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Physical-Chemical Treatment Tests For Stormwater

Introduction

A physical-chemical treatment scheme was developed and tested to reduce toxic and pathogenic discharges of stormwater (Pitt, *et al*. 1998). These laboratory, pilot-scale, and full-scale experiments were developed for a special purpose (the rapid treatment of relatively small volumes of stormwater), but the results may be indicative of general stormwater treatment behavior using similar treatment processes.

Both laboratory-scale and pilot-scale tests were used to examine many alternative treatment factors. The laboratory-scale tests were comprised of two activities: jar tests of different coagulants, and filterability of water (after chemical addition) through 5 and 25 µm bag filter material. The purpose of these tests was to identify the most effective chemical coagulant (and dosage range) that could be used to treat stormwater, and the effectiveness of final filtration after the chemical addition. After these laboratory tests, a pilot-scale setup was developed and tested. The pilot-scale tests included the following unit processes assembled on a trailer:

1) initial 100 µm membrane filter bag
2) 25 µm membrane filter bag
3) 5 µm membrane filter bag
4) activated charcoal filter
5) UV disinfection unit
6) final cascade aerator

Finally, a series of additional pilot-scale tests were conducted using the following selected processes:

1) pH adjustment, if needed
2) chemical coagulation
3) rapid sedimentation
4) post filtration to trap remaining floc

The above treatment method was expected to significantly reduce almost all of the suspended solids and associated pollutants from the water column, plus many of the dissolved constituents.

Characteristic of Water Affecting Treatability

Dissolved and Particulate Forms of Pollutants

Pitt, *et al.* (1998) analyzed 550 samples for a broad list of constituents, including the total and filtered observations shown in Table 4-3. The samples were collected from telecommunication manhole vaults that were mostly affected by stormwater. However, some other contaminating water, and groundwater, sources likely also influenced these samples. We found that these data are very similar to cold and warm season stormwater data collected during other projects. This is the largest and most representative data base available that contains both total and filtered analyses. These samples were obtained throughout the US and represent all seasons. They were collected from the winter of 1996 to the spring of 1998. The average TDS and total solids concentrations may appear to be unusually high, but these data include snowmelt influences.

The particle size distribution of the solids in the water samples indicates that about 80 to 90% removal of suspended solids can be expected during the coagulation and post filtration process. The coagulation process will also remove large fractions of dissolved metals and nutrients. A post filter process having an effective aperture of about 5 μm will ensure good particulate removal. Other post filters that were investigated include Zeolite (to reduce ammonia) and activated carbon (to reduce pesticides). The pretreatment with the coagulant will reduce the particulate burden on the post filters, which we have found to be mandatory to ensure maximum life from the filters. Therefore, the treated discharge concentrations should approach the concentrations listed in the filtered sample concentrations in Table 4.3, plus additional removal of toxicants and pathogens. The high dissolved solids concentrations will likely remain relatively high, as these process will have an insignificant effect on the chloride concentrations.

Table 4-3. Average Particulate Fraction of Constituents (mg/L, unless otherwise noted)

Constituents	Total Concentration	Filtered Concentration	Percent Associated with Particulates
Total Solids	1530	1460	5%
Dissolved Solids	1460	1460	0%
Suspended Solids	70	0	100%
Volatile total solids	140	120	14%
Volatile dissolved solids	120	120	0%
Volatile suspended solids	50	0	100%
Turbidity (NTU)	13	1.2	91%
COD	25	22	14%
Color (HACH)	34	20	41%
Toxicity (I25)	42	42	0%
Copper (μg/L)	29	9.5	67%
Lead (μg/L)	14	3	79%
Zinc (μg/L)	230	160	30%

Pitt, *et al.* (1998)

Other Stormwater Characteristics Affecting Physical-Chemical Treatment

Other water characteristics that affect physical-chemical treatability include pH, turbidity, conductivity and alkalinity. The following table lists these characteristics (median and COV) that may affect chemical treatment:

parameter	**Mid Atlantic and New England**	**East Coast**	**Southeast**
pH (overall range)	6.1 - 8.1	6.0 - 8.3	6.2 - 9.4
turbidity (NTU)	15 (1.2)	24 (1.3)	26 (1.7)
conductivity (µS/cm)	1800 (1.4)	1700 (0.8)	400 (1.0)
alkalinity (mg/L, as $CaCO_3$)	230 (0.6)	280 (0.6)	360 (0.6)

Pitt, *et al.* (1998)

Locations experiencing snowmelt are seen to have higher conductivity (and associated TDS) values, as expected. These conditions are close to optimal for coagulation treatment, except that the turbidity may be low.

Preliminary Treatability Tests

Numerous treatability tests were conducted by Pitt, *et al*. (1998) to identify the most effective coagulant, mixing time, and dosage, in addition to floc settling and capture and stability. These tests involved bench-scale jar tests using several categories of coagulants, with and without supplements. A range of conductivity and turbidity conditions were tested to examine the possible effects of these parameters on treatability.

Coagulation is a two-step process, the first step is destabilization of particles (by chemical addition), followed by amalgamation (by mixing) to form faster sinking particles. Added chemicals affect the surface charges on the particles so they will join into flocs. The flocs are larger than the initial primary particles, but have a much lower specific gravity (because of entrapped water). However, the increased size usually overcomes the decreased density and the flocs settle much more rapidly than the primary particles. In some cases and for some chemicals, the flocs will rise to the water surface where they are removed by skimming. In most water and wastewater treatment processes, initial flash mixing is followed by 20 to 60 minutes of slow mixing to help the particles collide to form the flocs. The floc is then allowed to settle for 2 to 8 hours in a sedimentation basin. These tests were conducted with much less time in an attempt to simulate field conditions where rapid treatment is desired. Chemicals that form heavy flocs quickly are needed, and filtration was investigated to replace slow sedimentation.

Hydrolyzing metal ions are a common family of coagulants used to destabilize the surface charges of the particles. These include alum (aluminum sulfate), the most commonly used coagulant used in the U.S., ferrous sulfate, ferric chloride, and mixtures of ferrous sulfate and ferric chloride (chlorinated copperas). Another common group of coagulants are organic polymers (polyelectrolytes) and synthetic polymers. Polymers are long chain molecules having many available active sites for adsorption. Besides coagulants and polymers, many coagulant aids are available to enhance coagulation and flocculation. In addition, many blends of chemicals are used. Because these chemicals react differently with different waters, bench-scale jar tests are needed to determine the most efficient dosages and pH conditions of the water being treated. The objective was to identify chemicals having relatively robust behavior for the range of water conditions likely found in stormwater.

Water can be grouped into four types according to turbidity and alkalinity conditions. Low turbidity is defined as <10 NTU and high turbidity is defined as >100 NTU. Turbidity is important because it has associated small particulates that form nuclei for the flocs. In most cases, stormwater is of intermediate turbidity, although locations affected by eroding areas can have extremely high turbidity values. Low alkalinity water has alkalinity levels < 50 mg/L, as $CaCO_3$, while high alkalinity water has alkalinity levels >250 mg/L. Alkalinity is important because the bicarbonates are important intermediate products in most coagulation processes. Most stormwaters likely have high alkalinity. Each water type has a preferred coagulant type:

- Type one water (high turbidity and high alkalinity): The easiest water to coagulate. Either alum (effective in pH range of 5 - 7), or ferric chloride (pH range of 6 - 7), or high molecular weight polymers work well. Cationic polymers are very effective, while anionic and non-ionic polymers may also be effective.

- Type two water (high turbidity, low alkalinity): The polymer recommendations are the same as for type one water, while alkalinity may need to be added for alum or ferric chloride, if the pH drops during water treatment.

- Type three water (low turbidity, high alkalinity): This is the likely category for many stormwaters. Polymers cannot work alone due to the low turbidity. Coagulant aids that increase the turbidity (such as clays) should be added before the polymer. Alum is needed in relatively large dosages, which forms a precipitate. Weighing agents may be needed to promote settling. Ferric chloride is also needed in relatively high dosages which also promotes hydroxide precipitates. Again, coagulant aids to weigh the floc is needed to improve settling.

- Type four water (low turbidity and low alkalinity): The most difficult water to coagulate. Must add alkalinity or turbidity to form type 2 or 3 water for either alum or ferric chloride. Polymers cannot work alone without added aids, such as clay, to increase the turbidity.

About 5% of the stormwaters collected from manholes by Pitt, *et al*. (1998) were type four waters, requiring additions of other chemicals besides the coagulants, while the majority of the waters sampled were type three. Few samples would be classified as type one or type two waters. Most were intermediate in turbidity. Therefore, the addition of coagulant aids to increase turbidity may be mandatory in some cases, and may improve the treatment in other cases. Microsand (silica sand with a nominal size range of about 75 to 150 μm in diameter) has recently been used to improve treatment of wastewaters. In most cases, the sand is separated from the floc after settling for recycling. This material is larger than clay material and may improve the weighting of the flocs for more rapid settling, while increasing turbidity.

Alum is commonly used in the U.S. for water treatment. However, during our preliminary tests on chemical treatment of stormwater, it was found to contribute toxicity to the finished waters (possibly due to dissolved aluminum at pH conditions encountered, or due to zinc contamination of the alum). The flocs formed with alum were also found to be more fragile and settle slower than with ferric chloride. Experience using full-scale ferric-chloride treatment of stormwater at European installations for phosphate control has been very successful, especially in low alkalinity waters where alum toxicity may be an issue. Ferric chloride also forms a floc that settles much more rapidly than alum flocs and does not add toxicity to the finished water. However, ferric chloride stock solutions are corrosive and must be handled carefully. The dilute solutions used for coagulation are not corrosive. Ferric chloride is also about twice as expensive as alum, on a weight basis.

Bench-Scale Jar Tests

These tests were evaluated by examining the reduction of turbidity, heavy metals, nutrients, and toxicity. A standard 6-place jar test apparatus was used, with initial fast stirring followed by slow stirring. The first two chemical tests (runs 1 through 3) for the most commonly used coagulants (ferric chloride and alum) were conducted as a full-factorial test to examine the effects of varying concentrations of dissolved solids (measured as salinity) and particulate solids (measured as turbidity) of the chemical's ability to coagulate the desired pollutants. A microsand, made of selectively sieving local soil to obtain particles between 75 and 150 μm in diameter, was used to adjust the particulate solids content of the mixture. Typical additions of the microsand were 120 mg/L, which produced turbidity values of about 22 NTU. The microsand is an inert particulate which is sometimes used to enhance coagulation by weighting the chemical floc, resulting in increased settling rates. A concentrated solution of NaCl was also used to adjust the dissolved solids content of the test water. The final chemical tests (runs 4 through 7) were conducted using proprietary compounds, mostly blends of alum or iron compounds with organic polymers. These tests were only conducted with a single initial turbidity (microsand addition which produced 22 NTU turbidity) and salinity (about 1600 μS/cm) condition. The following lists the coagulant chemicals that were used in the tests:

Ferric chloride (run 1)
DEPHOS-A (Aluminum sulfate (alum) and sodium bicarbonate buffer) (runs 2 and 3)
C-1015 Polyamine/alum blend (run 4a)
C-1325 Organic/Ferric sulfate blend (run 4b)

Accu-Clear (liquid alum slurry) (run 5a)
C-1150H Polyamine blend (run 5b)
C-318P Cationic Polymer (run 6a)
C-2238 Organic/aluminum chloride blend (run 6b)
C-1150 Polyamine blend (run 7a)
C-1025 Polyamine/alum blend (run7b)

The measured amounts of clay and salt were added to each sample and initially stirred. The test chemicals were then added, with rapid mixing at 130 rpm for 2 minutes. Flocculation was encouraged by stirring at 30 rpm for 2 minutes. Setting was then allowed for 15 minute before the samples were withdrawn for analyses. The following paragraphs describe the different test runs.

Ferric chloride (run 1). This run evaluated ferric chloride (purchased from HACH in a 40 gram/L stock solution). The recommended pH range of the water for ferric chloride coagulation is 6 to 9 pH. Before the tests, the pH of the water samples were 7.5. After the coagulation addition, the pH dropped to the range of 6.4 to 7.2. The test stormwater was spiked by lead and copper to add approximately 200 μg/L of each metal to the water. Initial phosphate concentrations were 0.34 mg/L and initial ammonia concentrations were 0.06 mg/L. No COD was detected in the test water. The design was divided into three subsets, each having the same ferric chloride concentration (either 25, 50, or 75 mg/L). Each set included 4 beakers, covering all combinations of high and low turbidity (3 and 24 NTU), plus high and low conductivity (500 and 1600 μS/cm), in a full 2^2 factorial experimental design, as follows:

Ferric chloride addition, mg/l	**Jar number**	**Turbidity**	**Conductivity**
25	1	high	low
25	2	low	low
25	3	high	high
25	4	low	high
50	5	high	low
50	6	low	low
50	7	high	high
50	8	low	high
75	9	high	low
75	10	low	low
75	11	high	high
75	12	low	high
Initial sample	(13)	low	low

There was good floc formation and fast setting was observed during this run for all concentrations of ferric chloride coagulant tested (25 to 75 mg/L). The percentage turbidity removals were very sensitive to the initial turbidities of the test waters. The high turbidity water (22 NTU) had the greatest turbidity reductions (87 to 95%), while the low turbidity test water (1.6 NTU) had minimal turbidity changes. The final turbidities (after the coagulation tests) were all less than 2 NTU. Initial turbidity conditions (affected by the presence of the microsand) did not affect the removal of any of the other pollutants examined. Salinity did not affect the removals of any of the pollutants examined during the ferric chloride tests. Figure 6.25 shows the trends of some of the analyzed pollutants. The optimal dosage of ferric chloride found during these tests was about 25 to 75 mg/L.

- pH decreased with increasing $FeCl_3$ dosage. The lowest pH of the test water was 6.4 (compared to an initial pH before the chemical addition of 7.5).
- turbidity decreased as the dosage increased. Removals of 90+% were observed at ferric chloride dosages

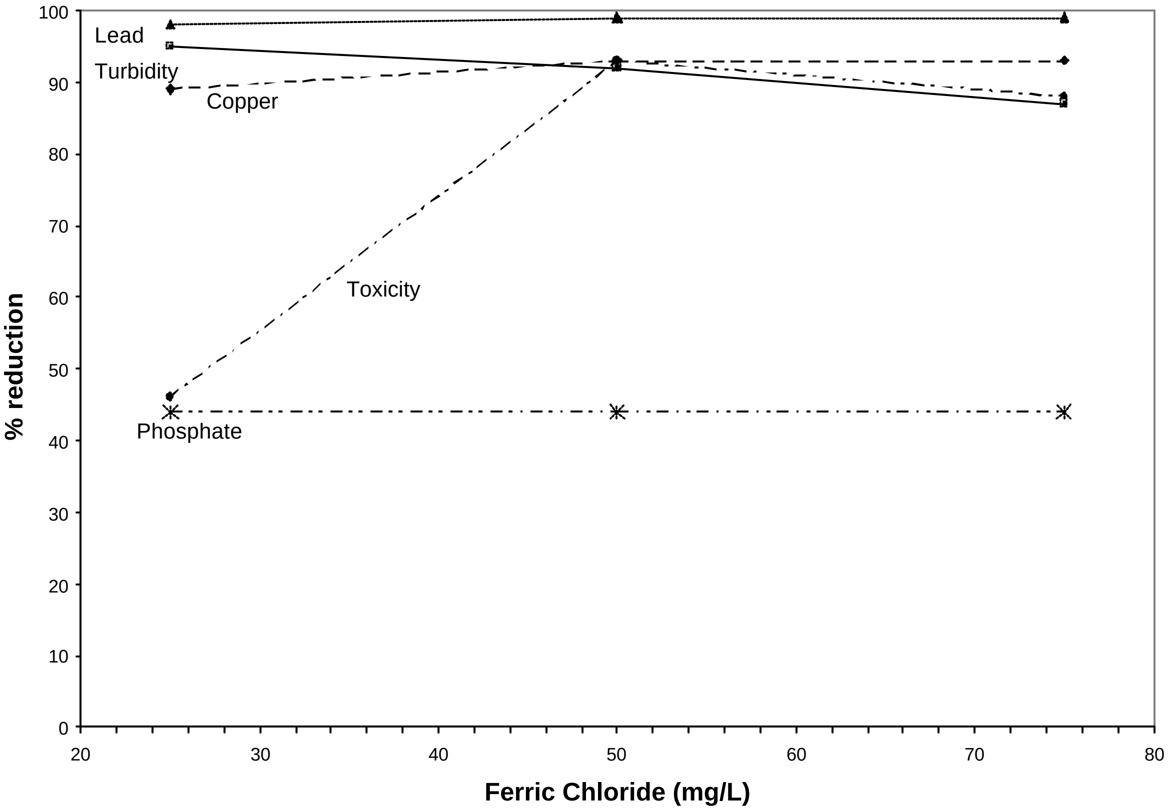
from 25 to 75 mg/L.

- lead, copper, and phosphate concentrations also decreased with increasing dosages. Lead was reduced by about 98%, copper by 90+% and phosphate by about 44% at dosages from 25 to 75 mg/L.

Run 1: Ferric Chloride Tests

coagulant conc. turbidity conc. salinity conc.	Low con. Low turb. Low cond	Low con. High turb. Low cond	Low con. Low turb. High con	Low con. High turb. High con	Med con. Low turb. Low cond	Med con. High turb. Low cond	Med con. Low turb. High con	Med con. High turb. High con	High con. Low turb. Low cond	High con. High turb. Low cond	High con. Low turb. High con	High con. High turb. High con	Zero c Low tu Low cond
$FeCl_3$ (mg/L)	25	25	25	25	50	50	50	50	75	75	75	75	0
Sand (mg/L)	0	120	0	120	0	120	0	120	0	120	0	120	0
Conductivity (µS/cm)	340	460	1720	1690	440	460	1680	1720	340	660	1620	1680	440
Initial jar conditions													
pH	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Conductivity (µS/cm)	340	460	1720	1690	440	460	1680	1720	340	660	1620	1680	440
Turbidity (NTU)	1.6	21.9	1.6	21.4	1.6	20.1	1.6	24.7	1.6	21.6	1.6	16.6	1.6
Toxicity (Microtox)	100	100	100	100	100	100	100	100	100	100	100	100	100
Cu (µg/L)	226	226	226	226	226	226	226	226	226	226	226	226	226
Pb (µg/L)	175	175	175	175	175	175	175	175	175	175	175	175	175
Phosphate (mg/L)	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34	0.34
Ammonia (mg/L)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
COD (mg/L)	0	0	0	0	0	0	0	0	0	0	0	0	0
After coagulation jar conditions													
pH	7	7.1	7	7.1	6.8	6.6	6.6	6.6	6.4	6.4	6.4	6.4	7.2
pH (% reduction)	7	5	7	5	9	12	12	12	15	15	15	15	4
Conductivity (µS/cm)	600	600	1620	1530	580	620	1690	1600	560	640	1680	1660	560
Conductivity (% reduc.)	-76	-30	6	9	-32	-35	-1	7	-65	3	-4	1	-27
Turbidity (NTU)	1.79	1.49	2.22	1.16	2.09	1.86	2.02	1.98	2.79	2.49	0.702	2.09	1.48
Turbidity (% reduction)	-12	93	-39	95	-31	91	-26	92	-74	88	56	87	8
Toxicity (Microtox)	57	31	51	54	19	4	19	7	9	14	14	12	100
Toxicity (% reduc.)	43	69	49	46	81	96	81	93	91	86	86	88	0
Cu (µg/L)	29	27	37	25	15	15	16	16	14	10	14	16	272
Cu (% reduction)	87	88	84	89	93	93	93	93	94	96	94	93	-20
Pb (µg/L)	8	6	8	4	2	2	1	1	1	1	1	1	191
Pb (% reduction)	95	97	95	98	99	99	99	99	99	99	99	99	-9
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.22
Phosphate (% reduc.)	44	44	44	44	44	44	44	44	44	44	44	44	35
Ammonia (mg/L)	1.2	0.05	0.07	0.08	0.02	1.13	0.03	0.07	0.06	0.1	0.02	0.1	0.02
Ammonia (% reduc.)	-1900	17	-17	-33	67	-1783	50	-17	0	-67	67	-67	67
COD (mg/L)	0	0	0	0	0	0	0	0	0	0	0	0	0

COD (% reduction)	na	na	na	na	na	na	na	na	na	na	na	na	na



Run 1 results using ferric chloride additions.

