant, a member of the Forsythe County Environmental Affairs Board, members of the UNC study group, and nine representatives of the different neighborhoods from which most of the odor complaints have been received. Virtually every group that had an interest in the outcome of the study was represented on the Advisory Board.

The following mission statement was developed for the advisory board:

> The Odor Advisory Board will advise on the direction of the public participation activities of the Elledge Plant Odor Study. They will assist in the development of a data collection form. They will be informed of data collection results and scientific findings of the study. They will act as a liaison to the community for the study and encourage public participation. Upon completion of the data collection and scientific findings, the Board will comment on recommendations made by the project staff. The Board will meet an expected four times during the study and disband upon completion of the study.

The board met at the start of the project to provide guidance in developing an odor evaluation form, and twice more to evaluate progress on the study. The Advisory Board also met at the completion of the study to hear a presentation of the findings and proposed actions to be taken by the City.

Community Meetings

Three public meetings, one for each of the neighborhoods affected most by the odors, were held at the start of the project in the Elledge treatment plant administration building. Each meeting opened with a brief introduction by city personnel and the UNC staff to discuss the scope and objectives of the odor study. A videotape about wastewater treatment then was presented, followed by a tour of the plant's operations laboratory. An informal odor sampling experiment was prepared and conducted in the laboratory by the plant superintendent, in which residents were asked to comment on odors of various unidentified wastewater samples that had recently been collected. Samples included raw wastewater from the Salem and South Fork outfalls, industrial wastewater from Stroh, CPC, Hanes and Reynolds, raw sludge from primary treatment, digested sludge, septage (from a septic tank), activated sludge from the biological treatment process and final effluent.

Following the odor sampling, the group was given a tour of the treatment plant. After the tour the group returned to the administration building for general discussion and questions. Data collectors were solicited at these meetings, and a number of people volunteered.

Two additional public meetings were held for the purpose of training data collectors to fill out odor evaluation forms (described below) properly.

Odor Data Collection

Data collectors were solicited through telephone interviews and at the public meetings. Thirty-five people initially volunteered to fill out odor evaluation forms, and several more were added as the study progressed. By the end of the study, 41 people had served as data collectors. For purposes of data analysis, data collectors were grouped into three study areas located to the east, northeast and west of the plant. The area to the east is referred to in this report as Janita Lakes, and initially consisted of 6 data collectors; however, due to inconsistent and infrequent response from this group, several more residents were asked to complete evaluation forms during the latter part of the study. The area northeast of the plant is referred to as Mountain Brook, and the area to the west is referred to as Huntington Woods. In the original analysis of odor evaluation data presented in a report to the City of Winston-Salem (Aitken and Okun, 1990), the Mountain Brook group included 18 respondents and the Huntington Woods group 13. For purposes of testing correlations of trends in odor data by location for this report, these groups were trimmed to 12 and 8 respondents, respectively, to include only those respondents within a very close distance to each other. The remaining respondents were included in analyses that did not take location into consideration.

Each data collector was sent an odor evaluation form for a particular month at the end of the previous month. The forms provided space for the collector's name, address, and a code number assigned by the project staff for purposes of computer tabulation. A sample form is shown in Figure 2. Each day was divided into three time periods: 1:00 a.m. to 9:00 a.m. ("a.m. data"); 9:00 a.m. to 5:00 p.m. ("day data"); and 5:00 p.m. to 1:00 a.m. ("p.m. data"). These specific periods were chosen to correspond to times of day in which some respondents would most likely not be home (i.e., the "day" period was selected for people who work typical daytime hours) and to avoid breaking up periods over which many residents indicated they most often smelled the odors (e.g., late evening and early morning). For each time period, a number from 1 (no odor) to 5 (high odor) was circled to indicate an average perception of odor strength over that 8 hour period (other investigators have used a scale of 0 to 5 in ranking odor strength (du Toit, 1987)). If the respondent was not home during a particular time period, none of the numbers was circled. These numerical data then were entered into personal computer spreadsheets and used to analyze trends in odor by time of day, day of week, neighborhood, wastewater characteristics, and other factors.

Data collectors also were encouraged to write comments on the forms regarding descriptions of the odor on specific days. In addition, they were asked to call the treatment

NAME____________________ ADDRESS______________________ CODE #_____________

ODOR SURVEY FOR JULY, 1989

Date	(day)	1 a.m. - 9. a.m.					9 a.m. - 5 p.m.					5 p.m. - 1 a.m.				
		No Odor				High Odor	No Odor				High Odor	No Odor				High Odor
1	Sat	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
2	Sun	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
3	Mon	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
4	Tue	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
5	Wed	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
6	Thurs	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
7	Fri	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
8	Sat	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
9	Sun	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
10	Mon	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
11	Tue	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
12	Wed	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
13	Thurs	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
14	Fri	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
15	Sat	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
16	Sun	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
17	Mon	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
18	Tue	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
19	Wed	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
20	Thurs	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
21	Fri	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
22	Sat	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
23	Sun	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
24	Mon	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
25	Tue	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
26	Wed	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
27	Thurs	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
28	Fri	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
29	Sat	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
30	Sun	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
31	Mon	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5

INSTRUCTIONS: This form is designed for you to record the extent of odors for each day of the month indicated. Simply circle the number that best indicates your perception of odors for that particular day. If you circle the number "1", that means odors were not a problem. On the other extreme, the number "5" indicates that odors were unbearable. Please note that each day is divided into three time periods: early morning, daytime, and evening. If possible, please record the odor for each of the three time periods; if you were not home for most of a particular time period, do not circle any of the numbers.

NOTE: **(1) Please record any additional comments you have on the back of this form. For example, if you can *describe* the odor ("rotten egg", "stale beer", etc.) then record the date and description on the back.**

(2) Return the completed form at the end of the month in the enclosed envelope.

(3) Please call 765-0156 if odors are extremely bad. The purpose of your call will be to register that odors are *abnormally* high. Even though the treatment plant operators may not be able to alleviate the problem immediately, this information will help us understand whether non-routine practices at the plant lead to exceptionally high odor releases.

We appreciate the time and effort you are contributing to this study of odors associated with the Elledge Wastewater Treatment Plant

FIGURE 2

plant on *extremely* bad days, to help plant personnel understand whether practices at the plant might be contributing to the odor. For each phone call received, plant operators filled in a log on which they recorded any potential causes of high odor at the treatment plant. Data were collected for over 6 months, from February 21 through August 31, 1989. Only those data from March 1 on were used in the data analysis.

Numerical odor evaluation data represented odor ratings on a scale of 1 to 5. Consequently, any group of data representing no odor would have a numerical average of 1.0. Data that were averaged for various purposes were adjusted by subtracting 1.0 from all values (i.e., "no odor" corresponds to an adjusted rating of 0), which made scaling for graphical presentation easier. These adjusted averages are indicated where used.

Other Data

In addition to odor evaluation data by residents in the vicinity of the treatment plant, a large variety and quantity of other data were used in this study. Plant operating data, odor evaluation data on individual sources at the treatment plant, and wind data were entered into personal computer spreadsheets for storage and analysis. Brief descriptions of data used and their sources are given below.

Plant Operating Records

Operating records were obtained from city personnel so that odor evaluation results could be correlated to wastewater characteristics. Characteristics of concern included flow to the treatment plant; various measures of organic strength of the wastewater at several points during the treatment process, including biochemical oxygen demand (BOD), chemical oxygen demand (COD) and total organic carbon (TOC); various measures of organic loading (flow times strength); and plant performance. Flows were reported for each 24 hour period beginning at midnight. Wastewater characteristics (such as BOD) for a given day represent averages over a 24 hour period beginning at 6 a.m., and were obtained from samples collected in refrigerated composite samplers. Although the 24 hour periods over which flows and waste characteristics were reported did not overlap, organic loadings were estimated by using reported flow times the concentration of the parameter of interest on the date reported. In retrospect, an effort should have been made to coordinate wastewater sampling and flow measurement with the odor evaluation time periods.

Special sampling events also were conducted at the plant. To characterize the variability in wastewater characteristics during the course of a day, four hour composite samples of primary effluent were collected for a 24 hour period on four different occasions (August 17-18, August 20-21, October 13, and October 14, 1989). These samples were analyzed for COD. Also, plant personnel collected a number of grab samples of trickling filter effluent for dissolved oxygen analysis.

Odor Evaluation of Plant Sources

Plant personnel toured the treatment plant three times a day to note odors from different sources. For each source, the operator completed the same odor evaluation form used by citizen data collectors. Sources investigated in this way included the Salem and South Fork outfalls (at manholes accessible from within the plant), the pretreatment basin area, sludge storage lagoons, primary clarifier area, trickling filter area, secondary clarifier area and waste activated sludge thickener area. Forms were completed for the entire six month period of the project.

Wind Data

Wind data for measurements made at Smith-Reynolds Field in Winston-Salem were obtained from the National Climatic Data Center in Asheville, North Carolina. Data were received in the form of hand-written records of hourly wind direction and speed. Hourly data over the entire six month study period were entered in a personal computer spreadsheet and summarized into 8 hour periods corresponding to the 8 hour periods used for the neighborhood odor evaluation forms. The summarized wind data for each 8 hour period represent the vectorial average of hourly records of wind speed and direction. Any shifts in wind speed and direction that occurred within the 8 hour period therefore are not accounted for except in their influence on the 8 hour average. Raw data for wind direction correspond to degrees clockwise from north, and were grouped into 8 sectors representing north, northeast, east, southeast, south, southwest, west and northwest. Each reported direction includes all wind directions within 22.5^{o} (on either side) of a line representing that direction, as shown in Table 3.1

TABLE 1
Directions of Wind Data Included in
Reported Wind Directions

Reported Wind Direction	Range of Directions Included
N (0^{o})	337.6 - 22.5^{o}
NE (45^{o})	22.6 - 67.5^{o}
E (90^{o})	67.6 - 112.5^{o}
SE (135^{o})	112.6 - 157.5^{o}
S (180^{o})	157.6 - 202.5^{o}
SW (225^{o})	202.6 - 247.5^{o}
W (270^{o})	247.6 - 292.5^{o}
NW (315^{o})	292.6 - 337.5^{o}

Analysis of Odor Evaluation Data

As discussed below, there was an excellent response frequency for the odor evaluation forms throughout the 6 month study period. Nevertheless, several steps were taken to reduce bias from infrequent respondents in analyzing the data. First, those data collectors who responded with less than 10% frequency (less than 10% of all possible data entries were circled) were eliminated from the database. In addition, all averaging of responses was done using responses weighted according to the response frequency of the individual; in this way, an infrequent respondent giving an odor rating significantly out of line with others in the same group would not have an undue influence on the calculated average. Weighting was accomplished by multiplying each response by a weighting factor (total responses of the individual divided by the total number of possible responses). Weighted averages were calculated by adding the weighted responses and dividing by the sum of the weighting factors for the individuals included in that particular set of data.

