Florida Water SERVICES

Marco Island Water System Enhanced Softening and Treatment Optimization

June 2000

Marco Island Lime Softening
Water Treatment Plant

BOYLE

Marco Island Water System
Lime Softening Water Treatment Plant

Enhanced Softening and Treatment Optimization

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OR-S25-103-66

June 2000

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1.0 Introduction

The Safe Drinking Water Act (SDWA) Amendments of 1996 sought to address numerous long-standing problems impeding the nation's primary drinking water protection program. The expense associated with implementing drinking water regulations underscores the need for water purveyors to have a sound scientific and information basis for decision making. The next reauthorization of the SDWA will certainly take drinking water into the 2010 timeframe, clearly motivating water purveyors to investigate the enhancement of water quality for long-term planning activities.

In anticipation of future drinking water challenges, Boyle Engineering Corporation (Boyle) has prepared this report to assist Florida Water Services Corporation (Florida Water) with professional engineering services in connection with performing bench-scale jar tests for enhanced softening and treatment optimization for the Marco Island Lime Softening Water Treatment Plant (LSWTP). The jar tests were developed as part of the evaluating enhanced softening and treatment optimization via pH adjustment and settling aid addition relative to compliance with existing and future water quality regulations.

1.1 Background

Marco Island is a popular tourist resort and is located off the southwest coast of Florida near Naples just west of the Everglades. The island measures approximately 6 miles long by 4 miles wide and has experienced rapid population growth over the past several years.

Florida Water owns and operates the surface water lime softening (LS) and ground water reverse osmosis (RO) water treatment plants on the island. Florida Water has historically been treating and distributing water from the 5.0-MGD LSWTP, designed in 1978 and constructed in 1981, located at the north end of the island. In Spring 2000 the LSWTP was re-rated to 6.3-MGD by the addition of a Zenon ultrafilter (UF) in parallel to the existing conventional sand filters. In response to growth and increasing water demands, Florida Water expanded its water services in 1992. A 4.0-MGD ROWTP expandable to 6.0-MGD was designed in 1990 and constructed in 1992 to treat groundwater having a varying total dissolved solids (TDS) concentration between 6,800 and 10,000 mg/L. In July 1996, the RO plant capacity was further increased by adding an additional 1.0-MGD of permeate capacity. In July 1998, the final 1.0-MGD train was placed into operation, thereby bringing the ROWTP to its design capacity of 6.0-MGD. Currently the two plants can provide 12.3-MGD average daily flow (ADF). A portion of the finished water from the LSWTP is blended with RO water at the ROWTP.

Raw source water to the LS plant is supplied by Marco Lakes, an off-site surface water source located 9 miles away from the plant, on the mainland. The surface water has a relatively high hardness and color content. Periods of high demand and low lake levels result in increased hardness. Treatment processes at the LS plant include lime softening for calcium removal, filtration, chloramination for disinfection, inhibitor addition for corrosion control and storage. From the high-service pumps, finished water is sent to the distribution system with a portion blended with finished RO water at the RO plant. The LS plant is typically operated at capacity to reduce RO usage, because of the cost of operating the RO plant.

1.2 Objectives

Specific tasks to be accomplished during this assessment include the following:

- Evaluate the existing lime softening water treatment plant facilities with respect to existing and proposed SDWA requirements in terms of water quality and treatment.
- Assist with the development of water quality goals and objectives for the assessment of enhanced softening treatment.
- Perform bench-scale enhanced softening and treatment optimization water quality evaluations.

2.0 Literature Review

2.1 Theory

Coagulation and flocculation theory can be described by a number of specific terms. Lime softening differs from coagulation in that precipitation is accomplished at a higher pH and $Mg(OH)_2$ or $CaCO_3$ is precipitated from water. The specific terms are:

- ***Coagulation:*** The formation of nuclei of a solid precipitate. Examples would be $Mg(OH)_2$ or $CaCO_3$. This would occur ideally in the rapid mixing process and would be more desirable in conditions of instantaneous or complete mixing. G levels of more than 300 sec^{-1} are desirable. Time of rapid mix should be limited to < 1 minute.
- ***Flocculation:*** The building of floc particles of an already formed solid precipitate. This is binding of $Mg(OH)_2$ or $CaCO_3$ particles and occurs during the slow mixing process. G levels of 35 to 50 sec^{-1} are desirable. Time of slow mix should be limited to less than 15 minutes.
- ***Sludge Addition:*** The addition of previously formed $Mg(OH)_2$ or $CaCO_3$ solids to the rapid mix or slow mix process in order to provide previously formed solids for nucleation sites. Effective both in coagulation and softening processes for enhancing turbidity removal and treatment.
- ***Settling Velocity:*** The surface loading rate of the clarified water as determined by the surface area for clarification divided by the flow of the settled water out of the clarification basin.
- ***Chemical Reaction***: The basic chemical reaction for Ca^{+2} or Mg^{+2} hydrolysis. This reaction will generate 2 H^+ for every mole of Ca^{+2} or Mg^{+2} reacted. The protons will react with and destroy HCO_3^- alkalinity. Consequently Ca^{+2} or Mg^{+2} reacts as a Lewis acid and will lower pH.
- ***Base Dose and pH:*** The dose of caustic, lime or soda ash in mg/L added to the rapid mix process. The pH of the settled water following coagulation and flocculation as measured in the overflow weirs of settling basin.
- ***Polymers:*** Any inorganic or organic chemical added to the rapid mix or slow mix processes to enhance settling of the floc. Typically organic polymers are used as settling aids for aluminum and iron coagulants, but aluminum and/or iron can be used as polymers for softening processes.
- ***pC-pH Solubility Diagrams:*** A thermodynamic model of the solid and ionic phases of any metal precipitate such as $Al(OH)_3$, $Fe(OH)_3$, and $CaCO_3$. This model can be constructed by plotting the negative log of the solubility products and the anionic form of the metal hydroxide such as $Al(OH)_4^-$ or $Fe(OH)_4^-$. This defines the optimum or acceptable pH range of the coagulation process for aluminum or iron salts. Softening usually does not begin until pH 8.5 and continues until pH 10.3. After pH 10.3 more calcium or sodium from the base hydroxide would come into solution than would precipitate from solution because most of the bicarbonate alkalinity would have been previously be precipitated.
- ***Sludge:*** The total volume of solids including water and TSS produced during the coagulation reaction. Typically aluminum or iron sludge will contain 0.1 to 0.5 percent TSS following sedimentation. Softening sludges contain 2 to 5 percent TSS.

The thermodynamic equilibrium diagram for $CaCO_3$ and $Mg(OH)_2$ is shown in Figure 2-1. Note the change of slope for $CaCO_3$ at pK_1 and pK_2. These slopes can be determined by taking the derivative of the $CaCO_3$ solubility product with respect to pH. Here the CO_3^{-2} species has to written as $\alpha_2 C_{T(CO3)}$. Also note the intersection of the $CaCO_3$ and $Mg(OH)_2$ equilibrium lines. The horizontal section of the $CaCO_3$ equilibrium line immediately to the left of this intersection is denoted as excess lime and represents the additional OH^- that must be added to precipitate $Mg(OH)_2$.

The lime softening equations are shown in Table 2-1. There are several forms of lime demand as described below:

- ***CO_2***: This is carbon dioxide and removes no hardness or alkalinity but does represent a demand for a base and must be considered to determine base dose.
- ***Calcium Carbonate Hardness (CaCH)***: This is calcium that is neutralized by carbonate alkalinity.
- ***Calcium Non-Carbonate Hardness (CaNCH)***: This is calcium that is neutralized by any other species (anionic) that carbonate species.
- ***Magnesium Carbonate Hardness (MCH)***: This is magnesium that is neutralized by carbonate alkalinity.
- ***Magnesium Non-Carbonate Hardness (MgNCH)***: This is magnesium that is neutralized by any other species (anionic) than carbonate species.
- ***Negative Hardness (NegH)***: This is any other cation that is neutralized by carbonate alkalinity other than calcium or magnesium.

Lime ($CaOH_2$ or CaO), soda ash (Na_2CO_3) or caustic (NaOH) is added as the base to cause the precipitation reactions. The only precipitation products are $CaCO_3$ or $MgOH_2$.

Softening goals can vary by source; however the goals assumed herein and that are presented in Table 2-2 are applicable to most softening facilities. Note that it is not possible to chemically soften any water to zero hardness as is shown in some references. The minimum hardness achieved by softening ranges from 0.30 to 1.2 meq/L.

FIGURE 2-1: $CaCO_3$ and $Mg(OH)_2$ pC – pH Solubility Diagram with $C_{TCO3} = 10^{-3}$ M

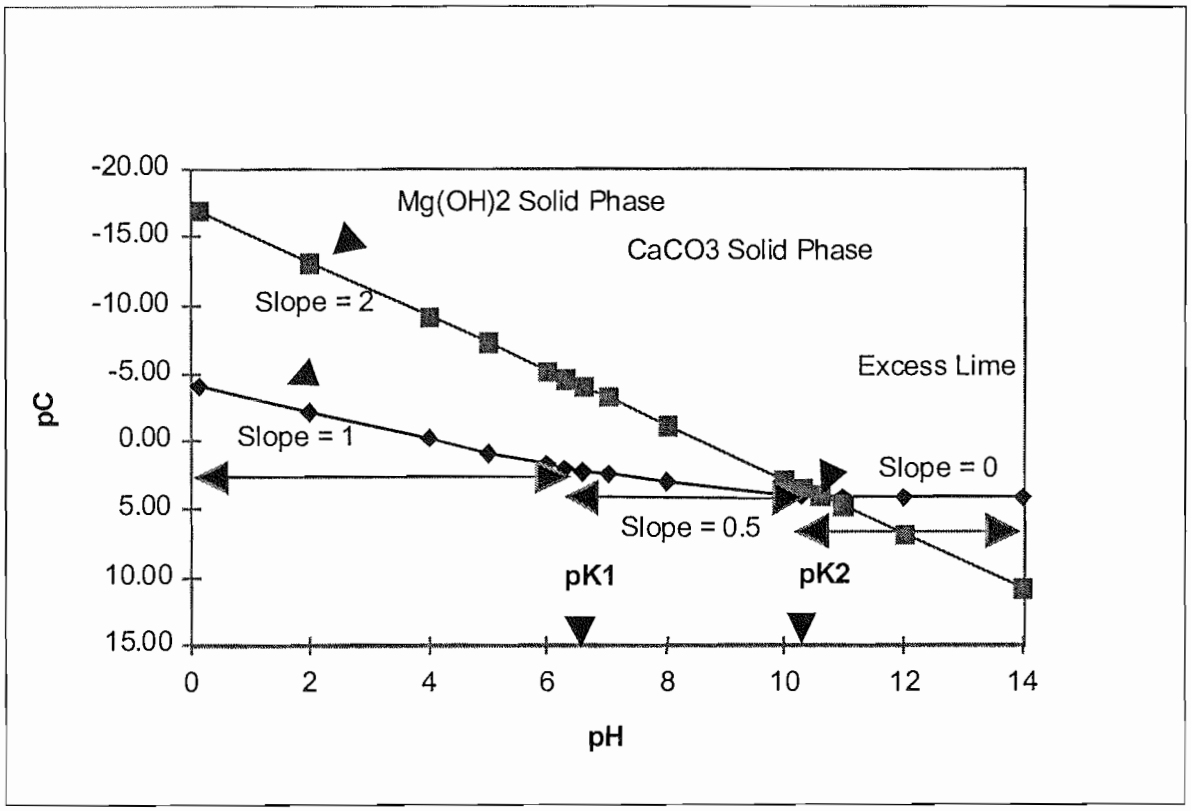


TABLE 2-1: Softening Reactions

Demand	Reaction	Meq Dose/Meq Sludge				
		CaO	Na_2CO_3	NaOH	$CaCO_3$	$Mg(OH)_2$
CO_2	$CO_2 + CaO + H_2O \Rightarrow CaCO_3 + H_2O$	1	0	0	1	0
CaCH	$Ca(HCO_3)_2 + CaO + H_2O \Rightarrow 2CaCO_3 + 2H_2O$	1	0	0	2	0
MgCH	$Mg(HCO_3)_2 + 2CaO + 2H_2O + Mg(OH)_2 + 2H_2O \Rightarrow 2CaCO_3$	2	0	0	2	1
CaNCH	$CaSO_4 + Na_2CO_3 \Rightarrow CaCO_3 + Na_2SO_4$	0	1	0	1	0
MgNCH	$MgSO_4 + CaO + H_2O + Na_2CO_3 \Rightarrow Mg(OH)_2 + CaCO_3 + H_2O$	1	1	0	1	1
	$MgSO_4 + 2NaOH \Rightarrow Mg(OH)_2 + Na_2SO_4$	0	0	2	0	1
NegH	$Na(HCO_3) + CaO \Rightarrow CaCO_3 + NaOH$	1	0	1	1	0
	$Ca(HCO_3)_2 + NaOH \Rightarrow CaCO_3 + Na(HCO_3) + H_2O$	0	0	1	1	0
	$CO_2 + NaOH \Rightarrow NaHCO_3$	0	0	1	0	0

TABLE 2-2: Goals for Softening

50 mg/L $CaCO_3 \leq TH \leq 100$ mg/L $CaCO_3$
0 mg/L $CaCO_3 \leq Mg \leq 40$ mg/L $CaCO_3$
35 mg/L $CaCO_3 \leq Alk \geq 200$ mg/L $CaCO_3$
$pH \geq pHs$

The following equation can be used to estimate the sludge volume produced during softening.

$$V = \frac{8.33QC}{\rho_w S_G} + \frac{(1-X)8.33QC}{X\rho_w}$$

Where:

V = Sludge Volume (ft^3/day)
Q = Flow Rate (MGD)
C = TSS formed (mg/L)
ρ_w = Density of water (lb/ft^3)
S_G = Specific gravity (2.8 = $CaCO_3$, 2.4 = $MgOH_2$)
X = Decimal fraction TSS

2.1.1 NOM Removal During Softening

Removal of natural organic material (NOM) is significant to the drinking water community in that color, total organic carbon (TOC) and disinfection by-products (DBPs) are NOM subsets and controlled by water treatment due to regulatory and/or asethetic constraints. Color, TOC and DBPs are partially removed by softening. The removal of color and DBPs can be related to TOC removal. TOC is measured as mg/L C and is a direct measure of NOM. Not all NOM or TOC produces color or regulated DBPs, hence TOC is a more universal measure of organic material in drinking water. Most if not all of the TOC removed during lime softening is in the form of non-purgeable dissolved organic carbon (NPDOC). TOC can be in a suspended or gaseous form in some drinking water sources. Some forms of TOC are easily removed during drinking water treatment. DBP precursor are typically in the form of NPDOC prior to disinfection. TOC is commonly used to describe NOM in drinking water treatment, but readers should realize that almost always the TOC is in the NPDOC form.

Investigators have found that softening removed TOC but was less effective for TOC removal than coagulation, addition of coagulants during softening enhanced TOC removal and chemical structure affected TOC removal. A survey of water treatment plants participating in the information collection rule (ICR) found that 30 percent and 40 percent of TOC was removed during lime softening in the 2-4 mg/L and 4-8 mg/L TOC groups respectively. They suggested additional TOC removal should not be required by regulation after 0.2 meq/L Mg removal, 0.8-1.2 meq/L alkalinity removal or if major changes of existing facilities were required to accommodate the more slowly settling $Mg(OH)_2$ floc or the additional sludge (Clark and Lawler, 1996). Increasing doses of ferric sulfate to 9.5 mg/L Fe^{+3} was observed to increase TOC removal to 75 % as softening pH increased to 10.3 (Quinn et al., 1992). Bench scale jar testing using waters from nine utilities found that TOC removal was correlated with increasing TOC concentration, hydrophobic TOC fraction and the magnesium removed during softening. A significant relationship between TOC removed and natural log (ln) magnesium removed was observed (Thompson et al., 1997). Softening of Mississippi River water was found to remove less

TOC than coagulation although higher molecular weight hydrophobic organic solutes were removed by both processes (Semmens and Staples, 1986). Liao and Randtke (1986) suggested co-precipitation was the primary mechanism for removal of organic solutes during softening, and organic removal was limited to anionic compounds which could absorb onto $CaCO_3$ solids. Polymeric electrolytes containing acidic oxygen-containers such as carboxyl, phenol and sulfonyl groups were not expected to be removed during lime softening unless they polymerized with or contained phosphorous containing functional groups which could interact with calcium or the calcium carbonate solids.

The removal of calcium and magnesium has been described in the sections discussing calcium carbonate and magnesium hydroxide equilibria, and softening. The phenomena described in these sections can be related to the removal of TOC by relating TOC removal to a pH domain where $CaCO_3$ precipitation occurs (less than pH 10.3) and to a pH domain where $Mg(OH)_2$ precipitation occurs (greater than pH 10.8). During lime softening, calcium removal due to $CaCO_3$ precipitation increases with pH to pH 10.3. At pH 10.3 nearly all of the calcium or carbonate alkalinity has been precipitated as $CaCO_3$ because of equilibrium (K_2, K_{sp}). Removal of calcium hardness is typically optimized at pH 10.3 in lime softening. Past pH 10.3, there is not enough carbonate alkalinity to precipitate the calcium solubilized from lime. Some slight additional calcium removal will be realized in a caustic softening process, but typically the vast majority of $CaCO_3$ precipitation is complete at pH 10.3. Because of $Mg(OH)_2$ equilibrium, adequate magnesium removal is typically not achieved until pH $\geq$ 10.8. The exact pH for optimized $CaCO_3$ and desired $Mg(OH)_2$ precipitation may differ slightly from 10.3 and 10.8 due to calcium and magnesium interactions with other solutes. However, $CaCO_3$ and $Mg(OH)_2$ precipitation occurs in different pH ranges and can be related to TOC removal.

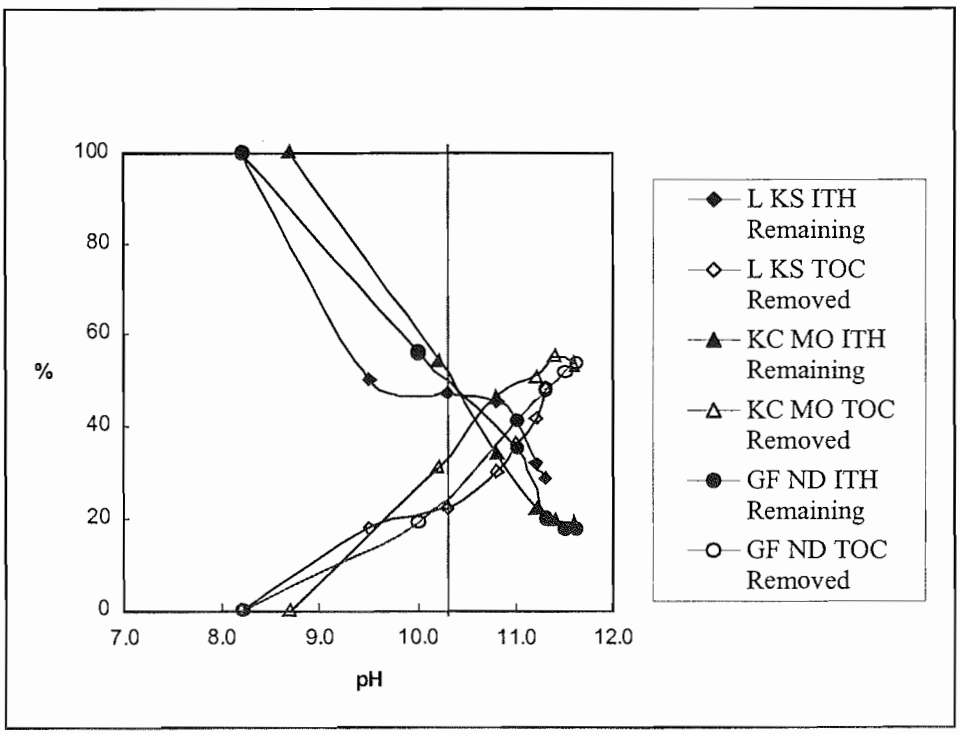
The removal of color, TOC and DBP precursors has been investigated by USEPA and AWWARF (Taylor 1986 and Randtke 1999). The raw water quality of three different sources investigated by Randtke (Randtke, 1999) is shown in Table 2-3. These waters vary from a Soft water with low magnesium content and low TOC concentration (Lawerence KS) to a hard water with high magnesuim content and high TOC concentration (Grand Forks ND). TOC varies directly with both calcium and magnesium hardness for these three waters. The removal of TOC and initial total hardness (ITH) for varying pH during lime softening of these three waters is shown in Figure 2-2. ITH removed was determined by deducting the calcium and magnesium removal from the initial hardness until calcium removal was maximized ($\approx$pH 10.3). Past pH 10.3 ITH removed was determined by deducting the magnesuim removed and the maximum calcium removal from the ITH. This allowed the calcium and magnesium removed to be related to the TOC removed as shown in Figure 2-2.

TOC removal increases with pH for each of these waters. Prior to pH 10.3 the TOC removal varies from approximately 20 to 30 percent. ITH reduction is approximately 50 percent at pH 10.3 and is due to $CaCO_3$ precipitation and occurs simultaneously with 20 to 30 percent TOC reduction. Past pH 10.3 TOC reduction is increased by approximately 25 percent and is associated with approximately 30 percent reduction of ITH which is due to $Mg(OH)_2$ precipition. TOC removal due to $CaCO_3$ precipitaion

TABLE 2-3: Raw Water Characteristics

Parameter	Source Waters		
	Lawrence KS	Kansas City MO	Grand Forks ND
TOC (mg/L)	3.7	5.15	14.02
Ca Hardness* (meq/L)	100	158	178
Mg Hardness* (meq/L)	29	74	132
Total Hardness* (meq/L)	129	232	310
pH	8.3	8.1	8.2
Alkalinity* (meq/L)	112	170	218
Turbidity** (NTU)	5.4	180	25

FIGURE 2-2: Percent TOC Remaining/Removal Versus Softening pH



was limited to 30 percent. TOC removal was increased to 55 percent when $Mg(OH)_2$ was precipitated and indicates that removal of magnesium hardness in a softening process will increase TOC removal. This has also been observed by Taylor (Taylor, 1986).

If magnesium is removed by lime softening, the excess calcium from the lime required to go from pH 10.3 to 10.8 or greater must be removed by primary recarbonation. The $CaCO_3$ precipitated in primary recarbonation must either be removed by sedimentation or by filtration. If sedimentation is used then a settling area equal to the settling area for the lime softening process is required. If additional settling is not provided then the $CaCO_3$ solids formed in primary recarbonation are passed to the filters.

2.1.2 Iron and Aluminum Enhancement

Iron and aluminum salts have been added during lime softening as settling aid and to increase color removal. Randtke investigated the addition of alum and ferric sulfate for TOC removal at Grand Forks ND (Randtke, 1996). As shown in Figure 2-3, TOC removal was increased from approximately 30 percent to 35 percent by the addition of 10 mg/L alum or ferric sulfate. These results show that addition of small amounts of alum or ferric sulfate can improve TOC removal by approximately 10 percent and indicate that the TOC removal by "in-situ" addition is limited to approximately 10 percent for this water. Taylor found that the addition of 20 mg/L of alum could increase TOC removal by approximately 10 percent during magnesium precipitation at Melbourne FL, but that further alum addition removed no more TOC and resulted in soluble aluminum in the finished water. Advantages of iron and alum in-situ addition with a softening process is a slight increase in removal of TOC and other organic solutes. Disadvantages of iron and aluminum in-situ addition are increased sludge volume, the possibility of aluminum post precipitation in the distribution system, and the possibility of adding soluble aluminum to the finished water.

2.1.3 Color and THMFP

Percent removal of THMFP, color and TOC is shown is shown in Figure 2-4 for Lake Washington FL. Lake Washington is a surface water source with very high natural color, TOC and formation potential. The relationship between TOC removal and pH is similar to what was observed previously for the KS, MO and ND waters. Moreover, increasing color and THMFP removal are also observed past pH 10.3 for the Lake Washington source. THMFP removal is similar to TOC removal, however even greater color removal is observed past pH 10.3. Consequently enhanced color and THMFP removal as well as enhanced TOC removal were attained at higher softening pH values.

Softening and coagulation have been used as serial unit operations in water treatment. Taylor observed at Acme Improvement District (AID) FL and Olga FL that TOC removal by alum coagulation and lime softening to pH 10.3 removed no more TOC that alum coagulation alone, and that the sequence of softening and coagulation has no effect on TOC removal (Taylor, 1986). Randtke observed similar results with ferric sulfate coagulation and softening of Austin TX waters.

Figure 2-3: TOC Removal by Lime Softening and in-situ Coagulant Addition

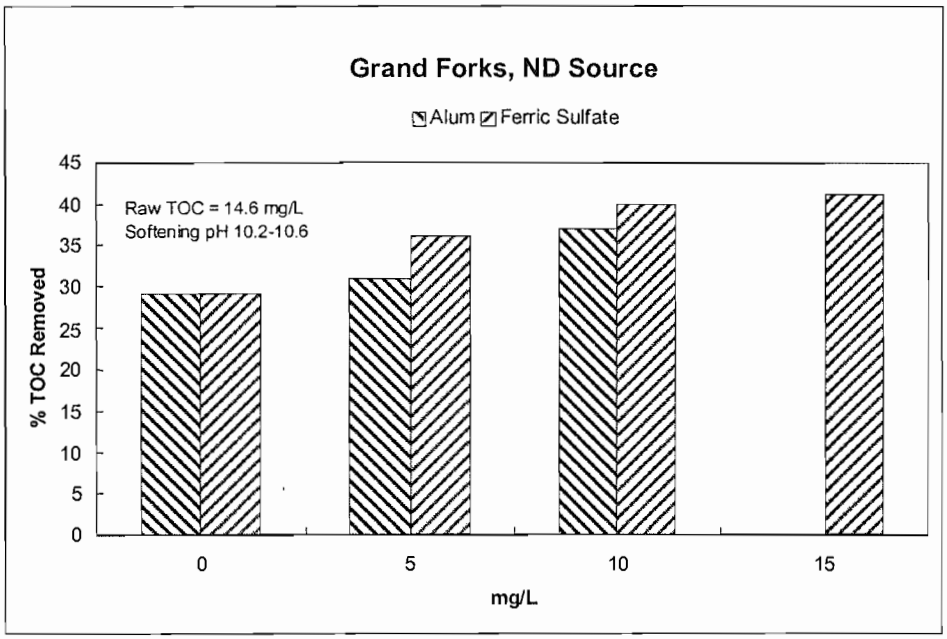
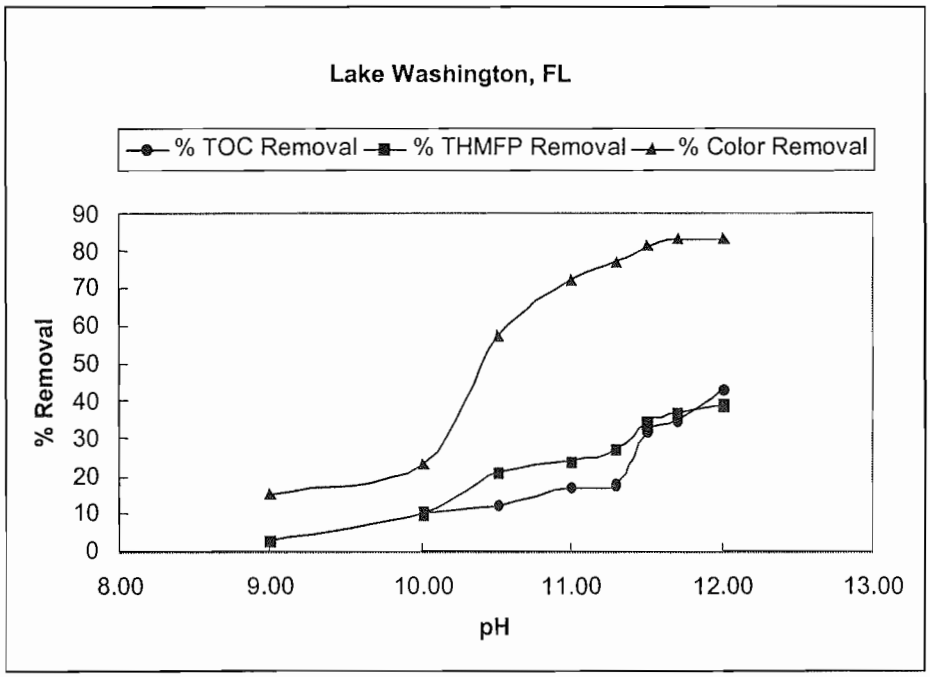


FIGURE 2-4: TOC, THMFP and Color Removal vs pH



3.0 Lime Softening Plant Evaluation

In order to evaluate the Marco Island LSWTP, historical plant operating information and water quality data provided by Florida Water was compiled and analyzed. The water quality data was compared to current operational practices and drinking water regulations. This section presents LS plant performance and its relation to the existing and future regulations. The plant layout flow diagram for the LS plant is described and then plant performance for LS is evaluated.

This chapter presents the SWTR evaluation for the LS plant which included:

- Historical water quality and operational evaluation of the LS facility relating to the SWTR.
- Lime-Softening treatability evaluations of LS plant.

3.1 Historical Lime Softening Plant Operating Parameters

Monthly operational reports (MORs) from May 1996 until February 1997 were utilized to determine typical water quality expected at the lime softening facility. The LS plant collects samples for water quality analysis for both raw and finished lime softened water. The water sources are representative of the current overall process. The current process at the LS plant is depicted in Figure 3-1. At the LS plant, raw water is withdrawn from the Marco Lakes located nine miles away. Quick lime (CaO) is added as a slurry in the solids contact unit (SCU); also, alum is added in the SCU to aid settling. To provide disinfection following the SCU, sodium hypochlorite (NaOCl) is added to the settled water. The pH is then adjusted to 8.3 using sulfuric acid (H_2SO_4) to avoid precipitation, and ammonia (NH_3) is added to form chloramines. The disinfected pH adjusted water then passes through one, four-cell filter that shows signs of post-precipitation on the filters. A phosphate corrosion inhibitor is added after filtration to control corrosion in the distribution system. The finished water then proceeds to storage and is pumped to the distribution system where it blends with RO finished water. Table 3-1 presents typical LS plant operation data.

At the time that the LS plant was designed, the SCU was designed to operate at a surface loading rate (SLR) of 1.5 gpm/ft^2. This is based on a flow rate of 5.0-MGD through a 54 ft diameter SCU. Typical lime softening plant SCUs are now designed to operate a SLR of 1.0 gpm/ft^2 (Ten States Standards). Addition of a settling aid can increase the SLR up to 1.5 gpm/ft^2. Alum is currently the settling aid used at the LS plant. However, carry-over turbidity and soluble aluminum continues to be a problem at the LS plant using alum as a settling aid. A cationic polymer was tested at the plant to assist the alum, but the sludge blow-down schedule was not adjusted to compensate for the additional sludge so this practice was discontinued. Alum typically precipitates effectively at pH 5.5 to 6.5. The LS plant SCU pH is approximately 9.0, so a portion of the alum remains dissolved and this can pass through the filters.

FIGURE 3-1: MIWS LS Process Flow Diagram

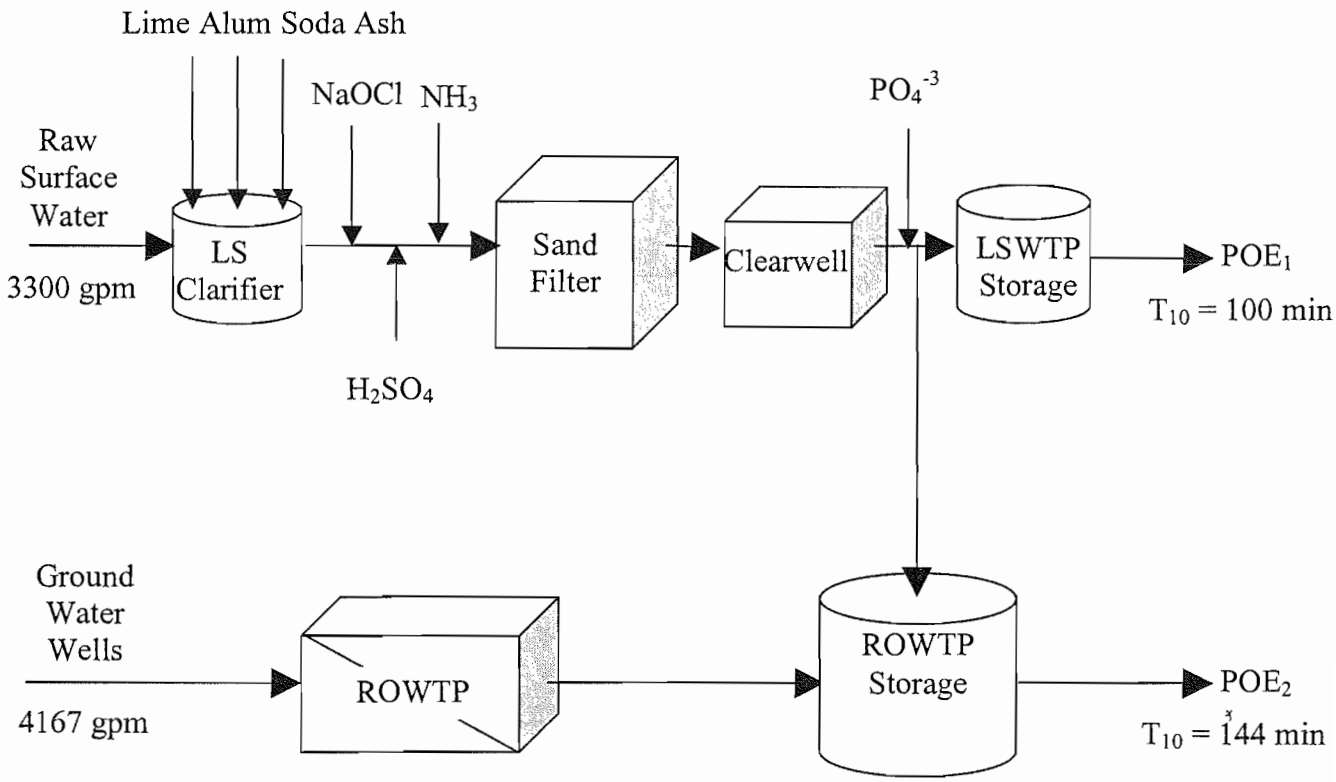


TABLE 3-1: Typical LS Plant Historical Operating Parameters

Parameter	Units
Flow	5.0-MGD
SCU Surface Loading Rate	1.5 gpm/ft^2
Filter Surface Loading Rate	2.43 gpm/ft^2
Lime Dose	152 mg/L as CaO
Alum Dose	10 mg/L
Soda Ash Dose	4 mg/L
Sodium Hypochlorite Dose	6.2 mg/L
Ammonia Dose	1.7 mg/L
Sulfuric Acid Dose	18 mg/L
Phosphate Dose	1.9 mg/L

3.1.1 Inorganic Water Quality

Samples of raw and finished water were collected and analyzed for inorganic water quality parameters. The MIWS raw and finished water were evaluated for fluoride, nitrite, nitrate, phosphate, strontium, sulfate, magnesium, chloride, iron, sodium, barium, potassium, total phosphorous, conductivity, total dissolved solids (TDS), calcium hardness, total hardness, alkalinity, pH, temperature and ammonia. Results of the inorganic water quality analysis are presented in Table 3-2. None of the inorganic finished water qualities for the LS plant exceeded their respected MCLs.

3.1.2 Organic Water Quality

Disinfection by-products (DBPs) have been considered to be a public health issue because trihalomethanes (THMs) are formed as a result of disinfection using chlorine. DBPs are formed by reactions between chlorine or other disinfectants such as chloramines, chlorine dioxide, and ozone with natural organic matter (NOM) (Bull, and Kopfler, 1991). Of these disinfectants, chloramines generally do not produce by-products (Amy et. al. 1990). Currently USEPA and the State of Florida allow the maximum total THM annual average concentration based on four quarterly samples collected in the distribution system to be 100 μg/L. Future DBP regulations will be implemented in two phases for reduction in THM levels (Stage I DBP Rule, EPA 815-F-98-010, December 1998). Phase I, effective January 2004 (for surface water systems serving less than 10,000), will lower the THM MCL to 80 μg/L, and the HAA MCL to 60 μg/L. In addition, total organic carbon (TOC) will be regulated based upon source water TOC and alkalinity values. The TOC reduction requirements are presented in Table 3-3.

Raising the pH of the finished water increases THMs and decreases HAAs. This option could be evaluated for control of HAAs as the THM and HAA MCLs are proposed to be reduced to 40 and 30 μg/L, respectively, for Phase II.

In 1999 the LSWTP converted from chlorine gas to liquid sodium hypochlorite for disinfection. The NaOCl dose currently is approximately 6.2 mg/L and depends upon raw water quality and maintenance of a residual of 4.0 mg/L as total Cl_2 in the distribution system. NaOCl is injected at the back side of the collection ring weir on the SCU. Sulfuric acid is also added at the back side of the collection ring weir to adjust the pH. Ammonia is then added in the transfer channel from the collection weir to the filter splitter box as 1.7 mg/L to form chloramines.

Samples of the raw and finished LS plant water were collected and analyzed for organic water quality at the University of Central Florida (4000 Central Florida Blvd., Orlando, Florida 32826) (Table 3-4). The samples were analyzed for non-purgeable dissolved organic carbon (NPDOC), UV-254, and color. NPDOC, UV-254, and color are all indicators of organic matter present in the water. UV-254 is not currently regulated, but it has shown to possess correlation to NPDOC and color.

TABLE 3-2: Marco Island Surface Water Supply Physical and Inorganic Water Quality Characteristics

DESCRIPTION	Raw	Finished	MCL
FIELD DATA			
pH	7.35	8.27	6.5-8.5
Temperature (°C)	24	23.7	---
Conductivity (umhos/cm @ 25 °C)	1311	714	---
INORGANIC (mg/L)*			
Fluoride (mg/L)	< 0.02	< 0.02	4.0
Chloride (mg/L)	138	147	250
Total Nitrite + Nitrate (mg/L as N)	0.258	0.269	10
Strontium (mg/L)	0.578	0.295	---
Sulfate (mg/L)	65.7	64.9	250
Iron (Total) (mg/L)	< 0.2	< 0.2	0.3
Magnesium (Total) (mg/L)	12	11.2	---
Sodium (Total) (mg/L)	73.7	69	160
Calcium (Total) (mg/L as $CaCO_3$)	315	103	---
Hardness (Total) (mg/L as $CaCO_3$)	344	158	---
Alkalinity (Total) (mg/L as $CaCO_3$)	259	44	---
Ammonia Nitrogen (mg/L as N)	0.1	1.45	---
TDS (mg/L)	948	299	500
Barium (Total) (ug/L)	36	15	---
Potassium (Total) (mg/L)	2.53	2.36	---
Total Phosphorous (as P) (mg/L)	0.03	0.36	---

TABLE 3-3: TOC Reduction Requirements @

TOC (mg/L as C)	Raw Water Alkalinity (mg/L as $CaCO_3$)		
	0-60	**60-120**	**>120**
2-4	40%	30%	20%
4-8	45%	35%	25%
>8	50%	40%	**30%**

@ = According to D-DBP Rule

TABLE 3-4: Marco Island Surface Water Supply Organic Water Quality Characteristics

Description	Raw	Finished	MCL
NPDOC (mg/L as C)	13.5	10.7	TT(1) (30% Reduction)
UV-254 (cm^{-1})	0.335	0.181	N/A
Color (CPU)	40	20	15
Chlorine Residual (mg/L)	---	3.7	4
TTHM (μg/L)	---	56(2)	100
Phase I TTHM (μg/L)	---	56(2)	80(3)
Phase I THAA (μg/L)	---	50(2)	60(3)

1) TT = Treatment Technique. Based on IESWTR effective January 2004
2) Based on results of Marco Island DBP Formation Potential Results (1/14/2000) 30 minutes of Cl_2 contact
3) D/DBP Rule level effective January 2004

Based on Table 3-3, since the MIWS alkalinity is > 120 mg/L and raw surface water TOC is > 8.0 mg/L, MIWS would be required to reduce raw water TOC by 30 percent for a limit of 9.8 mg/L. The MIWS currently exceeds the MCL for NPDOC and color with 10.7 mg/L and 20 CPU respectively.

3.1.4 Microbial Water Quality

Samples of raw LS water were collected and analyzed for microbial water quality at the University of South Florida. The surface water was evaluated for turbidity, heterotrophic plate count (HPC), total coliform, and the presence of *Giardia* and *Cryptosporidium*.

Giardia cysts and *Cryptosporidium* oocysts (parasitic "eggs") are recognized organisms for waterborne disease. *Giardia* and *Cryptosporidium* require a host body for viability so they remain dormant until they infiltrate a host body. Viability is the ability to live, develop, and prosper under favorable conditions. Ingested *Cryptosporidium* causes gastrointestinal illness that can become life threatening to persons with compromised immune systems. Ingestion of only one viable *Cryptosporidium* oocyst may lead to infection (Watanabe, 1996). Symptoms of cryptosporidiosis linger for 2 to 4 weeks and include nausea, diarrhea, and cramps. *Cryptosporidium* is similar to the *Giardia* organism, but it is more resistant to disinfection than *Giardia* and half the size. *Cryptosporidium* is approximately 4 - 6 microns in diameter (Rose, 1988). Therefore *Cryptosporidium* is more difficult to inactivate and physically remove from water supplies than *Giardia*. *Cryptosporidium* have a tough outer shell that makes them resistant to environmental conditions. *Giardia* cysts and *Cryptosporidium* oocysts are commonly found in the feces of most mammals. Surface water treatment plants located down stream of agricultural (grazing) areas waste water discharge, and sewage hazards are susceptible to a greater risk of contamination. Rainfall events increase the risk because the rain may rinse the feces in to nearby surface waters.

Results in monitoring *Giardia* and *Cryptosporidium* can vary significantly among laboratories. Commercial laboratories have shown a lack of proficiency in analyzing for *Giardia* and *Cryptosporidium* (Clancy et. al., 1994, Watanabe, 1996). A complicating factor in the current analysis is the discrimination between viable and non-viable oocysts. Performance of water treatment plants can be evaluated by HPC. HPC and turbidity measurements can be effective tools in determining expected removals of *Giardia*, and *Cryptosporidium*, but a correlation was not demonstrated between the removal of these organisms and heterotrophic bacteria (Nieminski, 1994).

Sub-optimal water treatment operations have been identified during outbreaks of *Giardia* and *Cryptosporidium* in other water systems across the nation (Rose, 1996), and include:

1. start-up of unwashed filters;
2. start-up of just-washed filters; and
3. recycling of backwash waters.

Recycled water can contain high levels of oocysts greater than 150 / L even after sedimentation (Rose et al., 1991, Colbourne, 1989). Since recycling is a common practice in an effort to conserve water, Cornwell and Lee (1994) recommend the following recycling practices:

1. recycle streams should be equalized and blended over a 24 hour time period;
2. recycle should be less than 10 percent of the flow;
3. recycle streams should be regularly monitored for contaminants of concern;
4. recycle sedimentation basins should be regularly cleaned; and
5. recycled turbidities should be less than 5 NTU or have a suspended solids concentration of less than 10 mg/L.

With respect to these recycling practices, the LSWTP recycles blow down water after dewatering sludge. In addition to the above recycling practices, regulatory rules are being developed in the prposed Backwash Filter Rule (LT1FBWR, April 10, 2000) that may include the following:

1. Limit the rate of recycled backwash water to a 2 to 5 percent rate of plant inflow. So return rates up to 10 percent may no longer be considered.
2. Require the recycled water quality to have a turbidity standard with possible periodic monitoring requirements for *Cryptosporidium* and *Giardia*.
3. Require filtration treatment down to 3 to 4 micron particle size of the recycled filter backwash water. So microfiltration may need to be considered.

