Chapter 5
Experimental Results: Combined Sewer Overflow

The purpose of this chapter is to examine the effectiveness of the MC process as a treatment technology for combined sewer overflows (CSO) (as was previously analyzed in the treatment for surface runoff). In developing this process, an experimental program was carried out. The analyses were based on past experience and information noted in Chapter 4. The experimental results are summarized hereby in four phases, namely, prescreening tests, effectiveness of MC process, control variable optimization, and response variable evaluation.

5.1 Prescreening Tests

Mixing Parameters. The mixing parameter setup for the CSO treatment is similar to those of the surface runoff tests as described in Chapter 4. For CSO samples, it was observed that flocs grow gradually within one to two minutes during slow mixing (flocculation). Along with the growth of flocs, the mixing rate should vary from 60 rpm at the beginning to 20 rpm at the latter part of mixing process in order to reduce shear stress and avoid floc break down. The total mixing time is less than two minutes.

Table 5-1 presents a summary of experimental settings to be used in subsequent tests in control variable optimization and response variable evaluation. These settings were based on prescreening tests.

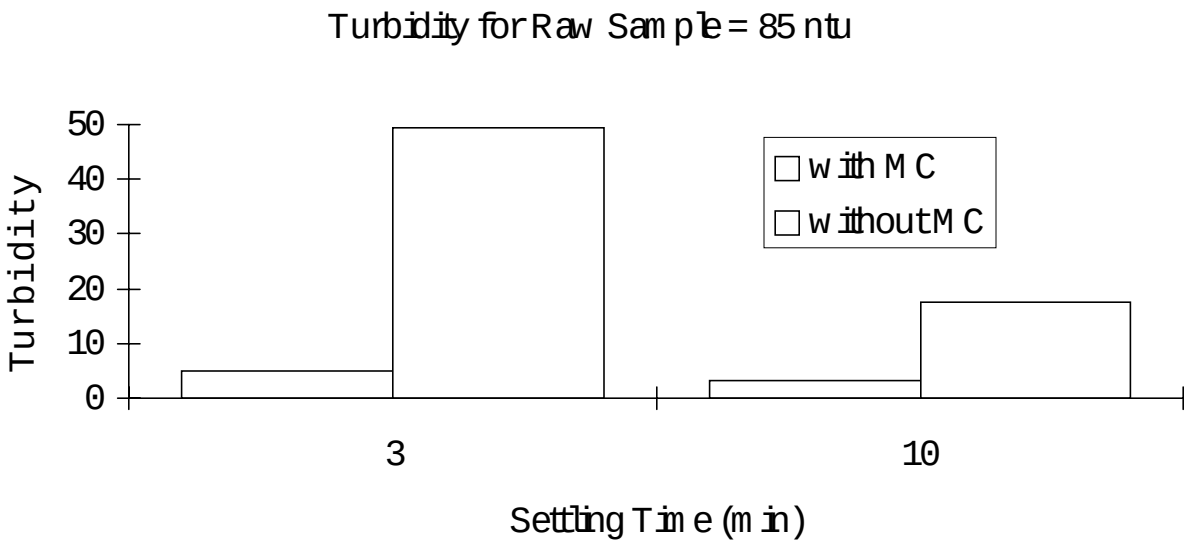
5.2 Effect of the MC

The effect of the MC weighted coagulation was evaluated via turbidity indicator as well as particle size distribution at the pre- and post-jar test of raw and supernatant samples, respectively. Figure 5-1 presents results of turbidity versus settling time with and without the use of an MC. With the MC process, the turbidity was reduced from 85 ntu (for the raw sample) to 5.0 and 3.1 NTU at the 3- and 10-minute settling times, respectively. At the 3- and 10-minute settling times, the turbidity without MC is 10 and 5.6 times that of the turbidity levels with MC, respectively. Thus, the MC treatment process is effective for removal of turbidity in CSO samples.

Figures 5-2 and 5-3 illustrate cumulative and non-cumulative volume distributions versus particle size before and after the MC treatment process, respectively. For the raw sample (before treatment), the measurable range of particle size was from 0.5 to 60 μm with 93% particles larger than 2 μm in size. After the MC treatment, the particles in the supernatant of the sample were found to be smaller than 2 μm, thus indicating that particles larger than 2 μm in the raw sample were totally removed.

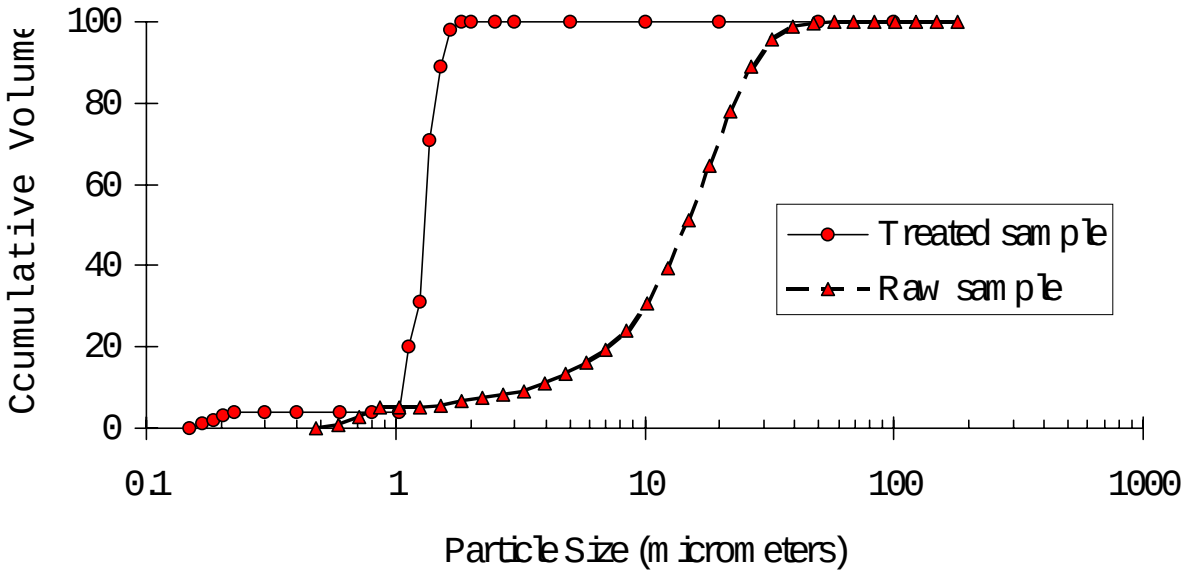
Table 5-1. Summary of Experimental Settings for CSO Treatment

Parameter	Value
Rapid mixing rate -- stage-1	150 rpm
Rapid mixing duration -- stage-1	10 sec
Rapid mixing rate -- stage-2	100 rpm
Rapid mixing duration -- stage-2	10 sec
Slow mixing (Flocculation)rate	20—60 rpm
Flocculation mixing duration	1—1.5 min
MC concentration	1—7 g/L
MC size range - 1	53—75 μm
MC size range - 2	150—250 μm
Settling time	1—20 min
Ferric chloride concentration	10—100 mg/L(as Fe^{+++})
Coagulant aid (polyelectrolyte) concentration	0.5—15 mg/L



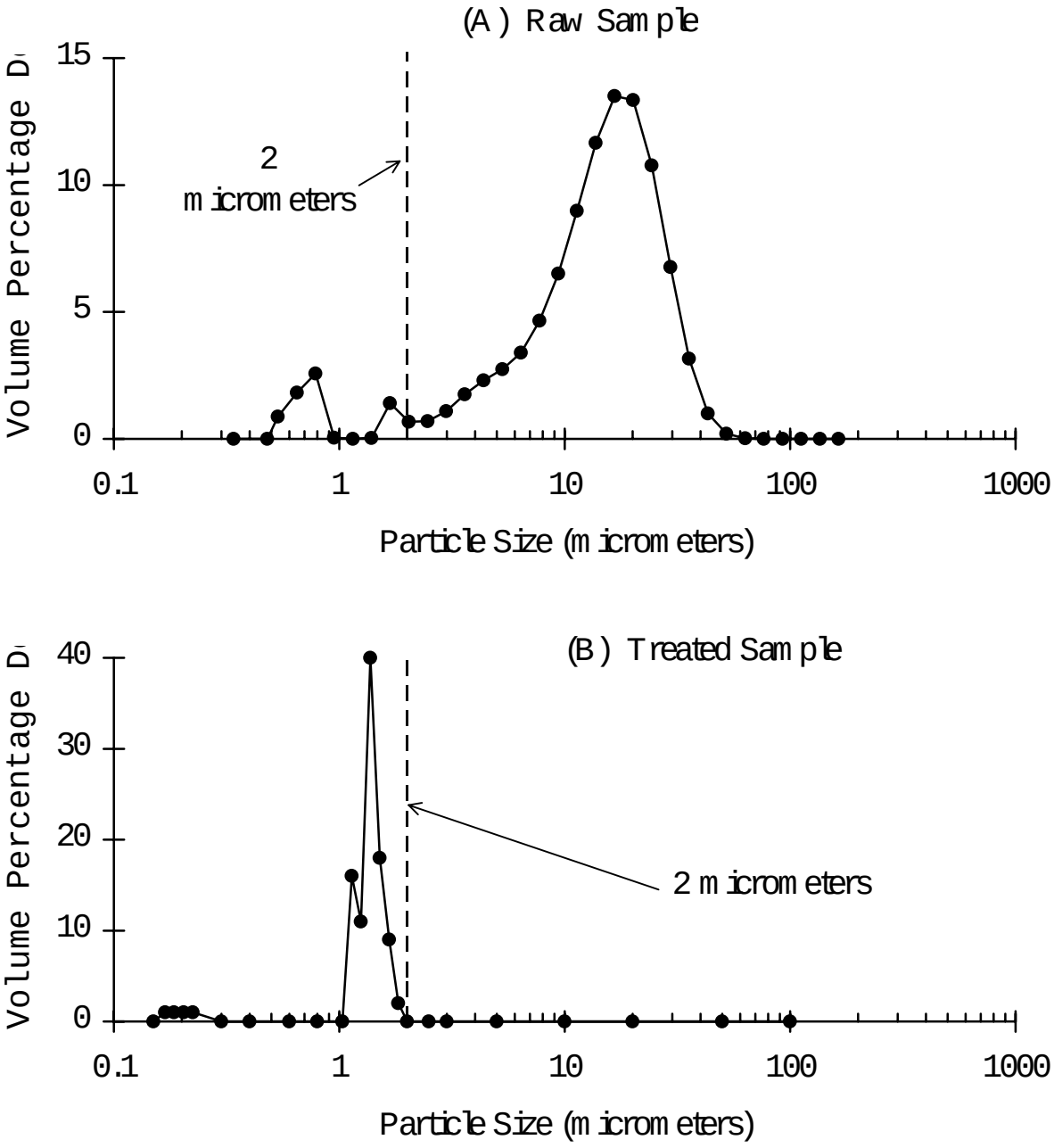
MC-5: MC Size Range = 53—75 µm; MC Concentration = 3g/L
E-2: Ferric Chloride Concentration = 40 mg/L(as Fe^{+++})
PE-5: Polyelectolyte 309C Concentration = 2 mg/L