It was recognized that odors could correlate to a variety of factors, including source characteristics (e.g., wastewater strength or flow rate) and atmospheric conditions (e.g., wind speed and direction, stability classes). Because a number of factors could be involved in odor generation and in transport of odor emissions to a specific neighborhood, simple regression of odor data to a single factor was not considered to be a valuable measure of correlation. Instead, individual factors were examined in a way that would reveal trends. This involved arranging the odor data into groups that were appropriate for a given factor (e.g., by day of the week, by wind direction, or by percentile interval for specific wastewater characteristics). The odor data then were averaged as described above over each group. Trends could then be easily observed through the use of bar graphs.

A rough measure of the significance of trends observed by grouping data was checked by using Chebyshev's inequality for comparing the mean of grouped data to the mean of the full data set. Chebyshev's inequality was used because the responses were not normally distributed (shown below), and because it gives a conservative estimate of statistical significance for data with unknown distributions (Dixon and Massey, 1983). The full data set, after eliminating respondents with less than 10% response frequency, consisted of 11,979 responses. For weighted averaging, however, the population size reduced to 8,690. The mean weighted odor rating for these data was 1.267 and the standard deviation 0.791. For grouped data using all neighborhoods, the smallest sample size used in any one group was about 11% of the population size. Using Chebyshev's inequality, the probability of the mean of a grouping of this size being within 0.1 of the overall population mean of 1.267 is 6.5%. The largest grouping contained about 20% of the population size, for which the probability of a mean within 0.1 of the overall mean is 3.6%. These probabilities reduce to 1.6% and 0.9%, respectively, for differences from the overall mean of 0.2. For most correlations presented and discussed below, differences of 0.1 or more from a value of 1.27 are easily observed for individual groupings of data. Furthermore, if the sampling distribution of the mean is assumed to be normally distributed, which may be true for the large sample sizes involved, then levels of significance for differences from the population mean become even greater than indicated by Chebyshev's inequality (Dixon and Massey, 1983). Thus, most trends illustrated in bar graphs and other presentations of averaged data are significant in the sense that the grouping of data for a particular purpose resulted in mean odor ratings at the extremes significantly different than the overall population mean. Levels of significance for means of smaller groups of data than those indicated above (e.g., neighborhood data grouped by wind direction) are provided in the text.

RESULTS AND DISCUSSION OF PUBLIC PARTICIPATION METHODS

Several important points surfaced as a result of public participation. First, people expressed a general appreciation of the efforts made by the city to understand and alleviate the problem, and to educate them about other issues involving wastewater collection and treatment. Many had little understanding of the scope of wastewater treatment and had never seen a treatment plant. Second, it was apparent that the odor problem is a serious public nuisance directly affecting the quality of life in affected neighborhoods. One data collector described the situation in comments written on the back of one of the odor evaluation forms:

> Thank you for asking us to participate in the Archie Elledge Odor Survey. It has been, I hope, helpful to have all of us report on the odor problem. I do hope it will help to eradicate the odor that moves into areas where people live. How discouraging it is to awaken in the night to a bad smell. How upsetting it is to try to entertain guests with a bad smell wafting about the house and grounds. And how unpleasant it is to try to eat breakfast on the porch with a bad smell drifting across the area.

In addition, many residents expressed concern that their property values might decrease as a result of the pervasive odor; several said they would not have bought their houses had they known of the proximity of the treatment plant. Finally, participation in the data collection seemed to allow many of the residents to direct their frustration and anger into a constructive activity; one advisory board member actually was disappointed when the data collection period ended.

It is important to note that the sincerity of city personnel directly involved with the public, especially the treatment plant superintendent, went a long way toward creating a cooperative atmosphere in public meetings. In addition, the city was able to convey that real efforts were being undertaken to solve the problem. A repeated concern of residents was that the study would be an end in itself, and that nothing further would be done to solve the problem. The final advisory board meeting was used as a forum to present specific tasks to be carried out by the city in response to each of the findings of the study. Estimated costs of carrying out these tasks were presented as well. To our knowledge, there has been little if any expression of frustration over current and planned progress toward solving the problem.

Another point brought out during the odor sampling experiments held at the public meetings, as well as during discussions of the advisory board, was that residents could readily distinguish different types of odors. Many people said the two major types of odors they smelled in their neighborhoods were those characteristic of raw sewage (hydrogen sulfide type odor) and sweeter smells reminiscent of stale beer.

RESULTS OF ODOR EVALUATION

Results are presented first for neighborhood odor evaluations, followed by results pertaining to identification of individual odor sources at the treatment plant.

Level of Response to Odor Evaluation Forms

Overall the level of response was excellent. Summaries of response frequency by month and by neighborhood are shown in Tables 2 and 3. Two indicators of response are presented: the percentage of respondents returning completed forms is given in Table 2, and the percentage of total possible entries actually circled is provided in Table 3. More than three-quarters of all evaluation forms mailed out were returned by the respondents, which includes one person who volunteered to be a data collector but never returned a form. The data in Table 3 are a more accurate reflection of the response frequency, since completed forms could be (and were) submitted with a large number of blank entries. Note that, although the overall response frequency was high, the frequency of responses for the Janita Lakes area was low (26% of total possible entries were actually circled); for this reason the Janita Lakes data were not used for individual neighborhood analysis, although they were included in pooled data analyses.

TABLE 2
Return Frequency of Completed Survey Forms

	% Completed Forms Returned			
Month	Mountain Brook	Janita Lakes	Huntington Woods	Total
March	83%	80%	92%	86%
April	89	80	85	86
May	89	60	77	81
June	94	70	85	85
July	78	50	77	71
August	60	40	62	59
Overall	82.4%	57.2%	79.5%	77.9%

TABLE 3
Overall Response Frequency

	% Entries Circled (of Total Possible)			
Month	Mountain Brook	Janita Lakes	Huntington Woods	Total
March	71.1%	46.2%	79.4%	70.6%
April	67.4	44.9	80.1	68.9
May	61.9	24.3	66.7	58.4
June	67.3	39.3	68.9	59.0
July	59.9	15.6	54.6	47.4
August	56.3	5.4	55.3	43.6
Overall	63.9%	26.1%	66.4%	57.4%

Distribution of Responses

The distribution of responses by time of day for the entire study period is shown in Table 4. Slightly fewer responses were entered in the daytime period (9 a.m. to 5 p.m.) in Mountain Brook and Huntington Woods, but there was substantially lower response from Janita Lakes during the daytime.

TABLE 4
Distribution of Evaluation Responses by Time of Day

	Number of Responses Entered			
Period	Mountain Brook	Janita Lakes	Huntington Woods	Total
AM	2,135	411	1,681	4,227
Day	2,024	290	1,497	3,811
PM	2,193	378	1,586	4,157

The distribution of data by odor rating is shown in Table 5. By far the most frequent odor rating circled was 1 (no odor), and the order of ratings in terms of decreasing frequency was 1, 2, 3, 5, 4. One of the concerns in the study was that data collectors might not discern shades of difference in odor, so that most perceived odors would be rated "5". However, there was a reasonable distribution of ratings higher than 1. To test whether individuals could distinguish among different ratings higher than 1, a "coefficient of discernment" was defined and evaluated for each respondent. Distributions were prepared for each person's responses so that the number of 1's, 2's, and so on were known for each respondent. Since the majority of responses were "1" and because it was assumed that all respondents could readily distinguish no odor from some odor, only those responses from 2 to 5 were included in calculating the coefficient of discernment. A person who could easily distinguish among different degrees of odor would have a wider distribution of responses than would a person who could not make such fine distinctions; one measure of the breadth

TABLE 5
Distribution of Odor Ratings by Time of Day
and by Neighborhood

Neighborhood	% of Responses Entered for Given Rating: 1	2	3	4	5
Mountain Brook					
AM	79.5%	10.3%	5.4%	2.7%	2.1%
Day	84.6	8.8	4.1	1.7	0.8
PM	83.9	8.8	3.6	2.3	1.3
Total	82.7%	9.3%	4.4%	2.2%	1.4%
Janita Lakes					
AM	67.9	5.4	7.1	5.8	13.9
Day	79.3	4.1	6.2	2.8	7.6
PM	76.5	4.0	3.2	5.0	11.4
Total	74.0%	4.5%	5.5%	4.7%	11.3%
Huntington Woods					
AM	92.8	1.8	2.1	0.9	2.4
Day	97.2	1.5	0.9	0.1	0.3
PM	84.0	1.6	4.2	4.0	6.2
Total	91.2%	1.7%	2.4%	1.7%	3.0%
All Neighborhoods					
AM	83.7	6.5	4.3	2.3	3.3
Day	89.1	5.6	3.0	1.1	1.1
PM	83.3	5.6	3.8	3.2	4.1
Total	85.2%	5.9%	3.7%	2.2%	2.9%

of the distribution is the standard deviation of the mean number of responses of 2, 3, 4, and 5. The higher the standard deviation, the more uniform are the responses (in other words, someone who only circled 5's would have a high standard deviation and a corresponding low level of discernment in rating odor strength; someone who circled an equal number of 2's, 3's, 4's and 5's would have a standard deviation of zero and a correspondingly high level of discernment). The coefficient of discernment (CD) is therefore defined as:

$$CD = 1 - \frac{\text{std. dev. of distribution of responses from 2 to 5}}{\text{maximum possible std. dev. for that number of responses}}$$

where the maximum possible standard deviation is calculated by assuming that only one rating was circled for all responses greater than 1 (e.g., "5" was the only response greater than 1 circled).