Buffered aluminum sulfate (runs 2 and 3). These tests examined aluminum sulfate (alum) with a sodium bicarbonate buffer (added first). Both reagents were supplied as the commercial product DEPHOS-A (40 lb. for $86, from Aquatic Eco-Systems, Inc., Apopka, FL). The buffer and alum were applied in equal concentrations, as recommended. Run 2 examined low coagulant dosages (3.5 to 10.5 mg/L), while run 3 examined higher coagulant dosages (35 to 105 mg/L). The test stormwater for these runs was spiked by lead and copper (about 200 µg/L), by phosphate (250 µg/L), and by ammonia (70 µg/L). Again, there was no COD detected in the initial water. As in run 1, these runs were divided into three sets each. Each set included four beakers having the same coagulant concentrations, but varying concentrations of salt and clay. The water in the beakers varied in turbidity (3 and 24 NTU) and in salt content (conductivity 500 and 1600 µS/cm). The following table shows the experimental design for run 3. Run 2 was identical, except that the coagulant concentrations were 0.1 of the concentrations used in run 3.

Aluminum sulfate addition, mg/l	**Jar number**	**Turbidity**	**Conductivity**
35	1	high	low
35	2	low	low
35	3	high	high
35	4	low	high
70	5	high	low
70	6	low	low

70	7	high	high
70	8	low	high
105	9	high	low
105	10	low	low
105	11	high	high
105	12	low	high
Initial sample	(13)	low	low

A buffered alum was tested during these runs over a wide range of coagulant concentrations (3.5 to 105 mg/L). As for ferric chloride, the percentage turbidity removal was very sensitive to the initial turbidities of the test waters for these alum tests. The high turbidity water (22 NTU) had the greatest turbidity reductions (37 to 83%), while the low turbidity test water (1.5 NTU) had increases in turbidity (to about 3 to 9 NTU). Initial turbidity conditions (affected by the presence of the microsand) did not affect the removal of any of the other pollutants examined. Salinity also did not affect the removals of any of the pollutants examined during these buffered alum tests. Because of the lack of noticeable effects of turbidity and salinity on the removal of the pollutants, the further coagulant tests only examined single turbidity (about 22 NTU) and salinity (about 1600 µS/cm) conditions with more coagulant concentrations. Figure 26 shows removal plots for this coagulant. The optimal dosage for this buffered alum coagulant is about 70 mg/L.

- pH remained relatively constant and did not change with the addition of the buffered alum.
- turbidity reductions improved with increasing coagulant concentrations, up to about 83% reductions at 70 mg/L.
- copper and lead removals improved with increasing coagulant dosages, up to about 70 mg/L alum. The removal rates were about the same for the highest dosage (105 mg/L) examined. The best copper removals were about 86%, and the best lead removals were about 97%.
- toxicity reductions were as high as 93% at 70 mg/L alum dosage, but the toxicity of the water increased at the highest alum dosage. All samples (except 1, 3 and 13) were transferred into Imhoff cones for longer settling periods. The supernatant from the Imhoff cones were then analyzed for toxicity screening (using the Microtox™ procedure) after 15 minutes and 24 hours of settling. As shown in the following table, the increased settling period significantly decreased the water toxicity.

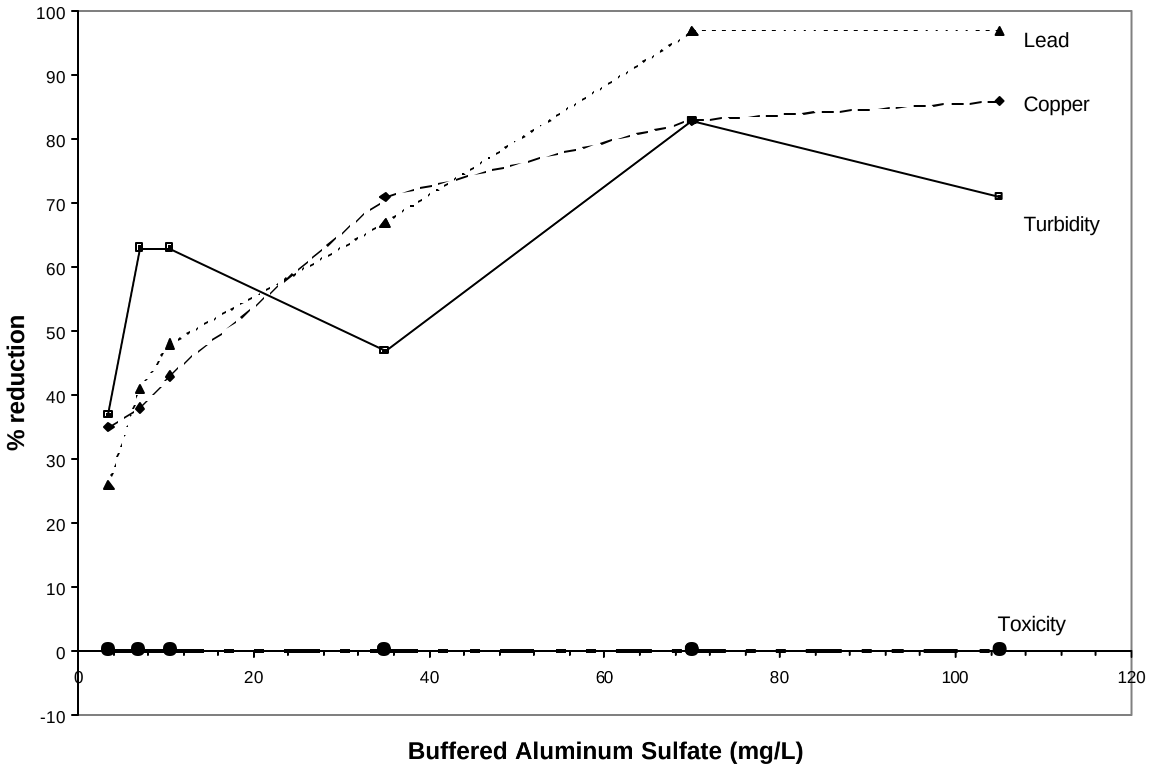
Sample number	**Toxicity after 15 min setting**	**Toxicity after 24 hours setting**
6	18 (% light reduction)	1
7	46	16
8	5	2
9	11	5
10	12	15
11	8	6
12	8	4

Run 2: Buffered Aluminum Sulfate Tests (low conc.)

coagulant conc. turbidity conc. salinity conc.	Low con. Low turb. Low cond	Low con. High turb. Low cond	Low con. Low turb. High con	Low con. High turb. High con	Med con. Low turb. Low cond	Med con. High turb. Low cond	Med con. Low turb. High con	Med con. High turb. High con	High con. Low turb. Low cond	High con. High turb. Low cond	High con. Low turb. High con	High con. High turb. High con	Zero Low Low cond
Aluminum sulfate (mg/L)	3.5	3.5	3.5	3.5	7	7	7	7	10.5	10.5	10.5	10.5	0
Sand (mg/L)	0	120	0	120	0	120	0	120	0	120	0	120	0
Conductivity (µS/cm)	540	530	1600	1650	540	580	1710	1690	540	620	1650	1690	540
Initial jar conditions													
pH	7.5	7.1	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5
Conductivity (µS/cm)	540	530	1600	1650	540	580	1710	1690	540	620	1650	1690	540
Turbidity (NTU)	1.5	22	1.5	22	1.5	22	1.5	22	1.5	22	1.5	22	1.5
Toxicity (Microtox)	100	100	100	100	100	100	100	100	100	100	100	100	100
Cu (µg/L)	260	260	260	260	260	260	260	260	260	260	260	260	260
Pb (µg/L)	171	171	171	171	171	171	171	171	171	171	171	171	171
Phosphate (mg/L)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Ammonia (mg/L)	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
COD (mg/L)	0	0	0	0	0	0	0	0	0	0	0	0	0
After coagulation jar conditions													
pH	7.2	7.5	7	7.4	7.2	7.3	7.2	7.3	7.1	7.3	7.2	7.3	7.1
pH (% reduction)	4	-6	7	1	4	3	4	3	5	3	4	3	5
Conductivity (µS/cm)	550	550	1630	1620	580	620	1710	1700	520	640	1680	1690	540
Conductivity (% reduc.)	-2	-4	-2	2	-7	-7	0	-1	4	-3	-2	0	0
Turbidity (NTU)	6.19	15.4	2.94	13.8	3.04	5.73	2.42	8.1	2.61	7.71	4.36	8.15	2.24
Turbidity (% reduction)	-313	30	-96	37	-103	74	-61	63	-74	65	-191	63	-49
Toxicity (Microtox)	100	100											
toxicity (% reduc.)	0	0	na	na	na	na	na	na	na	na	na	na	na
Cu (µg/L)		150	192	168	192	77	197	161	177	83	81	147	231
Cu (% reduction)	na	42	26	35	26	70	24	38	32	68	69	43	11
Pb (µg/L)		117	127	127	127	45	125	101	109	51	55	89	161
Pb (% reduction)	na	32	26	26	26	74	27	41	36	70	68	48	6
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	
Phosphate (% reduc.)	17	17	17	17	17	17	17	17	17	17	17	17	100
Ammonia (mg/L)	0.04	0.03	0.05	0.02	0.02	0.04	0.02	0.03	0.03	0.05	0.02	0.06	
Ammonia (% reduc.)	43	57	29	71	71	43	71	57	57	29	71	14	na
COD (mg/L)	0	0	0	0	0	0	0	0	0	0	0	0	0
COD (% reduction)	na	na	na	na	na	na	na	na	na	na	na	na	na

Run 3: Buffered Aluminum Sulfate Tests (high conc.)

coagulant conc. turbidity conc. salinity conc.	Low con. Low turb. Low cond	Low con. High turb. Low cond	Low con. Low turb. High con	Low con. High turb. High con	Med con. Low turb. Low cond	Med con. High turb. Low cond	Med con. Low turb. High con	Med con. High turb. High con	High con. Low turb. Low cond	High con. High turb. Low cond	High con. Low turb. High con	High con. High turb. High con	Z L L c
Sodium bicarbonate (mg/L)	35	35	35	35	70	70	70	70	105	105	105	105	0
Aluminum sulfate (mg/L)	35	35	35	35	70	70	70	70	105	105	105	105	0
Sand (mg/L)	0	120	0	120	0	120	0	120	0	120	0	120	0
Conductivity (µS/cm)	540	540	1560	1600	550	550	1620	1580	550	550	1600	1620	5
Initial jar conditions													
pH	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7
Conductivity (µS/cm)	540	540	1560	1600	550	550	1620	1580	550	550	1600	1620	5
Turbidity (NTU)	3.51	23	3.5	23	3.5	23	3.5	23	3.5	23	3.5	23	3
Toxicity (Microtox)	100	100	100	100	100	100	100	100	100	100	100	100	1
Cu (µg/L)	76	76	76	76	76	76	76	76	76	76	76	76	7
Pb (µg/L)	63	63	63	63	63	63	63	63	63	63	63	63	6
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0
COD (mg/L)	0	0	0	0	0	0	0	0	0	0	0	0	0
After coagulation jar conditions													
pH	7.4	7.4	7.5	7.3	7.3	7.3	7.4	7.3	7.3	7.3	7.3	7.3	7
pH (% reduction)	1	1	0	3	3	3	1	3	3	3	3	3	0
Conductivity (µS/cm)	530	550	1550	1600	550	550	1600	1590	540	520	1610	1620	5
Conductivity (% reduc.)	2	-2	1	0	0	0	1	-1	2	5	-1	0	0
Turbidity (NTU)	8.65	12.5	7.68	12.3	6.49	11.3	4.25	3.81	3.79	8.85	5.63	6.59	3
Turbidity (% reduction)	-146	46	-119	47	-85	51	-21	83	-8	62	-61	71	-
Toxicity (Microtox)	51	37	51	54	19	4	19	7	9	14	14	100	1
Toxicity (% reduc.)	49	63	49	46	81	96	81	93	91	86	86	0	0
Cu (µg/L)	40	22	30	22	22	18	19	13	13	11	13	11	7
Cu (% reduction)	47	71	61	71	71	76	75	83	83	86	83	86	-
Pb (µg/L)	43	19	33	21	39	15	14	2	4	4	4	2	5
Pb (% reduction)	32	70	48	67	38	76	78	97	94	94	94	97	1
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0
Phosphate (% reduc.)	0	0	0	0	0	0	0	0	0	0	0	0	0
COD (mg/L)	0	0	0	0	0	0	0	0	0	0	0	0	0
COD (% reduction)	na	na	na	na	na	na	na	na	na	na	na	na	n



Run 2 and 3 tests using buffered aluminum sulfate (low and high conc.)

C-1015, polyamine/alum blend solution (run 4a) and C-1325, organic/ferric sulfate blend solution (run 4b). This run initially examined a Polyamine/alum blend (C-1015 from Polydyne, Inc.). This material was advertised as being effective for color removal, phosphate removal, and for the treatment of oily waters. It is a combination of organic and inorganic coagulants. The other chemical coagulant tested during run 4 was an organic ferric sulfate blend (C-1325, also from Polydyne, Inc.). The test stormwater sample was spiked by lead (50 μg/L), by copper (75 μg/L), by phosphate (200 μg/L) and by ammonia (60 μg/L) for this series of tests. Again, no COD was detected in the test water. All samples contained sand and salt (high turbidity and high conductivity). One control sample was used for both coagulant tests. Six concentrations of each chemical were tested:

Jar number	Concentration of C-1015, mg/L
1	3
2	5
3	8
4	15
5	25
6	40

Jar number	Concentration of C-1325, mg/L
7	3
8	5
9	8
10	15
11	25
12	40

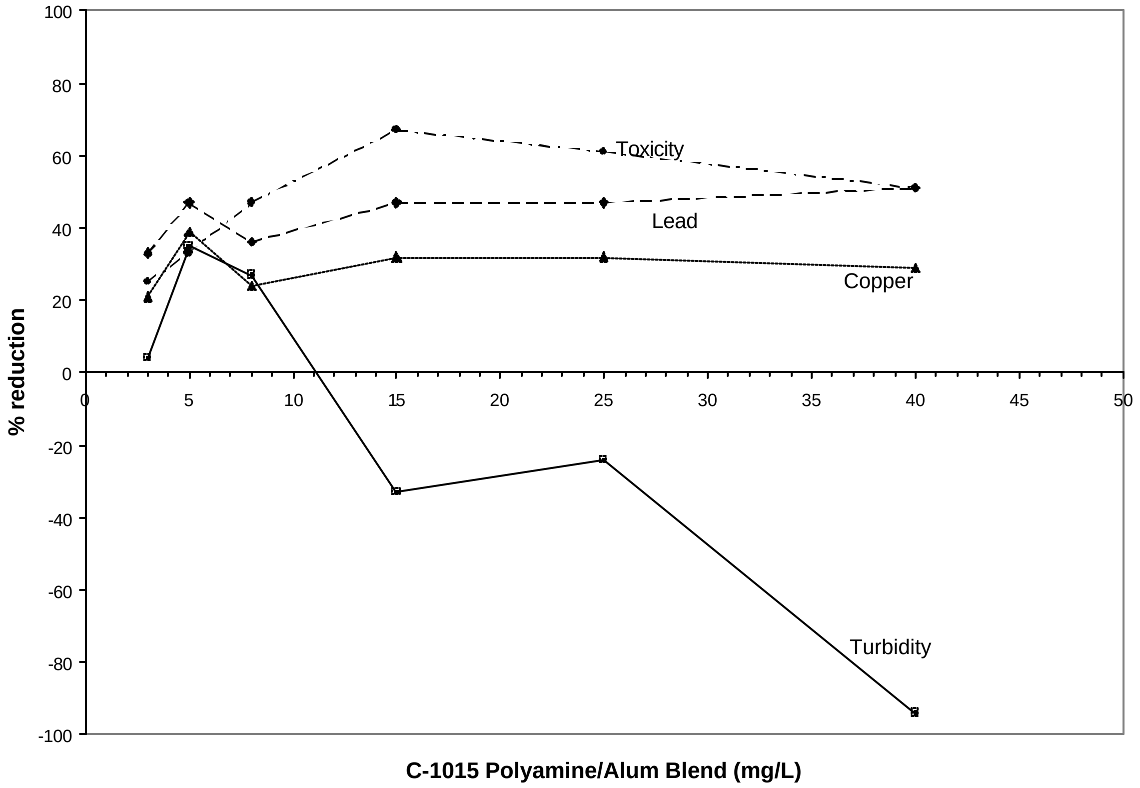
C-1015, polyamine/alum blend solution (run 4a) results. As noted above, all coagulant tests in runs 4 through 7 were only conducted with a single turbidity and salinity. Turbidity, COD and phosphate all worsened with increasing dosages, associated with increasing coagulant concentrations. The pH remained the same during the tests (7.2 to 7.4). Figure 6.27 shows removal plots for this coagulant. The optimal dosage for this coagulant was found to be about 15 mg/L.

- turbidity was reduced by up to 27% at a dosage of 8 mg/L, after which the turbidity increased (up to 43 NTU) because of the large dosages of coagulant (up to 40 mg/L).
- toxicity removal (67% reduction) was best at a 15 mg/L coagulant dosage, then the removal rate slightly decreased (to about 50%) at the highest coagulant dosage.
- copper and lead were removed at rates of about 20 to 40% (copper) and 33 to 51% (lead), with slight increasing removals at higher coagulant concentrations.
- COD increased to 8 to 30 mg/L at higher coagulant dosages (after 15 mg/L).
- phosphate also increased to about 1.2 mg/L at the highest coagulant dosages (40 mg/L)

Run 4a: C-1015 Polyamine/Alum blend solution

C-1015 conc. turbidity conc. salinity conc.	Lowest con. High turb. High con	Low con. High turb. High con	Medium con. High turb. High con	High con. High turb. High con	Higher con. High turb. High con	Highest con. High turb. High con	Zero con. Low turb. Low cond
C-1015 Polyamine/Alum blend solution (mg/L)	3	5	8	15	25	40	0
Sand (mg/L)	120	120	120	120	120	120	0
Conductivity (µS/cm)	1600	1600	1600	1600	1600	1600	500
Initial jar conditions							
pH	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Conductivity (µS/cm)	1600	1600	1600	1600	1600	1600	500
Turbidity (NTU)	22	22	22	22	22	22	2.1
Toxicity (Microtox)	76	76	76	76	76	76	76
Cu (µg/L)	76	76	76	76	76	76	76
Pb (µg/L)	55	55	55	55	55	55	55
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Ammonia (mg/L)	0.06	0.06	0.06	0.06	0.06	0.06	0.06
COD (mg/L)	0	0	0	0	0	0	0
After coagulation jar conditions							
pH	7.4	7.4	7.4	7.3	7.2	7.4	4.4
pH (% reduction)	0	0	0	1	3	0	41
Conductivity (µS/cm)	1600	1620	1540	1650	1660	1600	540
Conductivity (% reduc.)	0	-1	4	-3	-4	0	-8
Turbidity (NTU)	21.1	14.3	16.1	29.2	27.2	42.7	2.97
Turbidity (% reduction)	4	35	27	-33	-24	-94	-41

Toxicity (Microtox)	57	51	40	25	30	37	88
Toxicity (% reduc.)	25	33	47	67	61	51	-16
Cu (µg/L)	60	46	58	52	52	54	64
Cu (% reduc.)	21	39	24	32	32	29	16
Pb (µg/L)	37	29	35	29	29	27	43
Pb (% reduc.)	33	47	36	47	47	51	22
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.23	1.16	0.19
Phosphate (% reduc.)	0	0	0	0	-21	-511	0
Ammonia (mg/L)	0.04	0.02	0.03	na	na	na	na
Ammonia (% reduc.)	33	67	50	na	na	na	na
COD (mg/L)	0	0	0	8	15	30	0
COD (% reduction)	na	na	na	increase	increase	increase	na



Run 4a tests using C-1015 Polyamine/Alum blend solution

<u>C-1325, organic/ferric sulfate blend solution (run 4b) results.</u> Again, only high turbidity (22 NTU) and high salinity (1600 µS/cm) conditions were used for this test. The phosphate and COD levels also notably increased at high coagulant dosages. The pH remained the same during the tests (7.3 to 7.5). Figure 6.28 shows removal plots for this

coagulant. This coagulant was not found to be very suitable during these tests due to the generally low turbidity, toxicant, and metal removal rates observed, plus the large observed increases in phosphate and COD.