Chlorine and chloramines as disinfectants used in water treatment are relatively ineffective at killing or inactivating *Cryptosporidium* oocysts. Deactivation is primarily related to the concentration of the disinfectant and contact time. For example, Korich et al. (1991) reported that 80 mg/L of free chlorine or monochloramine required 90 minutes to produce 90 percent oocyst inactivation. The best disinfection approach for effectively killing *Cryptosporidium* oocysts has been shown to be ozone (Korich et al., 1991, Peeters et al., 1991, and Finch et al. 1993). Ozone required 4.5 minutes at 1 mg/L to produce 99 percent oocyst inactivation on average. The use of disinfectants to inactivate *Cryptosporidium* could create high levels of DBPs. Therefore physical removal (filtration) is a better process approach over disinfection alone (Rose, 1988, Jacangelo et. al., 1995). Because the LS plant water supply contains bromide, the use of ozone is precluded as a treatment option due to possible bromate formation.

For the microbial water quality collection of *Giardia*, and *Cryptosporidium* samples, 1 gallon per minute (gpm) of sample water was passed through a polypropylene yarn-wound filter cartridge and flow meter at about 30 psi. The filter was 1 micrometer (μm) nominal porosity. Organisms can potentially blow through the yarn filter therefore the test flow rate threshold is 2 gpm. The filters were used to collect and concentrate cysts and oocysts from the water. After collection of sample, the filters were then put on ice and transported back to the University of South Florida (USF) where they were analyzed utilizing

immunofluorescence microscopy with monoclonal antibodies (MAb) for detection of *Giardia* cysts and *Cryptosporidium* oocysts (Section 9711 Standard Methods 19th Edition, 1995).

Table 3-5 presents the *Giardia* and *Cryptosporidium* microbial water quality at MIWS for one sampling period. The volume collected represents the amount of water that passed through the yarn filters. No *Cryptosporidium* or *Giardia* organisms were detected at the detection limit in the volumes sampled. Not finding *Cryptosporidium* or *Giardia* present at the time of sampling should not be interpreted that the source water is safe in this regard.

For the microbial water sampling of HPC and total coliform grab samples were collected and analyzed by Florida Water. Table 3-6 presents the turbidity, HPC and total coliform microbial water quality for the LS plant. Turbidity was reduced by 67 percent. HPCs were maintained below 500 organisms/mL. Total coliforms concentrations for the LS plant were absent from the finished water.

3.1.5 Disinfection Effectiveness

The Surface Water Treatment Rule (SWTR) requires that all water treatment systems which utilize a surface water source must achieve an overall minimum 3-log removal/inactivation (99.9 percent) of *Giardia* cysts and an overall minimum of 4-log removal/inactivation (99.99 percent) of viruses. The SWTR prescribes CT (C, residual disinfectant concentration (mg/L), * T, contact time (minutes)) levels for specific treatment and disinfection conditions to achieve different levels of inactivation under various conditions.

The required minimum primary disinfection is the disinfection needed for the entire treatment process to meet the overall treatment requirement of 3-log *Giardia* and 4-log virus removal/inactivation. According to the *Guidance Manual for Compliance with the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources*, (AWWA 1990), the expected minimum level of treatment performance in a well operated, conventional filter system is 2.5-log removal of *Giardia* and 2-log removal of viruses. To achieve the overall removal/inactivation goal for *Giardia* and viruses, the recommended disinfection for *Giardia* is 0.5-log removal and 2.0-log removal for viruses. The MIWS utilizes chloramines as a disinfectant at the LS plant and free chlorine at the RO plant. The recommended minimum level of disinfection and assumed log removals by filtration are summarized in Table 3-7.

3.1.5.1 CT Calculation

The value of CT is specific for each treatment system. For the purpose of calculating the value of CT, T is the time, in minutes, it takes for the water during peak flow conditions to reach a point downstream where C, the residual disinfectant concentration, is measured. For purposes of this investigation, the residual is measured at a point-of-entry (POE_1) to the distribution system. The calculated value of CT

TABLE 3-5: *Giardia* and *Cryptosporidium* Microbial Water Quality at MIWS

Parameter	4/2/97	MCL
Volume Collected(liters)	383	N/A
Giardia (organisms)	Absent	TT
Cryptosporidium (organisms)	Absent	TT

TT = Treatment Technique required.

TABLE 3-6: LS Plant HPC and Total Coliform Microbial Water Quality

DESCRIPTION	Raw	Finished	MCL
Turbidity	1.18	0.39	TT
HPC (organisms/mL)	0.12	< 0.01	TT
Total Coliform(organisms/mL)	Present	Absent	< 5% *

* less than 5% of the number of samples collected should show the presence of Total Coliform Bacteria.

TABLE 3-7: Recommended Minimum Level of Disinfection

Treatment	*Giardia*	Virus	*Cryptosporidium*
Assumed Log Removal by Filtration	2.5-log	2.0-log	2.5-log
Recommended Minimum Level of Disinfection	0.5-log	2.0-log	NA
Required Removal	3.0-log	4.0-log	2.0-log

NA – Not Applicable, chlorine and chloramine disinfection have not been effectively demonstrated to inactivate *Cryptosporidium*. Turbidity standard of less than 0.3 NTU for 95 percent of the monthly samples help indicate potential *Cryptosporidium* removal.

(CT_{calc}) was calculated using the value of T_{10} obtained from the tracer study performed in April of 1994 by Florida Water, multiplied by the residual disinfectant concentration at the POE to the distribution system.

The value of T_{10} corresponds to the concentration of the tracer once 90 percent was retained in the system. The value of T_{10} was found graphically using the information obtained from the tracer study. The value of C/C_0 vs. time in minutes was graphed, where C was the concentration of the tracer and C_0 was the tracer dosage. The value of T_{10} was the time corresponding to the value of 0.1 on the C/C_0 axis.

The tracer study determined the value of T_{10} to be 100 minutes for a flow of 3300 gpm for the existing system. This value is assumed to be valid as long as no physical changes were made to the process basins or storage tanks since the time of the study.

3.1.5.2 Inactivation Ratios

Compliance with the Surface Water Treatment Rule requirements is determined by calculating inactivation ratios for *Giardia* and viruses. The inactivation ratios for *Giardia* and viruses must be 1.0 or greater. These ratios were determined by dividing the CT_{calc}, calculated as described above, by the $CT_{99.9}$ for *Giardia* and $CT_{99.99}$ for viruses for specific temperatures published in *The Guidance Manual for Compliance With the Filtration and Disinfection Requirements for Public Water Systems Using Surface Water Sources* (AWWA 1990). These values vary with pH and temperature.

An RO blend line modification was installed in 1998. Using the information and assumptions from the tracer study, CT calculations were performed by Florida Water. The results of the blend line indicated a T_{10} of 144 minutes for POE_2 from the ROWTP. Since the RO blend line and the larger storage capacity at the RO plant provided a longer contact time than the LSWTP POE_1, the blend line CT POE_2 was not further investigated.

The inactivation ratios for *Giardia* and viruses were determined using the following steps:

1. Determine the required log inactivation of *Giardia* and viruses, accounting for inactivation credits for the treatment process utilized.
2. Determine the value of T_{10} using a tracer study.
3. Calculate the value of CT by multiplying T_{10} by the residual chlorine concentration.
4. Determine the values of $CT_{99.9}$ for *Giardia* and $CT_{99.99}$ for viruses for chloramines using the Guidance Manual.
5. Calculate the inactivation ratios of *Giardia* ($CT_{calc}/CT_{99.9}$).
6. Calculate the inactivation ratio of viruses ($CT_{calc}/CT_{99.99}$).

7. If the inactivation ratio is greater than 1.0 for *Giardia*, the system provides greater that 99.9 percent inactivation of *Giardia* cysts. If the inactivation ratio is greater than 1.0 for viruses, the system provides 99.99 percent inactivation of viruses.

Disinfection requires a minimum level of disinfection to be 0.5 and 2.0 log removal for *Giardia* and virus, respectively. These values were used to calculate the inactivation ratios which should be greater than 1.0. A CT study conducted from September 1994 to February 1995 was conducted to determine the inactivation ratios over time. On average the inactivation ratios for *Giardia* and virus were 2.6 and 1.6, respectively. Tables 3-8 presents the results of the tracer study. The results of the tracer study indicated that the CT values for the existing system are in compliance with the SWTR at the LSWTP based on a review of available historical data.

3.1.6 Compliance and MCL Performance

The LS plant treats surface water. The surface water treatment consists of lime softening, coagulation, sedimentation, chloramination, filtration, inhibitor addition, stabilization, ground storage, and finally distribution. Currently, the LS plant relies on phosphate inhibitors and stabilization of the treated surface water in order to comply with the requirements of the Lead and Copper Rule (LCR).

As required by permit, Florida Water submits monthly operating permits (MORs) for the WTP to the FDEP. Based on regulatory monitoring data, operational logs, and other water quality records provided by Florida Water, the MIWS currently has difficulty complying with ESWTR and D-DBP regulations. Additionally, dissolved aluminum is passing through the filters and at times exceeds the secondary standard of 0.2 mg/L as aluminum. This data is based on water quality from 1996 and 1997, therefore the water quality data must be updated to reflect the recent changes in treatment at the LSWTP as well as the additional 2.0-MGD of RO treated water in the distribution system.

The newer regulatory provisions of the SDWA are more restrictive and are more difficult for water purveyors to comply with than in the past. Today, more emphasis has to be placed on compliance with water quality regulations at the consumer tap (especially as it relates to lead and copper corrosion control). Moreover, public water purveyors are under increased demands to maintain consumer confidence and manage water quality in expanding distribution systems as a result of economic and population growth. As regulations continue to be developed, it is assumed that Florida Water is preparing by implementing total quality management programs to increase productivity and enhance consumer attitudes.

TABLE 3-8: Comparison of CT Values for Compliance Using Chloramines

Parameter	Temp (°C)	Cl_2 Residual Min (mg/L)	$CT_{Calculated}$ (mg/L-min)	$CT_{Required}$ @ T°C 0.5-log Giardia Inactivation	$CT_{Required}$ @ T°C 2.0-log Virus Inactivation	Inactivation Ratio $CT_{Calculated}/CT_{Required}$ *Giardia*	Inactivation Ratio $CT_{Calculated}/CT_{Required}$ Virus
Average	24.9	3.8	379	126	216	3.01	1.75
Max	26.8	4.7	470	103	175	4.56	2.69
Min	20.8	2.5	220	175	304	1.26	0.80(1)

(1) Note: one discrete value measured 2.5 mg/L chlorine residual, which corresponds to an inactivation ratio of 0.8.

4.0 Methods and Materials

Florida Water provided updated historical water quality and operational information relative to the LSWTP. Laboratory treatability evaluations were conducted at the University of Central Florida's Environmental Systems Engineering Institute located in Orlando, FL (4000 Central Florida Blvd., 32826). The bench-scale lime softening jar testing demonstrated the application of precipitation processes for the removal of hardness, color, non-purgeable dissolved organic carbon (NPDOC), suspended solids, and disinfectant by-products (DBPs). The historical information was compared to the information obtained from the bench-scale lime softening jar tests.

A series of bench-scale jar test evaluations was performed and the following plots were prepared.

- Determine the effect of enhanced softening on color and NPDOC removal.
- Determine the effect of iron and aluminum coagulant addition on color and NPDOC removal.
- Determine the effect of iron and aluminum on settleability.
- Determine the effect of iron on DBP precursor removal.

Figure 4-1 and 4-2 present the enhanced softening and activated carbon bench-scale tests, respectively. That were performed for the Marco Island LSWTP. The bench-scale tests are briefly described below:

Lime Softening

Various doses of lime were utilized to determine the optimum pH range for organic removal via enhanced softening.

Coagulant Addition

After completion of the hardness removal investigation, an "optimum" pH range was selected for coagulant addition. The jar testing procedures were repeated, but alum and ferric chloride settling aids were added during the rapid mix at the selected lime softened pH values. The results of the softening experiments with iron and aluminum salt coagulant augmentation were plotted and graphically analyzed.

Settleability

Floc settling distribution curves were produced by measuring the turbidity from the 10 cm sampling port from each jar after flocculation was completed as a function of time. Time zero was identified as when mixing ceased. The data was plotted using a log-log scale to assess jar test conditions relative to other jar test conditions for settling efficiency. Settling velocity curves for softening at the selected pH values with and without Fe and Al coagulants were plotted and graphically analyzed.

Chlorine Demand

A capacity and chlorine demand curve of the raw and settled water were developed.

FIGURE 4-1: Enhanced Lime Softening Bench-Scale Testing

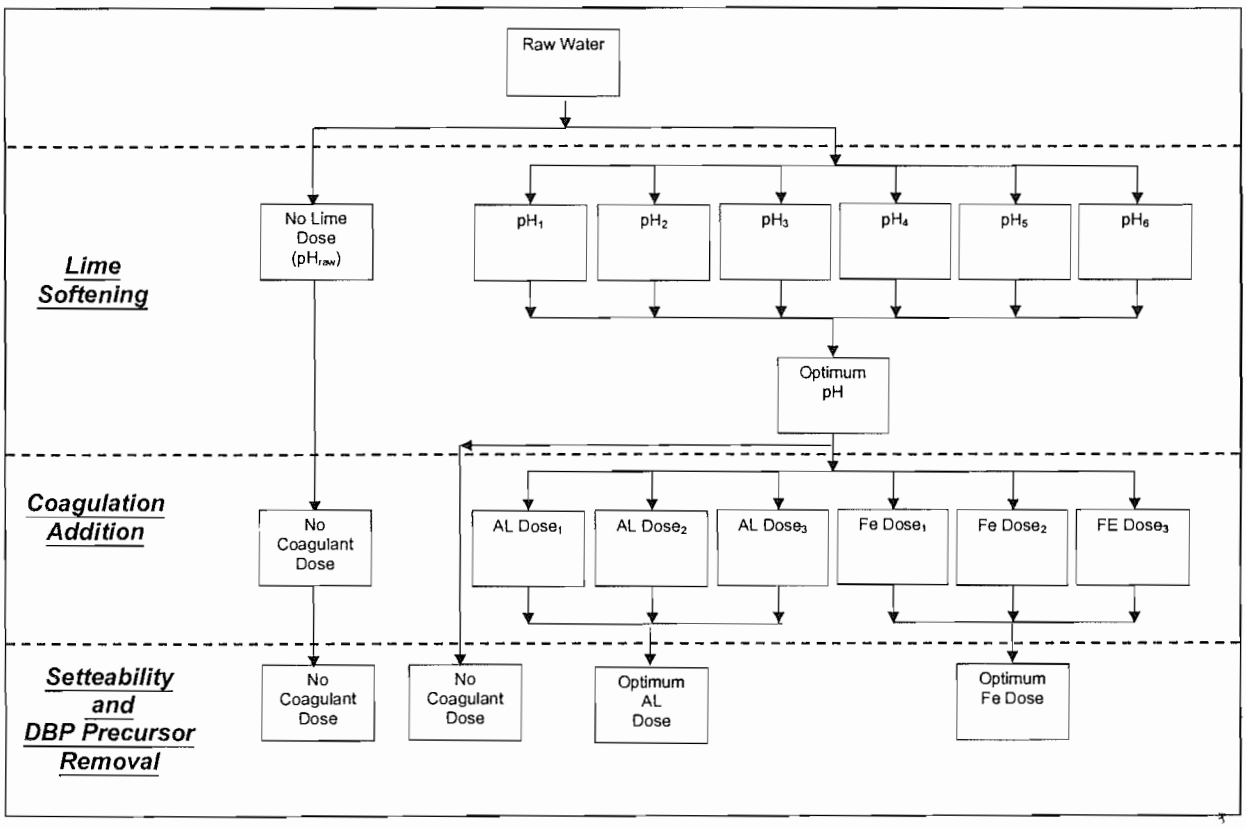
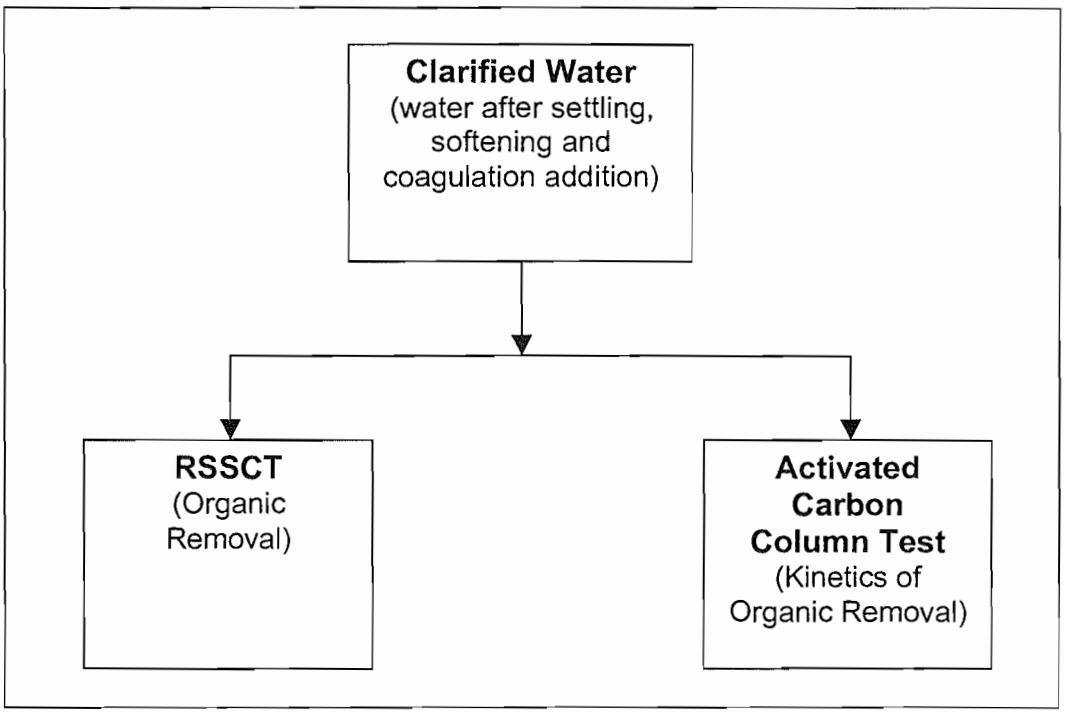


FIGURE 4-2: Activated Carbon Bench-Scale Testing



DBP Precursor Removal

Jar tests were conducted to assess DBP formation. The tests were performed at the selected pH with and without coagulant and for varying flocculation times. Varying flocculation time was investigated when it was noted that increased contact time removed additional turbidity and color in the settleability jar tests. DBP simulated distribution system (SDS) measurements for selected jar tests using 48-hours, pH_s and 25°C were plotted and graphically analyzed.

Activated Carbon

Utilizing EPA's rapid small scale column tests (RSSCTs) the ability for GAC to remove organics was evaluated and design information relative to GAC was ascertained. Also activated carbon isotherms were performed to determine the kinetic rates at which activated carbon could adsorb organics.

4.1 Jar Testing

The Jar Test is universally recognized as the most valuable and most commonly used tool for coagulation control. The following items are a listing of the typical uses of information generated from Jar Test evaluations.

- Coagulant and dosage selection
- Coagulant aid and dosage selection
- Optimum pH determination
- Determination of reagent addition sequences
- Optimization of rapid and slow mixing energy and time

Standardized jar testing procedures have been established which mimic as best as possible plant operating conditions while optimizing conditions for organics removal. In order to produce meaningful data for practical application, consideration was given to all pertinent control variables. These variables are as follows:

- Jar test temperature
- Coagulant solution strength
- Coagulant dose
- Jar test pH
- Method for coagulant addition
- Sludge addition

- Polymer dose
- Method for polymer dose
- Sequence and timing of reagent addition
- Duration and intensity of rapid and flocculation mix
- Sample collection technique
- Laboratory analyses to be performed

Most of these control variables have been established. A development of each of these parameters is presented in the paragraphs to follow.

All jar tests are being performed at roughly 22 °C. The four coagulants under investigation were diluted so as to enhance coagulant dispersion upon addition during rapid mix. In order to establish a level grounds for comparison, the coagulants were diluted to equal strength and expressed as equivalent alum dosages. Given the effect of pH on the minimum solubility of metal hydroxides formed during rapid mix and flocculation, pH was varied for each coagulant dosage.

Coagulants were added to the water surface of the jars during rapid mix. This was done as an effort to mimic plant operation given their addition of coagulant to the feed water surface at the SCU. Sludge generated from each respective coagulant and source water was added to each jar tested. This was done to enhance the coagulation process by providing a nucleation site for rapid floc formation and settling. The sludge volume addition was roughly 25 mLs (settled) and was used consistently throughout the testing procedures.

The sequence of reagent addition for all phase I and phase II jar test procedures was the same. Coagulant and sludge were added during rapid mix in order to achieve a uniform dispersion of the reagents. Following rapid mix, acid or base was added during the flocculation step for pH control. Rapid mix was performed for 30 seconds at 300 rpm, whereas slow mix conditions for floc formation were carried out for 15 minutes at 40 rpm. These mixing speeds for rapid and slow mix correspond to velocity gradients (G) at 22 °C of roughly 33 and 370 s^{-1}, respectively.

Samples for analysis were collected from each jar following a 5-minute settling period. These samples were collected at roughly 10 cm below the water surface. This corresponds to about a 0.5 gal/ft^2-min settling basin overflow rate. Upon collection, the samples were filtered with 0.45 micron organic free filter paper and stored in a refrigerator at 4 °C until chemically analyzed.

4.1.1 Methods of Analysis

All water quality samples generated and received were handled according to the Environmental Systems Engineering Institute (ESEI) laboratory protocol. Analysis usually began the day of collection; however,

those samples requiring storage were stored per Standard Methods recommendations. Refrigerated samples were stored at 4 °C. Most analyses were completed within three days and the maximum holding period was generally under one week.

Water quality analyses were used to evaluate the effectiveness of the individual Jar Test conditions. Organics removal was quantified by the measurement of non-purgable dissolved organic carbon (NPDOC), color and DBPs (TTHMFP and THAAFP). Ultraviolet absorbance (UV-254) was also measured which was in turn correlated to NPDOC. Additionally, turbidity and alkalinity were used to further characterize the raw and treated waters. Table 4-1 summarizes these analyses in terms of the equipment used and the methodology applied.

4.2 Kinetic Studies

Kinetic studies were conducted on the carbon to determine how long the isotherm samples will be shaken before sample collection. Seven 250 mL Erlenmeyer flasks were filled with 250 ml of sample and 1 gram of carbon. The same carbon was used in the column studies and in the isotherm studies. UV-254 was measured in these samples at varying times. UV-254 was plotted verses time and equilibrium conditions will be selected from this analysis.

4.3 Isotherm Studies

The following describes procedures for preparing carbon for the isotherm portion of this study.

- Six 250 mL Erlenmeyer flasks will be filled with 250 ml of settled water and varying masses of activated carbon. Two additional flasks will be used for a total of eight. The two additional flasks will consist of a settled water blank and a duplicate of any one of the five. These flasks will be shaken for a time period determined from the previous experiment. Each flask will be analyzed for UV-254, color and NPDOC. This data will be fitted to a isotherm and used to determine hypothetical carbon demand at the LSWTP.
- Rinse carbon with DI water to remove "fines".
- Vacuum out excess water and allow to dry over night.
- Weigh out carbon for kinetic rate and isotherm evaluation.
- Equilibrium Isotherm.
- Fill filtered settled water into a 250 mL Erlenmeyer flask.
- Analyze sample for UV-254, color, TOC.
- Place on shaker table.

TABLE 4-1: Water Quality Analysis Summary

Parameter	Standard Method	Equipment Used	Comments
True Color	Spectrophotometric SM-19th Ed.-2120	Hach DR 13 Spectrophotometer	Samples filtered with 0.45 micron filter paper, pH adjusted to 7.6, absorbance read at 454 nm.
NPDOC	Persulfate-UV Oxidation SM*-19th Ed. –5310	Dohrman DC-180 Carbon Analyzer	Samples filtered with 0.45 micron filter paper.
UV-254	Spectrophotometric SM*-19th Ed. –5910	Hach DR 4000 Spectrophotometer Model 48000	Samples filtered with 0.45 micron filter paper, pH adjusted to 7.6, absorbance read at 254 nm.
Turbidity	Nephelometric SM*-19th Ed. –2130	Hach Ratio Turbidimeter Model 18900	Equipment calibrated with Formazin standard.
Alkalinity	Potentiometric SM*-19th Ed. –2320	Accumet pH meter Model 925	All samples titrated to pH inflection point. Unit equipped with rapid response reference and glass electrode.
Trihalomethanes	SM*-19th Ed. -6232B	Hewlett-Packard HP5890A	Gas Chromatograph with DB-5 Capillary Column
Haloacetic Acids	SM*-19th Ed. -6251B	Hewlett-Packard HP5890A	Gas Chromatograph with DB-1701 Capillary Column

SM = Standard Methods

- Add varying concentrations of GAC to jars.
- Allow mixing until equilibrium time determined from kinetic rate study is reached.
- Collect 500 mL of sample at equilibrium time.
- Filter sample and analyze for UV-254, color, and TOC.

4.4 RSSCT Apparatus Set-up and Small-scale Carbon Preparation

The Rapid Small Scale Column Test (RSSCT) is a granular activated carbons (GAC) mini-column that uses dimensional analysis to simulate a full-scale GAC column. Similitude is applied to the particle diameter, empty bed contact time (EBCT), hydraulic loading and operation time factors. Dimensional analysis is then used to establish the relationships between these factors for appropriate scale-up of the resulting capacity and breakthrough information. Various cases with varied conditions and treated source waters are presented within the ICR manual which warrant the application of this technique.

The test column used consists of a glass column 14 inches in length and 10 mm in diameter. Influent flow is achieved via a diaphragm chemical feed pump (LMI, Milton Roy). The feed side of the column was equipped with a pressure gauge to monitor pressure. There is a stop cock at the column base. A bituminous based GAC (Filtrasorb 400) was used for evaluation and was prepared per the ICR manual guidelines. The characteristics of the GAC are shown in Table 4-2.

The carbon was "cracked" (i.e. ground) to an approximate size and then sieved so as to attain carbon of the desired average particle diameter (APD). The ground carbon was passed through and a 60x100 mesh (200 μm) sieve. The carbon retained on this sieve combination was used for the column studies. In order to remove the remaining fine particles (fines), the sieved carbon was repeatedly rinsed with distilled and de-ionized (DI) water which was decanted. Sonic cleaning was also used to facilitate fines removal and was applied sparingly. Rinsing, decanting and periodic sonic cleanings were performed until the presence of fines was unnoticeable. The carbon was then dried, weighed, volume measured, wetted again, and the remaining air within the carbon evacuated via vacuum. Following these procedures, the column was packed and readied for operation. The necessary steps are outlined as follows.

4.4.1 RSSCT Materials Required

Material required to set-up an RSSCT column are as follows:

- Glass column.
- Chemical feed-pump with stroke and frequency adjustment.
- Pressure gauge.
- Rubber plug.

TABLE 4-2: Characteristics of Filtrasorb 400 carbon

Parameter	Description
Carbon	Filtrasorb 400
Company	Calgon Carbon Corp.
Source	Bituminous Coal
Iodine number (min.)	1050
Abrasion number (min.)	78
Moisture (max.)	0.9%
Total surface area (ft^2)	NA
N2 BET method (m^2/g)	900-1100
Bulk density (lbs/ft^3)	27
Pore volume (cm^3/g)	0.85-0.95
Effective size (mm)	0.55-0.75
Uniform coefficient (max.)	1.9

- Tygon tubing and barbed nylon slip connections.
- 60 mesh and 100 mesh sieves.
- Sieve shaker.
- Coarse screen (100 mesh).
- Fine screen (200 mesh).
- Glass beads and glass wool.
- Sampling bottles

Guidelines for effective RSSCT evaluations are outlined in the ICR manual. These procedures are concerned with, but not limited to, materials and configuration, column design, water quality sampling and data interpretation. These items are discussed in the following sections.

4.4.2 GAC Preparation

Grind GAC in coffee grinder and sieve using the appropriate mesh. Wash GAC with low D.O. low carbon distilled water (LCW) by step-wise decanting in a beaker. Allow 1 to 2 minutes before decanting. The amount of washing depends on the carbon to wash vessel ratio. For ratios equal or less to 0.1, 100 to 150 decanting may be necessary. Brief sonic cleaning may be applied (10 seconds of less) but should be used cautiously due to possible formation of additional fines. Dry GAC to a constant weight at a temperature not exceeding 100°C. Store dried GAC in a desiccator until use.

4.4.3 Column Packing

Pre-wet the required GAC for the column. Place the carbon in LCW such that it is submerged at a level of about 1 inch and allow to stand overnight (16 to 24 hrs). De-aerate by applying vacuum for at least 15 min to remove trapped air in the pores of the carbon particles. Decant excess LCW and transfer into the column as a slurry. Fill the column with LCW to about 25 percent of the GAC bed depth. Pour the GAC slurry and tap the column while filling to pack the carbon particles. (the column bed should be completely submerged during and after the packing process). Connect the column to the rest of the RSSCT set-up. Test the column for leaks, air pockets or immediate head loss buildup by running LCW for about 10 minutes.

4.4.4 Column Pretreatment

Pre-filter influent water using about 1.0 μm pore size membrane or cartridge filters. The filter should be first flushed with LCW and the TOC of the effluent checked prior to actual filtration of the influent. An optional column containing filter media, *i.e.* glass beads, can be used as a pre-filter.

4.4.5 Column Sampling

Discard the first 20 min flow before sampling. Collect about 12 samples particularly for the following:

- 1 sample after 1 hour.
- 3 samples at regular intervals through 50% breakthrough.
- 1 sample following 50% breakthrough.
- 1 sample at the end of the run

Water quality monitoring was performed on both the pretreated influent and RSSCT treated effluent. The parameters of interest included true color, NPDOC, UV-254, alkalinity, pH, total and calcium hardness, TTHMFP, THAAFP, and dissolved oxygen (DO). The parameters pH, UV-254 and DO were monitored on a daily basis. Samples were also collected daily for analysis of the remaining parameters. Some of these samples were discarded depending on NPDOC breakthrough behavior. NPDOC measurements determined which samples were analyzed for DBPFPs. These efforts were warranted by the need to accurately identify breakthrough of DBP precursors and to minimize the high costs associated with TTHM and THAA formation potential measurement. A breakdown of the analyses that were performed and their respective frequency over the run period for both the pretreated raw water and the GAC filtered effluent is summarized in Table 4-3.

4.5 Quality Control

The precision and accuracy of analytical measurement systems was monitored by spiking and duplicating analysis of each laboratory phase. These results are shown in Tables 4-4 through 4-7 based on replicate samples (precision) and spiked samples (accuracy).

All analyses are performed in accordance with accepted methodologies in Standard Methods and/or other commonly available sources. Each analytical method used during the course of this project had quality control guidelines that were observed. The precision and accuracy measurements were statistically determined using the initial sample analysis as a base. Further assessments of accuracy were made by the use of reference samples of known concentrations and statistically generated 95% confidence intervals.

4.5.1 Precision

Precision was assessed by measuring the reproducibility observed between duplicate analyses. Duplicates were based on two determinations of the same analyte for the same sample made by repeating the analytical procedure in its entirety. Precision is expressed as percent relative deviation for each pair of analyses, and is presented as percent relative standard deviation (%RSD). Ten percent of all samples were analyzed for precision.

TABLE 4-3: RSSCT Experimental Water Quality Monitoring Summary

Sampling Point	Analyses	Sampling Frequency
GAC Influent(1)	Alkalinity, total and calcium hardness, true color, UV-254, NPDOC, DO and pH.	One sample after 1 hour of operation. The second sample will be collected at the runtime midpoint per RSSCT run.
GAC Influent(1)	SDS for TTHMFP, THAAFP, and chlorine demand.	Once at initial start-up per RSSCT run.
GAC Effluent(2)	pH, UV-254, DO and temperature.	Daily until 70% NPDOC breakthrough.
GAC Effluent(2)	SDS for TTHMFP, THAAFP, and chlorine demand.	Five samples per RSSCT run, three prior to initial breakthrough and two up to 70% NPDOC breakthrough.

TABLE 4-4: Quality Control For Non-DBP RSSCT Analyses

Parameter	Value	Value	RSD	Spike	Recovery	RSD
A. ***Alkalinity***	***mg/L***	***mg/L***	***%***	***mg/L***	***%***	
157 h RSSCT EBCT = 10 min	16.4	17.4	5	63.3	96	
94 h RSSCT EBCT = 20 min	14.0	13.0	7	57.8	90	
B. ***Total Hardness***	***mg/L***	***mg/L***	***%***	***mg/L***	***%***	
157 h RSSCT EBCT = 10 min	119	118	1	136.3	86	
94 h RSSCT EBCT = 20 min	134	136	1	152.9	94	
C. ***Calcium Hardness***	***mg/L***	***mg/L***	***%***	***mg/L***	***%***	
157 h RSSCT EBCT = 10 min	92	94	2	110.8	94	
94 h RSSCT EBCT = 20 min	105	106	1	122.5	88	
D. ***UV-254 and Color***	***cm^{-1}***	***cm^{-1}***	***%***	***cpu***	***cpu***	***%***
Softened water	0.1537	0.1536	<1	8	8	<1
21 h RSSCT EBCT = 10 min	0.0068	0.0069	<1	1	1	<1
50 h RSSCT EBCT = 10 min	0.0300	0.0310	3	1	1	<1
Influent 3	0.1502	0.1515	1	7	7	<1
149 h RSSCT EBCT = 10 min	0.0582	0.0587	1	1	1	<1
Influent 1 EBCT = 20 min	0.1619	0.1631	1	7	7	<1
Influent 3 EBCT = 20 min	0.1618	0.1638	1	9	10	9
E. ***NPDOC***	***mg/L***	***mg/L***	***%***	***mg/L***	***%***	
21 h RSSCT EBCT = 10 min	0.856	0.771	9	1.834	98	
42 h RSSCT EBCT = 10 min	1.860	1.905	2	3.799	97	
149 h RSSCT EBCT = 10 min	3.423	3.441	<1	5.504	104	
Tap water	2.185	2.168	1	3.175	99	

TABLE 4-5: Quality Control for DBP RSSCT Analyses

Parameter		Value (μg/L)	Value (μg/L)	RSD (%)	Spike (μg/L)	Recovery (%)
F. ***THM-1***	$CHCl_3$	11.63	13.46	13	32.33	103
	$BrCl_2CH$	23.23	22.57	3	45.88	113
	Br_2ClCH	45.46	44.87	1	66.66	106
	Br_3CH	26.38	26.32	<1	48.5	111
THM-2	THM_{total}	106.7	107.22	<1	1093.37	108
	$CHCl_3$	22.23	22.67	2	43.28	105
	$BrCl_2CH$	46.17	43.18	6	67.85	108
	Br_2ClCH	67.18	64.87	3	88.83	108
	Br_3CH	27.86	26.1	6	50.31	112
	THM_{total}	163.44	156.82	4	250.28	109
G. ***HAA-1***	MCAA	1.81	1.79	1		
	MBAA	3.65	3.88	5		
	DCAA	7.52	7.82	4		
	TCAA	6.30	6.73	6		
	BCAA	9.80	10.45	6		
	DBAA	6.66	7.12	6		
	HAA_{total}	35.75	37.78	5		
HAA-2	MCAA	1.64	13.29	58		
	MBAA	4.74	19.34	73		
	DCAA	5.99	23.23	86		
	TCAA	4.34	21.88	88		
	BCAA	9.73	26.87	86		
	DBAA	8.12	25.40	86		
	HAA_{total}	34.55	130.02	80		

TABLE 4-6: Quality Control for Non-DBP Lime Softening Analyses

Parameter		Value	Value	RSD	Spike	Recovery	RSD
A. *Alkalinity*	*Sample*	*mg/L*	*mg/L*	*%*	*mg/L*	*%*	
	3 meq/L $Ca(OH)_2$	95	95	0	139	92	
	5 meq/L $Ca(OH)_2$ + 0.3 meq/L Alum	48	48	0	91	90	
	5 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$	36	37	2	82	96	
B. *Total Hardness*	*Sample*	*mg/L*	*mg/L*	*%*	*mg/L*	*%*	
	4 meq/L $Ca(OH)_2$	128	129	1	148	100	
	5 meq/L $Ca(OH)_2$ + 0.1 meq/L Alum	110	112	2	131	109	
	7 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$	155	156	1	174	94	
C. *Calcium Hardness*	*Sample*	*mg/L*	*mg/L*	*%*	*mg/L*	*%*	
	5 meq/L $Ca(OH)_2$	73	73	<1	92	98	
	5 meq/L $Ca(OH)_2$ + 0.1 meq/L Alum	75	76	1	94	98	
	7 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$	138	140	1	158	101	
D. *UV-254/Color*	*Sample*	cm^{-1}	cm^{-1}	*%*	*CPU*	*CPU*	*%*
	Raw	0.3276	0.3276	<1	34	34 [3]	<1
	5 meq/L $Ca(OH)_2$ + 0.1 meq/L Alum	0.2213	0.2212	<1	19	19	<1
E. *NPDOC*	*Sample*	*mg/L*	*mg/L*	*%*	*mg/L*	*%*	
	5 meq/L $Ca(OH)_2$ + 0.1 meq/L Alum	8.283	8.251	<1	9.086	80	
	7 meq/L $Ca(OH)_2$	7.052	7.122	1	8.876	91	
	7 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$	6.086	6.116	<1	8.119	102	

TABLE 4-7: Quality Control for DBP Lime Softening Analyses

Parameter		Value (μg/L)	Value (μg/L)	RSD (%)	Spike (μg/L)	Recovery (%)	RSD (%)
F. ***THM-1***	$CHCl_3$	22.9	22.63	1	43.28	102	
	$BrCl_2CH$	13.62	13.55	<1	35.54	110	
	Br_2ClCH	11.08	11.03	<1	33.64	113	
	Br_3CH	1.98	2.01	1	24.05	110	
	THM_{total}	49.58	49.23	1	136.51	109	
THM-2	$CHCl_3$	49.8	48.62	2	68.39	93	
	$BrCl_2CH$	31.26	30.57	2	52.08	104	
	Br_2ClCH	17.77	17.34	2	40.79	115	
	Br_3CH	3.54	2.86	19	25.36	109	
	THM_{total}	102.37	99.4	3	186.62	105	
G. ***HAA-1***	MCAA	0.83	0.8	3	0.68	0.71	4
	MBAA	7.41	7.11	4	5.88	5.98	2
	DCAA	10.89	10.21	6	18.89	18.95	<1
	TCAA	6.71	6.39	4	15.09	15.26	1
	BCAA	8.02	7.57	5	11.74	11.82	1
	DBAA	5.5	5.27	4	8.37	8.52	1
	HAA_{total}	36.36	37.35	5	60.65	61.24	1
HAA-2	MCAA	0.8	13.9	66	0.8	13.5	63
	MBAA	8.1	22.3	71	5.8	20.1	72
	DCAA	9.7	26.8	85	19.6	35.9	81
	TCAA	5.3	23.9	93	17.7	34.5	84
	BCAA	6.6	25.8	96	13.0	30.7	89
	DBAA	4.4	25.1	103	5.3	25.6	101
	HAA_{total}	34.9	137.8	86	62.2	160.2	82

The assessment of precision is shown in Tables 4-4 through 4-7. All analyses were in acceptable ranges of precision as determined by ESEI laboratory procedures.

4.5.2 Accuracy

Accuracy evaluation encompassed the use of spikes, known reference samples, and control standards. Ten percent of all samples, with a minimum of one sample per day whenever analyzes are performed, were spiked whenever possible. Percent recovery was calculated for a known addition of standard to a given sample matrix. The added amount of standard as determined by analysis was compared to the amount of known standard actually added to determine recovery.

In addition to the duplicate and spike data, purchased reference check samples were used to assess analytical accuracy. The samples were purchased with preparation instructions, and a true value known within a ninety-five percent confidence interval that is computed by the vendor. Most of the samples were stored and reanalyzed on a daily basis for at least three months if refrigerated. Sample analyses were not to proceed if the results of the reference samples are outside the given confidence interval. Additionally some analytical methods make use of a check sample that is prepared by the laboratory staff to monitor analytical performance. An acceptable result must be obtained for the check standard before an analysis may proceed.

The assessment of accuracy is shown in Tables 4-4 through 4-7. All analyses were in acceptable ranges of precision as determined by ESEI laboratory procedures.

5.0 Results and Discussion

Specific data for results and discussion are presented in tabular and graphic format at the end of each discussion section. The tables and figures are presented in order of enhanced softening, DBP formation modeling and RSSCT.

5.1 Enhanced Softening

Laboratory investigations for enhanced lime softening consisted of evaluating pH, aluminum and iron based salts for the reduction of color and NPDOC in addition to settleability. The coagulants used as settling and enhanced NPDOC removal aids are shown in Table 5-1 and are $FeCl_3$, $Fe_2(SO_4)_3$ and $Al_2(SO_4)_3$ (alum). These are common coagulants and readily available to FWS. Polyvalent aluminum chloride (PACl) was not investigated because PACl is typically less effective than alum for NPDOC removal or enhanced settling, and is used when buffering capacity is limited, which is not the case at Marco Island.

The water quality of the Marco Island lime softening plant is shown in Table 5-2. This surface water has relatively high hardness, high alkalinity and high NPDOC for Florida surface waters. Such waters are not difficult to soften, but have a relatively high lime demand and high NPDOC and DBP formation potential. Softening reduced the alkalinity and hardness from 226 and 310 mg/L $CaCO_3$ to 22 and 112 mg/L respectively. Little magnesium is in the raw water (42 mg/L $CaCO_3$), and little magnesium removal is observed during softening (9 mg/L $CaCO_3$), which is due to the softening pH of 10 to 10.3. Magnesium removal is typically realized at pH values above 10.8. NPDOC is reduced from 10.8 to 6.9 during softening and represents 36 percent NPDOC reduction, which is good for softening at pH values less than 10.8. The settled turbidity is 18.4 NTU and indicates sedimentation could be improved. Assuming the turbidity immediately after lime was added was 105 NTU, which corresponds to the 5 meq/L dose shown in Table 5-3, the Ln (% Turbidity Remaining) is 2.32. This will be useful for discussion of floc settling distribution curves presented later. The finished water turbidity is very good and indicates the settled turbidity does not impact finished water quality. Longer filters runs may be realized at lower settled turbidities.