The mean coefficient of discernment for all respondents was 0.54, with a standard deviation of 0.24. Only 20% of the respondents had a coefficient less than 0.3, while half had coefficients greater than 0.6. These values indicate that most people were capable of distinguishing reasonably well among different degrees of odor. In fact, one member of the advisory board indicated that she could easily tell the difference between odor strength in her yard and that in a neighbor's yard.

Level of Agreement Among Individuals in a Specific Neighborhood

There were a relatively large number of time periods in which no odor was perceived in a particular neighborhood (no responses higher than 1 for that neighborhood). These odor-free periods are summarized in Table 6. Note that there were substantially fewer odor-free periods for Mountain Brook than for either Janita Lakes or Huntington Woods. Overall, 85% of the time periods for which data were collected in the study were odor-free in at least one neighborhood. Conversely, however, only 6% of the time periods were odor-free in all three neighborhoods at the same time. In other words, there was a 94% probability that some level of odor was perceived in at least one neighborhood at any given time.

TABLE 6
Summary of Odor-free Time Periods by Neighborhood

Odor-free Time Periods (% of Total)

Period	Mountain Brook	Janita Lakes	Huntington Woods
AM	13%	44%	66%
Day	14	72	84
PM	17	63	41

Note: All respondents included. Mountain Brook and Huntington Woods respondents not trimmed as described above under Study Methods.

The level of agreement in odor perception among neighbors over a given 8 hour period can be measured by determining the coefficient of variation (relative standard deviation) across the neighborhood group for that time period. This was done for the trimmed Mountain Brook and Huntington Woods groupings (12 and 8 respondents, respectively) for each 8 hour period of the study. The mean coefficient of variation was 0.383 for Mountain Brook, and for Huntington Woods was 0.126; the higher value for Mountain Brook reflects the higher mean odor rating for that group. Unanimous agreement was achieved among neighbors only when there was no odor. It was remarkable, however, that for the trimmed Huntington Woods group (which included only those people located within a short distance from each other), there was unanimously no odor detected 79% of the time. The relatively good agreement among neighbors (relatively low coefficients of variation) for both neighborhood groups lends confidence in the quality of the odor data, and in the validity of correlating odor data to factors that may be involved in odor generation or transport.

Seasonal Trends in Odor

Seasonal trends in odor perception were evaluated by plotting two-week averages of odor for each time period, using pooled data for all three neighborhoods. These plots are shown in Figure 3. There is no clear seasonal trend for the two-week averages, except that odors appeared to be uniformly lower during the first six weeks of the study. Daytime odors were uniformly low throughout the study, a trend which was observed in all data analyses. This trend for daytime data cannot be accounted for by a different response frequency in the daytime (see above).

Trends by Day of Week

Study data were arranged by day of week and adjusted average odor ratings over each of the three time periods were determined for each day. There was a clear trend in odor strength by day of week, as illustrated in Figures 4 (a) through (c). In both Huntington Woods and Mountain Brook, as well as in pooled data for all neighborhoods, odor ratings began to decrease on Saturday and remained substantially lower for the weekend than for the remainder of the week. Note again that daytime odor ratings are significantly lower than ratings over the other two time periods; daytime odors are especially low in Huntington Woods.

The trend in odor strength by day of week corresponds to trends in loading to the Elledge treatment plant. Patterns in loading to the treatment plant by day of week over the six month study period are illustrated in Table 7 for flow, raw BOD and raw COD. Because of the large industrial contributions to the plant, loading (both flow and organic loading) to the plant decreases dramatically on the weekend. All measures of organic loading, both for raw wastewater and for influent to the trickling filters (effluent from the primary clarifiers), follow similar patterns. Flow and organic load are, on average, slightly lower on Monday and slightly higher on Thursday than on Tuesday, Wednesday and Friday. Average loads decrease substantially on Saturday and decrease even further on Sunday.

Correlation of Odor to Wastewater Characteristics

Adjusted average odor ratings correlated well to various wastewater characteristics. Correlations were made by averaging odor data over percentile intervals of a particular characteristic, thereby allowing general trends to be observed.

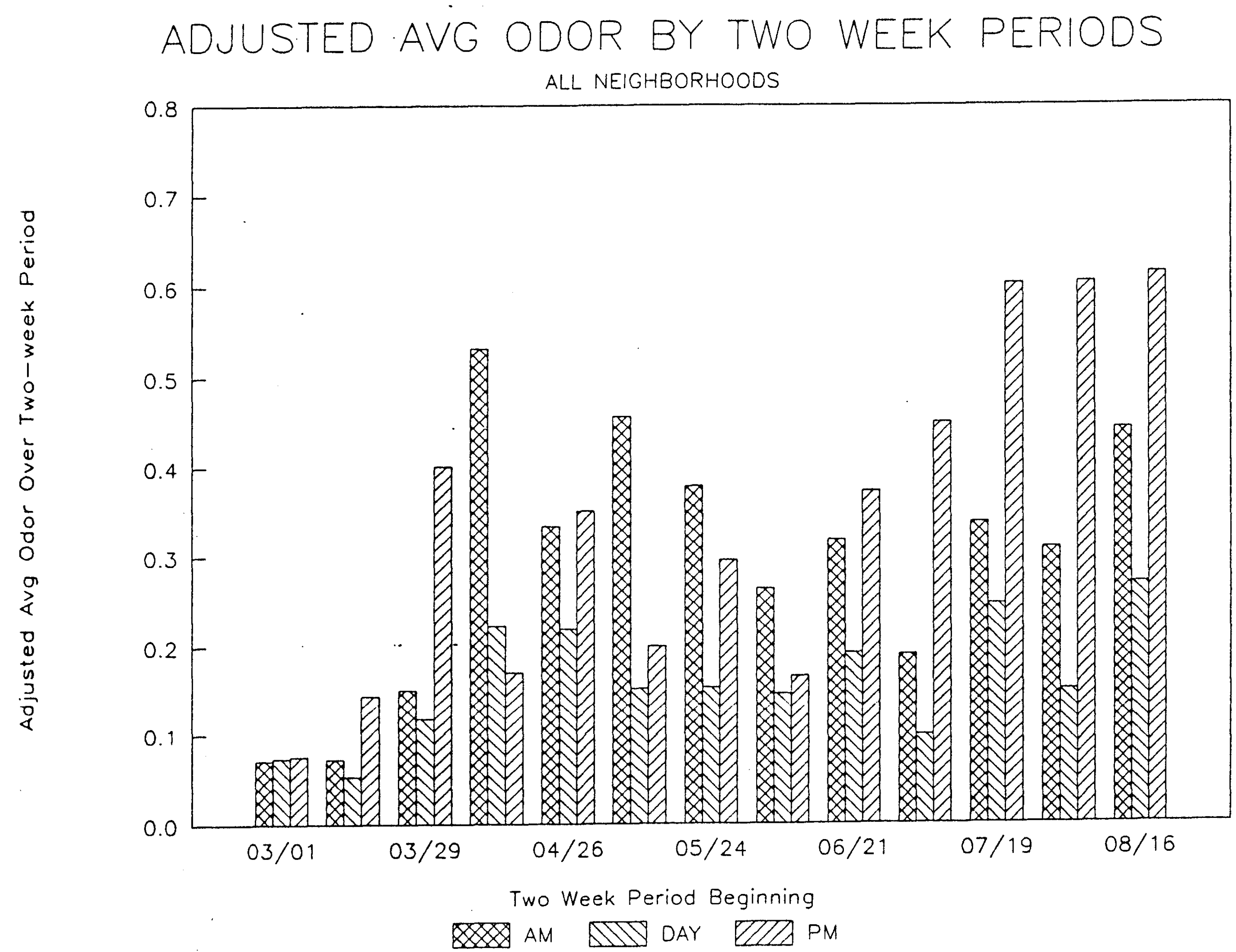

ADJUSTED AVG ODOR BY TWO WEEK PERIODS
ALL NEIGHBORHOODS
Adjusted Avg Odor Over Two-week Period
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
03/01
03/29
04/26
05/24
06/21
07/19
08/16
Two Week Period Beginning
AM
DAY
PM

