EVALUTION OF THE STORMWATER TREATMENT FACILITIES AT THE LAKE ANGEL DETENTION POND ORANGE COUNTY, FLORIDA

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16. Abstract

This is the final report on the use of Granulated Active Carbon (GAC) beds of Filtrasorb 400 in series to reduce the Trihalomethane Formation Potential (THMFP) concentrations at the Lake Angel detention pond, Orange County, Florida. The detention pond accepts runoff from an interstate highway and a commercial area. Breakthrough time was estimated from laboratory analyses and used to design two beds in series at the detention pond. Breakthrough occurred in the first bed after treating 138,000 liters of water. Exhaustion of the first bed was reached after treating 1270 bed volumes with a sorption zone length of 1.70 feet. The TOC adsorbed per gram of GAC was 6.3 mg. The liquid flow rate averaged 0.0011 cfs. Similar breakthrough curves for Total Organic Carbon (TOC) and color were also reported. The used GAC can be disposed of by substituting it for sand in concrete mixes.

An economic evaluation of the GAC system at Lake Angel demonstrated an annual cost of $4.39/1000 gallons to treat the stormwater runoff after detention and before discharge into a drainage well. This cost could be further reduced by using the stormwater to irrigate right-of-way sections of the watershed. An alternative method of pumping to another drainage basin was estimated to be more expensive.

The underdrain network for the GAC system initially became clogged with the iron- and sulfur-precipitating bacteria *Leptothrix*, *Gallionella* and *Thiothrix*. These bacteria were substantially reduced by altering the influent GAC system pipeline to take water directly from the lake. An alternate pipe system used a clay layer to reduce ground water inputs and did not exhibit substantial bacterial growth.

Environment
Granular Activated Carbon
Detention Pond
Best Management Practices
Underdrains
Highway Runoff

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ABBREVIATIONS AND CONVERSION FACTORS

[Factors for converting inch-pound units to International System of units (SI) and abbreviation of units]

Multiply	By	To Obtain
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
acre	0.4047	hectare (ha)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
square foot (ft^2)	0.09290	square meter (m^2)
pound (lb)	0.4536	kilogram (kg)
cubic foot (ft^3)	0.02832	cubic meter (m^3)

NOTICE

The opinions, findings, and conclusions expressed in this publication are those of the autors and not necessarily those of the Department of Transportation or the U.S. Department of Transportation.

The report was Prepared in cooperation with the State of Florida Department of Transportation and The U.S. Department of Transportation.

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EXECUTIVE SUMMARY

The Problem

Drainage wells were constructed in many parts of Florida to eliminate flooding problems associated with excess runoff waters. The wells were economical solutions to an otherwise costly transportation and disposal problem. Since 1905 when the first well was constructed in central Florida, a total of 413 were constructed up until 1970 when the State Board of Health stopped granting permits for new construction. Across the State of Florida, there are over 1000 drainage wells. Unfortunately, no one predicted that a water quality problem could result from the drainage well practice. Now, continual use of any drainage well must meet State requirements for drinking water quality standards.

The subject for investigation of this report is a 3.2 Acre detention pond with a drainage well located in central Florida that receives runoff water from an 130 Acre interstate highway and commercial area. The outlet from the pond is a drainage well whose depth is about 200 feet below the surface and into an aquifer that is the source of drinking water. Drinking water standards established by State and Federal regulations are related to stormwater quality measures. The measure of primary concern in this report is Trihalomethane Formation Potential.

A Possible Solution

One of the treatment methods to remove suspect cancer causing agents is granular activated carbon (GAC). However, no tests have been conducted outside of a laboratory to determine the technical and economic feasibility for the treatment of detained stormwater to remove the precursors that form suspect cancer causing agents. The authors of this report proposed to pass detained stormwater through a GAC bed before entering the drainage well. Filtrasorb 400 was the GAC used and recommended in the literature for similar applications. A horizontal gravity bed of GAC was used to minimize the operational problems and cost of a pressurized bed. Detained stormwater in the pond was passed through a pond bank underdrain that flowed into the gravity bed. Trihalomethane Formation Potential (THMFP) was used as the indicator measure for suspect cancer causing agents. However, the tests are expensive and time consuming. Thus, other indicating parameters may be useful, such as color and organic carbon measures.

Results and Findings

Color, Total Organic Carbon (TOC), and Trihalomethane Formation Potential (THMFP) reached breakthrough in the GAC beds at the Lake Angel Detention Pond. Excellent correlations between color, TOC, and THMFP were obtained. Correlation coefficients for THMFP and TOC, TOC and color, and THMFP and color were 84% 89% and 89%, respectively. Therefore, color and TOC are useful surrogate parameters for THMFP before and after the GAC filter beds at the Lake Angel stormwater detention pond.

Breakthrough occurred after 900 bed volumes and 138,000 liters of water. Exhaustion of the first carbon bed was reached after 1270 bed volumes and 185,000 liters of water. The length of the sorption zone was calculated to be 1.70 feet. Approximately 6.3 mg of TOC was adsorbed per gram of carbon. Long empty bed contact times of the carbon beds were indicative of the small quantities of water treated before the carbon required replacement.

Bacteria such as Leptothrix, Gallionella, and Thiothrix initially grew in the underdrain and the GAC bed due to elevated iron/manganese concentrations in the ground water. These bacteria created sheaths which sloughed off, partially clogged the influent pipe, and reduced the permeability of the carbon. This was remedied by prohibiting groundwater from entering the system and taking the water directly from the pond to the GAC bed. The GAC did not clog from bacterial agglomeration after this alteration.

The GAC system to treat all detained stormwater was found to be expensive. An annual cost of $316,000 would be required to treat THMFP precursors if a gravity flow horizontal bed is used. This is an annual cost of $4.39/1000 gallons to treat all the stormwater runoff after detention and before discharge into the drainage well.

However, the cost of treatment can be significantly reduced by irrigating part of the detained stormwater within the highway right-of-way and other parts of the watershed. About 16 Acres of land were assumed available for irrigation near the detention pond. The cost of irrigation is only about $0.15 to $0.25/1000 gallons. Most likely, the storage volume of the detention pond would have to be made larger to accommodate an irrigation plan that would reduce significantly the average yearly discharge to the drainage well.

An alternative which would involve the placement of a 24" pipe to Shingle Creek (5 miles away) was calculated to be more expensive and would not improve water quality. In addition, a permit for such construction may be denied.

Another alternative is the use of the sanitary sewer system in the adjacent area. The cost of waste water treatment may be as low as $2.00/1000 gallons. However, use of the sanitary sewer system would not be feasible because the sewer is near capacity and a significant pump station with increased storage would be necessary. A complete feasibility study for use of the sanitary sewer system would involve a treatment feasibility study and a cost analysis for enlarging the detention pond versus an enlarged sewer system. It is doubtful that the sewer system can take another 72 million gallons per year in approximately 10 percent of the time. An enlarged detention or on-line holding pond would be needed.

Recommendations

GAC can be used to remove THMFP precursors from detained stormwater at the study site. The disposal of the used GAC by substituting GAC for sand in concrete is possible. The strength of the concrete can be maintained at 3000 psi or greater.

Groundwater entering underdrains should be minimized. The construction of underdrains in high groundwater areas should be done so that the ponded water is separated from the groundwater. If this is not possible, the groundwater should be tested for iron and manganese or the formation of bacteria.

The dependency on and the cost of GAC as the only method for stormwater control can be reduced by using an irrigation system in the watershed. The irrigation system can reduce the cost of treatment and should be considered for future implementation. Additional area for irrigation should be found near the site. Recent State-wide stormwater reuse reports (Wanielista, et.al., 1991) can be used to aid in sizing the ponds and irrigation requirements.

CHAPTER I

INTRODUCTION

Drinking Water Regulations

In 1972, an Environmental Protection Agency (EPA) report identified potential toxic substances from public water supplies which used the Mississippi River as a drinking water source. This disclosure prompted a subsequent EPA study which discovered more than 82 organic compounds in New Orleans' potable water supply (Duke et al., 1980).

The purpose of the National Organics Reconnaissance Survey (NORS) of 1974 was to discover the extent to which organics were present in potable water systems nationwide. The survey sampled for the existence of four major trihalomethanes (THMs), carbon tetrachloride and 1,2-dichloroethane. THMs included chloroform ($CHCl_3$), bromoform ($CHBr_3$), bromodichloromethane ($CHBrCl_2$), and dibromochloromethane ($CHBr_2Cl$). The results from more than 80 treatment facilities confirmed the presence of widespread THM concentrations in treated waters and their formation by chlorination.

Consequently, the EPA conducted the National Organics Monitoring Survey (NOMS) to determine the frequency of 19 specific contaminants in drinking waters and for restrictions in regard to maximum contaminant levels (MCL) for organic compounds. The NOMS data showed that THMs had the highest concentrations of the sampled parameters and were produced by the chlorination of precursors such as humic acids and algae.

In 1976, the National Cancer Institute released results of a study which demonstrated chloroform produced cancer in mice and rats under laboratory conditions. The Cancer Institute supported previous studies of NORS and NOMS by stating organic compounds (Symons, 1978)"present a potential risk of cancer that should be reduced to the extent feasible."

The Safe Drinking Water Act (PL 93-523) and the courts have determined the EPA should regulate THM contamination due to their potential adverse health effects in lieu of absolute proof. A House report stated (Symons, 1978):

> "The committee did not intend to require conclusive proof that the contaminant will cause adverse health effects as a condition for regulation of a suspect contaminant. Rather, all that is required is that the Administrator make a reasoned and plausible judgement that a contaminant may have such an effect."

In 1979, an amendment to the National Interim Primary Drinking Water Regulations established the maximum contaminant level (MCL) of THMs at 100 $\mu g/l$. These regulations apply to systems serving 75,000 or more persons (Cotruvo and Wu, 1978).

Since the establishment of the MCL, consideration has been given to lowering the 100 $\mu g/l$ standard. Studies conducted by the World Health Organization recommend a guideline value of 30 $\mu g/l$ for chloroform (World Health Organization, 1984).

Stormwater Ponds

Stormwater ponds and lakes affected by stormwater runoff may have high potential for the formation of THMs partly as a result of organics in the stormwater. Oils and greases in runoff from six highways in the United States were reported to have an average concentration of 10 mg/l with a maximum value of 104 mg/l (Gupta et al., 1981). In the National Urban Runoff Program, Cole et al. (1984) reported eleven organic compounds were detected in at least 10 percent of the urban runoff samples. Documentation of THMs and the THM precursor formation potential of lakes and ponds receiving stormwater has not been completed.

Lake Angel is a 3.2 acre detention pond in Orange County, Florida (see Figure 1). It is situated between Interstate-4 on the east, Parramore Avenue on the west, and Harding Avenue on the north. The lake was originally a small marsh but later enlarged during the construction of Interstate 4. The maximum depth of the lake is twelve feet. The 130 acre drainage basin is predominantly commercial, industrial, and interstate right-of-way.

A twenty-inch Class V recharge well to the Floridan Aquifer was constructed in 1970 to accept stormwater runoff. The well replaced a previously existing 20-inch well that was damaged due to sink formation. It is located approximately twenty feet from the northeast edge of the lake (McBee, 1985).

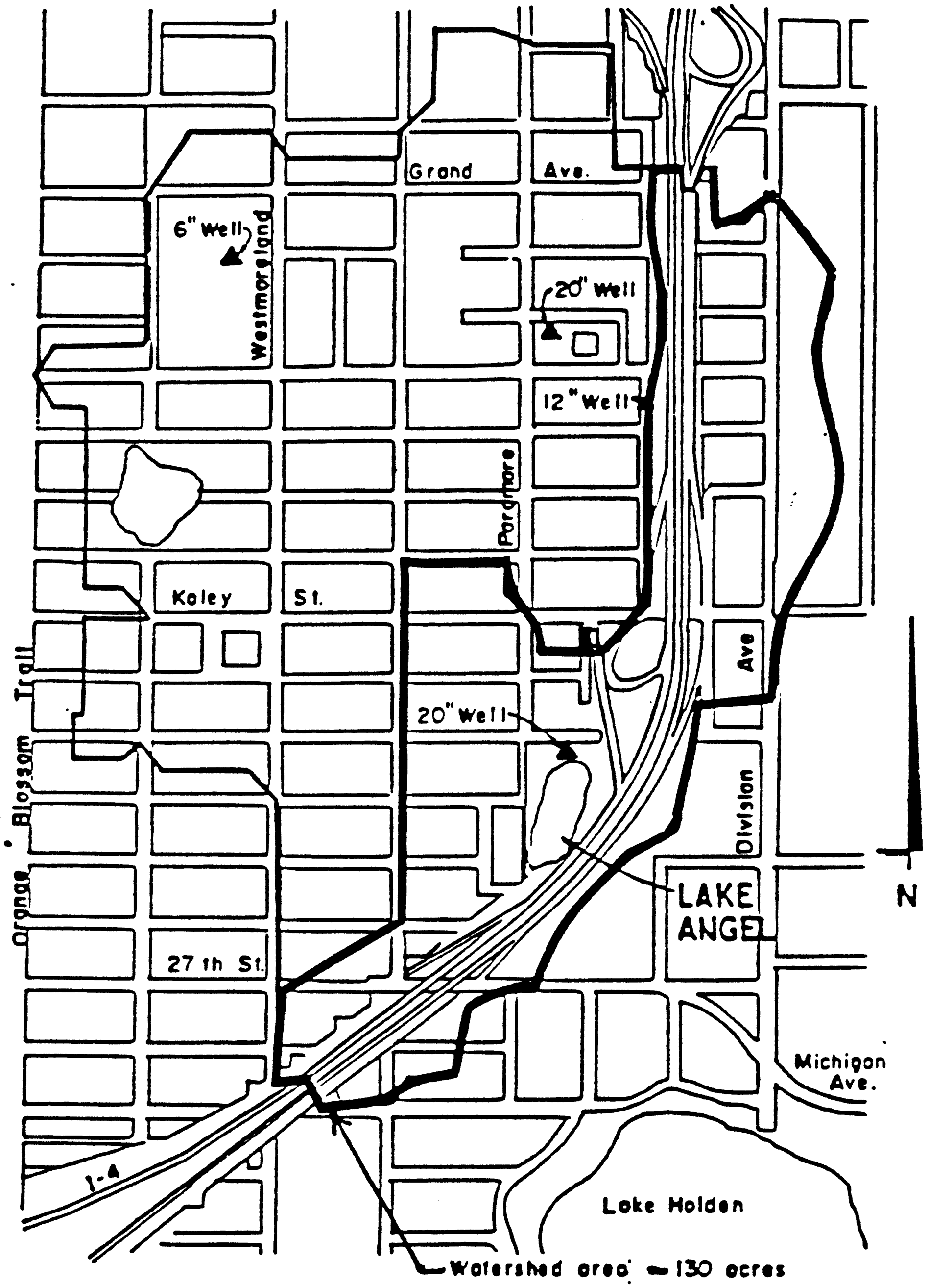


Figure 1. Watershed of the Lake Angel Detention Pond.

SOURCE: McBee (1985)

Pursuant to Chapter 17-28 of the Florida Administrative Code (FAC), influent waters to Class V wells must "not exceed current drinking water standards in Chapter 17-22, FAC." Preliminary analysis of surface water constituents from Lake Angel indicated Trihalomethane Formation Potential (THMFP) concentrations exceeded the MCL for THMs. According to Symons (1975), Granulated Active Carbon (GAC) is the "best broad spectrum adsorbent for the removal of organic compounds from drinking water."

Objectives

The objectives of this study are to determine: (1) whether color and total organic carbon (TOC) measured as nonpurgeable organic carbon (NPOC) may be used as surrogate parameters for THMFP at the Lake Angel pond; (2) adsorption characteristics of THMFP using two horizontal flow beds of GAC in series with a flow rate consistent with the natural horizontal permeability of the GAC; (3) hydraulic efficiency of the existing GAC system; (4) economic consideration of the existing GAC system and possible alternatives; (5) specific bacterial growth which exists in underground perforated pipes with the quantity of water that these underdrains release; and (6) feasibility for disposing used GAC in concrete mixtures.

The first objective included the evaluation of color and NPOC as possible surrogate parameters for THMFP at the Lake Angel site. Surrogate parameters for THMs are often used because THM analyses are expensive and time-consuming. As a general rule, surrogates are accurate and easily measurable. Since color and TOC may be measured easily within a short time period at a relatively inexpensive cost, they would make excellent surrogates for THMFP.

The second objective involved an evaluation of the time and amount of GAC required to reduce TOC and THMFP concentrations prior to breakthrough and exhaustion of the first bed.

The third objective evaluated the hydraulic efficiency of GAC by comparing calculated residence times (EBCT) with tracer studies (measured residence times) using sodium chloride.

The fourth objective involved a cost evaluation of the GAC bed configuration used in this study and possible alternatives which included (1) piping the stormwater to another watershed for discharge and (2) utilizing the detained stormwater for drip irrigation of the interstate right-of-way.

The fifth objective involved the identification of bacteria found growing within both the GAC chamber and the underground water collection pipes. The respective environments and nutritional needs of the bacteria were investigated. The flow rates from two underdrain systems were documented also.

The sixth and last objective involved the use of used GAC as a substitute for sand in a concrete mixture. Success was determined by the strength of the resulting concrete cylinders.

CHAPTER II

LITERATURE REVIEW

Adsorption

Adsorption is the "collection of a substance (adsorbate) onto the surface of the adsorbent solids" (Reynolds, 1982). Adsorption is a result of molecules within the adsorbent subjected to equal forces in all directions as opposed to surface molecules being subjected to unbalanced forces - creating a disparity which may be overcome by extraneous molecules becoming attached to the surface (Faust and Aly, 1987).

Adsorption may occur by either physical or chemical processes. Physical adsorption is primarily due to weak van der Waals forces which occur by instantaneous increased concentration of the electron cloud on one side of the molecule. This creates a dipole moment between the molecules. Physical adsorption is a low temperature, reversible process since electrons are not shared or transferred between molecules. In addition, physical adsorption is not site-specific since it allows for the adsorbate to cover the entire surface of the adsorbent. Chemical adsorption involves chemical bonding created by the transferring and sharing of electrons.

High temperatures originate from large interaction potentials and create a much stronger bond than that of physical adsorption (Faust and Aly, 1987).

Adsorption Processes

The first step of the adsorption process involves the transport of the adsorbate from the bulk solution to the outer surface of the adsorbent particle by diffusion (Figure 2). External, or film diffusion, includes the resistance to the transfer of the particle at the surface. The mass transfer of the adsorbate is proportional to the free liquid diffusivity of the solute and inversely proportional to the thickness of the diffusion layer. The driving force of film diffusion is the concentration gradiant of the adsorbate.

The second step entails the transfer of the adsorbate into the interior sites of the adsorbent by diffusion through the pore-liquid film and migration along the sites. This is called internal diffusion.

The third step involves the movement of the solute into active adsorption sites and their subsequent binding to the micropores within the interior of the particle. The rate of transfer is governed by the slower of either the film or internal diffusion steps (Faust and Aly, 1987).

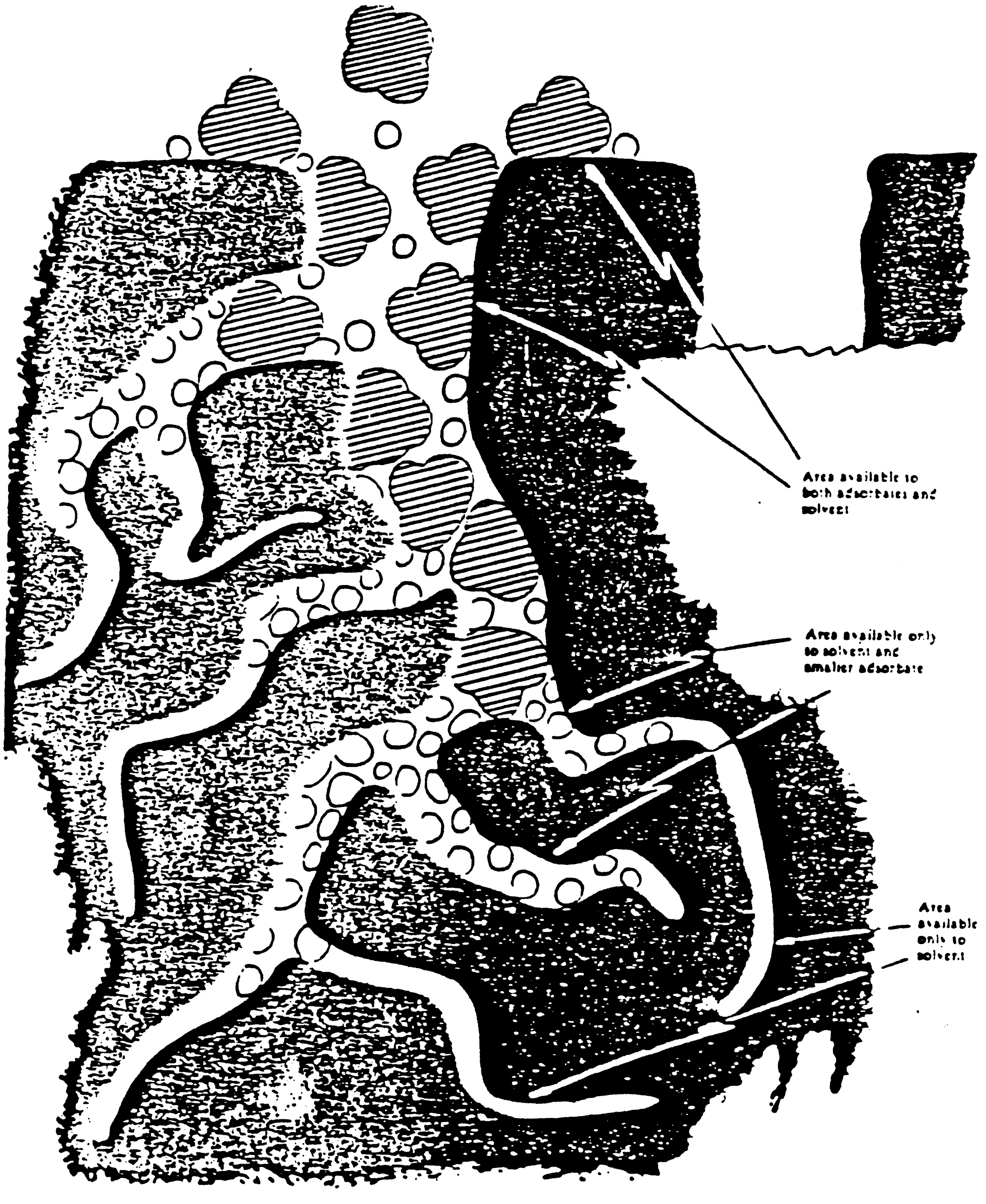


Figure 2. Concept of Molecular Screening in Micropores.
SOURCE: Calgon Corporation

Factors Affecting Adsorption

Six factors influence the rate of adsorption. They include: (1) pH; (2) temperature; (3) concentration of the adsorbate; (4) molecular weight and configuration of the adsorbate; (5) carbon particle size; (6) empty bed contact time (EBCT); (7) pre-treatment; and (8) addition of salts.

McCreary and Snoeyink (1979) conducted adsorption tests from humic acids in Michigan using PAC WV-6 over a seven day period at room temperature. They found increased adsorption with decreasing pH due to association of oxygen-containing functional groups. Decreasing the pH may neutralize negative charges at the surface of the carbon (Weber, 1972).

Temperature affects the rate of reaction as expressed in terms by the activation energy of Arrhenius' equation:

$$Ln\frac{K_1}{K_2}=E_a\frac{T_1-T_2}{RT_1T_2} \tag{1}$$

where K_1, K_2 = adsorption rates at temperatures T_1, T_2
R = ideal gas law constant
Ea = activation energy.

Due to changes in enthalpy, adsorption reactions are usually exothermic and similar in magnitude to those for condensation or crystallization. Therefore, small temperature changes have little effect on adsorption capacity (Faust and Aly, 1987).

However, Weber and Morris (1963) noted that a significant temperature increase from 10 to 30°C increased the removal rate of phenol by 21% and 2,4- DCP by 28 percent.

Adsorption increases with increasing concentrations of the adsorbate. Zogorski et al. (1976) changed the initial influent concentration of 2,4-DCP and cyanonitrile from 37.4 to 346 mmole/ liter and observed an increase in the removal rate from 82 to 712 umole/g/hr.

Low molecular weight molecules within a particular chemical series have a greater affinity for adsorption since they are able to penetrate the micropores of the carbon (Weber and Morris, 1963). Rook (1983) evaluated six types of activated carbon in the Kralingen Plant of Rotterdam and observed highest adsorption of low MW compounds and poor removal of high molecular weight materials.

Weber and Morris (1963) observed increasing slower rates of adsorption with a longer aliphatic-chained molecules (2-hexyl)-, (2-octyl)-, (2-decyl-)-, (2-dodecyl-), and (2-tetradecyl)-benzene-sulfonate. Increasing the chain length of the aliphatics probably resulted in a decrease of their solubility. These studies affirm Traube's Law which states "properties of molecules in a homologous series that have hydrophobic and hydrophilic components tend to change regularly with chain length" (Faust and Aly, 1987). Other factors of molecular structure on adsorption may be seen in Table 1.

Weber and Morris (1963) observed the adsorption of 3-dodecylbenzenesulfonate at 25°C by diverse particle sizes of Columbia LC carbon. They concluded radial intraparticle diffusion was a function of the inverse square of the particle diameter since the rate was limited by film diffusion. The study also noted the position of alkyl chains on the benzene ring affected the molecule's ability to diffuse through the carbon's micropores. Pulverization of GAC greatly decreased the time required for maximum adsorption in isotherm studies (Randtke and Snoeyink, 1983).

Increasing the EBCT allows for the adsorbent particles to affix themselves to the surface of the adsorbate with less elution. EBCT is calculated by dividing the volume occupied by the mass of adsorbate in contact with the adsorbent by the volumetric flow rate. Lower flow rates reduce shear forces which could detach the adsorbate from the adsorbent.

Symons (1978) studied three water treatment plants and demonstrated that removal of THMFP by activated carbon was variable and site-specific. Longer EBCT and lower THMFP concentrations increased the service life of the carbon bed. This may be due to elution of the organic particles or the large size of the organic molecules that could not be adsorbed into either the micro- or macropores of the carbon.

TABLE 1

INFLUENCE OF MOLECULAR STRUCTURE AND OTHER FACTORS ON ADSORBABILITY OF ORGANICS BY ACTIVATED CARBON.

1. Increasing solubility decreases its adsorbability.
2. Branched chains are usually more adsorbable than straight chain compounds.
3. Substituent groups affect adsorbability:

Substituent Group	Effect
Hydroxyl	Generally reduces adsorbability depending on structure.
Amino	Similar to that of hydroxyl but somewhat greater. Many amino acids are not adsorbed to any appreciable extent.
Carbonyl	Varies with molecule; glyoxylic acids are more adsorbable than acetic acid, but a similar increase does not occur when higher-molecular-weight fatty acids are introduced.
Double Bonds	Variable as with carbonyl.
Hologens	Variable.
Sulfonic	Usually decreases adsorbability.
Nitro	Often increases adsorbability.
Aromatic rings	Greatly increases adsorbability.

4. Generally, strongly ionized solutes are not as adsorbable as weakly ionized solutes; that is, undissociated molecules are in general preferentially adsorbed.
5. The extent of adsorption depends on the ability of hydrolysis to form an adsorbable acid or base.
6. Unless the screening action of the carbon pores intervene, large molecules are more sorbable than small molecules of similar chemical nature. This is attributed to more solute carbon chemical bonds being formed, making desorption more difficult.
7. Molecules with low polarity are more sorbable than highly polar solutes.