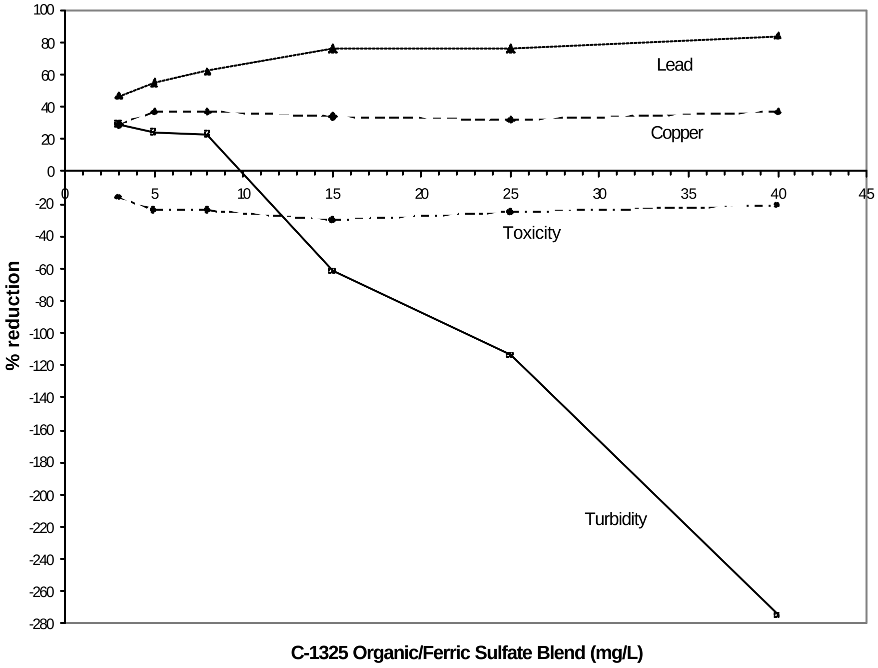
- turbidity was reduced by about 20 to 30% at low dosages, but the turbidity increased up to 82 NTU at a coagulant dosage of 40 mg/L.
- toxicity showed a general worsening (by about 20 to 30%) with this coagulant.
- copper decreased by about 30 to 40% and did not show any clear pattern with changing coagulant dosage.
- lead showed larger decreases (by 47 to 84%) with increasing dosages.
- phosphate increased to as high as 3.1 mg/L at the highest coagulant dosage (40 mg/L).
- COD also showed increases (up to 85 mg/L) with higher dosages.

Run 4b: C-1325 Organic/Ferric Sulfate blend solution

C-1325	Lowest con.	Low con.	Medium con.	High con.	Higher con.	Highest con.	Zero con.
turbidity conc.	High turb.	High turb.	High turb.	High turb.	High turb.	High turb.	Low turb.
salinity conc.	High con	High con	High con	High con	High con	High con	Low cond
C-1325 (mg/L)	3	5	8	15	25	40	0
Sand (mg/L)	120	120	120	120	120	120	0
Conductivity (µS/cm)	1600	1600	1600	1600	1600	1600	500
Initial jar conditions							
pH	7.4	7.4	7.4	7.4	7.4	7.4	7.4
Conductivity (µS/cm)	1600	1600	1600	1600	1600	1600	500
Turbidity (NTU)	22	22	22	22	22	22	2.1
Toxicity (Microtox)	76	76	76	76	76	76	76
Cu (µg/L)	76	76	76	76	76	76	76
Pb (µg/L)	55	55	55	55	55	55	55
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.19	0.19	0.19
COD (mg/L)	0	0	0	0	0	0	0
After coagulation jar conditions							
pH	7.5	7.5	7.4	7.4	7.3	7.3	7.4
pH (% reduction)	-1	-1	0	0	1	1	0
Conductivity (µS/cm)	1580	1540	1580	1550	1600	1570	540
Conductivity (% reduc.)	1	4	1	3	0	2	-8
Turbidity (NTU)	15.6	16.8	16.9	35.6	47	82.4	2.97
Turbidity (% reduction)	29	24	23	-62	-114	-275	-41
Toxicity (Microtox)	88	94	94	99	95	92	88
Toxicity (% reduc.)	-16	-24	-24	-30	-25	-21	-16
Cu (µg/L)	54	48	48	50	52	48	64
Cu (% reduc.)	29	37	37	34	32	37	16
Pb (µg/L)	29	25	21	13	13	9	43
Pb (% reduc.)	47	55	62	76	76	84	22
Phosphate (mg/L)	0.19	0.19	0.19	0.63	1.16	3.08	0.19
Phosphate (% reduc.)	0	0	0	-232	-511	-1521	0
COD (mg/L)	0	0	0	12	30	85	0
COD (% reduction)	na	na	na	increase	increase	increase	na

Accu-Clear, an alum slurry (run 5a) and C-1150H, polyamine blend solution (run 5b)

This run examined Accu-Clear (an alum slurry from Aquatic Eco-Systems), and a polyamine blend solution (C-1150H from Polydyne, Inc.). The Accu-Clear coagulant concentrations ranged from 0.01 to 0.16 mL/L and the C-1150H coagulant concentrations ranged from 3 to 40 mg/L. The C-1150H is a combination of organic and inorganic coagulants that performs better in low alkalinity water and in water with a high salt content. The test stormwater sample was spiked by lead (35 µg/L), by copper (55 µg/L), by phosphate (200 µg/L) and by ammonia (1.1 mg/L) for this series of tests. Again, no COD was detected in the test water. All samples contained sand and salt (high turbidity and high conductivity). One control sample was used for both coagulants. Accu-Clear is a slurry and was tested at additions of 0.01 to 0.16 mL/L. The C-1150H was tested at dosages ranging from 3 to 40 mg/L.



Run 4b using C-1325 Organic/Ferric Sulfate blend solution

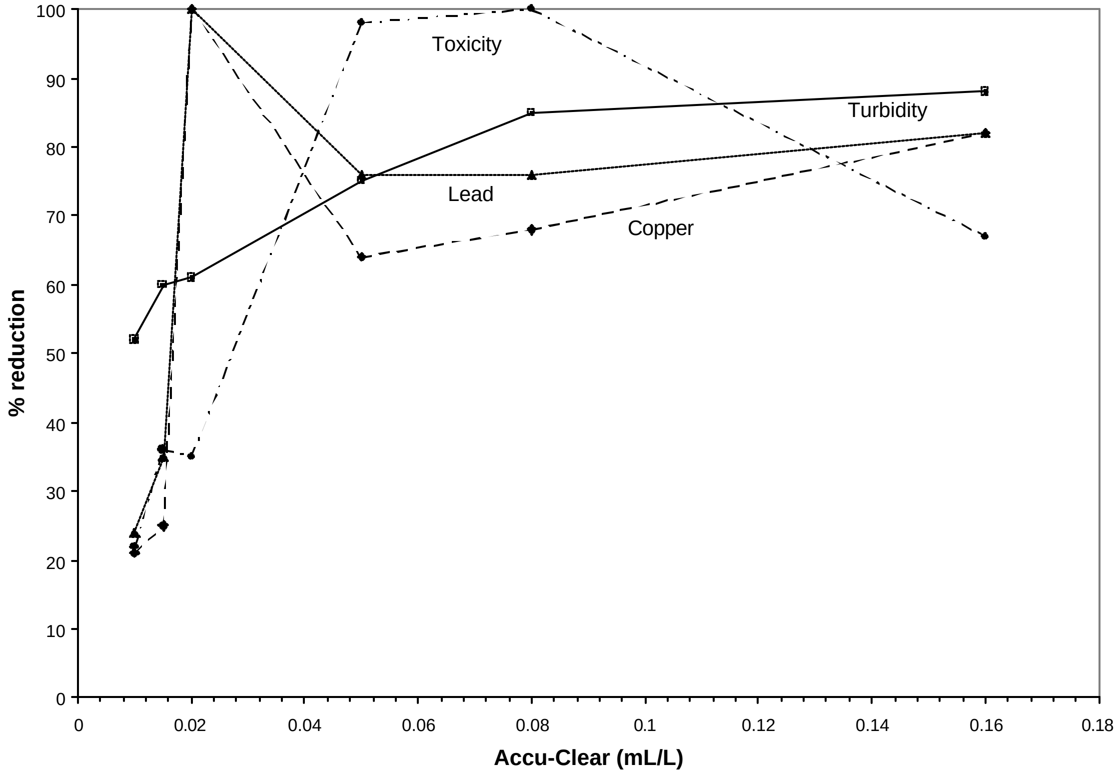
Accu-Clear, an alum slurry (run 5a) results. The pH generally remained the same during these tests (7.3 to 7.6). There was no noticeable change in phosphate (at 0.26 mg/L) or COD (not detected) with this material. Figure 6.29 shows removal plots for Accu-Clear. The optimal Accu-Clear dosage was found to be about 0.08 mL/L during these tests.

- turbidity was reduced by 50 to 88%, increasing in removal with increasing dosages, but leveling off at about 0.08 mL/L.
- toxicity reductions were as high as 100% at 0.05 to 0.08 mL/L, but decreased to 66% at 0.16 mL/L coagulant dosage.
- copper reductions of 70 to 100% occurred between 0.02 and 0.16 mL/L.
- lead reductions were 80 to 100% also between 0.02 and 0.16 mL/L.

Run 5a: Accu-Clear

Accu-Clear conc. turbidity conc. salinity conc.	Lowest con. High turb. High con	Low con. High turb. High con	Medium con. High turb. High con	High con. High turb. High con	Higher con. High turb. High con	Highest con. High turb. High con	Zero con. Low turb. Low cond
Accu-Clear mL/L	0.01	0.015	0.02	0.05	0.08	0.16	0

Sand, mg/L	120	120	120	120	120	120	0
Conductivity (µS/cm)	1700	1700	560	1500	1670	1680	400
Initial jar conditions							
pH	7.61	7.61	7.63	7.6	7.61	7.5	7.6
Conductivity (µS/cm)	1700	1700	560	1500	1670	1680	400
Turbidity (NTU)	22	22	22	22	22	22	22
Toxicity (Microtox)	94	94	94	94	94	94	94
Cu (µg/L)	56	56	56	56	56	56	56
Pb (µg/L)	34	34	34	34	34	34	34
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Ammonia (mg/L)	1.1	1.1	1.1	1.1	1.1	1.1	1.1
COD (mg/L)	0	0	0	0	0	0	0
After coagulation jar conditions							
pH	7.61	7.61	7.63	7.6	7.52	7.25	7.6
pH (% reduction)	0	0	0	0	1	3	0
Conductivity (µS/cm)	1700	1700	550	1550	1650	1680	400
Conductivity (% reduc.)	0	0	2	-3	1	0	0
Turbidity (NTU)	10.6	8.84	8.62	5.42	3.32	2.71	2.48
Turbidity (% reduc.)	52	60	61	75	85	88	89
Toxicity (Microtox)	73	60	61	2	0	31	94
Toxicity (% reduc.)	22	36	35	98	100	67	0
Cu (µg/L)	44	42	0	20	18	10	56
Cu (% reduction)	21	25	100	64	68	82	0
Pb (µg/L)	26	22	0	8	8	6	34
Pb (% reduc.)	24	35	100	76	76	82	0
Phosphate (mg/L)	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Phosphate (% reduc.)	-37	-37	-37	-37	-37	-37	-37
Ammonia (mg/L)	0.27	1.14	1.10	1.14	1.06	1.13	0.96
Ammonia (% reduc.)	75	-4	0	-4	4	-3	13
COD (mg/L)	0	0	0	0	0	0	0
COD (% reduction)	na	na	na	na	na	na	na



Run 5a using Accu-Clear, an alum solution

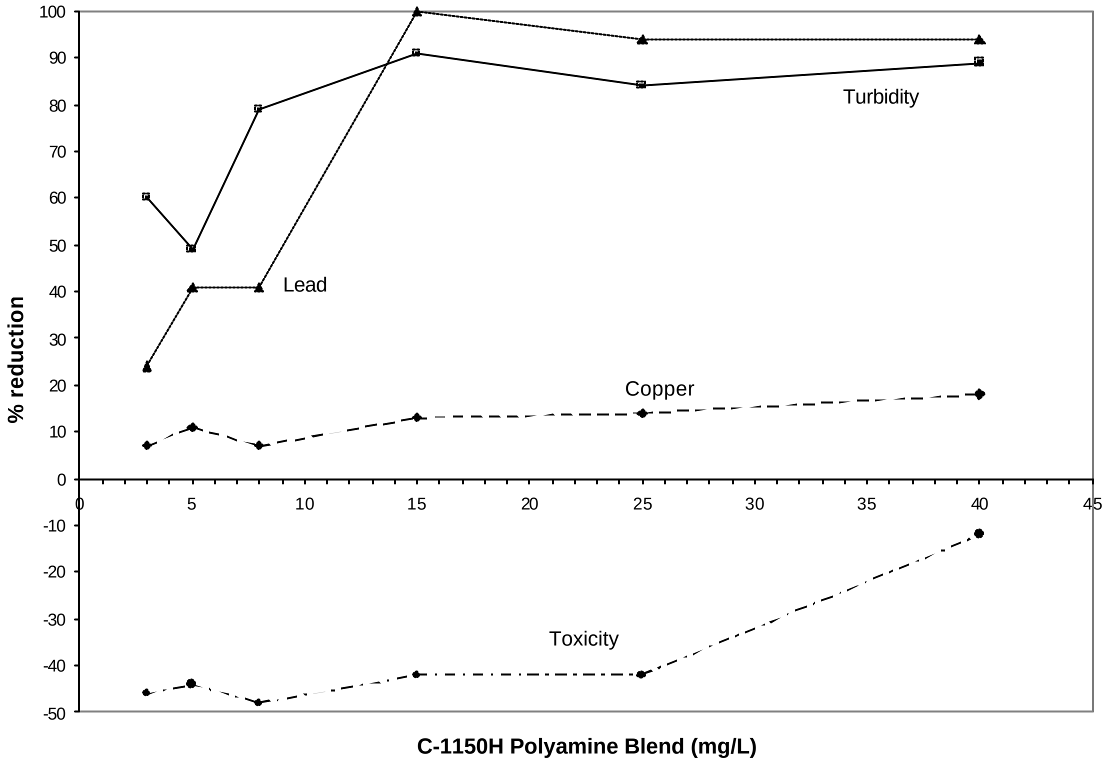
C-1150H, polyamine blend solution (run 5b) results. The pH dropped with increasing dosages (from 7.5 to 6.7 at 40 mg/L coagulant dosage). Both phosphate and COD had large increases with increasing coagulant dosages. Figure 6.30 shows removal plots for C-1150H. The optimal C-1150H coagulant dosage was found to be about 15 mg/L during these tests.

- turbidity was reduced by 60 to 90%, with better results with higher concentrations (leveling off at about 15 mg/L).
- toxicity increased by about 40% with coagulant additions.
- copper was reduced by as much as 18% at the highest coagulant dosage.
- lead was reduced by about 95% with coagulant dosages greater than 15 mg/L.
- phosphate had large increases after dosages of about 15 mg/L (up to 2.4 mg/L at the highest coagulant dosage of 40 mg/L).
- COD had large increases after dosages of about 8 mg/L (up to 120 mg/L at the highest coagulant dosage of 40 mg/L).

Run 5b: C-1150H Polyamine blend solution

C-1150H conc.	Lowest con.	Low con.	Medium con.	High con.	Higher con.	Highest con.	Zero con.
turbidity conc.	High turb.	High turb.	High turb.	High turb.	High turb.	High turb.	Low turb.
salinity conc.	High con	High con	High con	High con	High con	High con	Low cond
C-1150H (mg/L)	3	5	8	15	25	40	0
Sand (mg/L)	120	120	120	120	120	120	0
Conductivity (µS/cm)	1670	1660	1680	1690	1680	1670	400

Initial jar conditions							
pH	7.4	7.5	7.4	7.5	7.4	7.5	7.6
Conductivity (µS/cm)	1670	1660	1680	1690	1680	1670	400
Turbidity (NTU)	22	22	22	22	22	22	22
Toxicity (Microtox)	52	52	52	52	52	52	52
Cu (µg/L)	56	56	56	56	56	56	56
Pb (µg/L)	34	34	34	34	34	34	34
Phosphate (mg/L)	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Ammonia (mg/L)	1.1	1.1	1.1	1.1	1.1	1.1	1.1
COD (mg/L)	0	0	0	0	0	0	0
After coagulation jar conditions							
pH	7.34	7.25	7.25	6.99	6.86	6.71	7.6
pH (% reduction)	1	3	2	7	7	11	0
Conductivity (µS/cm)	1670	1650	1670	1670	1680	1660	400
Conductivity (% reduc.)	0	1	1	1	0	1	0
Turbidity (NTU)	8.75	11.2	4.66	1.9	3.55	2.48	
Turbidity (% reduc.)	60	49	79	91	84	89	na
Toxicity (Microtox)	76	75	77	74	74	58	94
Toxicity (% reduc.)	-46	-44	-48	-42	-42	-12	-81
Cu (µg/L)	52	50	52	49	48	46	56
Cu (% reduction)	7	11	7	13	14	18	0
Pb (µg/L)	26	20	20	0	2	2	34
Pb (% reduc.)	24	41	41	100	94	94	0
Phosphate (mg/L)	0.26	0.30	0.39	0.37	1.47	2.42	0.26
Phosphate (% reduc.)	-37	-58	-105	-95	-674	-1174	-37
Ammonia (mg/L)	1.06	1.18	1.10	1.08	1.11	1.10	0.96
Ammonia (% reduc.)	4	-7	0	2	-1	0	13
COD (mg/L)	0	0	22	22	70	121	0
COD (% reduction)	na	na	increase	increase	increase	increase	na



Run 5b using C-1150H Polyamine blend solution

C-318P, cationic polymer solution (run 6a) and C-2238, polmethydiallyl ammonium chloride/aluminum chloride blend (run 6b)

This run examined a low molecular weight, highly cationic organic coagulant (C-318 from Polydyne, Inc.) and an organic/aluminum chloride blend (C-2238, also from Polydyne, Inc.). The C-2238 is an organic/aluminum chloride blend that is advertised as being effective for color removal, phosphorus removal, and treatment of oily waters. The stormwater sample was spiked by phosphate (250 µg/L) and by ammonia (170 µg/L). No metal analyses were conducted for this test series. All samples contained sand and salt (high turbidity, high conductivity). One control sample was used for both coagulants. Six concentrations of each chemicals were tested:

Jar number	Concentration of C-318P
1	3
2	5
3	8
4	15
5	25
6	40

Jar number	Concentration of C-2238, mg/l
7	3
8	5
9	8

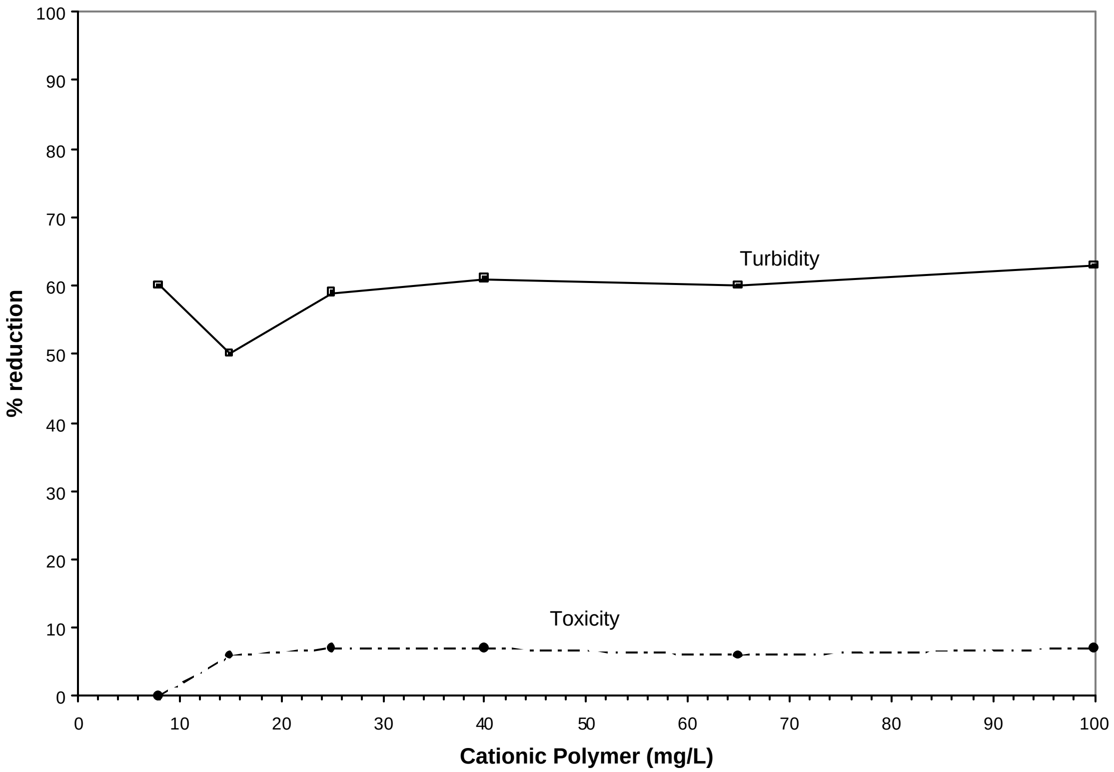
10	15
11	25
12	40

C-318P, cationic polymer solution (run 6a) results. The pH slightly increased during these tests, from 6.3 to 7.2 before coagulant addition, to 7.5 to 7.7 after the coagulant test. Large increases in phosphate and COD were observed at all coagulant dosages tested (8 to 100 mg/L). No floc formation was observed with this coagulant. Figure 6.31 indicates some of the pollutant trends for this coagulant. No metals were analyzed during these tests. This coagulant was not found to be very suitable during these tests due to the generally low turbidity and toxicant removal rates observed, plus the large observed increases in phosphate and COD.