The $Ca(OH)_2$ dose and pH, turbidity, alkalinity, total hardness and calcium hardness after softening are shown in Table 5-3. This data indicates that the most effective hardness reduction occurred at pH 9.9, which is expected for these pH values. Typically, maximum calcium hardness reduction will occur at pH 10.3, however the pH for maximum calcium hardness reduction can vary for individual waters as shown here. A titration curve for the Marco Island raw water and the percent alkalinity and hardness removal are shown in Figures 5-1 and 5-2 with $Ca(OH)_2$, respectively. Although hard to distinguish, the titration curve does shown the maximum buffering occurred at pH 10 ± 0.2 for 5 meq/L of $Ca(OH)_2$. This data corresponds well to the percent alkalinity and hardness removal shown in Figure 5-2. Maximum carbonate hardness reduction is limited by the alkalinity present, as both calcium and bicarbonate alkalinity are removed during the precipitation reaction. The minimum hardness for this water would range from approximately 80 to 110 mg/L $CaCO_3$. The problem with such high hardness removals is

TABLE 5-3: Water Quality at Various $Ca(OH)_2$ Doses

$Ca(OH)_2$ Dose (meq/L)	pH	Turbidity* (NTU)	Alkalinity (mg /L as $CaCO_3$)	Total Hardness (mg /L as $CaCO_3$)	Calcium Hardness (mg /L as $CaCO_3$)
Raw			226	310	278
3	8.4	105	95	170	134
4	8.9	130	52	128	93
5	9.9	181	31	107	73
6	10.7	170	54	127	99
7	11.1	152	91	164	138
Experimental QA/QC					
5 Dupe	9.6	206	30	104	73
%RSD	3	11	3	3	0

*Measured after 5 min settling

FIGURE 5-1: Titration Curve

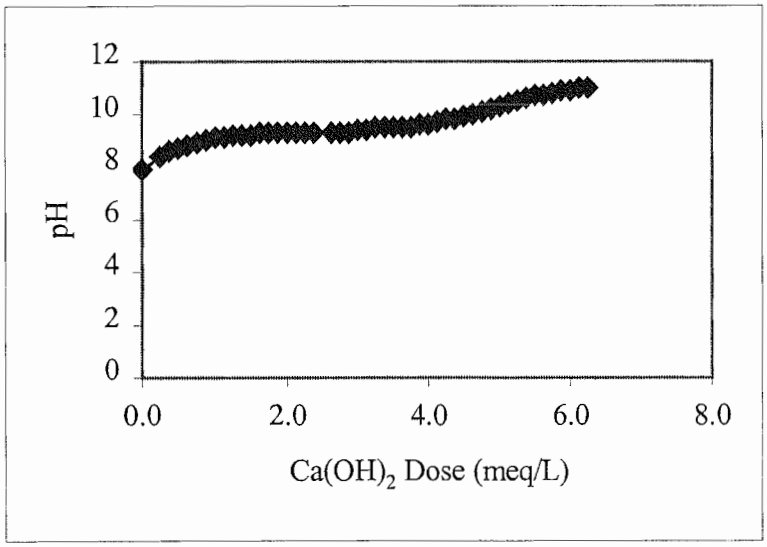


FIGURE 5-2: Alkalinity and Hardness Removal at Various $Ca(OH)_2$ Doses

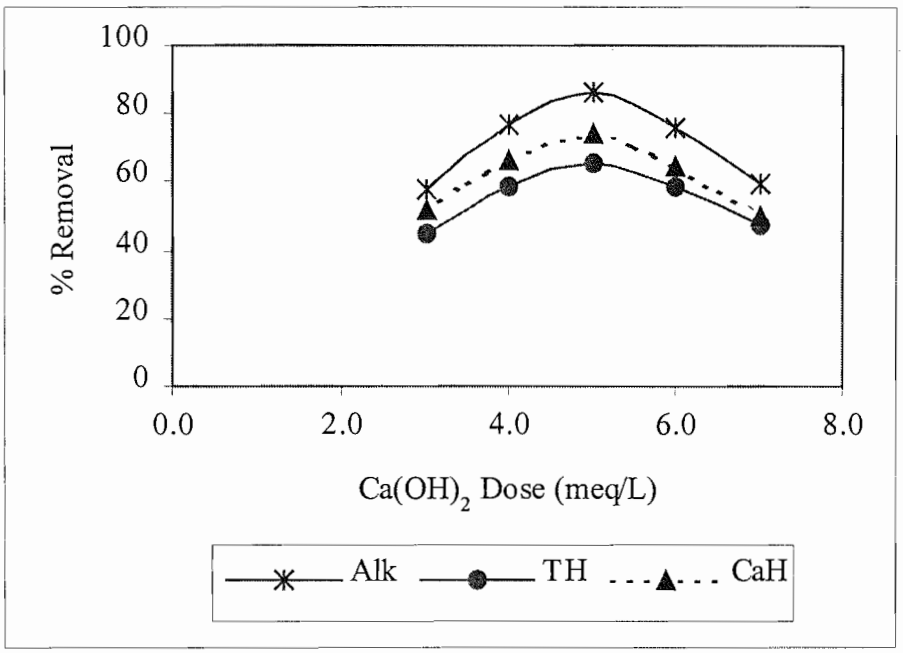
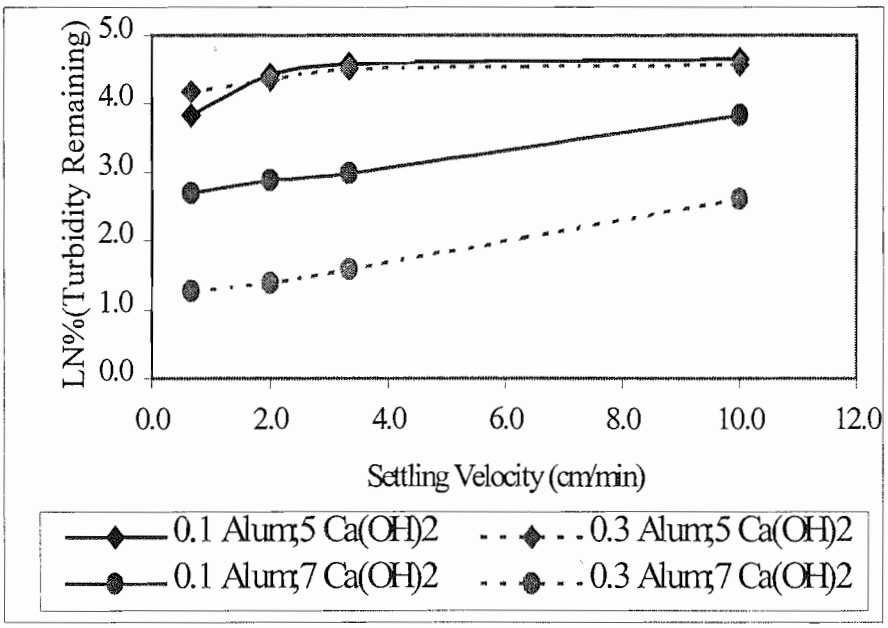


FIGURE 5-3: Settling Velocity for Enhanced Softening Using Alum Coagulant



low residual alkalinities as shown by the 22 mg/L $CaCO_3$ residual alkalinity. Such low alkalinities do not provide adequate buffering capacity nor passivation capacity in the distribution system. This is not always a problem in every distribution system; however, since carbonate is a part of the film that insulates the pipe interior from the water column, both low alkalinity and pH can adversely affect corrosivity.

The effects of alum, $FeCl_3$ and $Fe_2(SO_4)_2$ addition are presented in Tables 5-4, 5-5, 5-6 and 5-7, and Figures 5-3, 5-4, and 5-5. In each case, enhanced settling and NPDOC removal are realized for additions of the inorganic coagulant aids. The floc settling distribution curves shown in Figures 5-3, 5-4 and 5-5 related the natural log of remaining turbidity to settling velocity during jar tests. These tests are useful to compare relative treatment techniques, however, plant scale results should always exceed jar test results for settling and treatment. The plant scale data in Table 5-2 showed the settled turbidity of 18.4 NTU or the natural log of percentage turbidity remaining to be ln (2.32). The data in Figures 5-3, 5-4 and 5-5 and Tables 5-4 through 5-6 strongly shows that addition of settling aids greatly enhances turbidity removal.

The best method of comparing jar test to plant data is by simulating the plant operation in the jar and then comparing proposed changes to plant operation by comparing jars simulating plant operation and the change to plant operation. The data in Table 5-3 shows very poor settling of the softening sludge without coagulant addition. The data in Figures 5-3, 5-4 and 5-5 show that the best sedimentation is accomplished at a lime dose of 7 meq/L and coagulant aid dose of 0.3 meq/L. Ferric chloride and ferric sulfate settleability are slightly better than alum. Alum will dissolve aluminum into solution at high pH values. Ferric sulfate is easier to handle in plant and was selected for duplicate testing, the results are shown in Table 5-6. The sludge volume will increase by 6 percent when the $Fe(OH)_3$ solids are considered as shown below.

$$V = \frac{8.33QC}{p_w(sp)} + \frac{(1-X)8.33QC}{Xp_w}$$

Where : V = Volume (ft^3 / day)

Q = 6 MGD

C = TSS formed (200 mg/L $CaCO_3$, 12 mg/L $Fe(OH)_3$)

p_w = density of water (62.4 lb/ft^3)

sp = Specific gravity (2.8 = $CaCO_3$, 2.4 = $Fe(OH)_3$)

X = 0.1, Decimal fraction TSS

$$V = \frac{8.33*6*200}{62.4*(2.8)} + \frac{(1-.1)8.33*6*200}{0.1*62.4} + \frac{8.33*6*12}{62.4*(2.4)} + \frac{(1-.1)8.33*6*12}{0.1*62.4}$$

$$V = 57 + 1441 + 4 + 87 = 1589 ft^3 / day$$

As with settling, NPDOC and color removal increased at higher lime doses and higher coagulant aid doses. The plant data showed softening reduced NPDOC by 36 percent from 10.8 to 6.9 mg/L. The jar test data showed softening reduced NPDOC from 10.8 to 8.1 (25 percent) and 7.1 mg/L (34 percent) for 5 and 7 meq/L lime. The addition of coagulant aids reduced the NPDOC at 5 meq/L lime from 17 to 23

TABLE 5-4: Water Quality for Enhanced Softening Using Alum Coagulant

Parameter	Raw	Control ($Ca(OH)_2$)*		5 meq/L $Ca(OH)_2$		7 meq/L $Ca(OH)_2$	
		5 meq/L	7 meq/L	Alum		Alum	
		No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L
PH	7.9	9.9	11.1	9.6	8.8	10.9	10.7
Alkalinity (mg/L as $CaCO_3$)	226	31	91	33	48	65	45
Total Hardness (mg/L as $CaCO_3$)	310	107	164	110	133	150	139
Calcium Hardness (mg/L as $CaCO_3$)	278	73	138	75	97	132	132
UV-254 (cm^{-1})	0.3276	0.2193	0.1846	0.2213	0.2358	0.1336	0.1187
True Color (CPU)	34	19	13	19	20	8	7
NPDOC (mg/L)	10.8	8.1	7.1	8.3	8.7	6.6	5.8

* Control data used for comparison. Sample not collected from same bulk solution.

TABLE 5-5: Water Quality for Enhanced Softening Using $FeCl_3$ Coagulant

Parameter	Raw	Control ($Ca(OH)_2$)*		5 meq/L $Ca(OH)_2$		7 meq/L $Ca(OH)_2$	
		5 meq/L	7 meq/L	$FeCl_3$		$FeCl_3$	
		No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L
PH	7.9	9.9	11.1	9.7	9.5	11.0	10.9
Alkalinity (mg/L as $CaCO_3$)	226	31	91	36	39	71	64
Total Hardness (mg/L as $CaCO_3$)	310	107	164	119	128	155	155
Calcium Hardness (mg/L as $CaCO_3$)	278	73	138	82	95	136	138
UV-254 (cm^{-1})	0.3276	0.2193	0.1846	0.2308	0.2201	0.1405	0.1248
True Color (CPU)	34	19	13	19	18	8	7
NPDOC (mg/L)	10.8	8.1	7.1	8.7	8.5	6.5	6.0

* Control data used for comparison. Sample not collected from same bulk solution.

TABLE 5-6: Water Quality for Enhanced Softening Using $Fe_2(SO_4)_3$ Coagulant

Parameter	Raw	Control ($Ca(OH)_2$)*		5 meq/L $Ca(OH)_2$		7 meq/L $Ca(OH)_2$	
		5 meq/L	7 meq/L	$Fe_2(SO_4)_3$		$Fe_2(SO_4)_3$	
		No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L
pH	7.9	9.9	11.1	9.8	9.4	11.1	11
Alkalinity (mg/L as $CaCO_3$)	226	31	91	33	36	75	54
Total Hardness (mg/L as $CaCO_3$)	310	107	164	113	125	165	155
Calcium Hardness (mg/L as $CaCO_3$)	278	73	138	78	90	146	138
UV-254 (cm^{-1})	0.3276	0.2193	0.1846	0.2294	0.2242	0.1469	0.1250
True Color (CPU)	34	19	13	19	19	9	7
NPDOC (mg/L)	10.8	8.1	7.1	9.0	8.5	6.8	6.1

* Control data used for comparison. Sample not collected from same bulk solution.

TABLE 5-7: Water Quality for Optimized Enhanced Softening

Parameter	5 meq/L $Ca(OH)_2$ w/ 0.3 meq/L $Fe_2(SO_4)_3$			7 meq/L $Ca(OH)_2$ w/ 0.3 meq/L $Fe_2(SO_4)_3$		
	Optimum	Previous	Expt QC RSD (%)	Optimum	Previous	Expt QC RSD (%)
PH	9.3	9.4	1	10.85	11	1
Alkalinity (mg/L as $CaCO_3$)	42	36	14	64	54	15
Total Hardness (mg/L as $CaCO_3$)	133	125	6	145	155	6
Calcium Hardness (mg/L as $CaCO_3$)	96	90	6	134	138	3
UV-254 (cm^{-1})	0.2268	0.2242	1	0.1346	0.1250	7
True Color (CPU)	18.5	19	2	6	7	14
NPDOC (mg/L)	8.2	8.5	4	6.1	6.1	1

FIGURE 5-4: Settling Velocity for Enhanced Softening Using $FeCl_3$ Coagulant

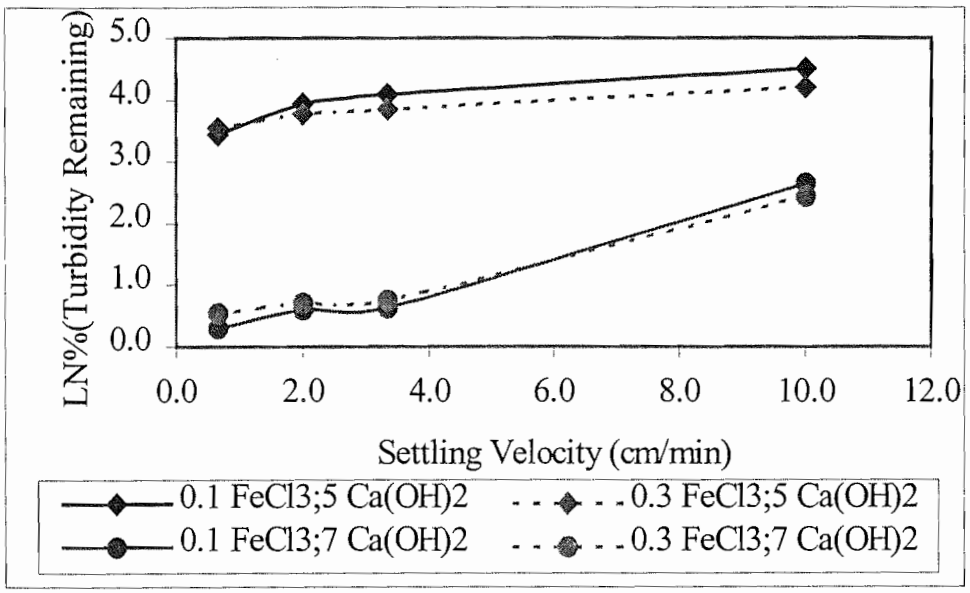
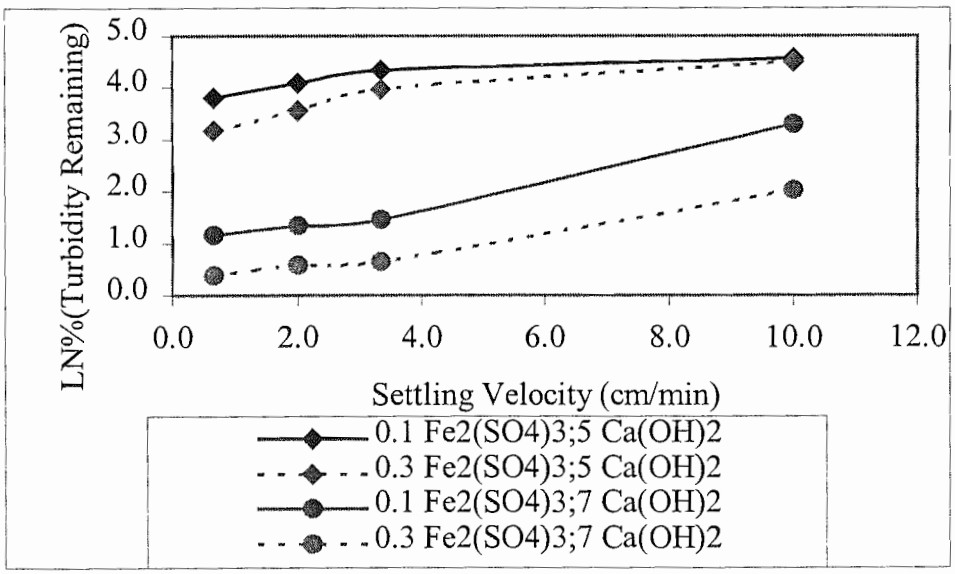


FIGURE 5-5: Settling Velocity for Enhanced Softening Using $Fe_2(SO_4)_3$ Coagulant



percent, and at 7 meq/L lime from 33 to 47 percent 0.3 meq/L. These data indicate NPDOC removal increases with increasing pH and coagulant dose. However, regulation criteria as defined by the Surface Water Treatment Rule (SWTR) requires that plants with alkalinities greater than 120 mg/L $CaCO_3$ must remove 30 percent NPDOC. Plant data suggests that Marco Island can meet this constraint with existing operation. The addition of inorganic coagulant aids and a higher softening pH would enhance NPDOC removal and increase the margin between the actual and required plant NPDOC removal.

5.2 DBP and Chlorine Residual Modeling

Multivariate natural log models were used to describe the formation of THMs, HAAs and dissipation of free chlorine as a function of organic carbon, chlorine dose, pH, temperature and time. The THM, HAA and Cl_2 Residual models considered NPDOC, pH, temperature, Cl_2 Dose and time as independent variables for predicted THM, HAA and Cl_2 residuals. These models were all of the form:

$$Y = K(\text{NPDOC})^a(\text{pH})^b(\text{Cl}_2\ \text{Dose})^c(\text{Temperature})^d(\text{Time})^e$$

where:

K = Constant

NPDOC= mg/L C

pH = pH of reaction

Temperature = °C

Time = time of reaction, minutes

This model is descriptive of THM formation, HAA formation or Cl_2 residual for the conditions of testing, a free Cl_2 residual is always present and NPDOC is always present. The models can be used to predict outside the limits of testing with reason. Extension of the models requires awareness of specific chemical reactions and water treatment. For example, THM nor HAAs could form if free chlorine or organic precursors were not present.

The constraints on the levels of testing were determined by the Marco Island plant conditions. Free chlorine is dosed following softening and reacts for a very short period before ammonia is added to form chloramines and stop DBP formation. Free chlorine is beneficial for determination of CT for surface water sources, hence the Marco Island facility operates in a narrow range to meet DBP and disinfection constraints. A full factorial approach was not required for model development as the general model form was known.

The sequence of regression analysis is to first test the complete model for all independent variables. If all variables are significant for selected confidence interval, then the model has been identified. If one or more variables are not significant at the selected confidence interval then the most insignificant variable is dropped and the regression is repeated. This method of eliminating insignificant variables is continued

until a model with only significant independent variables is developed. Models were developed for only total THM and HAA formation to be consistent with the regulations. However models for specific THMs and HAAs could be developed from the data set.

5.2.1 Chlorine Residual

The data, regression statistics and predicted versus actual for chlorine residual are shown in Tables 5-8, 5-9 and Figure 5-6, respectively. The selected confidence interval was 95 percent. The chlorine residual model is:

$$Cl_2 = (Cl_2\ \text{Dose})^{1.06}(\text{Time})^{-0.14}$$

where:

Cl_2 Dose = mg/L Cl_2

Time = time of reaction, minutes

The only significant variables statistically are chlorine dose and reaction time for this set of experimental data. This does not mean that temperature, pH, and NPDOC are not significant to chlorine dissipation. It means no change in chlorine residual was statistically significant for the test conditions of temperature, pH and dose. Within the limits of the test conditions, chlorine residual can be predicted using this model.

5.2.2 THM Formation

The data, regression statistics and predicted versus actual for THM formation are shown in Tables 5-10 and 5-11, and Figure 5-7. The range was determined by the operating conditions for the Marco Island softening facility. The most prevalent THMs were chloroform and dichlorobromomethane, which is consistent with THM formation for a low bromide source. These two species accounted for approximately 80 percent of the total THM formation.

The data clearly shows that the Stage I THM MCL can easily be exceeded under normal operating conditions. Marco Island does blend this water with a RO product ,which has very low DBPs. However, the data strongly indicates that the maximum blending ratio would be controlled by the lime softening product so as not to exceed the THM MCL.

The results of the statistical regression are shown in Table 5-11. The confidence interval was reduced to 0.88 from 0.95 to include chlorine dose as a significant independent variable. Chlorine dose is necessary to form THMs, therefore the confidence interval was slightly reduced to enhance model use. The exact conditions are shown in Table 5-11 The predicted versus the actual THMs are shown in Figure 5-7. The THM model is shown on the following page.

TABLE 5-9: Regression Statistics for Chlorine Dissipation Model

Multiple R	0.884006	Standard Error	0.097374			
R Square	0.781466	Observations	16			
Adjusted R Square	0.694428					
ANOVA	***df***	***SS***	***MS***	***F***	***Significance F***	
Regression	2	0.47468729	0.237344	25.0316655	3.48403E-05	
Residual	14	0.1327443	0.009482			
Total	16	0.60743159				
	Coefficients	***Standard Error***	***t Stat***	***P-value***	***Lower 95%***	***Upper 95%***
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
Ln Dose	1.062734	0.04057473	26.19203	2.7044E-13	0.975710268	1.149758721
Ln Time	-0.13886	0.0208284	-6.66675	1.0666E-05	-0.18353023	-0.094185179

FIGURE 5-6: Actual and Predicted Cl_2

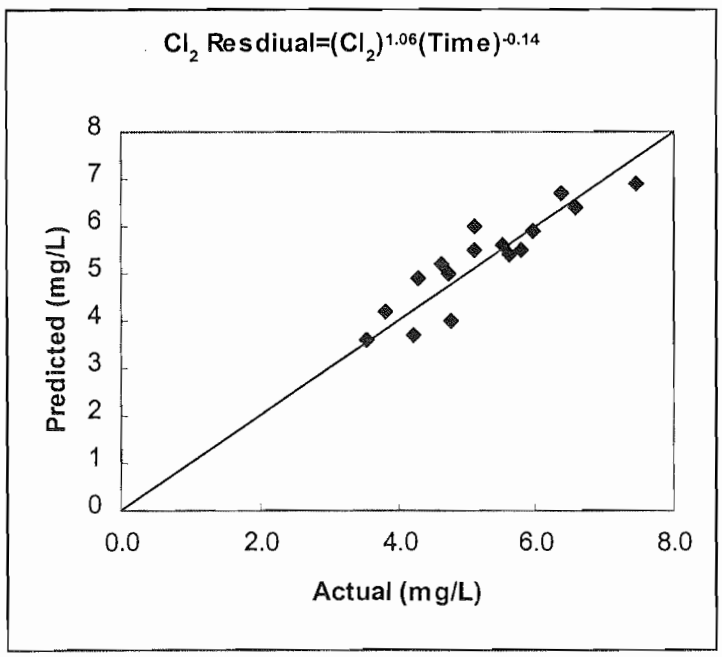
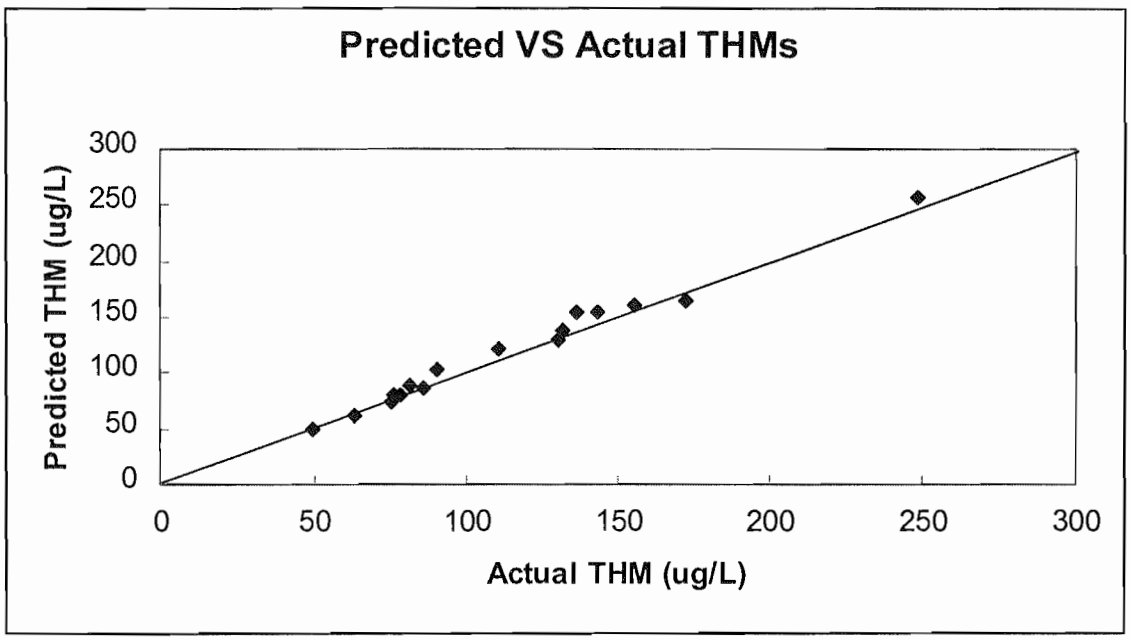


Table 5-10: THM results at different conditions of dose, TOC, pH, T and t

Dose (mg/L)	NPDOC (mg/L)	pH	T (°C)	t	$CHCl_3$ (μg/L)	$BrCl_2CH$ (μg/L)	Br_2ClCH (μg/L)	Br_3CH (μg/L)	THM_{total} (μg/L)
9	8.1	8.3	30	30	61.9	40.5	24.2	2.1	128.7
8	8.1	8.3	20	10	41.3	22.0	14.1	2.8	80.3
7.3	6.1	8.3	20	30	34.6	25.9	23.0	5.3	88.9
6.8	6.1	8.3	30	10	28.9	16.8	14.5	1.0	61.3
9	8.1	7.5	30	10	42.9	22.2	12.5	2.8	80.4
8	8.1	7.5	20	30	49.8	31.3	17.8	3.5	102.4
7.3	6.1	7.5	20	10	22.9	13.6	11.1	2.0	49.6
6.8	6.1	7.5	30	30	28.4	23.3	19.8	3.3	74.7
9	8.1	8.3	30	240	125.2	82.4	42.8	6.3	256.7
8	8.1	8.3	20	60	63.3	44.4	25.8	3.9	137.3
7.3	6.1	8.3	20	240	58.3	48.3	39.7	14.1	160.3
6.8	6.1	8.3	30	60	43.0	37.6	32.5	9.1	122.2
9	8.1	7.5	30	60	72.3	51.2	26.2	3.4	153.1
8	8.1	7.5	20	240	75.8	55.7	27.6	4.8	163.8
7.3	6.1	7.5	20	60	31.4	28.0	23.0	4.1	86.5
6.8	6.1	7.5	30	240	55.6	55.3	39.2	4.2	154.3

FIGURE 5-7: Comparison of the Actual THM Data and THM Model-Based



5.2.3 HAA Model

The results of the HAA formation testing are shown in Table 5-12. These are conditions that were used for THM formation and represent the operating conditions of the Marco Island lime softening facility. The three major HAA species are dichloroacetic acid, trichloroacetic acid and bromochloroacetic acid which account for 28, 26 and 20 percent, respectively of the HAAs. The formation data indicates both THMs and HAAs could limit the blending fraction of the lime-softened water.

The regression statistics are shown in Table 5-13 for the HAA formation model. NPDOC and pH were not significant statistically and were excluded from the model for the test conditions. The predicted versus the actual HAAs formed are shown in Figure 5-8. The model is:

$$HAA = (Cl_2\ Dose)^{1.49}(Temperature)^{0.13}(time)^{0.16}$$

where:

HAA= μg/L HAA
Cl_2 Dose = mg/L Cl_2
Temperature = °C
Time = time of reaction

5.2.4 Model Application

The three models can be used to predict formation and residual for given conditions and thereby define acceptable areas of operation. The lime-softening process at Marco Island maintains enough free chlorine to form a given NH_2Cl concentration. Assuming 5 mg/L NH_2Cl and a contact time of 5 to 30 minutes and remembering monochloramines are reported as Cl_2, the model as presented in Figure 5-9 shows a chlorine dose of 6 to 7 mg/L is required.

Once the chlorine dose is known for a desired chloramine concentration after a given reaction time, the corresponding formation of the associated formation of THMs and HAAs can be predicted. The model data shown in Figure 5-10 indicate HAAs will not exceed the Stage I MCL until after one hour. However, THMs are shown to exceed the Stage 1 MCL after approximately 5 minutes at 8 mg/L NPDOC, pH 8, 7 mg/L Cl_2 and 30 °C. THMs are limiting at Marco Island, FL. These three models can be used to define many modes operation with respect to the THM MCL, HAA MCL and Cl_2 residual.

TABLE 5-12: Haloacetic Acid Formation Data

Dose mg/L	NPDOC mg/L	pH	T °C	t min	MCAA □g/L	MBAA □g/L	DCAA □g/L	TCAA □g/L	BCAA □g/L	DBAA □g/L	HAA_{total} □g/L
9	8.1	8.3	30	30	0.7	5.9	18.9	15.1	11.7	8.4	60.7
8	8.1	8.3	20	10	0.8	6.6	16.3	10.0	9.1	3.8	46.6
7.3	6.1	8.3	20	30	0.8	7.4	10.9	6.7	8.0	5.5	39.4
6.8	6.1	8.3	30	10	0.8	8.1	9.7	5.3	6.6	4.4	34.9
9	8.1	7.5	30	10	1.7	6.2	16.2	13.4	9.9	5.4	52.9
8	8.1	7.5	20	30	0.9	6.6	17.7	17.8	10.9	3.9	57.8
7.3	6.1	7.5	20	10	1.0	7.1	8.5	6.8	7.0	4.1	34.4
6.8	6.1	7.5	30	30	0.8	6.6	9.4	9.1	8.1	4.4	38.5
9	8.1	8.3	30	240	0.8	4.0	30.1	30.5	18.5	7.3	91.2
8	8.1	8.3	20	60	0.8	5.8	19.6	17.7	13.0	5.3	62.2
7.3	6.1	8.3	20	240	0.8	5.7	14.4	11.1	11.9	7.6	51.5
6.8	6.1	8.3	30	60	1.4	6.4	11.5	7.9	9.4	6.2	42.9
9	8.1	7.5	30	60	0.7	5.7	20.7	27.0	13.4	5.0	72.6
8	8.1	7.5	20	240	2.2	5.2	22.5	34.2	15.4	5.0	84.4
7.3	6.1	7.5	20	60	1.0	6.6	9.7	11.0	8.9	4.6	41.7
6.8	6.1	7.5	30	240	0.7	4.9	13.8	17.9	13.0	6.2	56.4

Table 5-13: Regression Statistics for HAA Formation Model

Multiple R	0.990061	Standard Error	0.045022
R Square	0.980221	Observations	16
Adjusted R Square	0.900255		

ANOVA	df	SS	MS	F	Significance F
Regression	3	1.305946	0.435315	214.7573	1.09E-10
Residual	13	0.026351	0.002027		
Total	16	1.332297			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
Ln Cl2Dose	1.494962	0.060441	24.7343	2.56E-12	1.364387	1.625536
Ln Temp	0.134451	0.037117	3.622397	0.003096	0.054266	0.214637
Ln time	0.158611	0.009648	16.43945	4.44E-10	0.137767	0.179454

FIGURE 5-8: Comparison of the Actual HAA Data and HAA Model-Based Data

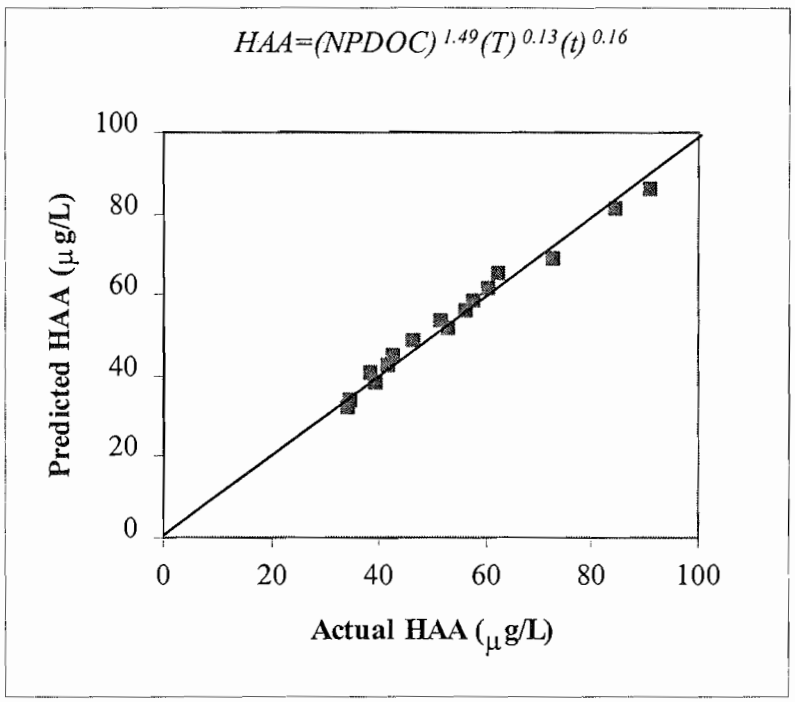


Figure 5-9: Predicted Chlorine Residual VS Time

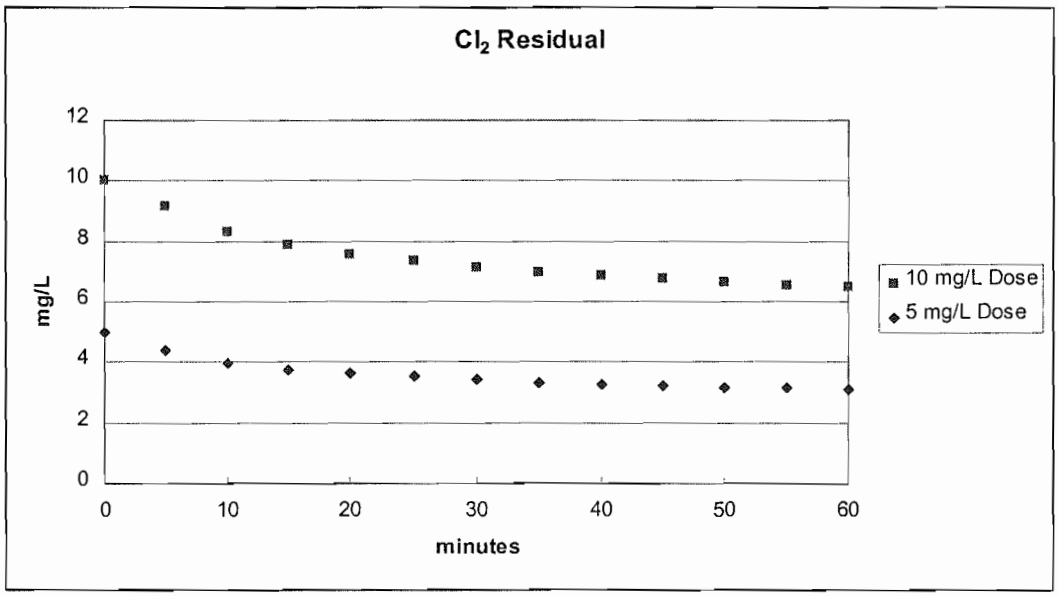
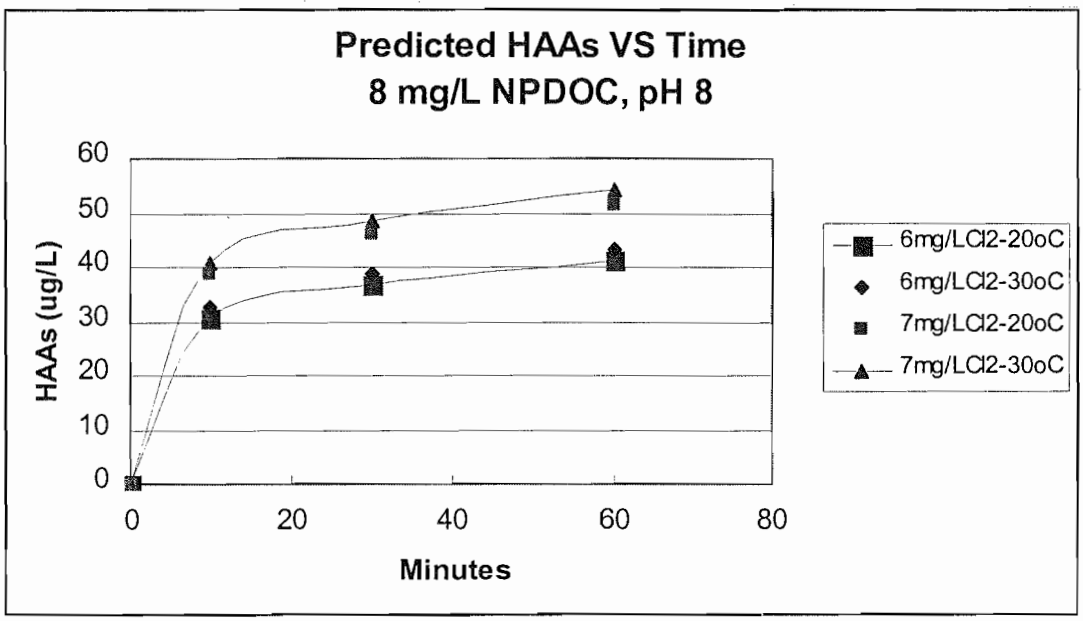
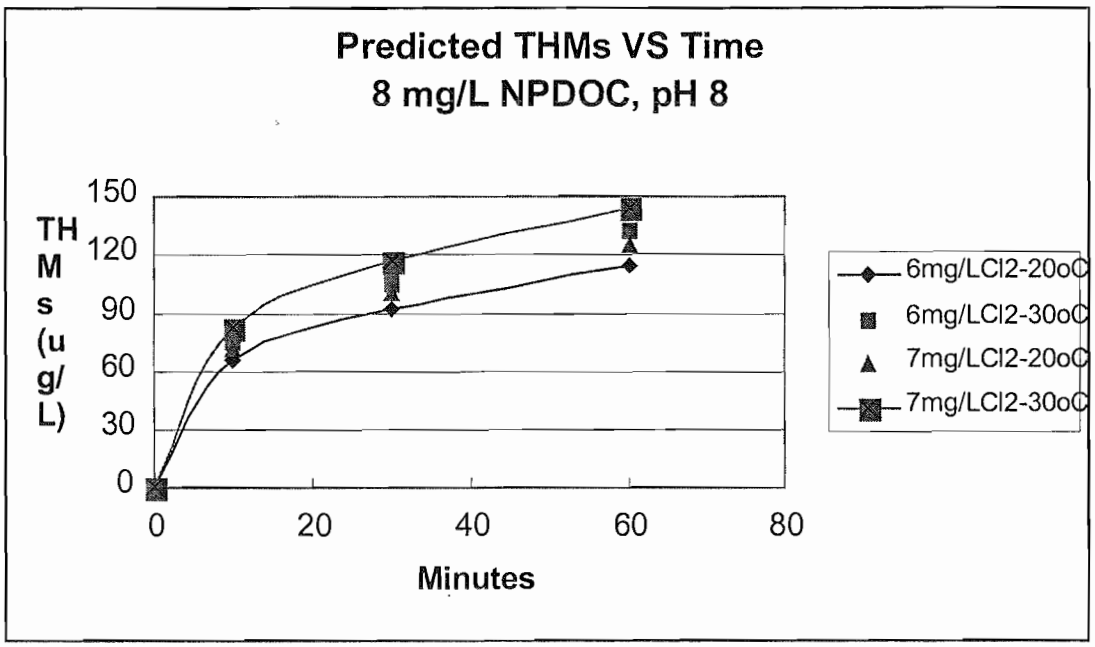


FIGURE 5-10: Predicted HAAs and THMs for Varying Chlorine Dose and Temperature at 8 mg/L NPDOC and pH 8





5.3 RSSCT

The RSSCT column results for UV-254 and NPDOC are shown in Figures 5-11 and 5-12 for an empty bed contact time (EBCT) of 10 and 20 minutes, respectively. This procedure is based on reducing the mass transfer limits through the outer GAC pores by reducing the GAC size by grinding. The capacity of the GAC is reduced, hence a scale up factor can be determined from the size and the time to breakthrough of each column. Breakthrough is defined by 50 percent of the influent NPDOC concentration. The summary data for the RSSCT columns is shown in Table 5-14. It was necessary to get additional water to complete the RSSCT. The average water quality for the RSSCT feed water is shown in Table 5-15 and 5-16.

As shown in Figures 5-11 and 5-12, the organics in the softened Marco Island Water can be removed by carbon adsorption. The results of RSSCT scaling are shown in Table 5-14 and indicate no increase in column efficiency by increasing EBCT from 10 to 20 minutes. The results of the RSSCT were used to estimate NPDOC breakthrough for DBP control using the ICR procedures. That is, breakthrough is defined by the passage of 10 percent of the non-adsorbable NPDOC fraction. Those points occurred in the 10 and 20 minute EBCT RSSCT columns at 7.5 and 14.2 hours respectively. The estimated runtimes for a full-scale column can be estimated by multiplying the breakthrough time for the small-scale column times the ratio of the diameters of the unground GAC to the ground carbon. That ratio "SF" is shown in Table 5-14 as 9.8.

The summary water quality of the RSSCT influent is shown in Table 5-15. Although three different aliquots of water were used for the RSSCT, there was little variation in the feed water quality. As shown in Table 5-16, the GAC filtration will have little effect on inorganic water quality. However, this column was probably not highly biologically active, and the feed water was stable with respect to calcium carbonate. High biological activity and an unstable feed water would reduce pH, alkalinity and calcium in the filtered water.

The full-scale GAC columns with 10 and 20 minutes EBCTs have estimated runtime times of 3 days and 5.8 days respectively. DBPs were measured at the beginning, midpoint and end of the RSSCT tests and are shown in Figure 5-13. This data indicates THMs are the controlling DBPs for GAC filtration of lime-softened water. Applying the same 10 percent passage of the non-adsorbable fraction, the estimated 10 and 20 minute EBCT GAC runtimes would be approximately 10 and 20 hours.

The NPDOC mass transfer coefficient and UV-254 equilibrium isotherm were determined for the lime-softened water. UV-254 was used in lieu of NPDOC because of the lower level of detection and the ability to predict NPDOC by UV-254. The results of the Freundlich equilibrium isotherm and kinetic studies are shown in Figures 5-14 and 5-15, respectively.