SOURCE: REIMERS (1980)

Occurrences of organic breakthrough immediately after placement of the carbon bed are widespread in literature (Symons, 1981), (Faust and Aly, 1987).

Additional pre-treatment methods will also increase the efficiency of adsorption. These include the pretreatment of water by coagulation and the addition of calcium and magnesium salts (Faust and Aly, 1987).

In summary, several factors may affect adsorption of organics onto the GAC. They include pH, temperature, concentration of the adsorbate, molecular weight and configuration of the adsorbate, carbon particle size, pretreatment, and the addition of salts. Therefore, the adsorption rates at the Lake Angel facility will be a function of these factors.

Activated Carbon

Activated carbon is a common adsorbent used at water treatment facilities to attenuate objectional taste, odor, or color. Carbon may be found in two different forms depending upon the size of the carbon particles-powdered (PAC) and granulated (GAC). PAC is often used once and then discarded whereas GAC may be reactivated by thermal expulsion of organics on the adsorbent in a furnace. However, financial and practical constraints in regard to the distance of the nearest regeneration facility often result in the GAC being discarded (Culp et al., 1987).

Granular activated carbon used in this study was Calgon F-400. A list of its physical properties is given in Table 2.

Operation of the activated carbon process involves the passage of influent water through a series of carbon beds whereupon adsorbate particles become diffused onto the adsorbent. Breakthrough occurs when the effluent concentration of the adsorbent rapidly approaches the influent concentration. Theoretically, the effluent and influent concentrations should coincide after the carbon bed has been exhausted. However, the effluent usually reaches a steady-state value lower than the influent due to biological activity or slow mass transfer of the adsorbate into the micropores of the activated carbon. The carbon bed is then taken off-line, replaced with new carbon, and placed back into operation (Faust and Aly, 1987).

Mathematical Models Using GAC

The quantity of carbon necessary to remove a certain mass of adsorbent may be estimated from batch studies. By this method the solution is analyzed to determine the initial concentration (C_0) of the adsorbate. Different amounts of pulverized GAC (m) are placed in containers along with a specific, filtered volume of liquid which contains the adsorbate. The solution is stirred or shaken for a period of time to allow the samples to reach equilibrium. Samples are taken until a continuous minimum concentration (C_e) has been

TABLE 2

Calgon F-400 GAC PHYSICAL PROPERTIES

Parameter	Value
Total Surface Area, sq. meters/g	900 -1100
Bulk Density, lbs/cu. ft.	27
Particle Density Wetted in Water, g/cc	1.3-1.4
Effective Size, mm	0.55 - 0.75
Uniformity Coefficient (Max)	1.9
Pore Volume, cc/g	0.85 - 0.95
U.S. Standard Series Sieve Sizes	
Larger than No. 8 - Max. percent	---
Larger than No. 12 - Max. percent	5
Smaller than No. 30 - Max. percent	---
Smaller than No. 40 - Max. percent	4
Iodine Number, minimum	1000
Abrasion Number, minimum	75
Moisture as Packed - Max. percent	2.0

SOURCE: Calgon Corporation

achieved in each of the containers. The ratio of the mass of solute adsorbed to the mass of adsorbent is then defined as a function of adsorbate concentration. This relationship is referred to as an isotherm; two common empirical forms are the Langmuir and Freundlich isotherms.

The Freundlich isotherm is an empirical formulation which is used to fit experimental data. It is given by the formula

$$\log\left(\frac{x}{m}\right)=\log(K)+\left(\frac{1}{n}\right)\log C_e \tag{2}$$

where x/m is the ratio of the mass of adsorbed solute per mass of adsorbent, and "K" and "n" are experimental constants. The isotherm should plot as a straight line on log-log paper if the y-axis represents the x/m ratio and the x-axis represents the equilibrium concentration (C_e).

The Langmuir isotherm assumes mono-layer adsorption, limited area available for adsorption, and a reversible process. Its formula is given by

$$\left(\frac{x}{m}\right)=\frac{aKC_e}{1+KC_e} \tag{3}$$

where "a" is the mass of adsorbed solute required to completely saturate a unit mass of adsorbent and "K" is an equilibrium constant (Reynolds, 1982).

Column studies are used to determine the required amount of carbon for a continuous flow operation. As solution is passed through a fixed bed of GAC, most of the impurities are removed in a specific zone of the GAC bed. This is called the primary adsorption zone (Figure 3). As time passes, the adsorption zone moves through the bed and a point is reached whereby effluent concentrations rapidly begin to approach the influent concentrations. This point is called breakthrough. After the adsorption zone leaves the bed, exhaustion occurs and influent/effluent concentrations may approximate each other. After a period of time, a steady-state is reached. This occurs because the mass adsorbed onto the carbon approximates the amount of mass desorbed from the carbon or consumed by bacterial activity. Breakthrough is often taken as either five percent of the ratio between the effluent and the influent concentrations or a regulated standard such as 100 ug/L for THMs. Likewise, exhaustion is taken as a 95 percent value of the same ratio (Figure 4).

Several variables are used to quantify the adsorption process. These variables include: time to exhaustion of the carbon bed (t_x), fractional capacity (f), time of passage through the adsorption zone (t_p), length of the adsorption zone (l), and percent of the carbon saturated with adsorbate at breakthrough (% sat). The formulas used to calculate these variables are given as follows:

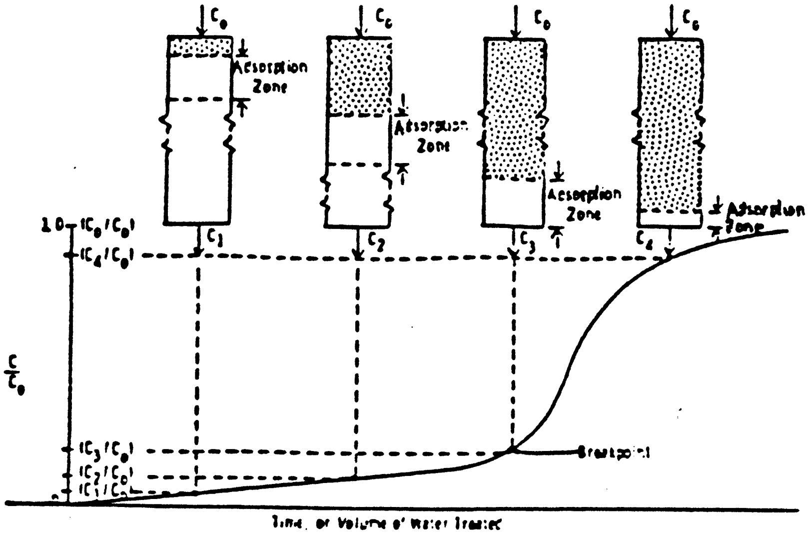


Figure 3. Schematic Representation of the Movement of the Adsorption Zone Through A GAC Bed.

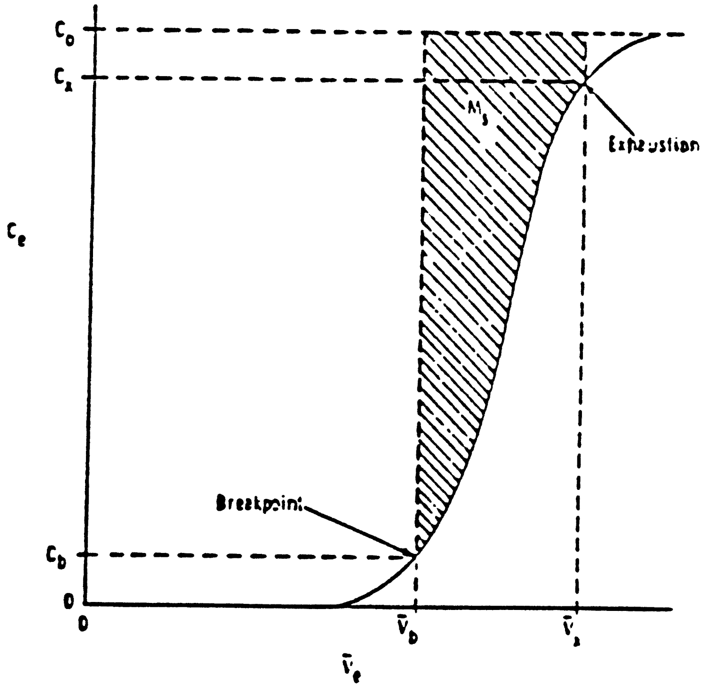


Figure 4. Ideal Breakthrough Curve of a GAC Bed.

SOURCE: Weber (1972)

$$t_x=\frac{Vx}{Q} \tag{4}$$

$$f=\int_{V_x}^{V_b}\frac{(C_i-C)\,dV}{(V_x-V_b)\,C_i} \tag{5}$$

$$t_p=\frac{V_x-V_b}{Q} \tag{6}$$

$$Z_s=\frac{L(V_x-V_b)}{V_b+f(V_x-V_b)} \tag{7}$$

$$t_f=(1-f)\,t_p \tag{8}$$

$$\%SAT=L-l(f-1)\,\frac{100}{L} \tag{9}$$

where C_i = influent concentration (mg/L)
C = concentration of effluent (mg/L)
V_x = volume of water treated at exhaustion (liters)
V_b = volume of water treated at breakthrough (liters)
Q = flow rate (cfs)
L = carbon bed length (ft).
f = fractional capacity
t_x = time to exhaustion
t_p = time to passage of the adsorption zone
Z_s = length of the adsorption zone
%SAT = percent saturation of the carbon bed at breakthrough

The fractional capacity (f) is the ratio of the quantity of material adsorbed in the adsorption zone between breakthrough and exhaustion (shaded area or "M_s" in Figure 4) to the total capacity of the carbon in the adsorption zone. As the fractional capacity approaches one, the adsorption zone formation time approaches zero and the reactor approximates a plug-flow reactor. In general, the more efficient carbon systems have small adsorption zone lengths and high fractional capacities.

Batch studies by Russell (1989) using Calgon F-400 and water from Lake Angel gave a maximum adsorption value of 16.8 mg TOC/g GAC. However, the batch test was run for only 48 hours and adsorption was still occurring when the experiment terminated. Therefore, this adsorption value may be very conservative.

Small and large column studies conducted by Russell with Lake Angel water used TOC as the only sampled parameter. Small columns showed an extrapolated volume of water treated at exhaustion (0.95Co) of 41.5 liters. The surface loading rate was 3.86 gal/min-sq.ft. with an empty bed contact time (EBCT) of 33.8 seconds, and a volumetric flow rate of 4.27 gal/day. A large column did appear to approach exhaustion after treating 68.9 liters with an EBCT of 49.5 seconds or 72.6 bed volumes per hour at 1.5 gallons per minute-square feet. A summary of adsorption values using laboratory batch, small column, and large column studies for Lake Angel detained water are given in Table 3.

TABLE 3

ADSORPTION CAPACITY COMPARISONS (MILLIGRAM TOC/GRAM GAC)

	ESTIMATES OF EXHAUSTION	OBSERVED MAXIMUM
BATCH	24 - 50	10(24 hrs) - 17(48 hr)
SMALL COLUMN	3 - 42	1 - 3
LARGE COLUMN	7 - 64	4 - 8

SOURCE: RUSSELL (1989)

In summary, mathematical models may be used to predict the adsorption characteristics of the GAC. Previous laboratory bench type studies using water from the Lake Angel detention facility resulted in estimates of adsorption capacities ranging from 1-17 mg TOC/g GAC. A column study which reported exhaustion had an EBCT of 49.5 seconds at a flow rate of 1.5 gallons per minute - square feet.

Humic Substances

Humic substances have been defined by Schnitzer and Khan (1972) as "amorphous, brown or black, hydrophilic, acidic, poly-disperse substances of molecular weights ranging from several hundreds to tens of thousands." Due to the great diversity in characteristics, humics vary greatly from location to location. Humic substances may act to concentrate heavy metals in peat (Snoeyink and Jenkins, 1980). Humic substances are primary contributors to color and the major precursors for chloroform and other THMs (Singer et al., 1981).

Humic substances have poorly defined physical and chemical characteristics and are divided into three groups based upon their solubility characteristics: fulvic acids, humic acids, and humin (Table 4). Fulvic acids are soluble in dilute acid and dilute base. They constitute the lower molecular weighted substances and are the dominant humic substance in natural waters (Table 5). Fulvic acids contain the highest percentage of oxygen in their carboxyl groups.

Humic acids are only soluble in dilute base but precipitate in dilute acids. Their molecular weights are intermediate in size. Molecular weights for fulvic acids range from 100 to 1000 while those for humic acids are greater than 100,000. Huminic substances are insoluble in both acids and bases and constitute high molecular weight substances (Trussell and Umphres, 1978).

The National Academy of Science (1977) estimated that 90 percent of the total organic matter in natural water is composed of high molecular weight organics. GAC is ineffective for removal of high molecular weight humic acids. Immediate breakthrough of humics through the carbon bed shortly after its placement occurs because the humic molecules are too large

TABLE 4
PHYSICAL AND CHEMICAL PROPERTIES OF HUMIC AND FULVIC ACIDS

PROPERTY	HUMIC ACIDS	FULVIC ACIDS
Elemental Composition (% by weight)		
C	50 - 60	40 - 50
H	4 - 6	4 - 6
O	30 - 35	44 - 50
N	2 - 4	<1 - 3
S	1 - 2	0 - 2
Solubility in Strong Acid (pH 1)	Not soluble	Soluble
Molecular Weight Range	Few 100 --> several million	180 - 10,000
Indicated Functional Group Distribution	Percentage of oxygen in Functional Groups	
Carboxyl	14 - 15	58 - 65
Phenol	10 - 38	9 - 19
Alcohol	13 - 15	11 - 16
Carbonyl	4 - 23	4 - 11
Methoxyl	1 - 5	1 - 2

SOURCE: Schnitzer and Khan 1972

TABLE 5

SCHEMATIC CLASSIFICATION OF ORGANIC COMPOUNDS FOUND IN WATER.

Volatility--->

POLARITY	VOLATILE	SEMIVOLATILE	NONVOLATILE
Polar	Alcohols Ketones Carboxylic Acids	Alcohols Ketones Carboxylic Acids Phenols Ethers	Poly-electrolytes Carbohydrates Fulvic Acids
Semipolar	Ethers Esters Aldehydes	Esters Aldehydes Epoxides Heterocyclics	Proteins Carbohydrates Humic Acids
Nonpolar	Aliphatic Hydrocarbons Aromatic Hydrocarbons	Aliphatics Aromatics Alicyclics Arenes	Nonionic Polymers Lignins Hynatomelanic Acid
	Low	Medium	High

Molecular Weight------------------------------------->

SOURCE: Cotruvo and Wu (1978)

to be adsorbed within the micro- and macro-pores of the carbon. Symons (1981) studied precursor removal from waters of the Ohio River and noted that when the carbon was fresh, all THMFP was removed. Shortly afterward, heavy molecular weight THM precursors began to pass through the carbon.

Babcock and Singer (1979) evaluated chloroform formation potential with humic and fulvic acids. Humic acids consumed 75 per cent more chlorine and produced 117 per cent more chloroform than did fulvic acids. However, the amount of humus present as humic acid in natural waters was so small so as to be insignificant.

McCreary and Snoeyink (1979) noted that adsorption of humic substances from various sources decreased with increasing total carboxyl groups. The lower molecular weight species from fulvic or humic acids were more adsorbable because more surface area was accessible to the substances. Waters with high concentrations of large molecular weight substances had an ill-defined front of penetration and more bled into the effluent than otherwise. Lower molecular weight species of humic substances were found to fluoresce. Adsorption increased with decreasing pH and increasing phosphate concentrations. Adsorption results were site-specific due to the variability of adsorption characteristics and haloform formation potential of the humic substances.

Algae

Algae are unicellular/multicellular organisms often associated with eutrophic processes in water bodies. Algae are divided into three main groups: (1) green algae - often found in fresh water bodies; (2) brown algae - found in marine environments; and (3) red algae. Algae use carbon dioxide and produce oxygen in light but use oxygen to produce carbon dioxide in the dark. Nitrogen is obtained in the form of either ammonia or nitrate (Gaudy and Gaudy, 1988).

Seasonal cycles of algae depend upon the physical, chemical, and biological factors that promote the growth of these autotrophic forms. After an algal bloom, slow degradation of the algal remains by microbes result in changes of the types of organic compounds that become available in the water. This contributes to a multitude of types and intensities of odor and tastes in the water supply.

As the algae begins to disintegrate, the gram-negative heterotrophic bacterial population begins to increase. As the population of these bacteria gradually begins to decline, specific metabolites are produced and become available to other types of organisms for their own assimilation and growth. A new phase of algae then begins and gram positive heterotrophic bacilli (rod-shaped bacteria) become predominant. As gram negative bacilli increase in population, the blue-green cyanobacteria algae increase at almost the same rate. The gelatinous sheath-like covers of the blue-green algal filaments contain high concentrations of attached or sorbed bacteria, most of which are gram-negative.

As algae begins to float on top of the water and actinomycetes (gram-positive non-photosynthetic, filamentous, rod-shaped bacteria) attack the remains of the blue-green algae, the population of the gram-negative heterotrophic bacteria is reduced. Metabolites from the actinomycetes result in musty, woody, and earthy odors. Many species of the family Actinomycetales often cause taste and odor problems in drinking water supplies. Populations of Actinomycetales species become optimum in warm weather and these gram-positive bacilli begin to increase in density. During times of high rainfall, algal populations are usually low (Silvey and Roach, 1964).

In summary, humic substances are the precursors of color, TOC, and THMs in surface waters. Due to the large variation in physical and chemical characteristics of humic substances, precursors of the aforementioned parameters vary from site to site. Algae and bacteria are cyclic contributors to TOC, color, and THM precursors also.

Color As A Surrogate Parameter For THMFP

Color is caused by negative charged colloidal particles from organic substances (Saville, 1979). In natural waters, these organic substances may include lignin (which decompose into humic and fulvic acids) and algae. These organics are not known to present human physiological problems. The primary drinking water standard for color is 15 color units on the platinum-cobalt scale. Because color in natural water has a yellowish brown color which resembles the color of urine, water treatment plants strive for effluent color not to exceed five color units for aesthetic reasons only (Sawyer and McCarty, 1978).

Black and Christman (1963) noted similar chemical and physical characteristics of color from various sources. Most of the color resulting from suspended colloidal particles and color was pH dependent. Conversely, Shapiro (1958) analyzed samples from all over the United States and discovered similar chemical patterns which contributed to color. Any differences were due to inorganic constituents. Organic color was mainly due to dicarboxylic hydroxy aliphatic organics with a molecular weight of 450. Christman and Ghassemi (1966) found carboxyl and phenol groups were the major building blocks in color molecules of lignin.

Singer et al. (1981) found acceptable correlations in North Carolina waters between color and instantaneous THM of raw water. The formula was INST THM = 1.11(color as color units) + 37.0 (r = 0.70). When treatment plants were excluded that did not practice prechlorination, a higher correlation coefficient of r = 0.76 was obtained. Correlation between color and TOC was less favorable (r = 0.59).

Herr (1983) had good correlations between THMFP and TOC from filtered water influent at Lake Washington, Florida. Correlation coefficients using color were 0.714 and 0.760 for THMFP and TOC, respectively. The models concerning these parameters were given as THMFP = 7.13 (Color as color units) + 386.4 and TOC = 0.259(Color) + 9.454.

In summary, color has been shown in previous studies to be an acceptable surrogate parameter for both TOC and THMs. However, color may vary greatly with location of water supply and should be verified on a site-by-site basis.

TOC As A Surrogate Parameter For THMFP

The relationship between THMs and TOC has been noted during previous investigations from facilities throughout the country. TOC is a good surrogate parameter since the test can be done quickly and inexpensively.

Good correlations were found by Lykins et al. (1987) at water facilities in Cincinnati and Miami. This correlation has been proposed by the formula maximum $THM = A(TOC)^a$

where TOC is total organic carbon in mg/l and the constants "A" and "a" are determined by regression. Correlation coefficients were 0.814 and 0.906 for the Cincinnati and Miami plants, respectively. However, correlations were not good at other water treatment plants of the same study.

In a separate study, Lykins and Clark (1987) considered treatment waters from utilities at Cincinnati, Ohio, Jefferson Parish, Louisiana, Manchester, New Hampshire, and Evansville, Indiana. They found a strong correlation ($r = 0.85$) between THMFP and TOC.

TOC is used to measure organically-bound carbon and represents the presence of humic and fulvic acids. Studies by Symons et al. (1975) for NORS and Suffett (1980) demonstrated the greatest THM concentrations were due to chloroform, followed by bromodichloromethane, dibromochloromethane, and bromoform. TOC reported as NPOC was an acceptable parameter for indicating total THMs in these studies.

Cotruvo and Wu (1978) commented that "...nonpurgeable total organic carbon (NPOC) correlated reasonably well with THM formation potential" from studies included in the NOMS of 113 community water supplies throughout the country.

Singer et al. (1981) had excellent correlations between terminal THM and TOC of raw water for water treatment plants in North Carolina ($r = 0.84$). Correlations between instantaneous THM and TOC in finished water were not as favorable ($r = 0.65$).

Herr (1983) had a 0.65 correlation coefficient between TOC and THMFP at Lake Washington, Florida. The model was given by THMFP = 42.1(NPOC) - 16.59.

Fisher and Taylor (1982) studied THM formation from three drinking water sources including Lake Washington near Melbourne, Florida. They developed the following model to describe THM formation:

$$\mathrm{THMFP} = 2.7(\mathrm{TOC})^{1.24}\ (\mathrm{Cl})^{.22}\ (\mathrm{OH})^{0.10}\ (T)^{0.17}\ (t)^{0.27} \tag{10}$$

where THMFP = THM Formation Potential as THM (umole/l)
TOC = Total organic carbon as C (mmole/L)
Cl = chlorine dose as Cl (mmole/l)
OH = hydroxide concentration as OH^- (mmole/l)
T = temperature (°C)
t = time (hour).

Therefore, temperature, pH, TOC, hydroxide concentration, chlorine dose and contact time were all factors that affected THM formation. Note that TOC had the greatest relative effect of all the variables as noted by the large exponential value.

In summary, TOC is a parameter which may be conducted relatively quickly and inexpensively. Previous studies at facilities throughout the country found good correlation between TOC and THMs. Therefore, TOC has been a proven surrogate parameter for THMs.

Trihalomethanes

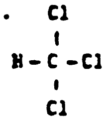
THMs are derivatives of methane formed when three out of four hydrogen atoms are replaced by three atoms of chlorine, bromine, or iodine (Figure 5) (Herr, 1983). The general equation which describes this reaction is

$$\text{chlorine} + \underset{\text{precursors}}{\text{organic}} \text{ ---> } \text{THMs} + \underset{\text{compounds.}}{\text{other halogenated}} \qquad (11)$$

The four primary THMs include chloroform (MW=119), dichlorobromomethane (MW=163), dibromochloromethane (MW=208), and bromoform (MW=253). Usually chloroform is the dominant THM unless bromine is a source whereby bromoform is formed.

Trihalomethanes may be subdivided into four classes: instantaneous, terminal, THM formation potential, and maximum total trihalomethane potential (Figure 6). Instantaneous THM is the THM concentration at the moment of sampling and is used to evaluate compliance with MCL. Terminal THM is a measurement of the THM present after a seven day period under controlled pH and temperature conditions with an adequate amount of chlorine to ensure residual after the time period. THM formation potential represents the increase in THM concentration during storage of the sample for the terminal THM test. Maximum total THM is the highest concentration of THMs under the most optimistic conditions of formation (Culp et al., 1987).

1.

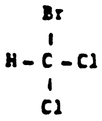


$\mathrm{H-\overset{Cl}{\underset{Cl}{C}}-Cl}$

$\mathrm{CHCl_3}$

Trichloromethane
(Chloroform)

2.

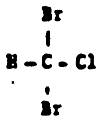


$\mathrm{H-\overset{Br}{\underset{Cl}{C}}-Cl}$

$\mathrm{CHBrCl_2}$

Bromodichloromethane

3.

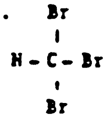


$\mathrm{H-\overset{Br}{\underset{Br}{C}}-Cl}$

$\mathrm{CHBr_2Cl}$

Dibromochloromethane

4.

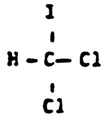


$\mathrm{H-\overset{Br}{\underset{Br}{C}}-Br}$

$\mathrm{CHBr_3}$

Tribromomethane
(Bromoform)

5.

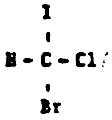


$\mathrm{H-\overset{I}{\underset{Cl}{C}}-Cl}$

$\mathrm{CHCl_2I}$

Dichloroiodomethane

6.

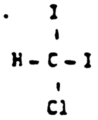


$\mathrm{H-\overset{I}{\underset{Br}{C}}-Cl}$

$\mathrm{CHBrClI}$

Bromochloroiodomethane

7.

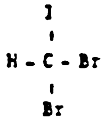


$\mathrm{H-\overset{I}{\underset{Cl}{C}}-I}$

$\mathrm{CHClI_2}$

Chlorodiiodomethane

8.

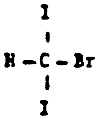


$\mathrm{H-\overset{I}{\underset{Br}{C}}-Br}$

$\mathrm{CHBr_2I}$

Dibromoiodomethane

9.

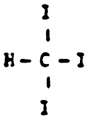


$\mathrm{H-\overset{I}{\underset{I}{C}}-Br}$

$\mathrm{CHBrI_2}$

Bromodiiodomethane

10.



$\mathrm{H-\overset{I}{\underset{I}{C}}-I}$

$\mathrm{CHI_3}$

Triiodomethane
(Iodoform)

Figure 5. Formulas and Names of Trihalomethanes.

SOURCE: U.S. Environmental Protection Agency

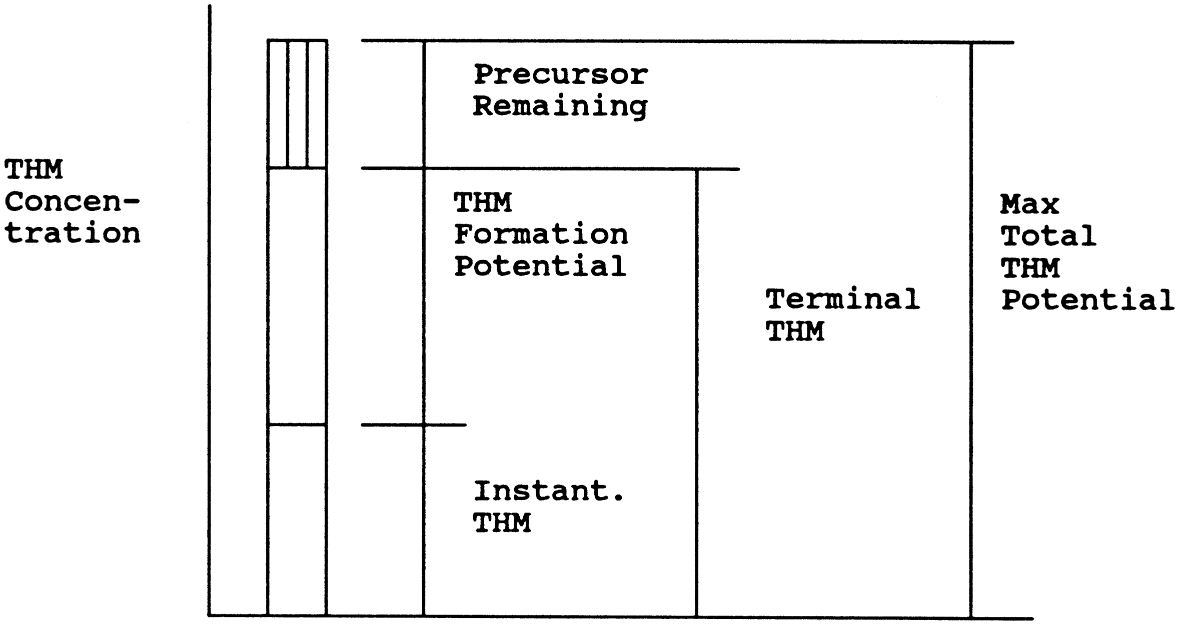


Figure 6. THM Measurement Parameters and Their Relationships.