- turbidity decreased by 50 to 60% at all dosages tested, with no apparent trend with coagulant dosage.
- toxicity had a slight improvement (by about 6 to 7%) at all dosages of 15 mg/L and greater.
- phosphate increased to as high as 2.3 mg/L during these tests (low of 1.1 mg/L phosphate at 8 mg/L coagulant dosage).
- COD increased to as high as >200 mg/L during these tests (low of 63 mg/L COD at 8 mg/L coagulant dosage).

Run 6a: C-318P Cationic Polymer solution

C-318P conc. turbidity conc. salinity conc.	Lowest con. High turb. High con	Low con. High turb. High con	Medium con. High turb. High con	High con. High turb. High con	Higher con. High turb. High con	Highest con. High turb. High con	Zero con. Low turb. Low cond
C-318P (mg/L)	8	15	25	40	65	100	0
Sand (mg/L)	120	120	120	120	120	120	0
Conductivity (µS/cm)	1650	1650	1650	1650	1650	1650	1650
Initial jar conditions							
pH	6.3	6.9	7.2	7.2	7.2	7.2	
Conductivity (µS/cm)	1650	1650	1650	1650	1650	1650	500
Turbidity (NTU)	22	22	22	22	22	22	22
Toxicity (Microtox)	95	95	95	95	95	95	95
Phosphate (mg/L)	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Ammonia (mg/L)	0.17	0.17	0.17	0.17	0.17	0.17	0.17
COD (mg/L)	0	0	0	0	0	0	0
After coagulation jar conditions							
pH	7.5	7.6	7.6	7.7	7.7	7.7	
pH (% reduction)	-19	-10	-6	-7	-7	-7	na
Conductivity (µS/cm)	1670	1650	1650	1600	1670	1620	500
Conductivity (% reduc.)	-1	0	0	3	-1	2	0
Turbidity (NTU)	8.82	11	9.06	8.68	8.81	8.17	4.76
Turbidity (% reduc.)	60	50	59	61	60	63	78
Toxicity (Microtox)	95	89	88	88	89	88	80
Toxicity (% reduc.)	0	6	7	7	6	7	16
Phosphate (mg/L)	1.14	1.37	1.76	1.79	2.08	2.34	0.26
Phosphate (% reduc.)	-338	-427	-577	-588	-700	-800	0
Ammonia (mg/L)	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Ammonia (% reduc.)	0	0	0	0	0	0	0
COD (mg/L)	63	120	199	o/r	o/r	o/r	0
COD (% reduction)	increase	increase	increase	increase	increase	increase	na



Run 6a using C-318P Cationic Polymer solution

C-2238, polmethydiallyl ammonium chloride/aluminum chloride blend (run 6b) results. The pH decreased during these tests, from 7.5 to 6.4 at the highest coagulant dosage (100 mg/L) and from 7.4 to 6.8 at a more modest dosage of 25 mg/L, for example. Large increases in phosphate and COD were observed at coagulant dosages greater than 15 mg/L. Large flocs and clear setting were observed with this coagulant.

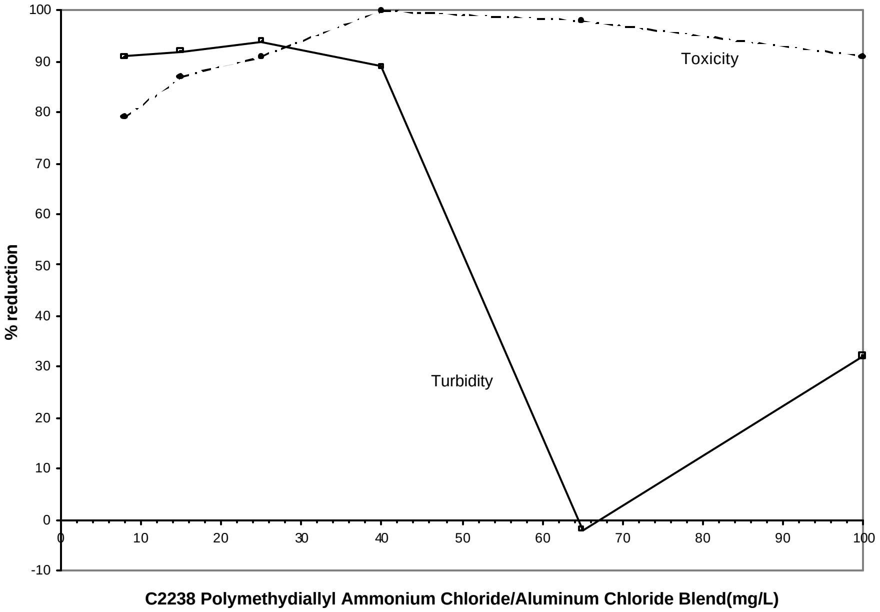
Figure 32 indicates some of the pollutant trends for this coagulant. No metals were analyzed during these tests. The optimal dosage for this coagulant was found to be about 8 to 15 mg/L during these tests.

- turbidity reductions were good (about 90%) at low coagulant dosages (8 to 40 mg/L). The turbidity then increased with increasing coagulant dosages.
- toxicity had very good removals (80 to 100%) at all dosages tested (8 to 100 mg/L).
- phosphates increased in concentration with increasing dosages, especially at dosages greater than 25 mg/L. At 100 mg/L coagulant, the phosphate concentration was 2.3 mg/L.
- COD also had increased concentrations with all dosages, from 10 mg/L at the lowest dosage (8 mg/L) to 86 mg/L at the highest dosage (100 mg/L).

Run 6b: C-2238 Polymethydiallyl ammonium chloride/aluminum chloride blend

C-2238 conc. turbidity conc. salinity conc.	Lowest con. High turb. High con	Low con. High turb. High con	Medium con. High turb. High con	High con. High turb. High con	Higher con. High turb. High con	Highest con. High turb. High con	Zero con. Low turb. Low cond
C-2238 (mg/L)	8	15	25	40	65	100	0
Sand (mg/L)	120	120	120	120	120	120	0

Conductivity (µS/cm)	1650	1650	1650	1650	1650	1650	500
Initial jar conditions							
pH	7.2	7.4	7.4	7.4	7.5	7.5	
Conductivity (µS/cm)	1650	1650	1650	1650	1650	1650	500
Turbidity (NTU)	22	22	22	22	22	22	22
Toxicity (Microtox)	95	95	95	95	95	95	95
Phosphate (mg/L)	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Ammonia (mg/L)	0.17	0.17	0.17	0.17	0.17	0.17	0.17
COD (mg/L)	0	0	0	0	0	0	0
After coagulation jar conditions							
pH	7.1	7	6.8	6.6	6.1	6.4	
pH (% reduction)	1	5	8	11	19	15	na
Conductivity (µS/cm)	1640	1600	1620	1600	1640	1610	500
Conductivity (% reduc.)	1	3	2	3	1	2	0
Turbidity (NTU)	1.9	1.84	1.33	2.48	22.4	15	4.76
Turbidity (% reduc.)	91	92	94	89	-2	32	78
Toxicity (Microtox)	20	12	9	0	2	9	80
Toxicity (% reduc.)	79	87	91	100	98	91	16
Phosphate (mg/L)	0.26	0.26	0.42	0.78	1.11	2.25	0.26
Phosphate (% reduc.)	0	0	-62	-200	-327	-765	0
Ammonia (mg/L)	0.18	0.37	0.45	0.29	0.17	0.17	0.17
Ammonia (% reduc.)	-6	-118	-165	-71	0	0	0
COD (mg/L)	10	15	24	38	56	86	0
COD (% reduction)	increase	increase	increase	increase	increase	increase	na



Run 6b using C-2238 Polymethydiallyl ammonium chloride/aluminum chloride blend

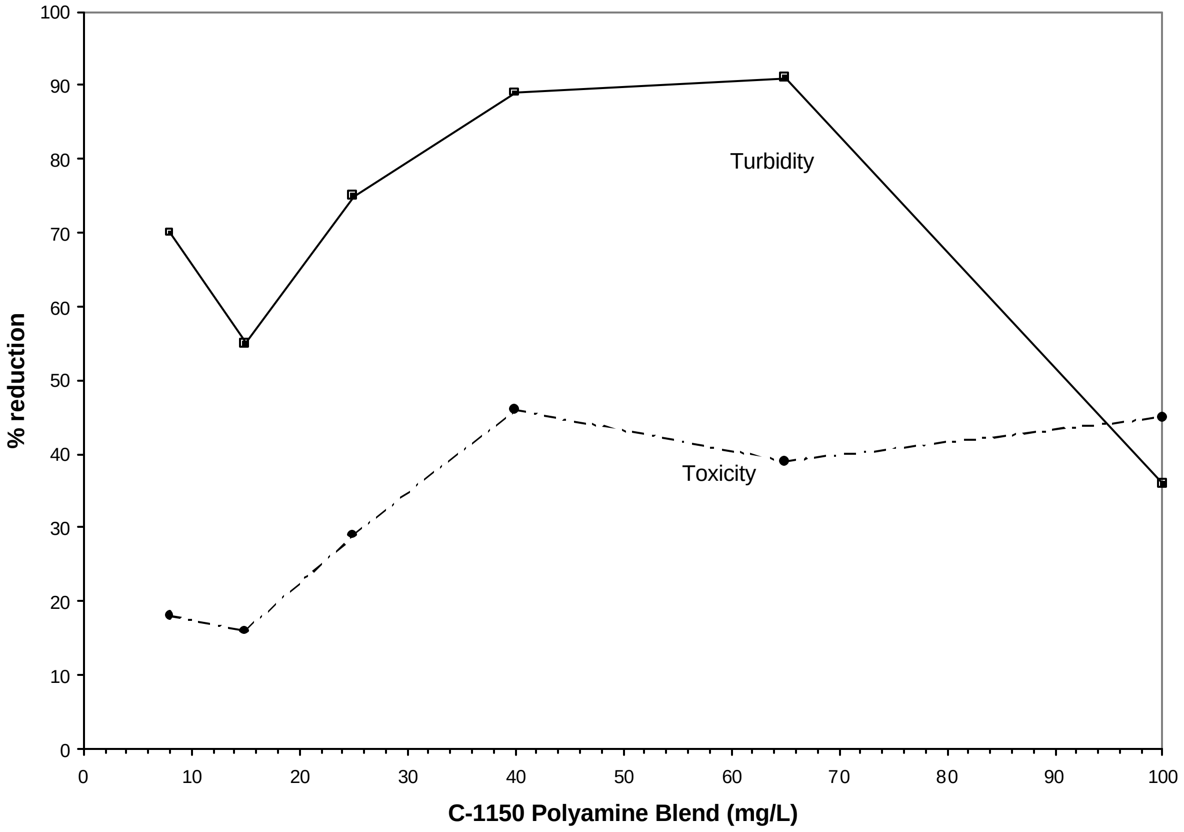
C-1150, polyamine blend solution (run 7a) and 1025, polyamine/alum blend solution (run 7b)
A polyamine blend (C-1150 from Polydyne, Inc.) and a polyamine/alum blend (C-1025, also from Polydyne, Inc.) were tested during this run. The C-1150 is a polyamine blend solution and is a combination of organic and inorganic coagulants. It is supposed to perform better in waters having low alkalinity and with high salt contents. The C-1025 is a polyamine/alum blend for color removal, phosphate removal, and the treatment of oily waters. The concentrations of both of these coagulants ranged from 8 to 100 mg/L during these tests. No metal or nutrient analyses were conducted for these tests, only turbidity, conductivity, pH, and toxicity were evaluated.

C-1150, polyamine blend solution (run 7a) results. The pH only changed slightly during these tests, from 7.7 to 7.8 before chemical addition, to 7.4 to 7.5 after chemical addition. Figure 6.33 indicates some of the pollutant trends for this coagulant. No metals, nutrients, or COD were analyzed during these tests. The optimal coagulant dosage may be between 40 and 65 mg/L, depending on potential increases in other pollutants at these relatively high dosages.

- turbidity had good reductions (70 to 90% removals) at coagulant dosages between 8 to 65 mg/L.
- toxicity had moderate removals (40 to 50% reductions) at coagulant dosages between 40 and 100 mg/L.

Run 7a: C-1150 Polyamine blend solution

C-1150 conc. turbidity conc. salinity conc.	Lowest con. High turb. High con	Low con. High turb. High con	Medium con. High turb. High con	High con. High turb. High con	Higher con. High turb. High con	Highest con. High turb. High con	Zero con. Low turb. Low cond
C-1150 (mg/L)	8	15	25	40	65	100	0
Sand (mg/L)	120	120	120	120	120	120	0
Conductivity (µS/cm)	1660	1630	1600	1580	1600	1610	500
Initial jar conditions							
pH	7.7	7.7	7.7	7.8	7.7	7.7	7.7
Conductivity (µS/cm)	1660	1640	1580	1620	1630	1660	490
Turbidity (NTU)	22	22	22	22	22	22	2.09
Toxicity (Microtox)	95	95	95	95	95	95	95
After coagulation jar conditions							
pH	7.5	7.4	7.5	7.5	7.5	7.4	7.5
pH (% reduction)	3	4	3	4	3	4	3
Conductivity (µS/cm)	1660	1630	1600	1580	1600	1610	500
Conductivity (% reduc.)	0	1	-1	2	2	3	-2
Turbidity (NTU)	6.71	10	5.41	2.53	2.08	14.08	2.09
Turbidity (% reduc.)	70	55	75	89	91	36	0
Toxicity (Microtox)	78	80	67	51	58	52	99
Toxicity (% reduc.)	18	16	29	46	39	45	-4



Run 7a using C-1150 Polyamine blend solution

1025, polyamine/alum blend solution (run 7b) results. The pH only changed slightly during these tests, from 7.7 to 7.8 before chemical addition, to 7.2 to 7.5 after chemical addition. Figure 34 indicates some of the pollutant trends for this coagulant. No metals, nutrients, or COD were analyzed during these tests.

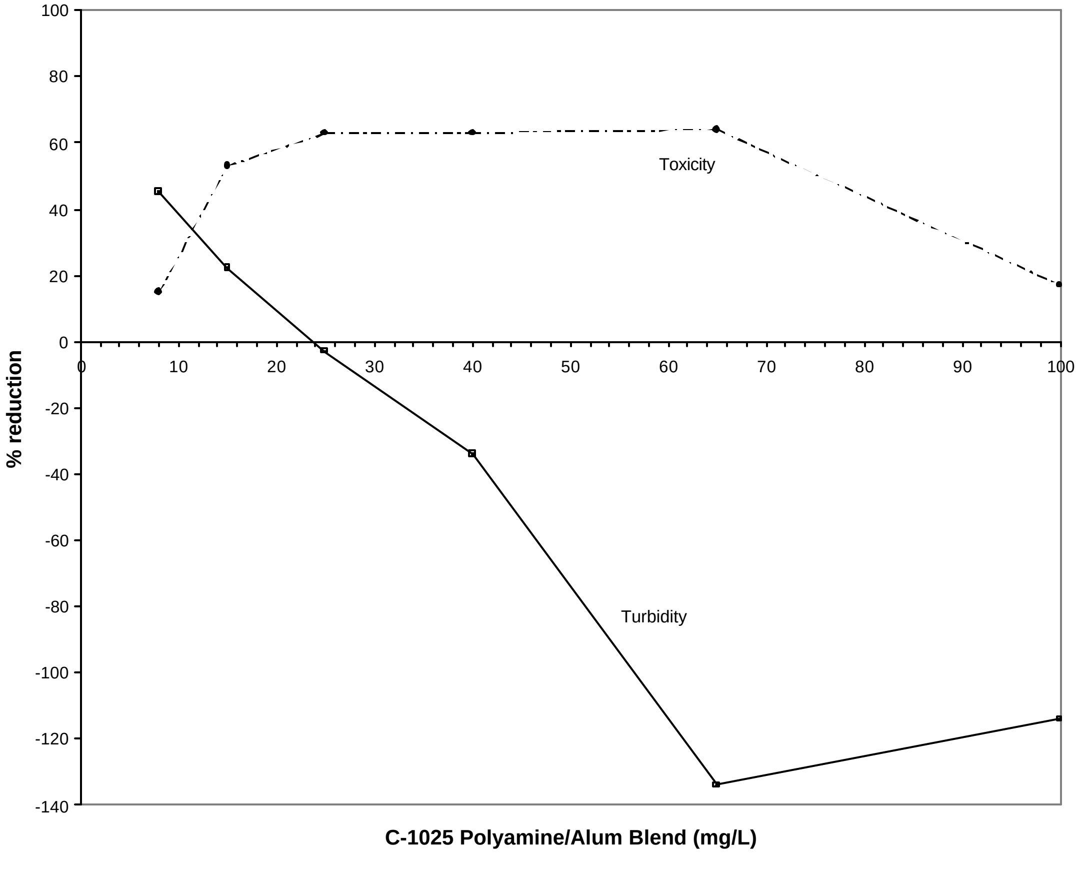
The optimal coagulant dosage may be between 15 and 40 mg/L, depending on potential increases in other pollutants at these relatively high dosages.