Figure 5-1. Effect of MC



MC-5: MC Size Range = 53—75 µm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L(as Fe^{+++})
PE-5: Polyelectolyte 309C Concentration = 1.5 mg/L

Figure 5-2. Particle Sizes of Raw and Treated Samples (Cumulative)



MC-5: MC Size Range = 53—75 μm; MC Concentration = 3g/L
E-2: Ferric Chloride Concentration = 40 mg/L(as Fe^{+++})
PE-5: Polyelectolyte 309C Concentration = 1.5 mg/L

Figure 5-3. Particle Sizes of Raw and Treated Samples (Distributions)

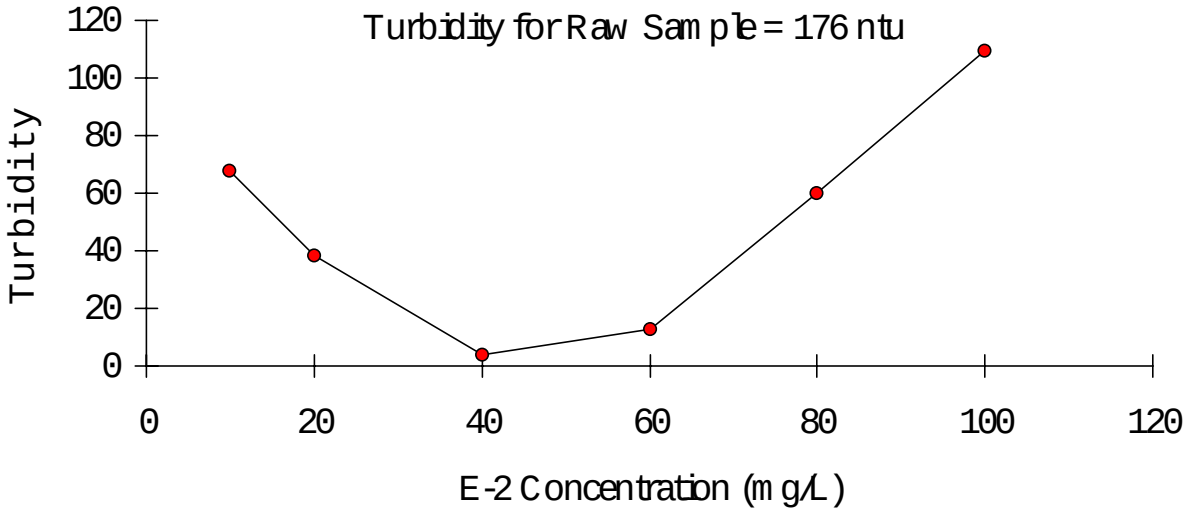
5.3 Control Variable Determination

In the determination of the effectiveness of the MC process, turbidity and particle count rate were employed as primary and secondary indicators, respectively. Six parameters, including coagulant concentration, coagulant aid concentration, MC size, MC concentration and settling time were identified as control variables. Results from each of the control variables with respect to the turbidity and particle count rate are presented in this section.

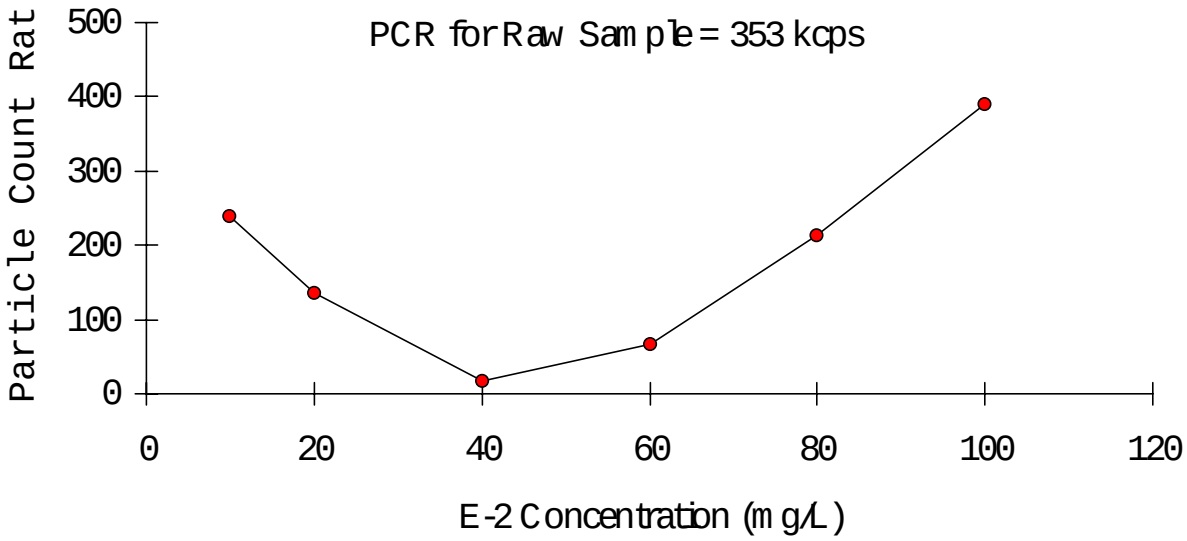
Coagulant Concentration

Turbidity and particle count rate of post treatment supernatant samples with respect to coagulant concentration are illustrated in Figure 5-4 (A) and (B), respectively. It can be seen that the optimal coagulant concentration is 40 mg/L for both turbidity and particle count rate indicators. The removal rates are 98% for turbidity and 95% for particle count rate at the optimal coagulant concentration. These results are confirmed in Figure 5-5 that also shows that the optimal dosage for coagulant is 40 mg/L. Although the raw samples for these two tests are from different batches, the results are similar.

It is of interest to note that the distribution trends for turbidity and particle count rate are very similar. Figure 5-6 indicates a linear relationship between these two parameters.