SOURCE: CULP et al. (1987)

Several factors may affect the extent to which THMs are formed. Dore et al. (1982) noted that chloroform yield increased to a maximum value near neutrality and then decreased with increasing pH. Jolley (1978) showed that a temperature increase resulted in an increase in the chloroform production rate.

Morris and Baum (1978) found THM concentrations corresponded well to the concentrations of chlorophyll-a and algal biomass measured in a reservoir. Two green algae and two blue-green algae were studied. TOC production and chloroform concentrations after chlorination were variable. Chloroform production per unit TOC appeared to vary perhaps due to different organic compounds derived from different stages in the algal life cycle.

The same study concluded that green algae and blue-green algae produced extracellular products (ECP) which, upon chlorination, yielded at least as much chloroform per unit organic carbon as that from humic or fulvic acids. Algal ECP upon reaction with chlorination yielded greater quantities of $CHCL_3$ for available TOC than algal biomass. High-yielding THM precursors were liberated by algae in greater abundance during late exponential phase of growth than at any other time during the algal life cycle.

In summary, THM precursors include algal extracellular products, humic acids, and fulvic acids. THMs are produced by the combination of chlorine used as a drinking water disinfectant with the precursors. Factors which affect the formation of THMs include the chlorine contact time, pH, and temperature.

Bacterial Growth

Bacteria Within the GAC Bed

Bacterial growth may occur on the carbon granules. Bacteria which consume carbonated organics may be expected to obtain their maximum concentration within 24 to 48 hours after fresh carbon has been installed (U.S. EPA, 1980). By comparison, Nitrosomonas and Nitrobacter (autotrophs) bacteria require 30 to 90 days to reach their optimum level (Herr, 1983).

The bacterial population may become established due to increased concentration of adsorbed organics on the carbon surface (which serve as a food source) and the large surface area of the granules to which they may affix themselves. After the organics have been consumed by the bacteria, their sites become free for other organics to adsorb onto the carbon. The highest density of bacteria occurs within macropores of the upper few decimeters of the carbon. However, the bacteria will only cover about 1 percent of the total adsorption area so that a uniform biofilm is not formed. Therefore, these bacteria should not interfere with the adsorption process (JAWWA Committee Report, 1981). The size of the population is a function of the nutrient content (phosphates, nitrates, minerals, etc.) of the influent water, temperature, and the hydraulic flow rate (Faust and Aly, 1987).

Types of bacteria affixing to the carbon have been identified and include species of Azomonas, Acinetobacter, Pseudomonas, Bacillus, Flavobacterium, and Alcaligenes. These bacteria are mainly water and soil chemoorganotrophs and do not pose an immediate threat to human health although the latter four "are known to be opportunistic pathogens, chlorine resistant, or suppressors of total coliform" (Cairo, 1979). Endotoxin concentrations produced by some of the bacteria are extremely low and do not pose a health threat either (JAWWA Committee Report, 1981).

Bacteria Outside the GAC Bed

Organisms which grow outside the media and have relatively impermeable structure when in great volume can hinder the operation of a GAC bed. These microorganisms must be removed. Microorganisms are generally classified as either eucaryotes or procaryotes (Figures 7 and 8). Eucaryotes are distinguished by having a cell wall (except protozoa), true nucleus (chromosomes enclosed in nuclear membrane) and several organelles (e.g., mitochondria -to generate bioenergy in the form of ATP or golgi bodies - to store and sort proteins). Examples of eucaryotic microorganisms include algae, fungi, and protozoa.

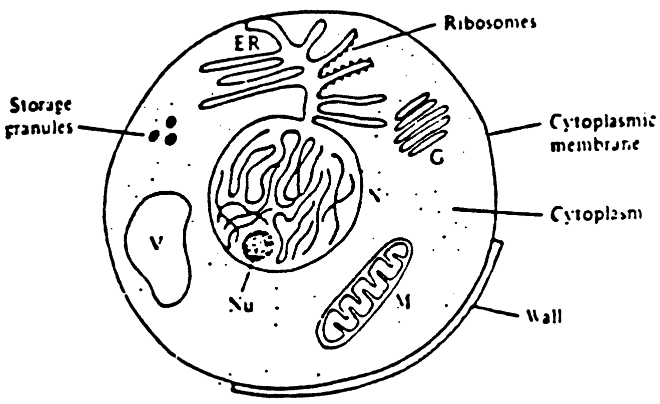


Figure 7. Structure of an Eucaryote Cell.
Source: Cullimore and McCann, 1977

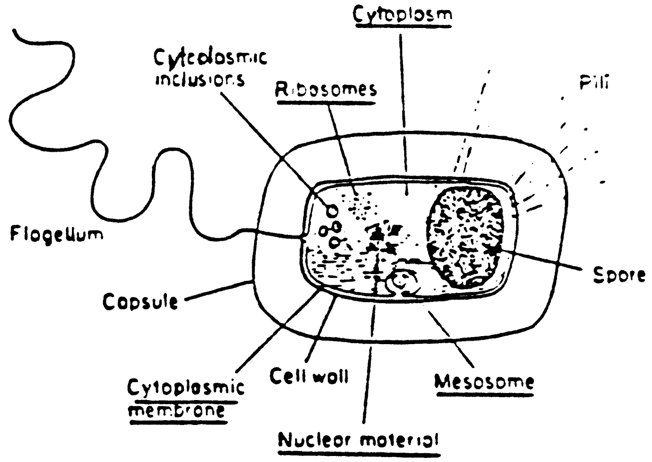


Figure 8. Structure of a Procaryote Cell.
Source: Cullimore and McCann, 1977
Note: The underlined labels denote structures essential to all procaryotes whereas the remaining designations are accessory parts of a limited number of species.

Procaryotes are distinguished by a single unbound DNA genome, ribosomes, cytoplasm, and at least two exterior layers of the cell: cytoplasmic membrane and a cell wall (Figure 8). The lipopolysaccharide (LPS) outer membrane is a third enveloping structure in gram-negative bacteria. All portions of the cell are contiguous in overall structure. Examples of procaryotes include non-aggregating bacteria, blue-green algae, and sheath-forming bacteria.

Procaryotes such as bacteria and blue-green algae can be classified physiologically by their source of energy (light or chemical), carbon (organic or inorganic), or electron donor for generation of reductant (organic or inorganic). Examples of the nomenclature relating to these functions are given in Table 6. Another division not listed in the table is electron acceptability: oxygen (aerobic) or sulfate, nitrate, etc. (anaerobic). These classifications are combined to describe the metabolic properties of the bacteria. For example, an organism which requires oxygen as an electron acceptor, sunlight as an energy source, and uses organic carbon would be termed aerobic/ phototrophic/heterotrophic. However, only five combined terms are currently used for physiological types: photolithotroph, photoorganotroph, chemolithotroph, chemoorganotroph, and mixothroph.

TABLE 6

CLASSIFICATION OF BACTERIA BY NUTRITION

	INORGANIC	ORGANIC	CHEMICAL	LIGHT
CARBON SOURCE	Autotroph	Heterotroph	---	---
ENERGY SOURCE	---	---	Chemotroph	Phototroph
ELECTRON DONOR	Lithotroph	Organotroph	---	---

Another simplified scheme dividing bacteria into two groups is related to retention of the primary dye staining ability of the organism following the Gram stain procedure. Initially, a primary purple stain (crystal violet) is applied to a smear of the organism which absorbs the stain. The smear is then flooded with iodine solution (mordant) to increase the binding of crystal violet after which the decolorizing agent (95% ethanol alcohol) is added in an attempt to remove the purple stain. Finally, safranin counterstain is then applied to the smear. Organisms which retain the purple stain after the decolorizing agent has been added are called gram positive. If the organisms loses the initial purple color but shows the red counterstain, they are termed gram negative.

Gram stain differentiation of bacterial cells is related to the composition of the cell wall envelope beyond the cytoplasmic membrane. Gram negative cells have a two-layered cell envelope: the inner wall consists of a thin layer of peptidoglycan while the outer envelope can be divided into an exterior layer of phosopholipids and lipoproteins and an inner layer of lipopolysaccharides. In contrast, the gram positive cells have beyond the cytoplasmic membrane a thick peptidoglycan cell wall only (Norton, 1986).

Alternative nutrition usage is another scheme by which bacteria may be described. Obligate autotrophs use carbon dioxide as the sole principle carbon source (chemolithotrophs and photolithotrophs) while faculative autotrophs may also use an organic carbon source. Mixotrophs are bacteria which may utilize both inorganic and organic carbon but use an inorganic chemical energy source, especially hydrogen sulfide. This flexibility allows for the ubiquitous growth of bacteria in diverse environments. Representative bacterial groups (known by descriptive terms) in waste waters or flowing ground water include the sheathed bacteria, iron-manganese bacteria and some of the sulfur oxidizing bacterial species.

Sheath Bacteria

Bacteria may grow within macropores of the carbon as well as in pipes or other drainage accoutrements. Sheath-forming bacteria have been previously studied as a result of clogging in ground water wells throughout the United States (Christian, 1975), (Lueschow and Mackenthun, 1962) and the world (Cullimore and McCann, 1977). Abundance of such bacteria result in economic loss of ground water wells because of clogging, increased drawdown, and reduction in the amount of water delivered to the well. These bacteria have been removed

30°C (optimum:26°C) and a pH range between 6.4 to 7.5. Haliscomenobacter is found in waters of high organic content. Nitrogen supply is obtained through organic acids (Bergey's Manual of Bacteriology, 1989).

Iron/Manganese Bacteria

Bacteria may remove iron (which acts as an electron donor) from solution by precipitating insoluble ferric hydroxides outside the cells on extracellular polymers. These polymers coat the external surface of the cell wall or sheath and serve as a site for the accumulation of precipitated $Fe(OH)_3$.

Several factors affect the conditions of iron oxidation/ reduction. They include redox potential (E_h), pH, presence of organic compounds, amount of dissolved oxygen, and the types of microorganisms (Smith and Tuovinen, 1985).

Iron is typically found in the ferrous (Fe^{++}) state at moderate pH in anaerobic ground waters (Figure 9). Due to its reduced state, excessive iron concentrations are possible. Under highly reduced conditions at coal mines, iron forms the minerals pyrite or marcasite with the aid of sulfur. Oxidation of iron by bacteria may result in the formation of insoluble ferric (Fe^{+++}) iron. However, iron reduction and oxidation may occur without bacteria. For example, pumping of ground water wells oxygenates iron-rich water from the aquifer and precipitates iron. Bacteria cause its precipitation in the oxidized state by changing the local redox conditions.

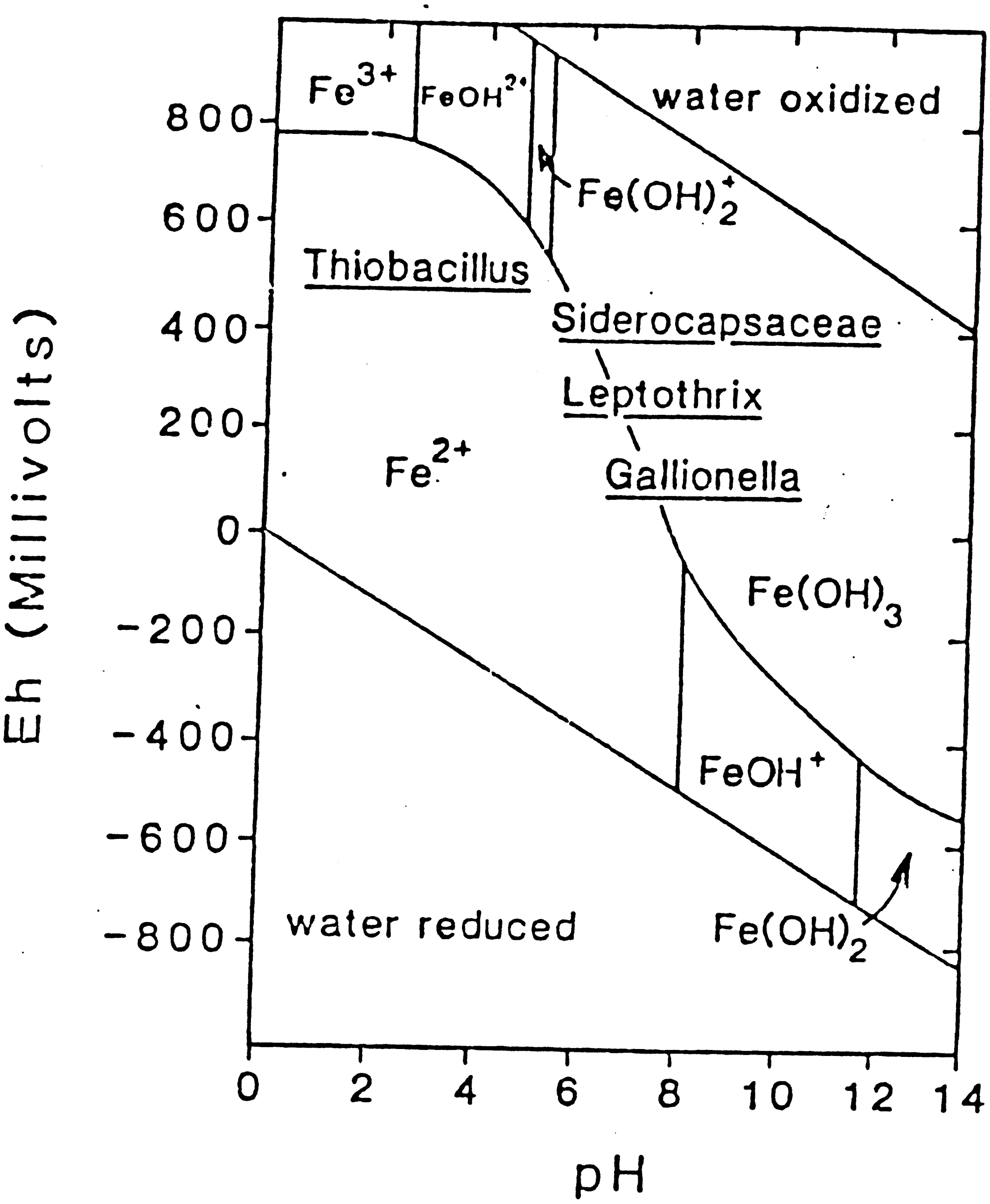


Figure 9. Relationship of Several Bacteria to E_h and pH Ranges.

SOURCE: Smith and Tuovinen (1985)

Bacteria of this type attach to solid surfaces by a biofilm (slime) composed of excreted extracellular polysaccharide polymers and help to bind the bacteria to the surface. Production of the biofilm may clog openings in porous media to which they affix themselves (Hackett, 1987). Deposition of either ferric hydroxide or manganese dioxide may occur on the sheath of bacteria having this structure. Since the environmental conditions of sheath bacteria and iron oxidation are similar, the bacterial surface may be a recipient but not a cause of iron precipitation. However, manganese oxidation naturally occurs at pH values higher than environmental conditions for the bacteria. Therefore, oxidation of manganese by the bacteria is known to occur. Some of the bacteria of this characterization include Metallogenium, Gallionella, and species of the family Siderocapsaceae.

Metallogenium (not sheathed) may oxidize ferrous iron in the pH range of 3.5-5.0 with an optimum pH range of 4.1 but predominantly oxidize manganese. These stalked organisms form rosette clusters but lack a conventional cell body (Walsh and Mitchell, 1972). Metallogenium are aerobic, chemoorganotroph/parasitic organisms often associated with surface waters near anaerobic sediments, decomposing layers of leaf litter, or bottom deposits of lakes (Bergey's Manual of Bacteriology, 1989). The optimum temperature for their growth occurs at

28°C while the pH ranges from 6.8 to 7.2. Redox potential values range from +0.2 to +0.65 volts and manganese concentrations of the source water are usually less than 50 mg/L.

Gallionella is characterized by twisted stalks comprised of iron hydroxide and bacterial fibers. Stalk fibriles contain organic material to which the ferric hydrate is bound (Ghiorse, 1984). This organism is chemolithotrophic (oxidizes inorganic ferrous iron and assimilates CO_2) and live in environments with E_h ranges from +200 to +320 mV. The pH range is slightly acidic due to uptake of CO_2. They typically have a darker reddish-ochre color and live in low organic waters (Bergey's Manual of Bacteriology, 1989). Other typical ionic concentrations in the source water inhabited by Gallionella include 0.1 to 1 mg/L oxygen, 5 to 25 mg/L Fe^{++}, >20 mg/L carbon dioxide, and >12 mg/L organic matter (Hanert, 1981).

Bacteria in the Siderocapsaceae family are non-filamentous, aerobic/anaerobic, faculative/obligate slime-encapsulated and they precipitate iron and manganese. They occur in swamp ditches, stagnant water, and in the hypolimnion of lakes - utilizing organic carbon of iron-manganese humates. Their preferred environment is characterized by very low dissolved organic carbon, elevated concentrations of iron and manganese, moderate pH, and temperature from 8° to 30°C (optimum temperature is 20°C). These sphere-like unicellular organisms have an extracellular capsule composed of excreted gelatinous material (of unknown chemical composition that may appear ring-shaped). They may form large masses of ferric hydrate which impregnates the capsular material (Smith and Tuovinen, 1985). Cells become the nuclei of metal precipitation and appear rust-brown due to iron encrustation or dark brown/olive-green/black due to MnO_2 (Bergey's Manual of Bacteriology, 1989). Optimum growth occurs at the beginning of a change from extremely reduced to oxidized conditions in a neutral to slightly alkaline environment (Hanert, 1981).

Sulfur Bacteria

Bacteria may affect iron solubility in water by catalyzing reactions of sulfur. In the most reduced form, sulfide ions have low solubilities when complexed with most metals as metal sulfides. Therefore, sulfur acts as the terminal electron acceptor in anaerobic environments to yield sulfide and this is exemplified by Desulforibrio. Other biofouling sulfur bacteria that oxidize sulfide or sulfur are represented by Thiothrix, Beggiatoa, and Thiobacillus.

Thiothrix is composed of multicellular filaments within a sheath that radially attach to polysaccharide holdfast material to form rosettes. These bacteria convert hydrogen sulfide from the water into intracellular sulfide globules which accumulates after sulfur oxidation. They are mixotrophic and are found in running waters containing sulfides/thiosulfides and sludge plants. Thiothrix lives in neutral pH water (6.8 to 7.5) within a temperature range between 25 to 30°C (optimum temperature is 32°C). They are white in color (the appearance of noncrystalline sulfur) and use alcohols and acetate for carbon supply (Bergey's Manual of Bacteriology, 1989).

Beggiatoa consist of colorless cylindrical chains of cells that contain intracellular granules of sulfur in the presence of hydrogen sulfide. These filamentous organisms produce polysaccharidic sheath-like slimes and are found at the sulfide/oxic interface of fresh or marine waters and estuaries. Mobility occurs by gliding (no flagella). Beggiatoa may be aerobic or microaerophilic, facultative autotrophic. Electron acceptors include oxygen or sulfur. Nitrogen supply is from nitrate or nitrite. Temperature ranges from zero to 40 degrees Celsius. These organisms can not tolerate high concentrations of organics or nitrogenous nutrients (Bergey's Manual of Bacteriology, 1989).

Thiobacillus is a non-aggregating bacterium which oxidizes reduced sulfur forms into sulfate. The resultant sulfuric acid becomes corrosive. These bacteria are invariably present in sulfur-bearing water and are dependent on aerobic conditions.

CHAPTER III

LABORATORY PROCEDURES

Laboratory Color Analyses

All samples for color were collected in 125 mL amber glass bottles and allowed to warm to room temperature before being analyzed. Approximately 50 milliliters (mL) of each sample were adjusted to pH 7.6 using a Corning Model 10 pH meter.

The HACH DR/3 spectrophotometer was used to measure the color at a wavelength of 455 nanometers. The instrument was calibrated using 20 and 100 cpu standards. The left- and right-set scale margins were then observed and adjusted if necessary. The flow cell was rinsed twice with deionized water before each sample was analyzed.

The sample was added to the flow cell and the color value was read after the flow stopped. Values to the nearest 1 unit on the expanded scale and 5 units on the normal scale were then recorded. All samples were analyzed twice to verify results. The 100 cpu standard and at least one sample was then observed on the normal scale at the conclusion of the samples in order to verify accuracy of the results.

Laboratory TOC Analyses

Total Organic Carbon (TOC) was measured using the ultraviolet (UV)-persulfate oxidation method as nonpurgeable organic carbon (NPOC). NPOC is carbon that remains after acidification and sparging (inert gas stripping) and is independent of the oxidation state of matter. The Dohrmann DC-180 carbon analyzer was used to measure the NPOC concentrations in milligrams per Liter.

All samples in the field were collected in 125 mL amber glass bottles and immediately preserved with 2 to 3 drops of phosphoric acid. Samples were placed in tubes in a closed-loop carousel. Ten milliliters (mL) of each sample for TOC analyses was obtained using a peristatic pump. The DC-180 then sent a pre-determined amount of 20 percent phosphoric acid and three 1.0 mL. aliquots of sample to a liquid sparger. Inorganic carbon was sparged out after being converted to CO_2 and the remaining liquid was analyzed for NPOC. A measured amount of the liquid was reacted with UV and persulfate to ensure complete oxidation of the organics by breaking them down into single carbon units.

The nonpurgeable organic carbon dioxide was carried to a nondispersive infrared detector calibrated to the adsorptive wavelength of CO_2. A microprocessor calculated the area of the peaks produced by the analyzer and compared them to peaks of the calibrated standards. These standards were 5, 10, and 25 mg/L of TOC as potassium hydrogen phthalate. The DC-180 then printed out the NPOC values (Dohrmann Rosemount Analytical Division, 1987).

Laboratory THMFP Analyses

Samples to be analyzed for THMFP were taken in 800 mL amber glass containers. At the lab they were analyzed using the Liquid/Liquid Extraction method. This method is only applicable for the determination of four trihalomethanes: chloroform, bromodichloromethane, chlorodibromomethane, and bromoform. This method is useful for THM concentrations ranging from 0.5 to 200 μg/L (Standard Methods, 1987).

Samples were chlorinated with a sufficient dose (20 mg/L) to maintain a free chlorine residual greater than 0.5 mg/L throughout the reaction period. Samples were then stored at 20°C in an incubator for 96 hours at which time sodium thiosulfate was used to quench all free available chlorine present. This was done to stop formation of THMs. Within a seven day period, samples were extracted with hexane using a 1,2-dichlorobenzene internal standard. The samples were then injected into a gas chromotograph (HP 5890 with auto sampler) that enabled the calculation of each THM by comparing the peak heights and areas of samples to those of standards. The total THMFP concentration was calculated by summing the four individual THMFP concentrations.

Laboratory Chloride Analyses

Chloride samples were titrated with 0.0141N mercuric nitrate to form mercuric chloride. This method was recommended for high chloride concentrations and its easy detection of the endpoint. Samples were diluted to 100 mL, given 1 mL of indicator, and titrated within a pH range of 7 to 10. The indicator consisted of 250 mg s-dipheny-carbazone, 4.0 mL concentrated HNO_3, and 30 mg xylene cyanol FF in 100 mL of 95 percent ethyl alcohol. The color of the sample turned from light green to a dark purple endpoint. A blank consisting of deionized water and 500 mg/L chloride standard was used for each set of samples. The chloride concentration was calculated from the following formula:

$$Cl\ (mg/L) = (a-b) * N * 35450/mL\ sample \tag{12}$$

where: a = mL titration for sample
b = mL titration for blank and
N = normality of $Hg(NO_3)_2$ (Standard Methods, 1987).

CHAPTER IV

FIELD GAC TREATMENT SYSTEMS

Setup Of The GAC Carbon Beds

An existing structural arrangement at the Lake Angel detention facility was utilized for this experiment (Figures 10, 11, and 12). The system consisted of an influent 8" PVC underdrain , an 11'-4" x 9'-4" concrete box, a concrete junction box, 20 feet of 8" PVC effluent pipe that connected the concrete box to a junction box, and an aquifer well.

The concrete structure consisted of two 4'-8" x 8' chambers and a 60° modified V-notch weir (Figure 12). GAC was originally placed inside burlap bags within the first chamber in December, 1989. Influent water consisting of ground and lake water entered the GAC chamber via an 8" perforated bank underdrain pipe.

Water was discharged from the first to the second chamber by the modified V-notch weir. The invert of the weir was 10 inches above the structure floor. An 8" concrete wall also separated the two compartments. Aluminum blades (36" x 1/4" x 24") were placed within the chambers to direct the flow of water and prevent short-circuiting - thus increasing the EBCT.