- turbidity had moderate reductions (20 to 45%) at low dosages (8 to 15 mg/L), but increased at high coagulant dosages (up to 47 NTU at 100 mg/L dosage).
- toxicity had good removals (50 to 65%) at moderate dosages (15 to 65 mg/L).

Run 7b: 1025 Polyamine/Alum blend solution

C-1025 conc. turbidity conc. salinity conc.	Lowest con. High turb. High con	Low con. High turb. High con	Medium con. High turb. High con	High con. High turb. High con	Higher con. High turb. High con	Highest con. High turb. High con	Zero con. Low turb. Low cond
1025 (mg/L)	8	15	25	40	65	100	0
Sand (mg/L)	120	120	120	120	120	120	0
Conductivity (µS/cm)	1640	1630	1640	1640	1650	1600	490
Initial jar conditions							

pH	7.8	7.7	7.7	7.7	7.7	7.7	7.7
Conductivity (µS/cm)	1640	1630	1640	1640	1650	1600	490
Turbidity (NTU)	22	22	22	22	22	22	2.09
Toxicity (Microtox)	95	95	95	95	95	95	95
After coagulation jar conditions							
pH	7.5	7.4	7.3	7.3	7.2	7.2	7.5
pH (% reduction)	4	4	5	5	6	6	3
Conductivity (µS/cm)	1650	1640	1620	1640	1650	1600	500
Conductivity (% reduc.)	-1	-1	1	0	0	0	-2
Turbidity (NTU)	12.13	17.18	22.6	29.5	51.4	47	2.09
Turbidity (% reduc.)	45	22	-3	-34	-134	-114	0
Toxicity (Microtox)	81	45	35	35	34	79	99
Toxicity (% reduc.)	15	53	63	63	64	17	-4



Run 7b using 1025 Polyamine/Alum blend solution

Results of Chemical Addition Tests

The results of the bench-scale chemical coagulation tests are presented on Figures 25 through 34. Ferric chloride with a microsand additive was the most successful for rapid treatment over a wide range of water conditions. Optimal ferric chloride levels produced excellent reductions of heavy metals (lead >99%, copper >90%) and phosphate (about 50%)

within about 10 minutes. In addition, the toxicity (measured using the Microtox™ screening method) also indicated >80% reductions. No adverse changes were observed with ferric chloride. Other major chemicals tested included alum (with and without organic polymers), ferric sulfate, organic polymers, plus several priority mixtures (most likely mixtures of alum and polymers). None of these other chemicals produced results as good as the ferric chloride.

Preliminary Evaluation of Filter Fabrics

Additional bench-scale tests were conducted to measure the stability of the floc that formed with the ferric chloride additions, and to see if most of the floc could be removed by filtration instead of by longer sedimentation. These simple tests involved jar test coagulation tests, but without the settling time. The treated water was filtered through the bag filter material instead in order to speed up the process. Only ferric chloride was used as a coagulant (at a of dose of 50 mg/L) and two bag filter materials were used (5 µm and 25 µm). A piece of the bag filter fabric (about 35 cm^2) was installed on a standard laboratory filtration apparatus and the test water was filtered under constant pressure.

The initial turbidity of water with the coagulant was 9.8 NTU during the tests with the 25 µm pore size material. Ten liters of water were filtered through the filter without any noticeable changes in filtering rate. The turbidity of filtrate was reduced to about 2 NTU at the end of the run. The filtrate had the yellow color of ferric chloride, indicating that the very rapid filtration under pressure probably broke apart some of the flocs.

The initial turbidity of water with the coagulant was 9.0 NTU during the tests with the 5 µm pore size filter material. Again, many liters of chemically treated water were poured through the filter without any visible change in flow rate. The final turbidity of the filtrate was approximately constant through the run (at 3 to 3.5 NTU). The filtered water was less colored than in the case with the 25µm filter material, and the fabric was much more colored by the ferric chloride, indicating greater retention of the floc and less passage of floc material through the filter fabric.

Pilot-Scale Treatability Tests

Based on the initial bench-scale tests, it was decided to examine chemical coagulation and/or precipitation, followed by physical treatment to remove any pumped floc, and possibly ion exchange or sorption, and disinfection as the treatment train to be investigated during field pilot-scale testing. The pilot-scale tests used a specially constructed treatment train having the following components:

1) initial 100 µm membrane filter bag
2) 25 µm membrane filter bag
3) 5 µm membrane filter bag
4) activated charcoal filter
5) UV disinfection unit
6) final cascade aerator

Seven sampling locations were located on this treatment train, an initial sample before any treatment, and six sampling locations after each of the above six unit processes. In addition, chemical addition (using either ferric chloride or alum) was used before this treatment train, resulting in additional samples. The design of the treatment train was unique for this project in order to evaluate the specific benefits of the individual treatment train components, based on the water characterizations and earlier bench-scale treatability tests. This treatment train was designed to enable us to isolate the most effective and rapid treatment process for full-scale applications.

All of the treatment train components were purchased from Aquatic Eco-Systems, Inc. of Apopka, FL (407-886-3939) and from local hardware stores and lumber yards, and were assembled on a wooden framework which was then placed on a trailer for the field studies. Figure 6.35 shows the treatment train. All treatment train components can be bypassed as indicated by the valves and lines. An evaluation of vapor and water hydrocarbon conditions was made using a Petrosense instrument. This unit was used to describe hydrocarbon vapors, floating hydrocarbons, and variations in hydrocarbon concentrations with depth in the water. The Petrosense was also used to measure increases in hydrocarbons in the water after complete mixing which may have disturbed the sediment during the tests. Initial treatability tests at each of the four test locations did not include chemical additions (labeled "unmixed, no coagulant treatment"). The water was carefully pumped from just under the water surface and then through the treatment train. At three of the four locations, the water was then mixed for about five minutes and the water was pumped from near the bottom through the treatment train (labeled "mixed, no coagulant treatment").

Figure 6.35. Pilot-scale treatment train showing configuration of treatment processes and sample collection locations.

At the four test locations, either ferric chloride or alum was added to the water in the telecommunication manholes. After pouring the stock solution into the manhole, the water was continuously mixed for about 5 minutes with the pump. The water was then allowed to sit undisturbed for up to 15 minutes. The pump was then placed barely under the water surface to pump the water to the treatment train through a 50 ft length of 1 in hose (labeled "coagulant treatment"). The pump used was a Beckett Big Versa, model PS3900A that had a rated maximum capacity of 1750 gal/hr with a maximum 25 ft lift. During our tests, the flow rate was only about 10 gpm (600 gal/hr) with physical lifts of about 10 to 15 ft.

Membrane Filter Bags

The first units on the treatment train were three membrane filter bags. The membrane filter bags were placed in individual polypropylene housings, (model X100B, from FSI Engineering, purchased from Aquatic Eco-Systems). The housings enabled us to control the individual flow rates through each filter and to modify the water flow direction (to by-pass an individual unit, if needed). As found later, the filter bag housings were also needed to help retain any captured material on the bags. The loose bag during the fifth simplified test (at the "Ranch House" site) easily lost captured material when the bag with flowing water through it was moved.

Aquatic Eco-Systems rated the flow through the bag filter vessel at 75 gpm for clean water, while the maximum recommended flow for particulate laden water is 40 gpm. For higher flows, the bag filters can be used in parallel, or a coarser pre-filter can be used before a finer filter (as in these tests). The individual bags are 6 in. in diameter and 20 in. long, having about 2 ft^2 of surface area. The nominal pore sizes of the available filter bags range from 1 µm to 1,000 µm. We selected a series of bags having pore sizes of 5, 25, and 100 µm.

In our treatment train, the water was first pumped through the 100 µm filter bag, then through the 25 µm filter bag, and finally through the 5 µm filter bag, before the later treatment components. As noted previously, samples were obtained before any treatment and between all treatment stages to indicate the individual effectiveness of each component. The bag filter vessels cost about $200 each (plus necessary fittings), while each bag only cost $4.15. The bags can be cleaned for re-use, if desired. The maximum pressure for the filter vessels is 100 psig, although we seldom observed any pressures greater than about 7 psig during our field tests. The flow rates during our pilot-scale tests (about 10 gpm) were substantially less than the maximum rated flows for these bags.

Activated Carbon Sorption Media

The next step in the treatment train was an activated carbon sorption unit. The canister unit was an Ocean Clear Filter model 320 Carbon Bio-Filter, also purchased from Aquatic Eco-Systems. The cost was about $130 and included 7.5 lbs of activated carbon granules in a net bag. The rated flow for this small plastic canister filter (about 1 ft in diameter and 1 ft tall) was 20 gpm, with a maximum pressure of 16 psig. Therefore, this unit was suitable for our reduced flow pilot-scale tests, but would not be suitable for actual full-scale field operations. This unit was included to measure the effectiveness and benefits of activated carbon in the treatment process. This unit can also be used to test other granular filtration media (such as Zeolites). During actual field operations, sorption media can usually be easily added to other treatment components, without requiring an additional stand-alone component.

Activated carbon is best used to adsorb organic compounds based on their molecular structure, solubility and the substitute groups on the organic molecule. Examples of compounds adsorbed by activated carbon include many pesticides, plus *n*-butyl phthalate, chlorobenzene, carbon tetrachloride, phenol, chloroform and nitrobenzene. Earlier tests using activated carbon in depth filters was encouraging, while tests using Zeolites was disappointing (Clark and Pitt 1999).

Our pilot-scale flow rates were about half of the rated flow for the test unit. In addition, the observed pressure never exceeded about 3 psig, substantially less than the rated 16 psig rating of the unit. The residence time in the activated carbon filter was very short, only being about 20 seconds for 10 gpm flow rates. This short contact time probably decreased the effectiveness of the carbon absorption media.

UV Disinfection

After the bag filters and activated carbon sorption, the treatment train included a UV disinfection unit. The unit was an Emperor Aquatics Ultraviolet Sterilizer, 65 watt model, with a built-in power supply. This was also purchased from Aquatic Eco-Systems for about $400. The replaceable 65 watt UV bulb (at about $63) has a 9,000 hour effective life and is operated on either 115 or 230 volts. The rated flow capacity for this unit to obtain 15,000 µwatt-s/cm^2 (MWS) is 25 gpm. The UV exposure would be doubled if the flow rate is halved. During our tests, with a pilot-scale flow rate of about 10 gpm, the UV exposure was therefore approximately 37,500 MWS. The maximum rated water pressure for the UV unit is 40 psig.

To be most effective, UV disinfection units must treat water that is very clear. Excessive turbidity and an aged lamp cause decreased UV exposures and therefore decreased disinfection performance. UV output from lamps may decrease by about 40% after 4,000 hrs of operation. UV exposures needed to kill various micro-organisms varies widely. Aquatic Eco-Systems reports ranges from about 3,400 MWS for *Shigella paradysenteriae*, to 440,000 MWS for the Tobacco Mosaic virus. Emperor Aquatics, Inc. gives the following maximum flow rates for the 65 watt unit used for each targeted species: water borne algae (15,000 MWS) 26 gpm; common bacteria (30,000 MWS) 13 gpm; and protozoa (45,000 MWS) 8.6 gpm. During our tests, the pilot-scale flow rates were generally about 10 gpm, and should have been effective against these three organism groups. Emperor Aquatics stresses the importance of correctly sizing the UV unit, with a single larger unit being much better than trying to use multiple smaller units together.

In the pilot-scale treatment train, the UV unit was placed near the end of the flow path, after all of the filtration and sorption processes, in order to produce water having the lowest turbidity for UV disinfection. During three of the disinfection tests, the turbidity of water entering the UV unit was very low (<1 NTU, which is the criteria for finished drinking water), the turbidity was between 1 and 3 NTU (still very low) during six of the tests. However, during three of the disinfection tests, the turbidity values were higher, from 14 to 20 NTU. The use of UV disinfection during actual operations may not be possible because of the fragility and size of the units. The unit tested was 6 ft long and was carefully transported to prevent breakage of the quartz sleeve and UV lamp.

Cascade Aerators

The final unit process in our pilot-scale treatment train was a packed column cascade aerator. This unit was comprised of five stacked buckets, each filled with 0.6 ft^3 of 1-1/2" Bio-Barrel aeration media in mesh bags, all from Aquatic Eco-Systems. The total cost was about $400 and is rated at up to 150 gpm. Water enters at the top of the cascade and is naturally aerated as it falls through the media in very small drops. There are no extra power requirements for this unit and it doesn't require any maintenance, besides infrequent cleaning of the media. Water leaving this aerator should be at near-saturation levels. This will include increased dissolved oxygen levels and decreased levels of other dissolved gases that may remain in the water from the telecommunication manhole (such as H_2S). Increased dissolved oxygen levels also assist in the removal of some dissolved metals (such as iron and manganese). Unfortunately, this specific unit design may prove to be too bulky for general full-scale use, as it was about 1 ft in diameter and about 6 ft tall.

Pilot-Scale Treatment Evaluations

The pilot-scale treatment train tests were performed at four locations in order to measure the performance of the different unit processes under a variety of actual conditions. The following list indicates the analyses that were performed on all samples:

- Conventional analyses
    - Turbidity
    - Color
    - Conductivity
    - pH
    - COD

- Ions and nutrients
    - Chlorine
    - Fluoride
    - Ammonia
    - Phosphate
    - Nitrate
    - Potassium
    - Surfactants

- Bacteria
    - Total coliforms
    - *E. coli*
    - *Enterococci*

- Heavy metals and toxicity
    - Cadmium
    - Copper

Lead
Zinc
Microtox™ screening toxicity

Not all analyses indicated sufficient concentrations to be useful for these tests. Only a few of the samples had detectable concentrations for cadmium, nitrate, and potassium and all detergent values were not detectable (<0.25 mg/L) for example. In addition, most of the total coliform observations were over-range (>200 MPN/100 mL). The toxicity tests indicated low levels of toxicity in the original water samples, with no significant changes during the treatment process. Similarly, the ammonia and phosphate concentrations were also quite low, and did not significantly change during the treatment process. The fluoride concentrations were moderate, but did not change significantly. The chlorine concentrations were very low, but observable during five of the tests, and were extremely low during the other six tests. The observable chlorine concentrations were all significantly reduced during treatment (from 50 to 97%), with little additional reductions observed after the last bag filter (5 µm). These parameters where therefore not included in the treatment evaluation.

Test Descriptions

Bessemer tests at Texaco station at corner of 9th Ave. and 28th St. These first pilot-scale tests were conducted on July 3, 1997. The water had a small amount of noticeable scum and an oil sheen before the tests. The estimated water volume in the telecommunication manhole was 290 ft^3. The Petrosense indicated the following hydrocarbon conditions:

	Vapor barely above water	Water at surface	Water at bottom of manhole
Before any tests:	34,500 ppm	4.7 ppm	0 ppm
After complete mixing	na	265 ppm	260 ppm

Mixing the water had an obvious effect on increasing hydrocarbon concentrations in the water. The initial observations showed low hydrocarbon values at the surface, and none detected near the bottom. Mixing greatly increased the hydrocarbon concentrations in the water by apparently disturbing hydrocarbons in the sediment. Only 45 grams of ferric chloride was added to the 8,200 L of water, resulting in a low concentration of only about 5.5 mg/L. Even at this low ferric chloride dosage, a yellowish floc was visible forming in the water. About 400 grams of ferric chloride should have been used to obtain the optimal coagulant concentration of about 50 mg/L. This test site only included two test series: the initial “unmixed, no coagulant treatment” and the “coagulant treatment.” A “mixed, no coagulant treatment” test series was not conducted at this location. The estimated treatment rate at this site was about 10 gpm. A total of about 500 gallons (of the total 2200 gallons) was pumped through the treatment train during about 50 minutes of pump operation at this site.

Birmingham tests near Buffalo Rock bottlers on W. Oxmoor Rd. These tests were conducted on July 7, 1997. No noticeable abnormal water conditions were noted. The estimated water volume in this telecommunication manhole was 315 ft^3. The Petrosense indicated the following hydrocarbon conditions:

	Vapor barely above water	Water at surface	Water at bottom of manhole
Before any tests:	28,500 ppm	36 ppm	47 ppm
After complete mixing	na	26 ppm	26 ppm

Mixing of the water had minimal effects on water hydrocarbon concentrations, which were relatively uniform before any mixing. There was little apparent hydrocarbon releases from the sediment, especially considering the large pump that was used to mix this water. A total of 90 grams of ferric chloride was added to the 8900 L of water, resulting in a low coagulant dosage of only about 10 mg/L. About 450 grams of ferric chloride would have been needed to obtain an optimal ferric chloride coagulant dosage of 50 mg/L for this site. The measured treatment rate was initially 13 gpm, decreasing to about 4 gpm at the end of the tests at this site. The treatment rate apparently slowed due to partial clogging of the bag filters. Assuming an average treatment rate of 8.5 gpm, a total of about 640 gallons (of the total 2400 gallons) was pumped through the treatment train during about 75 minutes of pump operation at this site. This site included all three test series.

Birmingham tests at 20th St. on Morris Ave. These tests were conducted on July 8, 1997. No noticeable abnormal water conditions were noted. The estimated water volume in this telecommunication manhole was about 100 ft^3. The Petrosense indicated the following hydrocarbon conditions:

	Vapor barely above water	**Water at surface**	**Water at bottom of manhole**
Before any tests:	43,500 ppm	55 ppm	35 ppm
After complete mixing	30,700 ppm	33 ppm	32 ppm

Mixing of the water had no apparent effects on water hydrocarbon concentrations, which were relatively uniform before any mixing. There was also little apparent hydrocarbon releases from any sediment. About 150 mL of an alum slurry, Accu-Clear, was added to the 2800 L of water, resulting in a dosage of about 0.05 mL/L (the optimal Accu-Clear dosage has since been determined to be about 0.08 mL/L). After the Accu-Clear addition and mixing, a noticeable fine floc (about 50 to 150 µm in size) was visible, having a light gray color. An average treatment rate of 9.4 gpm was measured during these tests. Therefore, a total of about 700 gallons (of the total 750 gallons) was pumped through the treatment train during about 75 minutes of pump operation at this site. This site also included all three test series.

Hoover tests at Hwy 150. These tests were conducted on July 9, 1997. No noticeable abnormal water conditions were noted. The estimated water volume in this telecommunication manhole was about 210 ft^3. The Petrosense indicated surface water hydrocarbon concentrations of about 85 ppm, with no hydrocarbons detected near the bottom of the manhole. About 300 mL of an alum slurry, Accu-Clear, was added to the 5900 L of water, resulting in a dosage of about 0.05 mL/L (the optimal Accu-Clear dosage has since been determined to be about 0.08 mL/L). An average treatment rate of 9.8 gpm was measured during these tests. Therefore, a total of about 730 gallons (of the total 1600 gallons) was pumped through the treatment train during about 75 minutes of pump operation at this site. This site also included all three test series.

Pilot-Scale Treatment Performance Results

The ten parameters shown on Figures 43 through 52 (pH, conductivity, turbidity, color, COD, copper, lead, zinc, *E. coli*, and *Enterococci*) were selected for treatability evaluations, in addition to particle size analyses, shown on Figures 53 through 58. These figures are plots of concentration changes at different treatment steps. Each figure is divided into four plots, with appropriate data trends shown: surface pumping, mixed, with $FeCl_3$, and with alum.