FIGURE 5-11: Breakthrough Curve for RSSCT EBCT of 10 Minutes

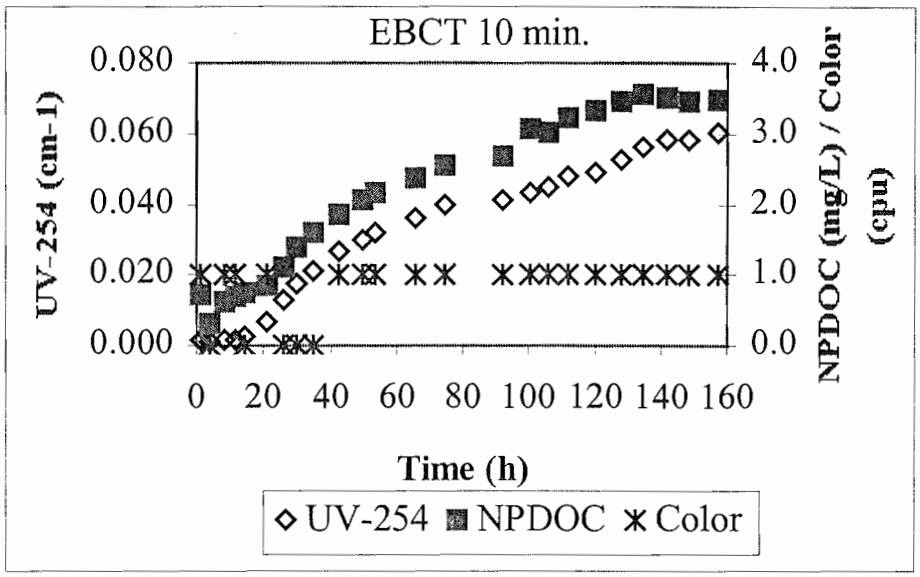


FIGURE 5-12: Breakthrough Curve for RSSCT EBCT of 20 Minutes

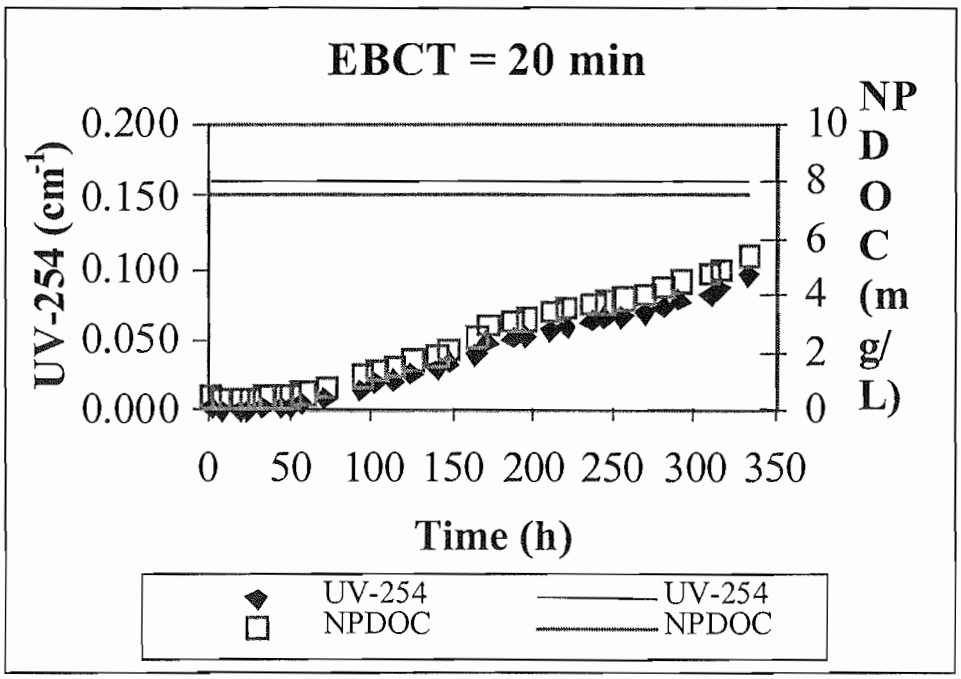


TABLE 5-14: RSSCT Column Data

Post filter GAC = 100 x 200 mesh (112 μm APD)	Re_{SC} = 0.5 min
d_{SC} = 0.112 mm	ε_{LC} = 0.45
GAC = Bituminous (Filtrasorb 400)	v_{LC} = 1 x 10^{-6} m^2/s at 20°C
TOC_o = 6.9 mg/L	DC_{SC} = 10 mm
	ρ_{SC} = 0.53 g/cm^3

EBCT (min)	10	20
SF	9.8	9.8
$EBCT_{SC}$ (min)	1.0	2.0
V_{SC} (m/h)	7.2	7.2
L_{SC} (cm)	12.2	24.5
Q_{SC} (mL/min)	9.4	9.4
m_{SC} (g)	5.1	10.2
BV_{50}	1762	1762
t_{50} (days)	12.2	24.5
t_{LC}^T (days)	24.4	49.0
t_{SC}^T (days)	2.5	5.0
V_{SC} (L)	33.9	67.8
Total Volume (L)	44.1	88.2

TABLE 5-15: Water Quality of RSSCT Influent

Parameter	Influent 1	Influent 2	Influent 3	Average
pH	8.4	7.3	7.2	
UV_{254} (cm^{-1})	0.1517	0.1495	0.1515	0.1509
NPDOC (mg/L)	7.3	6.8	7.0	7.0
Color (CPU)	7	7	7	7
Alkalinity (mg/L as $CaCO_3$)	17	17	16	17
Total Hardness (mg/L as $CaCO_3$)	118	118	118	118
Calcium Hardness (mg/L as $CaCO_3$)	92	92	92	92

TABLE 5-16: Effluent Alkalinity and Hardness Results for RSSCT EBCT of 10 Minutes

Parameter	4 h	42 h	157 h	Average
pH	7.8	7.0	6.8	
Alkalinity (mg/L as CaCO3)	15.9	15.9	16.9	16.2
Total Hardness (mg/L as $CaCO_3$)	117.0	117.0	119.0	117.7
Calcium Hardness (mg/L as $CaCO_3$)	91.0	92.0	93.0	92.0

FIGURE 5-13: RSSCT DBP Water Quality vs Time

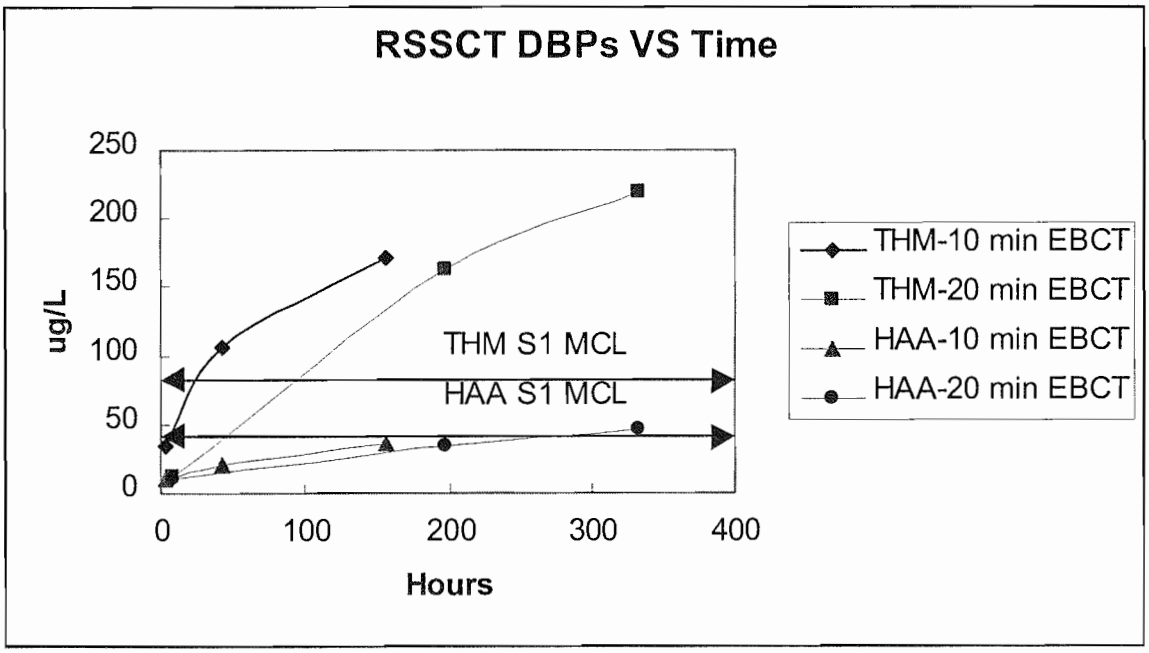


FIGURE 5-14: NPDOC-GAC Freundlich Model From Isotherm Study

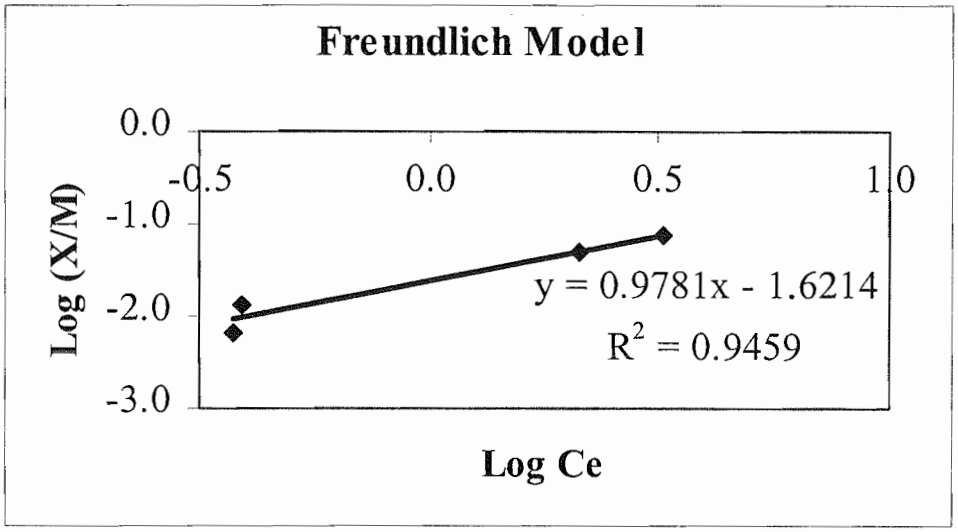
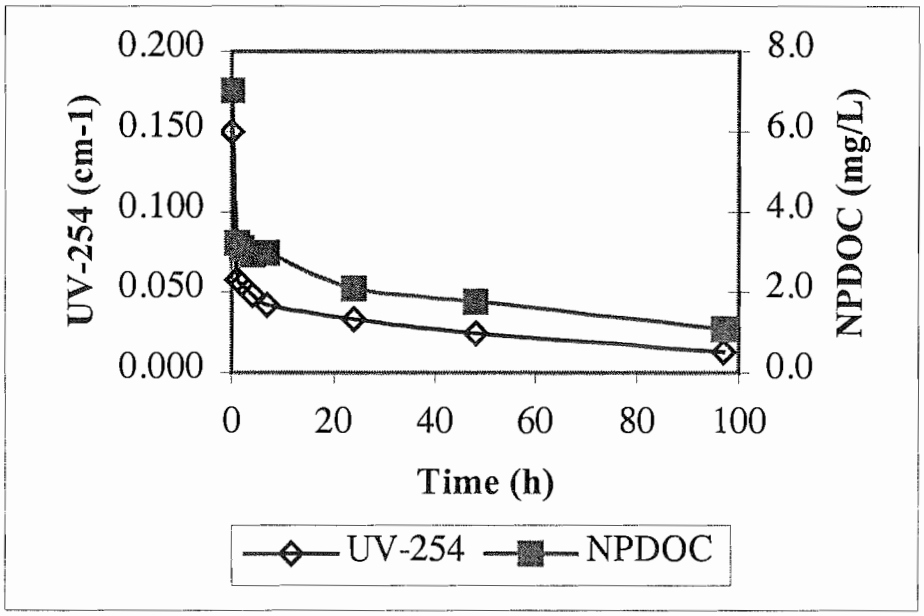


FIGURE 5-15: Kinetic Study Results Using Powdered Filtrasorb 400 Carbon



The equation for the Freundlich isotherm was graphed in Figure 5-14 and is shown below.

$$\frac{X}{M} = K * C_e^{\frac{1}{n}}$$

Where:

X= mg of NPDOC removed

M = gm of GAC

C_e = NPDOC equilibrium concentration

K,n = Constants, 0.024 and 0.98 respectively

The NPDOC mass transfer coefficient was determined from a plot of Ln ($dC/\Delta C_o$) versus time, and was 0.03/hr or 0.833 m/hr. This information could be combined with the isopleth information for development of column design. A correlation between UV-254 and NPDOC is shown in Figure 5-17 for future use. UV-254 is measurable in the field and less costly than NPDOC measurement, and can be used in lieu of NPDOC once the correlation is developed.

5.4 Carbon Application

The Freundlich isotherm can be used to estimate carbon requirements. Assuming feed water NPDOC concentration of 6.9 mg/L allows calculation of X/M, which indicates 2200 lbs/day of carbon will be needed to treat 6 MGD. This calculation assumes 100 percent efficiency in the carbon column and neglects transfer zone effects. Such effects could increase use to 6600 lbs/day for the same degree of treatment. A similar estimate can be made using the RSSCT analysis. A 10 minute EBCT with a 7.35 day runtime for a 6 MGD plant receiving 6.9 mg/L NPDOC would use 19000 lbs/day of GAC. The wide divergence between these two estimates is due to the methods of development. Equilibrium is seldom reached in a column relative to an isopleth, which decreases the absorptive capacity of the carbon relative to the isotherm; however the RSSCT estimate appears conservative. Annual carbon costs would vary from $1,200,000 to $2,500,000 depending on material cost.

The THM formation equation can be used to estimate the NPDOC required to maintain a free chlorine residual and not violate the THM MCL. Assuming pH 8, Cl_2 Dose of 5 mg/L, 30 °C water temperature and 48 hours of reaction time, the calculated NPDOC is 0.25 mg/L using the THM model. This is probably too high as this calculation is out of the range of the model. However, the Marco Island lime-softened water is similar to many high formation lime-softened waters in Florida. NPDOC concentrations of 2 mg/L will typically make Stage I MCL using free chlorine. Stage II MCLs require NPDOC concentrations of less than 1 mg/L. GAC in this study was shown to remove NPDOC to less than 1 mg/L; however, frequent regeneration/replacement of GAC would be expected to achieve lower NPDOC concentrations. Assuming a cost of $1/lb-GAC, the GAC annual cost of THM control ranges from $250,000 to $750,000.

FIGURE 5-16: Mass Transfer Coefficient Determination from Kinetic Investigation

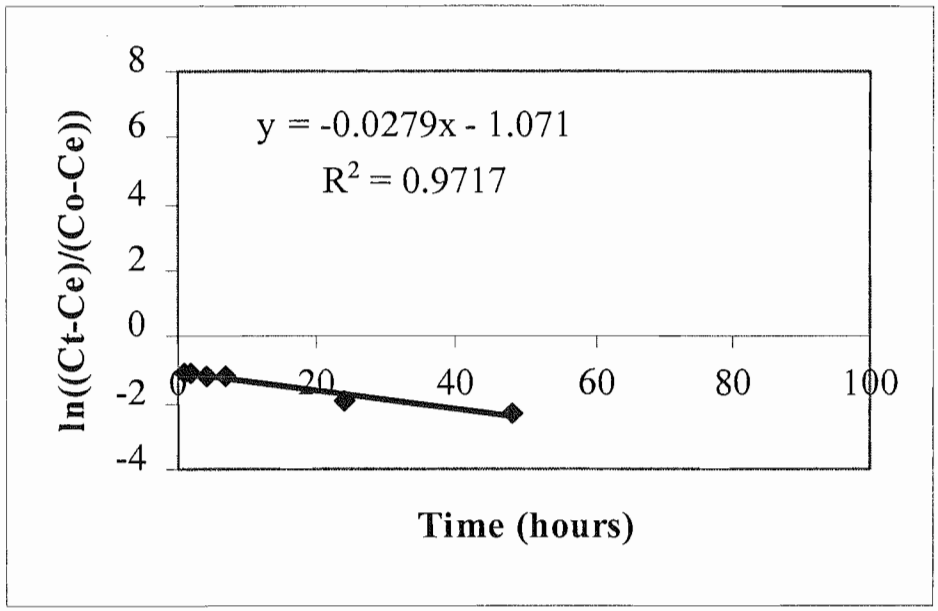
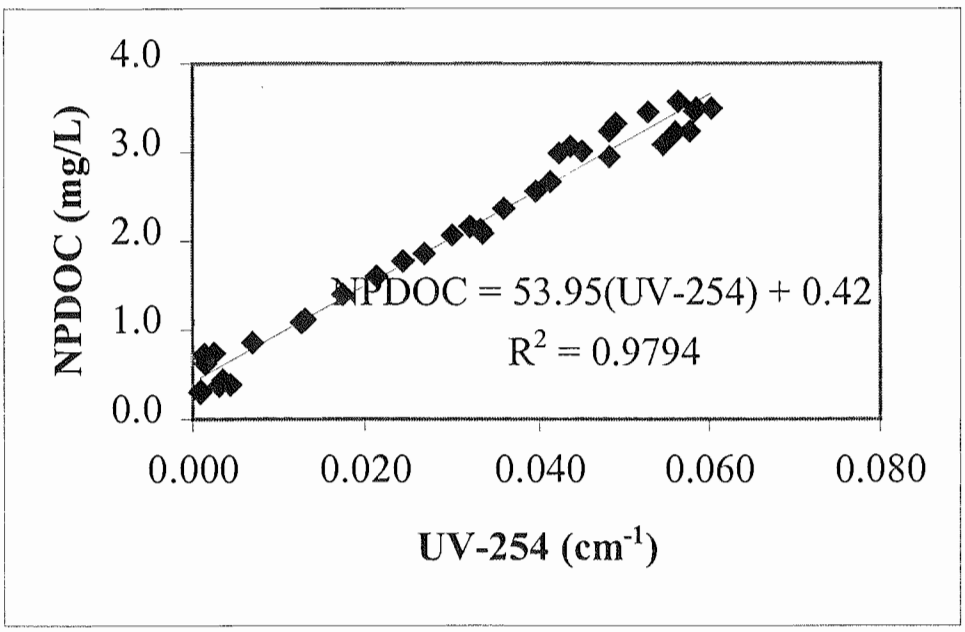


FIGURE 5-17: Correlation Between UV-254 and NPDOC for Lime-Softened Water



6.0 SUMMARY

The following statements describe the enhanced softening, modeling and RSSCT studies for the lime-softened Marco Island water.

6.1 Enhanced Softening

- The following conversions can be used to convert milliequivalents (meq) to milligrams (mg)
  1 meq $Ca(OH)_2$ = 37 mg $Ca(OH)_2$
  1 meq $Al_2(SO_4)_3$ = 57 mg $Al_2(SO_4)_3$
  1 meq $Fe_2(SO_4)_3$ = 67 mg $Fe_2(SO_4)_3$
  1 meq $FeCl_3$ = 54 mg $FeCl_3$
- Calcium carbonate precipitation at 5 meq/L lime removed from 17 to 23 percent of the NPDOC.
- Increasing the lime dose to 7 meq/L increased NPDOC removal to 33 to 47 percent.
- Increasing the lime dose will increase the finished hardness by 50 to 100 mg/L $CaCO_3$ unless primary recarbonation and settling are added.
- Iron and aluminum augmentation removed an additional 5 to 15 percent of the NPDOC. Ferric sulfate was slightly superior to either ferric chloride or alum, because ferric chloride is difficult to handle and alum can potentially dissolve aluminum back into solution at elevated pH values.
- Iron and aluminum addition enhanced sedimentation in jar testing, and indicated enhanced sedimentation on a plant scale.
- Iron augmentation for NPDOC removal will increase sludge formation by 6 percent.
- Marco Island LSWTP meets the required 30 percent NPDOC removal by the ESWTR. Increasing lime dose with a ferric sulfate dosage between 8 to 20 mg/L would improve this removal. Alum is not suggested as aluminum will dissolve back into solution at higher pH values and ferric chloride is difficult to handle.

6.2 Modeling

- Working models for Cl_2 residual, THM formation and HAA formation were developed using the conditions of the Marco Island lime-softening plant. Once the chlorine dose is known for a desired chloramine concentration after a given reaction time, the corresponding formation of the associated formation of THMs and HAAs can be predicted.
- HAAs will not exceed the Stage I MCL until after one hour. However, THMs are shown to exceed the Stage 1 MCL after approximately 5 minutes at 8 mg/L NPDOC, pH 8, 7 mg/L Cl_2 and 30 °C. Therefore, THMs are the limiting DBP for the Marco Island lime-softened water.
- The NPDOC can not be reduced by lime-softening with coagulant addition to the point where the MILSWTP could meet the THM or HAA MCL using free chlorine.

- The formation data indicates both THMs and HAAs could limit the blending fraction of the lime-softened water.

6.3 Carbon

- RSSCT, isotherm and kinetic mass transfer investigations were completed for the Marco Island lime-softened water.
- RSSCT analysis predicted a 7.35 day and 14.2 day runtime time for GAC columns with EBCTs of 10 and 20 minutes.
- Estimates of GAC consumption to meet Stage I THM MCL was 700 to 2100 lbs/day at 100 percent to 33 percent column efficiency, respectively.
- UV-254 was correlated to NPDOC for future use.
- GAC in this study was shown to remove NPDOC to less than 1 mg/L; however, frequent regeneration/replacement of GAC would be expected to achieve lower NPDOC concentrations.

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Appendices

Appendix A: Enhanced Softening Results A-1

Appendix B: DBP Modeling Results B-1

Appendix C: GAC – RSSCT, Kinetics and Isotherm Results C-1

Appendix A: Enhanced Softening Results

Marco Island 2 Water Quality

Parameter		Raw			Softened (Sedimentation)			Finished		
		Plant	Lab 10/99	Lab 1/00	Plant	Lab 10/99	Lab 1/00	Plant	Lab 10/99	Lab 1/00
TDS	mg/L		545			311			359	
TS	mg/L		529			357			347	
TSS	mg/L		16			46			<1	
pH		7.8	8.0	7.9	10.0	9.8	9.7	8.6	8.1	
Alkalinity	mg CaCO3/L	218	246	226	32	25	22	26	21	
Total Hardness	mg CaCO3/L	304	330	310	118	120	112	116	121	
Calcium Hardness	mg CaCO3/L	276	285	278	98	87	85	96	89	
Turbidity	ntu	2.3	2.9	2.5	5.8	18.4	18.4	0.11	0.24	
UV-254	cm-1		0.3342	0.3276		0.1591	0.1537		0.1761	
True Color	cpu	45	36	34	9	8	8	4	7	
NPDOC	mg/L		13.6	10.828		9.1	6.856		9.1	

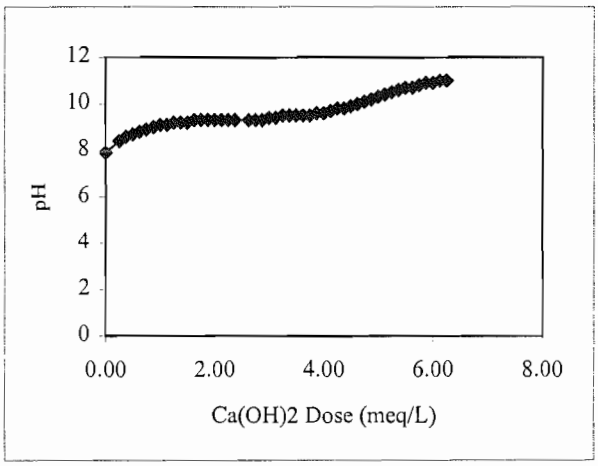
Approximate = TOC Analyzer problem

Marco Island 2 Raw Water Quality

Parameter	Units	Raw Water
pH		7.9
Alkalinity	mg CaCO3/L	226
Total Hardness	mg CaCO3/L	310
Calcium Hardness	mg CaCO3/L	278
Turbidity	ntu	
UV-254	cm-1	0.3276
True Color	cpu	34
NPDOC	mg/L	10.828

Titration Curve for Marco Island 2 Raw Water

	Ca(OH)2 meq/L	pH
0	0.00	7.9
1	0.25	8.4
1	0.38	8.6
2	0.50	8.7
3	0.63	8.8
4	0.75	8.9
5	0.88	9
6	1.00	9.1
7	1.13	9.1
8	1.25	9.2
9	1.38	9.2
10	1.50	9.2
11	1.63	9.3
12	1.75	9.3
13	1.88	9.3
14	2.00	9.3
15	2.13	9.3
16	2.25	9.3
17	2.38	9.3
19	2.63	9.3
20	2.75	9.3
21	2.88	9.3
22	3.00	9.4
23	3.13	9.4
24	3.25	9.5
25	3.38	9.5
26	3.50	9.5
27	3.63	9.5
28	3.75	9.5
29	3.88	9.6
30	4.00	9.6
31	4.13	9.7
32	4.25	9.8
33	4.38	9.8
34	4.50	9.9
35	4.63	10
36	4.75	10.1
37	4.88	10.2
38	5.00	10.3
39	5.13	10.4
40	5.25	10.5
41	5.38	10.6
42	5.50	10.7
43	5.63	10.7
44	5.75	10.8
45	5.88	10.9
46	6.00	10.9
47	6.13	11
48	6.25	11



Coagulant	Company	Specification	Stock Solution for Dosing
$FeCl_3$	Kemwater North America	43.2 % $FeCl_3$ Spec.Grav. = 1.474	1 meq/mL Fe
$Fe_2(SO_4)_3$	Kemiron	12.97 % Fe Spec.Grav. = 1.59	1 meq/mL Fe
Alum $Al_2(SO_4)_3$	Kemwater North America	8.27 % Al_2O_3 Spec.Grav. = 1.33	1 meq/mL Al

Marco Island 2 - Softening

A. Determination of Lime Dose

$Ca(OH)_2$ Dose meq/L	pH	Turbidity* ntu	Alkalinity mg $CaCO_3$/L	Total Hardness mg $CaCO_3$/L	Calcium Hardness mg $CaCO_3$/L
Raw			226	310	278
3	8.4	105	95	170	134
4	8.9	130	52	128	93
5	9.9	181	31	107	73
6	10.7	170	54	127	99
7	11.1	152	91	164	138

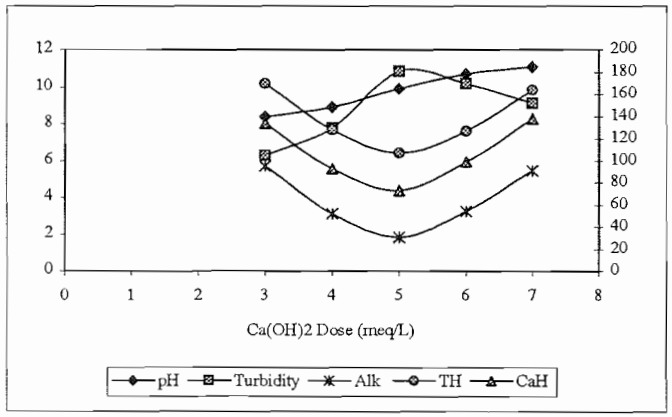
*Measured after 5 min settling

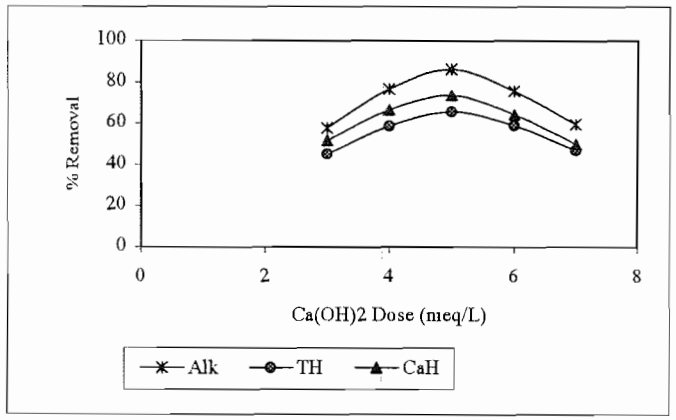
Experimental QA/QC

5 Dupe	9.6	206	30	104	73
%RSD	3	11	3	3	0

%Removal

$Ca(OH)_2$ Dose meq/L	Alkalinity	Total Hardness	Calcium Hardness
3	58	45	52
4	77	59	67
5	86	65	74
6	76	59	64
7	60	47	50





Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatement Optimization: Softening + Coag (WQ)

B. Determination of Coagulant and Dose using Established Lime Dose: Water Quality

$Al_2(SO_4)_3$ - Alum

Parameter		Raw	Control ($Ca(OH)_2$)		5 meq/L Ca(OH)2		7 meq/L Ca(OH)2		Parameter	Control ($Ca(OH)_2$)		5 meq/L Ca(OH)2		7 meq/L Ca(OH)2	
			5 meq/L	7 meq/L	Alum		Alum			5 meq/L	7 meq/L	Alum		Alum	
			No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L		No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L
pH		7.9	9.9	11.1	9.6	8.8	10.9	10.7							
Alkalinity	mg $CaCO_3$/L	226	31	91	33	48	65	45	Alkalinity	86	60	85	79	71	80
Total Hardness	mg $CaCO_3$/L	310	107	164	110	133	150	139	Total Hardness	65	47	65	57	52	55
Calcium Hardness	mg $CaCO_3$/L	278	73	138	75	97	132	132	Calcium Hardness	74	50	73	65	53	53
UV-254	cm^{-1}	0.3276	0.2193	0.1846	0.2213	0.2358	0.1336	0.1187	UV-254	33	44	32	28	59	64
True Color	cpu	34	19	13	19	20	8	7	True Color	44	62	44	41	76	79
NPDOC	mg/L	10.828	8.095	7.052	8.283	8.699	6.562	5.803	NPDOC	25	35	24	20	39	46

$FeCl_3$

Parameter		Raw	Control ($Ca(OH)_2$)		5 meq/L Ca(OH)2		7 meq/L Ca(OH)2		Parameter	Control ($Ca(OH)_2$)		5 meq/L Ca(OH)2		7 meq/L Ca(OH)2	
			5 meq/L	7 meq/L	$FeCl_3$		$FeCl_3$			5 meq/L	7 meq/L	$FeCl_3$		$FeCl_3$	
			No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L		No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L
pH		7.9	9.9	11.1	9.7	9.5	11.0	10.9							
Alkalinity	mg $CaCO_3$/L	226	31	91	36	39	71	64	Alkalinity	86	60	84	83	69	72
Total Hardness	mg $CaCO_3$/L	310	107	164	119	128	155	155	Total Hardness	65	47	62	59	50	50
Calcium Hardness	mg $CaCO_3$/L	278	73	138	82	95	136	138	Calcium Hardness	74	50	71	66	51	50
UV-254	cm^{-1}	0.3276	0.2193	0.1846	0.2308	0.2201	0.1405	0.1248	UV-254	33	44	30	33	57	62
True Color	cpu	34	19	13	19	18	8	7	True Color	44	62	44	47	76	79
NPDOC	mg/L	10.828	8.095	7.052	8.714	8.533	6.494	6.019	NPDOC	25	35	20	21	40	44

$Fe_2(SO_4)_3$

Parameter		Raw	Control ($Ca(OH)_2$)		5 meq/L Ca(OH)2		7 meq/L Ca(OH)2		Parameter	Control ($Ca(OH)_2$)		5 meq/L Ca(OH)2		7 meq/L Ca(OH)2	
			5 meq/L	7 meq/L	$Fe_2(SO_4)_3$		$Fe_2(SO_4)_3$			5 meq/L	7 meq/L	$Fe_2(SO_4)_3$		$Fe_2(SO_4)_3$	
			No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L		No Coag		0.1 meq/L	0.3 meq/L	0.1 meq/L	0.3 meq/L
pH		7.9	9.9	11.1	9.8	9.4	11.1	11							
Alkalinity	mg $CaCO_3$/L	226	31	91	33	36	75	54	Alkalinity	86	60	85	84	67	76
Total Hardness	mg $CaCO_3$/L	310	107	164	113	125	165	155	Total Hardness	65	47	64	60	47	50
Calcium Hardness	mg $CaCO_3$/L	278	73	138	78	90	146	138	Calcium Hardness	74	50	72	68	47	50
UV-254	cm^{-1}	0.3276	0.2193	0.1846	0.2294	0.2242	0.1469	0.1250	UV-254	33	44	30	32	55	62
True Color	cpu	34	19	13	19	19	9	7	True Color	44	62	44	44	74	79
NPDOC	mg/L	10.828	8.095	7.052	8.973	8.510	6.780	6.139	NPDOC	25	35	17	21	37	43

Appendix B: DBP Modeling Results

Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatement Optimization: Opt Lime + Coag

Generating the required sample volume for Cl2 dissipation study using the optimum condition

A: 5 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$

Parameter	Units	Jar 1	Jar 2	Jar 3	Jar 4	Average	Previous Results*	Experimental QA/QC %RSD
pH		9.2	9.3	9.3	9.4		9.4	
Alkalinity	mg $CaCO_3$/L	41	43			42	36	14
Total Hardness	mg $CaCO_3$/L	132	134			133	125	6
Calcium Hardness	mg $CaCO_3$/L	96	96			96	90	6
UV-254	cm^{-1}	0.2260	0.2276			0.2268	0.2242	1
True Color	cpu	19	18			19	19	2
NPDOC	mg/L	8.133	8.215			8.174	8.510	4

Jars 1 & 2 / Jars 3 & 4 were combined. The results are presented above.
*Results of the lime softening with coagulation study.

B: 7 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$

Parameter	Units	Jar 1	Jar 2	Jar 3	Jar 4	Average	Previous Results*	Experimental QA/QC %RSD
pH		10.8	10.9	10.8	10.9		11	
Alkalinity	mg $CaCO_3$/L	66	62			64	54	15
Total Hardness	mg $CaCO_3$/L	150	140			145	155	6
Calcium Hardness	mg $CaCO_3$/L	135	132			134	138	3
UV-254	cm^{-1}	0.1337	0.1354			0.13455	0.125	7
True Color	cpu	6	6			6	7	14
NPDOC	mg/L	6.055	6.086			6.071	6.139	1

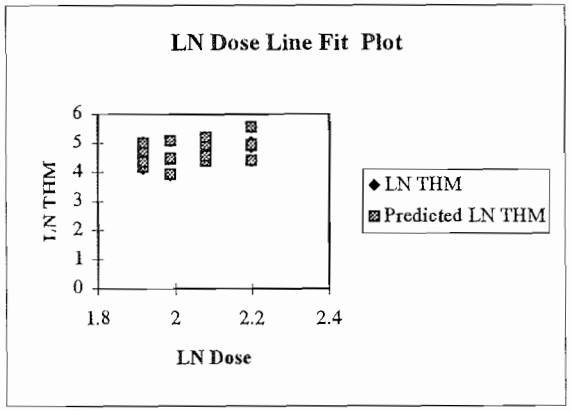
Jars 1 & 2 / Jars 3 & 4 were combined. The results are presented above.
*Results of the lime softening with coagulation study.

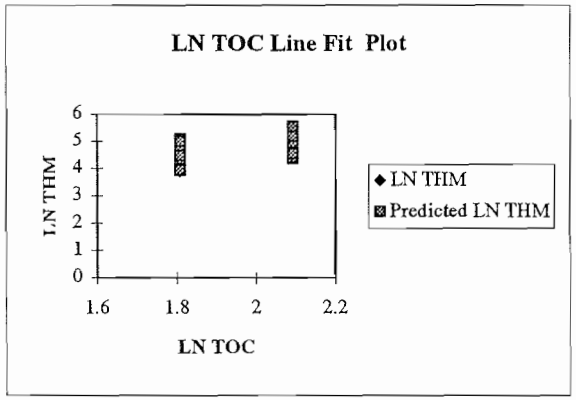
Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatement Optimization: THM&HAA (2)

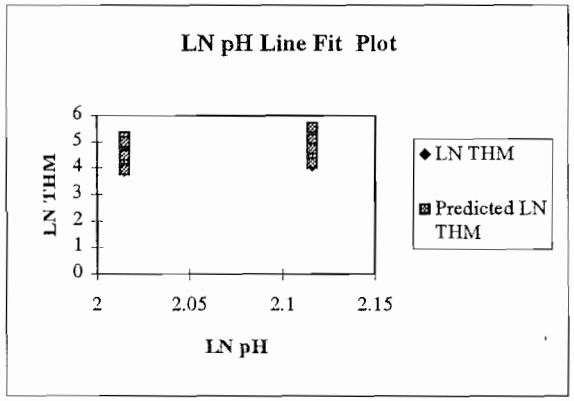
THM Results for the Sample Matrix using Optimum Softening & Coagulation Conditions

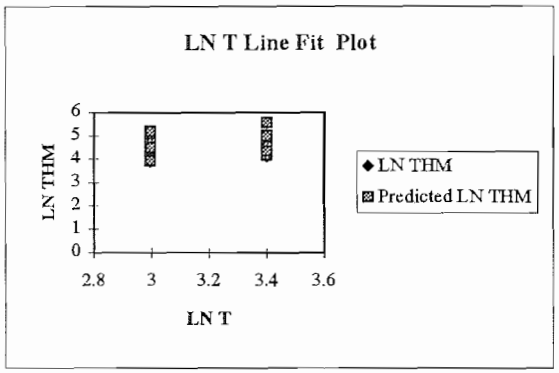
HAA Results for the Sample Matrix using Optimum Softening & Coagulation Conditions

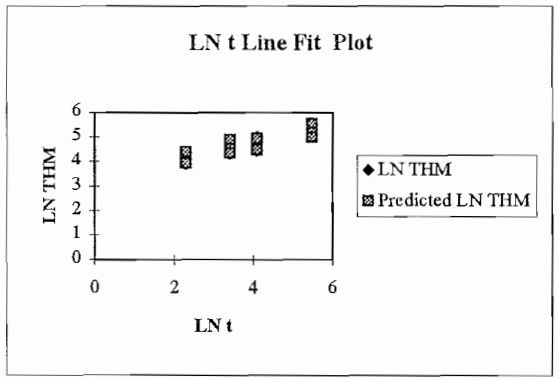
Dose	NPDOC	pH	T	t	$CHCl_3$	$BrCl_2CH$	Br_2ClCH	Br_3CH	THM_{total}	MCAA	MBAA	DCAA	TCAA	BCAA	DBAA	HAA_{total}
mg/L	mg/L		°C	min	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
9	8.1	8.3	30	30	61.9	40.5	24.2	2.1	128.7	0.7	5.9	18.9	15.1	11.7	8.4	60.7
8	8.1	8.3	20	10	41.3	22.0	14.1	2.8	80.3	0.8	6.6	16.3	10.0	9.1	3.8	46.6
7.3	6.1	8.3	20	30	34.6	25.9	23.0	5.3	88.9	0.8	7.4	10.9	6.7	8.0	5.5	39.4
6.8	6.1	8.3	30	10	28.9	16.8	14.5	1.0	61.3	0.8	8.1	9.7	5.3	6.6	4.4	34.9
9	8.1	7.5	30	10	42.9	22.2	12.5	2.8	80.4	1.7	6.2	16.2	13.4	9.9	5.4	52.9
8	8.1	7.5	20	30	49.8	31.3	17.8	3.5	102.4	0.9	6.6	17.7	17.8	10.9	3.9	57.8
7.3	6.1	7.5	20	10	22.9	13.6	11.1	2.0	49.6	1.0	7.1	8.5	6.8	7.0	4.1	34.4
6.8	6.1	7.5	30	30	28.4	23.3	19.8	3.3	74.7	0.8	6.6	9.4	9.1	8.1	4.4	38.5
9	8.1	8.3	30	240	125.2	82.4	42.8	6.3	256.7	0.8	4.0	30.1	30.5	18.5	7.3	91.2
8	8.1	8.3	20	60	63.3	44.4	25.8	3.9	137.3	0.8	5.8	19.6	17.7	13.0	5.3	62.2
7.3	6.1	8.3	20	240	58.3	48.3	39.7	14.1	160.3	0.8	5.7	14.4	11.1	11.9	7.6	51.5
6.8	6.1	8.3	30	60	43.0	37.6	32.5	9.1	122.2	1.4	6.4	11.5	7.9	9.4	6.2	42.9
9	8.1	7.5	30	60	72.3	51.2	26.2	3.4	153.1	0.7	5.7	20.7	27.0	13.4	5.0	72.6
8	8.1	7.5	20	240	75.8	55.7	27.6	4.8	163.8	2.2	5.2	22.5	34.2	15.4	5.0	84.4
7.3	6.1	7.5	20	60	31.4	28.0	23.0	4.1	86.5	1.0	6.6	9.7	11.0	8.9	4.6	41.7
6.8	6.1	7.5	30	240	55.6	55.3	39.2	4.2	154.3	0.7	4.9	13.8	17.9	13.0	6.2	56.4

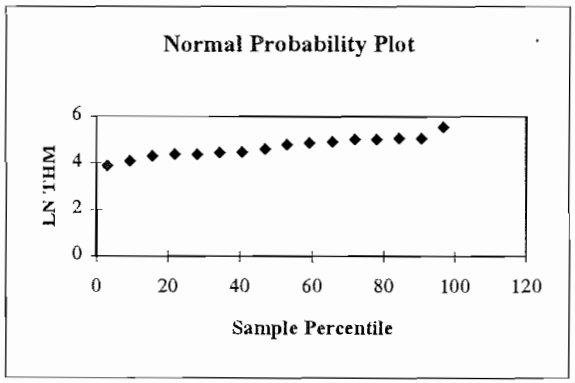

LN Dose Line Fit Plot
LN THM
LN Dose
LN THM
Predicted LN THM


LN TOC Line Fit Plot
LN THM
LN TOC
LN THM
Predicted LN THM


LN pH Line Fit Plot
LN THM
LN pH
LN THM
Predicted LN THM


LN T Line Fit Plot
LN THM
LN T
LN THM
Predicted LN THM


LN t Line Fit Plot
LN THM
LN t
LN THM
Predicted LN THM


Normal Probability Plot
LN THM
Sample Percentile

Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatement Optimization: Reg-HAA1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.993198607
R Square	0.986443473
Adjusted R Square	0.979665209
Standard Error	0.042498619
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	1.314236079	0.262847	145.53041	5.28028E-09
Residual	10	0.018061326	0.001806		
Total	15	1.332297405			

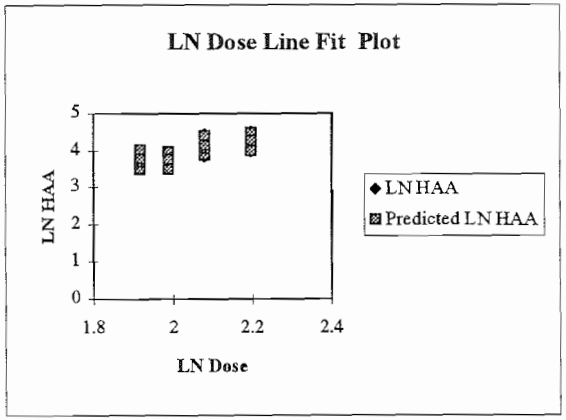
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.092450168	0.505494433	0.182891	0.8585386	-1.033861812	1.21876215
LN Dose	0.391408446	0.225176414	1.73823	0.1128066	-0.110315958	0.89313285
LN TOC	1.269581309	0.165570765	7.667907	1.704E-05	0.90066659	1.63849603
LN pH	-0.225258472	0.20965749	-1.07441	0.3078785	-0.692404552	0.24188761
LN T	0.136924989	0.053996503	2.535812	0.0295747	0.016613261	0.25723672
LN t	0.159537686	0.009220608	17.3023	8.803E-09	0.138992888	0.18008248

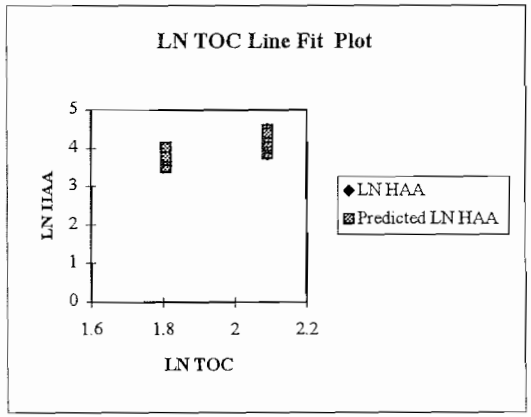
RESIDUAL OUTPUT

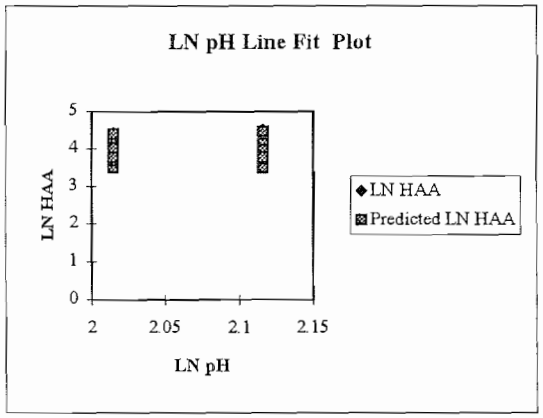
Observation	*Predicted LN HAA*	*Residuals*
1	4.139877526	-0.03475789
2	3.862987883	-0.020529341
3	3.642395884	0.030354188
4	3.494873019	0.05704058
5	3.987437972	-0.019223687
6	4.061088453	-0.004272703
7	3.48995633	0.048100234
8	3.692973589	-0.042055641
9	4.471626817	0.041756973
10	4.148841043	-0.018164551
11	3.974145175	-0.033146062
12	3.780726178	-0.022553897
13	4.273291131	0.012224603
14	4.392837745	0.042966596
15	3.775809489	-0.04530836
16	4.02472288	0.007568958