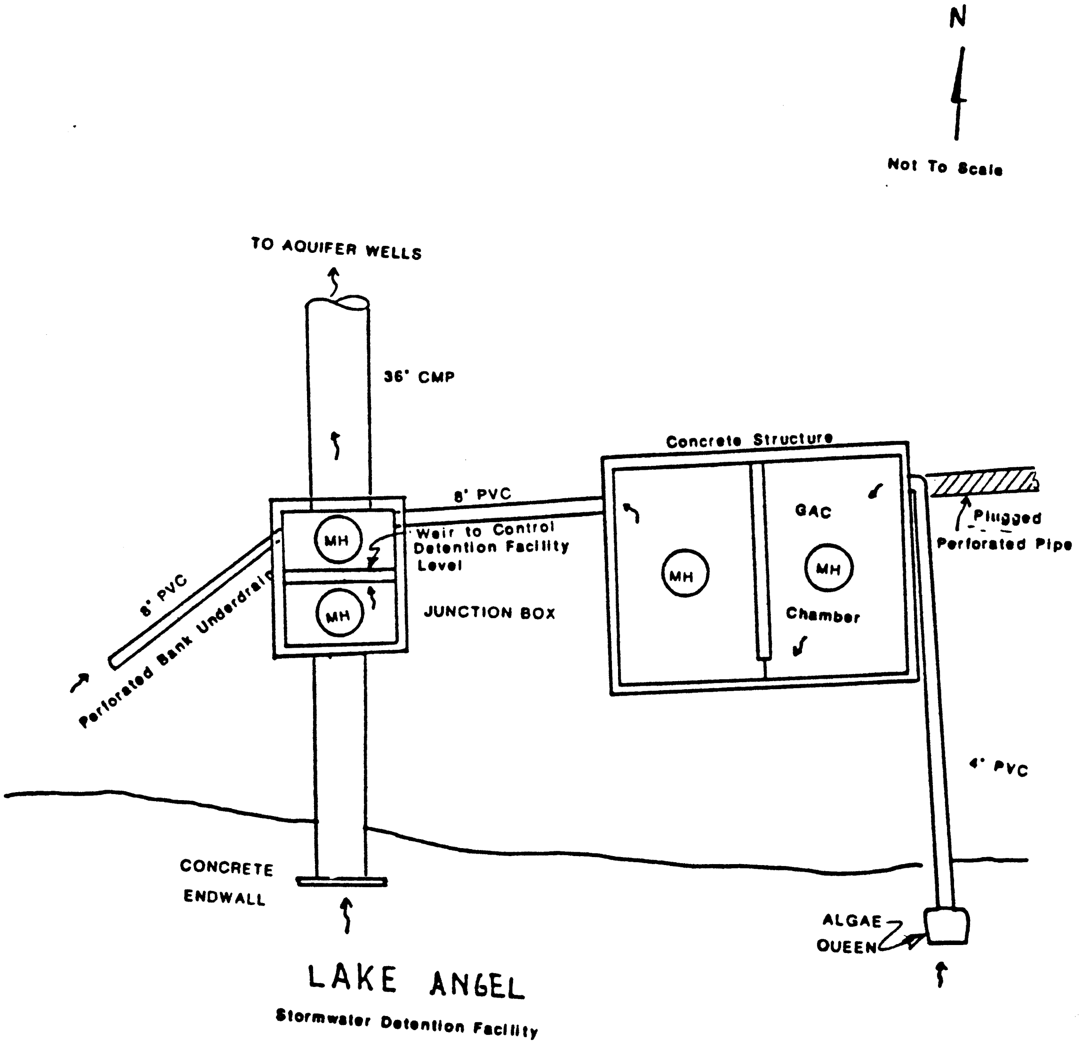
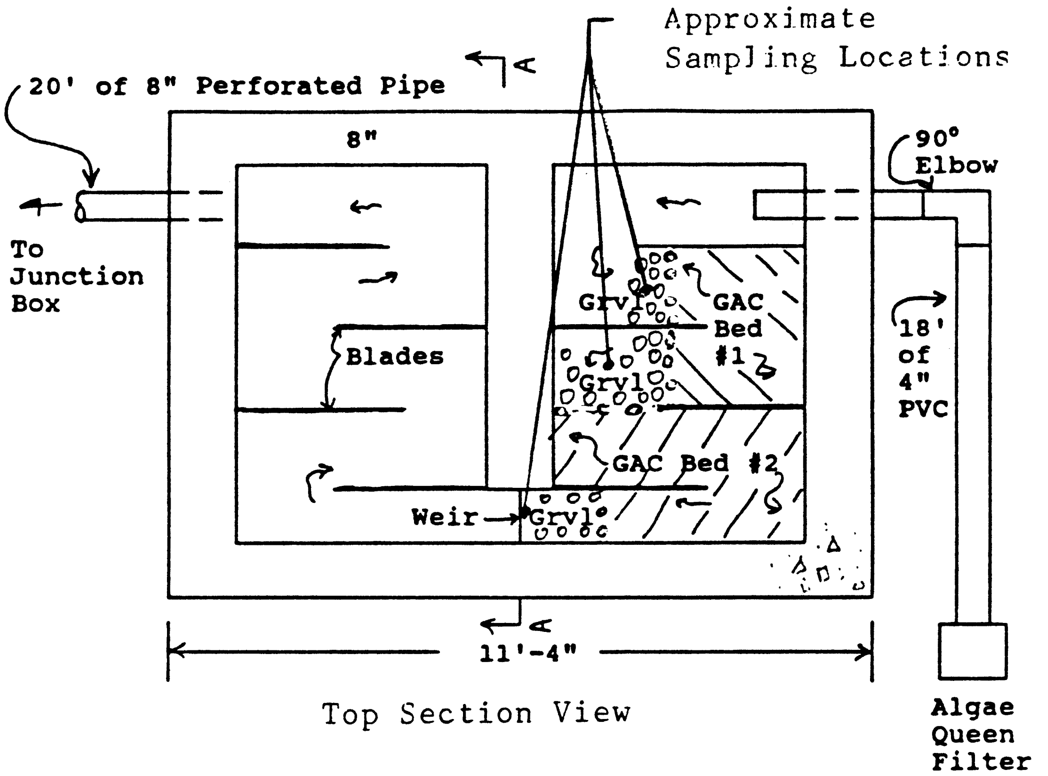
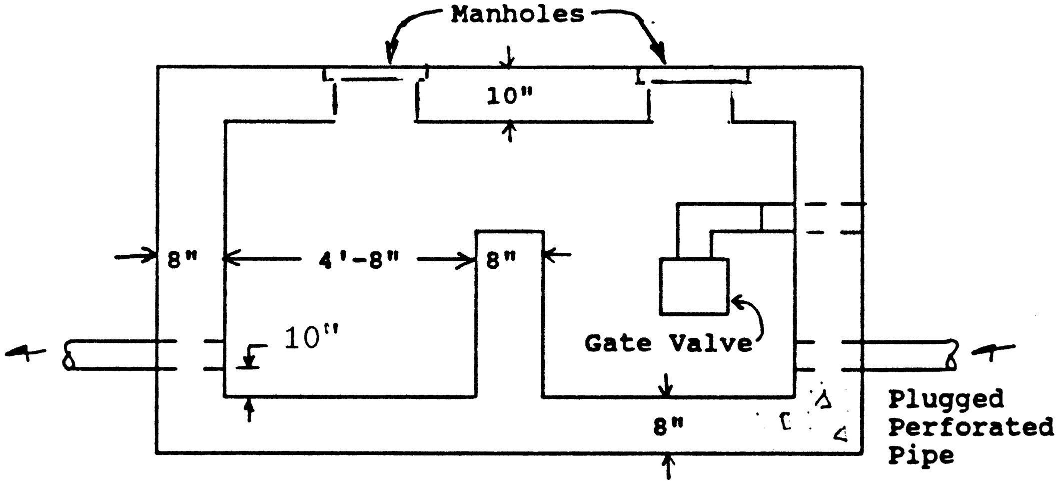


Figure 10. Layout of the GAC System at Lake Angel

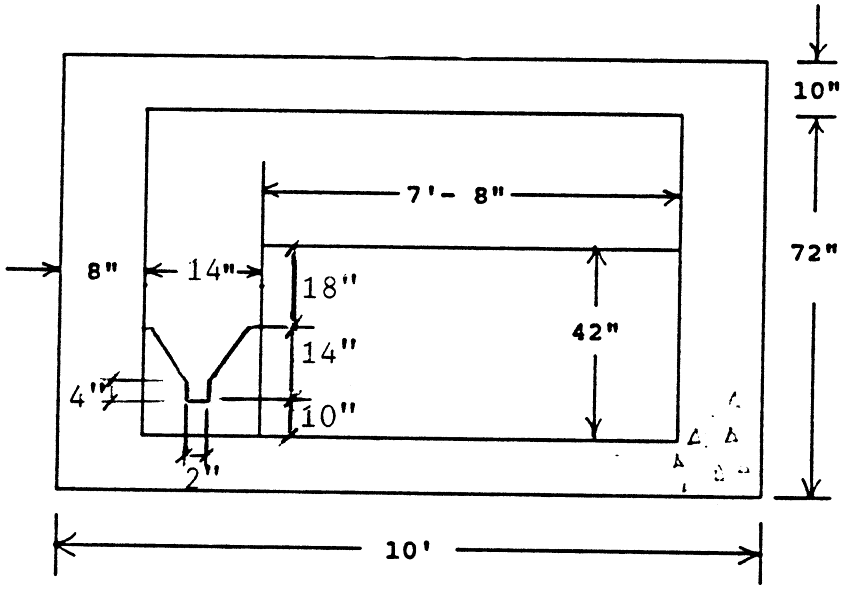


Top Section View



Front Section View (without GAC)

Figure 11. Top and Front Views of the GAC Chamber.



SIDE VIEW

Figure 12. Side View of the GAC Chamber

The influent and effluent pipe inverts were approximately 10-inches above the structure bottom.

Inside the junction box was a 44" weir which controlled the detention pond. The weir had a height of 47.5 inches. The east side of the weir was lower than the west side by 1/4 inch. Lake water entered the box via a 36" corrugated metal pipe (CMP) culvert and an attached concrete endwall. Also connected to the junction box was an 8" bank perforated pipe which predominantly received lake water. This was possible due to an impervious clay layer on the landward side of the pipe. Another 36" CMP conveyed water from the junction box to the aquifer well.

Modifications To The Existing Structure

Samples of TOC and THMFP were taken from January 9 to January 23, 1990. On the latter date it was observed that water coming into the first GAC chamber was short-circuiting the GAC by flowing over the top of the burlap bags. This observation was corroborated by similar chemical analyses of TOC and THMFP concentrations of the influent and effluent waters. In addition, the bacteria had partially clogged the underdrain-greatly reducing the amount of water entering the chamber. Sheaths from the bacteria sloughed-off from within the influent pipe into the GAC chamber. On January 24, the pipe was temporarily plugged up to prevent water from entering the GAC chamber.

Short-circuiting was caused by bacteria growing within the influent pipe and sloughing off their slimes and sheaths onto the burlap bags (Appendix III). This rendered the bags impervious to water flow. These bacteria were later identified as _Leptothrix_, _Thiothrix_, _Siderocapsa_, and _Gallionella_, a biocomplex which would require iron, sulfide, and manganese for energy, carbon,and nitrogen sources from the water. The fixed biomass of bacteria would not be adversely affected by low iron concentrations if it is uniformly delivered by flowing water.

It was believed the source of these nutrients originated from ground water or highway runoff. Typical iron concentrations at Lake Angel in 1988 were reported to average 0.47 and 0.34 mg/L at two sampling locations on the lake (Wanielista et al., 1988). These values are extremely low in comparison to values that varied between 0.1 to 45 mg/L as reported by highway runoff for various sections of the country (FHWA, 1981). Likewise, Harper (1985) reported total iron concentrations ranging from 0.044 to 2.2 mg/L in a detention pond adjacent to Interstate-4 five miles north of Lake Angel.

Manganese concentrations were not reported by Wanielista (1988) at Lake Angel. However, Harper (1985) reported manganese concentrations ranging from trace concentrations to 0.06 mg/L. The major bacterial groups detected in the GAC system were not dependent on manganese but some could utilize it if it were present in substantial concentrations.

The underdrain pipe which received predominantly lake water on the west side of the junction box contained a small colonization of Thiothrix but did not contain Leptothrix or Gallionella. Bacteria did not cause clogging of the pipe. A possible explanation could be the clay layer emplaced around the pipe acted to adsorb the iron and manganese constituents from the groundwater. Nutrients from lake water would have been filtered as it moved through the lake bank sediments to the underdrain pipe. This pipe system still discharged appreciable amounts of water of approximately 0.05 cfs (Table 7).

In an effort to discourage bacterial growth, it was decided to plug the underdrain entering the GAC chamber and take water directly from the lake. By March 8, 1990, the underdrain was permanently plugged with cement and a 4" PVC pipe was connected to the concrete structure to take water directly from the lake into the GAC chamber. Therefore, the adsorption process at Lake Angel was not aided by pressurized flow which is typically found in GAC treatment facilities.

An Algae Queen gravel filter was placed at the influent end of the pipe in the lake to discourage algal accumulation within the GAC chamber. A four-inch gate valve was emplaced to control the water flow into the structure. Due to the severity of short circuiting, it was believed that the GAC had done little to adsorb either TOC or THMs from the influent

TABLE 7

FLOW RATES OF UNDERGROUND PIPE SYSTEMS AT LAKE ANGEL

DATE	WEST DRAIN PIPE FLOW (cfs)	EAST DRAIN PIPE FLOW (cfs)
11/1	0.055	0.047
11/3	0.054	0.047
11/10	0.050	0.043
11/28	0.057	0.046
12/1	0.048	0.037
12/19	0.055	0.040
1/3	0.055	0.020
2/9	0.050	---
2/21	0.050	---
5/23	0.050	0.0014

water during the sampling period of January 9 to January 23. Therefore, GAC was taken out of the bags and placed in the first GAC chamber- supported by the concrete wall and aluminum blades. The total amount of GAC was 60 cu.ft. or 1620 lbs.

Additional modifications to the structure occurred on March 23, 1990. These changes included the placement of 20 - 15.5" (l) x 7.5" (w) x 7 5/8" (h) cinder blocks on a portion of the structure floor between the first and third aluminum blades. This was done to decrease the amount of dead space in the GAC chamber caused by the invert between the GAC chamber and the second chamber being ten inches above the floor of the structure. Gaps within the blocks were filled with the existing GAC. A 0.0006 centimeter polyethylene film (visqueen) was placed atop the blocks and attached to the aluminum blades by duct tape.

New GAC which constituted Bed #1 (front bed) was then placed atop the plastic film. An initial volume of 6.1 cu. ft. of GAC was added to the system. The top of the first carbon bed was 1.5 inches below the top of the second carbon bed. The second carbon bed was retained in its original form and not altered. Both GAC beds were separated by gravel. The second bed was about 7 5/8 inches deeper than Bed No.1 (corresponding height of the cinder block) and 1.5 inches higher than the first carbon bed.

Porosity Measurements

Porosity is defined as the ratio of the volume of the voids (V0) to the total volume (V). Determination of the GAC porosity was very simplistic. First, a specific volume of GAC was placed and measured in a graduated cylinder. This volume represented the volume of solids. Then a predetermined volume of water was added to the GAC and the total volume was noted. The volume of voids was equal to the difference between the total volume and the volume of the GAC. The porosity was calculated as the volume of the voids divided by the total volume. Four different measurements gave porosity values of 42%, 38%, 40 %, and 39% with an average porosity of 40%.

CHAPTER V

RESULTS AND DISCUSSION

Flow Rates

Water samples before and after the GAC beds were analyzed for TOC, THMFP, and flow rates from March 8, 1990 to June 12, 1990. Color and pH measurements were first taken on March 16, 1990. Temperature readings were taken with a Hartz aquarium thermometer beginning April 13, 1990.

As observed by Figure 13, flow rates varied between 0.0002 to 0.0011 cfs during the sampling period. This variability was partly due to head differences in the pond and clogging between sampling periods. A high flow rate would result in water overtopping the carbon beds and bypassing treatment. A low flow rate would result in partial utilization of the total carbon bed to treat the water. Toward the end of the sampling period (mid-May), which coincided with increasing water temperature and algal growth in the lake, the influent pipe between the lake and GAC chamber became partially clogged with algal material. This resulted in a decreasing flow rate during the time interval between sampling visits to the site.

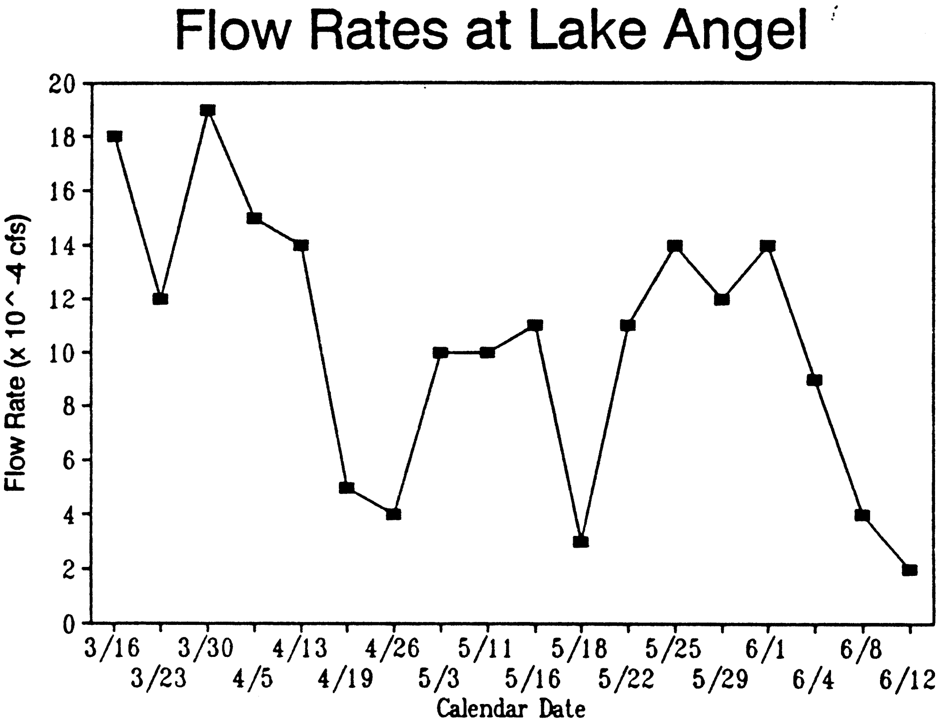


Figure 13. Flow Rates At the Lake Angel Detention Pond.

Rainfall events affect the quantity of detained stormwater and the amount of water input to the GAC beds. According to visual observations and rainfall data provided by the National Oceanic and Atmospheric Association (NOAA), there were at least seven rainfall episodes which resulted in submergence of the carbon beds during the sampling period. These precipitation events and their corresponding rainfall amounts were measured at the Orlando International Airport roughly 11 miles away (Appendix I).

The rainfall events which submerged the carbon beds resulted in the creation of great pressure and elevation head differential by stormwater flowing over the lake weir within the junction box before entering the 20-inch aquifer well. The pressurized water flowed from the junction box into the GAC chamber via the 8" pipe and submerged the carbon beds. The effect of these rainfall events on the GAC beds resulted in slight displacement of carbon within the beds or minor changes in the packing arrangement of the carbon particles. Minor amounts of carbon may have been carried away by the retreating waters. However, the decrease in carbon volume after each submergence episode was not believed to be significant - based upon calculations before and after the rainfall episodes which showed insignificant decreases in volume.

Conditions During The Sampling Period

It was noted during the sampling period that water levels in the GAC chamber did not necessarily coincide with the top of the carbon beds. This resulted in partial utilization of the carbon bed to treat the influent water quantity if the water level was lower than the top of the bed. Conversely, a water level higher than the first carbon bed resulted in water flowing over the top. However, the flow rates were never high enough for this possibility to occur.

In order to quantify the volume of carbon used for treatment during each sampling period, flow rates and corresponding water heights before and after the carbon beds were recorded from May 24 to June 28. From these observations it was noted that a 0.25 inch head loss occurred through the first bed. Since the water height between the first and second beds varied slightly and the water level on the effluent end of the second bed was controlled by the weir invert, the average head loss for the second bed was calculated to be five inches.

Using seven separate experiments of flow rate and height of water in the beds, a mathematical relationships between the two was developed for the two carbon beds are shown in Figures 14 and 15. The relationship was assumed to be linear with a correlation coefficients for beds 1 and 2 of 0.999 and 0.993, respectively. A ratio between the water height of each corresponding carbon bed and the height of the carbon bed was

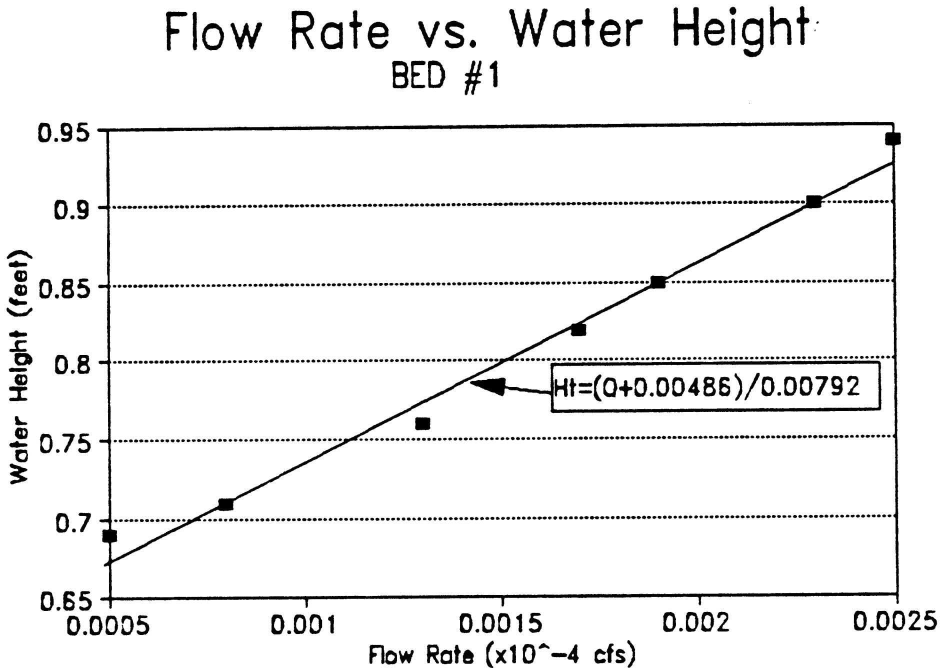


Figure 14. Flow Rate vs. Height of Water - Bed #1.

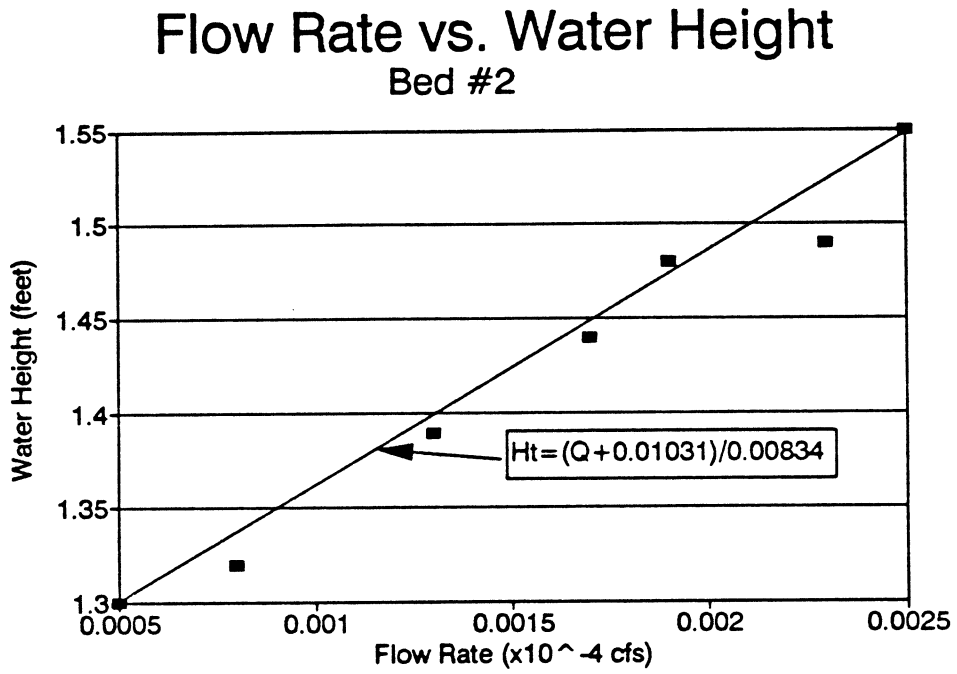


Figure 15. Flow Rate vs. Height of Water - Bed #2.

calculated. This value was then multiplied by the total bed volume to find the volume of carbon used for treatment during each sampling episode (Tables 8 and 9). These values assume (1) constant flow rates between sampling periods (which is a conservative assumption as previously discussed) and (2) high flow rates resulting in overtopping of the first carbon bed resulted in the entire quantity of water being treated by the bed(s).

The weighted volume of carbon utilized in the first bed was 5.25 cubic feet. The volume of the second carbon bed was determined by taking volume measurements of the length, width, and height of the bed. Thus, the porosity must be accounted for since the carbon bed was expanded and is calculated as 17.6 ft^3 x (1-0.40) or 10.6 ft^3. All future references to the number of bed volumes will be determined by the multiple volumes of 5.25 ft^3 or 10.6 ft^3 for beds one and two, respectively.

The amount of carbon utilized during the flow conditions was then used to calculate the empty bed contact time (EBCT). The EBCT was calculated by dividing the volume of carbon used by the flow rate. EBCT values are given in Tables 8 and 9. The average EBCT values for beds one and two were 80 minutes and 160 minutes, respectively.

TABLE 8
EMPTY BED CONTACT TIME AND BED VOLUME CALCULATIONS FOR CARBON BED #1

DATE	FLOW RATE (cfs)	WATER HEIGHT (ft.)	CARBON VOLUME USED (cu.ft.)	EBCT (min.)	CUMUL. BED VOLUMES
3/8	0.0	0.0	0.0	0.0	0.0
3/16	0.0018	0.77	5.37	48.61	237
3/23	0.0012	0.84	5.86	72.92	375
3/30	0.0019	0.80	5.58	46.05	594
4/5	0.0015	0.79	5.51	58.33	742
4/13	0.0014	0.68	4.74	62.50	927
4/19	0.0005	0.66	4.60	175.00	976
4/26	0.0004	0.74	5.16	218.75	1022
5/3	0.0010	0.74	5.16	87.50	1137
5/11	0.0010	0.75	5.23	87.50	1269
5/16	0.0011	0.65	4.53	79.55	1359
5/18	0.0003	0.75	5.23	291.67	1369
5/22	0.0011	0.79	5.51	79.55	1442
5/25	0.0014	0.77	5.37	67.50	1571
5/29	0.0012	0.79	5.51	72.92	1590
6/1	0.0014	0.73	5.09	62.50	1636
6/4	0.0009	0.66	4.60	92.22	1680
6/8	0.0004	0.64	4.46	218.75	1707
6/12	0.0002	0.61	4.25	437.50	1720
WEIGHTED MEAN	0.0011	0.75	5.25	79.55	---

Note: EBCT assumes a bed volume of 5.25 cubic feet.

TABLE 9

EMPTY BED CONTACT TIME AND BED VOLUME CALCULATIONS FOR CARBON BED #2

DATE	FLOW RATE (cfs)	WATER HEIGHT (ft.)	CARBON VOLUME USED (cu.ft.)	EBCT (min)	CUMUL. BED VOLUMES
3/8	0.0	0.0	0.0	0	0
3/16	0.0018	1.45	10.78	98	118
3/23	0.0012	1.38	10.51	147	272
3/30	0.0019	1.46	10.82	93	376
4/5	0.0015	1.42	10.64	118	515
4/13	0.0014	1.40	10.60	126	663
4/19	0.0005	1.30	10.20	352	766
4/26	0.0004	1.28	10.60	440	809
5/3	0.0010	1.36	10.42	176	842
5/11	0.0010	1.36	10.42	176	941
5/16	0.0011	1.37	10.47	160	1003
5/18	0.0003	1.27	10.12	587	1030
5/22	0.0011	1.37	10.47	160	1044
5/25	0.0014	1.40	10.60	126	1085
5/29	0.0012	1.38	10.51	147	1154
6/1	0.0014	1.40	10.61	126	1183
6/4	0.0009	1.34	10.31	196	1234
6/8	0.0004	1.28	10.16	440	1279
6/12	0.0002	1.26	10.07	880	1299
WEIGHTED MEAN	0.0011	1.39	10.56	160	---

Note: EBCT assumes a bed volume of 10.56 cubic feet

Correlation Between Color, TOC, and THMFP

The correlation between THMFP and other parameters is important due to the expense entailed by conducting THMFP samples and the long period of time before results are completed. Therefore, surrogate parameters which have a strong correlation with THMFP may be conducted quickly and inexpensively. TOC is often the most widely used surrogate parameter used for THM predictions. This correlation is possible because precursors of TOC and THMs are often the same. Correlations are possible only on a site-by-site basis due to the widely variable nature of humic and fulvic acids. The author found little correlation between color and THMs from literature probably for this very reason. Since color is very inexpensive to analyze and may be performed immediately after the sample is taken, it would be an ideal surrogate for THMs.