FIGURE 3

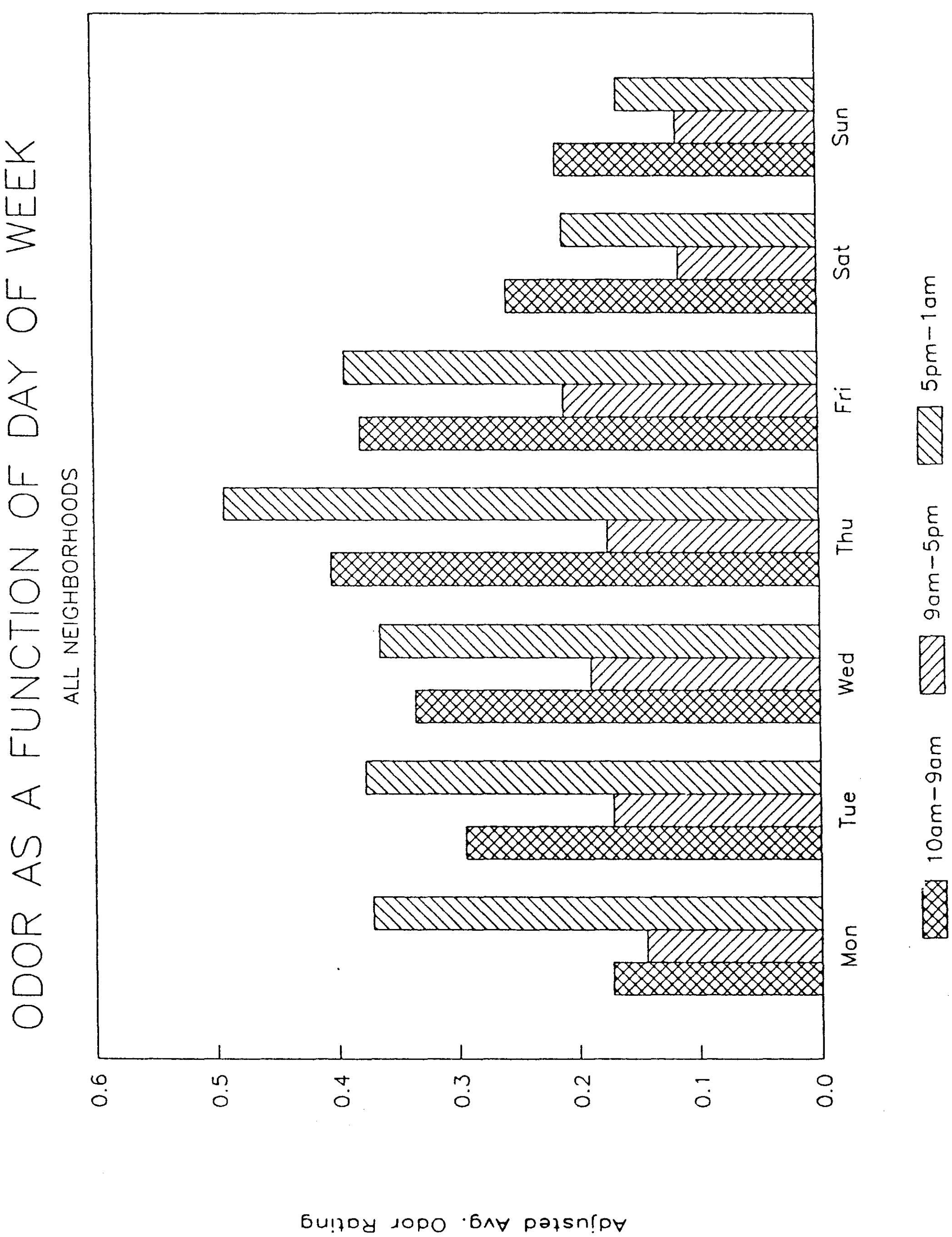

ODOR AS A FUNCTION OF DAY OF WEEK
ALL NEIGHBORHOODS
Adjusted Avg. Odor Rating
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Mon
Tue
Wed
Thu
Fri
Sat
Sun
10am-9am
9am-5pm
5pm-1am

FIGURE 4 (a)

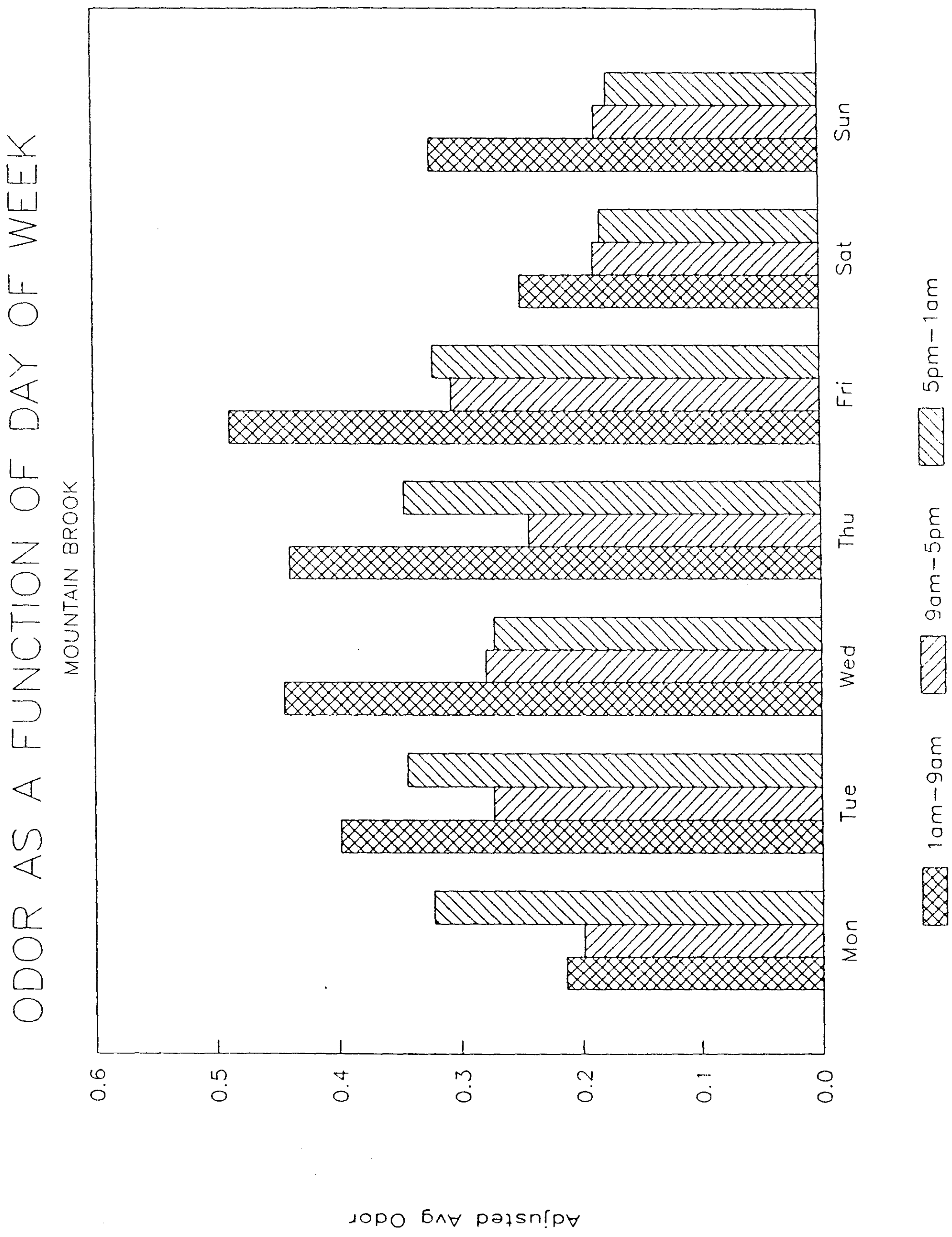

ODOR AS A FUNCTION OF DAY OF WEEK
MOUNTAIN BROOK
Adjusted Avg Odor
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Mon
Tue
Wed
Thu
Fri
Sat
Sun
1am-9am
9am-5pm
5pm-1am

FIGURE 4(b)

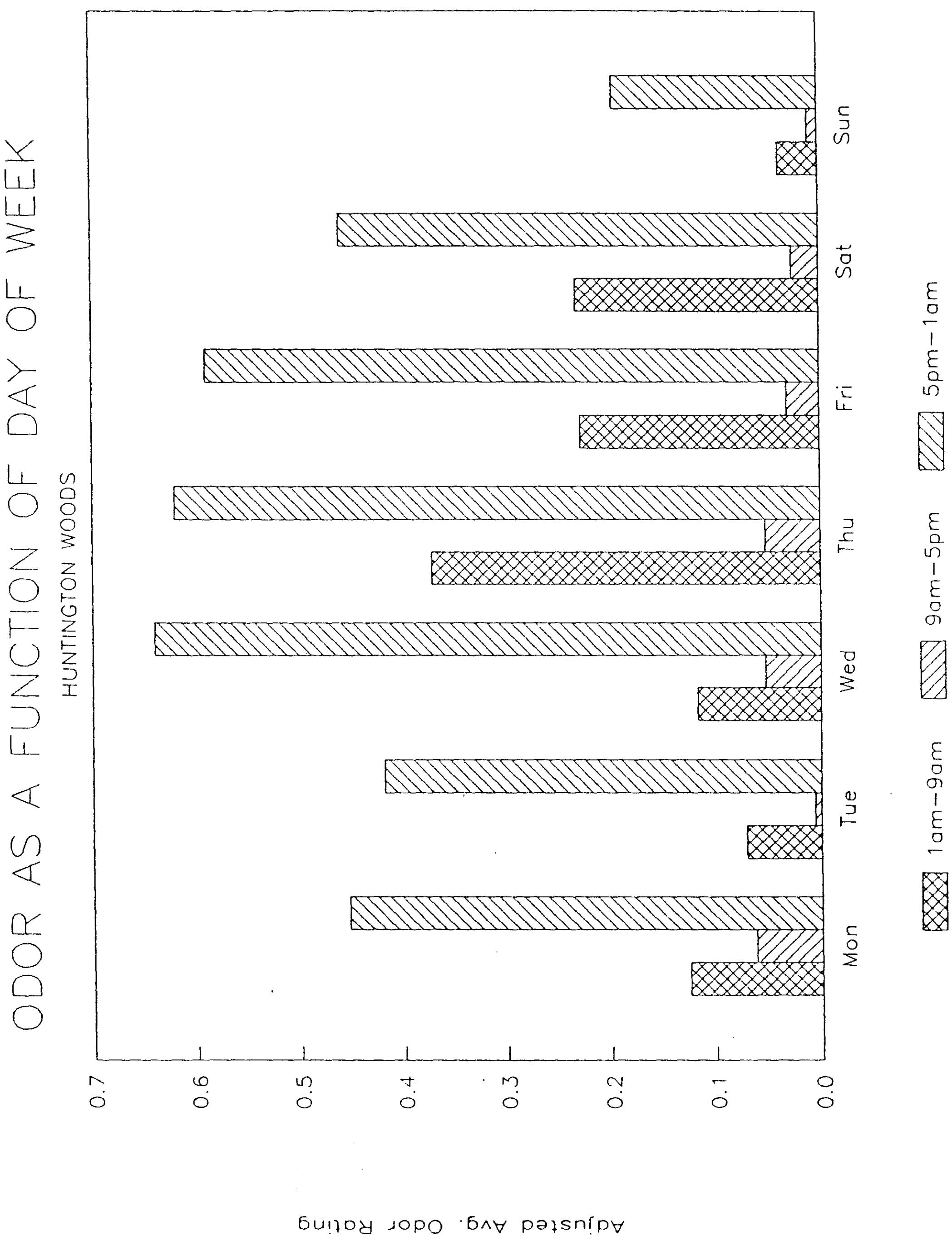

ODOR AS A FUNCTION OF DAY OF WEEK
HUNTINGTON WOODS
Adjusted Avg. Odor Rating
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Mon
Tue
Wed
Thu
Fri
Sat
Sun
1am−9am
9am−5pm
5pm−1am

