A CASE STUDY USING PILOT-SCALE EXPERIMENTATION FOR ENHANCED COAGULATION
CHARLESTON, SOUTH CAROLINA

Written by:

John B. Cook, P.E., Director of Engineering
Commissioners of Public Works of the
City of Charleston, South Carolina

Greg Helfrich, P.E., Director of Water Treatment
Jordan, Jones & Goulding, Inc.
Atlanta, Georgia

The 1995 South Carolina
Environmental Conference
Hilton Head Island, South Carolina

March, 1995

A Case Study Using Pilot-Scale Experimentation For Enhanced Coagulation Charleston, South Carolina

Pilot-scale experimentation was used to determine ways to optimize the coagulation and filtration processes at Charleston CPW's Hanahan Water Treatment Plant, including an evaluation of enhanced coagulation for TOC removal. The Hanahan WTP is a 118-MGD conventional rapid filtration plant, processing raw water from the Edisto River that may be characterized as low in turbidity, highly variable in color (from 80 to over 300 PCUs), high in TOC (mean of 10 mg/L), with a high trihalomethane formation potential. The pilot experimentation examined the efficacy of various coagulants and coagulant aids in maximizing TOC removal efficiency while achieving the goals of minimizing the color and turbidity of the finished water. Based upon the results of the pilot work, it was recommended to change from alum to ferric chloride as the primary coagulant, to use a coagulant aid, and to convert the existing sand filter media to a combination of granular activated carbon (GAC) and sand. The full-scale implementation of these various changes has demonstrated a TOC removal efficiency of 66 percent which exceeds the proposed U.S. EPA requirements for enhanced coagulation.

Background

Over the past twenty years, numerous studies have attempted to determine means to either remove disinfection by-products, as indicated principally by trihalomethanes (THMs), or to minimize their formation. One of the strategies evaluated by researchers to minimize THM formation has been to evaluate the removal of organic material that can serve as precursors to the formation of disinfection by-products. One measure of precursor levels is Total Organic Carbon (TOC), which is a broad collective measure of organics providing no information as to specific organic constituents or their distribution. However, according to Kavanaugh (1978), the large fraction of TOC consists of humic substances, namely fulvic, hymatomelanic, and humic acids. Several researchers, including Amy et al.(1987), have demonstrated the relationship between the presence of TOC and the formation potential of disinfection by-products. Chadik and Amy (1983) found that the reduction of THM formation potential as a percentage always exceeded TOC reductions as a percentage, and they suggested that this preferential removal of TOC is based upon the humic acid fraction being more reactive than fulvic acid in forming THMs and is more effectively removed by coagulation because of its lower charge density. Hence, various research studies have attempted to determine treatment methodologies for optimizing TOC removal. For example, Reckhow and Singer (1990) demonstrated that the formation potential of a variety of disinfection by-products (THMs, certain haloacetic acids, dichloroacetonitrile, 1, 1, l-trichloropropapone, and TOX) can all be reduced through enhanced coagulation. Further, in a study of 16 waters nationwide, enhanced coagulation provided a median reduction in THMs of 50 percent and a median reduction in dichloroacetic acid of 61 percent (James M. Montgomery, Consulting Engineers, Inc., 1991).

In a full-scale evaluation of 35 utilities using enhanced coagulation, alum doses were raised from 10 mg/L to 40 mg/L (Metropolitan Water District of So. Calif. et al, 1989), and the removal of TOC for low alkalinity water through the coagulation and settling process was increased from 25 to 50 percent.

Based upon the body of research available, it is anticipated that the U.S. EPA will propose in its Disinfectant-Disinfection By-product (D-DBP) Rule maximum contaminant levels of 80 mg/L for total THMs and 60 mg/L for the sum of five haloacetic acids (HAA5). The proposed Rule is currently scheduled to be promulgated in June 1995. In addition to the maximum contaminant levels for certain specific by-products, the proposed D-DBP Rule will require many surface water treatment plants to utilize enhanced coagulation for the purpose of removing precursors, using TOC as the surrogate indicator. The required percent removals for TOC will be a function of both the alkalinity of the raw water and the level of raw water TOC. Table 1 shows the range of requirements.