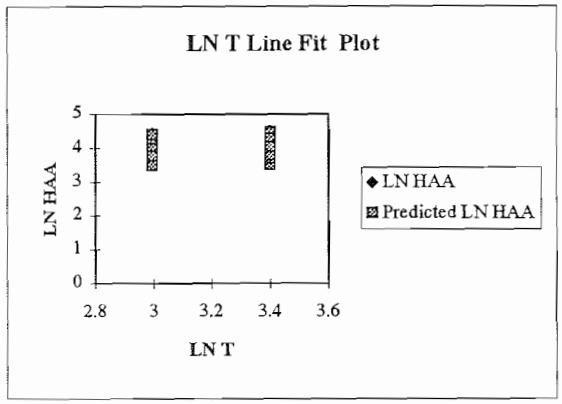
PROBABILITY OUTPUT

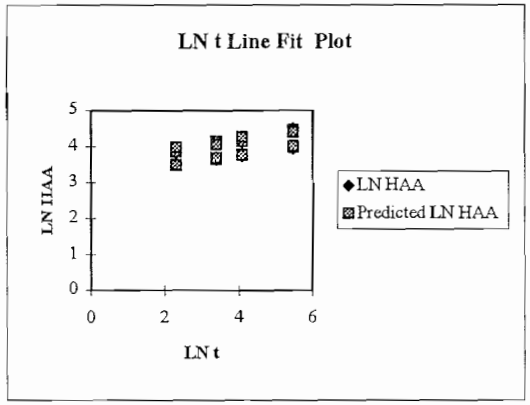
Percentile	*LN HAA*
3.125	3.538056564
9.375	3.551913599
15.625	3.650917948
21.875	3.672750072
28.125	3.730501129
34.375	3.758172281
40.625	3.842458542
46.875	3.940999114
53.125	3.968214285
59.375	4.032291838
65.625	4.05681575
71.875	4.105119635
78.125	4.130676491
84.375	4.285515734
90.625	4.43580434
96.875	4.51338379

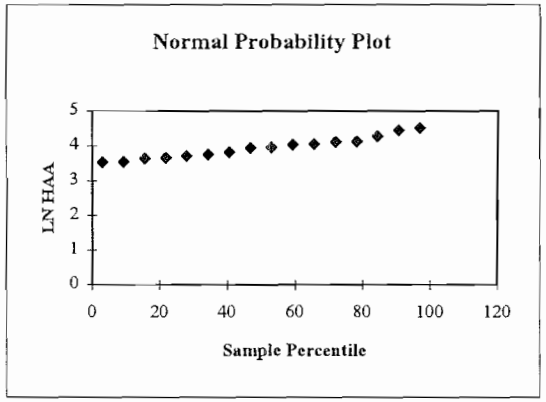

LN Dose Line Fit Plot
LN HAA
LN Dose
LN HAA
Predicted LN HAA


LN TOC Line Fit Plot
LN HAA
LN TOC
LN HAA
Predicted LN HAA


LN pH Line Fit Plot
LN HAA
LN pH
LN HAA
Predicted LN HAA


LN T Line Fit Plot
LN HAA
LN T
LN HAA
Predicted LN HAA


LN t Line Fit Plot
LN HAA
LN t
LN HAA
Predicted LN HAA


Normal Probability Plot
LN HAA
Sample Percentile

Analytical QA/QC

A: Alkalinity

Sample	Value mg/L	Value mg/L	RSD %	Spike mg/L	Recovery %
3 meq/L $Ca(OH)_2$	95	95	0	139	92
5 meq/L $Ca(OH)_2$ + 0.3 meq/L Alum	48	48	0	91	90
5 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$	36	37	2	82	96

B: Total Hardness

Sample	Value mg/L	Value mg/L	RSD %	Spike mg/L	Recovery %
4 meq/L $Ca(OH)_2$	128	129	1	148	100
5 meq/L $Ca(OH)_2$ + 0.1 meq/L Alum	110	112	2	131	109
7 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$	155	156	1	174	94

C: Calcium Hardness

Sample	Value mg/L	Value mg/L	RSD %	Spike mg/L	Recovery %
5 meq/L $Ca(OH)_2$	73	73	<1	92	98
5 meq/L $Ca(OH)_2$ + 0.1 meq/L Alum	75	76	1	94	98
7 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$	138	140	1	158	101

D: UV-254 and Color

Sample	UV-254 Value cm-1	UV-254 Value cm-1	UV-254 RSD %	Color Value cpu	Color Value cpu	Color RSD %
Raw	0.3276	0.3276	<1	34	34	<1
5 meq/L $Ca(OH)_2$ + 0.1 meq/L Alum	0.2213	0.2212	<1	19	19	<1

E: NPDOC

Sample	Value mg/L	Value mg/L	RSD %	Spike mg/L	Recovery %
5 meq/L $Ca(OH)_2$ + 0.1 meq/L Alum	8.283	8.251	<1	9.086	80
7 meq/L $Ca(OH)_2$	7.052	7.122	1	8.876	91
7 meq/L $Ca(OH)_2$ + 0.3 meq/L $Fe_2(SO_4)_3$	6.086	6.116	<1	8.119	102

F: THM

Sample	7.3mg/L Dose/6.1 mg/L NPDOC/7.5 pH/20°C/10 min				
	Value µg/L	Value µg/L	RSD %	Spike µg/L	Recovery %
$CHCl_3$	22.9	22.63	1	43.28	102
$BrCl_2CH$	13.62	13.55	<1	35.54	110
Br_2ClCH	11.08	11.03	<1	33.64	113
Br_3CH	1.98	2.01	1	24.05	110
THM_{total}	49.58	49.23	1	136.51	109

Sample	8mg/L Dose/8.1 mg/L NPDOC/7.5 pH/20°C/30 min				
	Value µg/L	Value µg/L	RSD %	Spike µg/L	Recovery %
$CHCl_3$	49.8	48.62	2	68.39	93
$BrCl_2CH$	31.26	30.57	2	52.08	104
Br_2ClCH	17.77	17.34	2	40.79	115
Br_3CH	3.54	2.86	19	25.36	109
THM_{total}	102.37	99.4	3	186.62	105

G: HAA

Sample	7.3mg/L Dose/6.1mg/L NPDOC/ 8.3 pH/20°C/30 min			9mg/L Dose/8.1mg/L NPDOC/ 8.3 pH/30°C/30 min		
	Value µg/L	Value µg/L	RSD %	Value µg/L	Value µg/L	RSD %
MCAA	0.83	0.8	3	0.68	0.71	4
MBAA	7.41	7.11	4	5.88	5.98	2
DCAA	10.89	10.21	6	18.89	18.95	<1
TCAA	6.71	6.39	4	15.09	15.26	1
BCAA	8.02	7.57	5	11.74	11.82	1
DBAA	5.5	5.27	4	8.37	8.52	1
HAA_{total}	36.36	37.35	5	60.65	61.24	1

Sample	6.8mg/L Dose/6.1mg/L NPDOC/ 8.3 pH/30°C/10 min			8mg/L Dose/8.1mg/L NPDOC/ 8.3 pH/20°C/1 h		
	Value µg/L	Spike µg/L	Recovery %	Value µg/L	Spike µg/L	Recovery %
MCAA	0.8	13.9	66	0.8	13.5	63
MBAA	8.1	22.3	71	5.8	20.1	72
DCAA	9.7	26.8	85	19.6	35.9	81
TCAA	5.3	23.9	93	17.7	34.5	84
BCAA	6.6	25.8	96	13.0	30.7	89
DBAA	4.4	25.1	103	5.3	25.6	101
HAA_{total}	34.9	137.8	86	62.2	160.2	82

Cl2 Dissipation Study using Optimum Lime and Coagulant Dose

A: Determination of Cl_2 Dose

$Ca(OH)_2$/Fe Dose meq/L	pH	T °C	Cl_2 Dose mg/L	Cl_2 Residual at t = 4h mg/L	Demand mg/L	Proposed Actual Dose (mg/L)
5 $Ca(OH)_2$ / 0.3 Fe	7.5	20	6	2.2	3.8	8
				5.7	4.3	
		30	6	1.2	4.8	9
			10	4.8	5.2	
	8.3	20	6	2.3	3.7	8
			10	5.9	4.1	
		30	6	3.1*	2.9	9
				1.2	4.8	
			10	7.2*	2.8	
				5.2	4.8	
7 $Ca(OH)_2$ / 0.3 Fe	7.5	20	6	3.9*	2.1	6.8
				3.5	2.5	
			10	7.8*	2.2	
				7.0	3.0	
		30	6	2.8	3.2	7.3
			10	6.8	3.2	
	8.3	20	6	3.3	2.7	6.8
			10	7.3	2.7	
		30	6	2.6	3.4	7.3
			10	6.5	3.5	

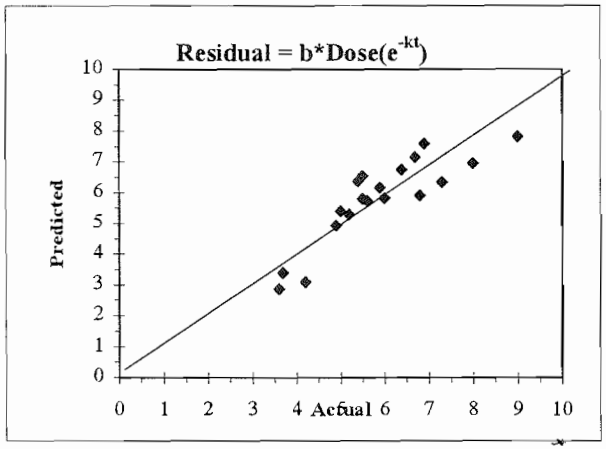
$Ca(OH)_2$/Fe Dose meq/L	pH	T °C	Cl2 Demand (mg/L) Dose (mg/L) 6	10
5 $Ca(OH)_2$ / 0.3 Fe	7.5	20	3.8	4.3
		30	4.8	5.2
	8.3	20	3.7	4.1
		30	4.8	4.8
7 $Ca(OH)_2$ / 0.3 Fe	7.5	20	2.5	3
		30	3.2	3.2
	8.3	20	2.7	2.7
		30	3.4	3.5

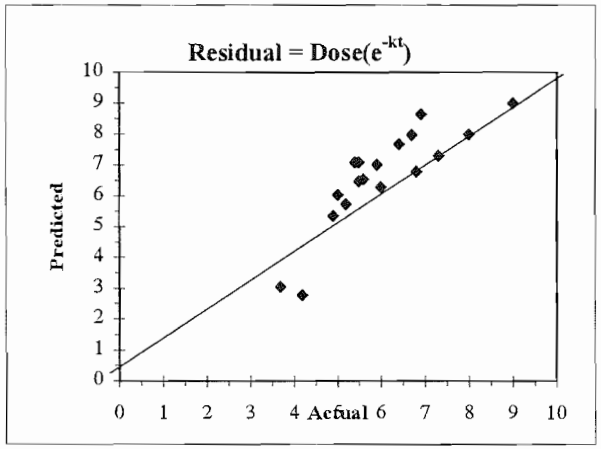
* Cl2 residual after 1h.

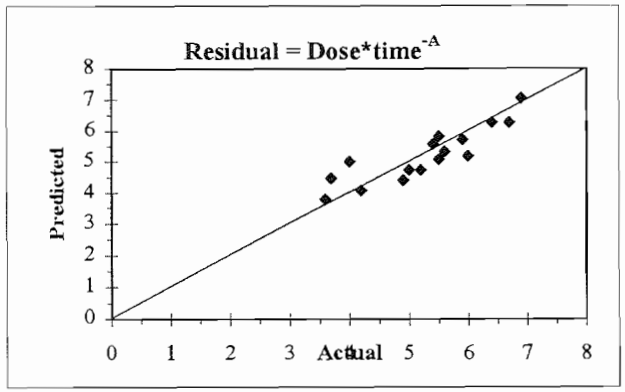
Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatment Optimization: resd-model

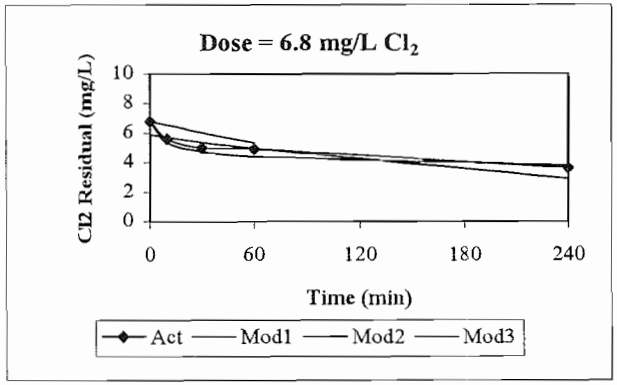
Dose	Time	Act	r=Dexp-at Mod1	r=bdexp-at Mod2	r=d*t^-a Mod3
6.8	0	6.8	6.8	5.9	6.8
6.8	10	5.6	6.5	5.7	5.3
6.8	30	5	6.0	5.4	4.7
6.8	60	4.9	5.3	4.9	4.4
6.8	240	3.6		2.9	3.8
7.3	0	7.3	7.3	6.4	7.3
7.3	10	5.9	7.0	6.2	5.7
7.3	30	5.5	6.5	5.8	5.1
7.3	60	5.2	5.7	5.3	4.7
7.3	240	4.2	2.8	3.1	4.1
8	0	8	8.0	7.0	8.0
8	10	6.4	7.7	6.8	6.3
8	30	5.4	7.1	6.4	5.6
8	60	6	6.3	5.8	5.2
8	240	3.7	3.1	3.4	4.5
9	0	9	9.0	7.8	9.0
9	10	6.9	8.6	7.6	7.1
9	30	6.7	8.0	7.2	6.3
9	60	5.5	7.1	6.5	5.8
9	240	4	3.4	3.8	5.0

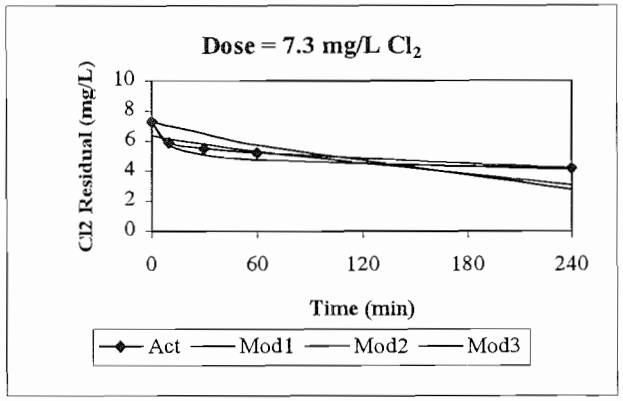
Dose	Time	Act	r=d*t^-a Pred
6.8	10	5.6	5.3
6.8	30	5	4.7
6.8	60	4.9	4.4
6.8	240	3.6	3.8
7.3	30	5.5	5.1
7.3	10	5.9	5.7
7.3	240	4.2	4.1
7.3	60	5.2	4.7
8	10	6.4	6.3
8	30	5.4	5.6
8	60	6	5.2
8	240	3.7	4.5
9	30	6.7	6.3
9	10	6.9	7.1
9	240	4	5.0
9	60	5.5	5.8

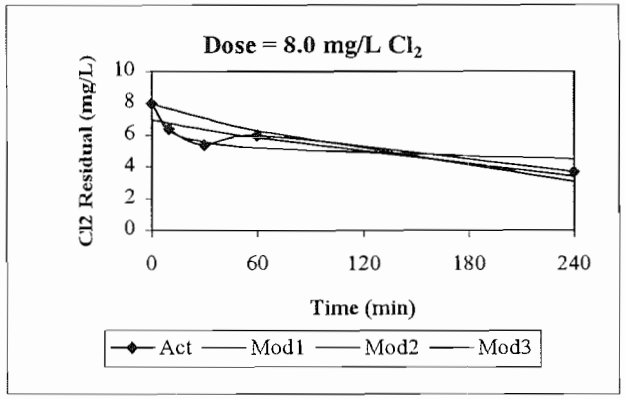


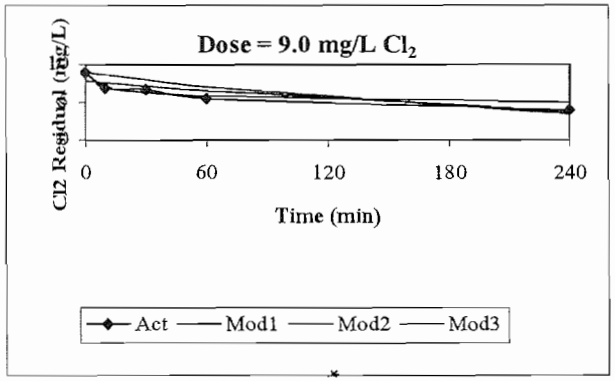



Residual = Dose*time^-A
Predicted
Actual
0
1
2
3
4
5
6
7
8


Dose = 6.8 mg/L Cl2
Cl2 Residual (mg/L)
Time (min)
0
60
120
180
240
Act
Mod1
Mod2
Mod3


Dose = 7.3 mg/L Cl2
Cl2 Residual (mg/L)
Time (min)
0
60
120
180
240
Act
Mod1
Mod2
Mod3

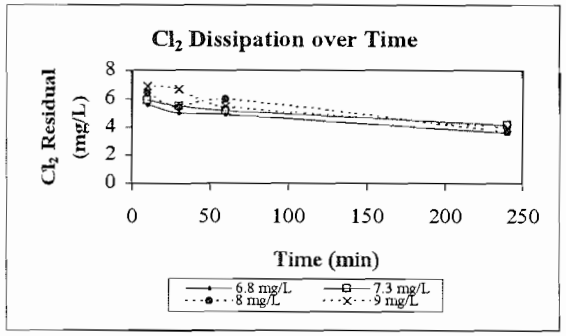

Dose = 8.0 mg/L Cl2
Cl2 Residual (mg/L)
Time (min)
0
60
120
180
240
Act
Mod1
Mod2
Mod3

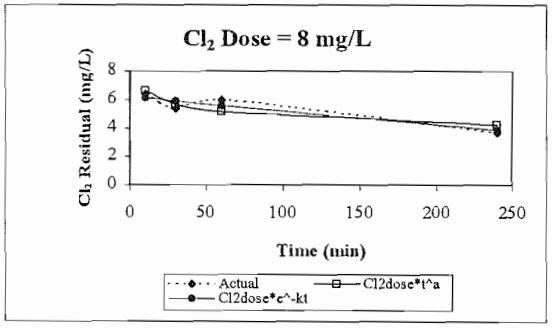

Dose = 9.0 mg/L Cl2
Cl2 Residual (mg/L)
Time (min)
0
60
120
180
240
Act
Mod1
Mod2
Mod3

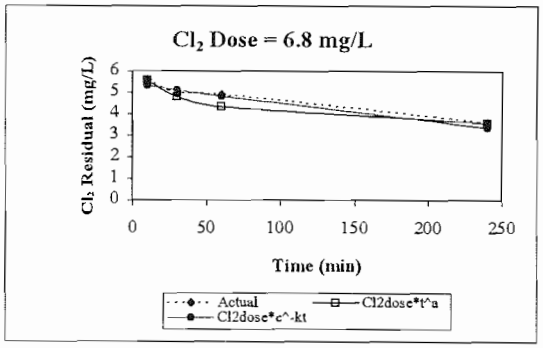
Cl2 Dissipation / DBP Formation Study using Optimum Lime and Coagulant Dose

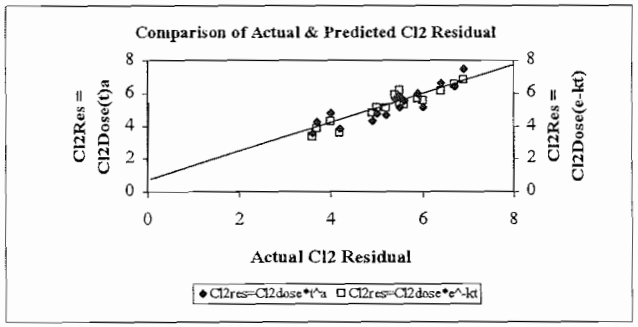
mg/L Dose mg/L	mg/L NPDOC mg/L	pH	°C T °C	min t min	ACTUAL mg/L Cl_2 Residual mg/L	PREDICTED mg/L Cl_2 Residual $Cl2_{Res} = Cl2_{Dose}(t)^a$	mg/L Cl_2 Residual $Cl2_{Res} = Cl2_{Dose}e^{-kt}$
6.8	6.1	8.3	30	10	5.6	5.6	5.3
6.8	6.1	7.5		30	5.0	4.8	5.1
6.8	6.1	8.3	30	60	4.9	4.3	4.8
6.8	6.1	7.5	30	240	3.6	3.6	3.4
7.3	6.1	7.5	20	10	5.9	6.0	5.7
7.3	6.1	8.3	20	30	5.5	5.2	5.4
7.3	6.1	7.5	20	60	5.2	4.7	5.1
7.3	6.1	8.3	20	240	4.2	3.9	3.6
8	8.1	8.3	20	10	6.4	6.6	6.1
8	8.1	7.5	20	30	5.4	5.7	5.9
8	8.1	8.3	20	60	6.0	5.2	5.6
8	8.1	7.5	20	240	3.7	4.3	3.9
9	8.1	7.5	30	10	6.9	7.5	6.8
9	8.1	8.3	30	30	6.7	6.4	6.6
9	8.1	7.5	30	60	5.5	5.9	6.2
9	8.1	8.3	30	240	4.0	4.8	4.3

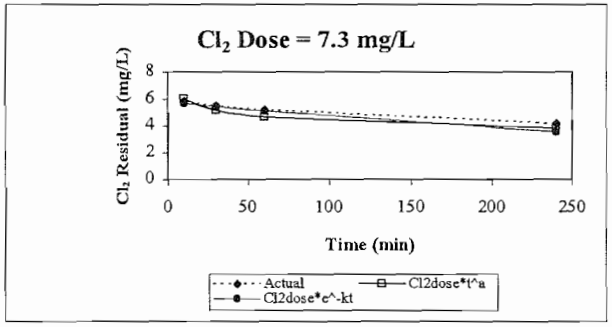
Ln NPDOC	lnDose	Ln Time	LnH	Ln Temp	Ln pH	Ln Cl2 Residual	lnDose	min
1.81	1.92	2.30	-19.09	3.40	2.12	1.72	1.72	10
1.81	1.92	3.40	-17.25	#NUM!	2.01	1.61	1.56	30
1.81	1.92	4.09	-19.09	3.40	2.12	1.59	1.47	60
1.81	1.92	5.48	-17.25	3.40	2.01	1.28	1.28	240
1.81	1.99	2.30	-17.25	3.00	2.01	1.77	1.79	10
1.81	1.99	3.40	-19.09	3.00	2.12	1.70	1.64	30
1.81	1.99	4.09	-17.25	3.00	2.01	1.65	1.54	60
1.81	1.99	5.48	-19.09	3.00	2.12	1.44	1.35	240
2.09	2.08	2.30	-19.09	3.00	2.12	1.86	1.89	10
2.09	2.08	3.40	-17.25	3.00	2.01	1.69	1.74	30
2.09	2.08	4.09	-19.09	3.00	2.12	1.79	1.64	60
2.09	2.08	5.48	-17.25	3.00	2.01	1.31	1.45	240
2.09	2.20	2.30	-17.25	3.40	2.01	1.93	2.02	10
2.09	2.20	3.40	-19.09	3.40	2.12	1.90	1.86	30
2.09	2.20	4.09	-17.25	3.40	2.01	1.70	1.77	60
2.09	2.20	5.48	-19.09	3.40	2.12	1.39	1.57	240



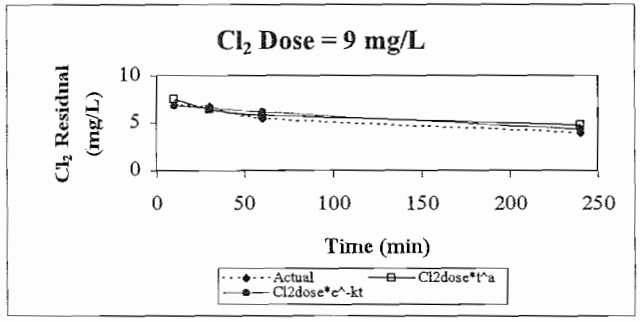


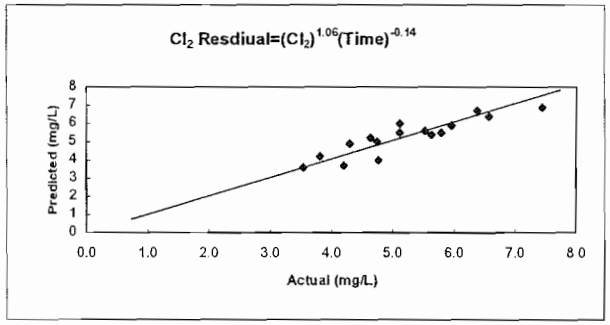






5.5	5.6
4.7	5.0
4.3	4.9
3.5	3.6
6.0	5.9
5.1	5.5
4.6	5.2
3.8	4.2
6.6	6.4
5.6	5.4
5.1	6.0
4.2	3.7
7.4	6.9
6.4	6.7
5.8	5.5
4.8	4.0





SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.884005797
R Square	0.781466249
Adjusted R Square	0.694428124
Standard Error	0.097374206
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.474687288	0.237344	25.03167	3.48403E-05
Residual	14	0.132744304	0.009482		
Total	16	0.607431592			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	1.062734495	0.040574734	26.19203	2.7E-13	0.975710268	1.14975872	0.975710268	1.149758721
X Variable 2	-0.1388577	0.020828405	-6.666747	1.07E-05	-0.18353023	-0.09418518	-0.18353023	-0.094185179

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.892114461
R Square	0.795868212
Adjusted R Squar	0.709858799
Standard Error	0.094110914
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.483435495	0.241718	27.29157	2.22168E-05
Residual	14	0.123996097	0.008857		
Total	16	0.607431592			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
X Variable 1	1.010914222	0.01797119	56.25194	6.75E-18	0.972369819	1.049458625	0.972369819	1.049458625
X Variable 2	-0.000237027	0.000238488	-0.993872	0.337154	-0.000748533	0.00027448	-0.000748533	0.00027448

Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatment Optimization: Reg-Cl2Res1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.884005797
R Square	0.781466249
Adjusted R Square	0.694428124
Standard Error	0.097374206
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.474687288	0.237344	25.03167	3.48403E-05
Residual	14	0.132744304	0.009482		
Total	16	0.607431592			

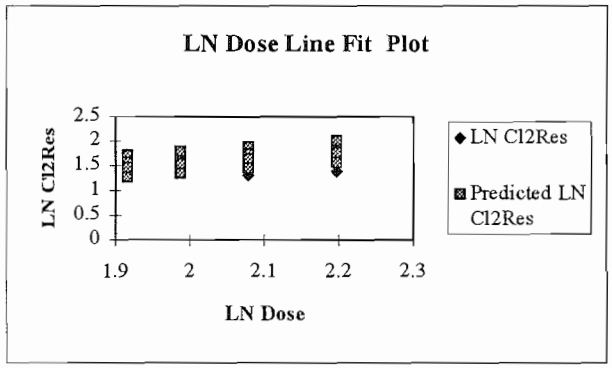
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
LN Dose	1.062734495	0.040574734	26.19203	2.7E-13	0.975710268	1.14975872
LN t	-0.138857705	0.020828405	-6.66675	1.07E-05	-0.18353023	-0.0941852

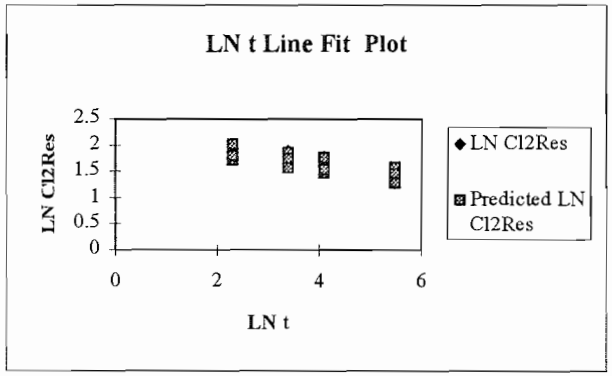
RESIDUAL OUTPUT

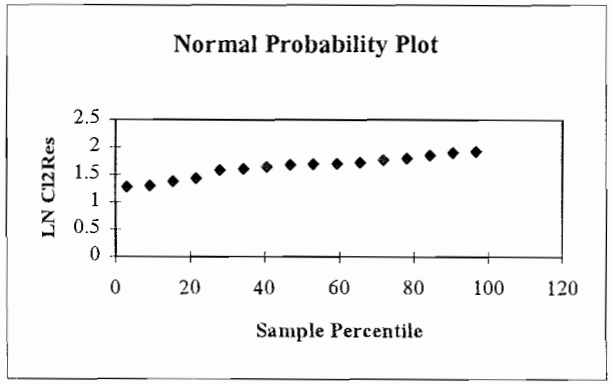
Observation	*dicted LN Cl2R*	*Residuals*
1	1.86278389	0.039323636
2	1.890162576	-0.033864585
3	1.64030018	0.064447912
4	1.717448103	0.005318494
5	2.015334671	-0.083813259
6	1.737611795	-0.051212842
7	1.792850961	-0.01789861
8	1.564897323	0.04454059
9	1.574037411	-0.187743049
10	1.641362969	0.150396501
11	1.351553701	0.083530825
12	1.468648496	0.120586709
13	1.766535064	-0.061786971
14	1.448865316	-0.140532496
15	1.544051353	0.104607272
16	1.276150843	0.004783002

PROBABILITY OUTPUT

Percentile	*LN Cl2Res*
3.125	1.280933845
9.375	1.30833282
15.625	1.386294361
21.875	1.435084525
28.125	1.589235205
34.375	1.609437912
40.625	1.648658626
46.875	1.686398954
53.125	1.704748092
59.375	1.704748092
65.625	1.722766598
71.875	1.774952351
78.125	1.791759469
84.375	1.85629799
90.625	1.902107526
96.875	1.931521412







SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.940513223
R Square	0.884565123
Adjusted R Square	0.804891203
Standard Error	0.070770651
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.537312801	0.268656	53.64025	5.24038E-07
Residual	14	0.070118791	0.005008		
Total	16	0.607431592			

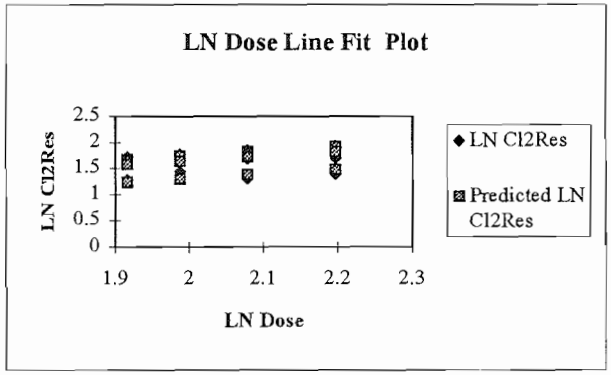
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
LN Dose	0.883023252	0.011793177	74.87577	1.25E-19	0.85772938	0.90831712
t	-0.00190413	0.00019369	-9.83083	1.15E-07	-0.002319557	-0.0014887

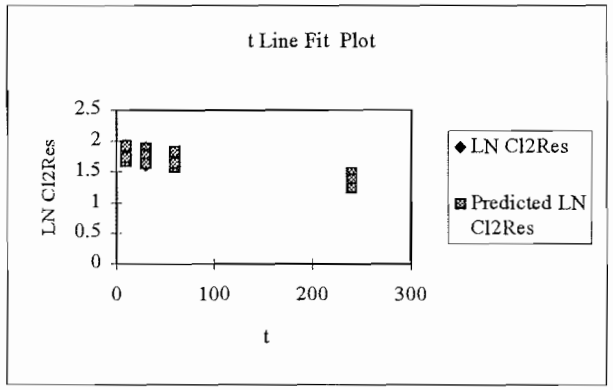
RESIDUAL OUTPUT

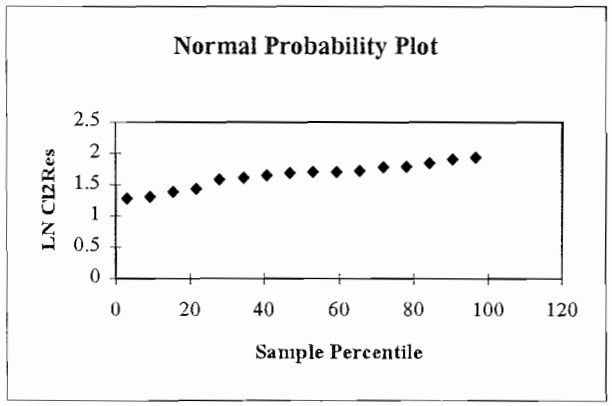
Observation	*dicted LN Cl2R*	*Residuals*
1	1.883076394	0.019031133
2	1.8171539	0.039144091
3	1.698215274	0.006532818
4	1.673645906	0.049120692
5	1.921159059	0.010362353
6	1.779071235	-0.092672281
7	1.736297939	0.038654412
8	1.635563241	-0.026125329
9	1.483208413	-0.096914051
10	1.721947237	0.069812232
11	1.298347292	0.136737233
12	1.578439244	0.010795961
13	1.825952397	-0.121204304
14	1.379203253	-0.070870434
15	1.641091276	0.007567349
16	1.23569526	0.045238586

PROBABILITY OUTPUT

Percentile	*LN Cl2Res*
3.125	1.280933845
9.375	1.30833282
15.625	1.386294361
21.875	1.435084525
28.125	1.589235205
34.375	1.609437912
40.625	1.648658626
46.875	1.686398954
53.125	1.704748092
59.375	1.704748092
65.625	1.722766598
71.875	1.774952351
78.125	1.791759469
84.375	1.85629799
90.625	1.902107526
96.875	1.931521412







Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatment Optimization: Application Models

	Cl2 Dose	NPDOC	pH	Temperature	Time	Cl2 Residual	THM	HAA	Blend Ratio	THM_{Blend}	HAA_{Blend}		
1	6	5	7.5	20	10	4.8	39.4	25.1					
2	6	5	7.5	20	30	4.1	55.3	28.2					
	6	5	7.5	30	10	4.8	45.4	25.1					
4	6	5	7.5	30	30	4.1	63.8	28.2					
5	6	5	7.5	20	10	4.8	39.4	25.1					
6	6	5	7.5	20	30	4.1	55.3	28.2					
7	6	5	7.5	30	10	4.8	45.4	25.1					
8	6	5	7.5	30	30	4.1	63.8	28.2					
9	6	8	7.5	20	10	4.8	68.2	25.1					
10	6	8	7.5	20	30	4.1	95.9	28.2					
11	6	8	7.5	30	10	4.8	78.6	25.1					
12	6	8	7.5	30	30	4.1	110.6	28.2					
13	6	8	8.3	20	10	4.8	80.7	25.1					
14	6	8	8.3	20	30	4.1	113.4	28.2					
15	6	8	8.3	30	10	4.8	93.0	25.1					
16	6	8	8.3	30	30	4.1	130.7	28.2					
17	10	5	7.5	20	10	8.3	39.4	58.5					
18	10	5	7.5	20	30	7.1	55.3	65.8					
19	10	5	7.5	30	10	8.3	45.4	58.5					
20	10	5	7.5	30	30	7.1	63.8	65.8					
21	10	5	8.3	20	10	8.3	46.5	58.5					
22	10	5	8.3	20	30	7.1	65.4	65.8					
23	10	5	8.3	30	10	8.3	53.6	58.5					
24	10	5	8.3	30	30	7.1	75.4	65.8					
25	10	8	7.5	20	10	8.3	68.2	58.5					
26	10	8	7.5	20	30	7.1	95.9	65.8					
27	10	8	7.5	30	10	8.3	78.6	58.5					
28	10	8	7.5	30	30	7.1	110.6	65.8					
29	10	8	8.3	20	10	8.3	80.7	58.5	20	10	81	59	
30	10	8	8.3	20	30	7.1	113.4	65.8	20	30	113	66	
31	10	8	8.3	30	10	8.3	93.0	58.5	30	10	93	59	
32	10	8	8.3	30	30	7.1	130.7	65.8	30	30	131	66	
									4.8	333.9	52.7	20.0	10.0
									4.1	469.4	73.8	20.0	30.0
									4.8	384.9	52.7	30.0	10.0
									4.1	541.0	73.8	30.0	30.0

Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatment Optimization: THM&HAA

THM Results for the Sample Matrix using Optimum Softening & Coagulation Conditions

HAA Results for the Sample Matrix using Optimum Softening & Coagulation Conditions

Dose	NPDOC	pH	T	t	$CHCl_3$	$BrCl_2CH$	Br_2ClCH	Br_3CH	THM_{total}	MCAA	MBAA	DCAA	TCAA	BCAA	DBAA	HAA_{total}
mg/L	mg/L		°C	min	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L
9	8.1	8.3	30	30	61.9	40.5	24.2	2.1	128.7	0.7	5.9	18.9	15.1	11.7	8.4	60.7
8	8.1	8.3	20	10	41.3	22.0	14.1	2.8	80.3	0.8	6.6	16.3	10.0	9.1	3.8	46.6
7.3	6.1	8.3	20	30	34.6	25.9	23.0	5.3	88.9	0.8	7.4	10.9	6.7	8.0	5.5	39.4
6.8	6.1	8.3		10	28.9	16.8	14.5	1.0	61.3	0.8	8.1	9.7	5.3	6.6	4.4	34.9
9	8.1	7.5	30	10	42.9	22.2	12.5	2.8	80.4	1.7	6.2	16.2	13.4	9.9	5.4	52.9
8	8.1	7.5	20	30	49.8	31.3	17.8	3.5	102.4	0.9	6.6	17.7	17.8	10.9	3.9	57.8
7.3	6.1	7.5	20	10	22.9	13.6	11.1	2.0	49.6	1.0	7.1	8.5	6.8	7.0	4.1	34.4
6.8	6.1	7.5	30	30	28.4	23.3	19.8	3.3	74.7	0.8	6.6	9.4	9.1	8.1	4.4	38.5
9	8.1	8.3	30	240	125.2	82.4	42.8	6.3	256.7	0.8	4.0	30.1	30.5	18.5	7.3	91.2
8	8.1	8.3	20	60	63.3	44.4	25.8	3.9	137.3	0.8	5.8	19.6	17.7	13.0	5.3	62.2
7.3	6.1	8.3	20	240	58.3	48.3	39.7	14.1	160.3	0.8	5.7	14.4	11.1	11.9	7.6	51.5
6.8	6.1	8.3	30	60	43.0	37.6	32.5	9.1	122.2	1.4	6.4	11.5	7.9	9.4	6.2	42.9
9	8.1	7.5	30	60	72.3	51.2	26.2	3.4	153.1	0.7	5.7	20.7	27.0	13.4	5.0	72.6
8	8.1	7.5	20	240	75.8	55.7	27.6	4.8	163.8	2.2	5.2	22.5	34.2	15.4	5.0	84.4
7.3	6.1	7.5	20	60	31.4	28.0	23.0	4.1	86.5	1.0	6.6	9.7	11.0	8.9	4.6	41.7
6.8	6.1	7.5	30	240	55.6	55.3	39.2	4.2	154.3	0.7	4.9	13.8	17.9	13.0	6.2	56.4
					0.4806497	0.315045	0.188063	0.016242	1	0.011212	0.09695	0.311459	0.248805	0.19357	0.138005	1
					0.5151402	0.273769	0.176075	0.035016	1	0.016081	0.142153	0.350343	0.213336	0.195755	0.082333	1
					0.389758	0.291953	0.258526	0.059764	1	0.021087	0.188262	0.276677	0.170478	0.20376	0.139736	1
					0.4721724	0.273707	0.237147	0.016974	1	0.022936	0.231651	0.278956	0.150516	0.189507	0.12672	1
					0.5342125	0.275815	0.155014	0.034959	1	0.031953	0.117981	0.306485	0.254112	0.186614	0.102666	1
					0.4864706	0.305363	0.173586	0.03458	1	0.015401	0.114207	0.306281	0.307839	0.188787	0.067486	1
					0.4618798	0.274708	0.223477	0.039935	1	0.028198	0.205233	0.247384	0.197384	0.203488	0.118895	1
					0.3796197	0.311596	0.264596	0.044189	1	0.021813	0.172423	0.244352	0.237081	0.211374	0.112958	1
					0.4876719	0.321077	0.166868	0.024384	1	0.008769	0.044284	0.330374	0.333772	0.203223	0.079579	1
					0.4607765	0.32333	0.187559	0.028334	1	0.012858	0.093218	0.314851	0.284796	0.208775	0.085503	1
					0.3636534	0.301017	0.247489	0.087841	1	0.015932	0.111521	0.279969	0.215077	0.23062	0.147076	1
					0.3520262	0.307491	0.266312	0.074171	1	0.033123	0.149522	0.268486	0.185211	0.219967	0.143457	1
					0.4724019	0.334248	0.171402	0.021948	1	0.009637	0.078744	0.285518	0.371834	0.184747	0.069383	1
					0.4624306	0.339987	0.168406	0.029177	1	0.026179	0.061478	0.266051	0.405117	0.181947	0.059228	1
					0.3628799	0.323818	0.265573	0.047729	1	0.022782	0.157074	0.232134	0.264269	0.213189	0.110552	1
					0.3605782	0.358374	0.253954	0.027094	1	0.011882	0.086718	0.24437	0.317255	0.230537	0.109239	1
					0.4401451	**0.308206**	**0.212753**	**0.038896**	**1**	**0.019365**	**0.128214**	**0.283981**	**0.259805**	**0.202866**	**0.105801**	1

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.990505
R Square	0.981099
Adjusted R	0.974226
Standard Er	0.068855
Observation	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	2.707054	0.676763	142.7471411	2.12101E-09
Residual	11	0.052151	0.004741		
Total	15	2.759205			

	Coefficients	*andard Erro*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	-3.305737	0.790981	-4.17929	0.001538395	-5.046674642	-1.5648	-5.046675	-1.5648
X Variable	1.171248	0.121405	9.647447	1.05697E-06	0.904037074	1.438458	0.904037	1.438458
X Variable	1.646974	0.33968	4.848601	0.000511905	0.899342497	2.394606	0.899342	2.394606
X Variable	0.349364	0.084909	4.114593	0.00171636	0.162481548	0.536247	0.162482	0.536247
X Variable	0.312462	0.014939	20.91594	3.30395E-10	0.279581359	0.345342	0.279581	0.345342

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.991134
R Square	0.982347
Adjusted R	0.975928
Standard Er	0.046239
Observation	16

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regression	4	1.308779	0.327195	153.0348	1.46E-09
Residual	11	0.023518	0.002138		
Total	15	1.332297			

	Coefficient	Standard Ert	Stat	P-value	Lower 95%	Upper 95%	Lower 95.0	Upper 95.0%
Intercept	0.320261	0.531177	0.602927	0.558783	-0.848852	1.489374	-0.848852	1.489374
X Variable	1.52622	0.081529	18.72007	1.09E-09	1.346777	1.705663	1.346777	1.705663
X Variable	-0.225258	0.22811	-0.987501	0.344621	-0.727325	0.276808	-0.727325	0.276808
X Variable	0.159529	0.05702	2.797787	0.017343	0.034029	0.285028	0.034029	0.285028
X Variable	0.159538	0.010032	15.90269	6.15E-09	0.137457	0.181618	0.137457	0.181618

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.990345
R Square	0.980783
Adjusted R	0.975978
Standard Er	0.046191
Observation	16

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regression	3	1.306694	0.435565	204.144	1.46E-10
Residual	12	0.025603	0.002134		
Total	15	1.332297			