FIGURE 4 (c)

TABLE 7
Wastewater Characteristics by Day of Week

Day	Flow, mgd[1]	Raw BOD Conc.[2]	Raw BOD Load[3]	Raw COD Conc.	Raw COD Load
Monday	17.6	522	34,600	1,070	70,800
Tuesday	19.0	581	41,600	1,250	90,000
Wednesday	18.8	575	40,900	1,280	91,100
Thursday	19.4	602	44,300	1,320	97,200
Friday	18.9	601	42,400	1,290	91,900
Saturday	17.1	ND[4]	ND	872	55,500
Sunday	14.5	344	18,700	680	37,400

[1] mgd = million gallons per day
[2] concentration in milligrams per liter (mg/L)
[3] loading rate in kilograms per day (kg/d)
[4] ND = no data

The following wastewater characteristics were evaluated for their correlation to odor data: daily flow; raw waste BOD (concentration and load); raw waste COD (concentration and load); trickling filter influent TOC (concentration and load); trickling filter effluent TOC (concentration and load); and TOC removal by the trickling filters (concentration and load). TOC data were used for the trickling filter analysis because TOC was the only measure of organic strength that was available for both the influent and effluent. For each characteristic the data were ranked in increasing order, then divided into four or five percentile intervals; each percentile interval represented one fourth or one fifth, respectively, of all the days for which data were available for that characteristic. Odor ratings then were averaged for the entire percentile interval, either by neighborhood or for the pooled data of all the neighborhoods.

As discussed above under Study Methods, except for flow all wastewater characteristics were measured from composite samples for a 24 hour period beginning at 6 a.m.. Thus it was not possible to break down the correlation of wastewater characteristics with odor by time of day, and odor data for the three individual time periods had to be grouped into 24 hour periods. However, the 24 hour period of wastewater sampling did not overlap with the 24 hour period used to collect odor data. Therefore, odor data were adjusted for analysis of correlation to measured wastewater characteristics by assigning a.m. data to the previous date. This rearrangement of the odor data is believed to be most representative for purposes of correlating wastewater characteristics with odor ratings. Correlation to flow was done using unadjusted odor data, since the overlap of 24 hour flow data with odor data was essentially complete (midnight to midnight versus 1 a.m. to 1 a.m., respectively). The lack of complete overlap in the periods used to measure reported flow with those used to measure reported concentration can be expected to introduce some uncertainty into the correlation analysis, especially for load correlations, which must be kept in mind when interpreting the data. The inaccuracies are probably less important for correlations of Huntington Woods data because a.m. period odor ratings from Huntington Woods generally were much lower than p.m. period data (see Figure 4 (c)). For Mountain Brook, however, the inaccuracies in wastewater characteristics would have more of an effect on the overall trends in odor because odors were the worst over the a.m. period (Figure 4 (b)).

To illustrate the kinds of trends observed in these analyses, correlations of odor to raw waste COD (both concentration and loading) are presented in Figures 5 through 7. The

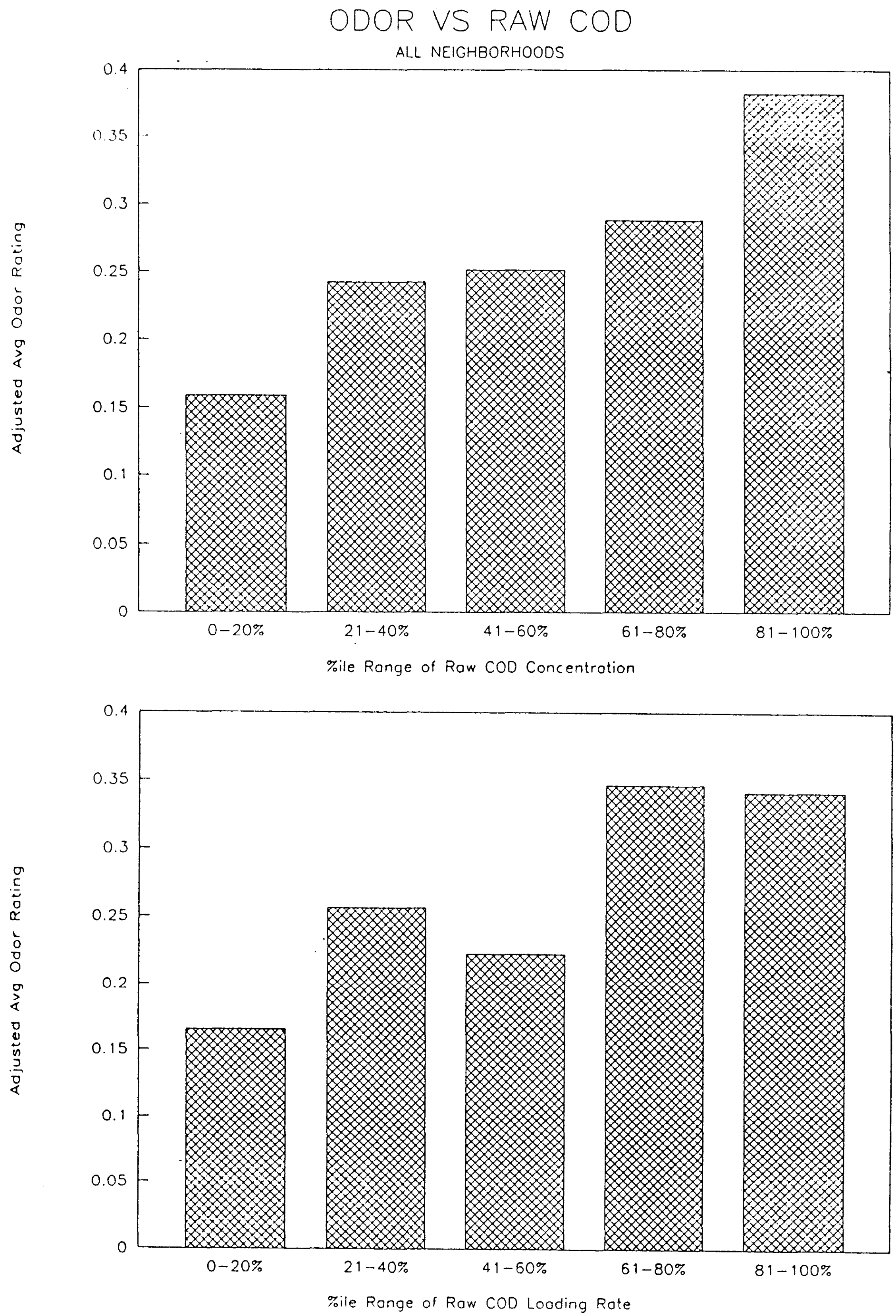

ODOR VS RAW COD
ALL NEIGHBORHOODS
Adjusted Avg Odor Rating
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0-20%
21-40%
41-60%
61-80%
81-100%
%ile Range of Raw COD Concentration
%ile Range of Raw COD Loading Rate

FIGURE 5

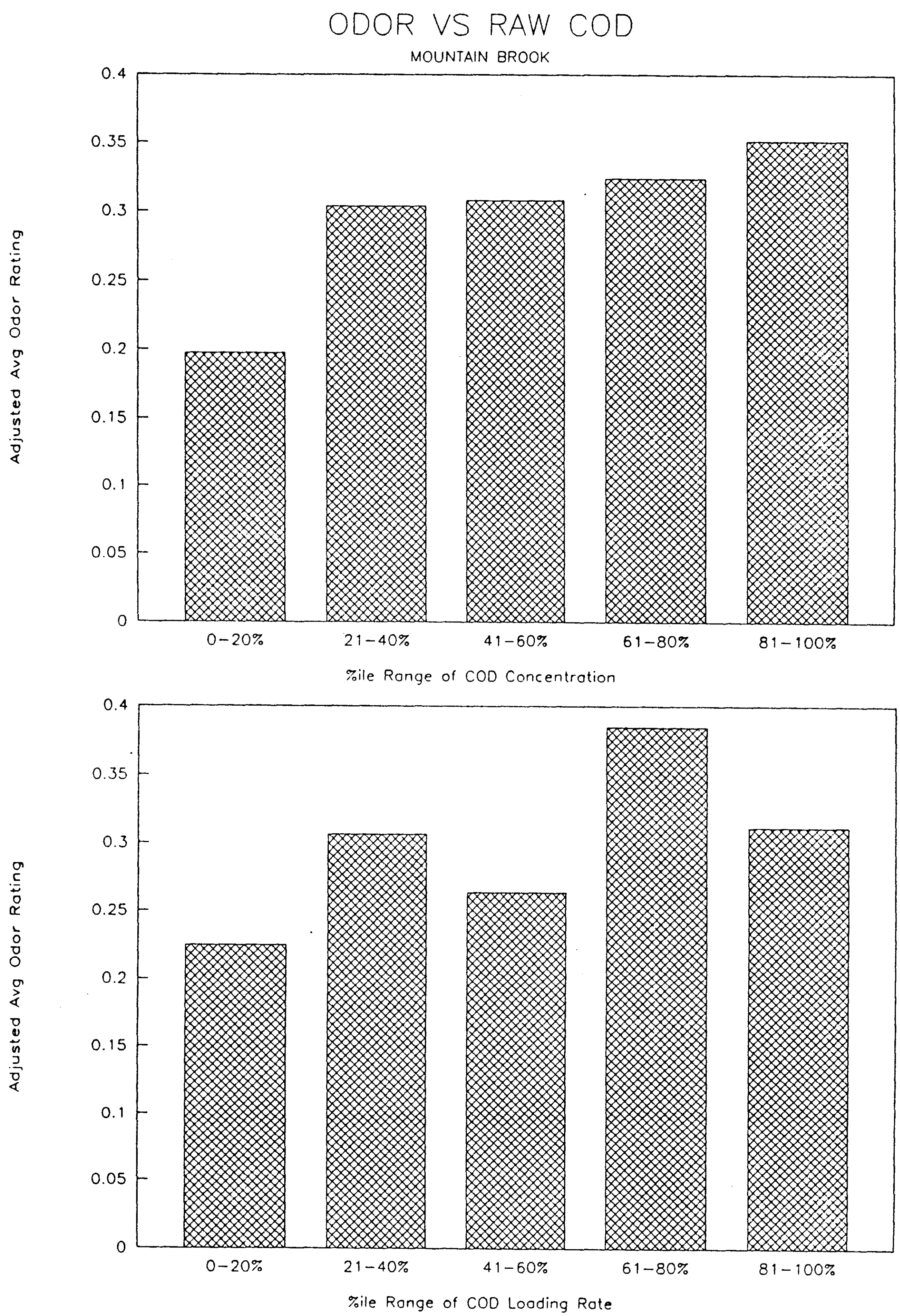

ODOR VS RAW COD
MOUNTAIN BROOK
Adjusted Avg Odor Rating
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0-20%
21-40%
41-60%
61-80%
81-100%
%ile Range of COD Concentration
Adjusted Avg Odor Rating
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0-20%
21-40%
41-60%
61-80%
81-100%
%ile Range of COD Loading Rate