Table 1
Required Percent Removal of TOC by Enhanced Coagulation

Source Water TOC, (mg/L)	Source Water Alkalinity, (mg/L)		
	0-60	>60-120	>120
≥2-4	40%	30%	20%
>4-8	45%	35%	25%
>8	50%	40%	30%

This matrix recognizes that TOC removal efficiency is easier in less alkaline waters because optimum coagulation has been shown to be achieved at low pH ranges and at higher initial raw water TOC levels. Various researchers have shown that Al (III) doses to achieve TOC removal occur optimally within a pH of 5 to 6, and coagulation of organics using Fe (III) exhibit optimal performance within a pH of 3 to 5.

In addition, research has shown that TOC removal is dependent upon molecular weight distribution, among other things; and TOC removal efficiencies can be hindered in water with organic carbon of low molecular weights. In the event the requirements of the matrix cannot be realized at certain treatment plants, it is anticipated that the Rule will allow bench- and pilot-scale testing to determine the limitations on coagulant addition for small incremental increases in TOC removal.

Objectives of Pilot Scale Experimentation

There were a number of objectives in performing the pilot-scale work from July 1989 to December 1989. These objectives included an evaluation of various coagulants and coagulant aids to determine optimal removal of turbidity and color, as well as minimization of the production of residuals. Objectives of the experimentation related to this paper included optimizing TOC removal and minimizing THM formation in the pilot-scale and moving the selected technology to full-scale demonstration testing.

Experimental Design of Pilot Plant Study

Introduction

Bench-scale testing was used to select the operating parameters and chemical for use in the pilot plant experimentation.

The testing program was developed, in part, to compare the best chemical combinations of alum against ferric chloride at a number of color levels to determine which would yield the most economical chemical and solids handling costs, while producing high quality treated water. The comparison of alum and ferric chloride was selected based on a number of factors, including:

- Clear indications in the jar testing phase that lower finished water TOC, color, and THMF values could be achieved using ferric chloride in place of alum.
- Ferric provided a "non-aluminum" coagulant alternative.
- Concerns over the regulatory impact of land applying aluminum sludge versus iron sludge.

Filter tests were performed at 4, 6, and 8 gpm/ft^2, which are equivalent to 78, 118, and 157 MGD full-scale output. Initially, treated water from one train was diverted to all six filter columns. The best three media were then selected and loaded into the filter columns in each train.

Pilot Plant Design

The pilot plant consists of two flow trains, each having the same facilities. Table 2 lists the pilot plant design criteria. These agree reasonably well with the full-scale plant design criteria, except for the settling facilities, where tube settlers replace the conventional settling basin to reduce tank volume. In addition to the pilot facilities reflecting the existing full-scale plant, ozone could be added prior to coagulation and between sedimentation and filtration. However, because the full-scale plant does not have ozone capabilities and the use of ozone is not relevant to this paper, no further information is presented.

Table 2
Pilot Plant Design Criteria(1)

Component	Surface Area (sq. in.)	Water Depth (in.)	Water Volume (cu. in.)	Detention Time (min.)	Energy Gradient (G sec-1)	GT Value	Surface Loading (gpm/ft^2)
Rapid Mix	144.0	12.0	1,728	1.0	331	20,600	N/A
Flocculation Basin (each) (4-Stage)	324.0	27.0	8,748	5.3	5-40	1,500-12,500(3)	N/A
Sedimentation Basin	1,152.0	26.0	29,952	18.0	N/A	N/A	0.94
Filters (6 total) 6" diam. columns(2)	28.0	N/A	N/A	N/A	N/A	N/A	6.1

Notes:
(1) Design flow = 7.2 gpm.
(2) 7.5 gpm total flow to pilot plant. Normal flow to each filter is 1.2 gpm which is approximately 6 gpm/ft^2
(3) Tapered flocculation is utilized resulting in a total GT of 26,400 at the design flow.