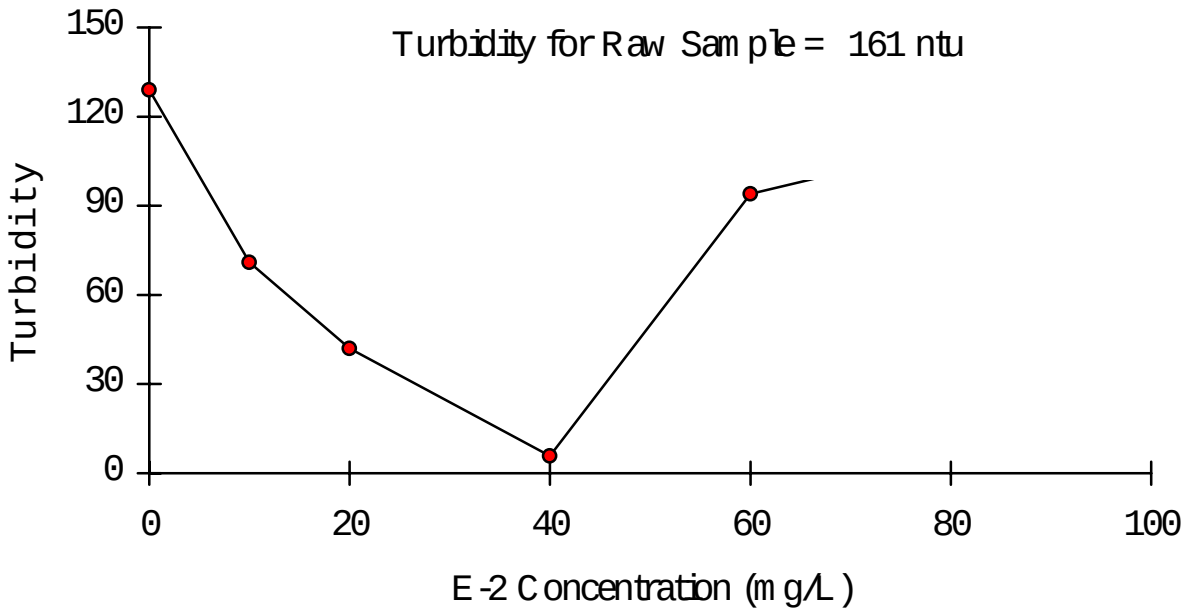
(A) By Turbidity Indicator



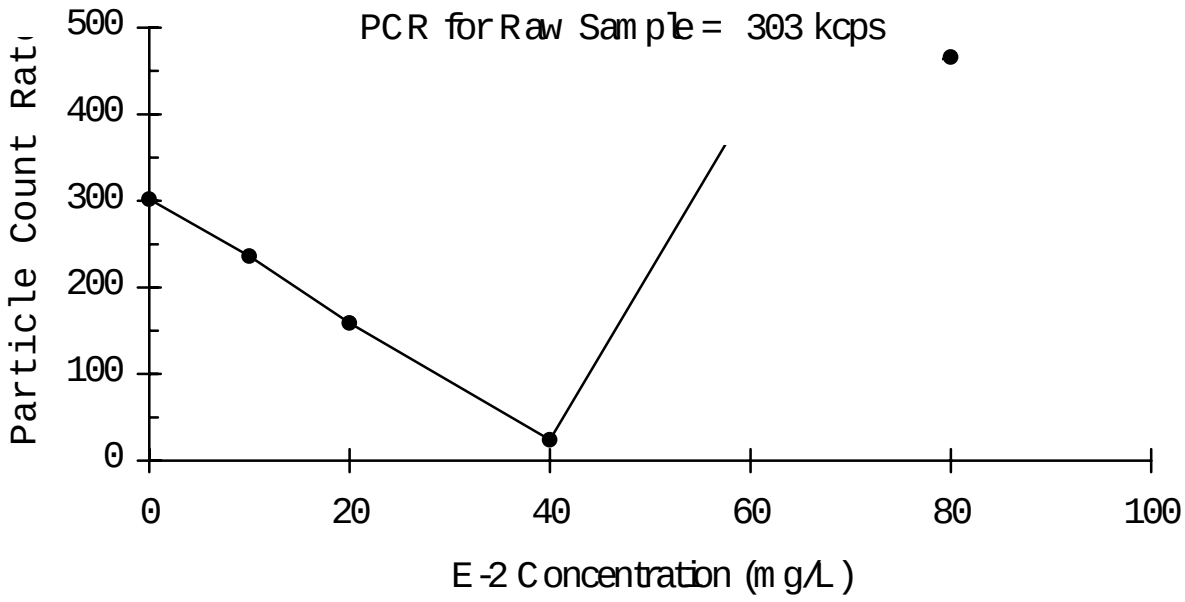
(B) By Particle Count Rate Indicator

MC-5: MC Size Range = 53—75 µm; MC Concentration = 3g/L
E-2: Ferric Chloride Concentration Range: 10—100 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 2 mg/L
Settling Time = 3 min

Figure 5-4. Coagulant Concentration Selection (Test-1)



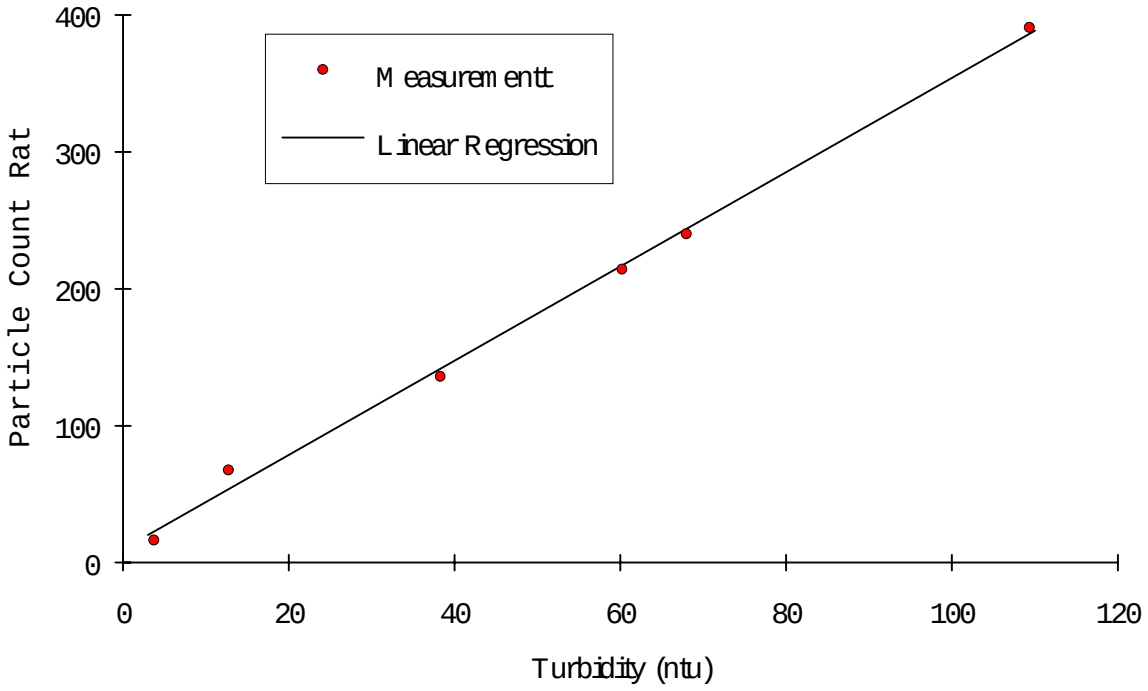
(A) By Turbidity Indicator



(B) By Particle Count Rate Indicator

MC-5: MC Size Range = 53—75 μm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration Range: 0—80 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 1 mg/L
Settling Time = 3 min

Figure 5-5. Coagulant Concentration Selection (Test-2)



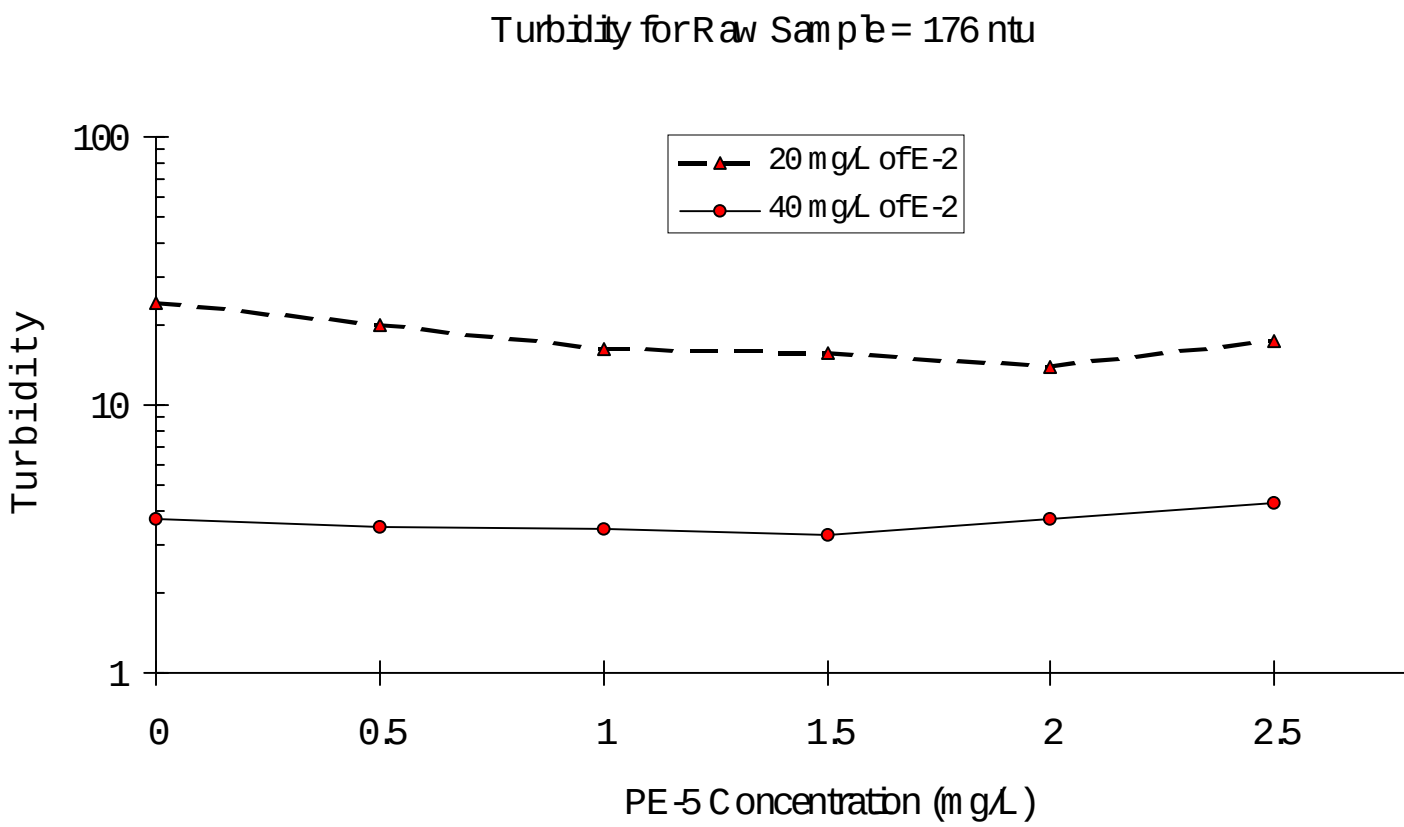
MC-5: MC Size Range = 53—75 µm; MC Concentration = 3g/L
E-2: Ferric Chloride Concentration Range: 2—110 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 2 mg/L
Settling Time = 3 min