Correlations between THMFP and TOC, TOC and color, and THMFP and color were 0.840, 0.890, and 0.893. The data used are shown in Figures 16, 17, and 18, respectively. The corresponding equations are:

$$\mathrm{THM}(\mu g/L) = 32.165(\mathrm{TOC}) + 74.51 \qquad R = 0.840 \tag{13}$$

$$\mathrm{TOC}(mg/L) = 0.123(\mathrm{Color}) - 1.49 \qquad R = 0.890 \tag{14}$$

$$\mathrm{THM}(\mu g/L) = 5.55(\mathrm{Color}) - 14.86 \qquad R = 0.893. \tag{15}$$

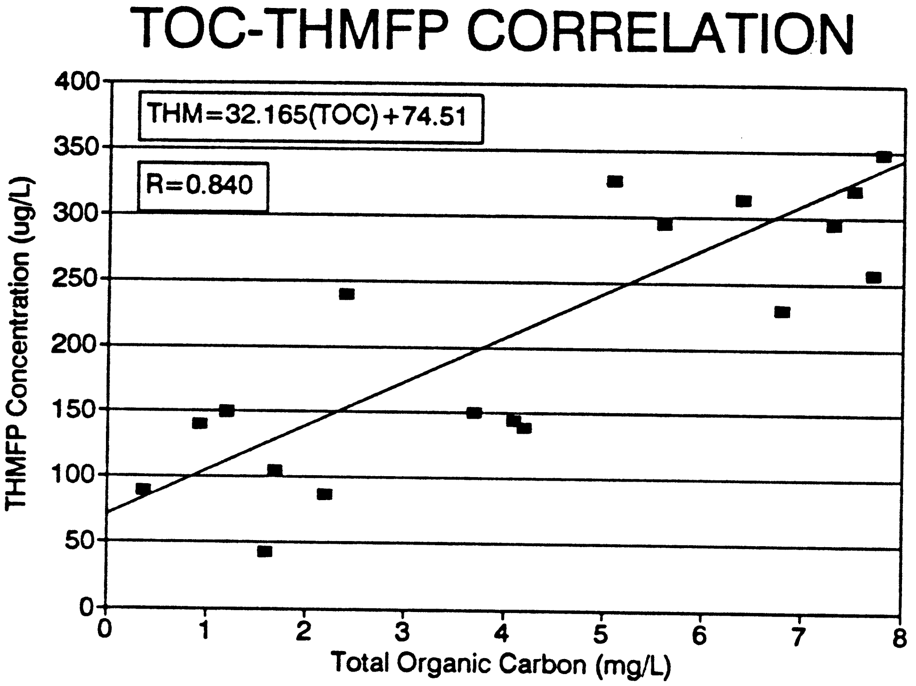


Figure 16. THMFP and TOC Correlation.

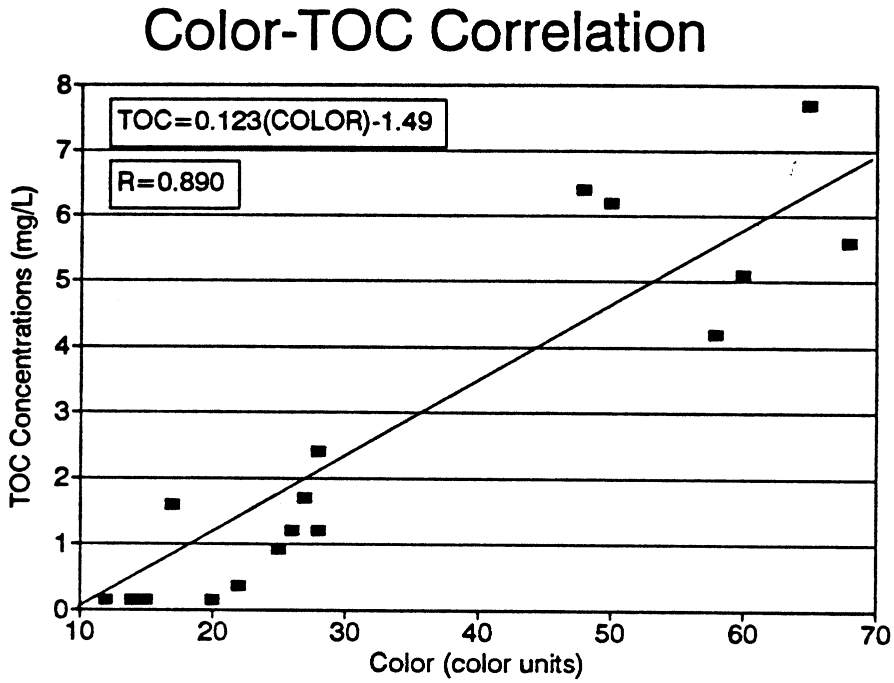


Figure 17. TOC and Color Correlation

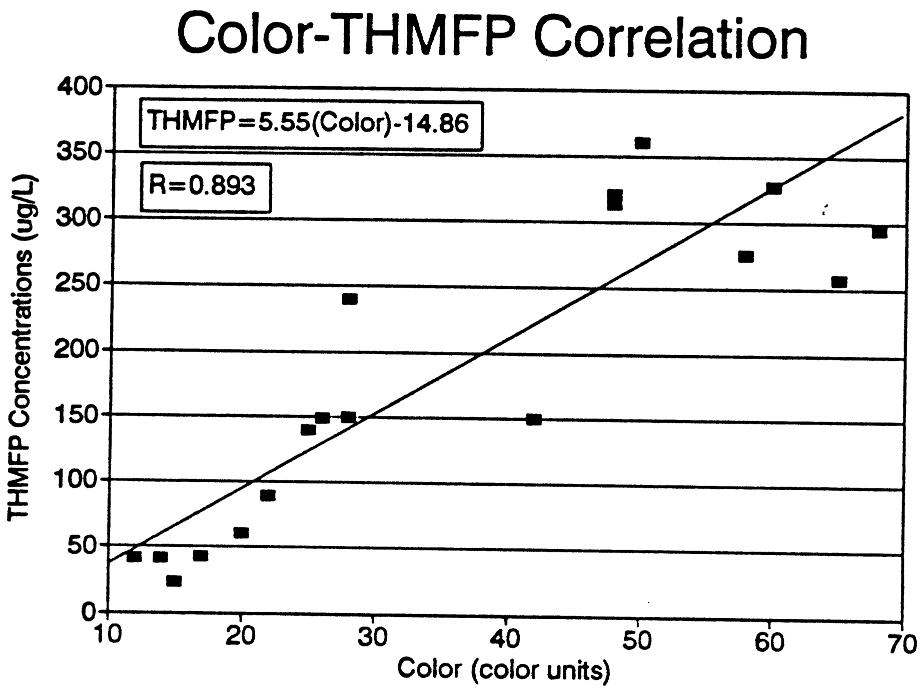


Figure 18. THMFP and Color Correlation

Objective One Summary

The general correlations between THMFP, TOC, and color were acceptable. Therefore, TOC and color may serve as useful surrogate parameters for THMFP at Lake Angel.

Color Measurements

As mentioned previously, color measurements were initiated on March 23, 1990 (Appendix II) and ranged from 12 to 70 color units. The overall average color measured was 40.5 color units with a standard deviation of 17.3 color units.

A progressive decrease in color as the water flowed through the GAC system is evident by observing the average color measurements of the lake (influent) and the two carbon beds effluents. The average values were 56.5, 42.0 and 23.0 for influent, bed #1 effluent, and bed #2 effluent, respectively.

Adsorption of color by the GAC is shown by a plot of color with time (Figure 19) for the influent and effluent of the two carbon beds. Color measurements of the first carbon bed were initially divergent as adsorbate was adsorbed onto the carbon. However, the concentrations began to approximate each other after April 11 as breakthrough began to occur (850 bed volumes). However, the opposite sequence occurred for the second carbon bed since the influent and effluent concentrations were close together before exhaustion of the

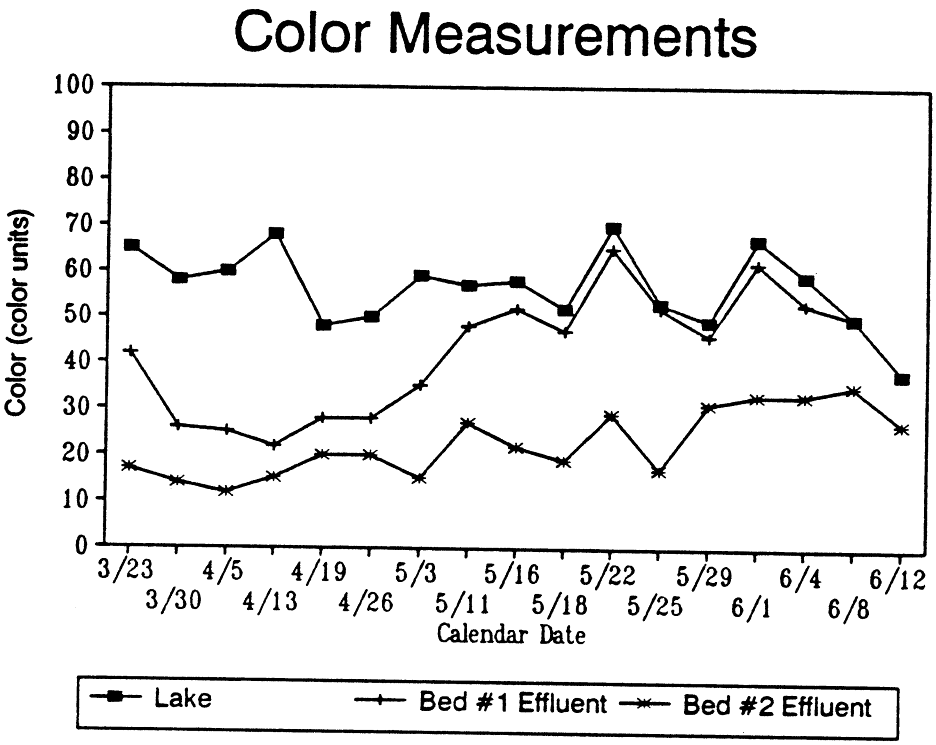


Figure 19. Color Measurements.

first carbon bed. After breakthrough and exhaustion of the first carbon bed, greater concentrations of color were transported to the second carbon bed. Since adsorption capacity increases with increasing adsorbate concentrations, the influent and effluent concentrations of the second carbon bed diverged. This same sequence occurred in TOC.

Concentration ratios (C_1/C_0) for color as well as NPOC, and THMFP were high for the first three sampling dates. This occurred because the first aluminum blade closest to the gate valve became detached from the wall and allowed water to short-circuit through the first carbon bed. The problem was remedied on April 5, 1990 by wedging the blade against the wall. The samples of that date were taken approximately four hours after the corrective measure was accomplished.

The breakthrough curve of the first bed for color is shown in Figure 20. Breakthrough appears to have occurred around 138,000 liters of treated water (900 bed volumes). Exhaustion appears to have occurred around 1150 bed volumes after treating 185,000 liters of lake water.

It is not believed that either color breakthrough or exhaustion was reached in the second carbon bed (Figure 21) though bioactivity within the carbon bed would prevent the C2/C1 ratio from reaching 0.95. In order to clarify whether the second carbon bed reached breakthrough, additional data should be obtained. The effluent/influent ratio value of 0.71 on the last sampling date probably indicates that if

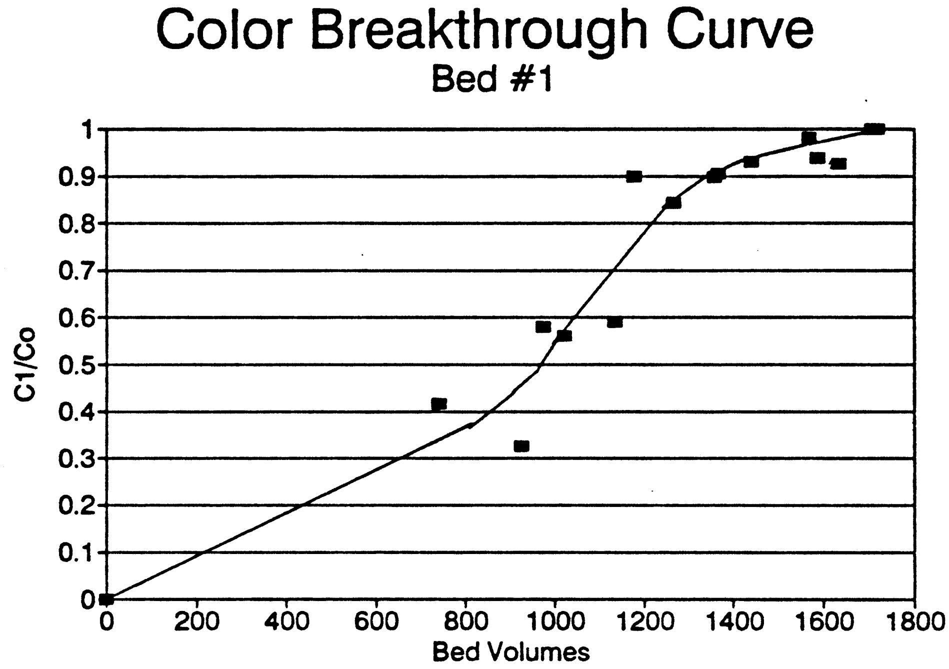


Figure 20. Color Breakthrough Curve - Bed #1.

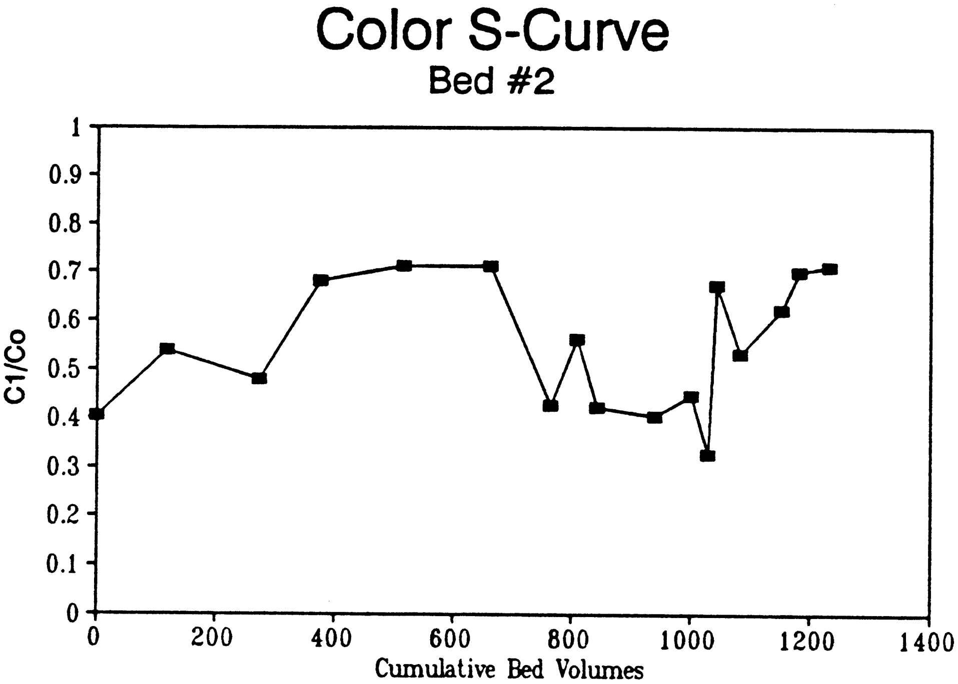


Figure 21. Color S-Curve - Bed #2.

exhaustion had not already occurred, it would occur shortly.

Total Organic Carbon Concentrations

TOC values (measured as nonpurgeable organic carbon or NPOC) within the GAC chamber varied between 8.4 mg/L NPOC and BDL (below detectable limit) as shown in Appendix II. In general, the TOC concentrations of the lake increased with increasing water temperature, color and THMFP concentrations. The average TOC concentration was 4.91 mg/L with a standard deviation of 2.82 mg/L.

The average TOC concentrations for lake and carbon beds 1, and 2 were 6.99, 4.62, and 2.07 mg/L, respectively. This overall reduction in TOC concentrations demonstrates that GAC is an excellent media for adsorbing TOC at the Lake Angel detention pond. TOC removal can also be seen by comparison of the influent and effluent concentrations of the carbon beds (Figure 22). Note the relationship of influent and effluent TOC concentrations of the two carbon beds were similar to the color measurements. Influent and effluent concentrations of the first bed were divergent from April 26 to May 11 and similar afterward after reaching exhaustion (similar to color). The opposite pattern existed for the second bed.

The breakthrough curve of bed #1 (Figure 23) indicates a breakthrough volume similar to that of carbon (900 bed volumes or 138,000 liters of treated water). Exhaustion was reached around 185,000 liters (1270 bed volumes). Note that after

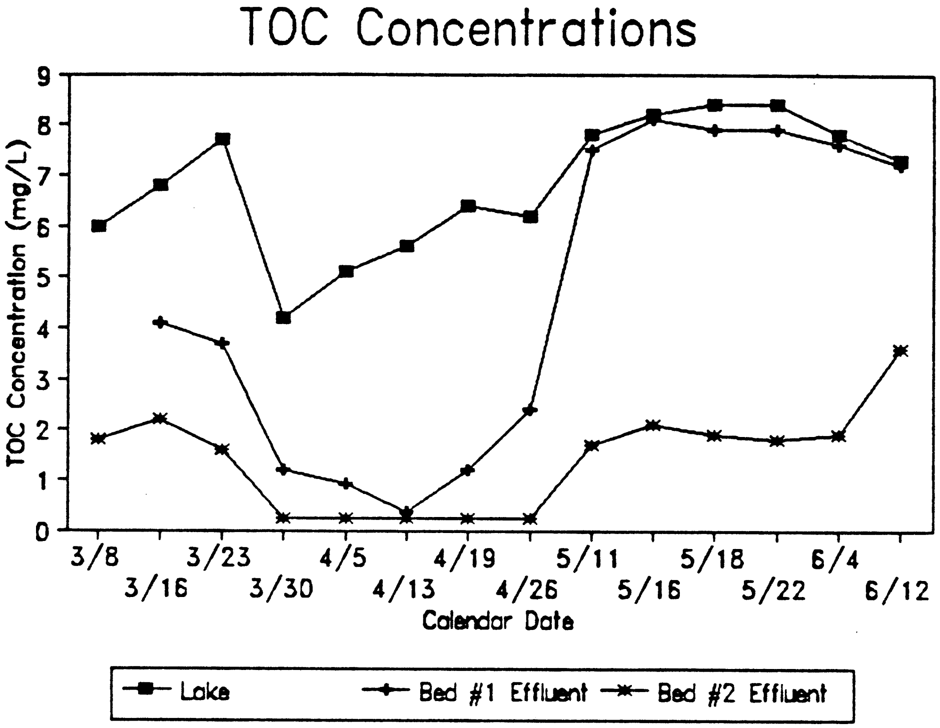


Figure 22. Total Organic Carbon Concentrations.

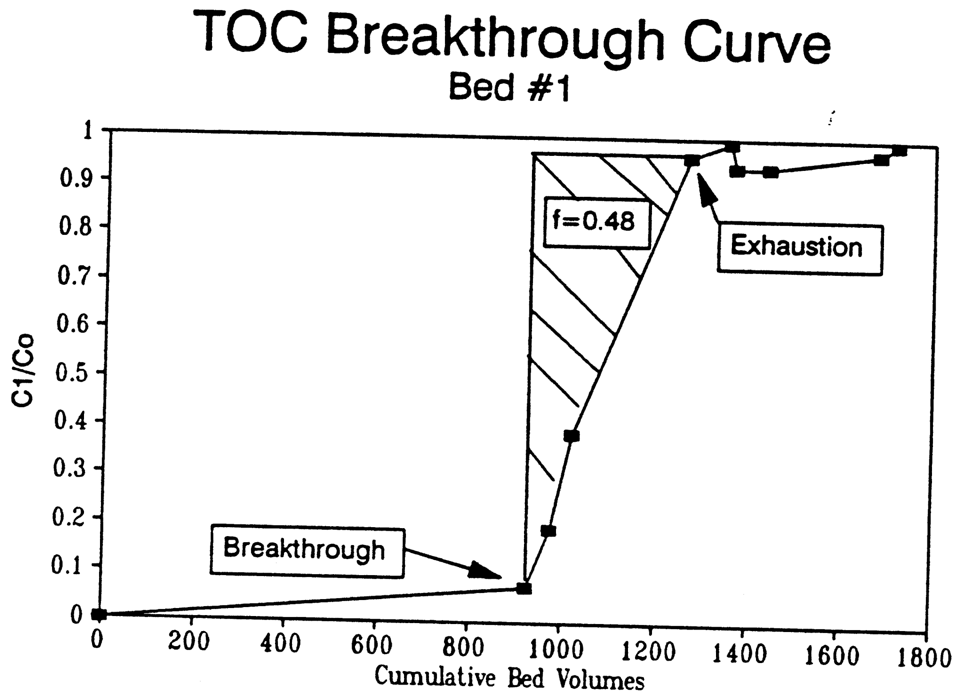


Figure 23. Total Organic Carbon Breakthrough Curve - Bed #1.

exhaustion, a pseudo steady-state may have been reached. However, more data are probably needed to confirm this.

As can be seen in Figure 24, bed #2 did not reach breakthrough for TOC. However, the breakthrough curve for bed #1 and the difference between influent and effluent TOC concentrations demonstrate that GAC can adsorb the constituents which constitute TOC.

Accumulated mass of TOC was used to provide a measure for breakthrough and exhaustion. It was calculated by multiplying the difference between influent and effluent concentrations by the quantity of treated water. Breakthrough and exhaustion should be easily identified by noting slope changes of the cumulative mass.

Breakthrough and exhaustion points of cumulative mass of TOC in the first carbon bed are not obvious (Figure 25). It does appear that the slope of cumulative mass becomes horizontal after 900 bed volumes. Exhaustion of TOC by BED #1 indicates that 6.3 mg TOC/gram carbon was obtained from this study. This value falls within the range of values that Russell (1989) found for his large column study (Table 3).

The same pattern of change appears in bed #2 (Figure 26). After 400 bed volumes, the second bed begins to adsorb a greater amount of adsorbate.

In general, the smaller the adsorption zone, the more efficient is the carbon bed. Using a bed length of 5.83 feet, breakthrough volume of 138,000 liters, and an exhaustion

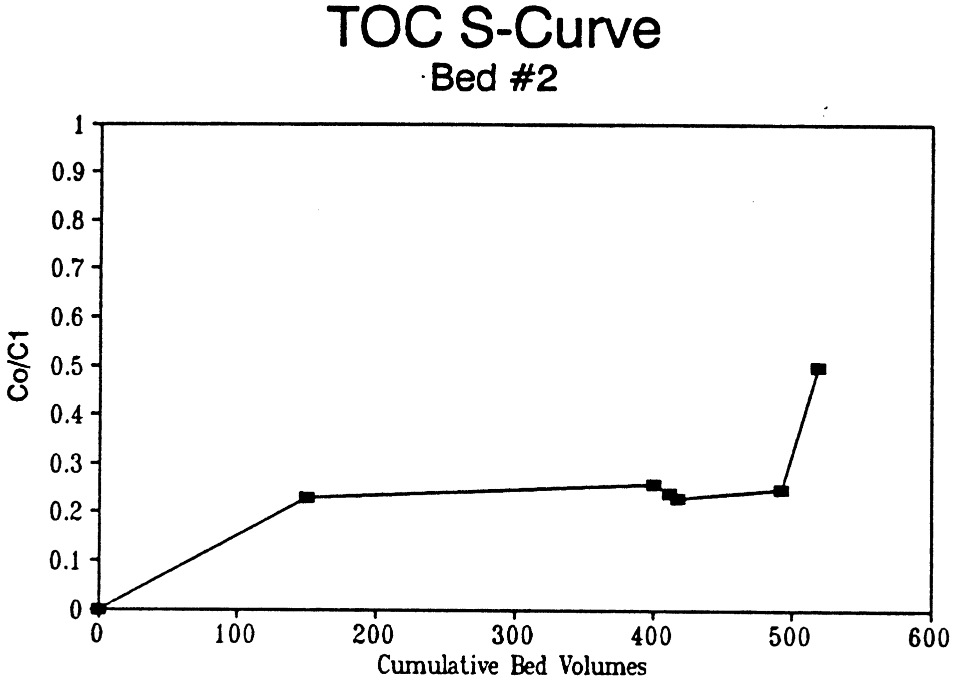


Figure 24. Total Organic Carbon S-Curve - Bed #2.

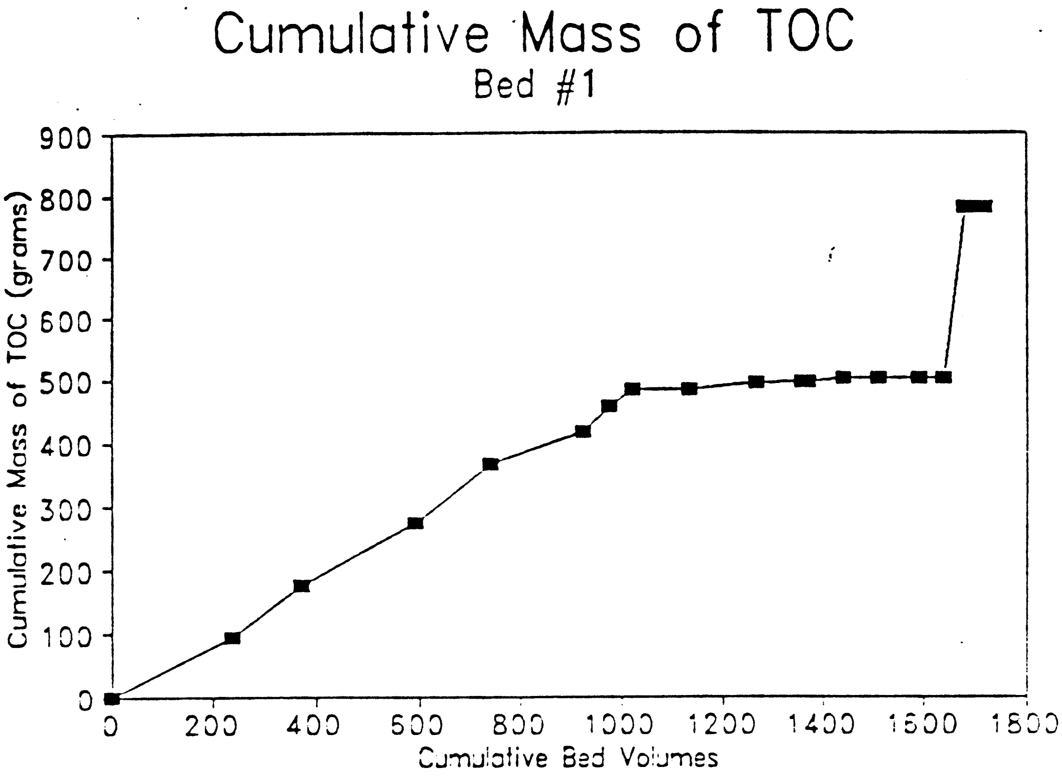


Figure 25. Cumulative Mass of TOC - Bed #1.