Sampling Locations

Water samples were taken from various locations during a given pilot plant run and are summarized below.

- *pH* - Raw water pH was analyzed at least once per day using an Orion ATC pH meter. coagulated water pH was measured in Flocculation Basin No. 1 to obtain optimal conditions. Settled water pH was measured after sodium hydroxide addition to between 7.0 and 8.0 prior to filtration.

- ***Turbidity*** - Raw water turbidity was measured at least once a day using a Hach turbidimeter. Settled water turbidity was measured after sodium hydroxide addition. Filter effluent turbidity was monitored to determine plant performance. This was accomplished using two continuous-reading turbidimeters with strip chart recorders. The turbidity of any filter in each train could be monitored and recorded during a pilot plant run.

- *Color* - The apparent color of the raw water was measured at least once each day during a pilot plant run using a Hach DR-2000 spectrophotometer. Settled water was collected prior to filtration and after pH adjustment and analyzed for apparent color. The filtered water color was also monitored periodically during each pilot plant run.

- *TOC* - One sample was collected for the analysis from the raw, settled, and filtered water during each run using a Dohrman TOC analyzer.

- *THM* - One sample was collected and analyzed for THM formation from the raw, settled, and filtered water during each pilot plant run using gas chromatography methods. Each sample collected was chlorinated and allowed to react for 2.5 hours. The 2.5-hour time period was chosen based on the approximate detention times that might be available in the full-scale plant.

- ***Iron*** - One sample was collected from the raw, settled, and filtered water during each pilot plant run and analyzed for iron concentration using the atomic absorption (AA) method.

- ***Aluminum*** - One sample was collected from the raw, settled, and filtered water during each pilot plant run and analyzed for aluminum concentration using AA methods.

Pilot Scale Tests

The non-ozone pilot testing program was divided into three phases, based on the jar test results. Phase 1 evaluated alum through the six alternative filter medias at rates of 4, 6, and 8 gpm/ft^2. Phase 2 testing was similar to Phase 1, except that ferric chloride was used as the primary coagulant.

The results of Phase 1 and 2 were reviewed with respect to filtration to select the best three performing medias. These were then loaded into the six columns to allow side-by-side testing of alum and ferric in Phase 3. Because a goal of the full-scale plant was to high rate the filters to 6 gpm/ft^2, the Phase 3 work was only conducted at that filter loading rate. Plant performance was based on turbidity and color removal, TOC and THM values, iron and aluminum residuals, and solids production.

Phase 4 testing was conducted to determine the impact of ozonation on plant performance. Although that evaluation is beyond the scope of this paper, numerous pilot runs were completed where ozone was not applied to one train. This allowed a comparison with the train that had ozone applied to it. Therefore, the data from the non-ozonated runs is also provided in the alum/ferric comparison.

Phase 1 and 2 Testing

Phase 1 and 2 testing occurred over the time period of July 18, 1989 to August 18, 1989. During this time, the raw water temperature was approximately 25°C. The raw water color and alkalinity were also relatively high. Organics and metals analyses were not performed during this phase of pilot plant testing.

The results of Phases 1 and 2 testing indicated that GAC was consistently an excellent filter media for turbidity and color removal, although not quite as good as the alternative sand/anthracite design. The CPW sand/anthracite media had the lowest performance.

Based on this testing, three media designs were selected and loaded into each pilot plant train for further testing. The media used in Phase 3 are summarized in Table 3.

Phase 3 Testing

As noted above, the purpose of Phase 3 was to compare alum to ferric chloride in side-by-side tests using the three media selected from Phases 1 and 2. Testing was performed during the time period of August 31, 1989 through September 16, 1989. The Edisto River raw water quality for Phase 3 testing is summarized in Table 4. Treatment chemical dosages are listed in Table 5.