Figure 5-6. Particle Count Rate Versus Turbidity

Coagulant Aid Concentration

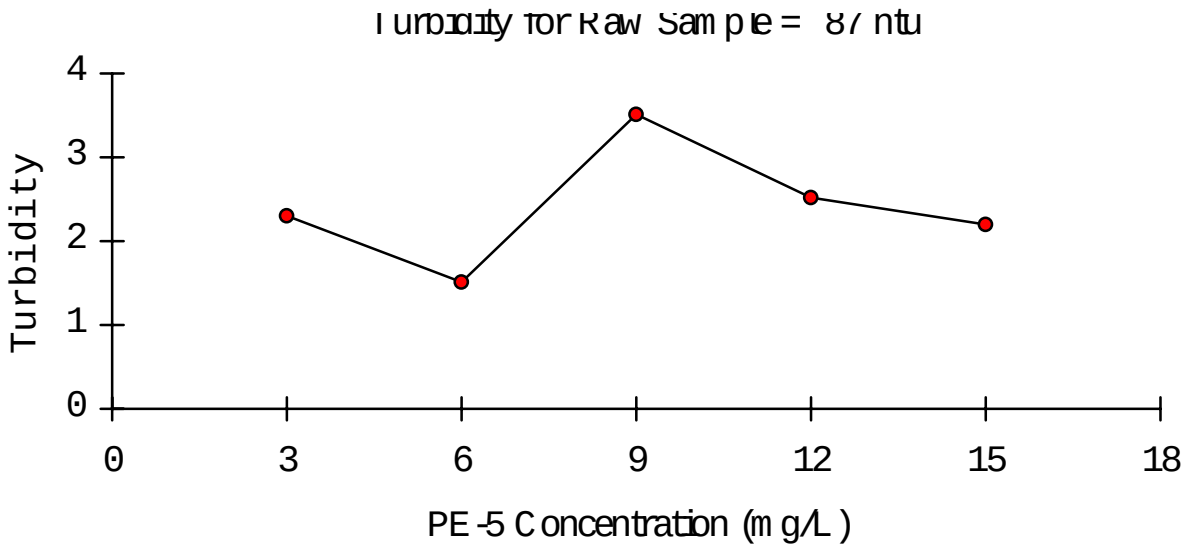
Figure 5-7 presents a comparison of the turbidity distribution versus coagulant aid concentration for two coagulant concentrations (20 and 40 mg/L). The coagulant aid concentration appears to have less influence on final turbidity in low dosages (ranged 0—2.5 mg/L) for both coagulant concentrations.

For higher coagulant aid concentration ranged 3—15 mg/L, 6 mg/L dosage resulted lowest turbidity as illustrated in Figure 5-8.



MC-5: MC Size Range = 53—75 µm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectrolyte 309C; Settling Time = 3 min

Figure 5-7. Polyelectrolyte Concentration Selection (Low Dose)



MC-5: MC Size Range = 53—75 μm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectrolyte 309C; Settling Time = 3 min

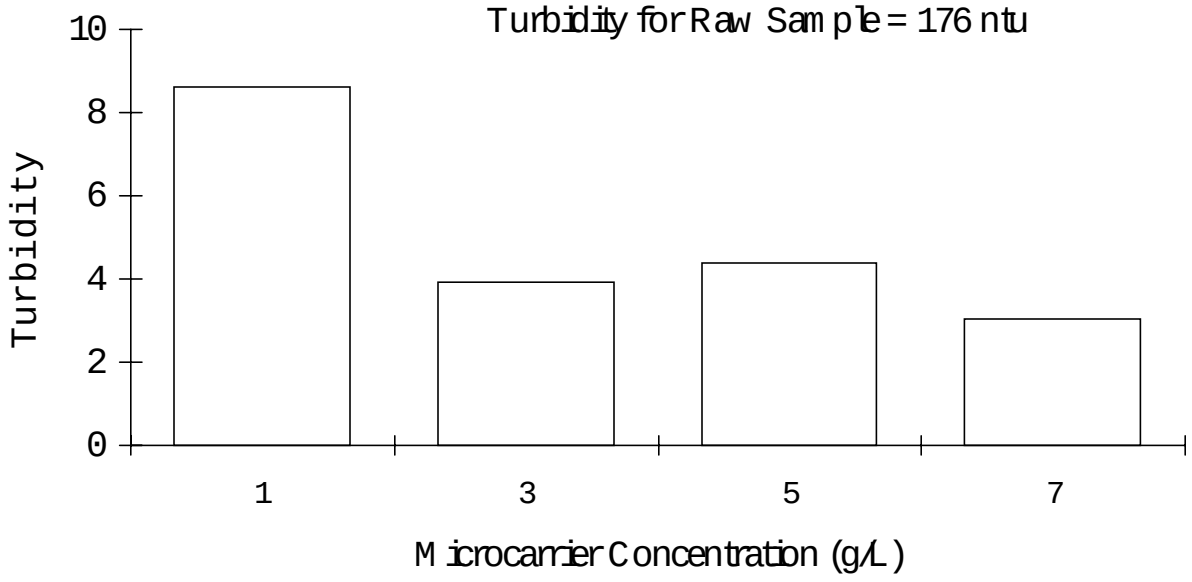
Figure 5-8. Polyelectrolyte Concentration Selection (High Dose)

MC Concentration

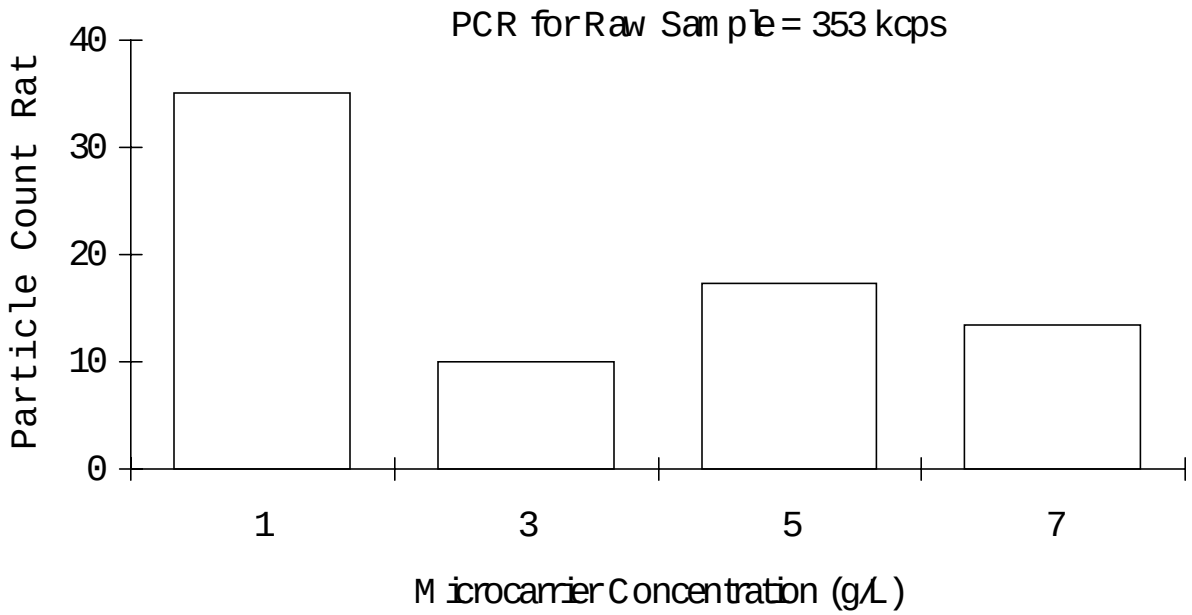
Four different MC concentrations, ranging between 1 and 7 g/L were utilized to determine an optimal value. Figures 5-9(A) and (B) illustrate turbidity and particle count rate distributions versus four different MC concentrations, respectively. In Figure (A), a sharp decrease in turbidity was observed for MC concentrations between 1 and 3 g/L, with slight fluctuations at 5 and 7 g/L of MC. Although 7 g/L MC yields the lowest turbidity, the improvement is only 23% greater compared with 3 g/L MC while the MC concentration level is increased by 133%. Using particle count rate as an indicator in Figure (B), 3 g/L MC appears to yield the lowest result. Based on the results of both turbidity and particle count rate, a 3-g/L of MC was selected as the optimal concentration.

MC Size

Five different size ranges for MCs were employed in the tests. Turbidity and particle count rate versus the five different MC sizes, along with one sample without MC, are shown in Figure 5-10 (A) and (B), respectively. It can be seen that the size range from 53 to 75 μm yields the best results for both turbidity and particle count rate. Thus, this size range was selected as the optimal MC size.