	Coefficients	*ndard Erro*	*t Stat*	*P-value*	*ower 95%*	*pper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	-0.145028	0.24498	-0.592001	0.564838	-0.678793	0.388737	-0.678793	0.388737
X Variable	1.52622	0.081444	18.73948	2.98E-10	1.348768	1.703671	1.348768	1.703671
X Variable	0.159529	0.056961	2.800688	0.016024	0.035422	0.283635	0.035422	0.283635
X Variable	0.159538	0.010022	15.91917	1.97E-09	0.137702	0.181373	0.137702	0.181373

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.990061
R Square	0.980221
Adjusted R Square	0.900255
Standard Error	0.045022
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1.305946	0.435315	214.7573	1.08745E-10
Residual	13	0.026351	0.002027		
Total	16	1.332297			

	Coefficients	*ndard Erro*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A
LnCl2Dose	1.494962	0.060441	24.7343	2.56E-12	1.364387354	1.62553623
LnTemp	0.134451	0.037117	3.622397	0.003096	0.054265689	0.21463724
LnTime	0.158611	0.009648	16.43945	4.44E-10	0.137767028	0.179454233

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.990505
R Square	0.981099
Adjusted R	0.974226
Standard Er	0.068855
Observation	16

ANOVA

	df	*SS*	*MS*	*F*	*gnificance F*
Regression	4	2.707054	0.676763	142.7471	2.12E-09
Residual	11	0.052151	0.004741		
Total	15	2.759205			

	Coefficients	*ndard Erro*	*t Stat*	*P-value*	*ower 95%*	*pper 95%*	*ower 95.0%*	*pper 95.0%*
Intercept	-3.305737	0.790981	-4.17929	0.001538	-5.046675	-1.5648	-5.046675	-1.5648
LnTOC	1.171248	0.121405	9.647447	1.06E-06	0.904037	1.438458	0.904037	1.438458
LnpH	1.646974	0.33968	4.848601	0.000512	0.899342	2.394606	0.899342	2.394606
LnTemp	0.349364	0.084909	4.114593	0.001716	0.162482	0.536247	0.162482	0.536247
LnTime	0.312462	0.014939	20.91594	3.3E-10	0.279581	0.345342	0.279581	0.345342

Cl2 Dissipation / DBP Formation Study using Optimum Lime and Coagulant Dose

Run	mg/L Dose	mg/L NPDOC	pH	°C T	min t	mg/L Cl_2 Residual	mg/L Cl_2 Demand	µg/L THM_{total}	µg/L HAA_{total}	LN Dose	LN TOC	LN pH	LN T	LN t	LN THM	LN HAA	LN Cl2Res	LN Dose	LN t	LN Cl2Res	LN Dose	t
1	9	8.1	8.3	30	30	6.7	2.3	128.7	60.7	2.19722458	2.0918641	2.11625551	3.40119738	3.401197382	4.857328702	4.10512	1.902107526	2.197224577	3.401197382	1.902107526	2.197224577	30
2	8	8.1	8.3	20	10	6.4	1.6	80.3	46.6	2.07944154	2.0918641	2.11625551	2.99573227	2.302585093	4.385146762	3.842459	1.85629799	2.079441542	2.302585093	1.85629799	2.079441542	10
3	7.3	6.1	8.3	20	30	5.5	1.8	88.9	39.4	1.98787435	1.8082888	2.11625551	2.99573227	3.401197382	4.486949555	3.67275	1.704748092	1.987874348	3.401197382	1.704748092	1.987874348	30
4	6.8	6.1		30	10	5.6	1.2	61.3	34.9	1.91692261	1.8082888	#NUM!	3.40119738	2.302585093	4.115290327	3.551914	1.722766598	1.916922612	2.302585093	1.722766598	1.916922612	10
5	9	8.1	7.5	30	10	6.9	2.1	80.4	52.9	2.19722458	2.0918641	2.01490302	3.40119738	2.302585093	4.38688979	3.968214	1.931521412	2.197224577	2.302585093	1.931521412	2.197224577	10
6	8	8.1	7.5	20	30	5.4	2.6	102.4	57.8	2.07944154	2.0918641	2.01490302	2.99573227	3.401197382	4.628593701	4.056816	1.686398954	2.079441542	3.401197382	1.686398954	2.079441542	30
7	7.3	6.1	7.5	20	10	5.9	1.4	49.6	34.4	1.98787435	1.8082888	2.01490302	2.99573227	2.302585093	3.903587527	3.538057	1.774952351	1.987874348	2.302585093	1.774952351	1.987874348	10
8	6.8	6.1	7.5	30	30	5.0	1.8	74.7	38.5	1.91692261	1.8082888	2.01490302	3.40119738	3.401197382	4.313346214	3.650918	1.609437912	1.916922612	3.401197382	1.609437912	1.916922612	30
9	9	8.1	8.3	30	240	4.0	5.0	256.7	91.2	2.19722458	2.0918641	2.11625551	3.40119738	5.480638923	5.547985997	4.513384	1.386294361	2.197224577	5.480638923	1.386294361	2.197224577	240
10	8	8.1	8.3	20	60	6.0	2.0	137.3	62.2	2.07944154	2.0918641	2.11625551	2.99573227	4.094344562	4.922095477	4.130676	1.791759469	2.079441542	4.094344562	1.791759469	2.079441542	60
11	7.3	6.1	8.3	20	240	4.2	3.1	160.3	51.5	1.98787435	1.8082888	2.11625551	2.99573227	5.480638923	5.076984675	3.940999	1.435084525	1.987874348	5.480638923	1.435084525	1.987874348	240
12	6.8	6.1	8.3	30	60	4.9	1.9	122.2	42.9	1.91692261	1.8082888	2.11625551	3.40119738	4.094344562	4.805331661	3.758172	1.589235205	1.916922612	4.094344562	1.589235205	1.916922612	60
13	9	8.1	7.5	30	60	5.5	3.5	153.1	72.6	2.19722458	2.0918641	2.01490302	3.40119738	4.094344562	5.031091303	4.285516	1.704748092	2.197224577	4.094344562	1.704748092	2.197224577	60
14	8	8.1	7.5	20	240	3.7	4.3	163.8	84.4	2.07944154	2.0918641	2.01490302	2.99573227	5.480638923	5.098829305	4.435804	1.30833282	2.079441542	5.480638923	1.30833282	2.079441542	240
15	7.3	6.1	7.5	20	60	5.2	2.1	86.5	41.7	1.98787435	1.8082888	2.01490302	2.99573227	4.094344562	4.460606735	3.730501	1.648658626	1.987874348	4.094344562	1.648658626	1.987874348	60
16	6.8	6.1	7.5	30	240	3.6	3.2	154.3	56.4	1.91692261	1.8082888	2.01490302	3.40119738	5.480638923	5.038769133	4.032292	1.280933845	1.916922612	5.480638923	1.280933845	1.916922612	240

$\ln THM = -3.648 + 0.588 \ln Dose + 0.786 \ln TOC + 1.647 \ln pH + 0.315 \ln T + 0.312 \ln t$

$THM = 0.026\,(Dose)^{0.588}(TOC)^{0.786}(pH)^{1.647}(T)^{0.315}(t)^{0.312}$

HAA = intercept, dose, pH are not significant at 95% confidence level

HAA = intercept, pH are not significant at 75% confidence level

Run	mg/L Dose	mg/L NPDOC	pH	°C T	min t	mg/L Cl_2 Residual	mg/L Cl_2 Demand	µg/L THM_{total}	µg/L HAA_{total}
4	6.8	6.1	8.3	30	10	5.6	1.2	61.3	34.9
8	6.8	6.1	7.5	30	30	5.0	1.8	74.7	38.5
12	6.8	6.1	8.3	30	60	4.9	1.9	122.2	42.9
16	6.8	6.1	7.5	30	240	3.6	3.2	154.3	56.4
3	7.3	6.1	8.3	20	30	5.5	1.8	88.9	39.4
7	7.3	6.1	7.5	20	10	5.9	1.4	49.6	34.4
11	7.3	6.1	8.3	20	240	4.2	3.1	160.3	51.5
15	7.3	6.1	7.5	20	60	5.2	2.1	86.5	41.7
2	8	8.1	8.3	20	10	6.4	1.6	80.3	46.6
6	8	8.1	7.5	20	30	5.4	2.6	102.4	57.8
10	8	8.1	8.3	20	60	6.0	2.0	137.3	62.2
14	8	8.1	7.5	20	240	3.7	4.3	163 8	84.4
1	9	8.1	8.3	30	30	6.7	2.3	128.7	60.7
5	9	8.1	7.5	30	10	6.9	2.1	80.4	52.9
9	9	8.1	8.3	30	240	4.0	5.0	256.7	91.2
13	9	8.1	7.5	30	60	5.5	3.5	153.1	72.6

LN Dose	LN pH	LN TOC	LN T	LN t	LN THM	LN HAA	LN Dose	LN TOC	LN T	LN t	LN pH
2.1972246	2.116256	2.09186406	3.401	3.4012	4.8573287	4.105119635	2.197224577	2.0918641	3.4011974	3.40119738	2.1162555
2.0794415	2.116256	2.09186406	2.996	2.3026	4.3851468	3.842458542	2.079441542	2.0918641	2.9957323	2.30258509	2.1162555
1.9878743	2.116256	1.80828877	2.996	3.4012	4.4869496	3.672750072	1.987874348	1.8082888	2.9957323	3.40119738	2.1162555
1.9169226	2.116256	1.80828877	3.401	2.3026	4.1152903	3.551913599	1.916922612	1.8082888	3.4011974	2.30258509	2.1162555
2.1972246	2.014903	2.09186406	3.401	2.3026	4.3868898	3.968214285	2.197224577	2.0918641	3.4011974	2.30258509	2.014903
2.0794415	2.014903	2.09186406	2.996	3.4012	4.6285937	4.05681575	2.079441542	2.0918641	2.9957323	3.40119738	2.014903
1.9878743	2.014903	1.80828877	2.996	2.3026	3.9035875	3.538056564	1.987874348	1.8082888	2.9957323	2.30258509	2.014903
1.9169226	2.014903	1.80828877	3.401	3.4012	4.3133462	3.650917948	1.916922612	1.8082888	3.4011974	3.40119738	2.014903
2.1972246	2.116256	2.09186406	3.401	5.4806	5.547986	4.51338379	2.197224577	2.0918641	3.4011974	5.48063892	2.1162555
2.0794415	2.116256	2.09186406	2.996	4.0943	4.9220955	4.130676491	2.079441542	2.0918641	2.9957323	4.09434456	2.1162555
1.9878743	2.116256	1.80828877	2.996	5.4806	5.0769847	3.940999114	1.987874348	1.8082888	2.9957323	5.48063892	2.1162555
1.9169226	2.116256	1.80828877	3.401	4.0943	4.8053317	3.758172281	1.916922612	1.8082888	3.4011974	4.09434456	2.1162555
2.1972246	2.014903	2.09186406	3.401	4.0943	5.0310913	4.285515734	2.197224577	2.0918641	3.4011974	4.09434456	2.014903
2.0794415	2.014903	2.09186406	2.996	5.4806	5.0988293	4.43580434	2.079441542	2.0918641	2.9957323	5.48063892	2.014903
1.9878743	2.014903	1.80828877	2.996	4.0943	4.4606067	3.730501129	1.987874348	1.8082888	2.9957323	4.09434456	2.014903
1.9169226	2.014903	1.80828877	3.401	5.4806	5.0387691	4.032291838	1.916922612	1.8082888	3.4011974	5.48063892	2.014903

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.990061249
R Square	0.980221278
Adjusted R S	0.90025532
Standard Err	0.045022337
Observations	16

ANOVA

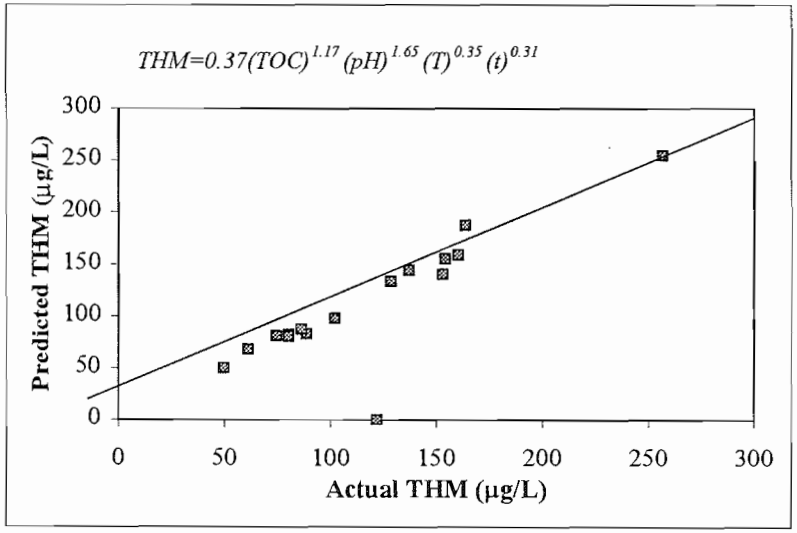
	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1.305946265	0.435315	214.7573262	1.08745E-10
Residual	13	0.026351141	0.002027		
Total	16	1.332297405			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
LnCl2Dose	1.494961792	0.060440825	24.7343	2.56423E-12	1.364387354	1.62553623	1.364387354	1.62553623
LnTemp	0.134451465	0.037116717	3.622397	0.00309639	0.054265689	0.21463724	0.054265689	0.21463724
Lntime	0.15861063	0.009648171	16.43945	4.43523E-10	0.137767028	0.179454233	0.137767028	0.179454233

Comparison of the THM Model to the Actual THM Data

					Maria Model		Selected Model
					ACTUAL	PREDICTED	Predicted
mg/L	mg/L		°C	min	µg/L	µg/L	
Dose	NPDOC	pH	T	t	THM_{total}	THM_{total}	
6.8	6.1	8.3	30	10	61.3	65.0	68.0
6.8	6.1	7.5	30	30	74.7	77.5	81.0
6.8	6.1	8.3		60	122.2	0.0	0.0
6.8	6.1	7.5	30	240	154.3	148.2	155.1
7.3	6.1	8.3	20	30	88.9	84.0	83.1
7.3	6.1	7.5	20	10	49.6	50.5	49.9
7.3	6.1	8.3	20	240	160.3	160.7	159.0
7.3	6.1	7.5	20	60	86.5	88.2	87.3
8	8.1	8.3	20	10	80.3	78.6	82.2
8	8.1	7.5	20	30	102.4	93.8	98.0
8	8.1	8.3	20	60	137.3	137.5	143.8
8	8.1	7.5	20	240	163.8	179.4	187.5
9	8.1	8.3	30	30	128.7	134.9	133.5
9	8.1	7.5	30	10	80.4	81.0	80.2
9	8.1	8.3	30	240	256.7	258.1	255.4
9	8.1	7.5	30	60	153.1	141.7	140.2

$$THM = 0.026\,(Dose)^{0.588}(TOC)^{0.786}(pH)^{1.647}(T)^{0.315}(t)^{0.312}$$



Intercept	-3.30574	0.036672
LnTOC	1.171248	
LnpH	1.646974	
LnTemp	0.349364	
LnTime	0.312462	

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.992756334
R Square	0.985565139
Adjusted R Square	0.978347708
Standard Error	0.063110014
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	2.719376044	0.543875209	136.553	7.21931E-09
Residual	10	0.039828739	0.003982874		
Total	15	2.759204783			

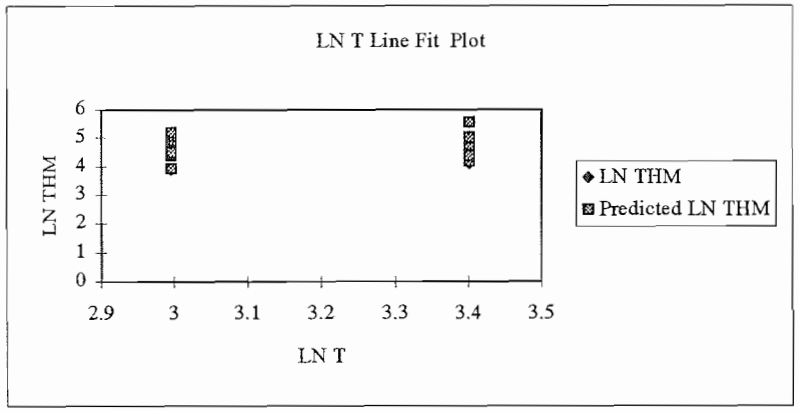
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-3.648060652	0.750654055	-4.8598427	0.00066157	-5.320622405	-1.975498899
LN Dose	0.588155668	0.334384669	1.75891936	0.10909446	-0.156899932	1.333211269
LN TOC	0.785605912	0.24587089	3.19519693	0.00956937	0.237771334	1.333440489
LN pH	1.646974079	0.311339225	5.28996653	0.00035257	0.953266935	2.340681223
LN T	0.315397982	0.080184254	3.93341541	0.00280465	0.136736298	0.494059666
LN t	0.312461736	0.013692508	22.8199055	5.8897E-10	0.281952922	0.34297055

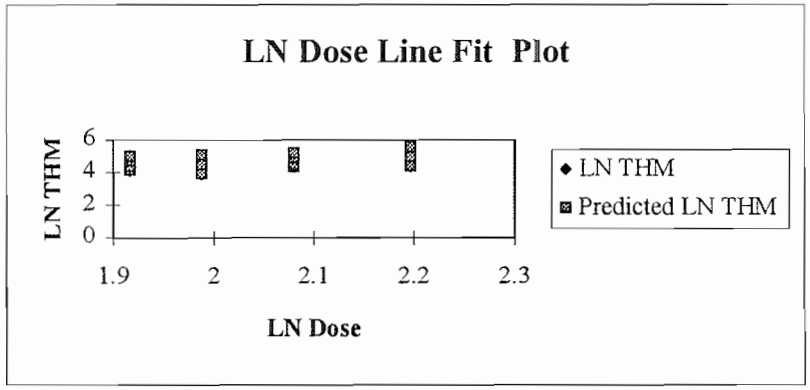
RESIDUAL OUTPUT

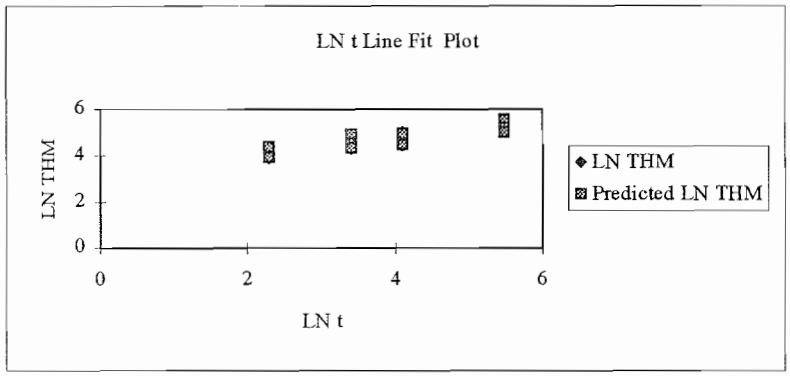
Observation	*Predicted LN THM*	*Residuals*
1	4.908523018	-0.051194315
2	4.368091078	0.017055684
3	4.434731192	0.052218362
4	4.1776091	-0.062318774
5	4.398323784	-0.011433993
6	4.54444045	0.084153251
7	3.924531958	-0.020944432
8	4.353958473	-0.040612258
9	5.558268932	-0.010282936
10	4.927947352	-0.005851876
11	5.084477107	-0.007492432
12	4.737465375	0.067866286
13	4.958180058	0.072911244
14	5.194186365	-0.09535706
15	4.484388233	-0.023781498
16	5.003704387	0.035064746

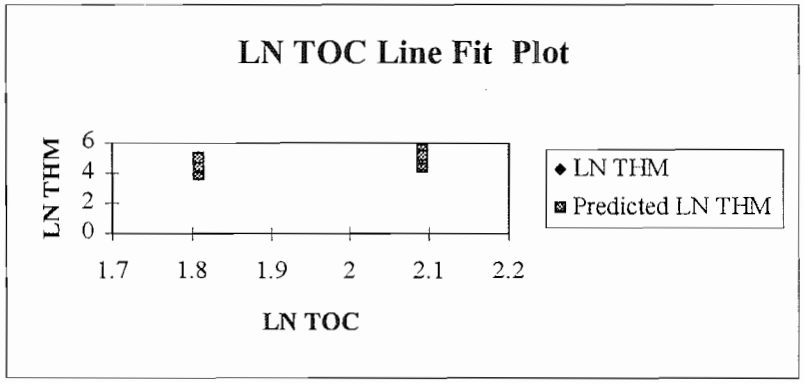
PROBABILITY OUTPUT

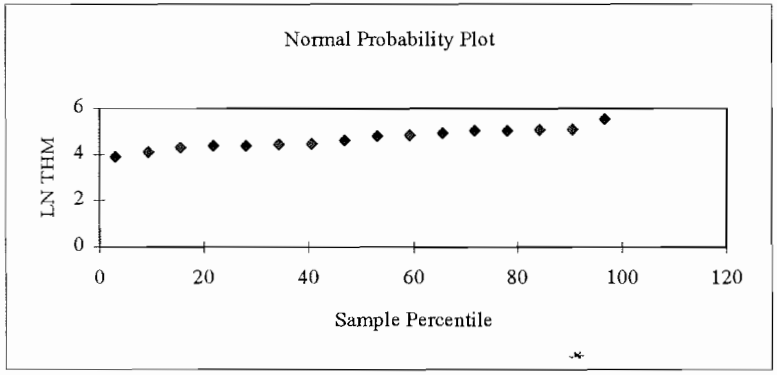
Percentile	*LN THM*
3.125	3.903587527
9.375	4.115290327
15.625	4.313346214
21.875	4.385146762
28.125	4.38688979
34.375	4.460606735
40.625	4.486949555
46.875	4.628593701
53.125	4.805331661
59.375	4.857328702
65.625	4.922095477
71.875	5.031091303
78.125	5.038769133
84.375	5.076984675
90.625	5.098829305
96.875	5.547985997

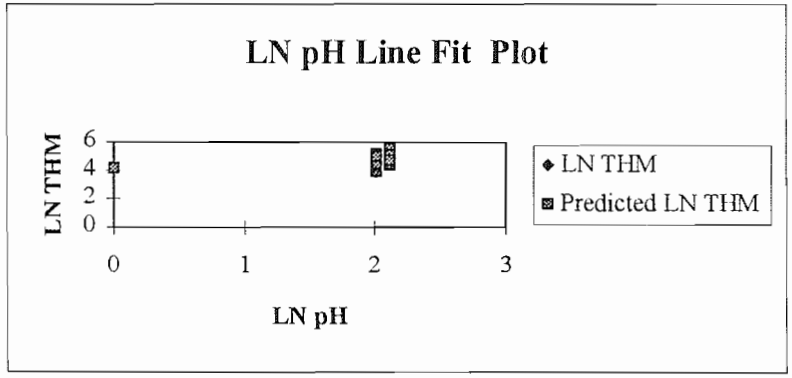

LN T Line Fit Plot
LN THM
6
5
4
3
2
1
0
2.9
3
3.1
3.2
3.3
3.4
3.5
LN T
LN THM
Predicted LN THM


LN Dose Line Fit Plot
LN THM
6
4
2
0
1.9
2
2.1
2.2
2.3
LN Dose
LN THM
Predicted LN THM


LN t Line Fit Plot
LN THM
6
4
2
0
0
2
4
6
LN t
LN THM
Predicted LN THM


LN TOC Line Fit Plot
LN THM
6
4
2
0
1.7
1.8
1.9
2
2.1
2.2
LN TOC
LN THM
Predicted LN THM


Normal Probability Plot
LN THM
6
4
2
0
0
20
40
60
80
100
120
Sample Percentile


LN pH Line Fit Plot
LN THM
6
4
2
0
0
1
2
3
LN pH
LN THM
Predicted LN THM

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.993198607
R Square	0.986443473
Adjusted R Square	0.979665209
Standard Error	0.042498619
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	1.314236079	0.262847216	145.53	5.28028E-09
Residual	10	0.018061326	0.001806133		
Total	15	1.332297405			

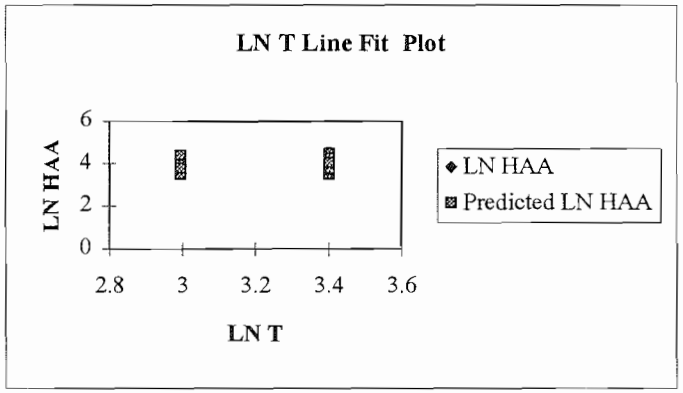
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.092450168	0.505494433	0.1828906	0.8585386	-1.033861812	1.218762149
LN Dose	0.391408446	0.225176414	1.7382302	0.1128066	-0.110315958	0.89313285
LN TOC	1.269581309	0.165570765	7.6679075	1.704E-05	0.90066659	1.638496027
LN pH	-0.225258472	0.20965749	-1.074412	0.3078785	-0.692404552	0.241887608
LN T	0.136924989	0.053996503	2.5358121	0.0295747	0.016613261	0.257236717
LN t	0.159537686	0.009220608	17.302296	8.803E-09	0.138992888	0.180082483

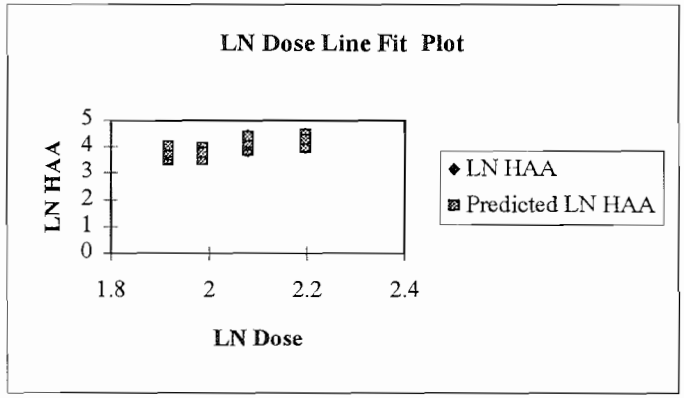
RESIDUAL OUTPUT

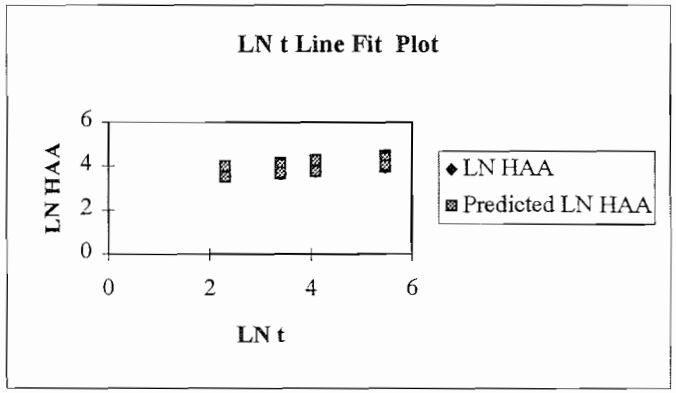
Observation	*Predicted LN HAA*	*Residuals*
1	4.139877526	-0.03475789
2	3.862987883	-0.020529341
3	3.642395884	0.030354188
4	3.494873019	0.05704058
5	3.987437972	-0.019223687
6	4.061088453	-0.004272703
7	3.48995633	0.048100234
8	3.692973589	-0.042055641
9	4.471626817	0.041756973
10	4.148841043	-0.018164551
11	3.974145175	-0.033146062
12	3.780726178	-0.022553897
13	4.273291131	0.012224603
14	4.392837745	0.042966596
15	3.775809489	-0.04530836
16	4.02472288	0.007568958

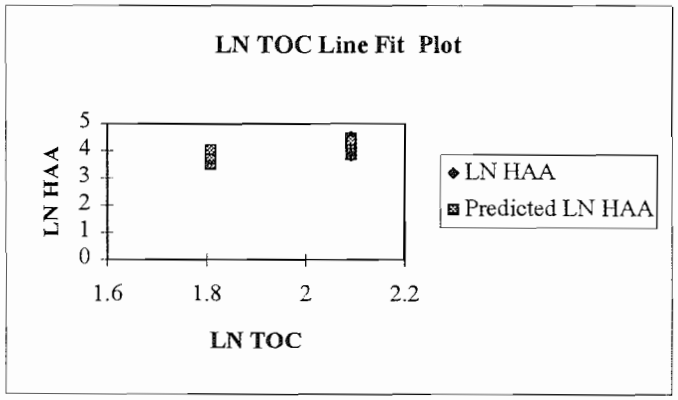
PROBABILITY OUTPUT

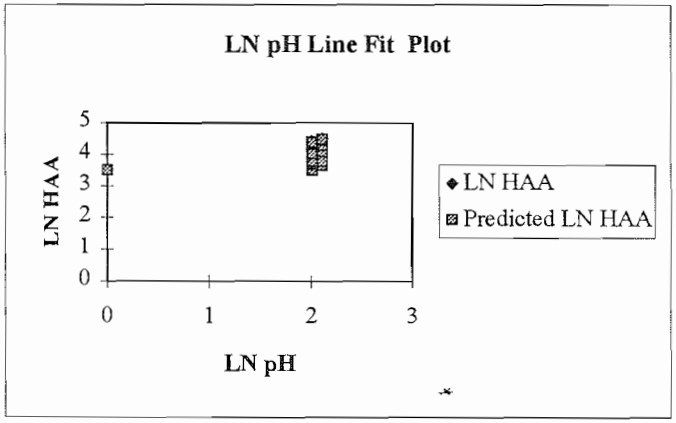
Percentile	*LN HAA*
3.125	3.538056564
9.375	3.551913599
15.625	3.650917948
21.875	3.672750072
28.125	3.730501129
34.375	3.758172281
40.625	3.842458542
46.875	3.940999114
53.125	3.968214285
59.375	4.032291838
65.625	4.05681575
71.875	4.105119635
78.125	4.130676491
84.375	4.285515734
90.625	4.43580434
96.875	4.51338379

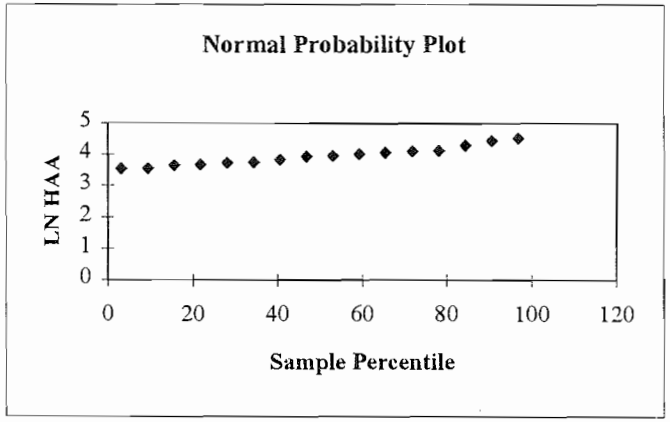

LN T Line Fit Plot
LN HAA
6
4
2
0
2.8
3
3.2
3.4
3.6
LN T
LN HAA
Predicted LN HAA


LN Dose Line Fit Plot
LN HAA
5
4
3
2
1
0
1.8
2
2.2
2.4
LN Dose
LN HAA
Predicted LN HAA


LN t Line Fit Plot
LN HAA
6
4
2
0
0
2
4
6
LN t
LN HAA
Predicted LN HAA


LN TOC Line Fit Plot
LN HAA
5
4
3
2
1
0
1.6
1.8
2
2.2
LN TOC
LN HAA
Predicted LN HAA


LN pH Line Fit Plot
LN HAA
5
4
3
2
1
0
0
1
2
3
LN pH
LN HAA
Predicted LN HAA


Normal Probability Plot
LN HAA
5
4
3
2
1
0
0
20
40
60
80
100
120
Sample Percentile

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.993198607
R Square	0.986443473
Adjusted R Square	0.979665209
Standard Error	0.042498619
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	1.314236079	0.262847216	145.5304066	5.28028E-09
Residual	10	0.018061326	0.001806133		
Total	15	1.332297405			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 75.0%*	*Upper 75.0%*
Intercept	0.092450168	0.505494433	0.18289058	0.85853863	-1.033861812	1.218762149	-0.524887862	0.709788198
LN Dose	0.391408446	0.225176414	1.73823021	0.112806594	-0.110315958	0.89313285	0.116410434	0.666406458
LN TOC	1.269581309	0.165570765	7.66790749	1.70366E-05	0.90066659	1.638496027	1.067377044	1.471785573
LN pH	-0.225258472	0.20965749	-1.07441176	0.307878533	-0.692404552	0.241887608	-0.481303907	0.030786963
LN T	0.136924989	0.053996503	2.53581213	0.029574742	0.016613261	0.257236717	0.070981443	0.202868534
LN t	0.159537686	0.009220608	17.3022963	8.80332E-09	0.138992888	0.180082483	0.148276965	0.170798407

RESIDUAL OUTPUT

Observation	*Predicted LN HAA*	*Residuals*
1	4.139877526	-0.03475789
2	3.862987883	-0.020529341
3	3.642395884	0.030354188
4	3.494873019	0.05704058
5	3.987437972	-0.019223687
6	4.061088453	-0.004272703
7	3.48995633	0.048100234
8	3.692973589	-0.042055641
9	4.471626817	0.041756973
10	4.148841043	-0.018164551
11	3.974145175	-0.033146062
12	3.780726178	-0.022553897
13	4.273291131	0.012224603
14	4.392837745	0.042966596
15	3.775809489	-0.04530836
16	4.02472288	0.007568958

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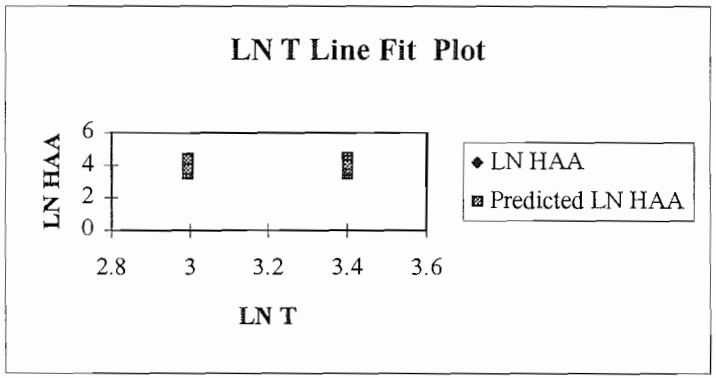
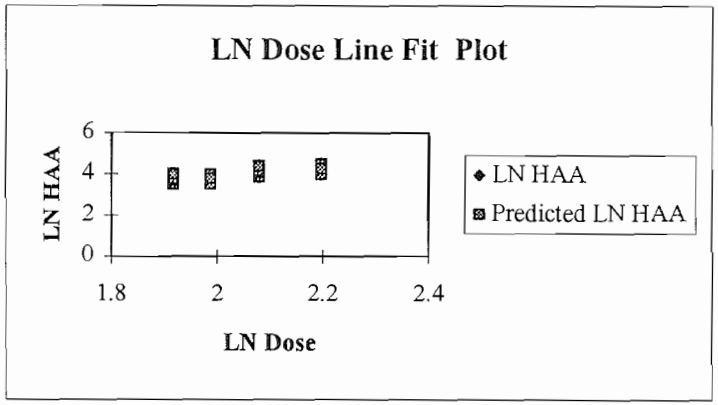
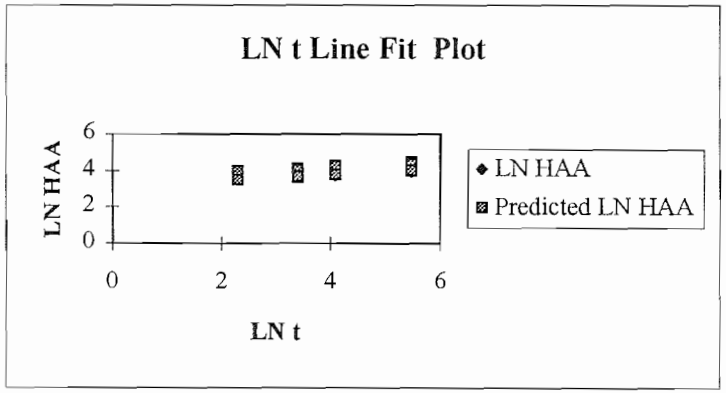
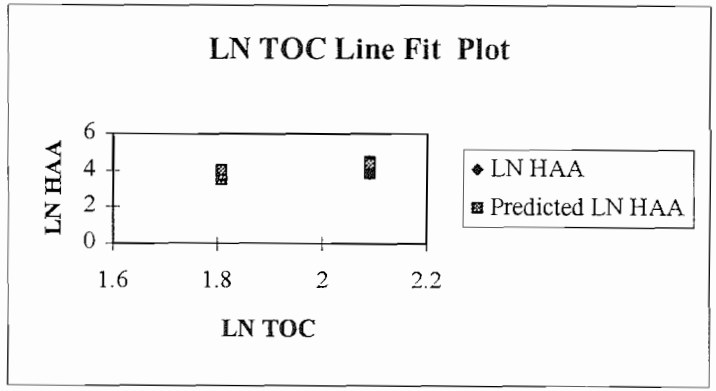
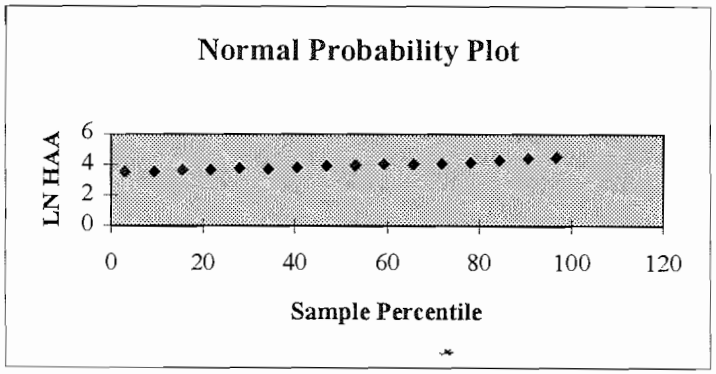
Percentile	*LN HAA*
3.125	3.538056564
9.375	3.551913599
15.625	3.650917948
21.875	3.672750072
28.125	3.730501129
34.375	3.758172281
40.625	3.842458542
46.875	3.940999114
53.125	3.968214285
59.375	4.032291838
65.625	4.05681575
71.875	4.105119635
78.125	4.130676491
84.375	4.285515734
90.625	4.43580434
96.875	4.51338379

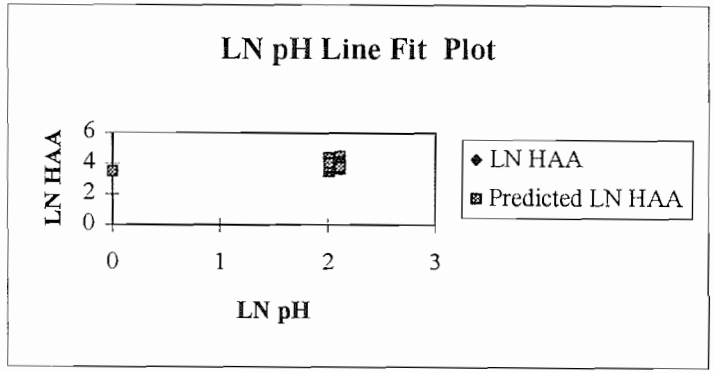

LN T Line Fit Plot
LN HAA
6
4
2
0
2.8
3
3.2
3.4
3.6
LN T
LN HAA
Predicted LN HAA


LN Dose Line Fit Plot
LN HAA
6
4
2
0
1.8
2
2.2
2.4
LN Dose
LN HAA
Predicted LN HAA


LN t Line Fit Plot
LN HAA
6
4
2
0
0
2
4
6
LN t
LN HAA
Predicted LN HAA


LN TOC Line Fit Plot
LN HAA
6
4
2
0
1.6
1.8
2
2.2
LN TOC
LN HAA
Predicted LN HAA


Normal Probability Plot
LN HAA
6
4
2
0
0
20
40
60
80
100
120
Sample Percentile


LN pH Line Fit Plot
LN HAA
6
4
2
0
0
1
2
3
LN pH
LN HAA
Predicted LN HAA

Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatment Optimization: THM&HAA

THM Results for the Sample Matrix using Optimum Softening & Coagulation Conditions

Dose	NPDOC	pH	T	t	$CHCl_3$	$BrCl_2CH$	Br_2ClCH	Br_3CH	THM_{total}
mg/L	mg/L		°C	min	µg/L	µg/L	µg/L	µg/L	µg/L
9	8.1	8.3	30	30	61.9	40.5	24.2	2.1	128.7
8	8.1	8.3	20	10	41.3	22.0	14.1	2.8	80.3
7.3	6.1	8.3	20	30	34.6	25.9	23.0	5.3	88.9
6.8	6.1	8.3	30	10	28.9	16.8	14.5	1.0	61.3
9	8.1	7.5	30	10	42.9	22.2	12.5	2.8	80.4
8	8.1	7.5	20	30	49.8	31.3	17.8	3.5	102.4
7.3	6.1	7.5	20	10	22.9	13.6	11.1	2.0	49.6
6.8	6.1	7.5	30	30	28.4	23.3	19.8	3.3	74.7
9	8.1	8.3	30	240	125.2	82.4	42.8	6.3	256.7
8	8.1	8.3	20	60	63.3	44.4	25.8	3.9	137.3
7.3	6.1	8.3	20	240	58.3	48.3	39.7	14.1	160.3
6.8	6.1	8.3	30	60	43.0	37.6	32.5	9.1	122.2
9	8.1	7.5	30	60	72.3	51.2	26.2	3.4	153.1
8	8.1	7.5	20	240	75.8	55.7	27.6	4.8	163.8
7.3	6.1	7.5	20	60	31.4	28.0	23.0	4.1	86.5
6.8	6.1	7.5	30	240	55.6	55.3	39.2	4.2	154.3

HAA Results for the Sample Matrix using Optimum Softening & Coagulation Conditions

MCAA	MBAA	DCAA	TCAA	BCAA	DBAA	HAA_{total}	LnDose	LnNPDOC	LnpH	LnT	Lnt	LnTTHM	THMs Dose Out
µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L							
0.7	5.9	18.9	15.1	11.7	8.4	60.7	2.2	2.1	2.1	3.4	3.4	4.9	
0.8	6.6	16.3	10.0	9.1	3.8	46.6	2.1	2.1	2.1	3.0	2.3	4.4	
0.8	7.4	10.9	6.7	8.0	5.5	39.4	2.0	1.8	2.1	3.0	3.4	4.5	
0.8	8.1	9.7	5.3	6.6	4.4	34.9	1.9	1.8	2.1	3.4	2.3	4.1	
1.7	6.2	16.2	13.4	9.9	5.4	52.9	2.2	2.1	2.0	3.4	2.3	4.4	
0.9	6.6	17.7	17.8	10.9	3.9	57.8	2.1	2.1	2.0	3.0	3.4	4.6	
1.0	7.1	8.5	6.8	7.0	4.1	34.4	2.0	1.8	2.0	3.0	2.3	3.9	
0.8	6.6	9.4	9.1	8.1	4.4	38.5	1.9	1.8	2.0	3.4	3.4	4.3	
0.8	4.0	30.1	30.5	18.5	7.3	91.2	2.2	2.1	2.1	3.4	5.5	5.5	
0.8	5.8	19.6	17.7	13.0	5.3	62.2	2.1	2.1	2.1	3.0	4.1	4.9	
0.8	5.7	14.4	11.1	11.9	7.6	51.5	2.0	1.8	2.1	3.0	5.5	5.1	
1.4	6.4	11.5	7.9	9.4	6.2	42.9	1.9	1.8	2.1	3.4	4.1	4.8	
0.7	5.7	20.7	27.0	13.4	5.0	72.6	2.2	2.1	2.0	3.4	4.1	5.0	
2.2	5.2	22.5	34.2	15.4	5.0	84.4	2.1	2.1	2.0	3.0	5.5	5.1	
1.0	6.6	9.7	11.0	8.9	4.6	41.7	2.0	1.8	2.0	3.0	4.1	4.5	
0.7	4.9	13.8	17.9	13.0	6.2	56.4	1.9	1.8	2.0	3.4	5.5	5.0	