Table 3
Pilot Plant Phase 3 Testing - Filter Media

Filter #		Code	Type and Depth
Train #1	*Train #2*		
1	4	A	24" Granular Activated Carbon (Calgon Filtrasorb 300) Effective Size = 0.8 to 1.0 mm Uniformity Coefficient = 2.1 maximum 6" Sand Effective Size = 0.45 to 0.55 mm Uniformity Coefficient = 1.5 or less
2	5	B	20" Anthracite (Unifilt) Effective Size 0.95 to 1.05 mm Uniformity Coefficient = 1.4 or less 10" Sand Effective Size = 0.45 to 0.55 mm Uniformity Coefficient = 1.5 or less
3	6	E*	20" Anthracite Effective Size = 1.4 to 1.6 mm Uniformity Coefficient = 1.5 or less 9" Sand Effective Size = 0.34 mm Uniformity Coefficient = 1.56

* Simulates CPW's plant media

Table 4
Phase 3 Testing - Edisto River Raw Water Characteristics

Run #	Temp (°C)	pH	Turbidity (NTU)	Alkalinity (mg/L as CaCo$_3$)	Apparent Color (PCU)	TOC (mg/L)	2.5 Hr THM (μg/L)	Fe (mg/L)	Al (mg/L)
7	26.0-27.5	6.6-7.1	2.0-3.0	28-30	159-181	12.9	681	1.48	0.65
8	26.2	6.8	3.1	31	165-166	12.5	808	1.08	0.53
9	27.0	7.1-7.6	2.2-3.3	N/A	132-142	11.8	738	0.91	0.54

N/A - Not Analyzed

Table 5
Pilot Plant Phase 3 Testing - Chemical Feed Data

Run#	Pilot Plant Train#	Primary Coagulant	Dose (mg/L)	Secondary Coagulant	Dose (mg/L)	Flocculant Aid Dose (mg/L)
7	1	AL	80	-	-	0.09
7	2	FC	41	-	-	0.09
8	1	AL	70	-	-	0.075-0.10
8	2	AL	60	Nalco 8120	4.0	0.075-0.10
9	1	FC	45	-	-	0.075
9	2	FC	39	Nalco 8102	5.0	0.075

Notes:
AL = Alum as $AL_2(S0_4)_3.14H_2O$
FC= Ferric Chloride as $FeCl_3$
Flocculant Aid = Nalco polymer 8110

Phase 3 settled water data is shown in Table 6. Filtered water quality is summarized in Table 7. Note that Filter Nos. 1 and 4 contain GAC media. Therefore, color and organics testing will be affected. For TOC removal efficiency testing, only Filter Nos. 2, 3, 5, and 6 were considered.

Table 6
Pilot Plant Phase 3 Testing - Settled Water Data

Run#	Pilot Plant Train	Apparent Color (PCU)	Turbidity (NTU)	TOC (mg/L)	2.5 Hr THM (μg/L)	Fe (mg/L)	Al (mg/L)
7	1	18	1.2	4.24	138	0.10	0.36
7	2	24	1.9	2.62	37	0.59	0.29
8	1	25	0.94	4.69	142	0.24	0.79
8	2	31	1.4	5.10	130	0.19	0.33
9	1	85	3.3	N/A	99	1.52	0.39
9	2	31	1.4	N/A	69	0.74	0.14

Table 7
Pilot Plant Phase 3 Testing -- Filtered Water Data
Train 1

	Filter #2 (Media B)						Filter #3 (Media E)					
Run#	Color (PCU)	Turb (NTU)	TOC (mg/L)	2.5Hr THM (μg/L)	Fe (mg/L)	Al (mg/L)	Color (PCU)	Turb (NTU)	TOC (mg/L)	2.5Hr THM (μg/L)	Fe (mg/L)	Al (mg/L)
7	7	0.12	3.97	96	<0.05	0.12	8	0.13	4.05	90	<0.05	0.15
8	15	0.17	5.30	142	0.05	0.25	15	0.17	4.78	143	<0.05	0.53
9	11	0.3	N/A	92	<0.05	0.15	11	0.36	N/A	N/A	0.05	0.53