FIGURE 6

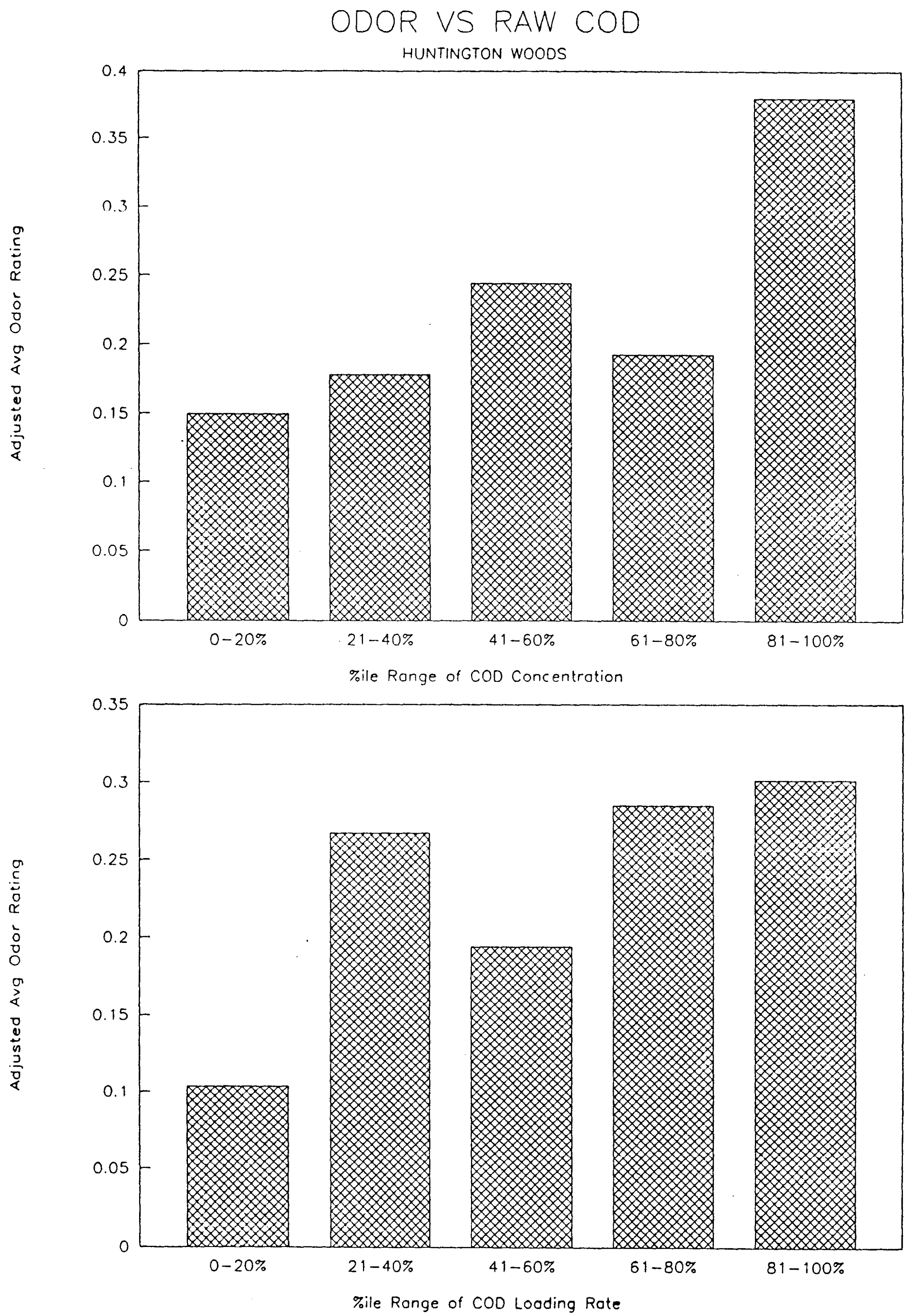

ODOR VS RAW COD
HUNTINGTON WOODS
Adjusted Avg Odor Rating
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0-20%
21-40%
41-60%
61-80%
81-100%
%ile Range of COD Concentration
Adjusted Avg Odor Rating
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0-20%
21-40%
41-60%
61-80%
81-100%
%ile Range of COD Loading Rate

FIGURE 7

actual ranges of values for each percentile interval of COD are provided in Table 8. For combined data from all neighborhoods, there is in general a trend toward increasing odor as raw wastewater strength and load increase. The general trends observed in correlations of odor for all neighborhoods are repeated in correlations for the individual neighborhoods. Similar trends were observed when odor data were grouped by percentile interval of other wastewater characteristics (BOD, trickling filter influent and effluent TOC), which are likely to be highly cross-correlated.

TABLE 8
Ranges of Values for COD Percentile Intervals
Shown in Figures 5 Through 7

Percentile Interval	Range of COD Concentrations, mg/L
0-20%	466 - 767
21-40%	774 - 1,070
41-60%	1,070 - 1,210
61-80%	1,210 - 1,390
81-100%	1,400 - 1,970

The pattern of increasing odor severity as organic strength and loading increase fits the observations that odors correlate strongly to day of week, and that wastewater characteristics also strongly correlate to day of week. However, it would be desirable to isolate any effects of wastewater characteristics from those associated with the changing nature of the waste from weekend to weekday (changes in industrial contributions). Therefore, evaluations similar to those described above were made on waste characteristic data excluding Saturday and Sunday data for this reason. Results for COD are summarized in Table 9. Trends similar to those reported above are still observed even when weekend data are excluded, indicating that there is a relationship between odor and waste strength or loading that is independent of factors related to day of week; the trend is particularly strong for Huntington Woods.

TABLE 9
Relationship of Odor to Raw Waste COD Concentration
Excluding Saturday and Sunday Data

	Adjusted Average Odor Rating for Given Percentile Interval of COD Concentration	
Neighborhood	0-25%	75-100%
All	0.248	0.385
Huntington Woods	0.177	0.391
Mountain Brook	0.318	0.339

Correlation to Waste Strength in Individual Outfalls

Plant records are maintained for COD concentration in each of the three outfalls entering the plant. Correlations were investigated between odor in individual neighborhoods and waste strength (COD concentration) in each outfall. One reason for doing this is that the Salem outfall runs through the Mountain Brook area; a strong correlation between odor in Mountain Brook and COD in the Salem outfall might indicate that part of the odor problem could be attributed to manholes along the sewer system. Correlations to flow or organic loading in the outfalls could not be made because outfall flows are not measured. The odor data for Mountain Brook did not correlate more strongly with COD in the Salem outfall than with the South Fork outfall, nor did they correlate better to the Salem outfall than Huntington Woods data do. There was, therefore, no way to distinguish from these data whether manholes in the Mountain Brook area are leading to at least some of the odor problem.

Correlation to Wind

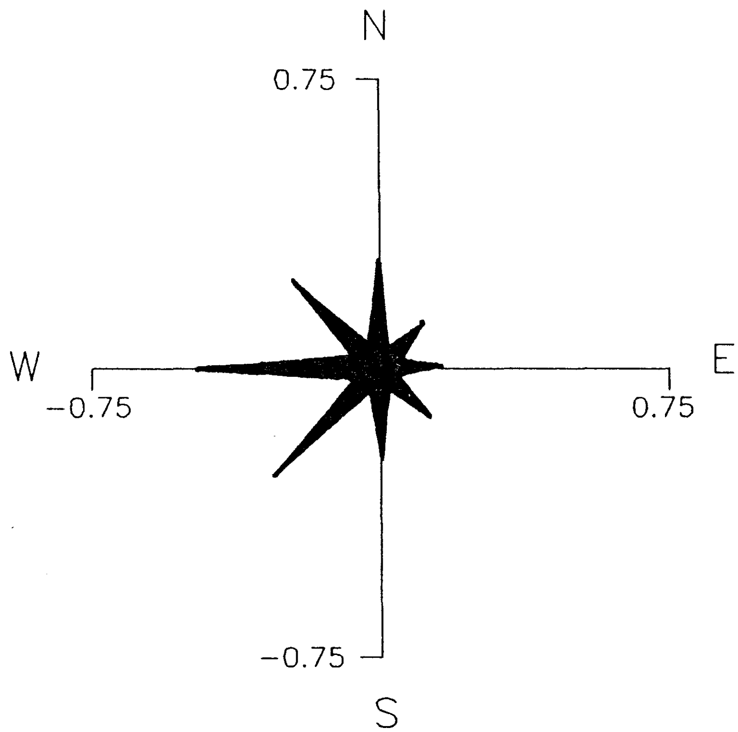
Wind data averaged over 8 hour periods corresponding to the odor evaluation periods were grouped by wind direction, and adjusted average odor data were calculated for each of 8 directions. There were a total of 552 wind direction data (184 days of study times 3 periods per day). Frequency distributions of wind directions are shown in Table 10.