(A) By Turbidity Indicator

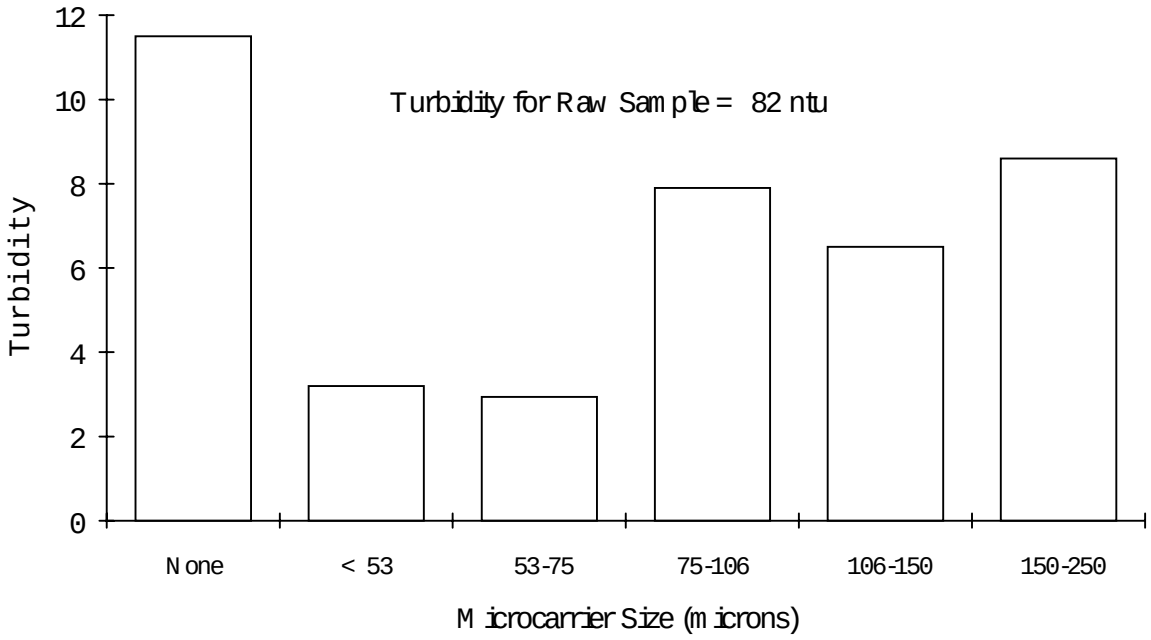


(B) By Particle Count Rate Indicator

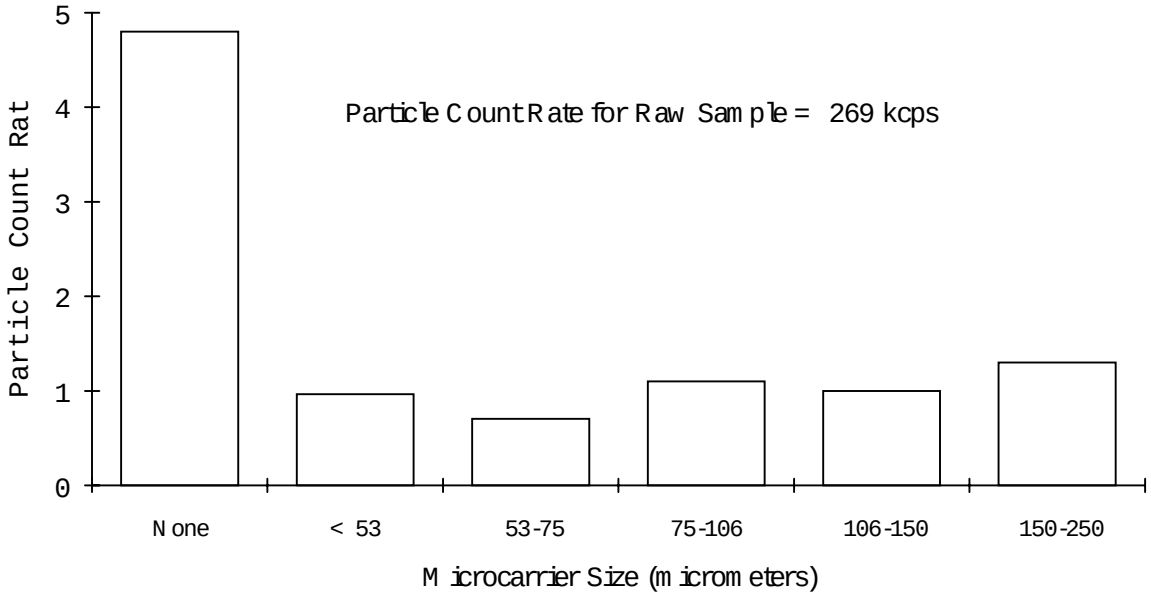
MC Size Range = 53—75 μm;

E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++};
PE-5: Polyelectolyte 309C Concentration = 2 mg/L

Figure 5-9. MC Concentration Selection



(A) By Turbidity Indicator



(B) By Particle Count Rate Indicator

MC Concentration = 3g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++};
PE-5: Polyelectolyte 309C Concentration = 2 mg/L

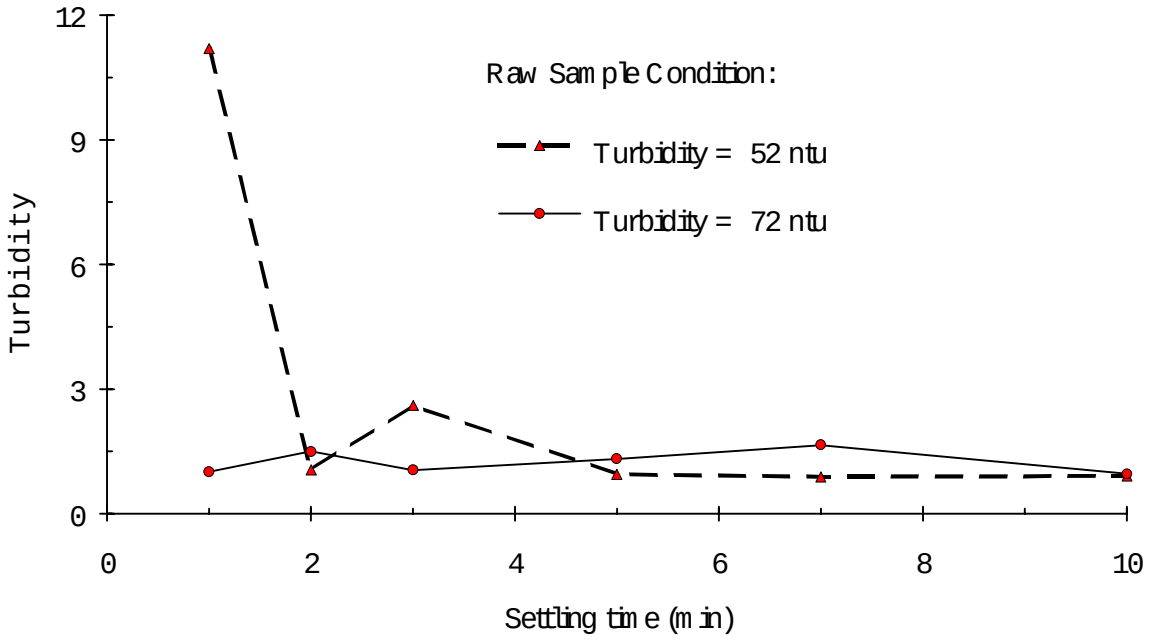
Figure 5-10. MC Size Selection

Settling Time

Settling time required is one of the key factors in the coagulation-flocculation treatment process since settling kinetics governs the treatment efficiency, duration, and thus the size of the treatment facility. The MC process appears to provide very efficient settling characteristics for CSO treatment.

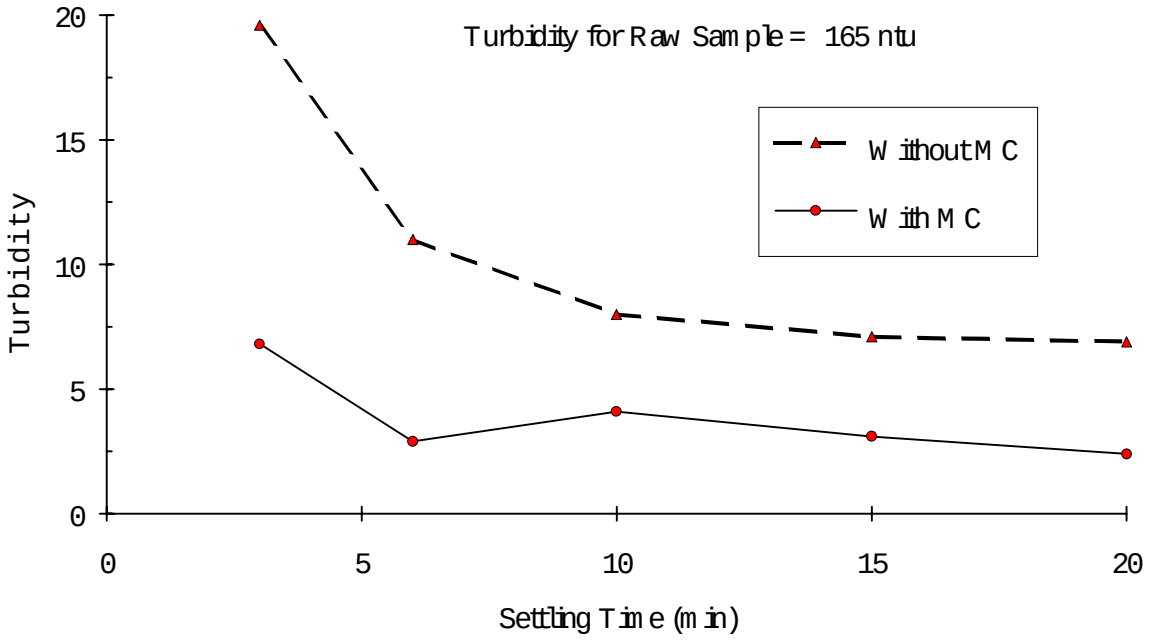
Figure 5-11 shows results of turbidity versus settling time from 1 to 10 minutes. In both tests, the post-treatment turbidity was reduced to 1.3 ntu with a minor fluctuation within a two-minute settling period. The average turbidity removal rate was 98% over the settling duration of 2 to 10 minutes.