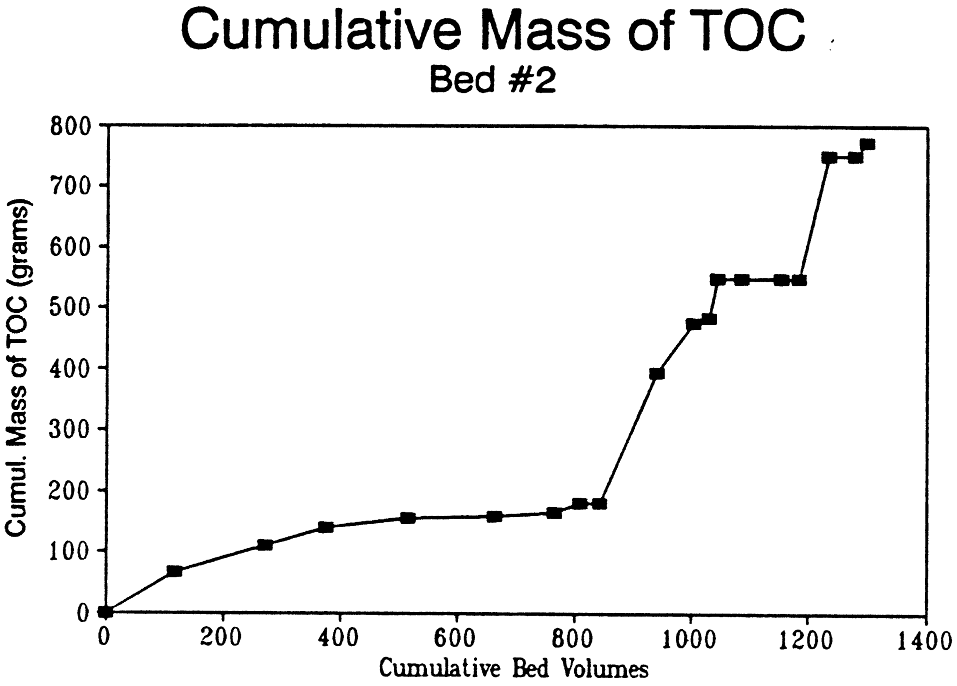


Figure 26. Cumulative Mass of TOC - Bed #2.

volume of 185,000 liters, the length of the sorption zone was calculated to be 1.70 feet or 30 percent of the total bed length. The fractional capacity of the adsorption zone was calculated to be 48% by measuring the area above the curve between breakthrough and exhaustion and dividing this value by the total area between breakthrough and exhaustion. The time required for the adsorption zone to break through the carbon bed was 17.5 days. The time required for the bed to reach exhaustion was 69 days and the formation time of the adsorption zone was 9.1 days.

Trihalomethane Formation Potential Concentrations

A dramatic change in the THMFP concentrations occurred after May 11, 1990 (Appendix II). Until that time, influent THMFP concentrations were ranging from 260 to 361 μg/L with corresponding TOC concentrations ranging from 4.2 to 7.7 mg/L. After the aforementioned date, influent THMFP concentrations decreased to values of 116, 80, and 141 μg/L on May 16, 18, and 22, respectively, while corresponding TOC values increased to 8.2, 8.4, and 8.4, mg/L, respectively.

An investigation in regard to the dramatic decrease of the THMFP values was conducted by the Priority Pollutant Lab at the University of Central Florida. Sampling procedures and standards were reevaluated but found to be correct. Other samples analyzed simultaneously with those of Lake Angel showed little significant change. The residual chlorine and pH both before and after the dosing showed no significant changes from those of the month earlier. Possible explanations for the concentration discrepancy include: an irregular carbon source; contamination by the bottle; or difference in analysis as a result of a personnel change which occurred at this time.

Unused portions of the original May 16th sample were retrieved and reanalyzed at the UCF Priority Pollutant Laboratory. Due to the long period of time between the date at which the sample was taken and its reanalysis on June 29, 1990 (during which time the sample was at room temperature), biological activity should have consumed much of the organic carbon-resulting in low THMFP concentrations. The original THMFP was 116 μg/L on May 16th. However, the THMFP concentration was reanalyzed to be 483 μg/L.

THMFP concentrations ranged from 42 to 600 μg/L as shown in Appendix II. The overall concentration was 165.3 μg/L with a standard deviation of 107 μg/L. The average THMFP concentrations for lake and beds 1 and 2 were 286.9, 151.7, and 55.7 μg/L, respectively.

Influent and effluent THMFP concentrations are shown in Figure 27. The sequence of converging/diverging concentrations before and after breakthrough are not as clear as in color and TOC.

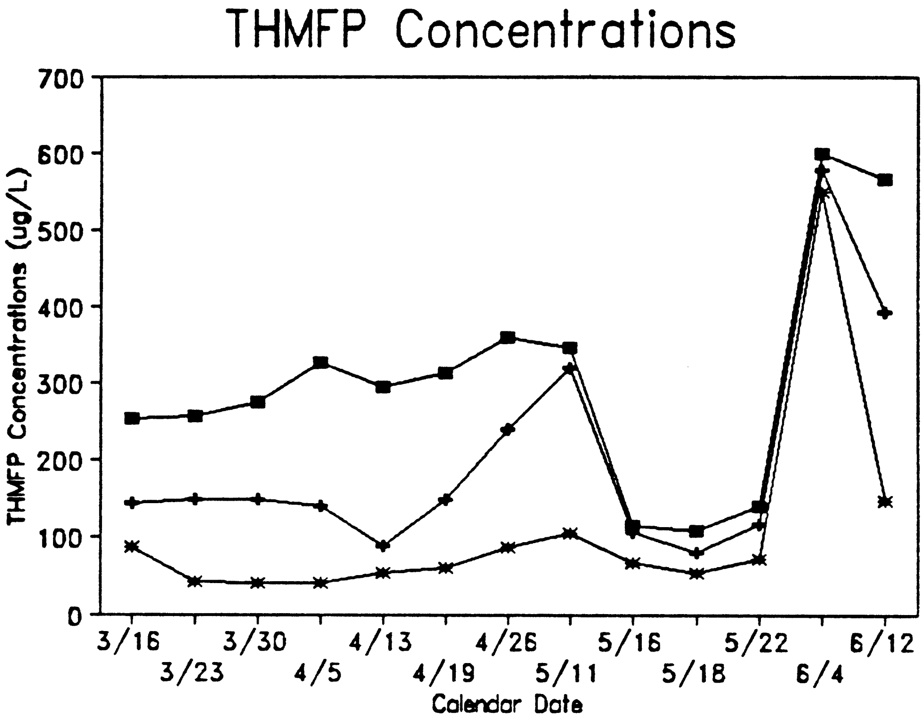


Figure 27. Trihalomethane Formation Potential Concentrations.

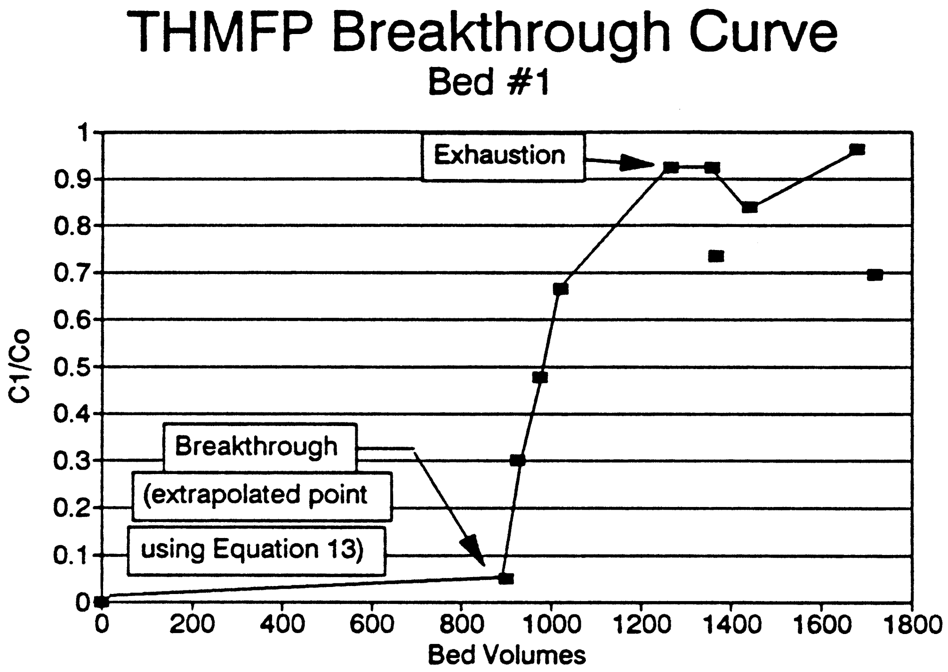


Figure 28. THMF Breakthrough Curve - Bed #1.

Breakthrough of bed #1 appears to have occurred around 138,000 liters of treated water (900 bed volumes) as shown in Figure 28. Exhaustion in bed #1 appears to have occurred around May 11th since the relative concentrations after this date are similar. This correlates to a value of 188,000 liters of treated water.

Despite the high effluent/influent concentration ratios during the latter portion of the sampling period, it is not believed that breakthrough was reached in the second bed (Figure 29). While a high ratio value of 0.95 was obtained on June 4th, the preceding and succeeding values were very low (0.60 and 0.38, respectively).

The cumulative mass of THMFP of bed #1 is shown in Figure 30. As in the case of color, breakthrough and exhaustion may be identified by changes in slope. Breakthrough occurred around 600 bed volumes. Exhaustion occurred around 900 bed volumes - earlier than was observed by the breakthrough curve. The cumulative mass of THMFP for bed #2 is shown in Figure 31.

Concentrations of the individual THMs are found in Appendix II. Chloroform was the most common THM found in the lake water (Figure 32) followed by bromoform ($CHBr_3$) and bromochloromethane ($CHBrCl_2$). Dibromochloromethane ($CHBrCl_2$) was rarely encountered at the Lake Angel site. Therefore, the precursors of THMs at the Lake Angel detention facility are composed of the lower molecular weight humic acids and algal products.

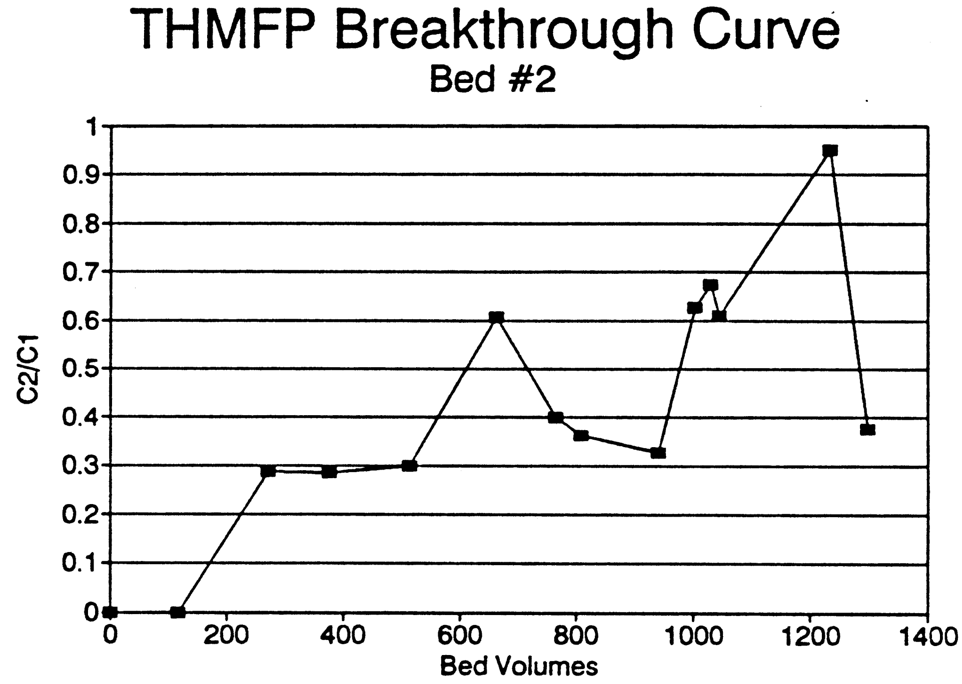


Figure 29. THMFP S-Curve - Bed #2.

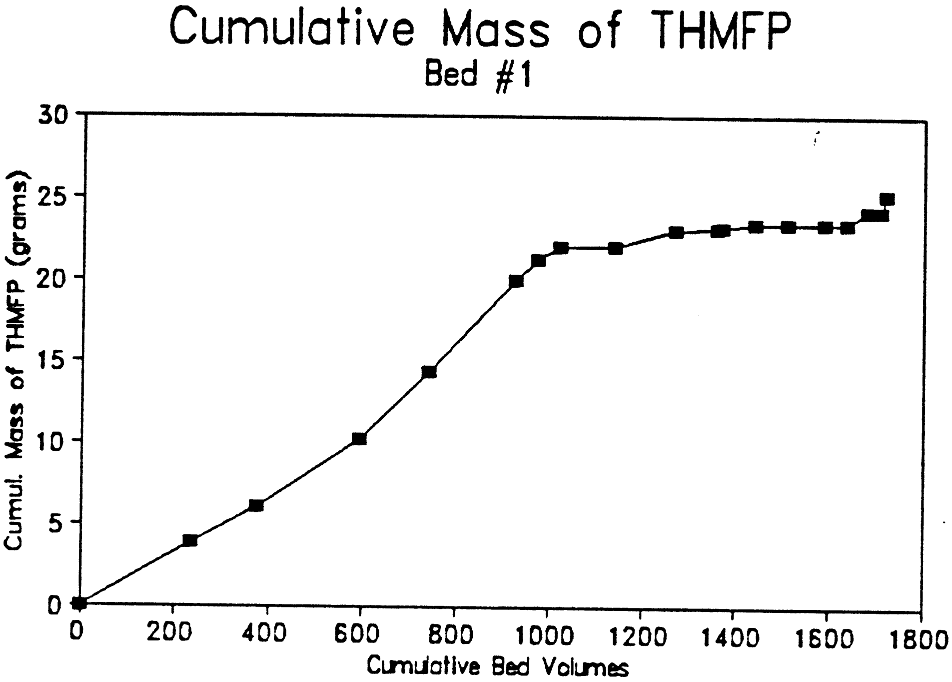


Figure 30. Cumulative Mass of THMFP - Bed #1.

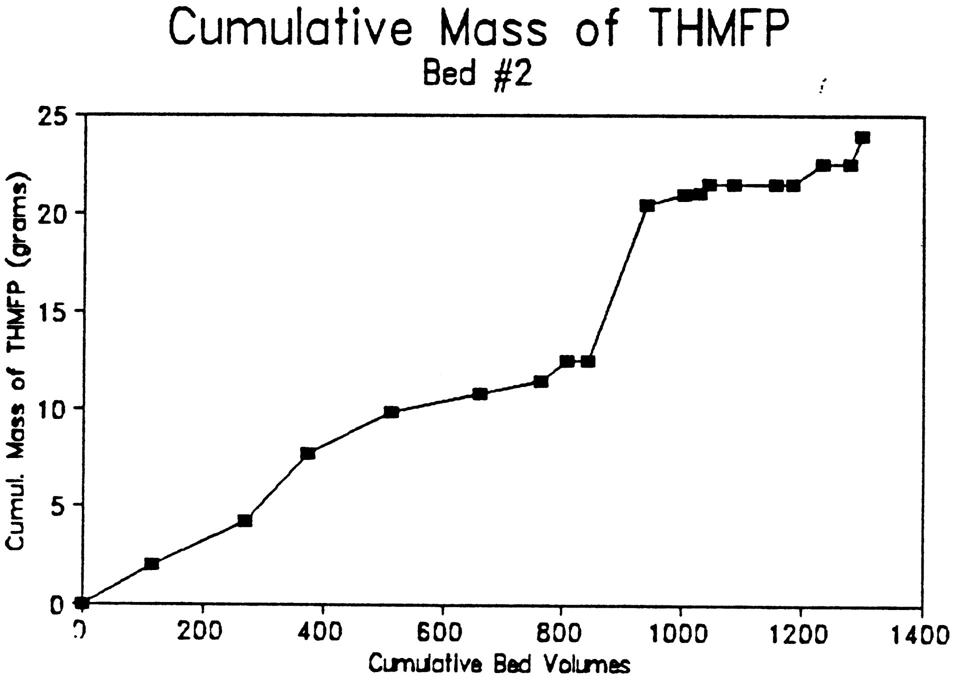


Figure 31. Cumulative Mass of THMFP - Bed #2.

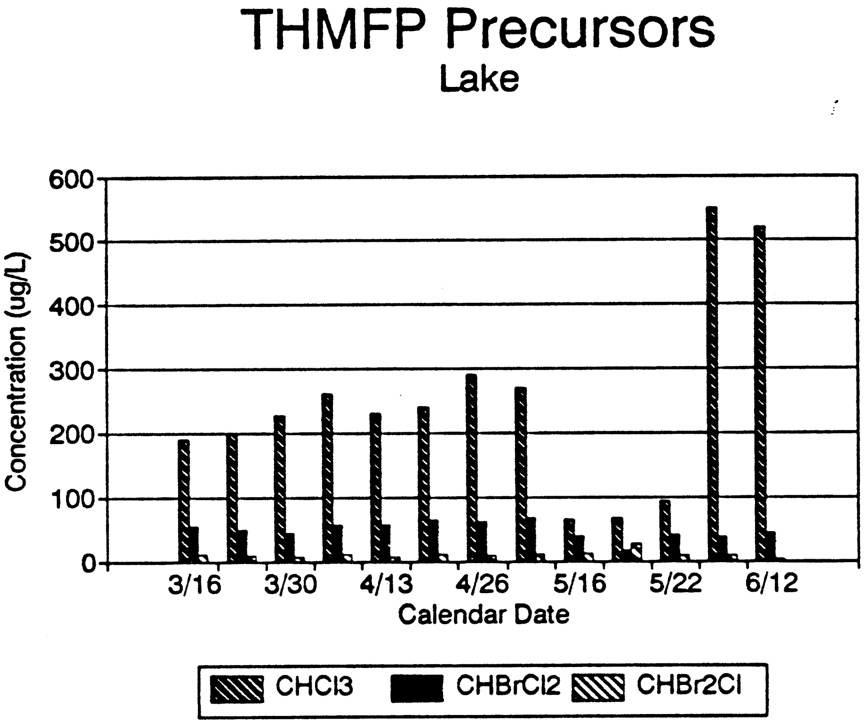


Figure 32. Trihalomethane Precursor Constituents - Lake.

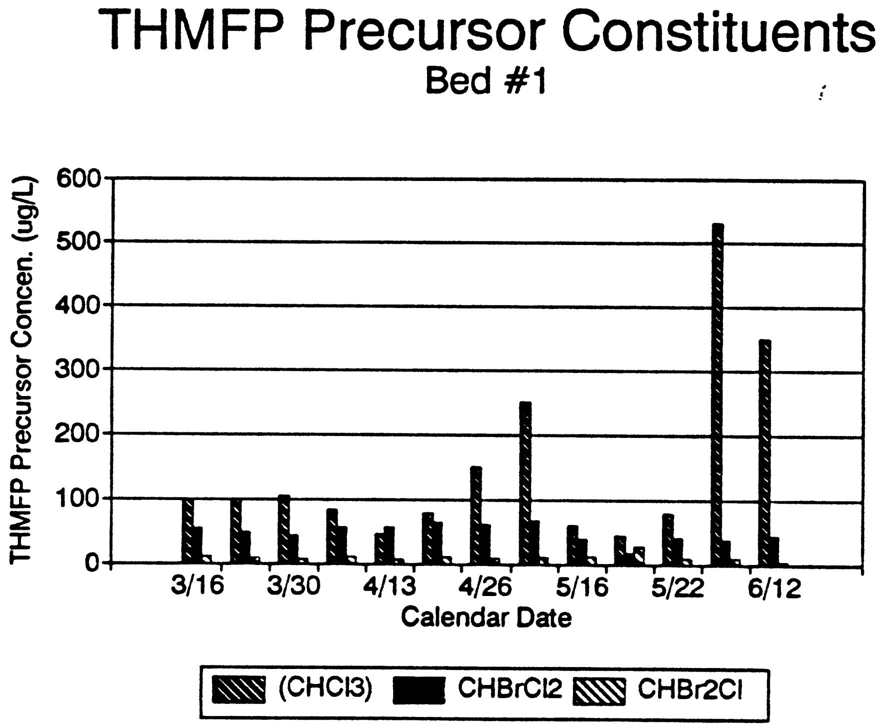


Figure 33. Trihalomethane Precursor Constituents - Bed #1

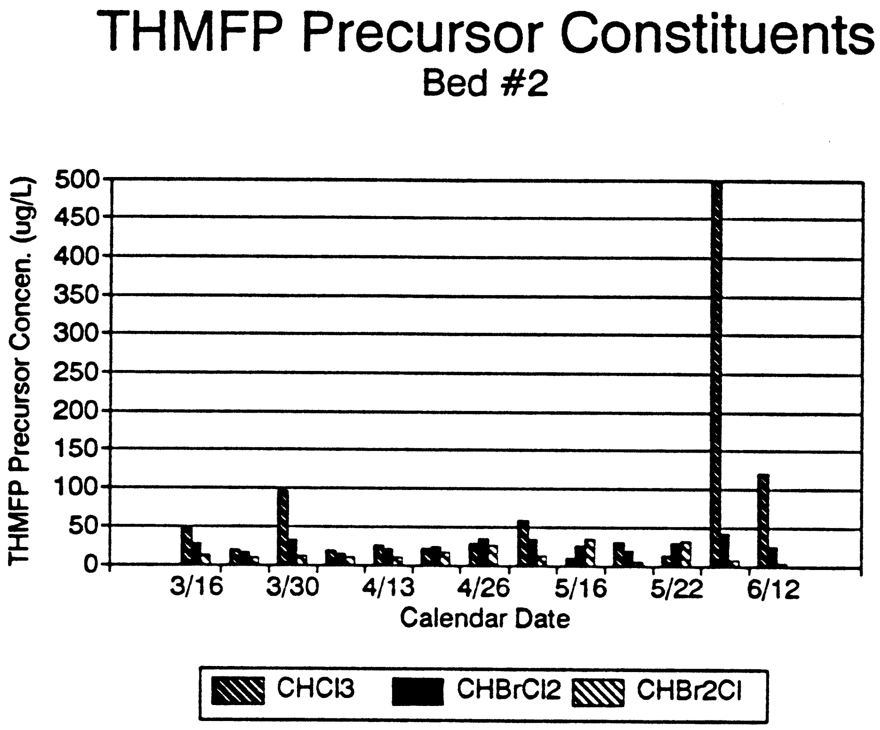


Figure 34. Trihalomethane Precursor Constituents - Bed #2

Reduction of the THM constituents may be seen by comparing Figures 32, 33, and 34. Exhaustion for the three species occurred around May 11th. This can be seen by the small differences between the two concentrations after May 11. This pattern may also be seen in bed #2 (Figures 34). Figures 35, 36, and 37 show concentrations for chloroform, Dichlorobromomethane, and Dibromochloromethane, respectively. Therefore, GAC is an excellent adsorbent for the removal of the lower to moderate molecular weight THMs (chloroform, dibromochloromethane, and bromodichloromethane).

Temperature and pH Measurements

As can be seen in Appendix II, pH readings remained in the "neutral" range since they varied between 7.0 and 7.3. These neutral pH ranges provide an excellent environment for bacterial growth. The pH measurements were recorded with a Corning pH Meter Model 10.

Temperature of the lake water increased with time. The lowest recorded temperature was 22.5°C and the highest was 29 degrees Celsius. Therefore, adsorption probably increased with time during the experiment's duration.

Objective Two Summary

In summary, color, TOC, and THMFP appear to have reached breakthrough in the first carbon bed after 900 bed volumes or 138,000 liters of treated water. Exhaustion was reached after 1270 bed volumes or 185,000 liters of treated water for color

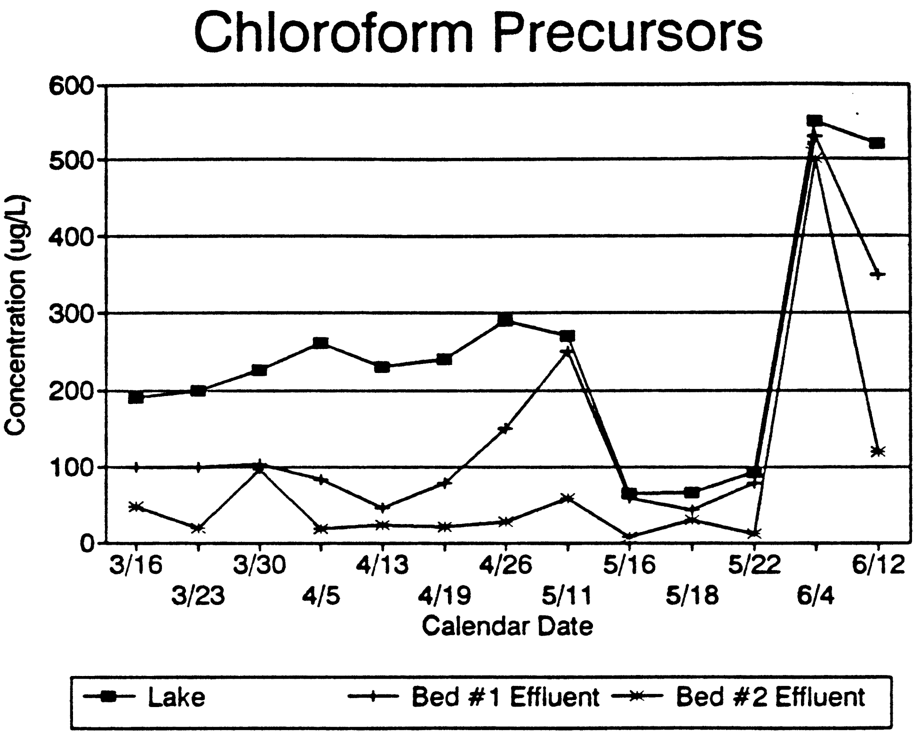


Figure 35. Chloroform Precursor Concentrations.

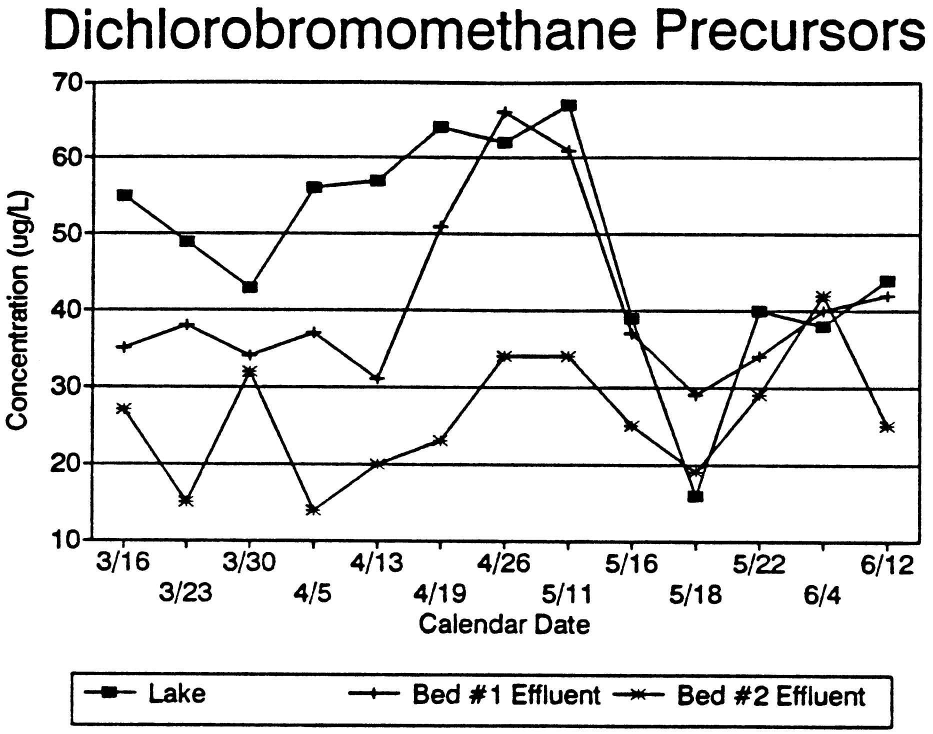


Figure 36. Dichlorobromomethane Precursor Concentrations.