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.990506284
R Square	0.981102699
Adjusted R Square	0.974230954
Standard Error	0.068851581
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	2.707292715	0.676823179	142.7734291	2.11891E-09
Residual	11	0.052145942	0.00474054		
Total	15	2.759438657			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-3.306727335	0.790942622	-4.180742372	0.001534629	-5.047581189	-1.56587348	-5.047581189	-1.56587348
X Variable 1	1.171327268	0.121399119	9.648564812	1.05576E-06	0.904129473	1.438525062	0.904129473	1.438525062
X Variable 2	1.6474628	0.339663969	4.850272482	0.000510539	0.899867068	2.395058533	0.899867068	2.395058533
X Variable 3	0.34928666	0.084904446	4.113879489	0.00171844	0.162413139	0.53616018	0.162413139	0.53616018
X Variable 4	0.312472907	0.014938213	20.91769027	3.30098E-10	0.279594105	0.345351708	0.279594105	0.345351708

Cl2 Dissipation / DBP Formation Study using Optimum Lime and Coagulant Dose

Run	mg/L Dose	mg/L NPDOC	pH	°C T	min t	mg/L Cl_2 Residual	mg/L Cl_2 Demand	µg/L THM_{total}	µg/L HAA_{total}	LN Dose	LN TOC	LN pH	LN T	LN t	LN HAA	LN Dose	LN TOC	LN T	LN t	LN HAA
1	9	8.1	8.3	30	30	6.7	2.3	128.7	60.7	2.197225	2.091864	2.116256	3.401197	3.401197	4.10512	2.197225	2.091864	3.401197	3.401197	4.10512
2	8	8.1	8.3	20	10	6.4	1.6	80.3	46.6	2.079442	2.091864	2.116256	2.995732	2.302585	3.842459	2.079442	2.091864	2.995732	2.302585	3.842459
3	7.3	6.1	8.3	20	30	5.5	1.8	88.9	39.4	1.987874	1.808289	2.116256	2.995732	3.401197	3.67275	1.987874	1.808289	2.995732	3.401197	3.67275
4	6.8	6.1	8.3	30	10	5.6	1.2	61.3	34.9	1.916923	1.808289	2.116256	3.401197	2.302585	3.551914	1.916923	1.808289	3.401197	2.302585	3.551914
5	9	8.1	7.5	30	10	6.9	2.1	80.4	52.9	2.197225	2.091864	2.014903	3.401197	2.302585	3.968214	2.197225	2.091864	3.401197	2.302585	3.968214
6	8	8.1	7.5	20	30	5.4	2.6	102.4	57.8	2.079442	2.091864	2.014903	2.995732	3.401197	4.056816	2.079442	2.091864	2.995732	3.401197	4.056816
7	7.3	6.1	7.5	20	10	5.9	1.4	49.6	34.4	1.987874	1.808289	2.014903	2.995732	2.302585	3.538057	1.987874	1.808289	2.995732	2.302585	3.538057
8	6.8	6.1	7.5	30	30	5.0	1.8	74.7	38.5	1.916923	1.808289	2.014903	3.401197	3.401197	3.650918	1.916923	1.808289	3.401197	3.401197	3.650918
9	9	8.1	8.3	30	240	4.0	5.0	256.7	91.2	2.197225	2.091864	2.116256	3.401197	5.480639	4.513384	2.197225	2.091864	3.401197	5.480639	4.513384
10	8	8.1	8.3	20	60	6.0	2.0	137.3	62.2	2.079442	2.091864	2.116256	2.995732	4.094345	4.130676	2.079442	2.091864	2.995732	4.094345	4.130676
11	7.3	6.1	8.3	20	240	4.2	3.1	160.3	51.5	1.987874	1.808289	2.116256	2.995732	5.480639	3.940999	1.987874	1.808289	2.995732	5.480639	3.940999
12	6.8	6.1	8.3	30	60	4.9	1.9	122.2	42.9	1.916923	1.808289	2.116256	3.401197	4.094345	3.758172	1.916923	1.808289	3.401197	4.094345	3.758172
13	9	8.1	7.5	30	60	5.5	3.5	153.1	72.6	2.197225	2.091864	2.014903	3.401197	4.094345	4.285516	2.197225	2.091864	3.401197	4.094345	4.285516
14	8	8.1	7.5	20	240	3.7	4.3	163.8	84.4	2.079442	2.091864	2.014903	2.995732	5.480639	4.435804	2.079442	2.091864	2.995732	5.480639	4.435804
15	7.3	6.1	7.5	20	60	5.2	2.1	86.5	41.7	1.987874	1.808289	2.014903	2.995732	4.094345	3.730501	1.987874	1.808289	2.995732	4.094345	3.730501
16	6.8	6.1	7.5	30	240	3.6	3.2	154.3	56.4	1.916923	1.808289	2.014903	3.401197	5.480639	4.032292	1.916923	1.808289	3.401197	5.480639	4.032292

$\ln THM = -3.648 + 0.588 \ln Dose + 0.786 \ln TOC + 1.647 \ln pH + 0.315 \ln T + 0.312 \ln t$

$THM = 0.026\,(Dose)^{0.588}(TOC)^{0.786}(pH)^{1.647}(T)^{0.315}(t)^{0.312}$

HAA = intercept, dose, pH are not significant at 95% confidence level

HAA = intercept, pH are not significant at 75% confidence level

HAA = model with no pH at 75% confidence level, variables were significant

$\ln HAA = -0.373 + 0.391 \ln Dose + 1.270 \ln TOC + 0.137 \ln T + 0.160 \ln t$

$HAA = 0.689\,(Dose)^{0.391}(TOC)^{1.270}(T)^{0.137}(t)^{0.160}$

Run	mg/L Dose	mg/L NPDOC	pH	°C T	min t	mg/L Cl_2 Residual	mg/L Cl_2 Demand	µg/L THM_{total}	µg/L HAA_{total}
4	6.8	6.1	8.3	30	10	5.6	1.2	61.3	34.9
8	6.8	6.1	7.5	30	30	5.0	1.8	74.7	38.5
12	6.8	6.1	8.3	30	60	4.9	1.9	122.2	42.9
16	6.8	6.1	7.5	30	240	3.6	3.2	154.3	56.4
3	7.3	6.1	8.3	20	30	5.5	1.8	88.9	39.4
7	7.3	6.1	7.5	20	10	5.9	1.4	49.6	34.4
11	7.3	6.1	8.3	20	240	4.2	3.1	160.3	51.5
15	7.3	6.1	7.5	20	60	5.2	2.1	86.5	41.7
2	8	8.1	8.3	20	10	6.4	1.6	80.3	46.6
6	8	8.1	7.5	20	30	5.4	2.6	102.4	57.8
10	8	8.1	8.3	20	60	6.0	2.0	137.3	62.2
14	8	8.1	7.5	20	240	3.7	4.3	163.8	84.4
1	9	8.1	8.3	30	30	6.7	2.3	128.7	60.7
5	9	8.1	7.5	30	10	6.9	2.1	80.4	52.9
9	9	8.1	8.3	30	240	4.0	5.0	256.7	91.2
13	9	8.1	7.5	30	60	5.5	3.5	153.1	72.6

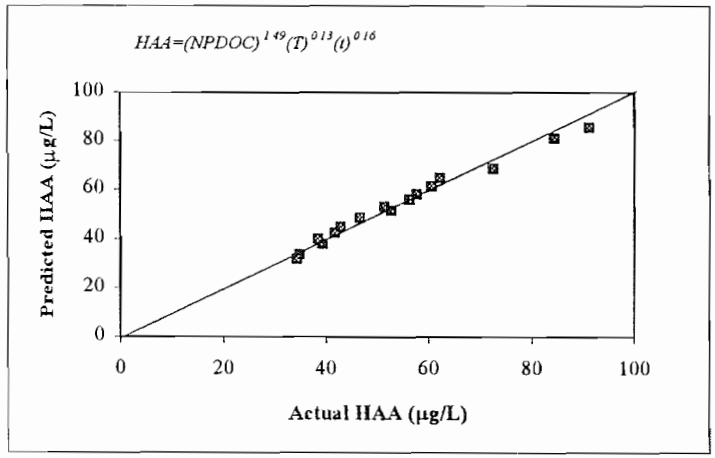
Comparison of the HAA Model to the Actual HAA Data

mg/L Dose	mg/L NPDOC	pH	°C T	min t	ACTUAL µg/L HAA_{total}	PREDICTED µg/L HAA_{total}	Predicted JST
9	8.1	8.3	30	30	60.7	63.7	61.4
8	8.1	8.3	20	10	46.6	48.2	48.8
7.3	6.1	8.3	20	30	39.4	38.7	38.1
6.8	6.1	8.3	30	10	34.9	33.4	33.7
9	8.1	7.5	30	10	52.9	53.4	51.5
8	8.1	7.5	20	30	57.8	57.5	58.1
7.3	6.1	7.5	20	10	34.4	32.5	32.0
6.8	6.1	7.5	30	30	38.5	39.8	40.2
9	8.1	8.3	30	240	91.2	88.8	85.6
8	8.1	8.3	20	60	62.2	64.2	64.9
7.3	6.1	8.3	20	240	51.5	54.0	53.1
6.8	6.1	8.3	30	60	42.9	44.5	44.9
9	8.1	7.5	30	60	72.6	71.1	68.6
8	8.1	7.5	20	240	84.4	80.2	81.1
7.3	6.1	7.5	20	60	41.7	43.2	42.6
6.8	6.1	7.5	30	240	56.4	55.5	56.1

Intercept	0
LnCl2Dose	1.494961792
LnTemp	0.134451465
Lntime	0.15861063

lnHAA	lnDose	LnTemp	LnTime	lnNPDOC
4.105119635	2.197224577	3.401197382	3.401197382	2.091864062
3.842458542	2.079441542	2.995732274	2.302585093	2.091864062
3.672750072	1.987874348	2.995732274	3.401197382	1.808288771
3.551913599	1.916922612	3.401197382	2.302585093	1.808288771
3.968214285	2.197224577	3.401197382	2.302585093	2.091864062
4.05681575	2.079441542	2.995732274	3.401197382	2.091864062
3.538056564	1.987874348	2.995732274	2.302585093	1.808288771
3.650917948	1.916922612	3.401197382	3.401197382	1.808288771
4.51338379	2.197224577	3.401197382	5.480638923	2.091864062
4.130676491	2.079441542	2.995732274	4.094344562	2.091864062
3.940999114	1.987874348	2.995732274	5.480638923	1.808288771
3.758172281	1.916922612	3.401197382	4.094344562	1.808288771
4.285515734	2.197224577	3.401197382	4.094344562	2.091864062
4.43580434	2.079441542	2.995732274	5.480638923	2.091864062
3.730501129	1.987874348	2.995732274	4.094344562	1.808288771
4.032291838	1.916922612	3.401197382	5.480638923	1.808288771

$$HAA = 0.689\ (Dose)^{0.391}(TOC)^{1.270}(T)^{0.137}(t)^{0.160}$$



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.990061249
R Square	0.980221278
Adjusted R Squar	0.90025532
Standard Error	0.045022337
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1.305946265	0.435315422	214.7573262	1.08745E-10
Residual	13	0.026351141	0.002027011		
Total	16	1.332297405			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
LnTemp	0.134451465	0.037116717	3.622396516	0.00309639	0.054265689	0.21463724	0.054265689	0.21463724
LnTime	0.15861063	0.009648171	16.43945019	4.43523E-10	0.137767028	0.179454233	0.137767028	0.179454233
LnNPDOC	1.494961792	0.060440825	24.73430498	2.56423E-12	1.364387354	1.62553623	1.364387354	1.62553623

SUMMARY OUTPUT - Model as is at 95% confidence level

Regression Statistics	
Multiple R	0.993198607
R Square	0.986443473
Adjusted R Square	0.979665209
Standard Error	0.042498619
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	1.314236079	0.262847216	145.5304066	5.28028E-09
Residual	10	0.018061326	0.001806133		
Total	15	1.332297405			

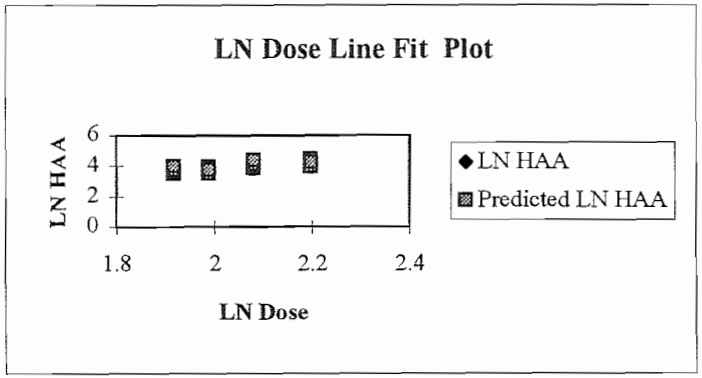
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.092450168	0.505494433	0.182890577	0.85853863	-1.033861812	1.218762149
LN Dose	0.391408446	0.225176414	1.73823021	0.112806594	-0.110315958	0.89313285
LN TOC	1.269581309	0.165570765	7.667907488	1.70366E-05	0.90066659	1.638496027
LN pH	-0.225258472	0.20965749	-1.07441176	0.307878533	-0.692404552	0.241887608
LN T	0.136924989	0.053996503	2.535812132	0.029574742	0.016613261	0.257236717
LN t	0.159537686	0.009220608	17.30229634	8.80332E-09	0.138992888	0.180082483

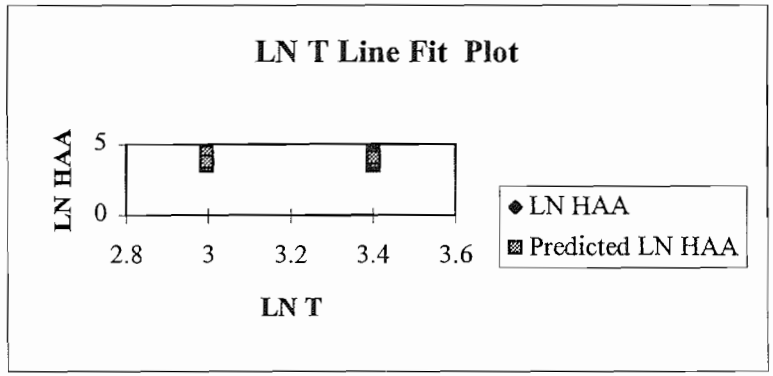
RESIDUAL OUTPUT

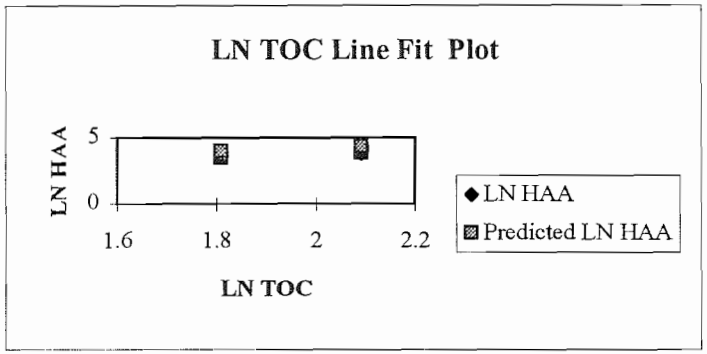
Observation	*Predicted LN HAA*	*Residuals*
1	4.139877526	-0.03475789
2	3.862987883	-0.020529341
3	3.642395884	0.030354188
4	3.494873019	0.05704058
5	3.987437972	-0.019223687
6	4.061088453	-0.004272703
7	3.48995633	0.048100234
8	3.692973589	-0.042055641
9	4.471626817	0.041756973
10	4.148841043	-0.018164551
11	3.974145175	-0.033146062
12	3.780726178	-0.022553897
13	4.273291131	0.012224603
14	4.392837745	0.042966596
15	3.775809489	-0.04530836
16	4.02472288	0.007568958

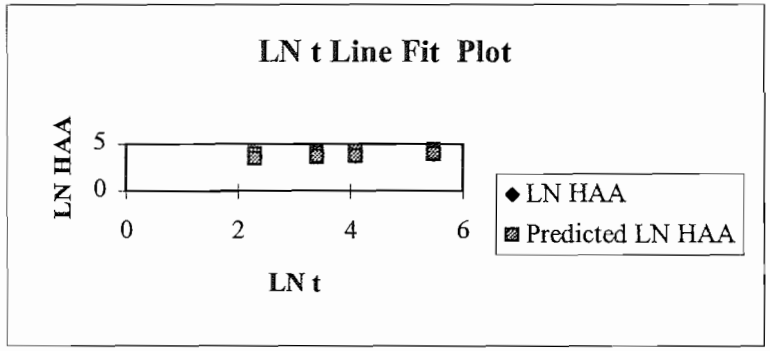
PROBABILITY OUTPUT

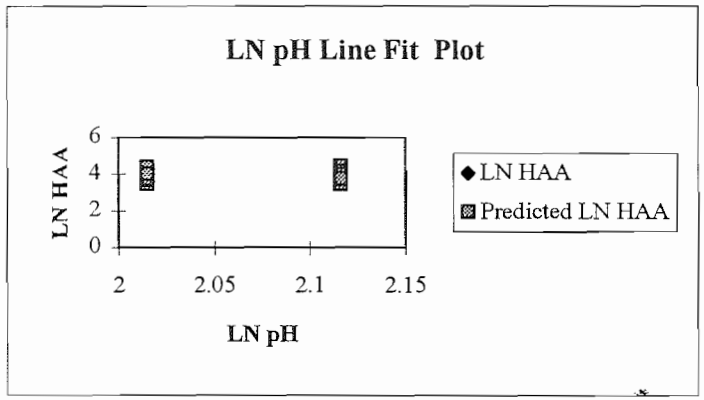
Percentile	*LN HAA*
3.125	3.538056564
9.375	3.551913599
15.625	3.650917948
21.875	3.672750072
28.125	3.730501129
34.375	3.758172281
40.625	3.842458542
46.875	3.940999114
53.125	3.968214285
59.375	4.032291838
65.625	4.05681575
71.875	4.105119635
78.125	4.130676491
84.375	4.285515734
90.625	4.43580434
96.875	4.51338379

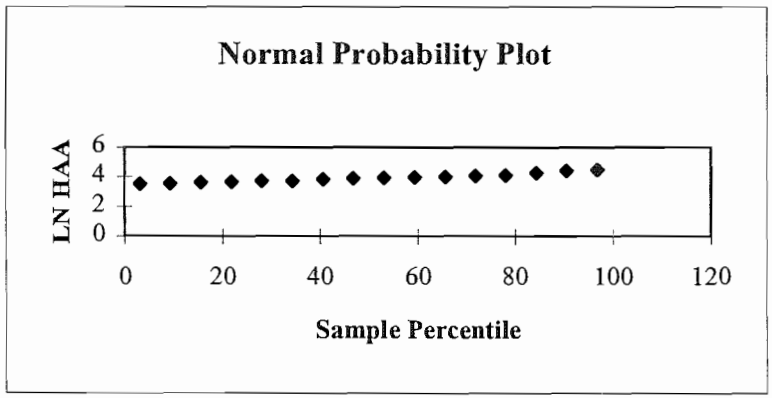

LN Dose Line Fit Plot
LN HAA
6
4
2
0
1.8
2
2.2
2.4
LN Dose
LN HAA
Predicted LN HAA


LN T Line Fit Plot
LN HAA
5
0
2.8
3
3.2
3.4
3.6
LN T
LN HAA
Predicted LN HAA


LN TOC Line Fit Plot
LN HAA
5
0
1.6
1.8
2
2.2
LN TOC
LN HAA
Predicted LN HAA


LN t Line Fit Plot
LN HAA
5
0
0
2
4
6
LN t
LN HAA
Predicted LN HAA


LN pH Line Fit Plot
LN HAA
6
4
2
0
2
2.05
2.1
2.15
LN pH
LN HAA
Predicted LN HAA


Normal Probability Plot
LN HAA
6
4
2
0
0
20
40
60
80
100
120
Sample Percentile

SUMMARY OUTPUT - Model as is at 75% confidence level

Regression Statistics	
Multiple R	0.993198607
R Square	0.986443473
Adjusted R Square	0.979665209
Standard Error	0.042498619
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	1.314236079	0.262847216	145.5304066	5.28028E-09
Residual	10	0.018061326	0.001806133		
Total	15	1.332297405			

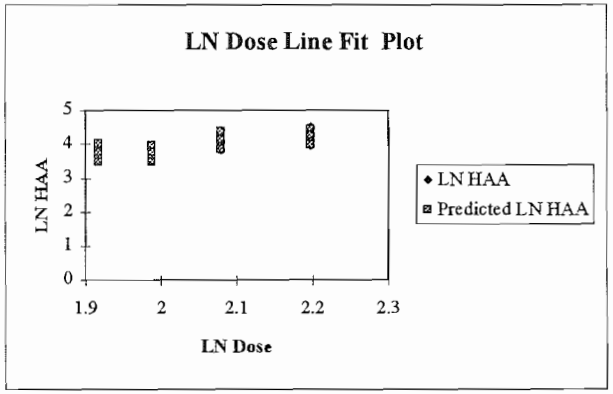
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 75.0%*	*Upper 75.0%*
Intercept	0.092450168	0.505494433	0.182890577	0.85853863	-1.033861812	1.218762149	-0.524887862	0.709788198
LN Dose	0.391408446	0.225176414	1.73823021	0.112806594	-0.110315958	0.89313285	0.116410434	0.666406458
LN TOC	1.269581309	0.165570765	7.667907488	1.70366E-05	0.90066659	1.638496027	1.067377044	1.471785573
LN pH	-0.225258472	0.20965749	-1.074411757	0.307878533	-0.692404552	0.241887608	-0.481303907	0.030786963
LN T	0.136924989	0.053996503	2.535812132	0.029574742	0.016613261	0.257236717	0.070981443	0.202868534
LN t	0.159537686	0.009220608	17.30229634	8.80332E-09	0.138992888	0.180082483	0.148276965	0.170798407

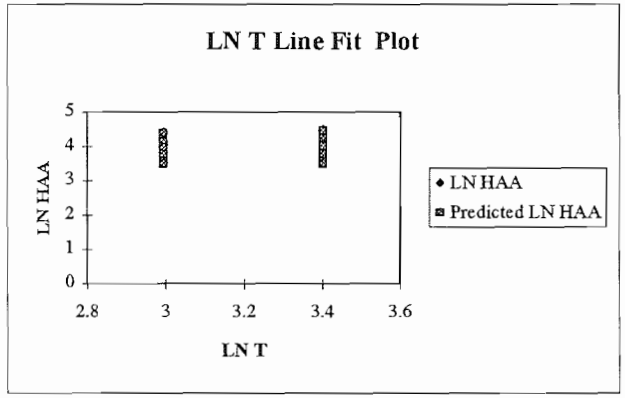
RESIDUAL OUTPUT

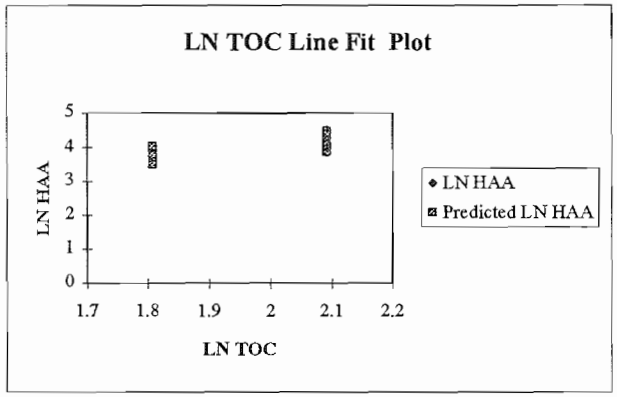
Observation	*Predicted LN HAA*	*Residuals*
1	4.139877526	-0.03475789
2	3.862987883	-0.020529341
3	3.642395884	0.030354188
4	3.494873019	0.05704058
5	3.987437972	-0.019223687
6	4.061088453	-0.004272703
7	3.48995633	0.048100234
8	3.692973589	-0.042055641
9	4.471626817	0.041756973
10	4.148841043	-0.018164551
11	3.974145175	-0.033146062
12	3.780726178	-0.022553897
13	4.273291131	0.012224603
14	4.392837745	0.042966596
15	3.775809489	-0.04530836
16	4.02472288	0.007568958

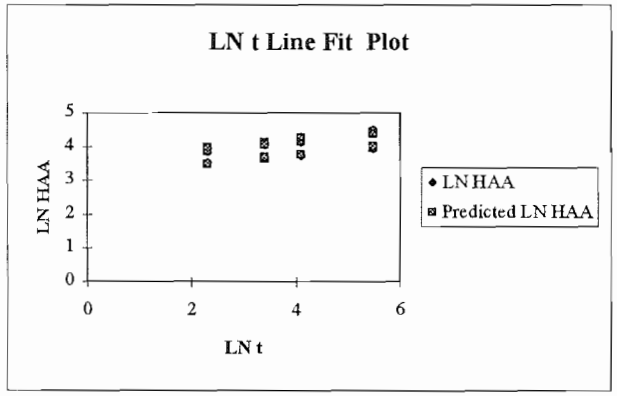
PROBABILITY OUTPUT

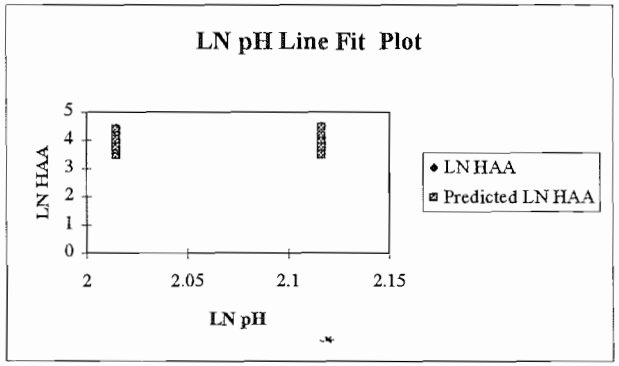
Percentile	*LN HAA*
3.125	3.538056564
9.375	3.551913599
15.625	3.650917948
21.875	3.672750072
28.125	3.730501129
34.375	3.758172281
40.625	3.842458542
46.875	3.940999114
53.125	3.968214285
59.375	4.032291838
65.625	4.05681575
71.875	4.105119635
78.125	4.130676491
84.375	4.285515734
90.625	4.43580434
96.875	4.51338379

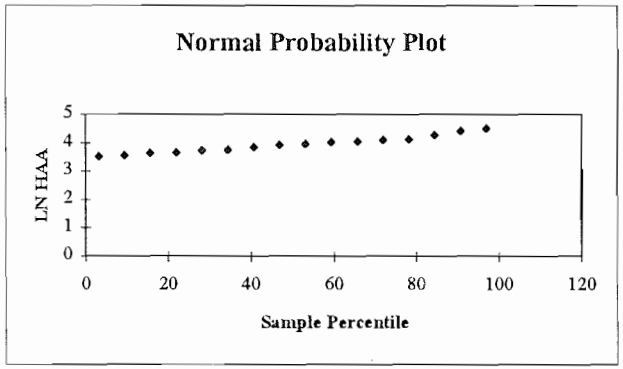

LN Dose Line Fit Plot
LN HAA
LN Dose
LN HAA
Predicted LN HAA


LN T Line Fit Plot
LN HAA
LN T
LN HAA
Predicted LN HAA


LN TOC Line Fit Plot
LN HAA
LN TOC
LN HAA
Predicted LN HAA


LN t Line Fit Plot
LN HAA
LN t
LN HAA
Predicted LN HAA


LN pH Line Fit Plot
LN HAA
LN pH
LN HAA
Predicted LN HAA


Normal Probability Plot
LN HAA
Sample Percentile

SUMMARY OUTPUT - Model with no pH at 95% confidence level

Regression Statistics	
Multiple R	0.99241048
R Square	0.98487856
Adjusted R Square	0.979379855
Standard Error	0.042795767
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	1.312151151	0.328037788	179.1109923	6.23854E-10
Residual	11	0.020146255	0.001831478		
Total	15	1.332297405			

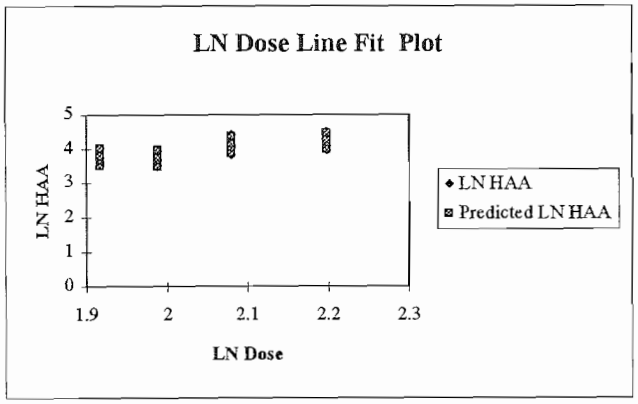
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.372839062	0.262552852	-1.420053367	0.183308281	-0.950714286	0.205036162
LN Dose	0.391408446	0.226750836	1.726160982	0.112258558	-0.107667032	0.890483924
LN TOC	1.269581309	0.166728427	7.614666136	1.04118E-05	0.902614329	1.636548288
LN T	0.136924989	0.054374044	2.518204973	0.028566579	0.017248464	0.256601513
LN t	0.159537686	0.009285078	17.18215957	2.70718E-09	0.139101357	0.179974014

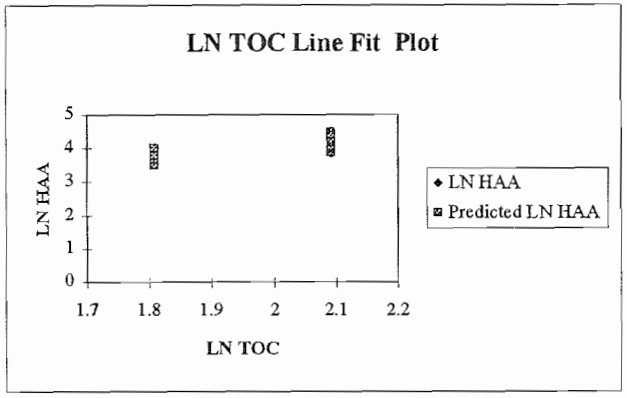
RESIDUAL OUTPUT

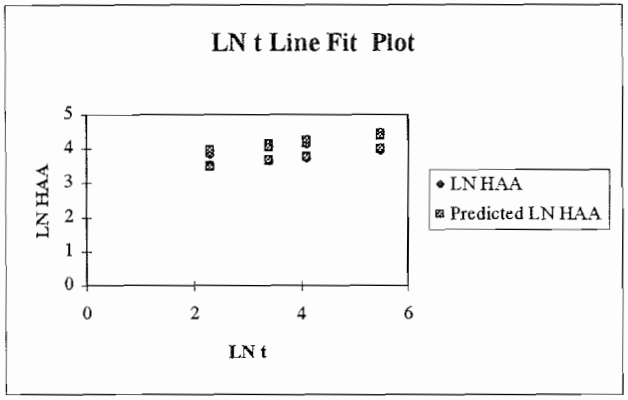
Observation	*Predicted LN HAA*	*Residuals*
1	4.15129278	-0.046173144
2	3.874403137	-0.031944595
3	3.653811138	0.018938934
4	3.506288273	0.045625326
5	3.976022718	-0.007808433
6	4.049673199	0.007142551
7	3.478541076	0.059515488
8	3.681558335	-0.030640387
9	4.483042071	0.030341719
10	4.160256297	-0.029579805
11	3.985560429	-0.044561316
12	3.792141432	-0.033969151
13	4.261875877	0.023639857
14	4.381422491	0.05438185
15	3.764394235	-0.033893106
16	4.013307626	0.018984212

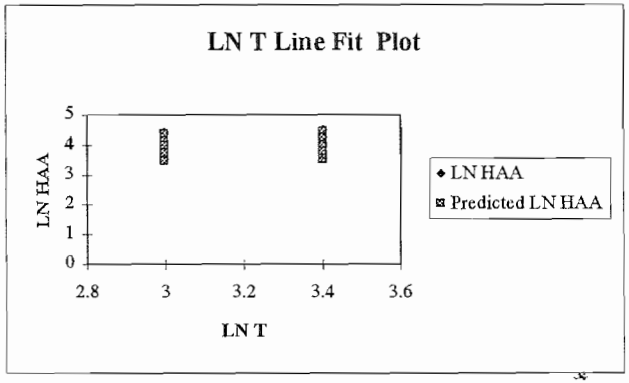
PROBABILITY OUTPUT

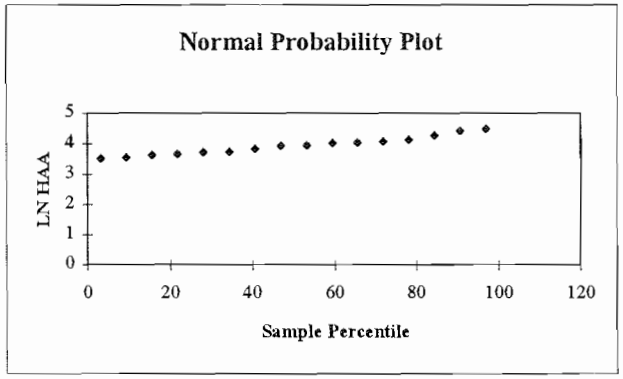
Percentile	*LN HAA*
3.125	3.538056564
9.375	3.551913599
15.625	3.650917948
21.875	3.672750072
28.125	3.730501129
34.375	3.758172281
40.625	3.842458542
46.875	3.940999114
53.125	3.968214285
59.375	4.032291838
65.625	4.05681575
71.875	4.105119635
78.125	4.130676491
84.375	4.285515734
90.625	4.43580434
96.875	4.51338379


LN Dose Line Fit Plot
LN HAA
LN Dose
LN HAA
Predicted LN HAA


LN TOC Line Fit Plot
LN HAA
LN TOC
LN HAA
Predicted LN HAA


LN t Line Fit Plot
LN HAA
LN t
LN HAA
Predicted LN HAA


LN T Line Fit Plot
LN HAA
LN T
LN HAA
Predicted LN HAA


Normal Probability Plot
LN HAA
Sample Percentile

SUMMARY OUTPUT - Model with no pH at 75% confidence level

Regression Statistics	
Multiple R	0.99241048
R Square	0.98487856
Adjusted R Square	0.979379855
Standard Error	0.042795767
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	1.312151151	0.328037788	179.1109923	6.23854E-10
Residual	11	0.020146255	0.001831478		
Total	15	1.332297405			

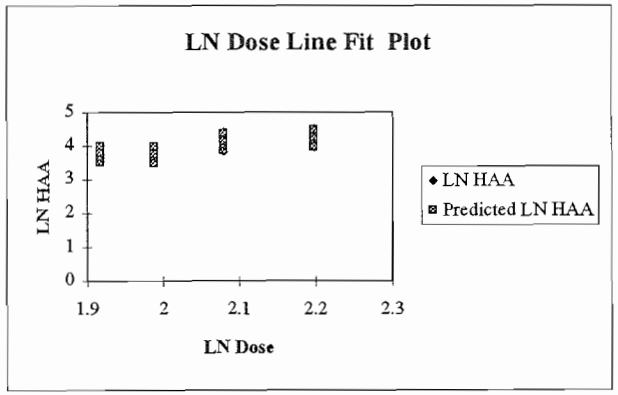
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 75.0%*	*Upper 75.0%*
Intercept	-0.372839062	0.262552852	-1.420053367	0.183308281	-0.950714286	0.205036162	-0.691698905	-0.053979218
LN Dose	0.391408446	0.226750836	1.726160982	0.112258558	-0.107667032	0.890483924	0.116028706	0.666788186
LN TOC	1.269581309	0.166728427	7.614666136	1.04118E-05	0.902614329	1.636548288	1.067096362	1.472066255
LN T	0.136924989	0.054374044	2.518204973	0.028566579	0.017248464	0.256601513	0.070889906	0.202960071
LN t	0.159537686	0.009285078	17.18215957	2.70718E-09	0.139101357	0.179974014	0.148261334	0.170814038

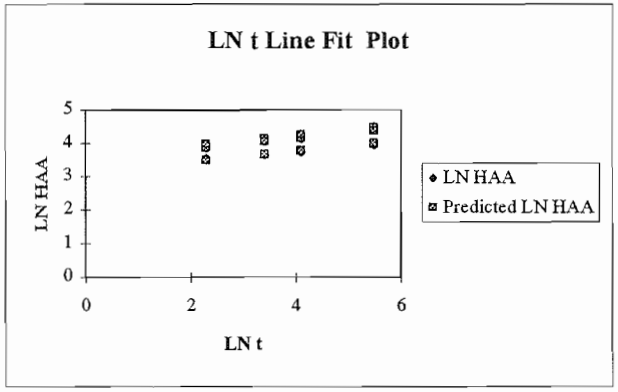
RESIDUAL OUTPUT

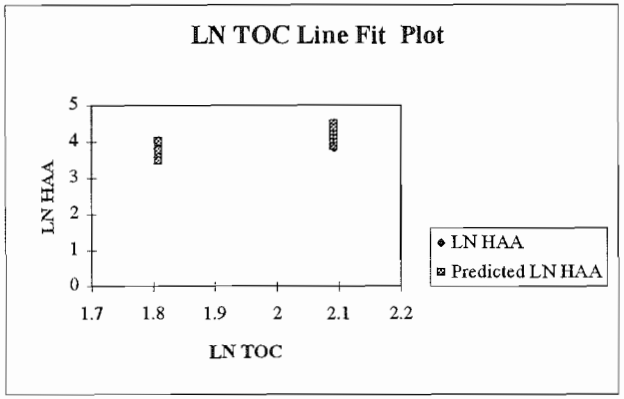
Observation	*Predicted LN HAA*	*Residuals*
1	4.15129278	-0.046173144
2	3.874403137	-0.031944595
3	3.653811138	0.018938934
4	3.506288273	0.045625326
5	3.976022718	-0.007808433
6	4.049673199	0.007142551
7	3.478541076	0.059515488
8	3.681558335	-0.030640387
9	4.483042071	0.030341719
10	4.160256297	-0.029579805
11	3.985560429	-0.044561316
12	3.792141432	-0.033969151
13	4.261875877	0.023639857
14	4.381422491	0.05438185
15	3.764394235	-0.033893106
16	4.013307626	0.018984212

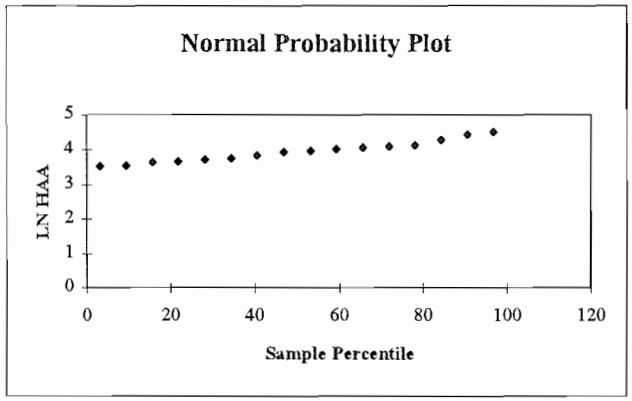
PROBABILITY OUTPUT

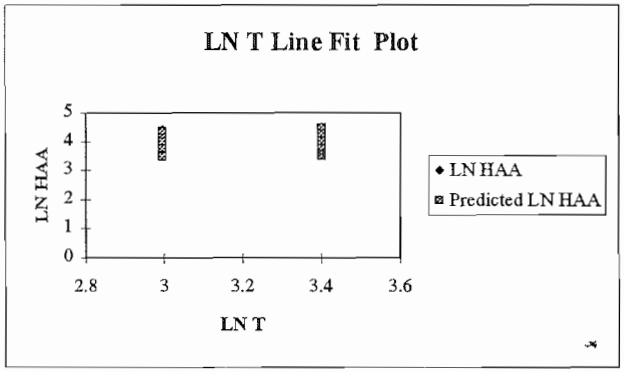
Percentile	*LN HAA*
3.125	3.538056564
9.375	3.551913599
15.625	3.650917948
21.875	3.672750072
28.125	3.730501129
34.375	3.758172281
40.625	3.842458542
46.875	3.940999114
53.125	3.968214285
59.375	4.032291838
65.625	4.05681575
71.875	4.105119635
78.125	4.130676491
84.375	4.285515734
90.625	4.43580434
96.875	4.51338379


LN Dose Line Fit Plot
LN HAA
LN Dose
LN HAA
Predicted LN HAA


LN t Line Fit Plot
LN HAA
LN t
LN HAA
Predicted LN HAA


LN TOC Line Fit Plot
LN HAA
LN TOC
LN HAA
Predicted LN HAA


Normal Probability Plot
LN HAA
Sample Percentile


LN T Line Fit Plot
LN HAA
LN T
LN HAA
Predicted LN HAA

SUMMARY OUTPUT - Model with no dose & pH at 95% confidence level

Regression Statistics	
Multiple R	0.990344653
R Square	0.980782531
Adjusted R Square	0.975978164
Standard Error	0.046191074
Observations	16

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1.306694021	0.435564674	204.1439577	1.46496E-10
Residual	12	0.025603384	0.002133615		
Total	15	1.332297405			

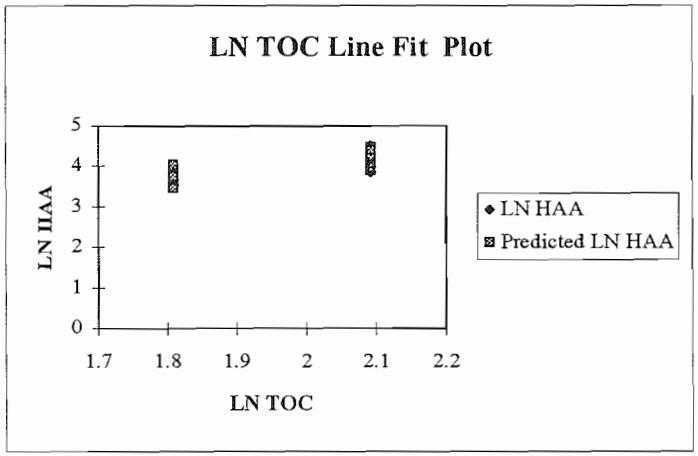
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.145028203	0.244979839	-0.592000565	0.564837677	-0.678793411	0.388737004
LN TOC	1.526219906	0.081444109	18.73947567	2.97849E-10	1.348768438	1.703671373
LN T	0.159528865	0.056960603	2.800687791	0.016023796	0.035422375	0.283635355
LN t	0.159537686	0.010021732	15.91917311	1.9651E-09	0.137702208	0.181373164