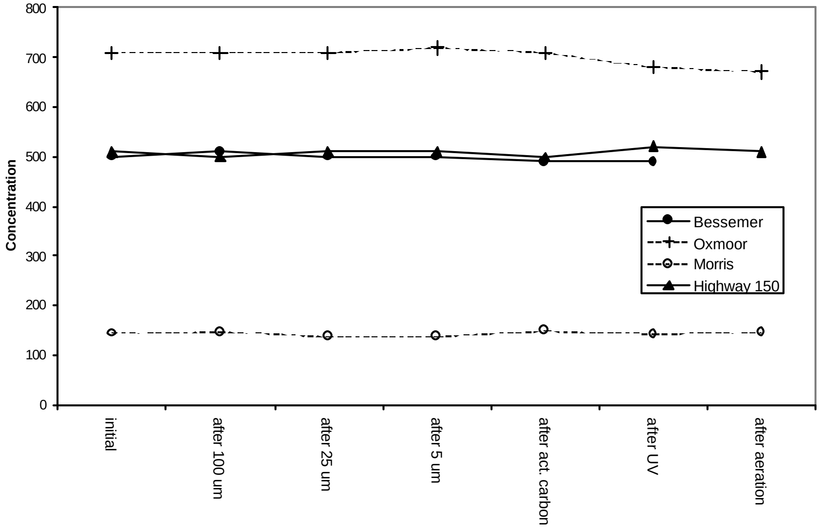
The filter bags after the above four tests were dried and weighed, and compared to the weights of new dried filter bags. The following table summarizes the loadings on the bags, for the ferric chloride and for the alum tests:

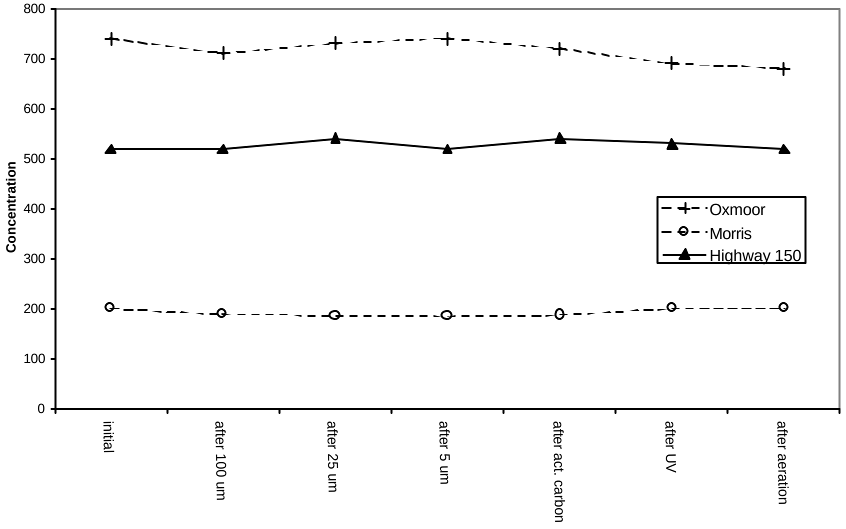
	100 μm filter bags	**25 μm filter bags**	**5 μm filter bags**	**Total**
Ferric chloride test sites				
Total flow through filter bag (gal/ft^2)	570 gal/ft^2	570 gal/ft^2	570 gal/ft^2	570 gal/ft^2

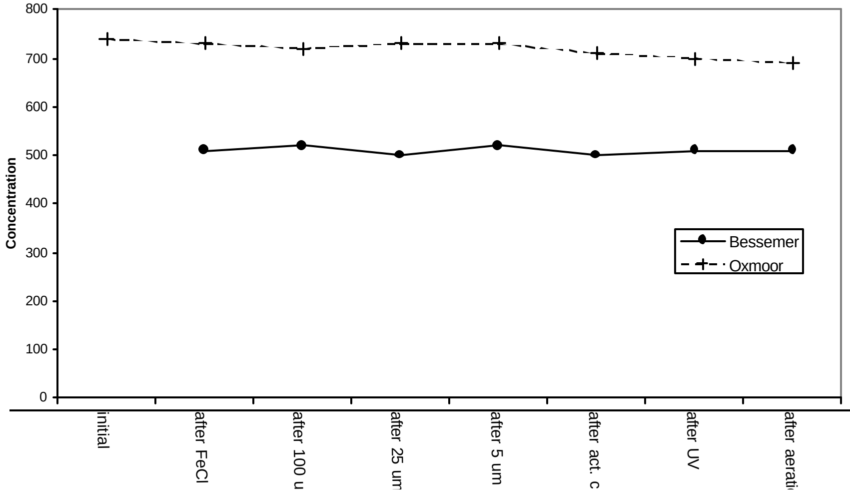
Sediment surface loading (g/m^3)	195 g/m^3	53 g/m^3	121 g/m^3	na
Concentration reduction for treated water (mg/L)	8.1 mg/L	2.2 mg/L	5.1 mg/L	15.4 mg/L
% captured in filter bag	53 %	14 %	33 %	100 %
Alum test sites				
Total flow through filter bag (gal/ft^2)	715 gal/ft^2	715 gal/ft^2	715 gal/ft^2	715 gal/ft^2
Sediment surface loading (g/m^3)	85 g/m^3	107 g/m^3	157 g/m^3	na
Concentration reduction for treated water (mg/L)	2.9 mg/L	3.6 mg/L	5.2 mg/L	11.7 mg/L
% captured in filter bag	25 %	31 %	44 %	100 %

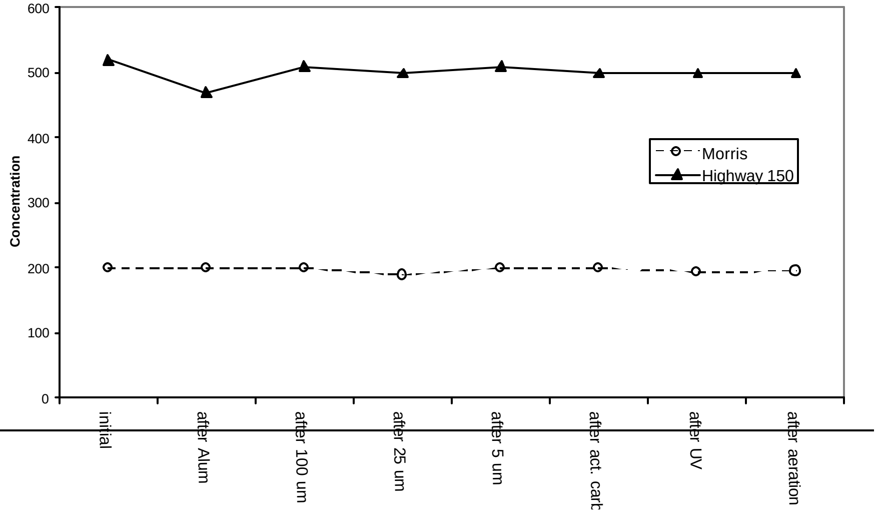
The filter bags were each 2 ft^2, and a total of about 1140 gallons was treated at the two ferric chloride test sites and about 1430 gallons was treated at the two alum test sites. These total treatment amounts are close to the typical 1000 gallons present in a telecommunication manhole. The ferric chloride test series caused some partial clogging of the bag filters, most likely from the W. Oxmoor mixed (without coagulation) test series that had a large amount of suspended solids (the turbidity was about 94 NTU after mixing, much greater than for any other test). Therefore, these sized filter bags (2 ft^2 each) would probably be suitable for a single telecommunications manhole pump out, at least. The total suspended solids reductions were about 10 to 15 mg/L.

Conductivity (µs/cm)

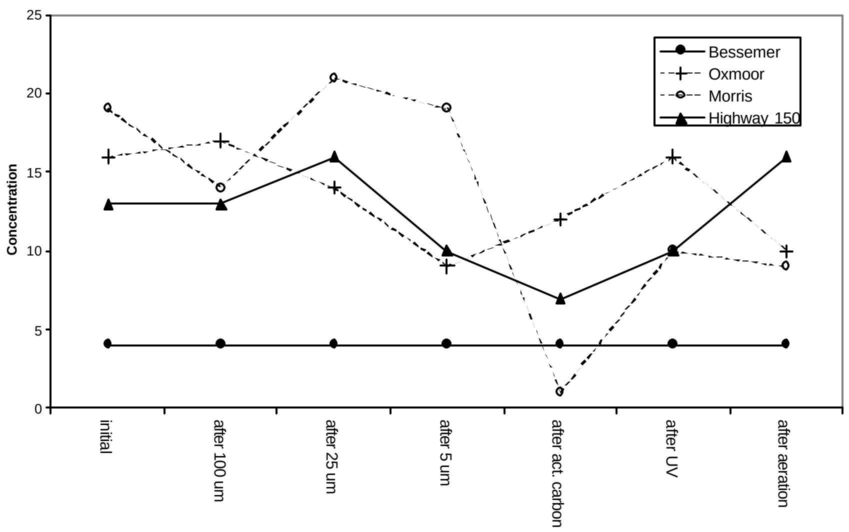

Surface Pumping


Mixed

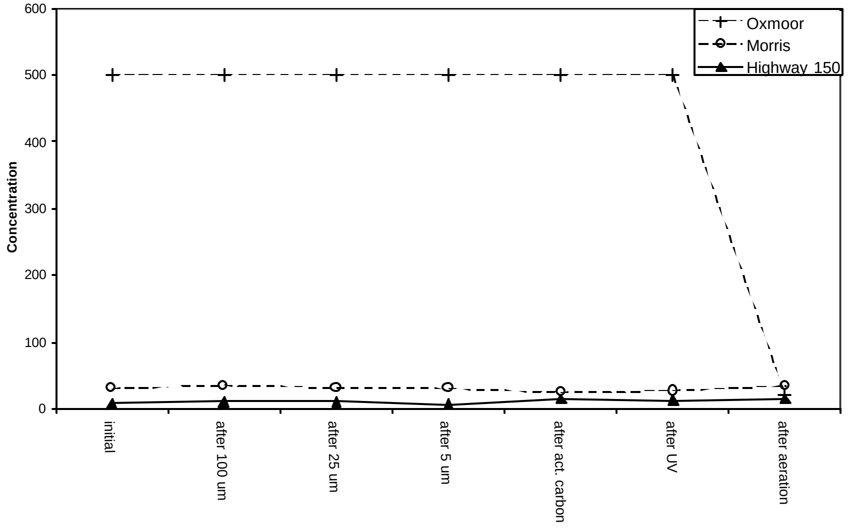

With Fe Cl


With Alum

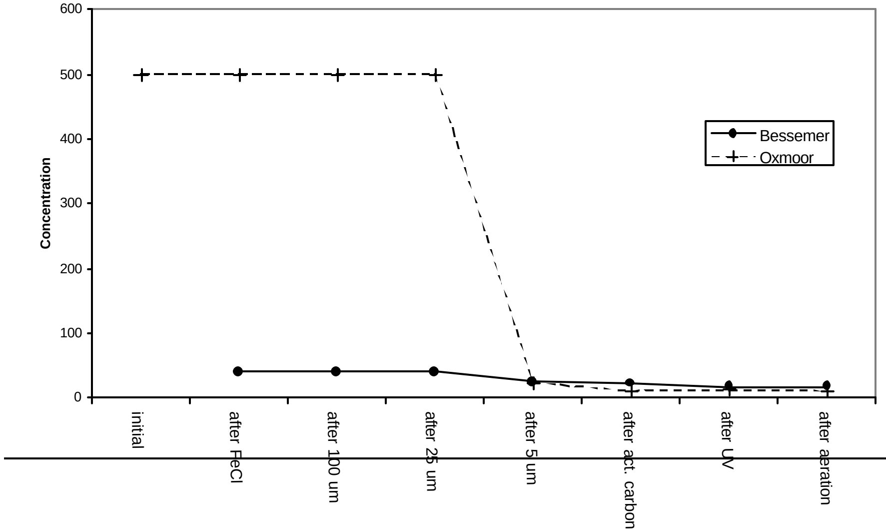
Color (Units)



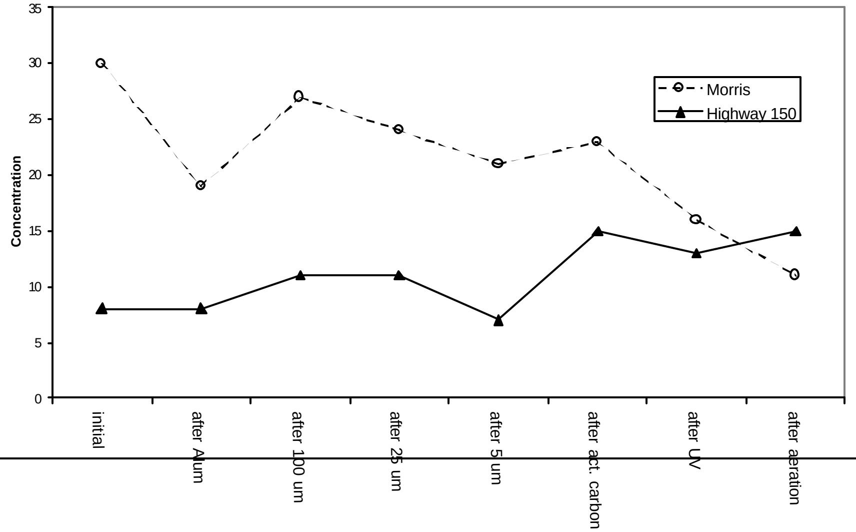
Surface Pumping



Mixed



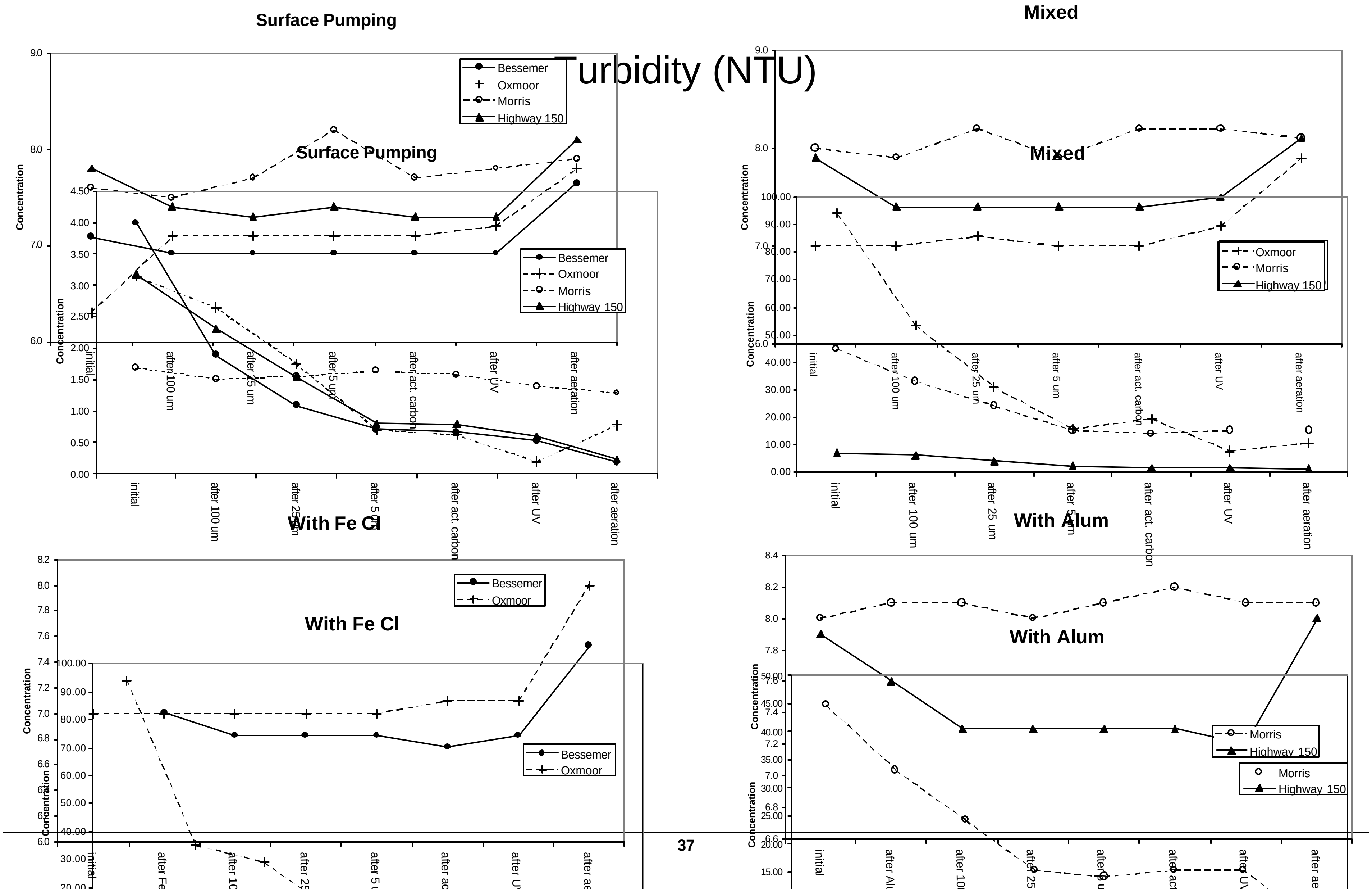
With Fe Cl



With Alum

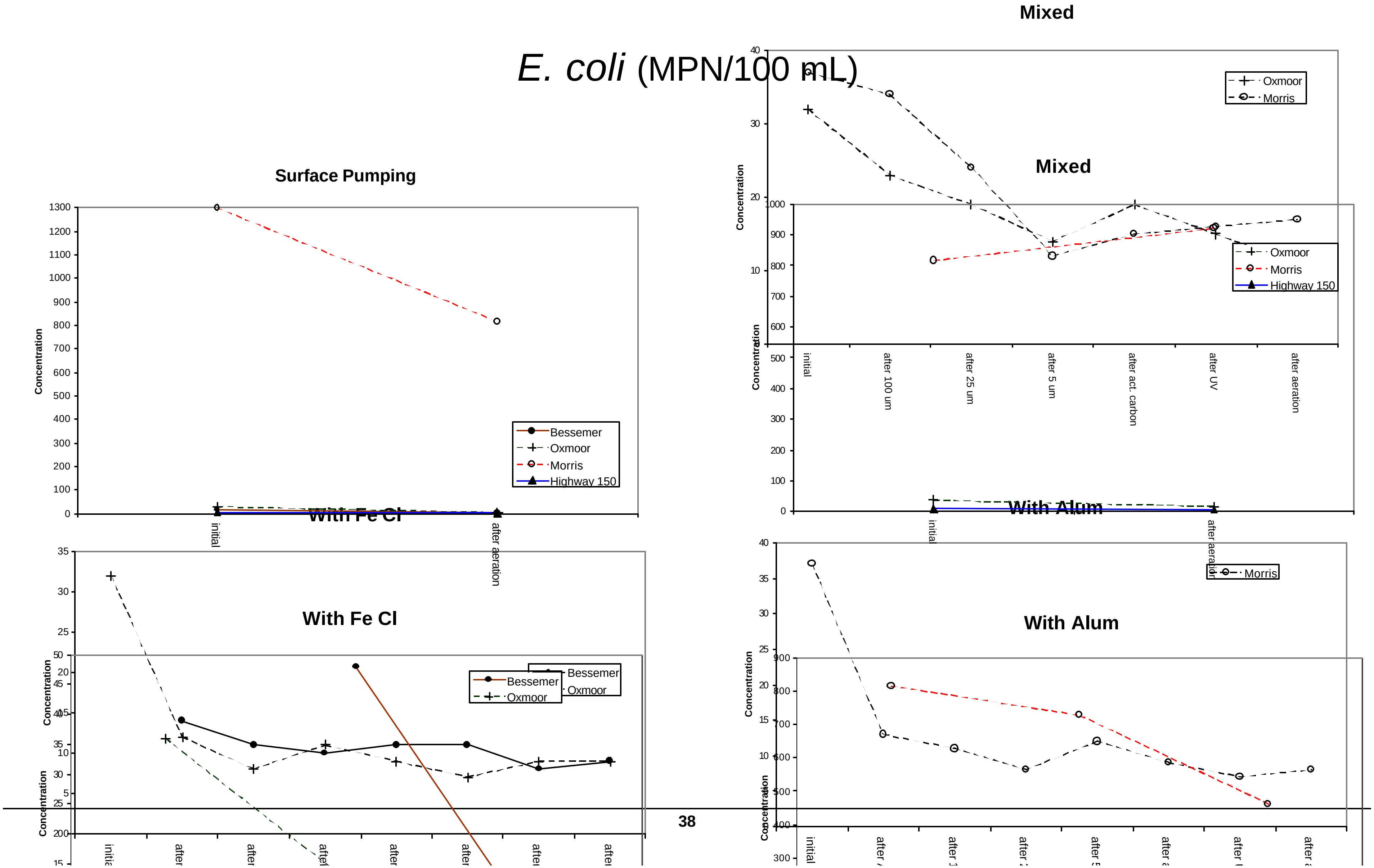
pH

Turbidity (NTU)