Train 2

	Filter #6 (Media B)						Filter #5 (Media E)					
Run#	Color (PCU)	Turb (NTU)	TOC (mg/L)	2.5Hr THM (μg/L)	Fe (mg/L)	Al (mg/L)	Color (PCU)	Turb (NTU)	TOC (mg/L)	2.5Hr THM (μg/L)	Fe (mg/L)	Al (mg/L)
7	4	0.13	2.49	45	<0.05	0.17	6	0.19	2.53	38	<0.05	0.36
8	8	0.13	4.22	115	<0.05	0.13	9	0.19	4.17	110	<0.05	0.10
9	5	0.12	N/A	49	<0.05	0.26	5	0.11	N/A	46	<0.05	0.14

Notes:
N/A = Not Analyzed
Media Codes: B = Alternative Sand/Anthracite
E = CPW Sand/Anthracite
Dates shown are average of all data collected for each run.

Phase 4 Testing

Raw water characteristics are listed in Table 8. Chemical feed data for non-ozonated runs are shown in Table 9. Tables 10 and 11 show settled and filtered water quality, respectively.

Table 8
Pilot Plant Phase 4 Testing - Edisto River Raw Water Characteristics

Run #	Temp (°C)	pH	Turbidity (NTU)	Alkalinity (mg/L as $CaCo_3$)	Apparent Color (PCU)	TOC (mg/L)	2.5 Hr THM (µg/L)	Fe (mg/L)	Al (mg/L)
10	N/A	6.7	1.5-1.6	N/A	203-210	17.1	1134	0.78	0.15
11	N/A	6.2-7.3	1.5-2.0	26	165-193	19.6	828	0.78	0.22
12	N/A	6.8-7.9	1.3-2.2	28-37	129-152	19.2	1156	0.56	0.50
13	18.8	7.6-7.9	1.4-2.4	N/A	113-130	12.3	911*	0.82	0.15
14	17.0	N/A	1.8-2.3	N/A	111-123	11.2	890	0.68	0.27
15	N/A	7.0-7.5	1.6-2.4	N/A	107-126	10.6	N/A	0.61	0.30

Notes:
N/A = Not Analyzed
*THMFP for Run 13 reacted for 4.5 hours.

Table 9
Pilot Plant Phase 4 Testing - Chemical Feed Data

Run #	Primary Coagulant	Dose (mg/L)	Secondary Coagulant	Dose (mg/L)	Flocculant Aid Dose (mg/L)
10	AL	135	-	-	0.075
11	AL	100	-	-	0.075
12	AL	97-104	-	-	0.075
13	FC	34	-	-	0.075
14	FC	39	-	-	0.075
15	FC	35	-	-	0.075

Notes:
AL = Alum as $Al_2(SO_4)_3.14\ H_2O$
FC = Ferric Chloride as $FeCl_3$
Flocculant Aid = Nalco polymer 8110

Table 10
Pilot Plant Phase 4 Testing Settled Water Data

Run #	Apparent Color (PCU)	Turbidity (NTU)	TOC (mg/L)	2.5 Hr THM (ug/L)	Fe (mg/L)	Al (mg/L)
10	24	2.0	5.9	237	0.06	0.28
11	20	1.4	6.3	56	0.16	1.64
12	39	2.1	8.0	276	0.26	2.76
13	31	1.9	2.6	86	1.40	0.14
14	58	3.5	6.2	295	4.45	0.20
15	30	2.2	2.9	N/A	1.21	0.14

Notes:
Data show are averages of all data collected for each run.