TABLE 10
Frequency Distribution of 8-Hour Average Wind Direction

Direction	Percent of All 8-Hour Average Directions			
(wind from)	AM	Day	PM	Total
N	10.9%	6.5%	5.4%	7.4%
NE	20.1	23.4	16.3	20.1
E	3.8	3.3	8.7	5.1
SE	2.7	3.8	6.5	4.3
S	15.2	7.1	17.4	13.2
SW	21.2	26.6	22.8	23.7
W	12.5	14.7	12.5	13.0
NW	10.3	14.1	10.3	11.8
no wind	3.3	0.5	0	1.3

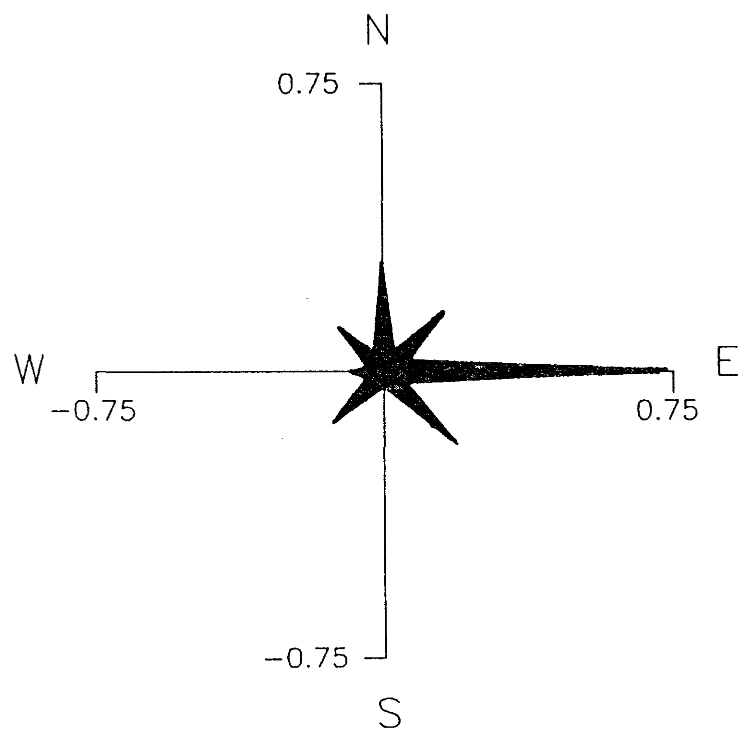
Adjusted average odor ratings by wind direction are shown in Figure 8 for Mountain Brook and in Figure 9 for Huntington Woods. Winds from the southwest and west result in the highest odor ratings by far for Mountain Brook, and winds from the northwest appear to result in relatively high odor as well. The correlation of odor to southwesterly and westerly winds directly implicates the Elledge treatment plant as a major source of odor in Mountain Brook, which is located to the northeast of the treatment plant. Note that winds from the southwest (averaged over 8 hours) account for 24% of all average wind directions recorded for the six month study period (Table 10). This is probably why odors are more consistent over the course of the day and from weekday to weekend in Mountain Brook than in Huntington Woods (compare Figures 4.2 (b) and 4.2 (c)). It also explains why there were substantially fewer odor-free periods in Mountain Brook than in either of the other two neighborhoods (Table 6).

For Huntington Woods, winds from the east are responsible for the most severe odors (Figure 9). Again, this clearly implicates the treatment plant as a major source of odor in



Adjusted Average Odor Rating by Wind Direction, Mountain Brook. Level of significance of difference from overall population mean is 6% for winds from the west and 10% for winds from the southwest.

FIGURE 8



Adjusted Average Odor Rating by Wind Direction, Huntington Woods. Rating for winds from the east is different from overall population mean at 5% level of significance.

FIGURE 9

Huntington Woods. Average odors over periods with no wind (although there were very few of these, as shown in Table 10) also were quite high. Winds from the east only account for 5.1 % of the recorded wind directions, which explains the very high number of time periods over which no odors were detected in Huntington Woods (Table 6). Note, however, from Table 10 that easterly winds are more than twice as frequent in the evening (5 p.m. to 1 a.m.) than they are over the remainder of the day. This fact correlates with the fact that the highest odors are observed in Huntington Woods in the evening (Figure 4 (c)).

Odor also correlates well to wind speed as shown in Table 11; average odor ratings decrease substantially as wind speed increases, most likely as a result of atmospheric mixing and dilution.

TABLE 11
Odor as a Function of Wind Speed

Percentile Interval of Wind Speed	Adjusted Average Odor Rating (all wind directions)	
	Mountain Brook	Huntington Woods
0-20%	0.407	0.261
21-40%	0.295	0.450
41-60%	0.337	0.280
61-80%	0.255	0.131
81-100%	0.193	0.043

Comments Written on Evaluation Forms by Data Collectors

Data collectors were asked to describe odors on the backs of their survey forms. Many of the data collectors did so, but usually only for days on which odors were exceptionally bad. By far the most common descriptions of odor on all survey forms were those characteristic of raw sewage, including terms such as "sewage," "rotten eggs," "sulfide," and "rotting cabbage." The next most common descriptions were those that could be described as fermentation odors, such as "stale beer" or "sweet." Several other descriptions were used infrequently, including "tobacco." None of these descriptions was surprising, since the raw waste entering the Elledge plant contains domestic sewage, fermentation wastes and tobacco wastes. Fermentation type odors were noted in comments from all three study neighborhoods, even though fermentation wastes are present only in the South Fork outfall. Such a result again implicates the treatment plant as a major source of odor in all neighborhoods.

Summary and Discussion of Results from Odor Evaluation

The level of response in neighborhood surveys was sufficiently high for the entire six month period to draw valid conclusions from these data. Response from the Janita Lakes group of data collectors (which was the smallest group), however, was believed to be too low to warrant evaluations on this group individually.

One of the concerns when the survey was planned was that many data collectors might not be home during the day, so that significantly fewer data would be available for this period. Response frequency during the day was 91% of the average frequency for the other two time periods, so that daytime data are believed to be as valid and representative as data for the other periods.

Despite the fact that there were a fairly large number of periods during which odors were not detected at all in a given neighborhood, odors were detected in at least one neighborhood almost all the time. In fact, it can be said that odors were a problem in *only* one neighborhood most of the time (comparing Mountain Brook with Huntington Woods). This is supported by the fact that there is a strong correlation of odor in a particular neighborhood with wind direction, since Mountain Brook and Huntington Woods are on opposite sides of the treatment plant. There were substantially fewer odor-free periods in Mountain Brook compared to the other two neighborhoods. Again, this corresponds to the high frequency of winds from the general direction of the plant.

There was no real indication of a seasonal trend in odors, although much of the study was conducted in warm weather periods. Average odors were lower for the first six weeks of the study (March and the first ten days in April) than for the remainder of the study, although there was considerable variability from mid-April through August. In general, odors were significantly less of a problem in the daytime hours (9 a.m. to 5 p.m.) than either early morning or evening, mostly due to the very low average odor ratings in the daytime for Huntington Woods. Variability in odor over the three time periods was most pronounced for Huntington Woods, and odors were highest in the evening. This corresponds to the much higher frequency of wind from the general direction of the treatment plant during this period.

The general decrease in odor during the day can not be explained at this time. Tests were conducted on combined influent in which average COD concentration and flow were measured in each of six 4-hour periods over a 24 hour sampling period. These tests were conducted on four different days (two during the week and two on Sunday), and in all cases the organic load (kilograms of COD entering the plant over each 4-hour period) was significantly higher from 9 a.m. to 9 p.m. than during the rest of the day. In all cases the COD loading was highest or near the highest from 5 p.m. to 9 p.m.. Since odors generally increased as organic load increased, the low average odor ratings in the daytime are probably due to other factors. These other factors are likely to include atmospheric conditions other than wind, which have not yet been evaluated. Daytime hours are most likely to lead to unstable atmospheric conditions, which would lead to the highest degree of dispersion (Wark and Warner, 1976) and therefore lowest odor impact at sites remote from the treatment plant.

Odors were much more of a problem during the week than on weekends. Again, the variability in odor by day of week was greatest in Huntington Woods, although odors decreased on Saturday and Sunday in Mountain Brook as well. Trends in odor by day of week were the same for each of the three time periods (a.m., day, p.m.). Trends in odor followed trends in waste strength and organic loading by day of week. Organic loads in particular are dramatically lower on weekends than during the week, due to the large decrease in organic concentrations as well as a decrease in flow. Such patterns are indicative of the large fraction of Elledge wastewater derived from industrial sources.

General trends in correlations of odor to wastewater characteristics were the same when Saturday and Sunday data were excluded, although the correlations were somewhat weaker; this might have been a result of the narrower range of values for waste characteristics when weekends were excluded.

Another concern was that odors in Mountain Brook might originate from manholes located along the Salem outfall, which runs through the neighborhood. There was no indication that odor ratings for Mountain Brook correlated better with waste strength in the Salem outfall than with the South Fork outfall, nor was the relationship of odor to waste strength in the Salem outfall any stronger in Mountain Brook than in Huntington Woods. These results do not exclude a possibility that at least part of the odor problem in Mountain

Brook may be due to manholes, but neither do they implicate manholes as a major source of odor.

The strong correlation of odor to wind blowing in a direction from the treatment plant for both Mountain Brook and Huntington Woods is a strong indication that the treatment plant is the major source of odors in both neighborhoods, and probably in Janita Lakes as well. This conclusion is reinforced by descriptions of odors in comments on survey forms. In both Mountain Brook and Huntington Woods, for example, sweet-type odors were detected that would have originated from wastewater in the South Fork outfall, which is not located near either neighborhood.

SOURCES OF ODOR AT THE TREATMENT PLANT

Several major sources of odor were identified after reconnaissance of the treatment plant grounds by the principal investigator on several occasions. These sources include:

(i) pretreatment basins used periodically to treat incoming waste from the South Fork outfall, including the splitter box from which the waste is delivered to the basins;

(ii) preliminary treatment area, including bar screen, grit chamber, and dumpster for grit and screenings;

(iii) primary clarifiers (strongest at the overflow weirs and particularly at the exit from the effluent collection trough);

(iv) the general vicinity of the trickling filters;

(v) the effluent collection trough in the intermediate clarifiers following the trickling filters, especially at the exit structure;

(vi) the waste activated sludge thickener.