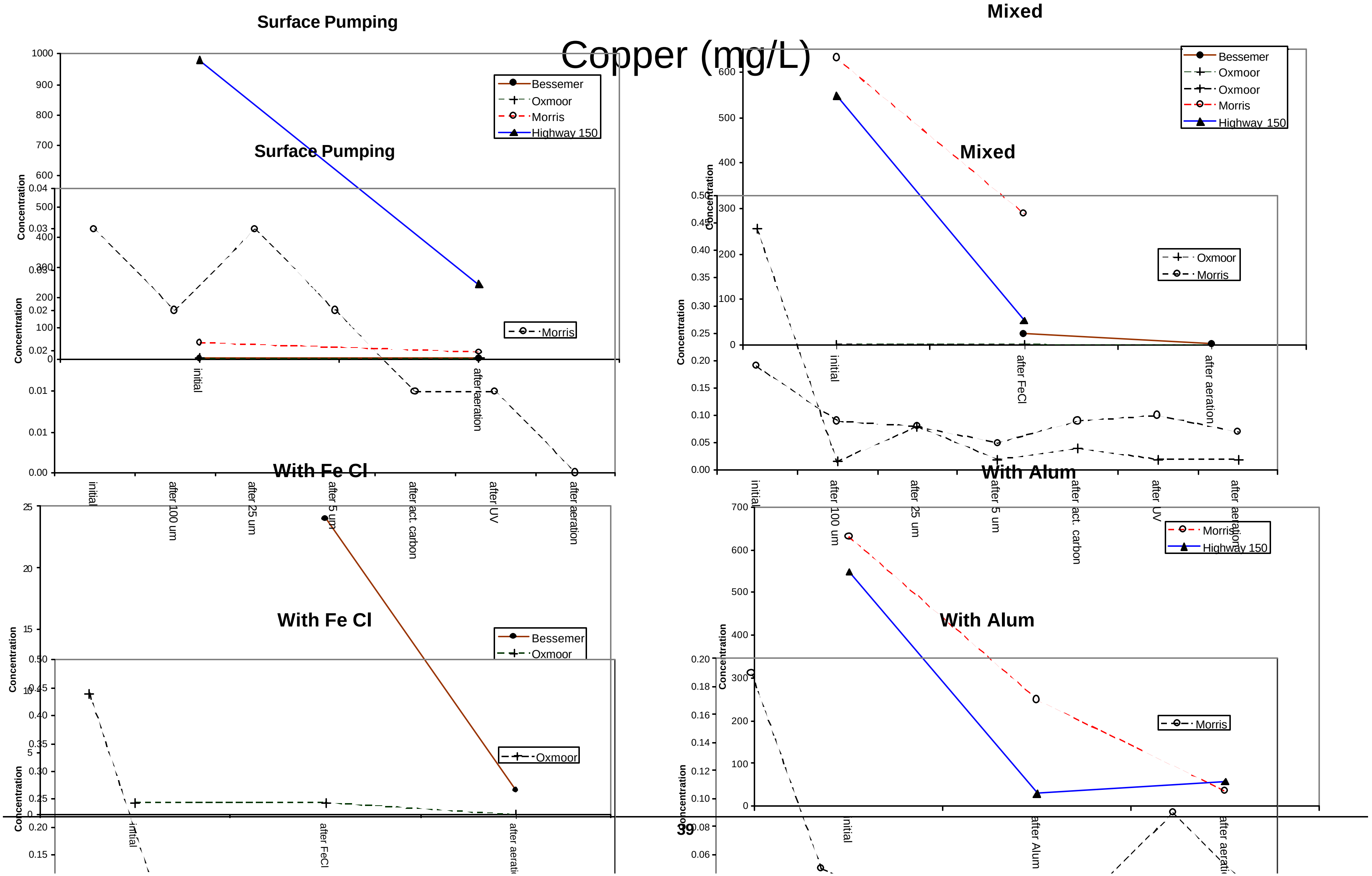
COD (mg/L)

E. coli (MPN/100 mL)



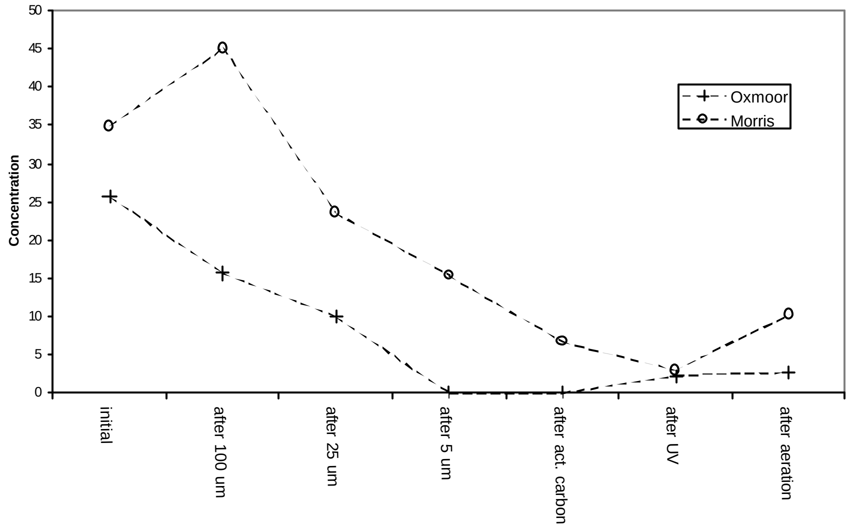
Enterococci (MPN/100 mL)

Copper (mg/L)



Lead (µg/L)

Mixed



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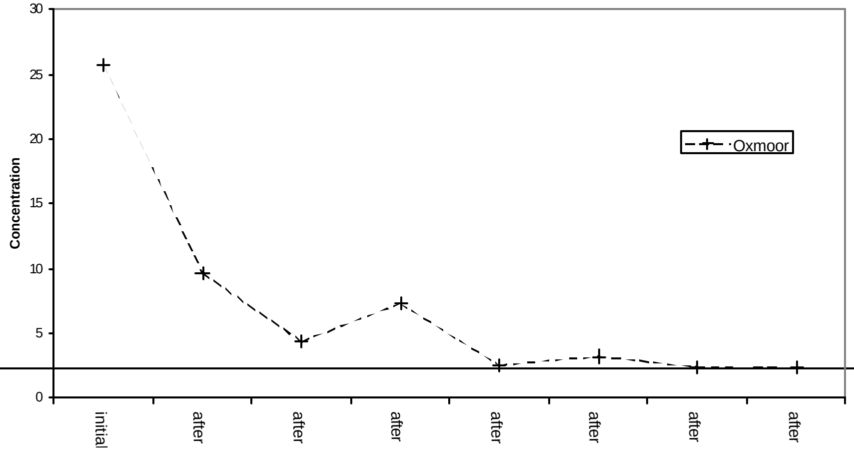
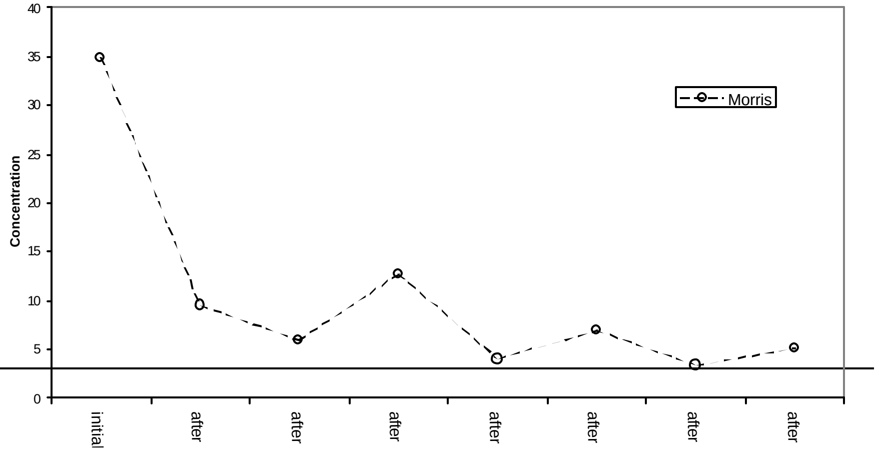
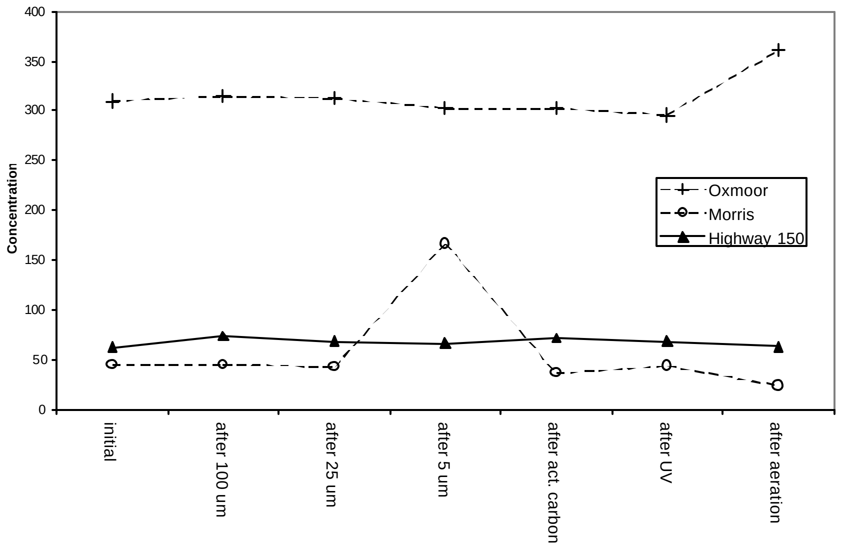


With Alum

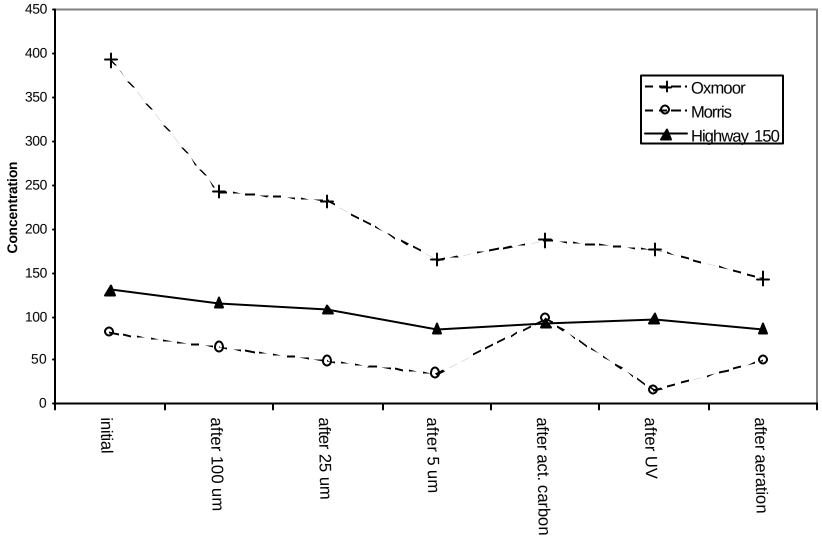


Zinc (µg/L)

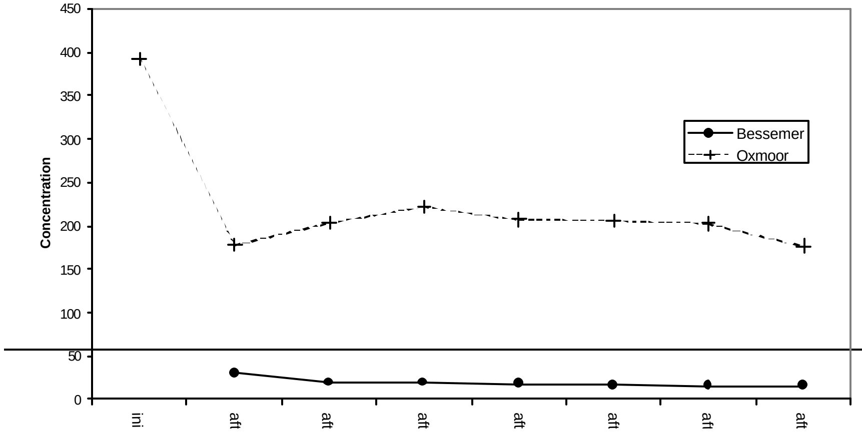
Surface Pumping



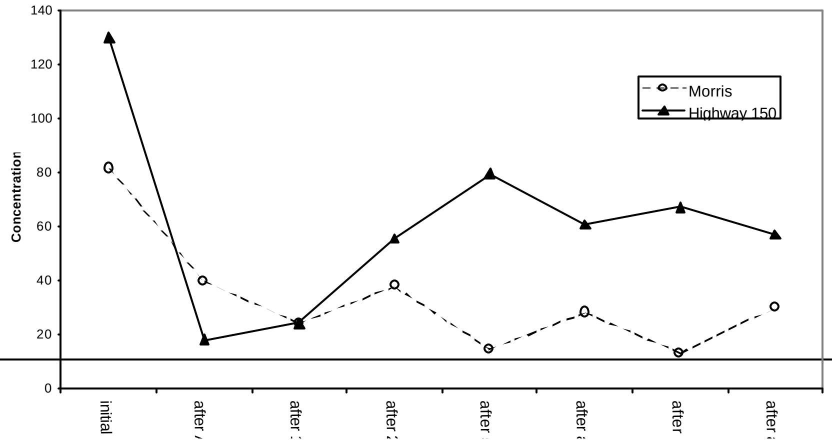
Mixed



With Fe Cl



With Alum



The “surface pumping” plots show up to four test results for surface pumping of the water from the manholes, without any mixing or chemical addition. All four of the treatment train tests (Bessemer, Oxmoor, Morris, and Hwy 150 locations) included data for this plot. These data were obtained from samples collected from the manholes without any disturbance to the water, with the pump held just below the water surface. The pump was operated for about 10 minutes, with water flowing through all of the treatment units before the sampling was initiated. Composite samples were obtained from each of the seven sampling locations, composited four times, five minutes apart:

1) Initial sample (before any treatment)
2) After 100 μm bag filter
3) After 25 μm bag filter
4) After 5 μm bag filter
5) After activated carbon sorption
6) After UV disinfection
7) Final sample, after cascade aeration

The “mixed” plots were prepared using data from samples collected while treating the water from the manholes during, or immediately after, complete mixing of the manhole water, including re-suspending some of the settled sediment. All of the sites, except for the initial tests at Bessemer included samples collected during this test series. The sampling pump was disconnected from the treatment train and the short hose was used to mix the water in the manhole for 5 to 10 minutes. At the Oxmoor site, a BellSouth manhole pump was used to continuously stir the water during the testing, while at the Morris and Hwy 150 test locations, the sampling pump was immediately re-connected to the sampling train, without continuous stirring during the mixed tests. The mixed water was directed through the treatment train for 5 to 10 minutes before sampling started. The same composite sampling scheme noted above was used for these tests.

The “with $FeCl_3$” plots were prepared from data from samples collected during treatment tests that used ferric chloride additions to the water in the manholes. After the “mixed” treatment sampling series was completed, ferric chloride was added to the water in the manhole and completely mixed for another 5 minutes using the sampling pump. The water was then allowed to settle for 15 minutes before the pump was placed barely below the water surface to deliver water to the treatment train. The “initial” data point therefore is the same as the “initial” data point from the “mixed” plot and the “after $FeCl_3$” data point was obtained the first sampling port on the treatment train. As before, the water was pumped through the treatment train for 5 to 10 minutes before the composite sampling started. The Bessemer and Oxmoor test sites included ferric chloride. However, “mixed” water tests (without any chemical additions) were not conducted at the Bessemer site, so the Bessemer plot doesn’t show an “initial” data point.

The “with alum” plots were prepared from data collected identically as the above “with $FeCl_3$” plots, except that alum was added to the water in the manhole before the treatment train. The alum test sites were the Morris and Hwy 150 test locations, both of which included “mixed” water tests and therefore have “initial” data points for their plots.

Tables 8 and 9 summarize the levels of treatment obtained during these tests, as shown on Figures 43 through 52. Several pollutants significantly increased in concentration when the water was aggressively stirred with the pump during the “mixed” water tests. This mixing action re-suspended some of the sediment. The Oxmoor and Morris test sites showed the largest effects, with lead, copper, turbidity, and ammonia increasing by at least five times in concentration (some by more than 30 times). Color and COD also significantly increased in at least one of these two test locations during mixing. Zinc, conductivity, pH, fluoride, and phosphate, plus the bacteria, had much smaller changes during mixing. The particle size analyses (shown of Figures 53 through 58) showed significant decreases in particles as the treatment progresses in the treatment train from the initial samples through the 5 μm filter bag. It is interesting to note that the bag filters did not act as cut-off filters at their rated pore sizes (100, 25, and 5 μm), but appear to reduce particles in a broad range of sizes. This is most likely due to depth filtering capability of the felted bags, plus the effects of a filter cake that would build up on the inside of the bag filter, reducing the effective aperture size.

These performance tests indicate that water treatment with ferric chloride and final filtering through a 5 µm filter offers the best pollutant reductions. Any additional treatment only provided small marginal benefits. Therefore, the following discussion presents an example interim best management practice for controlling water pumped from telecommunication manholes.