Table 11
Pilot Plant Phase 4 Testing - Filtered Water Data - Non-Ozonated Testing
Pilot Plant Train #2

	Filter #5 (Media E)						Filter #6 (Media B)					
Run #	Color (PCU)	Turb (NTU)	TOC (mg/L)	2.5 Hr THM (mg/L)	Fe (mg/L)	Al (mg/L)	Color (PCU)	Turb (NTU)	TOC (mg/L)	2.5 Hr THM (mg/L)	Fe (mg/L)	Al (mg/L)
10	6	0.43	5.7	153	<0.05	0.18	3	0.22	5.6	132	<0.05	0.4
11	6	0.51	5.7	15	0.09	1.03	6	0.47	5.9	40	0.09	1.13
12	18	0.82	7.4	310	0.1	2.01	17	0.74	N/A	326	0.08	3.26
13	4	0.42	2.6	60	0.1	0.03	4	0.32	2.5	47	<0.05	0.05
14	9	0.8	4.3	120	0.6	0.34	4	0.53	4	108	0.09	0.01
15	<1	0.24	3	27	<0.05	0.07	<1	0.02	2.4	52	<0.05	0.04

Notes:
N/A - Not Analyzed

Media Codes:
B = Alternative Sand/Anthracite
E = CPW Sand/Anthracite

Data shown are averages of all data collected for each run.
GAC column results are not presented.

Test Results

Table 12 contains a summary of the removal efficiency of alum and ferric chloride for the TOC and 2.5 Hour THM formation.

Table 12
Coagulant Removal Efficiency

Run #	Coagulant	Dosage mm Metal*	TOC Removal (mg/L)	TOC Removal (%)		2.5 Hr THM Formation Reduction (%)	TOC Removal/ mm Metal*
				Settled Water	Filtered Water		
7	Alum	.27	8.89	67	69	86	33.0
7	Ferric	.26	10.39	80	81	94	40.0
8	Alum	.23	7.46	62	60	82	32.4
8	Alum	.20	8.31	59	66	86	41.6
9	Ferric	.28	N/A	N/A	N/A	88	N/A
9	Ferric	.25	N/A	N/A	N/A	94	N/A
10	Alum	.45	11.45	66	67	87	25.4
11	Alum	.33	13.8	68	70	97	41.8
12	Alum	.34	11.8	58	61	72	34.7
13	Ferric	.21	9.75	79	79	94	46.4
14	Ferric	.25	7.05	45	63	87	28.2
15	Ferric	.22	7.90	73	75	N/A	36.0

* Millimole Coagulant Metal

Reviewing the data indicates:

- Average TOC Removal Efficiency
  - Alum, 65.6%
  - Ferric Chloride, 74.5%

- Average 2.5 Hour THM Formation Reduction
  - Alum, 85.2%
  - Ferric Chloride, 91.3%

- TOC Removal/Millimole Coagulant
    - Alum, 34.8 mg TOC/Millimole Aluminum
    - Ferric Chloride, 37.6 mg TOC/Millimole Iron

In each case, the removal efficiency of iron was higher than aluminum for TOC and 2.5 hour THM Formation reduction. Based on this data, it was recommended to convert the full-scale plant over to ferric chloride as the primary coagulant.

Evaluation of Full-Scale Performance

The removal efficiencies for TOC were evaluated for the period of time from January 1, 1990 to April 26, 1992, when alum was being used as the primary coagulant. This evaluation revealed that the raw water TOC during this period ranged from 2.80 mg/L to 43.00 mg/L, and the settled water TOC ranged from 1.40 mg/L to 13.20 mg/L, with a mean removal efficiency between raw and settled water of 59 percent. The coagulation pH during this period was 5.8 and the alum dose ranged from 20 to 85 mg/L. Based upon the proposed enhanced coagulation requirements for TOC greater than 8 mg/L and low alkalinity water, the removal efficiency requirement of 50 percent was achieved. The raw water characteristics are shown on Table 13.