Odor Evaluations by Plant Operators

Based on preliminary findings from plant reconnaissance and on the experience of the operational staff, selected sources were identified for daily odor evaluation. Plant personnel completed an odor evaluation form for each source once during each of the three 8 hour periods of interest every day over the entire project period. In addition to the sources listed above, the Salem and South Fork outfalls, the sludge storage lagoons and the secondary clarifiers were inspected. Results are summarized in Tables 12 and 13.

It is apparent that plant operators perceived most sources to emit significant odors. The trickling filters were rated, on average, to have the strongest odors of all the sources (Table 12). It is surprising that the sources ranked second highest were the secondary clarifiers; it appears from inspection of Table 13 that this is a result of the relatively large number of ratings of 3 and a relatively low number of ratings of 1. Average ratings for the South Fork outfall, pretreatment basins and primary clarifiers were similar, which is not surprising.

TABLE 12
Odor Ratings of Individual Sources by Plant Personnel
(in order of decreasing average odor rating)

Source	Adjusted Average Odor Rating[1]
Trickling filters	1.67
Secondary clarifiers	1.26
South Fork outfall	1.25
Pretreatment basins	1.14
Primary clarifiers[2]	1.12
Sludge thickener	1.06
Salem outfall	1.00
Sludge storage lagoons	0.85

1 adjusted average from March 1 through August 30
2 excludes May, for which data were not available

TABLE 13
Frequency Distribution of Odor Ratings for Individual Sources

	Frequency of Given Rating as Percent of all Entries in Operator Odor Logs				
Source	1	2	3	4	5
Trickling filters	2.7%	46.2%	33.9%	16.2%	1.0%
Secondary clarifiers	8.0	67.7	19.9	4.0	0.4
South Fork outfall	4.8	76.1	13.3	3.1	3.1
Pretreatment basins	5.0	78.3	14.2	2.5	0.0
Primary clarifiers	8.7	75.1	12.2	3.8	0.0
Sludge thickener	14.1	69.4	13.5	2.5	0.4
Salem outfall	9.8	82.7	5.4	1.5	0.6
Sludge lagoons	22.1	71.7	5.4	0.8	0.0

Pretreatment Basins

Although the pretreatment basin area was noted by the principal investigator to be a source of high strength odor on several site visits, the basins are not used all the time. Odor ratings would not be expected to be very high on days when the basins were not in use; consequently, average odor ratings for the pretreatment basins may not be indicative of their potential to be major sources of odor. In addition to the basins themselves, there is a strong odor emitted from a splitter box used to distribute wastewater from the South Fork outfall into the basins.

Plant operating records identify the number of hours per day that the pretreatment basins are used (number of hours per day that wastewater from the South Fork outfall is treated in the basins). For the study period, the basins were used on slightly more than half the days. Therefore an evaluation could be made on whether average odors were different on days when the basins were used than when they were not in use. Results from the evaluation are presented in Table 14. Saturday and Sunday data were excluded from the evaluation, thereby eliminating severe variations in raw waste organic strength, loading and flow, to which odors were observed to be well correlated. There was essentially no difference in average plant flow for days in which the basins were in use compared to days in which they were not used. Average raw waste organic concentrations and loads (measured as BOD and COD) were about 20% higher on days in which the basins were used than on days in which they were not in use. Results shown in Table 14 therefore are not believed to be influenced significantly by correlations of odor to organic strength or load. The average odor rating is significantly higher in all neighborhoods when the pretreatment basins are in use.

TABLE 14
Odor as a Function of Pretreatment Basin Use
(Weekends Excluded)

	Adjusted Average Odor	
Neighborhood	In Use	Not in Use
All	0.340	0.251
Mountain Brook	0.371	0.267
Huntington Woods	0.324	0.214

Odors are emitted from the pretreatment basins as a result of surface aeration, in which liquid in the basins is sprayed into the air. The spraying action allows oxygen to be transferred to the liquid, which is necessary for the aerobic biological activity in the basins. At the same time, however, any volatile chemicals in the liquid are transferred to the atmosphere. Hydrogen sulfide has been measured at high concentrations along the South Fork outfall, and this sewer line also carries fermentation wastes that would be expected to contain some of the odor-causing organic chemicals (these organic chemicals are responsible for the "sweet" or "stale-beer" smells detected occasionally in neighborhoods and near the pretreatment basins).

Trickling Filters

The trickling filters also can emit a substantial amount of odor causing substances, in either of two ways. Wastewater is distributed over the surface of the trickling filters by rotating distributor arms. Each arm is a pipe or channel containing a series of holes along its length, from which wastewater flowing along the pipe is ejected. The spraying action of the wastewater from the distributor arms, and its subsequent splashing on the rocks at the top of the filter, create conditions for release of volatile chemicals to the atmosphere. Another way in which trickling filters can contribute to odors is by allowing odor causing conditions to exist within the filter itself. When organic concentrations or loads to a filter are too high, oxygen is rapidly depleted in the wastewater and anaerobic conditions result; these conditions lead to odor generation.

It is difficult to estimate the relative contribution of each mechanism to odor emissions from the trickling filters. However, several pieces of information indicate that organic overloading may be the major cause of odor from the trickling filters. First, plant operators indicate that extremely bad odors emanate from the filters within several hours after they are shut down (which is done infrequently for maintenance); obviously, in such cases these odors are derived from within the filters themselves. Second, as presented and discussed above, there is a general correlation of organic strength and load to odors detected in neighborhoods. Third, organic removals (measured as TOC) across the trickling filters are, on average, less than 40% of the applied load. Filters of this type should be able to remove a higher fraction of the applied load at lower loading rates.

To confirm organic overloading in the filters, actual dissolved oxygen concentrations in filter effluent was measured twice a day for over two weeks. Results are shown in Table 15.

TABLE 15
Dissolved Oxygen Concentrations in Trickling Filter Effluent[1]

Item	4 AM #1	4 AM #4	4 PM #1	4 PM #4
mean dissolved oxygen, mg/L	1.05	0.93	0.72	0.59
standard deviation, mg/L	1.21	1.00	1.01	0.94
% values less than 0.3 mg/L	54%	42%	67%	73%

[1] Data collected at 4 a.m. and 4 p.m. on 15 days from August 5 through August 22, 1989. Trickling filters are arranged in series, so that #4 is downstream of #1.

It is apparent that the trickling filters are operating with limited oxygen much of the time, particularly in the afternoon (which corresponds to periods of higher loading). Dissolved oxygen concentrations less than 0.5 mg/L are commonly acknowledged to represent severe oxygen limitation in aerobic biological systems. The high standard deviation of dissolved oxygen concentrations (relative to the average) is indicative of the wide variability in the data; values as high as 3.8 were recorded. Nevertheless, oxygen depletion within the filters appears to be a frequent problem.

Other Sources

Odors from the remaining sources generally derive from turbulence at exit structures in effluent collection troughs (primary clarifiers, intermediate clarifiers, secondary clarifiers, thickener).

CONCLUSIONS AND RECOMMENDATIONS

Specific conclusions and recommendations relative to the odor problem at the Elledge wastewater treatment plant were presented to the City of Winston-Salem in January, 1990 (Aitken and Okun, 1990). These recommendations and subsequent actions taken by the City focus on reducing odor releases in the pretreatment basins and the trickling filters. The following conclusions relate to the efficacy of methods used in this project to evaluate the odor problem.

Use of the odor evaluation form was an effective and inexpensive means of quantifying odors in affected neighborhoods. In general, there was very good agreement among neighbors with respect to odor ratings, particularly in the absence of odors. Respondents also exhibited a reasonable ability to distinguish among different degrees of odor. A ranking scale beginning with zero would be more intuitive and may be more compatible with spreadsheet graphics output, although it is important during data analysis that zeroes be distinguishable from blank entries (for example, in some spreadsheet programs, arithmetic formulas that use an entry from a blank cell interpret the blank as a zero).

The amount of information made available through the odor evaluation forms was sufficient to allow observation of trends that would have been difficult to perceive otherwise. We hope to couple the odor evaluation data to an atmospheric dispersion model for use in predicting odor impacts in potentially new residential developments, and for estimating decreases in source strength that would be necessary for negligible impact in currently affected neighborhoods.

Analysis of the odor data identified the wastewater treatment plant as the major source of odors in affected neighborhoods, which city personnel were not convinced of at the start of the project. Data analysis also revealed that odors are strongly correlated to waste strength, leading at least partially to identifying causes of odor at the treatment plant. Other activities undertaken in conjunction with the neighborhood odor evaluation gave a better picture of specific major sources of odor.

With a better understanding of sources of odor, well-directed methods to reduce odor emissions could be conceived and implemented. The city began implementing control strategies before the study was complete and has since initiated several other projects to control odors further. Measures initiated by the city include reducing the organic loading to the trickling filters, reducing the concentration of hydrogen sulfide in the outfall carrying the highest strength wastewater, and pre-stripping and scrubbing odorous substances from the influent wastewater before it is sent to the pretreatment basins. Detailed discussion of specific odor control strategies is beyond the scope of this report.

Participation in the evaluation allowed residents to become involved in the solution process, thereby reducing tension and creating a more cooperative atmosphere. It was important, however, for the City to convey that the evaluation was not a delaying tactic and that information obtained from the evaluation would be used to arrive at a rational solution. The Advisory Board also served as a useful forum in which specific concerns of residents could be discussed.

It is important for future studies of this type that a sufficient number of data collectors be recruited from at least two concentrated areas in different directions from the treatment plant or other suspected source of odor. Depending on the attrition rate, if too few residents are selected there may not be enough reliable data collectors remaining by the end of the study, making data interpretation difficult. Also, odor data collection should be coordinated with the collection of other data (e.g., from wastewater sampling) to facilitate correlations among the data sets.

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