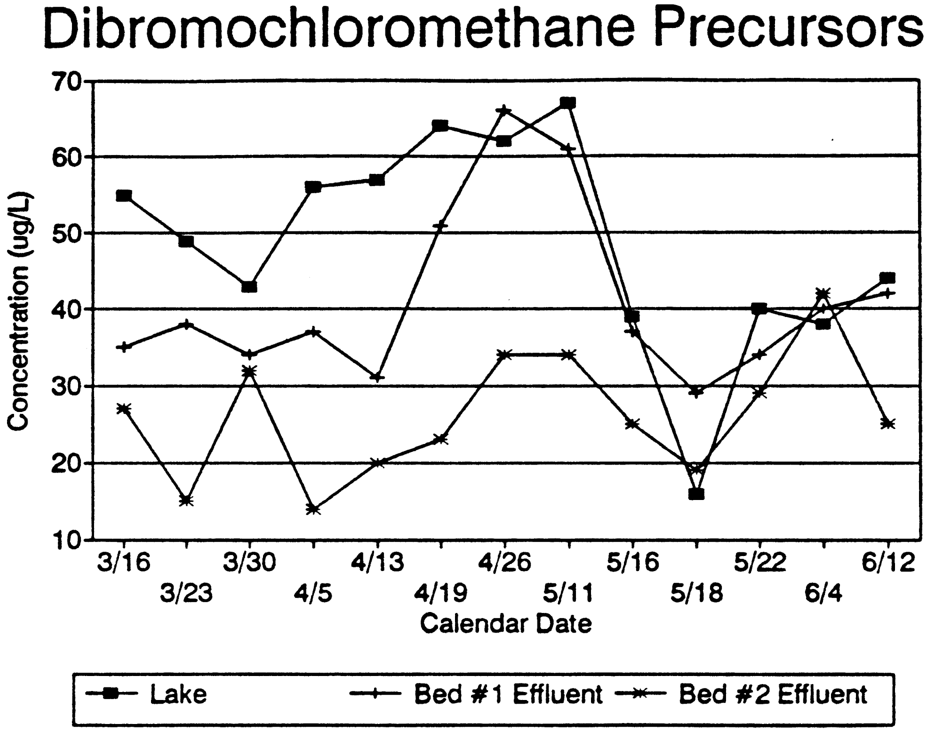


Figure 37. Dibromochloromethane Precursor Concentrations.

and TOC and around 188,000 liters of treated water for THMFP. The volume of treated water was very low. The length of the sorption zone was calculated to be 1.70 feet. The mass of TOC adsorbed onto the carbon was calculated to be 6.3 mg TOC/g carbon.

Comparison of lake and effluent concentrations from the two carbon beds indicate that GAC can be used as an adsorbent of color, TOC, and THMFP precursors. In addition, the cumulative mass adsorbed for these particular parameters may further help to identify the breakthrough and exhaustion points at other locations.

Hydraulic Efficiency of the GAC

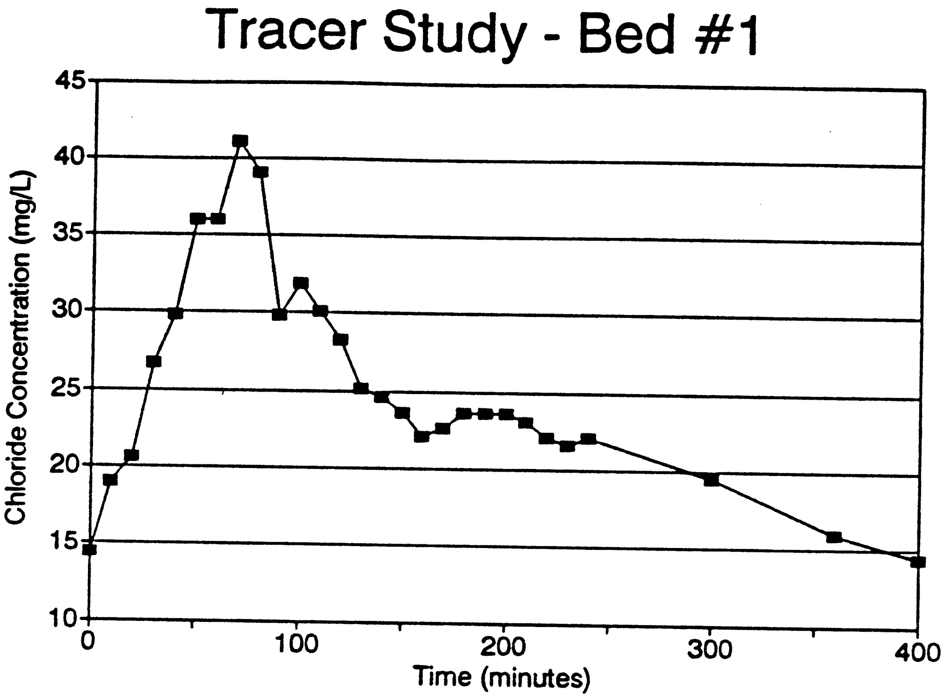
The residence times within the first carbon bed using tracer studies with NaCl were conducted to determine actual detention time in the first carbon bed. The purpose of the tests were to compare theoretical (calculated) and measured detention time of water through the carbon bed.

The test was conducted on July 12, 1990 and lasted seven hours and forty minutes. A mass of 68.254 grams of 0.0146 M NaCl was placed in a plastic container. One hundred milliliters of deionized water was added to the container and shaken.

At the site, the sodium chloride in the plastic container was again vigorously shaken. The contents were emptied immediately upstream of the first carbon bed. The empty container was then filled with water at a point one foot farther upstream, shaken, and its contents were emptied at the location at which the original tracer slug was placed. This was done to insure the entire contents of the sodium chloride were emptied out of the container. A background chloride sample was taken immediately preceding the experiment.

Samples were taken in 100 mL plastic bottles every ten minutes beginning at the time the slug was placed in the water column. The samples were taken at a point immediately downstream of the first carbon bed at a depth halfway between the bottom of the carbon bed and the water surface. The flow rate at the commencement and outset of the test was measured to be 0.0016 cfs. All samples were measured in the University of Central Florida Primary Pollutant Laboratory using the mercuric nitrate method for determining chlorides concentration. Chloride concentrations are shown in Figure 38. Test data are given in Table 10. Results indicate a measured average residence time of 132 minutes. Sample calculations are given in Appendix IV.

The theoretical residence time (empty bed contact time) was based upon a volume of 5.25 cubic feet of carbon (which corresponded to a flow rate of 0.0016 cfs) and was calculated by dividing the volume of the carbon bed by the flow rate. The theoretical residence time was calculated to be 59 minutes.



Background Chloride Concentration - 14.39 mg/L

Flow Rate - 0.0016 cfs

Figure 38. Tracer Analysis of Carbon Bed #1.

TABLE 10

TRACER ANALYSIS DATA
CARBON BED #1

TIME (min.)	CHLORIDE CONC. (mg/L)	CONC. x TIME	CONC.x TIME^2	MASS OF NaCl(MG)
0	14.39	0	0	0
10	19.02	190.20	1902.00	208
20	20.56	411.20	8224	277
30	26.73	801.90	24057	553
40	29.81	1192.40	47,696	691
50	35.98	1799.00	89,950	968
60	35.98	2158.80	129,480	968
70	41.12	2878.4	201,488	1199
80	39.07	3125.60	250,048	1107
90	29.81	2682.90	241,461	692
100	31.87	3187.00	318,700	784
110	30.12	3313.20	364,452	705
120	28.27	3392.40	407,088	622
130	25.19	3274.70	425,711	484
140	24.67	3453.80	483,532	461
150	23.65	3547.50	532,125	415
160	22.10	3536.00	565,760	346
170	22.62	3845.40	653,718	369
180	23.65	4257.00	766,260	415
190	23.65	4493.50	853,765	415
200	23.65	4730.00	946,000	415
210	23.13	4857.30	1,020,033	392
220	22.10	4862.00	1,069,640	346
230	21.59	4965.70	1,142,111	323
240	22.1	5304.00	1,272,960	346
300	19.53	5859.00	1,757,700	1383
360	15.94	5738.40	2,065,824	417
400	14.39	5756	2.302,400	0
Sum	710.7	93,613.3	17,942,133	15,302.69

Background Concentration: 14.39 mg/L
Initial NaCl Mass: 68254 mg.

The measured residence time was greater than the theoretical residence time by 45 percent. Therefore, empty bed contact time was not an exact measure of the time by which adsorbate was in contact with the carbon bed. An explanation for this discrepancy may be due to a change of the large resistance imposed by the carbon upon the flow rate by the carbon bed. This resistance resulted in small flow rates, exceedingly long EBCT, and small quantities of treated water through the system.

The dispersion coefficient was calculated to be 0.045 square feet per minute. The dispersion coefficient assumed that flow was not disturbed as it passed through and out of the bed (open vessel). The vessel dispersion number was 0.455. Calculations for these values are given in Appendix IV.

The recovery of NaCl was calculated to be only 22 percent. An explanation for the mass recovery would have involved adsorption of the sodium chloride on the GAC or poor sampling methodology which missed a major portion of the NaCl sampled. In order to evaluate this consideration, a 35" long, transparent 1 1/4 inch pipe was filled with activated carbon and connected to a vertical 52-inch long transparent pipe connected by a 90 degree elbow. An initial slug of 1285.6 mg NaCl was placed in the pipe. The entire effluent was collected in 100 ml plastic containers every thirty seconds for 29.5 minutes. Tracer analyses are given in Table 11 and shown in Figure 39. Seventy percent recovery of the sodium chloride was achieved. Therefore, some sodium chloride was most likely retained within the carbon bed.

A constant head of 35 inches (2.9') was maintained for the duration of the experiment since it approximated the head difference between the lake water and the influent pipe invert. The flow rate varied from 0.00020 to 0.00017 cfs with an average value of 0.00018 cfs. The EBCT for the pipe was 2.3 minutes. Using a proportion of length of the pipe to the first carbon bed, the EBCT would only be 4.6 minutes. The lower EBCT is a result of the greater head differential in the experiment (35") as opposed to that encountered in the carbon beds (5.25").

Objective Three Summary

It was concluded that greater hydraulic efficiency may be achieved if the carbon were to placed in pipes (instead of the current GAC configuration at Lake Angel) to utilize the greater head differential.

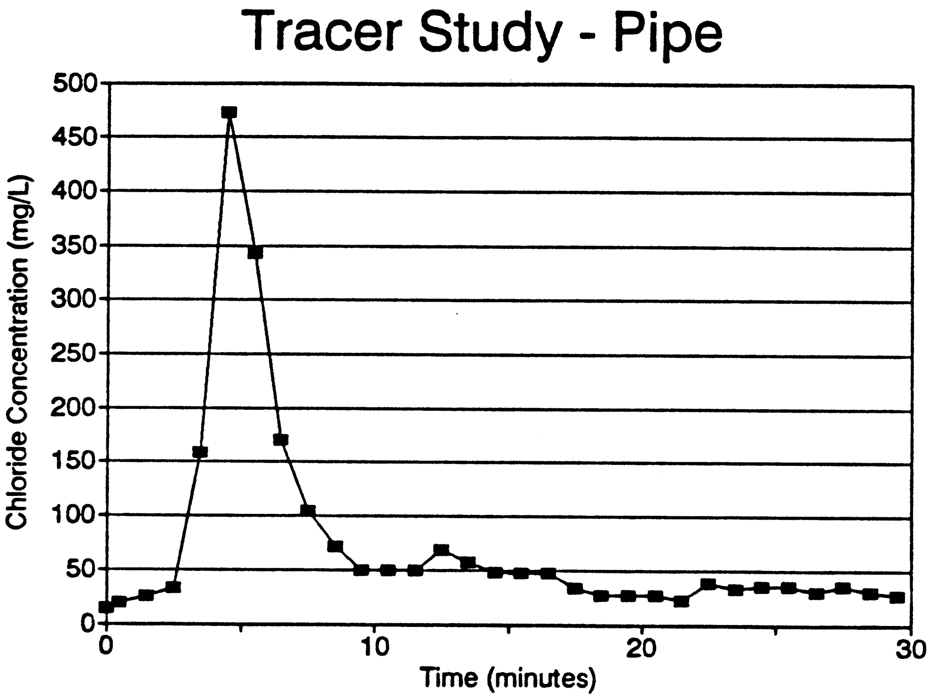
Tracer studies were performed to determine the hydraulic residence time of water in the first carbon bed. The study showed an average residence time of 114 minutes. The average residence time was longer than empty bed contact time in the first carbon bed. The discrepancy between the empty bed contact time and measured time was most likely due to the

TABLE 11

TRACER ANALYSIS OF PIPE FLOW DATA

TIME (min)	CHLORIDE CONCENTRATION (MG/L)	MASS OF NaCl (MG)
0.5	24.73	6.07
1.5	19.23	3.07
2.5	32.97	10.46
3.5	159.35	74.55
4.5	472.6	234.94
5.5	343.2	171.43
6.5	170.34	81.43
7.5	104.30	46.42
8.5	71.43	28.61
9.5	49.45	17.71
10.5	49.45	17.83
11.5	49.45	18.28
12.5	68.68	27.25
13.5	57.70	21.45
14.5	47.80	17.17
15.5	46.71	15.83
16.5	46.71	16.09
17.5	13.74	0.00
18.5	27.47	6.59
19.5	27.47	6.59
20.5	27.47	6.59
21.5	21.98	3.96
22.5	38.46	11.67
23.5	33.00	9.24
24.5	35.72	10.37
25.5	35.72	10.37
26.5	30.22	7.78
27.5	35.72	10.55
28.5	30.22	7.65
29.5	27.47	6.37
	SUM	900.0

Flow Rate: 0.00034 cfs
Initial Mass NaCl: 1285.6 mg



Background Chloride Concentration - 14.39 mg/L.

Figure 39. Tracer Analysis of A Horizontal Pipe.

resistance of flow due to the activated carbon in the bed and clogging of the interstices between the grains.

Economic Evaluation

An economic evaluation of stormwater management was performed. As previously discussed, about 138,000 liters of water (1.34 acre-inches) were treated in the first carbon bed before breakthrough occurred. The cost of purchasing Calgon F-400 is $1.10 per pound and the cost of replacing the first carbon bed with 5.25 ft^3 is $156 (see Appendix IV).

To determine the volume of runoff from the Lake Angel watershed, the 130 acre watershed had a runoff coefficient of 0.40 (McBee, 1985). The average annual rainfall at the site is about 51 inches per year. This corresponds to 2652 acre-inches of runoff per year. Therefore, the cost of carbon alone would be $308,740 or approximately $309,000.

The amount of labor required to change the carbon after every one-inch of rainfall was estimated at $6120 per year. This value assumed a two man crew and six hours of work per person at a cost of ten dollars per hour.

The initial construction cost of the GAC system at Lake Angel was $9,600. Assuming a 60-year service life of the structure at a ten percent interest rate, the annual cost is $963. Therefore, the total annual cost of the Lake Angel GAC system is $316,000 or $4.39/1000 gallons.

The Florida Department of Transportation (FDOT) may wish to consider an irrigation scheme to decrease the amount of water treated by the GAC system. Four ten horse-power irrigation pumps could be used and detained stormwater could be pumped to irrigate the interstate right-of-way. The capital cost of the pumps and piping system for 16 acres of right-of-way was estimated at $40,000, and the operating cost was estimated at about $4,357 per year (see Appendix IV). The annual cost of four backup pumps and replacement every five years would total $11,172 annually. This would result in irrigating 35 million gallons of water over the watershed each year - or roughly half of the volume of runoff which flows into Lake Angel. Therefore, the irrigation system would reduce the cost of treating the entire volume of runoff by decreasing the amount of carbon used. The total cost for this alternative was calculated to be approximately $178,000.

A possible alternative for treating THM precursors at Lake Angel with GAC would be to place the GAC in twelve-inch PVC pipes instead of the present GAC "open-air" configuration. The pipes could be laid within both sides of the concrete structure at Lake Angel. The measured length of the pipe would be about 47 feet and would include 37 ft^3 of carbon. A connector should be placed every three feet to reduce the weight of carbon when it needs to be replace. Replacement of the GAC in the pipes would be accomplished by disconnecting them, emptying the GAC, refilling the pipe with GAC, and placing the pipe back online. The effluent pipe which connects the junction box to the concrete structure could still be used as an outfall pipe.

An alternative to the GAC system under consideration is to pump lake water from Lake Angel to Shingle Creek - a distance of five miles. Assuming a construction cost of $60.00 per foot of 24" pipe, the cost alone for the pipe would be $1.6 million dollars or an annual cost of $161,000 (assuming a service life of 60 years).

The capital cost of the pump station with a service life of 10 years to pump at an assumed maximum of 25 cfs of stormwater from Lake Angel was calculated to be about 2.1 million dollars. Assuming partial replacement of one-third of the original cost of the pump station every ten years at a 10 percent interest rate, the annual cost for the pump station was $254,000. The total annual cost of this alternative was $415,000. This value does not take into account maintenance of traffic, pumping, inconvenience to traffic, and the possibility that a stormwater application would be denied. Therefore, while the GAC system may not be economical, it may be favorable to other present methods being considered to remedy the problem. In view of the high cost of the GAC system, and the daily maintenance, it does not appear that complete dependence on GAC is a cost efficient or practical means to reduce THMs at Lake Angel. However, if the lake discharge can be reduced using an irrigation system, the cost of the GAC system can also be reduced.

Objective Four Summary

The estimated annual cost for treatment using only GAC is $316,000. To reduce the use of GAC, a feasible alternative is to irrigate the detained stormwater, thus reducing the use of GAC and the total annual cost to $178,000. If more land for irrigation can be identified, the annual cost can be further reduced. Another alternative to pump the water from Lake Angel to Shingle Creek has an annual cost of $415,000.

Bacterial Environmental Conditions

The correct identification of bacteria found in slow moving waters of the GAC chamber and bank infiltration pipes allowed for an evaluation of the underdrain performance. Specimens of bacteria were obtained from the burlap bags in January, 1990 and water from the effluent pipes in July, 1990. The specimens were placed on glass slides with a bacteriological inoculating loop and heat fixed slightly to aid adherence of bacterial smears to slides. All samples were viewed through a Nikon Photophot Model UFX-11 microscope and pictures were taken with a Nikon FX-35A camera. Some of the slides were dyed with crystal violet to bring out contrasting features of cell structure.

The dominant bacteria found in the underdrains and GAC chamber which resulted in the burlap bags being rendered impervious were *Leptothrix* with minor amounts of *Siderocapsaceae* types and *Gallionella*. Leptothrix was visually identified by its rusty, brown color (Appendix III). Under the microscope, the cells are chained, enclosed within sheaths by which ferric oxide and/or manganese oxide has accumulated, and offset from each other. False branching of the organisms was also observed.

The presence of Leptothrix as the dominant bacteria indicates a high iron and/or manganese concentration in the source water. The carbon source is carbon dioxide and is found in concentrations less than 20 mg/L. Dissolved oxygen in the water is low and Eh values are approximately 300 mV. Water temperatures are moderate and pH values are slightly acidic due to carbonic acid in the water.

Minor amounts of Siderocapsaceae and Gallionella were also observed. Siderocapsaceae is identified by rusty brown, circular shapes (Appendix III). Gallionella is easily identified by its twisted stalks (Appendix III). These organisms are also indicative of high iron and/or manganese concentrations. Oxygen content is low (1-3 mg/L).

Thiothrix was also observed on the burlap bags as well as the effluent pipe on the west end of the junction box. Since Thiothrix must utilize sulfide, it is possible that hydrogen sulfide exists in the lake water. Sulfur globules within the trichomes are readily apparent (Appendix III).

Objective Five Summary

The dominant bacteria which existed in the underdrains and Lake Angel GAC Chamber included Leptothrix, Gallionella, Thiothrix, and species of Siderocapsaceae. These organisms live in waters of neutral pH, moderate to temperate temperatures, and moderate to high concentrations of iron, manganese, hydrogen sulfide, and low amounts of dissolved oxygen. Their presence reduced the underdrain pipe flow rate. The underdrain with no groundwater input operated at a flow rate 50 times higher than the underdrain with groundwater.

Disposal of Used GAC

The used activated carbon can be either regenerated or enclosed in an impermeable membrane for reuse or disposal. Presently, a regeneration facility is located about 1000 miles from Lake Angel and regeneration is too costly (more than the cost of new GAC at $1.10/pound). Thus, the reuse option was considered to be the only cost effective and ecologically safe alternative. The addition of waste materials to concrete has been done before with maintanence of strength and retention of the waste after toxicity extraction (Benson,1985).

Twelve (12) concrete cylinders were made with different mixes of water, cement, sand, and GAC. All mixes had four parts of gravel. The cylinders were tested for compressive strength and the results indicate that the moisture content must be monitored and the GAC volume should not excced the volume of sand. The results are summarized as:

#	Parts(Volume)				Weight	Strength
	Water	Cement	Sand	Carbon	LBS.	PSI.
1	2	2	4	0	27.4	3431
2	2	2	3	1	26.9	3360
3	2	2	2	2	25.7	3289
4	2	2	1	3	24.3	3006
5	2	2	0	4	22.4	2423
6	1.5	2	4	0	27.1	2540
7	1.5	1	4	0	27.0	2476
8	2.5	1	0	4	19.5	1100
9	2	1	2	2	24.4	1325
10	1.75	1	3	1	25.9	1750
11	2.25	1	1	3	23.0	1235
12	2.75	1	0	4	20.6	1045

Objective Six Summary

The used GAC can be disposed of by using it as a substitute for sand in concrete. The basis for recommendation is the strength of the concrete. Also, the volume of used GAC should not exceed the volume of sand in any mixture.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A 3.2 Acre detention pond in central Florida receives runoff water from an interstate highway and commercial area totally approximately 130 Acres. The outlet from the pond is a drainage well whose depth is about 200 feet below the surface and into an aquifer that is the source of drinking water. Thus, continual use of the drainage well must meet State requlations related to drinking water quality measures. The measures of primary concern in this report are those related to the formation of suspect cancer causing agents.

One of the treatment methods to remove suspect cancer causing agents is granular activated carbon (GAC). However, no tests have been conducted outside of a laboratory to determine the technical and economic feasibility for the treatment of detained stormwater to remove the precursors that form suspect cancer causing agents. The authors of this report proposed to pass detained stormwater through a GAC bed before entering the drainage well. A horizontal gravity bed of GAC was used to minimize the operational problems and cost of a pressurized bed. Trihalomethane Formation Potential (THMFP) was used as the indicator measure for suspect cancer causing agents. However, the tests are expensive and time consuming. Thus, other indicating parameters may be useful, such as color and organic carbon measures.

Color, Total Organic Carbon (TOC), and Trihalomethane Formation Potential (THMFP) reached breakthrough in the GAC beds at the Lake Angel Detention Pond. Excellent correlations between color, TOC, and THMFP were obtained. Correlation coefficients for THMFP and TOC, TOC and color, and THMFP and color were 84% 89% and 89%, respectively. Therefore, color and TOC are useful surrogate parameters for THMFP before and after the GAC filter beds at the Lake Angel stormwater detention pond.

Breakthrough occurred after 900 bed volumes and 138,000 liters of water. Exhaustion of the first carbon bed was reached after 1270 bed volumes and 185,000 liters of water. The length of the sorption zone was calculated to be 1.70 feet. Approximately 6.3 mg of TOC was adsorbed per gram of carbon. Long empty bed contact times of the carbon beds were indicative of the small quantities of water treated.

Bacteria such as Leptothrix, Gallionella, and Thiothrix initially grew in the GAC bed due to elevated iron/manganese concentrations of the ground water. These bacteria created sheaths which sloughed off, partially clogged the influent pipe, and reduced the permeability of the GAC bed. This was remedied by prohibiting groundwater from entering the system and taking the water directly from the pond to the GAC bed.

The GAC did not clog from bacterial agglomeration after this alteration.

The GAC system to treat all detained stormwater was found to be expensive. An annual cost of $316,000 would be required to treat THMFP precursors if a gravity flow horizontal bed is used. Replacement of the carbon beds would be required after every one inch storm event. For future application, the placement of more carbon in PVC pipes should significantly decrease replacement frequencies. The cost of treatment can be significantly reduced by irrigating the detained stormwater within the highway right-of-way and other parts of the watershed.

An alternative which would involve the placement of a 24" pipe to Shingle Creek (5 miles away) was calculated to be more expensive and would not improve water quality. In addition, a permit for such construction may be denied.

The use of the sanitary sewer system in the adjacent area would not be feasible because the sewer is near capacity and significant pump station and increased storage would be necessary. A complete feasibility study for use of the sanitary sewer system would involve a treatment feasibility study and a cost analysis for enlarging the detention pond versus an enlarged sewer system. It is doubtful that the sewer system can take another 72 million gallons per year and in approximately 10 percent of the time. An enlarged detention or on-line holding pond would be needed.

Recommendations

GAC can be used to remove THMFP precursors from detained stormwater. The disposal of the used GAC by substituting GAC for sand in concrete is possible. The strength of the concrete can be maintained at 3000 psi or greater.

Groundwater entering underdrains should be minimized. The construction of underdrains in high groundwater areas should be done so that the ponded water is separated from the groundwater. If this is not possible, the groundwater should be tested for iron and manganese or the formation of bacteria.

The dependency on GAC as the only method for stormwater control can be reduced by using an irrigation system in the watershed. The irrigation system can reduce the cost of treatment and should be considered for future implementation. Additional area for irrigation should be found near the site. Recent State-wide stormwater reuse reports (Wanielista, et.al., 1991) can be used to aid in sizing the ponds and irrigation requirements.

APPENDICES

APPENDIX I

RAINFALL AMOUNTS AT THE ORLANDO INTERNATIONAL AIRPORT

TABLE 12

LOCAL CLIMATOLOGICAL DATA FROM NOAA AT THE ORLANDO INTERNATIONAL AIRPORT.

DATE	PRECIPITATION (inches)	DATE	PRECIPITATION (inches)
March		May	
17	0.19	9	0.10
29	0.76*	10	0.02
30	0.59*	22	0.16
31	0.36*	27	0.12
April		28	0.15
3	0.08	June	
11	0.53*	1	0.71*
19	0.65*	3	0.94*
22	0.29*	4	0.07
23	0.15*	6	0.23*
28	0.03	7	0.06
		8	1.41*
		10	0.04

Note: * Indicates rainfall events which resulted to submergence of the carbon beds.

APPENDIX II

LABORATORY RESULTS OF CHEMICAL PARAMETERS

TABLE 13

COLOR MEASUREMENTS FROM LAKE ANGEL, FLORIDA.

DATE	LAKE COLOR (Co)	BED #1 COLOR (C1)	BED #2 COLOR (C2)	C1/Co	C2/C1
3/23	65	42	17	----	0.405
3/30	58	26	14	----	0.538
4/5	60	25	12	0.417	0.480
4/13	68	22	15	0.324	0.682
4/19	48	28	20	0.583	0.714
4/26	50	28	20	0.560	0.714
5/3	59	35	15	0.593	0.429
5/11	57	48	27	0.842	0.563
5/16	58	52	22	0.897	0.423
5/18	52	47	19	0.904	0.404
5/22	70	65	29	0.929	0.446
5/25	53	52	17	0.981	0.327
5/29	49	46	31	0.939	0.674
6/1	67	62	33	0.925	0.532
6/4	59	53	33	0.898	0.623
6/8	50	50	35	1.00	0.700
6/12	38	38	27	1.00	1.00

Notes: (1) Values between 3/23 and 4/5 represent short-circuiting in Bed No. 1.