Table 13
Raw Water Characteristics for
January 1, 1990 to April 26, 1992

Parameter		Mean	Range
TOC	mg/L	12.8	2.8 to 43.0
Alkalinity	mg/L	22	12 to 44
Color	PCU	134	34 to 323
Ambient pH	SU	6.9	6.4 to 7.6

During the period of May 16, 1992 to July 14, 1994, ferric chloride was used as the primary coagulant, and the TOC removal efficiencies were evaluated. Raw water characteristics are shown on Table 14. This evaluation revealed that the raw water TOC during this period ranged from 2.70 mg/L to 31.60 mg/L, and the settled water TOC ranged from 1.10 mg/L to 8.30 mg/L, with a mean removal efficiency between the raw and settled water of 66 percent. The coagulation pH during this period was 4.7, and the ferric chloride dose ranged from 15 to 41 mg/L. In addition to the proposed enhanced coagulation requirements of 50 percent being easily satisfied, the TOC removal efficiency for ferric chloride was superior to the period in which alum was used. Nonetheless, it has been well established that TOC removal efficiency is a function of the TOC concentration in the raw water; and, in order to compare the performance of the two coagulation methodologies, it was necessary to normalize the raw water TOC data to remove this bias.

Table 14
Raw Water Characteristics for
May 16, 1992 to July 14, 1992

Parameter		Mean	Range
TOC	mg/L	10.1	2.7 to 31.6
Alkalinity	mg/L	19	10 to 30
Color	PCU	141	77 to 248
Ambient pH	SU	7.3	6.7 to 8.2

To accomplish this, a model using regression analysis was developed for each time period to formulate the relationship between TOC removal efficiency and TOC concentrations in the raw water. An evaluation of the data produced the following model results and statistical information:

For the period in which alum was used:

$\text{TOCREA} = 20.2\ (\text{TOCI})^{0.43}$ in which,

TOCREA = TOC removal efficiency in percent

TOCI = TOC concentrations in mg/L in the influent water before coagulation

$n = 777$ $R^2 = 0.73$

The model for the period in which alum was used is shown graphically in Figure 1. For a mean TOC concentration during this period of 12.83 mg/L, the model gives reasonably good results of a 60 percent predicted removal efficiency compared to the actual removal efficiency at this TOC concentration of 59 percent.

For the period in which ferric chloride was used:

$\text{TOCREF} = 31.2\ (\text{TOCI})^{0.33}$ in which,

TOCREF = TOC removal efficiency in percent

TOCI = TOC concentration in mg/L in the influent water before coagulation

$n = 761$ $R^2 = 0.70$

The model for the period in which ferric chloride was used is shown graphically in Figure 2. For a mean TOC concentration during this period of 10.14 mg/L, the model gives reasonably good results of a 67 percent predicted removal efficiency, which compares favorably to the actual removal efficiency of 66 percent at this same TOC concentration.

As can be seen, in both periods there is a strong functionality between raw water concentration and removal efficiency. For the time period in which alum was used, the mean TOC raw water concentration was 12.83 mg/L; and for the time period in which ferric chloride was used, the mean TOC raw water concentration was 10.14 mg/L. Therefore, to remove the bias of this difference in concentrations, the removal efficiency using the alum model was computed using a raw water concentration of 10.14 mg/L as follows:

$$\text{TOCREA} = 20.2\ (10.14)^{0.43}$$

$$\text{TOCREA} = 55\%$$

By normalizing the raw water TOC concentration, the removal efficiency for alum was reduced from 59 to 55 percent, as compared to a removal efficiency using ferric chloride of 66 percent for the same raw water concentration. There may be other factors outside of TOC influent concentration, such as temperature, which can effect removal efficiencies. However, Knocke, et al. (1986) showed that the effects of temperature on coagulation were slight; and with certain water samples, alum coagulation resulted in differences of only 0.1 to 0.5 mg/L TOC at 35.6°F and 71.6°F, respectively. In addition, with the relatively long time periods and large number of data points evaluated, these secondary factors should be of minimal concern.