Figure 5-12 illustrates a comparison of settling kinetics with and without the use of MC, respectively. In this test, it can be seen that the MC process enhances both short-term (3 minutes) and long term (20 minutes) settling characteristics.



MC-5: MC Size Range = 53—75 µm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 6 mg/L

Figure 5-11. Turbidity Versus Settling Time with Optimal Condition



MC-5: MC Size Range = 53—75 µm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 1 mg/L

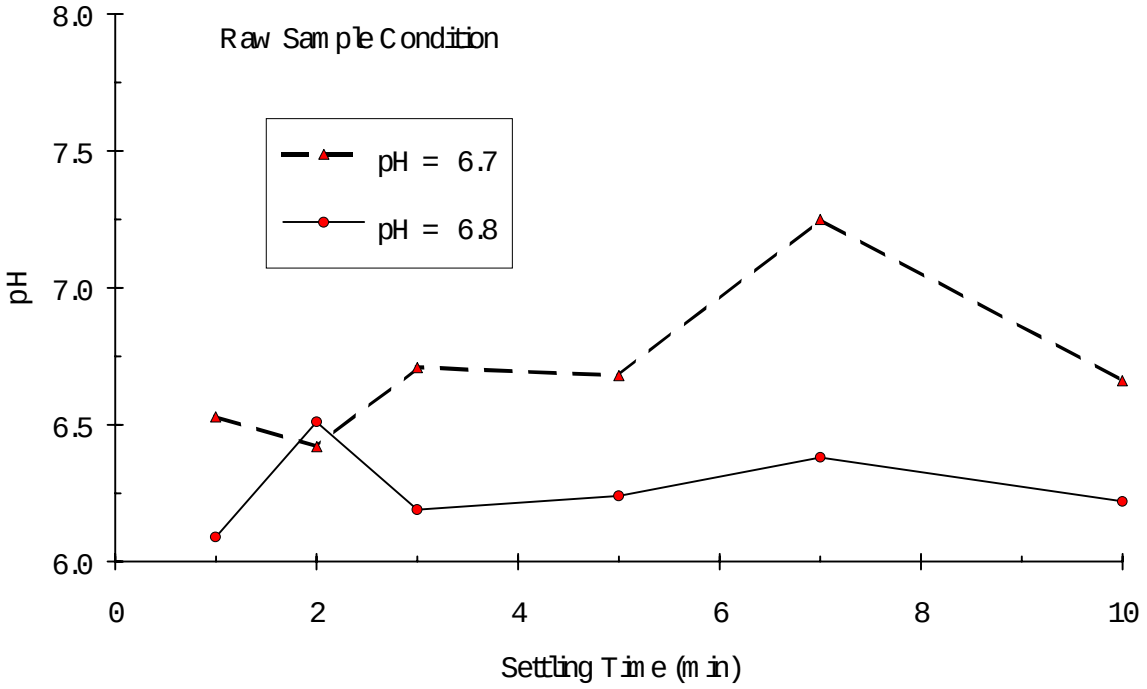
Figure 5-12. Turbidity Versus Settling Time

5.4 Response Variable Evaluation

During the CSO treatment stage, the response variables included the following parameters: turbidity, particle count rate, pH, suspended solids, total solids, total volatile solids, particle size distribution, total organic carbon, total inorganic carbon, fecal coliform, and zeta potential. Among these parameters, turbidity and particle count rate have been presented in Section 5.3. In this section, the results of the other response variables are evaluated.

pH

Figure 5-13 illustrates pH distributions for two different raw samples along with settling time from 1 to 10 minutes. It can be seen that under the optimal control variable setup, all pH values are within the range of 6.0 to 7.5.

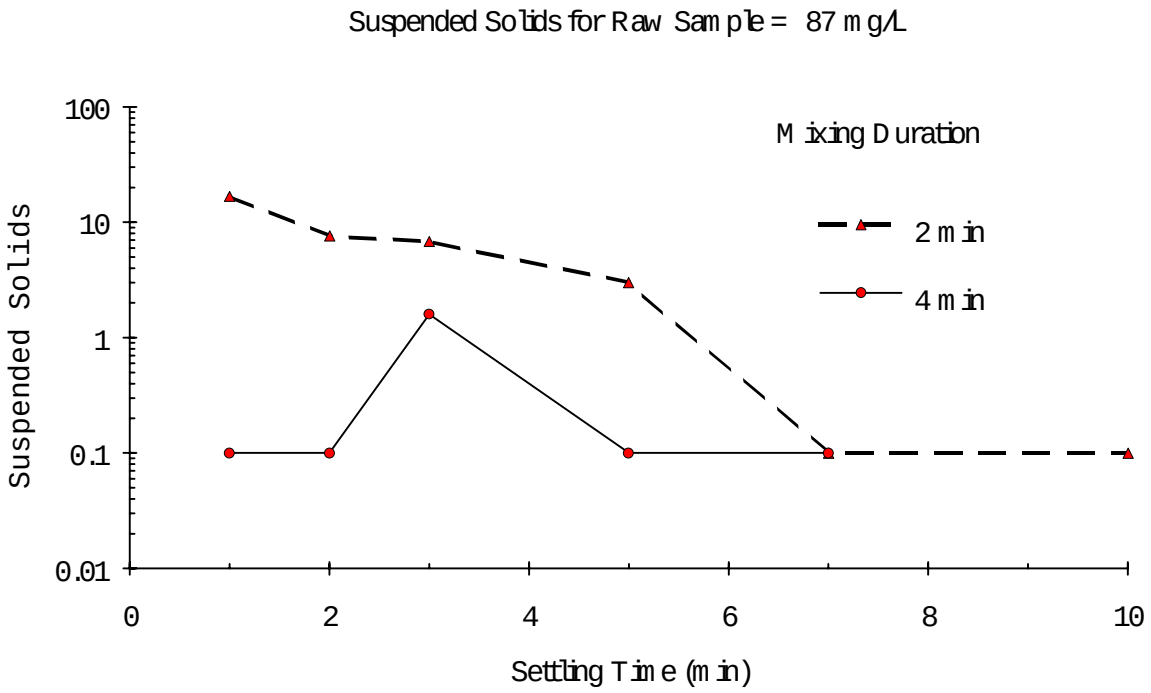


MC-5: MC Size Range = 53—75 μm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 6 mg/L

Figure 5-13. pH Versus Settling Time with Optimal Condition

Suspended Solids

Figure 5-14 illustrates suspended solids versus settling time with two different mixing periods, i.e., 2 and 4 minutes, respectively. Excellent results for both samples were found to be less than 10 mg/L with the exception of one sample with a one-minute settling time. Suspended solids were found to be less than 2 mg/L with a 4-minute mixing time. The removal efficiency is 97% after 2 minutes of mixing (average from 3 to 10 minute settling) and 99.5% after 4 minute of mixing (average from 1 to 7 minute settling), respectively. For both tests, the supernatant suspended solids reach the lower measurement limit (0.1 mg/L) after 7 minutes of settling.



MC-5: MC Size Range = 53—75 µm; MC Concentration = 3 g/L

E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}

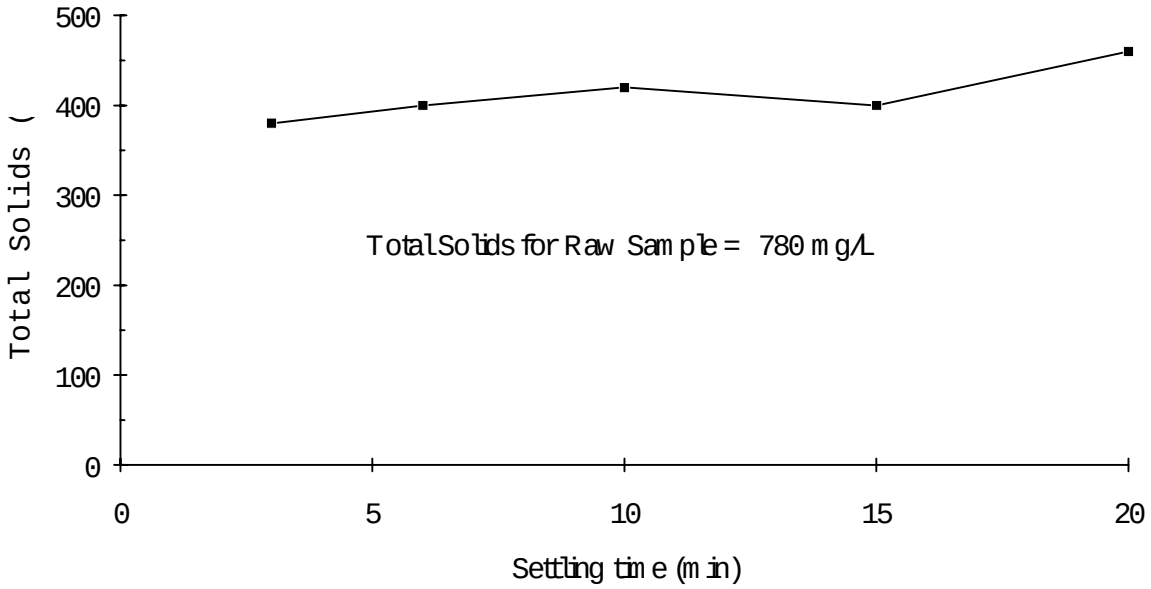
PE-5: Polyelectolyte 309C Concentration = 6 mg/L

Figure 5-14. Suspended Solids Versus Settling Time

Total Solids

The MC process was designed to remove suspended solids and any contaminants associated with suspended solids. Therefore, if suspended solids are the major component in the total solids, as

for surface runoff treatment, then the total solids removal could be effective. However, if dissolved solids were the major component in total solids, the total solids removal efficiency would be significantly limited by the content of organic portion of suspended solids in the raw sample. For the CSO treatment, total solids removal rates are approximately 50% as illustrated in Figure 5-15.