Table 8. Effective Treatment Levels (with concentrations and reductions)

Turbidity (NTU)	**Bessemer**	**Oxmoor**	**Morris**	**Hwy 150**
Surface pumping	after 5 µm (0.7 NTU, 82% reduction)	after 5 µm (0.7 NTU, 78% reduction)	little change (all 1 to 2 NTU)	after 5 µm (0.8 NTU, 75% reduction)
Mixed	na	after 5 µm (16 NTU, 83% reduction)	after 5 µm (15 NTU, 66% reduction)	after 5 µm (2.5 NTU, 65% reduction)
With $FeCl_3$	little change (all 2 to 5 NTU)	after 5 µm (2.4 NTU, 97% reduction)	na	na
With alum	na	na	after 25 µm (15 NTU, 66% reduction)	little change (all 4 to 8 NTU)
COD (mg/L)	**Bessemer**	**Oxmoor**	**Morris**	**Hwy 150**
Surface pumping	na	na	na	na
Mixed	na	after 5 µm (14 mg/L, 56% reduction)	after 5 µm (12 mg/L, 68% reduction)	na
With $FeCl_3$	little change (all 8 to 14 mg/L)	after $FeCl_3$ (12 mg/L, 63% reduction)	na	na
With alum	na	na	after alum (13 mg/L, 65% reduction)	na
Copper (mg/L)	**Bessemer**	**Oxmoor**	**Morris**	**Hwy 150**
Surface pumping	na	na	after activated carbon (0.01 mg/L, 67% reduction)	na
Mixed	na	after 100 µm (0.02 mg/L, 96% reduction)	after 5 µm (0.05 mg/L, 74% reduction)	na
With $FeCl_3$	na	after $FeCl_3$ (0.06 mg/L, 86% reduction)	na	na
With alum	na	na	after alum (0.05 mg/L, 74% reduction)	na
Lead (mg/L)	**Bessemer**	**Oxmoor**	**Morris**	**Hwy 150**
Surface pumping	na	na	na	na
Mixed	na	after 5 µm (0 µg/L,	After activated	na

		100 reduction)	carbon (7 µg/L, 81% reduction)	
With $FeCl_3$	na	after 100 µm (4 µg/L, 83% reduction)	na	na
With alum	na	na	after alum (10 µg/l, 73 % reduction)	na
Zinc (mg/L)	**Bessemer**	**Oxmoor**	**Morris**	**Hwy 150**
Surface pumping	na	increase (from 310 to 340 µg/L)	little change (all 24 to 166 µg/L)	little change (all 63 to 74 µg/L)
Mixed	na	after 5 µm (164 µg/L, 58 % reduction)	after 5 µm (35 µg/L, 57 % reduction)	after 5 µm (86 µg/L, 34 % reduction)
With $FeCl_3$	little change (all 16 to 30 µg/L)	after $FeCl_3$ (178 µg/L, 55 % reduction)	na	na
With alum	na	na	after 100 µm (24 µg/L, 71% reduction)	after alum (18 µg/L, 86% reduction)

Table 9 Observed Effluent Bacteria Levels after Treatment (including UV disinfection)

***E. coli* (MPN/100 mL)**	**Bessemer**	**Oxmoor**	**Morris**	**Hwy 150**
Surface pumping	2/100 mL (88% reduction)	4/100 mL (85 % reduction)	816/100 mL (37% reduction)	2/100 mL (73 % reduction)
Mixed	na	16/100 mL (55 % reduction)	921/100 mL (13% increase)	6/100 mL (27 % reduction)
With $FeCl_3$	1/100 mL (98% reduction)	2/100 mL (94 % reduction)	na	na
With alum	na	na	461/100 mL (43% reduction)	5/100 mL (42 % reduction)
***Enterococci* (MPN/100 mL)**	**Bessemer**	**Oxmoor**	**Morris**	**Hwy 150**
Surface pumping	1/100 mL (50 % reduction)	1/100 mL (50 % reduction)	22/100 mL (59 % reduction)	245/100 mL (75 % reduction)
Mixed	na	0/100 mL (100 % reduction)	288/100 mL (54 % reduction)	54/100 mL (90 % reduction)
With $FeCl_3$	2/100 mL (92 % reduction)	0/100 mL (100 % reduction)	na	na
With alum	na	na	35/100 mL (95 % reduction)	58/100 mL (89 % reduction)

Recommended Control Program

The current treatment approach used by the telecommunications industry is to not discharge any water found in manholes that is obviously contaminated by sewage or petroleum products. These manholes are identified by vapor analyses, obvious odors, and the presence of floating material. When these elements are present, the field workers contact certified waste hauling and disposal firms that come to the manhole site, pump out the water and any sediment, and clean the manhole, before any workers enter the manhole for the repair operation. The removed water is therefore not discharged to any receiving water without undergoing adequate treatment.

This project investigated another method for treating water at the manhole location for waters that are not obviously grossly contaminated, but may otherwise benefit from treatment before discharge to the storm drainage system. These manholes would be identified by several of the following methods, such as by simple field analyses of the water, by prior knowledge of potential problems at the manhole site, by the presence of critical factors in the manhole, or if influencing factors are present in the surrounding area that may adversely affect runoff water that could inflow into the manhole. The treatment method that was developed and tested to reduce these constituent concentrations included the following steps:

1) Place oil-sorbent pads/pillows into any telecommunication manhole that smells of petroleum, registers on the portable vapor meter, or has a light to moderate visible oil sheen. These should be left undisturbed in the manhole for at least 5 minutes, during forced ventilation, to absorb any floating material. They should then be removed and placed in bags or cans for proper disposal, or for cleaning and reuse. If a large amount of petroleum is present, then hazardous waste contractors should be contacted to remove the material for proper disposal and clean the manhole before the repair or maintenance operation. After the maintenance or repair operation is completed, new oil-sorbent pads/pillows should be placed in any telecommunication manhole where contamination by petroleum products is expected.

2) The sediment in the telecommunication manhole needs to be evaluated. The depth of the sediment can be estimated using a probe. A flat plate (at least 6 inches in diameter) is attached to a pipe that is long enough to extend several feet above the street level from the bottom of the manhole. This pipe is lowered into the manhole until the plate rests on the sediment. A pointed rod, a couple of feet longer than the pipe, is then lowered through the pipe and pushed through the sediment until it touches the bottom of the manhole. The sediment depth can then be estimated by knowing the distance that the inner probe extends beyond the bottom of the flat plate on the pipe. A petit ponar dredge can be used to collect a sample of the sediment. The sediment sample is brought to the surface and dumped into a pan where it is examined. If it is oily or smells of sewage, especially if it is of a very fine texture and dark, a hazardous material removal crew should be called to clean the manhole and properly dispose of the material before the repair or maintenance operation. If it appears to be clean sand or silt, then the following steps can be taken.

3) Ferric chloride, or alum, is to be added to the water in the telecommunication manhole at a concentration of between 50 and 100 mg/L (ppm). Technical grade ferric chloride is suitable and is usually supplied as anhydrous ferric chloride ($FeCl_3$*$6H_20$), yielding about 70 grams of ferric chloride per 100 grams of anhydrous ferric chloride (Fisher Scientific, catalog # I86 10). The cost is about $120 for 10 kg. A stock solution of the ferric chloride can be prepared with 100 grams of the anhydrous ferric chloride per liter of water. One liter of this stock solution is sufficient to treat about 40 ft^3 (or 290 gallons) of water at a concentration of 50 mg/L. Therefore, if the telecommunication manhole is 6 ft by 10 ft, one liter of this stock solution would be used for every 8 inches of water depth. The concentration is not extremely critical. The ferric chloride stock solution is corrosive and care should be taken not to get any on skin or eyes. The MSDS supplied with the ferric chloride describes the potential hazards. The working solution is not hazardous or harmful. After pouring the coagulant material into the water, the water needs to be mixed for at least 5 minutes using a pump. Care should be taken not to disturb any bottom sediments more than necessary. The same mixing process is also used with alum. If alum is used, it can be directly added as a powder into the manhole, without any need of a stock solution, if desired. When using alum, concentrations closer to 100 mg/L should be used: 100 grams would be used for every 28 ft^3 of water.

4) After the chemical addition and mixing, the water is left undisturbed for at least 15 minutes to allow the flocs to begin to settle. The water is then pumped out of the telecommunication manhole from the surface. If an inlet hose is used on a pump located outside of the manhole, the hose can be attached to a float. If a submerged pump is

used, it should be located as close to the water surface as possible, and lowered as the water level drops. The pump can be attached to a line connected to a winch located on a tripod located over the manhole to control the pump depth. If this is not possible, the submerged pump can be located at the bottom of the manhole, but elevated at least a foot above any sediment and with a deflector pan located under the pump to minimize the pump from drawing up any sediment (basically, a small table, with up-turned edges). If the pump must be located near the bottom, then a much longer period of time is needed to allow the settling of the chemical flocs. At least 15 minutes per foot of water depth will be needed to reduce the pumping of the flocs. Any pumped flocs will likely be forced through the outlet filters, with reduced benefit.

5) The water is to be pumped until the water level approaches any sediment in the bottom of the telecommunication manhole. When the water level is reduced to about a foot, extra care needs to be taken to slowly drop the water level further to reduce sediment discharges. The pump can have a pan installed (with an upturned edge about 2 inches high) that can be rested on the sediment to draw the water level down to the final depth. It is anticipated that almost all repair and maintenance operations can be conducted with the sediment remaining in the manhole. As noted previously, if the sediment is of a fine texture (oily/muddy consistency), or if it is too deep to allow the repair or maintenance operation, it would be removed by a licensed contractor before any entry. The amount of any sediment in the telecommunication manhole should be reported to the supervisor who will arrange removal of excessive amounts during non-emergency conditions, if warranted.

6) The water pumped from the telecommunication manhole is finally discharged through a filter located on the end of the discharge hose. This filter is to be made of several components that are capable of handling the pumping rate (about 100 gpm for most applications) and the water volume before needing replacement (at least 1,000 gallons). The most important aspect of this filter is a final pore size of no greater than 5 µm. It is recommended that a pre-filter (having a pore size of about 25 µm) be located before this final filter. Finally, a pack of granulated activated carbon can be located within the filter.

The largest decreases in concentrations using this example interim BMP would be associated with turbidity, COD, copper, lead, and zinc. Conductivity, pH, and ammonia are not expected to change during the treatment process. In areas where conductivity is a problem (such as in northern areas where de-icing salts are used for traction control in the winter), extra pre-cautions should be made to seal the manhole entrances of the telecommunication manholes from inflowing water during snowmelt periods. Infiltration of shallow groundwater may also be slowed using the sealing products described previously.

Preliminary Field Evaluation of Simplified Treatment Scenario

A preliminary field evaluation of a simplified treatment scenario was conducted at a BellSouth telecommunication manhole at the Ranch House BBQ on Columbiana Rd in Vestavia Hills, AL. This telecommunication manhole has historically had problems with the quality of the water which collected in it, due to a nearby gasoline station leak contaminating near-surface groundwater. The water in the manhole smelled of petroleum, but no visible oil sheen was seen.

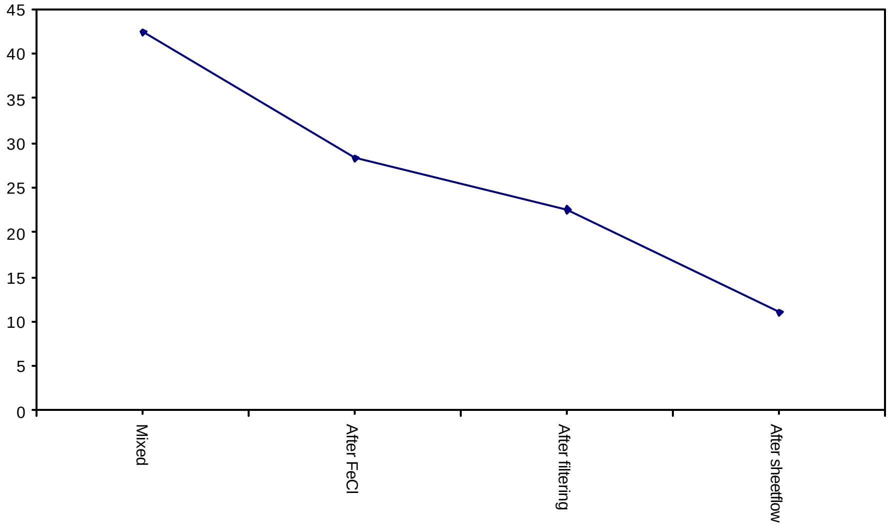
The test procedure and sample descriptions are as follows:

- an initial sample of water (sample #1) was obtained using a depth-integrating pump sampler, before any disturbance.
- the water was then completely mixed for five minutes, including disturbing the bottom sediment. Another depth-integrated sample (sample #2) was taken while the water was mixed.
- ferric chloride was added to the mixed water, with mixing continuing for another five minutes. About 200 g of ferric chloride was added to the telecommunication manhole, and the water was about 3 feet deep. If the manhole was 6 ft by 8 ft, the resulting concentration was about 50 mg/L. However, the manhole may have been as large as 12 ft by 10 ft, resulting in a reduced concentration of the coagulant of about 17 mg/L.

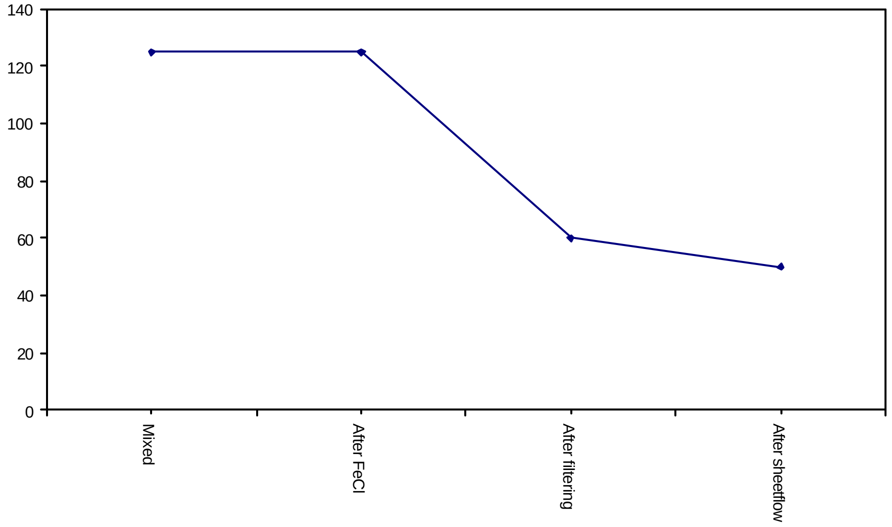
- after a 15 minute settling period, the withdrawal pump was suspended immediately below the water surface to start the pumpout. A composite sample was also initiated, withdrawing surface water using a long-handled dipper every five minutes for four portions (sample #3).
- the water was pumped through an end-of-hose filter comprised of a felted polypropylene 25 µm bag filter placed inside another felted filter having 5 µm pores. A net bag containing about 4 pounds of pelletized activated carbon was placed inside both bags. The effluent sample (sample #4), collected after filtration, was also composited every five minutes. The pumpout and treatment rate during this test was about 24 gpm. Pumping lasted for about 27 minutes, with about 510 gallons beomg treated.
- a final sample (sample #5) was collected at the point of discharge after the filtered water was allowed to run as sheetflow across about 50 ft of asphaltic pavement.

The bag filters were made of felted polypropylene and were purchased (along with the adapter) from Aquatic Eco-Systems, Apopka, FL, for about $5 each. The end-of pipe adapter cost about $25. A 40 lb bag of activated carbon costs about $100. The filter bags are 7 inches in diameter and 32 inches long, and can be rinsed for re-use, if desired.

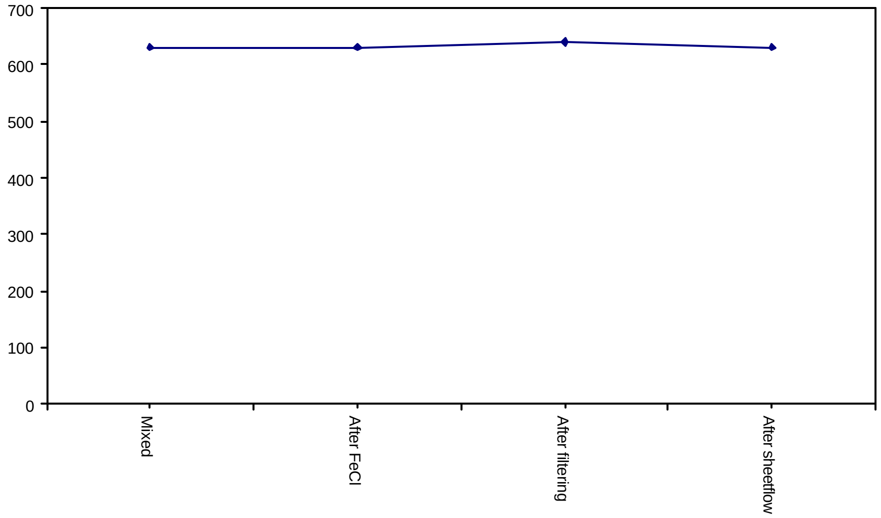
The results of these tests are shown on Figure 63. Turbidity, color, and lead all significantly decreased during this example treatment method. The turbidity decreased by about 33% just from the ferric chloride addition. After filtering, the turbidity decreased by about 47%, with another 51% decrease after the sheetflow. The color did not change solely due to the ferric chloride, but the final filtration caused a 52% color reduction. The sheetflow caused a further 17% color reduction. The lead was non-detected after the ferric chloride addition, compared to an initial value of about 5 µg/L. The complete mixing of the water in the telecommunication manhole did not cause any significant increase in concentration of any of the measured parameters due to the minimal amount of sediment present. A slight increase in pH was found after the sheetflow (similar to the cascade aeration unit during the treatment train tests), but otherwise remained quite steady (at about 7.3). Except for the above mentioned turbidity and color reductions, the sheetflow did not significantly affect any of the other measured parameters. Conductivity (about 630 µS/cm), COD (about 40 mg/L), ammonia (about 3.5 mg/L), potassium (about 8 mg/L), cadmium (about 9 µg/L), and zinc (about 15 µg/L) did not change appreciably during the tests. These final discharge concentrations are all quite low, with the exception of the moderate COD values.



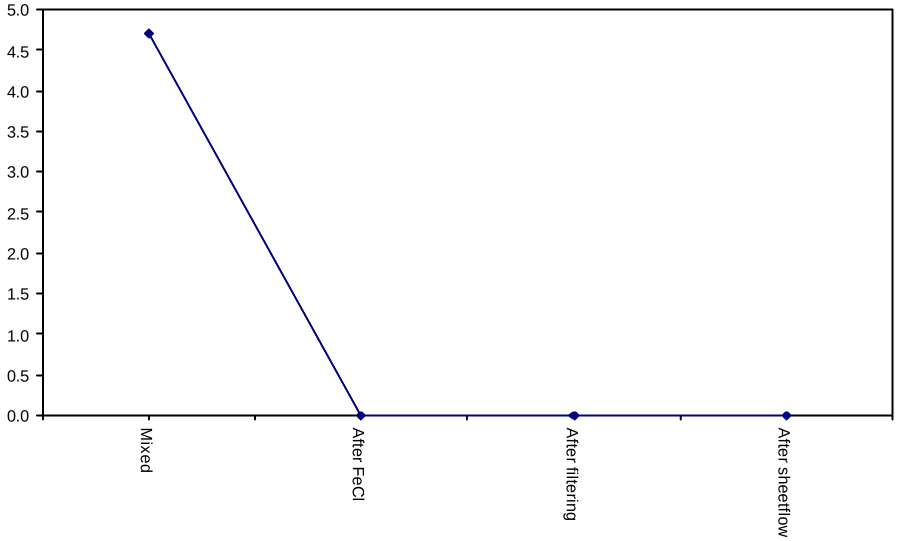
Turbidity (NTU)



Color (Units)



Conductivity (us/m)



Lead (ug/L)

The particle size distribution measurements showed significant reductions at each treatment stage. Coagulation, alone provided about 30 percent removal of solids greater than 1 µm in size. All of this reduction occurred for particles greater than about 6 µm. The filtration step provided about another 30 percent removal (for a total particulate removal of about 60 percent). The filtration step removed a wider range of particle sizes, to as low as about 2 µm. The removal of these small particles was possible because of the build-up of particles on the filter bag material reduced the effective pore size of the material. The sheetflow did not appreciably change the particle size distribution, or the removal of any further particulate material, as most of the particles after the final filtration were between 1 and 8 µm (compared to initial particles mostly in the range of 1 to 20 µm).

Conclusions

As noted previously, the following constitute the most serious likely problems associated with water found in telecommunication manholes:

- High dissolved solids and chlorides in samples affected by snowmelt water. The dissolved solids and chlorides will not be reduced with the simple treatment scenario tested during the pumping operations. However, enhanced sealing of manhole covers, manhole walls, and conduit entrances (as summarized earlier) will reduce the inflow and infiltration of saline snowmelt waters into the manholes.

- High suspended solids, volatile solids, and COD in many samples, likely from sewage contamination. The suspended and volatile solids will be substantially reduced, while the COD levels will be reduced to a lesser extent, by the simple treatment scenario tested. Based on the observed filterable fractions for these analyses and on the bench-scale coagulation tests, the filtration and coagulation should provide up to 80% reductions in total COD and volatile solids (median about 50%). The suspended solids should be reduced by up to 95% (median about 75%). Periodically, the percentage removals may be quite low, especially when the initial concentrations are low.

- High toxicity likely due to high chlorides, plus filterable heavy metals and pesticides. As noted above, the high chlorides will only be reduced by enhanced sealing. The filterable heavy metals and pesticides will be reduced by the coagulation processes (by up to 90%, expected median of about 50 to 75%, depending on the metal and influent concentrations).

- High filterable copper and zinc. As noted above, the filterable heavy metals will be reduced by the coagulation processes. Observed copper removals during the pilot-scale treatability tests ranged from 33 to 95%, while the zinc removals ranged from 40 to 65%.

References

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