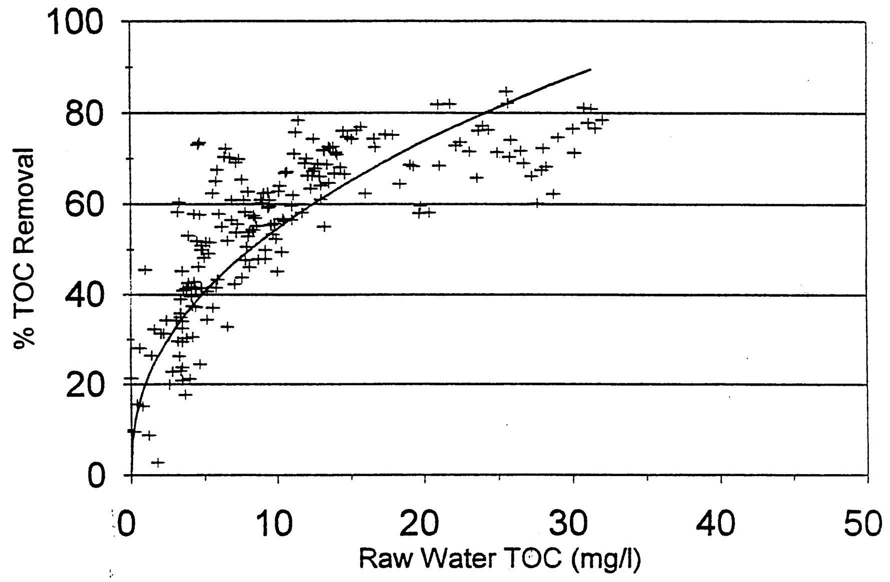

Figure 1

TOC removal efficiency as a function of raw water TOC concentration, using alum

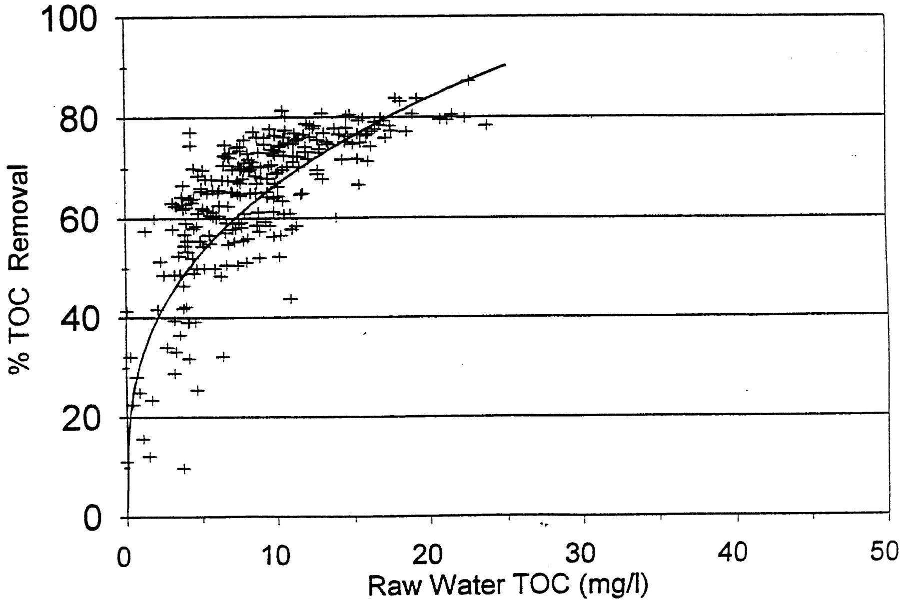

Figure 2

TOC removal efficiency as a function of raw water TOC concentration. using Ferric Chloride

Conclusions

Based upon the results of the bench-scale testing and full-scale performance, several conclusions can be drawn.

- Both the pilot-scale study and full-scale performance demonstrate that ferric chloride is more effective than alum in TOC removal.
- For the Edisto River water, both ferric chloride and alum were effective in achieving the proposed TOC removal efficiencies of 50 percent for high TOC, low alkalinity water.
- The observed removal efficiencies were greater for THM formation than for TOC removal in the pilot testing.

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