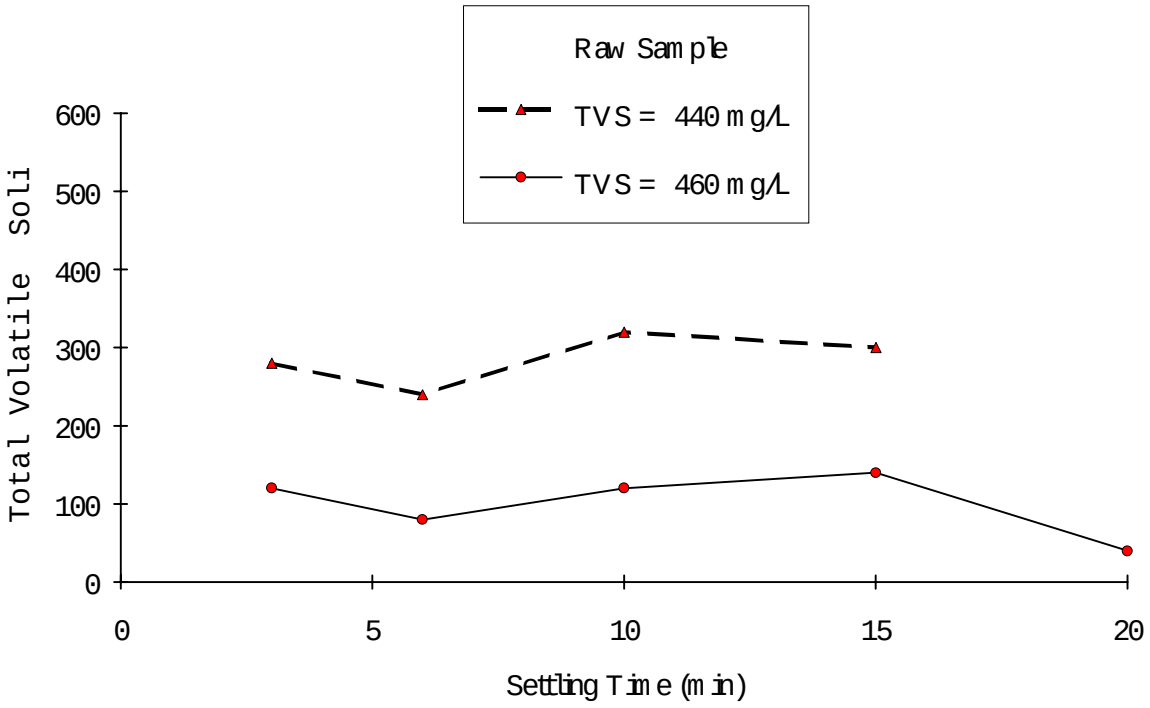


MC-5: MC Size Range = 53—75 μm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 1 mg/L

Figure 5-15. Total Solids Versus Settling Time

Total Volatile Solids

As with total solids removal, the total volatile solids removal efficiency was also limited by the content of organic portion of suspended solids in the raw samples. It was found that the total volatile solids removal rate was in the range of 60% to 80%. The results of the two sets of jar tests with similar conditions but different sample batches are illustrated in Figure 5-16.

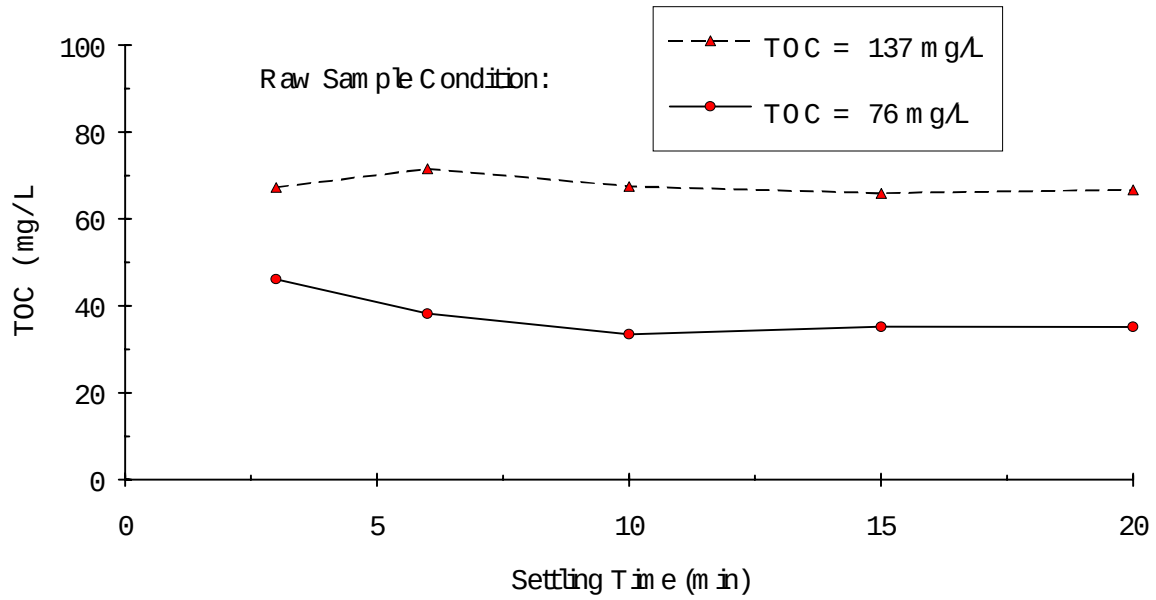


MC-5: MC Size Range = 53—75 μm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 1 mg/L

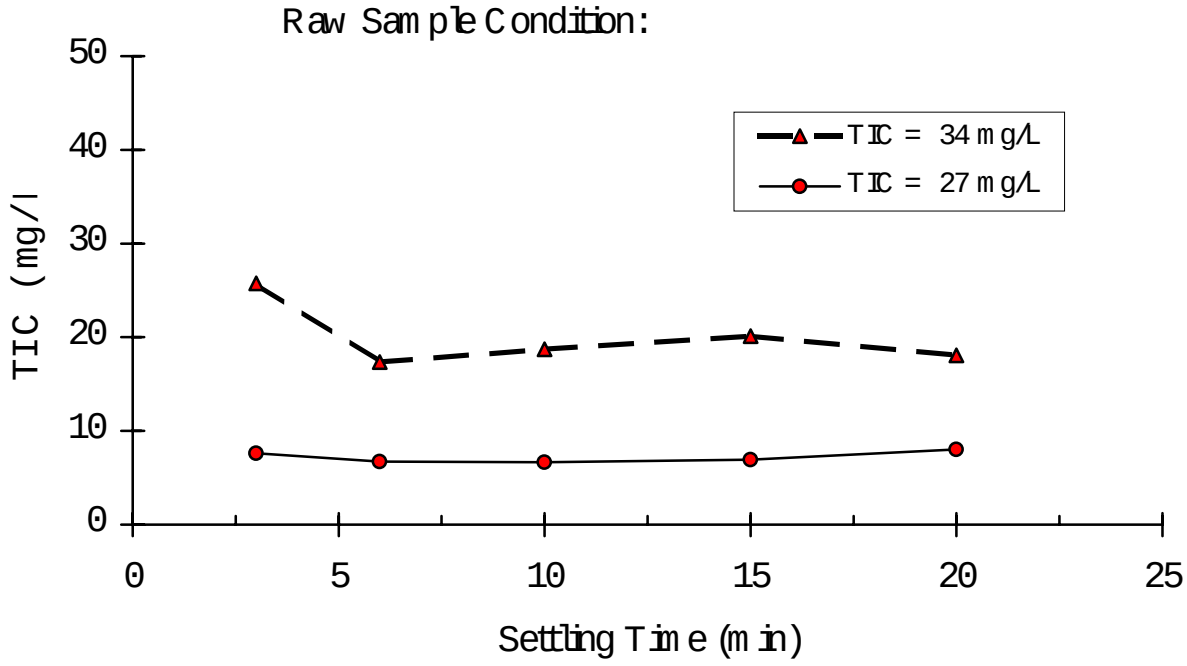
Figure 5-16. Total Volatile Solids Versus Settling Time

Total Organic and Inorganic Carbon

Figures 5-17 (A) and (B) show the results of total organic and inorganic carbon with respect to settling time for two different raw samples. It appears that a 3-minute settling time would be sufficient to achieve a stable condition. It was observed that the average total organic and inorganic carbon removal rates over the settling times from 3 to 20 minutes are approximately 50 and 70 percent, respectively. It was found that these removal rates remained the same although the post-treatment total organic and inorganic carbon values varied for different raw sample conditions. These removal rates were limited by the fact that only total organic carbon associated with the suspended solids were removed while total organic carbon in the dissolved format still remained in the solution after the MC process treatment. Figure 5-18 illustrates comparison results from two different mixing durations, 2- and 4-minute, respectively. It appears that the influence of mixing duration (2- to 4-minute) is insignificant with respect to total organic and inorganic carbon removals.