TABLE 14

TOTAL ORGANIC CARBON CONCENTRATIONS GIVEN AS NONPURGEABLE ORGANIC CARBON (NPOC) FROM LAKE ANGEL, FLORIDA.

DATE	LAKE CONC. Co (MG/L)	BED #1 EFFLUENT CONC. C1 (MG/L)	BED #2 EFFLUENT CONC. C2 (MG/L)	C1/Co	C2/C1
1/9	4.90	----	4.00	----	----
1/12	4.8	----	4.40	----	----
1/16	4.70	----	4.20	----	----
1/19	5.30	----	5.10	----	----
1/23	5.20	----	4.70	----	----
3/8	6.00	----	1.80	----	----
3/16	6.80	4.10	2.20	----	0.537
3/23	7.70	3.70	1.60	----	0.432
3/30	4.20	1.20	BDL(1)	----	0.125
4/5(2)	5.10	0.93	BDL	----	0.161
4/13	5.60	0.37	BDL	0.0660	0.405
4/19	6.40	1.20	BDL	0.188	0.125
4/26	6.20	2.40	BDL	0.387	0.063
5/11	7.80	7.50	1.70	0.962	0.227
5/16	8.20	8.10	2.10	0.988	0.259
5/18	8.40	7.90	1.90	0.940	0.241
5/22	8.40	7.90	1.80	0.940	0.228
6/4	7.80	7.60	1.90	0.976	0.250
6/12	7.30	7.20	3.60	0.986	0.500

Notes: (1) BDL = below detectable limit
(2) Values from 3/16 to 4/5 represent short-circuiting in Bed No. 1

TABLE 15

TOTAL TRIHALOMETHANE FORMATION POTENTIAL CONCENTRATIONS FROM LAKE ANGEL, FLORIDA.

DATE	LAKE CONC. Co (UG/1)	BED #1 CONC. C1 (UG/L)	BED #2 CONC. C2 (UG/L)	C1/Co	C2/C1
1/9	271	----	267	----	----
1/12	233	----	225	----	----
1/16	250	----	222	----	----
1/19	271	----	---	----	----
1/23	291	----	255	----	----
3/16(1)	255	144	87	----	----
3/23	257	150	43	---	.287
3/30	276	149	42	----	.285
4/5	327	140	42	----	.300
4/13	295	89	54	.302	.607
4/19	314	150	60	.478	.400
4/26	361	240	87	.665	.363
5/11	348	321	105	.922	.327
5/16(2)	116	67	67	.922	.626
5/18	109	80	54	.734	.675
5/22	141	118	72	.837	.610
6/4	600	578	549	.963	.95
6/12	567	394	148	.695	.376

Notes: (1) Values from 3/16 to 4/5 represent short-circuiting in Bed No. 1.
(2) Concentrations beyond 5/22 are approximate only.

TABLE 16

CHLOROFORM FORMATION POTENTIAL CONCENTRATIONS FROM LAKE ANGEL, FLORIDA.

DATE	LAKE CONC. Co (ug/L)	BED #1 CONC. C1 (ug/L)	BED #2 CONC. C2 (ug/L)
3/16	190	100	47
3/23	200	100	19
3/30	226	104	96
4/5	261	84	18
4/13	230	46	24
4/19	240	78	21
4/26	290	150	27
5/11	270	250	58
5/16	65	59	8
5/18	66	43	30
5/22	93	78	12
6/4	550	530	500
6/12	520	350	120

TABLE 17

DICHLOROBROMOMETHANE FORMATION POTENTIAL CONCENTRATIONS FROM LAKE ANGEL, FLORIDA.

DATE	LAKE CONCEN. Co (ug/l)	BED #1 CONCEN. C1 (ug/L)	BED #2 CONCEN. C2 (ug/L)
3/16	55	35	27
3/23	49	38	15
3/30	43	34	32
4/5	56	37	14
4/13	57	31	20
4/19	64	51	23
4/26	62	66	34
5/11	67	61	34
5/16	39	37	25
5/18	16	29	19
5/22	40	34	29
6/4	38	40	42
6/12	44	42	25

TABLE 18

DIBROMOCHLOROMETHANE FORMATION POTENTIAL CONCENTRATIONS FROM LAKE ANGEL, FLORIDA.

DATE	LAKE CONCEN. Co (ug/L)	BED #1 CONCEN. C1 (ug/L)	BED #2 CONCEN. C2 (ug/L)
3/16	10	9	12
3/23	8	12	9
3/30	7.4	11	11
4/5	9.6	19	10
4/13	7.9	12	9.7
4/19	10	21	16
4/26	9	24	26
5/11	11	10	13
5/16	12	11	34
5/18	27	8	5
5/22	8	6	31
6/4	8	7	7
6/12	3	2	3

TABLE 19

BROMOFORM FORMATION POTENTIAL CONCENTRATIONS FROM LAKE ANGEL, FLORIDA.

DATE	LAKE CONCEN. Co (ug/L.)	BED #1 CONCEN. C1 (ug/L)	BED #2 CONCEN. C2 (ug/L)
3/16	BDL	BDL	BDL
3/23	BDL	BDL	BDL
3/30	BDL	BDL	BDL
4/5	BDL	BDL	BDL
4/13	BDL	BDL	BDL
4/19	BDL	BDL	BDL
4/26	BDL	BDL	BDL
5/11	BDL	BDL	BDL
5/16	BDL	BDL	BDL
5/18	BDL	BDL	BDL
5/22	BDL	BDL	BDL
6/4	2.8	1.3	BDL
6/12	BDL	BDL	BDL

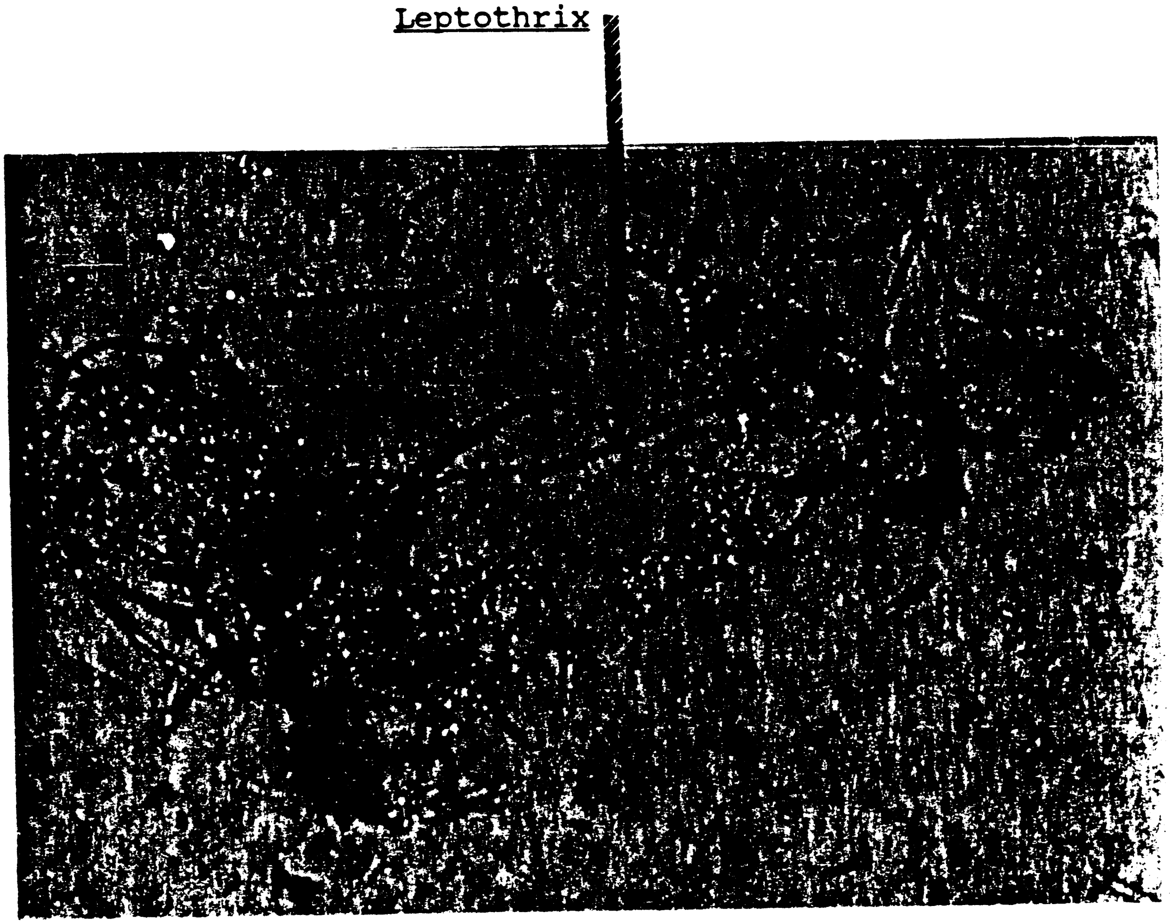
TABLE 20

TEMPERATURE AND pH MEASUREMENTS FROM LAKE ANGEL, FLORIDA.

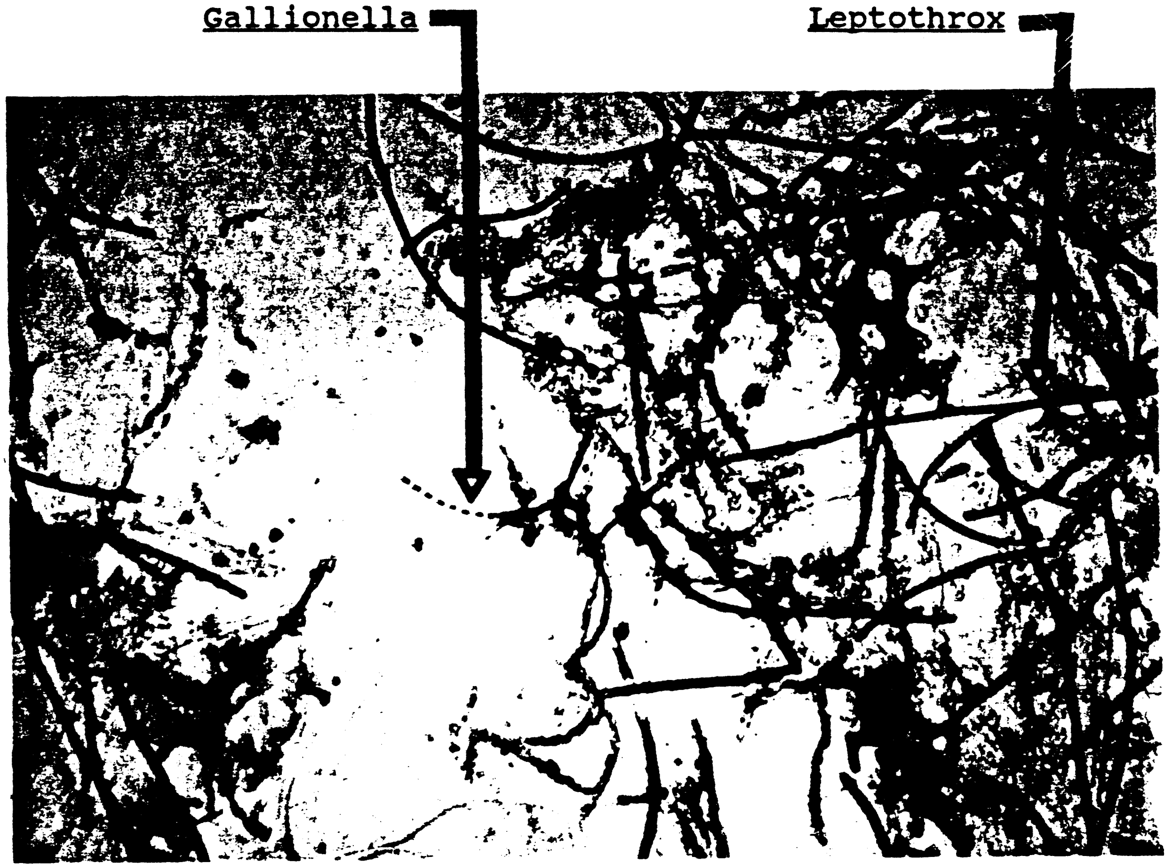
DATE	LAKE pH	BED #1 ph	BED #2 pH	TEMP. (DEGREES CELSIUS)
3/8	7.2	7.2	7.2	----
3/16	7.2	7.2	7.2	----
3/23	7.2	7.3	7.2	----
3/30	7.1	7.1	7.1	----
4/5	7.2	7.1	7.2	----
4/13	7.0	7.2	7.3	22.5
4/19	7.1	7.2	7.1	25.5
4/26	7.2	7.3	7.1	25.5
5/3	7.1	7.1	7.2	28.0
5/11	7.1	7.3	7.2	25.0
5/16	7.2	7.2	7.2	29.0
5/18	7.0	7.1	7.1	27.0
5/22	7.1	7.1	7.3	28.0
5/25	7.1	7.2	7.2	26.0
5/29	7.2	7.2	7.1	29.0
6/1	7.2	7.2	7.2	28.5
6/4	7.0	7.3	7.1	29.0
6/8	7.0	7.4	7.2	28.5
6/12	7.0	7.2	7.3	29.0

APPENDIX III

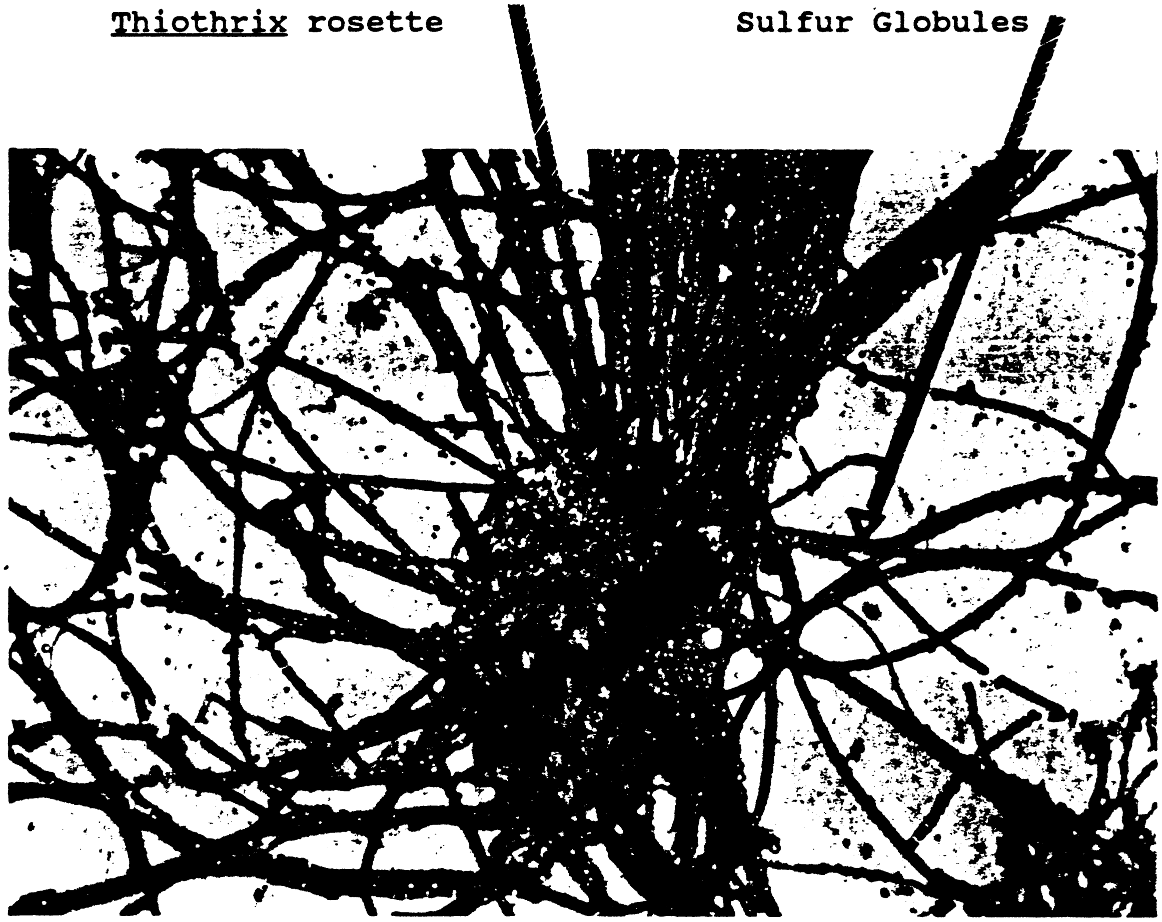
PHOTOGRAPHS OF SELECTED BACTERIA



Leptothrix Bacteria in the GAC Chamber



Gallionella and Leptothrix in the GAC Chamber



Thiothrix Bacteria with Sulfur Globules in the GAC Chamber

APPENDIX IV

SAMPLE CALCULATIONS

CARBON BED CALCULATIONS

CALCULATE THE VOLUME OF CARBON INTERACTING WITH THE FLOW:
GIVEN: WATER HEIGHT: 0.77 FT.
BED VOLUME: 6.1 CUBIC FEET
HEIGHT OF BED: 0.875 FEET

$$\frac{(0.77\ \text{ft.})(6.1\ \text{cu.ft.})}{0.875\ \text{ft.}} = 5.36\ \text{cubic feet}$$

CALCULATE THE EMPTY BED CONTACT TIME:
GIVEN: WEIGHTED AVERAGE VOLUME OF BED: 5.25 CU.FT.
FLOW RATE: 0.0018 CUBIC FEET / SECOND

$$\frac{5.25\ \text{cu.ft.}}{0.0018\ \text{cfs.}} = 48.61\ \text{MINUTES}$$

CALCULATE THE NUMBER OF BED VOLUMES:
GIVEN: VOLUME OF BED: 5.25 CU.FT.
TIME DURATION: 192 HOURS

$$\frac{\text{BV}}{5.25\ \text{cu.ft.}} \times \frac{0.0018\ \text{ft}^3}{\text{second}} \times \frac{192\ \text{hr.}}{} \times \frac{3600\ \text{sec}}{\text{hour}} = 237\ \text{BV}$$

FIND THE ACCUMULATED MASS:
GIVEN: Ci = 6.80 mg/L   TIME DURATION: 192 hr.
Co = 4.10 mg/L
Q = 0.0018 cfs

$$\frac{(6.8 - 4.1\ \text{mg})}{\text{liter}} \times \frac{(0.0018\ \text{cu.ft.})}{\text{second}} \times \frac{192\ \text{hr.}}{} \times$$

$$\frac{3600\ \text{sec}}{\text{hour}} \times \frac{\text{gram}}{1000\ \text{mg}} \times \frac{3.785\ \text{l}}{\text{gal}} \times \frac{7.481\ \text{gal.}}{\text{cu.ft.}} = 95\ \text{g TOC}$$

DISPERSION CALCULATIONS

CALCULATE THE DISPERSION COEFFICIENT:

GIVEN: SUM OF C_iT_i = 93,613

BED LENGTH: 5.83 ft.

SUM OF $C_iT_i^2$ = 17,942,133 AREA:0.875 ft. x 2 FT

SUM OF C_i = 710.7 FLOW: 0.0016 cfs

$$Tc = \frac{93,613}{710.7} = 131.7 \text{ minutes}$$

$$Sigma^2 = \frac{17,942,133}{710.69} - 131.7^2 = 7895.92$$

$$Sigma\ Delta^2 = \frac{7895.92}{131.7^2} = 0.455$$ = VESSEL DISPERSON NUMBER

$$0.455 = 2X + 8X^2$$

where X = D/ul

D = dispersion coefficient

u = velocity

l = bed length

BY TRIAL AND ERROR, X = 0.142

D = 0.0454 SQ.FT./MIN.

CALCULATE THE MASS OF NaCl:

GIVEN: CHLORIDE CONCEN. = 19.02 - 14.39 = 4.63 mg/L

FLOW RATE: 0.0016 cfs

TIME INTERVAL: 10 minutes

$$\frac{4.63 \text{ mg}}{\text{liter}} \times \frac{0.0016 \text{ FT}^3}{\text{second}} \times \frac{60 \text{ seconds}}{\text{minute}} \times \frac{10 \text{ minutes}}{}$$

$$\frac{7.48 \text{ gallon}}{\text{cu.ft.}} \times \frac{3.785 \text{ liter}}{\text{gallon}} \times 1.65 = 208 \text{ milligrams}$$

ADSORPTION PARAMETER CALCULATIONS

CALCULATE THE LENGTH OF THE SORPTION ZONE:

GIVEN: Z = COLUMN LENGTH = 5.83 FEET.

V_x = VOLUME OF TREATED WATER AT EXHAUSTION

V_b = VOLUME OF TREATED WATER AT BREAKTHROUGH

Zs = LENGTH OF THE SORPTION ZONE

f = 0.48

$V_z = V_x - V_b$ = 185,000 l - 138,000 L = 47,000 liters

$$Zs = 5.83 \text{ FT. } \frac{47{,}000 \text{ LITERS}}{185{,}000 \text{ LITERS} - (.48)(47{,}000 \text{ LITERS})}$$

Zs = 1.70 FT.

CALCULATE THE TIME TO EXHAUSTION:

$$t_x = \frac{V_x}{Q} \times \frac{185{,}000 \text{ liters-sec}}{0.0011 \text{ cu.ft.}} \times \frac{\text{gallon}}{3.785 \text{ l}} \times \frac{\text{min.}}{60 \text{ sec}} \times \frac{\text{ft}^3}{7.48 \text{ gal}} =$$

t_x = 69 days

CALCULATE THE TIME OF PASSAGE OF THE ADSORPTION ZONE:

$$T_p = \frac{V_x - V_b}{Q} = \frac{47{,}000 \text{ l}}{0.0011 \text{ cfs}} = 17.5 \text{ days}$$

CALCULATE THE TIME OF FORMATION OF THE ADSORPTION ZONE:

$T_f = (1-f)t_p = (1-0.48)17.5 = 9.1$ days

CALCULATE THE PERCENT SATURATION OF THE CARBON AT BREAKTHROUGH:

$\%SAT = L - Z_s(1-f)100/L = 5.83' - 1.70'(1-.48)100/5.83' = 85\%$

CALCULATE THE VOLUME OF WATER TREATED BY BED #1:
GIVEN: BREAKTHROUGH VOLUME: 138,000 LITERS

$$\frac{138{,}000\ \text{liters}}{} \times \frac{\text{gallon}}{3.785\ \text{l}} \times \frac{\text{cu.ft.}}{7.48\ \text{gal}} \times \frac{12\ \text{inches}}{\text{ft}} \times \frac{\text{acre}}{43{,}560\ \text{sq.ft.}}$$

= 1.34 acre-inches

CALCULATE THE COST TO REPLACE THE FIRST CARBON BED:
GIVEN: COST OF CARBON: \$1.10/#
WEIGHTED VOLUME OF CARBON: 5.25 CU.FT.
DENSITY OF CARBON: 27 #/CU.FT.

$$\frac{5.25\ \text{ft}^3}{} \times \frac{27\ \#}{\text{ft}^3} \times \frac{\$1.10}{\#} = \$156$$

CALCULATE THE COST OF CARBON PER YEAR

$$\frac{2652\ \text{acre-inches per year}}{1.34\ \text{acre-inch/carbon bed}} \times \frac{\$156}{\text{bed}} = \$308{,}740$$

CALCULATE THE YEARLY COST OF THE GAC SYSTEM AT LAKE ANGEL:

GIVEN:	COST OF CARBON:	\$ 308,740
	COST OF LABOR:	\$ 6,120
	COST OF STRUCTURE:	\$ 963
		\$ 315,823

IRRIGATION SYSTEM ALTERNATIVE

CALCULATE THE COST OF ELECTRICITY TO PUMP LAKE WATER TO THE FDOT R.O.W. OF 16 ACRES.
GIVEN: ONE 10 HP PUMP WILL IRRIGATE 1 ACRE/HOUR AT 1.5" PER WEEK:

$$\frac{4\ \text{hours}}{\text{day}} \times \frac{4\ \text{pumps}}{} \times \frac{10\ \text{HP}}{\text{pump}} \times \frac{0.746\ \text{KwH}}{\text{HPHr}} \times \frac{\$0.10}{\text{KwH}} \times \frac{365\ \text{days}}{\text{year}}$$

= \$4,357 per year
CALCULATE THE COST OF THE PUMPING SYSTEM:
GIVEN: 4 BACKUP PUMPS AND REPLACEMENT EVERY 5 YEARS:
EACH PUMP COSTS \$10,000

$$\$40{,}000(A/P,10\%,60)(2) + \$40{,}000((p/F,10\%,5)+\ldots(P/F,10\%,60)$$

(A/P,10%,60)) = $11,172

CALCULATE THE VOLUME OF WATER IRRIGATED PER YEAR:

$$\frac{\text{100 gpm}}{\text{pump}} \times \frac{\text{4 pumps}}{} \times \frac{\text{4 hours}}{\text{day}} \times \frac{\text{60 min.}}{\text{hour}} \times \frac{\text{365 days}}{\text{year}} =$$

35,040,000 gal/year

CALCULATE THE YEARLY VOLUME OF RUNOFF:

$$\frac{51''}{\text{yr}} \times \frac{\text{130 acres}}{} \times \frac{43560\text{ ft}^2}{\text{acre}} \times \frac{0.40}{} \times \frac{\text{7.48 gal}}{\text{cu.ft.}} \times \frac{\text{ft.}}{12''} =$$

72,008,165 gal/year

CALCULATE THE REMAINING VOLUME OF WATER TO BE TREATED IN LAKE:

GIVEN: CHANGE OF VOLUME: 72 MGY - 35 MGY = 37 MGY

$$\frac{\text{37,000,000 gal}}{\text{year}} \times \frac{\text{cu.ft.}}{\text{7.48 gal}} \times \frac{\text{acre}}{\text{43,560 sq.ft.}} \times \frac{\text{12 inch}}{\text{foot}}$$

= 1,363 ac.-in.

CALCULATE THE YEARLY CARBON COST:

$$\frac{\text{1,363 ac-in.}}{\text{1.34 ac-in}} \times \frac{\$\ 156}{\text{bed}} = \$158{,}500$$

CALCULATE THE REMAINING COST:

LABOR: (37/72)$6,120 =	$ 3,145
STRUCTURE:	$ 963
PUMPS:	$ 11,172
ELECTRICITY:	$ 4,357
CARBON:	$158,500
	$178,137 per year

PIPE TO SHINGLE CREEK ALTERNATIVE

CALCULATE THE ANNUAL PIPE COST:

GIVEN: (A/P,10%,60) = 0.1004

$1,600,000(A/P,10%,60) = $161,000/year

CALCULATE THE COST OF THE PUMPING STATION:

GIVEN: (P/F,10%,10)..(P/F,10%,60) = 0.6168

INITIAL PUMP STATION COST: $2.1 MILLION

REPLACE ONE-THIRD OF ORIGINAL COST EVERY
10 YEARS

$2,100,000(A/P,10,60) + 700,000((P/F,10%,10)+...(P/F,10%,60)
x (A/P,10%,60)) = $2,106,300 + $160,480 = $254,000/year

TOTAL COST OF ALTERNATIVE: $161,000 + 254,000 = $415,000/year

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