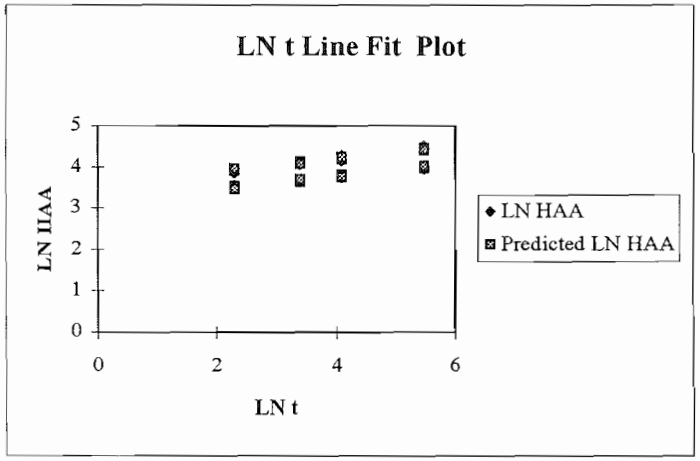
RESIDUAL OUTPUT

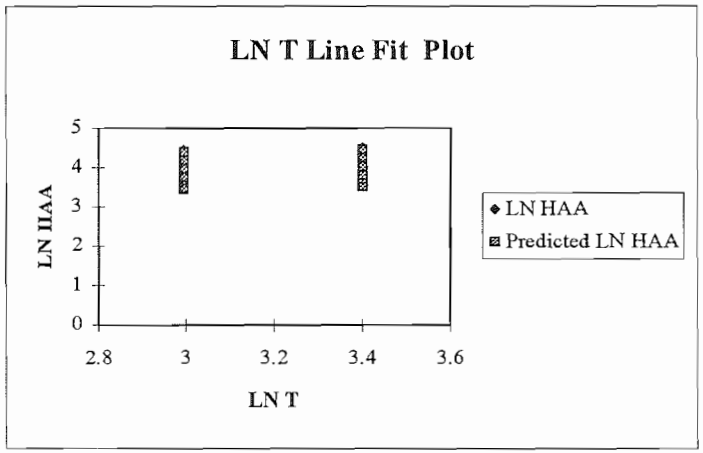
Observation	*Predicted LN HAA*	*Residuals*
1	4.132824684	-0.027705048
2	3.892871233	-0.050412691
3	3.635343042	0.03740703
4	3.524756369	0.02715723
5	3.957554622	0.010659663
6	4.068141295	-0.011325545
7	3.46007298	0.077983584
8	3.700026431	-0.049108483
9	4.464573975	0.048809815
10	4.178724392	-0.048047901
11	3.967092334	-0.02609322
12	3.810609528	-0.052437247
13	4.243407781	0.042107953
14	4.399890587	0.035913754
15	3.745926139	-0.015425011
16	4.031775722	0.000516116

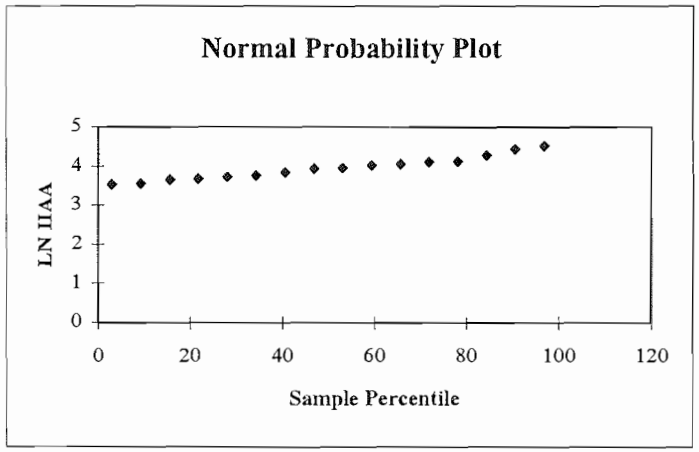
PROBABILITY OUTPUT

Percentile	*LN HAA*
3.125	3.538056564
9.375	3.551913599
15.625	3.650917948
21.875	3.672750072
28.125	3.730501129
34.375	3.758172281
40.625	3.842458542
46.875	3.940999114
53.125	3.968214285
59.375	4.032291838
65.625	4.05681575
71.875	4.105119635
78.125	4.130676491
84.375	4.285515734
90.625	4.43580434
96.875	4.51338379


LN TOC Line Fit Plot
LN HAA
5
4
3
2
1
0
1.7
1.8
1.9
2
2.1
2.2
LN TOC
LN HAA
Predicted LN HAA


LN t Line Fit Plot
LN HAA
5
4
3
2
1
0
0
2
4
6
LN t
LN HAA
Predicted LN HAA


LN T Line Fit Plot
LN HAA
5
4
3
2
1
0
2.8
3
3.2
3.4
3.6
LN T
LN HAA
Predicted LN HAA


Normal Probability Plot
LN HAA
5
4
3
2
1
0
0
20
40
60
80
100
120
Sample Percentile

Appendix C: GAC – RSSCT, Kinetics and Isotherm Results

Marco Island 2 - Plant Softened Water Quality

Parameter	Units	Softened Water	2nd Batch 2/00 Softened Water
pH		9.7	10
Alkalinity	mg $CaCO_3$/L	22	25
Total Hardness	mg $CaCO_3$/L	112	134
Calcium Hardness	mg $CaCO_3$/L	85	102
Turbidity	ntu	18.4	
UV-254	cm^{-1}	0.1537	0.1652
True Color	cpu	8	9
NPDOC	mg/L	6.856	7.85

2nd Batch 2/00 = used for RSSCT EBCT = 20 min

Characteristics of Carbon used for Isotherm and RSSCT studies

Carbon	Filtrasorb 400
Company	Calgon Carbon Corporation
Source	Bituminous Coal

Specifications

Iodine number (min.)*	1050
Abrasion number (min.)*	78
Moisture (max.)*	0.9%
Total surface area (N_2 BET method), m^2/g	900-1100
Bulk density, lbs/ft^3	27
Pore volume,cc/g	0.85-0.95
Effective size, mm	0.55-0.75
Uniform coefficient (max.)	1.9

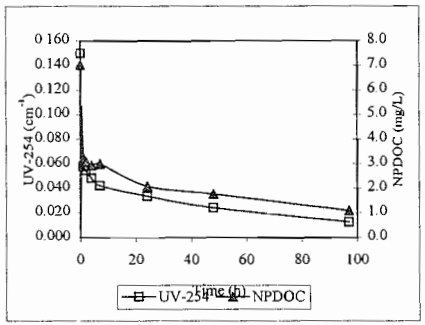
*Typical analysis

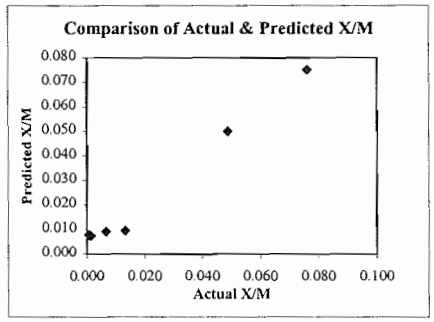
Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatment Optimization: Isotherm

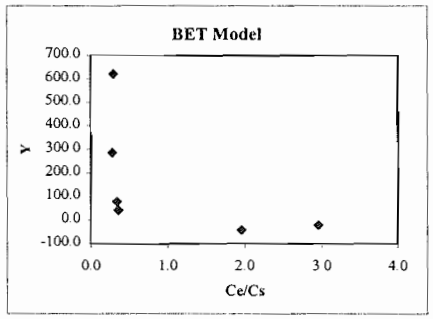
Isotherm Study using Powdered Filtrasorb 400

A: Kinetic Study : Determination of Equilibration Time

PAC Dose	Time (h)							
0.2g/L	0	1	2	4	7	24	48	97
UV_{254} (cm^{-1})	0.1500	0.0577	0.0546	0.0482	0.0423	0.0335	0.0243	0.0126
NPDOC (mg/L)	7.027	3.232	3.087	2.942	2.994	2.083	1.771	1.091







B: Isotherm Study

Parameter	Dose g/L						Experimental QA/QC	
	0	0.05	0.1	0.5	1	5	10	1g/L Dupe	%RSD
UV_{254} (cm^{-1})	0.1500	0.0560	0.0333	0.0044	0.0030	0.0009	0.0009	0.0035	14
NPDOC (mg/L)	7.027	3.222	2.134	0.392	0.373	0.303	0.321	0.444	15
Color (cpu)	8	1	1	0	0	0	0	0	<1
Freundlich Model:									
X/M		0.0761	0.0489	0.0133	0.0067	0.0013	0.0007		
log (X/M)		-1.1186	-1.3105	-1.8771	-2.1770	-2.8714	-3.1736		
log Ce		0.5081	0.3292	-0.4069	-0.4281	-0.5188	-0.4932		
Langmuir Model:									
M/X		13.14	20.44	75.36	150.30	743.64	1491.36		
1/Ce		0.310	0.469	2.552	2.680	3.303	3.113		
BET Model:									
Y		-19.866	-41.801	42.253	78.189	285.826	622.594		
Ce/Cs	Cs ?	2.954	1.957	0.359	0.342	0.278	0.295		

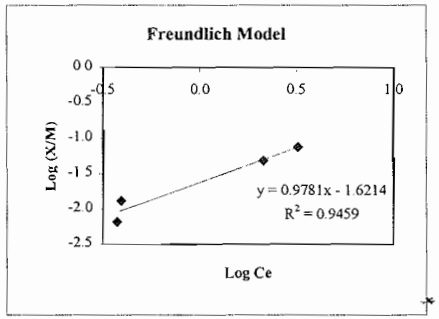
Ce	3.222	2.134	0.392	0.373	0.303	0.321
X/M Predicted	0.0751	0.0502	0.0096	0.0091	0.0074	0.0079
X/M	0.0761	0.0489	0.0133	0.0067	0.0013	0.0007

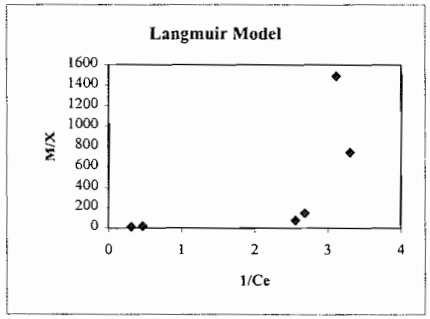
Freundlich Model:						
X/M	0.0761	0.0489	0.0133	0.0067	0.0013	0.0007
log (X/M)	-1.1186	-1.3105	-1.8771	-2.1770	-2.8714	-3.1736
log Ce	0.5081	0.3292	-0.4069	-0.4281	-0.5188	-0.4932

$X/M = k*Ce^{1/n}$

$\log X/M = -1.6214 + 0.9781 \log Ce$

$X/M = 0.0239*Ce^{0.9781}$





RSSCT Design for Full-Scale 12 x 40 mesh GAC (d_{LC} = 1.1 mm)

Assumptions:

Post filter GAC = 100 x 200 mesh (112 μm APD)
d_{SC} = 0.112 mm
GAC = Bituminous (Filtrasorb 400)
Re_{SC} = 0.5 min
ε_{LC} = 0.45
$v_{LC} = 1 \times 10^{-6}$ m^2/s at 20°C
DC_{SC} = 10 mm
ρ_{SC} = 0.53 g/cm^3
TOC_o = 6.9 mg/L

EBCT (min)	10	20
SF	9.8	9.8
$EBCT_{SC}$ (min)	1.0	2.0
V_{SC} (m/h)	7.2	7.2
L_{SC} (cm)	12.2	24.5
Q_{SC} (mL/min)	9.4	9.4
m_{SC} (g)	5.1	10.2
BV_{50}	1762	1762
t_{50} (days)	12.2	24.5
t_{LC}^T (days)	24.4	49.0
t_{SC}^T (days)	2.5	5.0
V_{SC} (L)	33.9	67.8
Total Volume (L)	44.1	88.2

RSSCT Study of Marco Island 2 Plant Softened Water

A: Water Quality of Influent

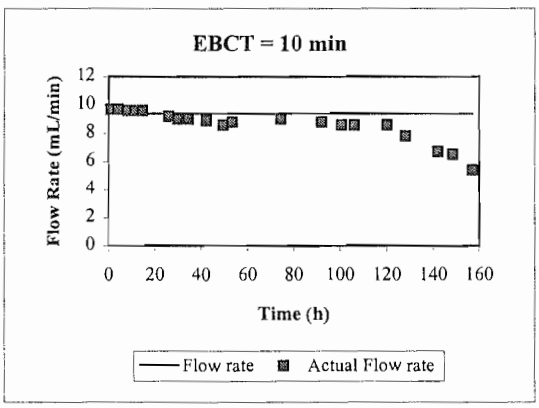
Parameter	Units	Influent 1	Influent 2	Influent 3	Average
pH		8.4	7.3	7.2	
UV_{254}	(cm^{-1})	0.1517	0.1495	0.1515	0.1509
NPDOC	(mg/L)	7.322	6.771	6.958	7.017
Color	cpu	7	7	7	7
Alkalinity	mg $CaCO_3$/L	17.4	17.4	16.4	17.1
Total Hardness	mg $CaCO_3$/L	118.0	118.0	118.0	118.0
Calcium Hardness	mg $CaCO_3$/L	92.0	92.0	92.0	92.0

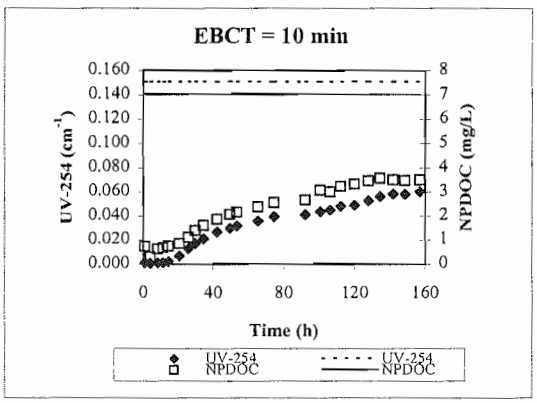
B: EBCT = 10 min

Time (h)	Flow Rate (mL/min)	Actual Flow Rate (mL/min)	UV_{254} (cm^{-1})	Influent	NPDOC (mg/L)	Influent	Color cpu
1	9.4	9.7	0.0013	0.1509	0.733	7.017	1
4	9.4	9.7	0.0008	0.1509	0.297	7.017	0
8	9.4	9.6	0.0014	0.1509	0.628	7.017	1
12	9.4	9.6	0.0014	0.1509	0.688	7.017	1
15	9.4	9.6	0.0025	0.1509	0.745	7.017	0
21	9.4		0.0069	0.1509	0.856	7.017	1
26	9.4	9.2	0.0130	0.1509	1.116	7.017	0
30	9.4	9.0	0.0174	0.1509	1.395	7.017	0
35	9.4	9.0	0.0213	0.1509	1.604	7.017	0
42	9.4	8.9	0.0268	0.1509	1.860	7.017	1
50	9.4	8.6	0.0300	0.1509	2.064	7.017	1
54	9.4	8.8	0.0320	0.1509	2.157	7.017	1
66	9.4		0.0359	0.1509	2.367	7.017	1
75	9.4	9.0	0.0396	0.1509	2.558	7.017	1
92	9.4	8.8	0.0413	0.1509	2.672	7.017	1
101	9.4	8.6	0.0436	0.1509	3.069	7.017	1
106	9.4	8.6	0.0450	0.1509	3.007	7.017	1
112	9.4		0.0482	0.1509	3.234	7.017	1
120	9.4	8.6	0.0490	0.1509	3.325	7.017	1
128	9.4	7.8	0.0528	0.1509	3.454	7.017	1
135	9.4		0.0563	0.1509	3.568	7.017	1
142	9.4	6.7	0.0585	0.1509	3.497	7.017	1
149	9.4	6.5	0.0582	0.1509	3.465	7.017	1
157	9.4	5.4	0.0602	0.1509	3.492	7.017	1

C: Water Quality of Effluent

Parameter	Units	4 h	42 h	157 h	Average
pH		7.8	7.0	6.8	
UV_{254}	(cm^{-1})		refer to B		
NPDOC	(mg/L)		refer to B		
Color	cpu		refer to B		
Alkalinity	mg $CaCO_3$/L	15.9	15.9	16.9	16.2
Total Hardness	mg $CaCO_3$/L	117.0	117.0	119.0	117.7
Calcium Hardness	mg $CaCO_3$/L	91.0	92.0	93.0	92.0





RSSCT Study of Marco Island 2 Plant Softened Water

A: Water Quality of Influent

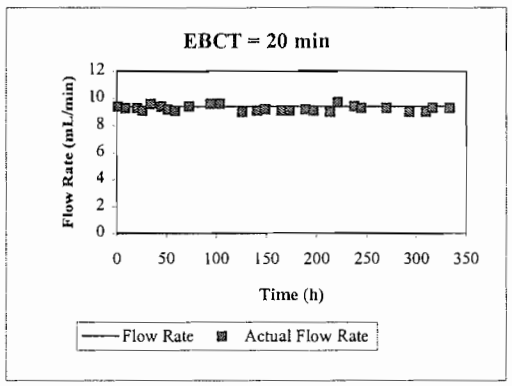
Parameter	Units	Influent 1	Influent 2	Influent 3	Average
pH		7.2	7.0	7.2	
UV_{254}	(cm^{-1})	0.1619	0.1607	0.1618	0.1615
NPDOC	(mg/L)	7.71	7.65	7.70	7.69
Color	cpu	7	8	9	8
Alkalinity	mg $CaCO_3$/L	13	14	14	14
Total Hardness	mg $CaCO_3$/L	138	136	138	137
Calcium Hardness	mg $CaCO_3$/L	107	106	107	107

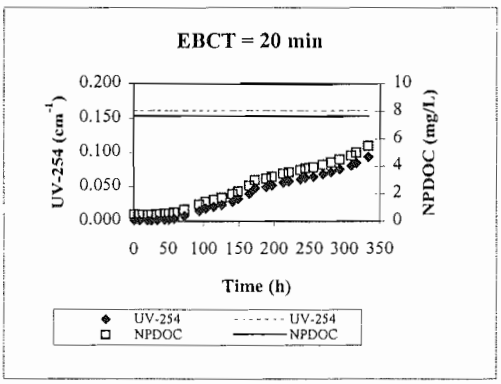
B: EBCT = 20 min

Time (h)	Flow Rate (mL/min)	Actual Flow Rate (mL/min)	UV_{254} (cm^{-1})	Influent	NPDOC (mg/L)	Influent	Color cpu
1	9.4	9.4	0.0014	0.1612	0.50	7.68	0
9	9.4	9.3	0.0008	0.1612	0.46	7.68	0
20	9.4	9.3	0.0008	0.1612	0.46	7.68	0
26	9.4	9.1	0.0008	0.1612	0.46	7.68	0
34	9.4	9.6	0.0013	0.1612	0.49	7.68	0
45	9.4	9.4	0.0022	0.1612	0.54	7.68	0
51	9.4	9.2	0.0026	0.1612	0.56	7.68	0
58	9.4	9.1	0.0038	0.1612	0.63	7.68	0
73	9.4	9.4	0.0078	0.1612	0.84	7.68	0
94	9.4	9.6	0.0149	0.1612	1.22	7.68	0
103	9.4	9.6	0.0188	0.1612	1.43	7.68	1
114	9.4		0.0214	0.1612	1.57	7.68	1
126	9.4	9.0	0.0242	0.1612	1.73	7.68	0
141	9.4	9.1	0.0290	0.1612	1.98	7.68	1
149	9.4	9.2	0.0326	0.1612	2.18	7.68	1
165	9.4	9.1	0.0401	0.1612	2.58	7.68	1
173	9.4	9.1	0.0479	0.1612	3.00	7.68	4
189	9.4	9.2	0.0500	0.1612	3.12	7.68	3
197	9.4	9.1	0.0524	0.1612	3.25	7.68	4
213	9.4	9.0	0.0565	0.1612	3.47	7.68	3
221	9.4	9.7	0.0586	0.1612	3.58	7.68	4
237	9.4	9.4	0.0614	0.1612	3.73	7.68	3
244	9.4	9.3	0.0638	0.1612	3.86	7.68	3
255	9.4		0.0653	0.1612	3.94	7.68	3
269	9.4	9.3	0.0688	0.1612	4.13	7.68	3
281	9.4		0.0718	0.1612	4.29	7.68	3
293	9.4	9.0	0.0759	0.1612	4.51	7.68	4
309	9.4	9.0	0.0811	0.1612	4.80	7.68	3
316	9.4	9.3	0.0848	0.1612	4.99	7.68	4
333	9.4	9.3	0.094	0.1612	5.49	7.68	3

C: Water Quality of Effluent

Parameter	Units	9 h	94 h	197 h	333 h	Average
pH		8.3	6.9	6.9	6.9	
UV_{254}	(cm^{-1})		refer to B			
NPDOC	(mg/L)		refer to B			
Color	cpu		refer to B			
Alkalinity	mg $CaCO_3$/L	15	14	13	15	14
Total Hardness	mg $CaCO_3$/L	134	134	136	140	136
Calcium Hardness	mg $CaCO_3$/L	107	105	107	108	107



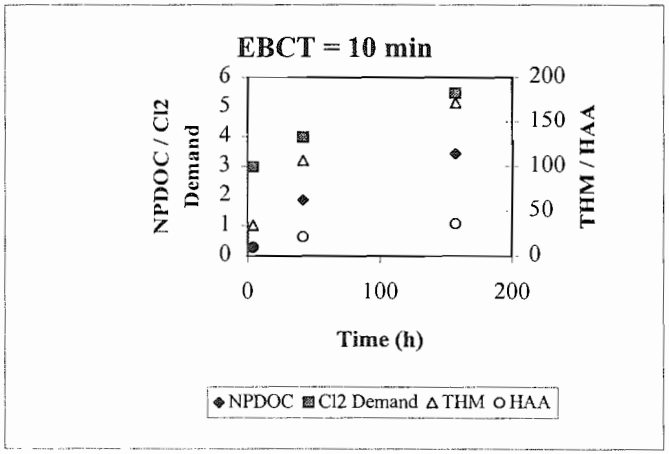


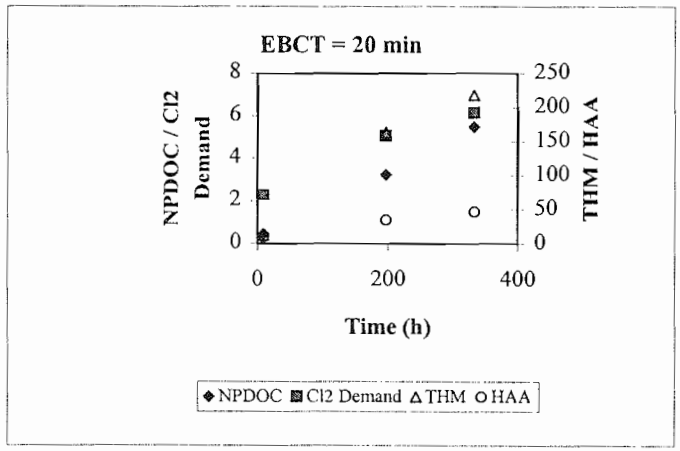
Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening and Treatment Optimization: RSSCT-DBP

DBP Results for the RSSCT Study

Sample	NPDOC (mg/L)	Cl_2 Dose* (mg/L)	Cl_2 Residual* (mg/L)	Cl_2 Demand* (mg/L)	THM (µg/L) $CHCl_3$	$BrCl_2CH$	Br_2ClCH	Br_3CH	TOTAL	HAA (µg/L) MCAA	MBAA	DCAA	TCAA	BCAA	DBAA	TOTAL
EBCT = 10 min																
Influent	7.017	9.5	1.85	7.65	146.24	90.72	53.43	5.94	296.33	4.58	3.13	26.8	24.95	14.89	5.46	79.81
4	0.297	3.5	0.52	2.99	6.3	0.5	4.11	23.26	34.17	0.99	8.61	<0.5	<0.5	<0.5	<0.5	9.6
42	1.860	5.0	1.03	3.97	11.63	23.23	45.46	26.38	106.7	1.23	4.57	2.91	1.78	5.12	5.52	21.13
157	3.423	6.5	1.03	5.47	34.82	55.92	63.17	17.74	171.65	1.81	3.65	7.52	6.30	9.80	6.66	35.74
EBCT = 20 min																
Influent	7.69	9.5	1.65	7.85	111.18	97.78	67.21	10.43	286.6	3.06	3.54	20.74	21.41	14.89	6.60	70.24
9	0.46	3.0	0.72	2.28	5.88	<0.5	1.06	5.74	12.68	0.74	9.13	<0.5	<0.5	<0.5	<0.5	9.87
197	3.25	6.5	1.44	5.06	22.23	46.17	67.18	27.86	163.44	1.64	4.74	5.99	4.34	9.73	8.12	34.56
333	5.49	7.5	1.34	6.16	54.94	74.33	71.82	17.26	218.35	2.05	3.10	11.01	10.71	12.30	7.47	46.64
Experimental QA/QC																
333	5.49	7.5	1.44	6.06	53.62	70.39	72.18	19.18	215.37	2.25	3.96	11.37	10.17	12.63	7.81	48.19
%RSD			6		2	5	<1	9	1	8	22	3	5	2	4	3

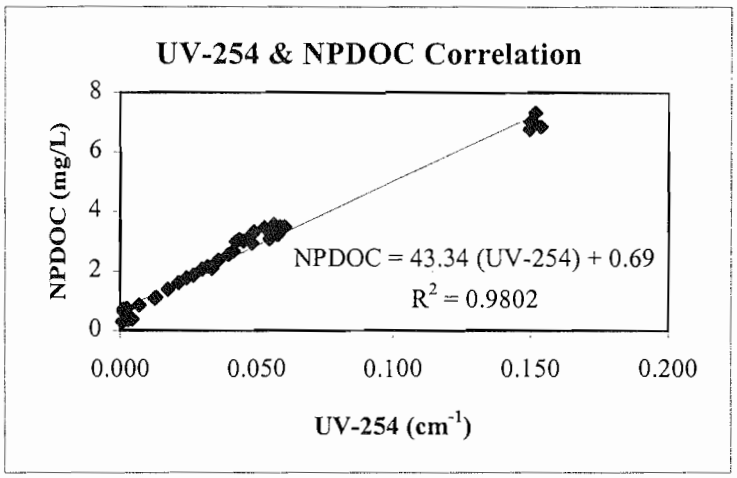
*Samples were dosed at pH 7.6, T 22°C (room temperature) and incubated for 48 h.

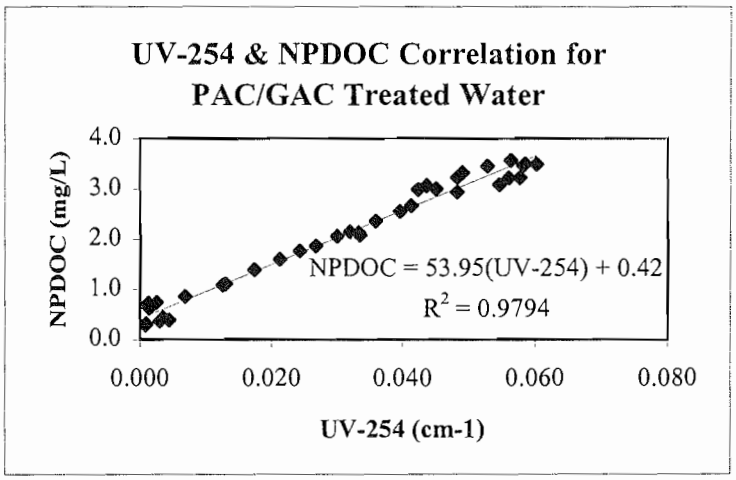




UV-254 and NPDOC Correlation

UV-254	NPDOC	UV-254	NPDOC
cm^{-1}	mg/L	cm^{-1}	mg/L
0.1537	6.856	0.1537	6.856
0.1500	7.027	0.1500	7.027
0.0577	3.232	0.1500	7.027
0.0546	3.087	0.1517	7.322
0.0482	2.942	0.1495	6.771
0.0423	2.994	0.1515	6.958
0.0335	2.083		
0.0243	1.771	0.0577	3.232
0.0126	1.091	0.0546	3.087
0.1500	7.027	0.0482	2.942
0.0560	3.222	0.0423	2.994
0.0333	2.134	0.0335	2.083
0.0044	0.392	0.0243	1.771
0.0030	0.373	0.0126	1.091
0.0009	0.303	0.0560	3.222
0.0009	0.321	0.0333	2.134
0.0035	0.444	0.0044	0.392
0.1517	7.322	0.0030	0.373
0.1495	6.771	0.0009	0.303
0.1515	6.958	0.0009	0.321
0.0013	0.733	0.0035	0.444
0.0008	0.297	0.0013	0.733
0.0014	0.628	0.0008	0.297
0.0014	0.688	0.0014	0.628
0.0025	0.745	0.0014	0.688
0.0069	0.856	0.0025	0.745
0.0130	1.116	0.0069	0.856
0.0174	1.395	0.0130	1.116
0.0213	1.604	0.0174	1.395
0.0268	1.860	0.0213	1.604
0.0300	2.064	0.0268	1.860
0.0320	2.157	0.0300	2.064
0.0359	2.367	0.0320	2.157
0.0396	2.558	0.0359	2.367
0.0413	2.672	0.0396	2.558
0.0436	3.069	0.0413	2.672
0.0450	3.007	0.0436	3.069
0.0482	3.234	0.0450	3.007
0.0490	3.325	0.0482	3.234
0.0528	3.454	0.0490	3.325
0.0563	3.568	0.0528	3.454
0.0585	3.497	0.0563	3.568
0.0582	3.465	0.0585	3.497
0.0602	3.492	0.0582	3.465
		0.0602	3.492





Analytical QA/QC for the Isotherm/RSSCT Studies

A: Alkalinity

Sample	Value mg/L	Value mg/L	RSD %	Spike mg/L	Recovery %
157 h RSSCT EBCT =10 min	16.4	17.4	5	63.3	96
94 h RSSCT EBCT =20 min	14.0	13.0	7	57.8	90

B: Total Hardness

Sample	Value mg/L	Value mg/L	RSD %	Spike mg/L	Recovery %
157 h RSSCT EBCT =1 0 min	119	118	1	136.3	86
94 h RSSCT EBCT =20 min	134	136	1	152.9	94

C: Calcium Hardness

Sample	Value mg/L	Value mg/L	RSD %	Spike mg/L	Recovery %
157 h RSSCT EBCT =10 min	92	94	2	110.8	94
94 h RSSCT EBCT =20 min	105	106	1	122.5	88

D: UV-254 and Color

		UV-254			Color	
Sample	Value cm-1	Value cm-1	RSD %	Value cpu	Value cpu	RSD %
Softened water	0.1537	0.1536	<1	8	8	<1
21 h RSSCT EBCT = 10 min	0.0068	0.0069	<1	1	1	<1
50 h RSSCT EBCT = 10 min	0.0300	0.0310	3	1	1	<1
Influent 3	0.1502	0.1515	1	7	7	<1
149 h RSSCT EBCT = 10 min	0.0582	0.0587	1	1	1	<1
Influent 1 EBCT = 20 min	0.1619	0.1631	1	7	7	<1
Influent 3 EBCT = 20 min	0.1618	0.1638	1	9	10	9

E: NPDOC

Sample	Value mg/L	Value mg/L	RSD %	Spike mg/L	Recovery %
21 h RSSCT EBCT = 10 min	0.856	0.771	9	1.834	98
42 h RSSCT EBCT = 10 min	1.860	1.905	2	3.799	97
149 h RSSCT EBCT = 10 min	3.423	3.441	<1	5.504	104
Tap water	2.185	2.168	1	3.175	99

F: THM

Sample	EBCT = 10 min/ 42h				
	Value	Value	RSD	Spike	Recovery
	µg/L	µg/L	%	µg/L	%
$CHCl_3$	11.63	13.46	13	32.33	103
$BrCl_2CH$	23.23	22.57	3	45.88	113
Br_2ClCH	45.46	44.87	1	66.66	106
Br_3CH	26.38	26.32	<1	48.5	111
THM_{total}	106.7	107.22	<1	1093.37	108
Sample	EBCT = 20 min/ 196h				
	Value	Value	RSD	Spike	Recovery
	µg/L	µg/L	%	µg/L	%
$CHCl_3$	22.23	22.67	2	43.28	105
$BrCl_2CH$	46.17	43.18	6	67.85	108
Br_2ClCH	67.18	64.87	3	88.83	108
Br_3CH	27.86	26.1	6	50.31	112
THM_{total}	163.44	156.82	4	250.28	109

G: HAA

Sample	EBCT = 10 min/ 157h		
	Value	Value	RSD
	µg/L	µg/L	%
MCAA	1.81	1.79	1
MBAA	3.65	3.88	5
DCAA	7.52	7.82	4
TCAA	6.30	6.73	6
BCAA	9.80	10.45	6
DBAA	6.66	7.12	6
HAA_{total}	35.75	37.78	5
Sample	EBCT = 20 min/ 196 h		
	Value	Spike	Recovery
	µg/L	µg/L	%
MCAA	1.64	13.29	58
MBAA	4.74	19.34	73
DCAA	5.99	23.23	86
TCAA	4.34	21.88	88
BCAA	9.73	26.87	86
DBAA	8.12	25.40	86
HAA_{total}	34.55	130.02	80

Marco Island 2 - Plant Softened Water Quality

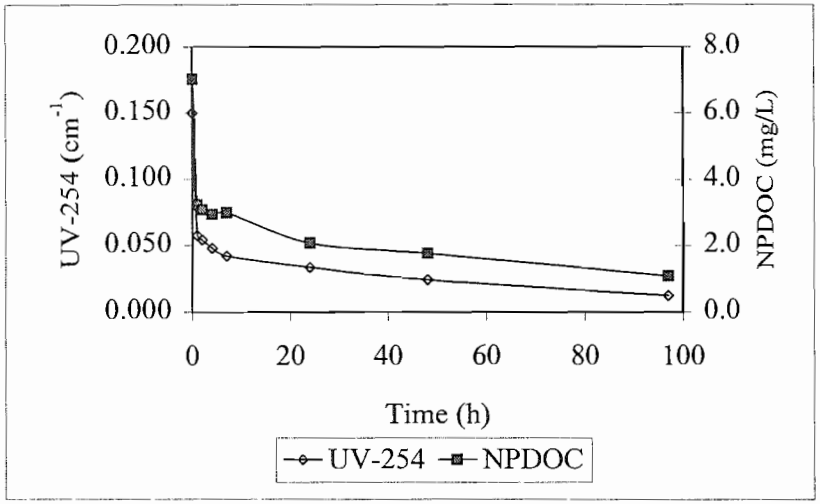
Parameter	Units	Softened Water
pH		9.7
Alkalinity	mg $CaCO_3$/L	22
Total Hardness	mg $CaCO_3$/L	112
Calcium Hardness	mg $CaCO_3$/L	85
Turbidity	ntu	18.4
UV-254	cm^{-1}	0.1537
True Color	cpu	8
NPDOC	mg/L	6.856

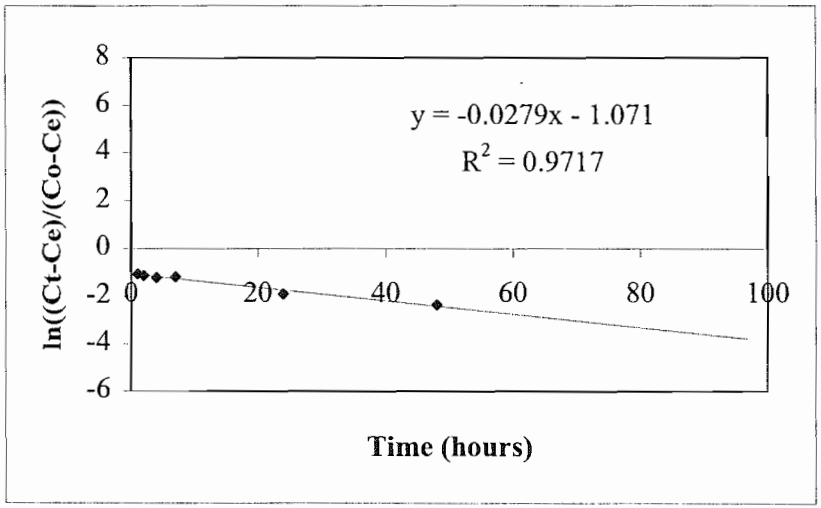
Isotherm Study using Powdered Filtrasorb 400

A: Kinetic Study : Determination of Equilibration Time

PAC Dose	Time (h)							
0.2g/L	0	1	2	4	7	24	48	97
UV_{254} (cm^{-1})	0.1500	0.0577	0.0546	0.0482	0.0423	0.0335	0.0243	0.0126
NPDOC (mg/L)	7.027	3.232	3.087	2.942	2.994	2.083	1.771	1.091

t	0	1	2	4	7	24	48	97
ln((Ct-Ce)/(Co-Ce)	-0.000602	-1.0575	-1.132327	-1.212921	-1.18297	-1.898123	-2.342291	





ka = 0.0279 hr-1

Florida Water Marco Island
Lime Softening Water Treatment Plant
Enhanced Softening Treatment and Optimization: Isotherm (2)

B: Isotherm Study

Parameter	Dose g/L							Experimental QA/QC	
	0	0.05	0.1	0.5	1	5	10	1g/L Dupe	%RSD
UV_{254} (cm^{-1})	0.1500	0.0560	0.0333	0.0044	0.0030	0.0009	0.0009	0.0035	14
NPDOC (mg/L)	7.027	3.222	2.134	0.392	0.373	0.303	0.321	0.444	15
Color (cpu)	8	1	1	0	0	0	0	0	<1

Freundlich Model:

X/M		0.0761	0.0489	0.0133	0.0067	0.0013	0.0007
log (X/M)		-1.1186	-1.3105	-1.8771	-2.1770	-2.8714	-3.1736
log Ce		0.5081	0.3292	-0.4069	-0.4281	-0.5188	-0.4932

Langmuir Model:

M/X	13.14	20.44	75.36	150.30	743.64	1491.36
1/Ce	0.310	0.469	2.552	2.680	3.303	3.113

BET Model:

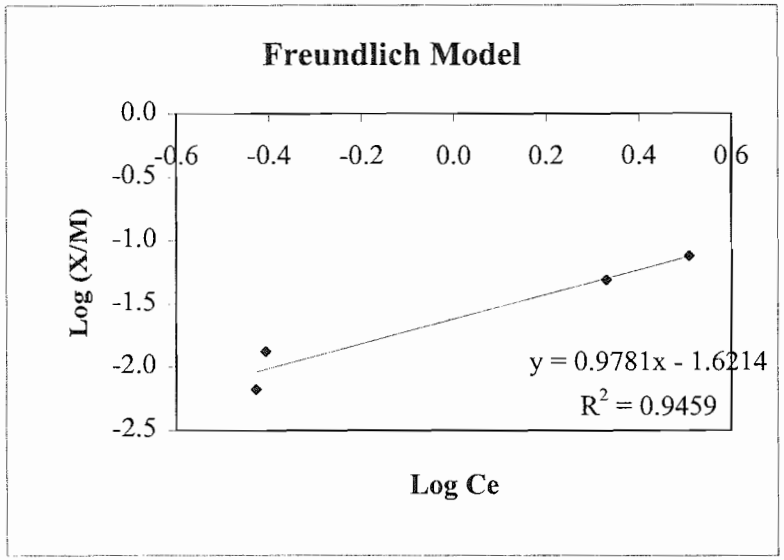
Y		-19.866	-41.801	42.253	78.189	285.826	622.594
Ce/Cs	Cs ??	2.954	1.957	0.359	0.342	0.278	0.295

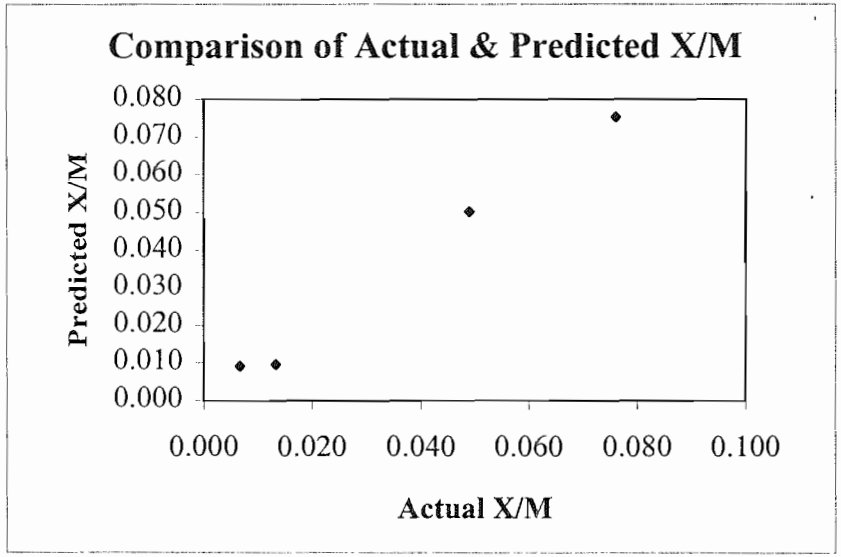
Freundlich Model:

X/M	0.0761	0.0489	0.0133	0.0067
log (X/M)	-1.1186	-1.3105	-1.8771	-2.1770
log Ce	0.5081	0.3292	-0.4069	-0.4281

$X/M = k*Ce^{1/n}$
log X/M = -1.621 + 0.978 log Ce
X/M = 0.024*Ce0.978

Ce	3.222	2.134	0.392	0.373
X/M Predicted	0.0754	0.0504	0.0096	0.0092
X/M	0.0761	0.0489	0.0133	0.0067



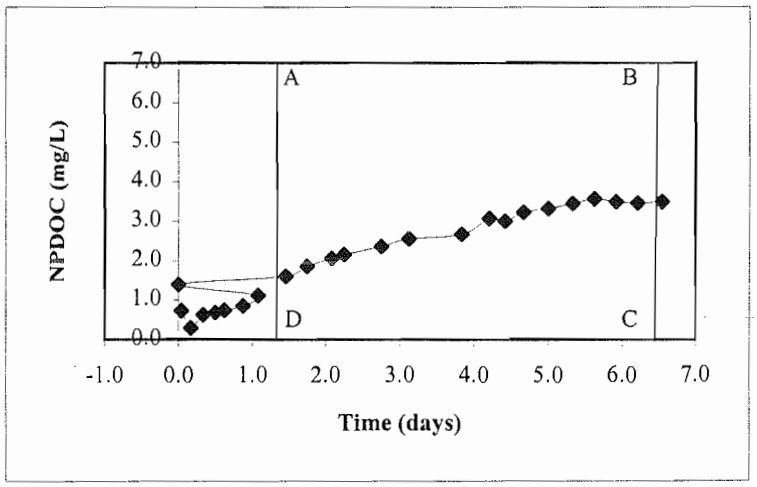


K =	0.0239111	
n=	1.0223903	
Ce =	1.2115	0.02909
		0.02909

Determination of the transfer zone for RSSCT EBCT = 10 min

Time hr	Time days	NPDOC mg/L	Area	
1	0.04	0.733		
4	0.17	0.297		
8	0.33	0.628		
12	0.50	0.688		
15	0.63	0.745		
21	0.88	0.856		
26	1.08	1.116		
0	0.00	1.395		
35	1.46	1.604		
42	1.75	1.860		
50	2.08	2.064		
54	2.25	2.157	0.815	
66	2.75	2.367	2.369	
75	3.13	2.558	1.702	
92	3.83	2.672	3.106	
101	4.21	3.069	1.549	
106	4.42	3.007	0.825	
112	4.67	3.234	0.970	
120	5.00	3.325	1.240	
128	5.33	3.454	1.204	
135	5.63	3.568	1.018	
142	5.92	3.497	1.011	
149	6.21	3.465	1.026	
157	6.54	3.492	1.174	18.008

Breakthrough



target TOC = 2 mg/L
breakthrough = 2 days
TOCave = 7 mg/L
Qave = 8.6 mL/min
ABCD surface = (6.5-2)*7 = 31.5 mg-d/L
TOC removed in transfer zone = 18.0 mg-d/L

$$TOCremoved\ ,transferzo\ ne = \frac{18 * 8.6 * 1440}{1000} = 223\ mg$$

f = 18/31.5 = 0.57 ; 57% efficiency of transfer zone

$$\delta = \frac{L(Vx - Vb)}{Vb + f(Vx - Vb)} = 4.7 inches$$

Vx = 81 L
Vb = 24.8 L
Lsc = 12.2 cm = 4.8 inches