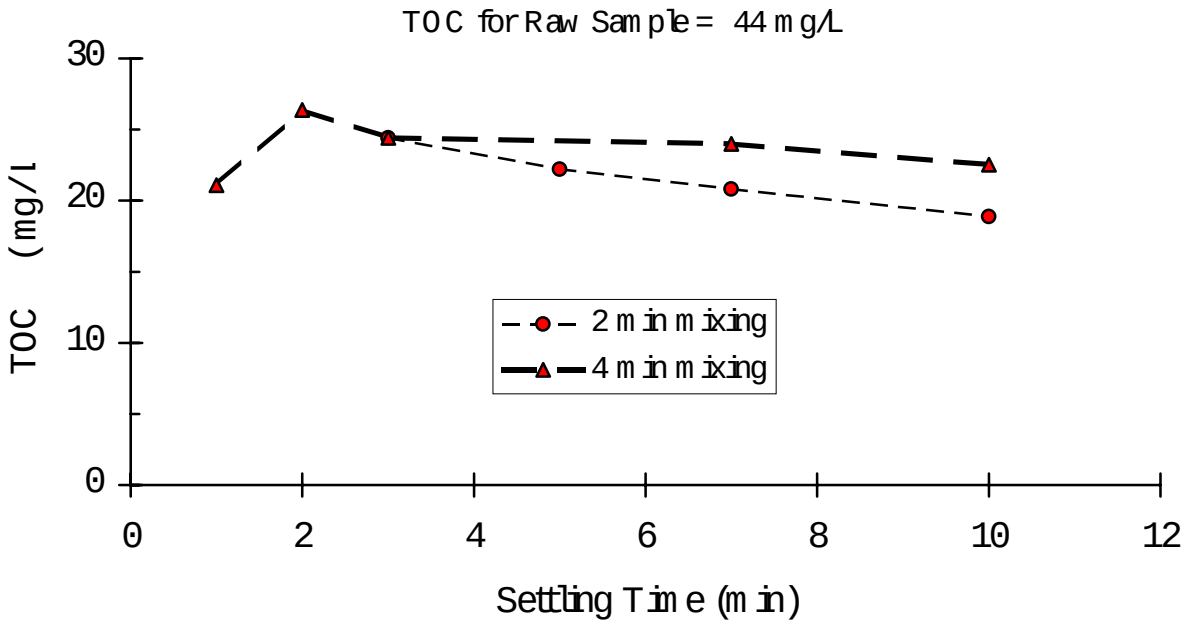
(A) Total Organic Carbon



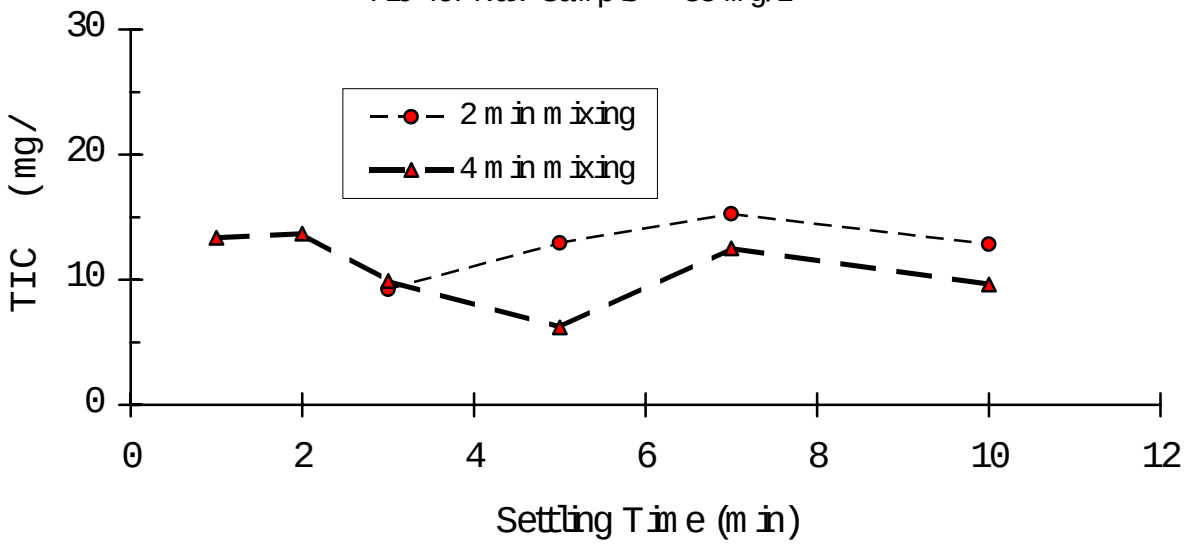
(B) Total Inorganic Carbon

MC-5: MC Size Range = 53—75 μm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 1 mg/L

Figure 5-17. Total Organic and Inorganic Carbon Distributions (with different raw samples)



(A) Total Organic Carbon



(B) Total Inorganic Carbon

MC-5: MC Size Range = 53—75 µm; MC Concentration = 3 g/L

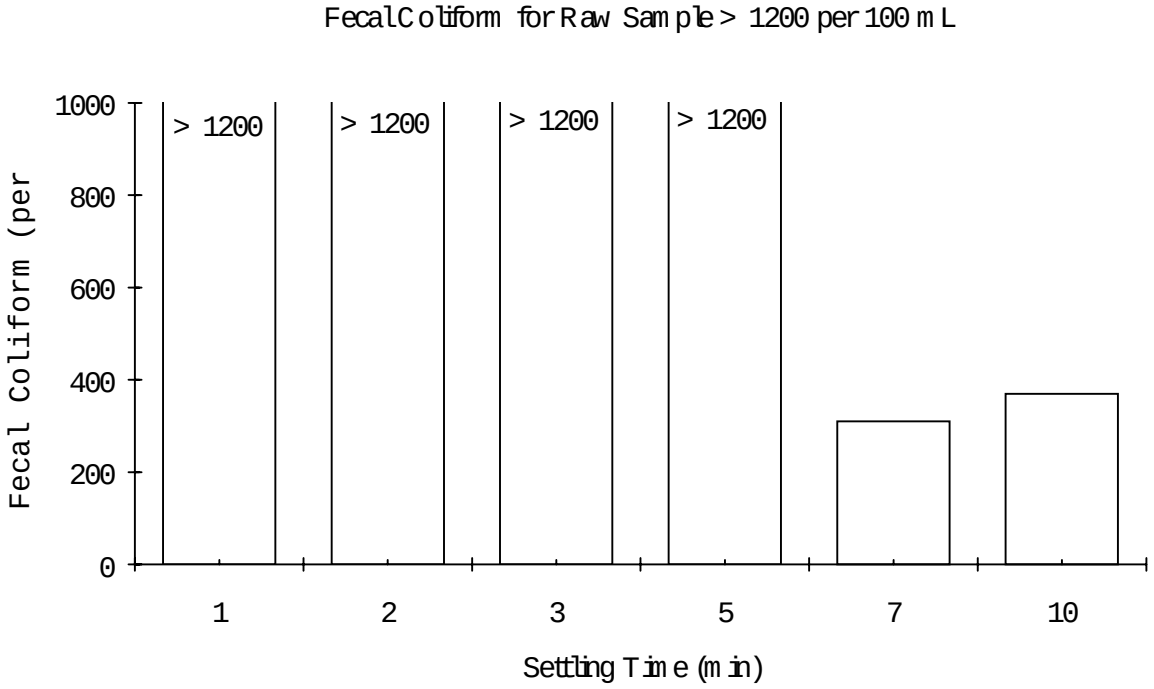
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}

PE-5: Polyelectolyte 309C Concentration = 6 mg/L

Figure 5-18. Total Organic and Inorganic Carbon Distributions (with different mixing duration)

Fecal Coliform

Figure 5-19 shows fecal coliform distribution versus settling time. It appears that for a 7-minute settling time, the fecal coliform is reduced to approximately 300 per 100 mL. The removal rate was observed as greater than 75% (considering the initial concentration was 1200 per 100 mL).



MC-5: MC Size Range = 53—75 µm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration = 40 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration = 6 mg/L

Figure 5-19. Fecal Coliform Distributions

Relationship of Particle Count Rate and Turbidity

Figure 5-20 illustrates the particle count rate distribution versus turbidity. A linear regression between these two parameters was performed and the correlation coefficient is 0.94, which indicates a strong relationship. Since the data ranges over more than two magnitudes, a log-log distribution of particle count rate and turbidity is shown in Figure 5-21. The log-log correlation of these two parameters was found to be 0.8. A log-log linear regression was also performed. The regression equations are expressed as follows:

$PCR = 3(Turbidity) + 4.4$ For linear regression
$Log(PCR) = 0.91 Log(Turbidity) + 0.54$ For log-log regression

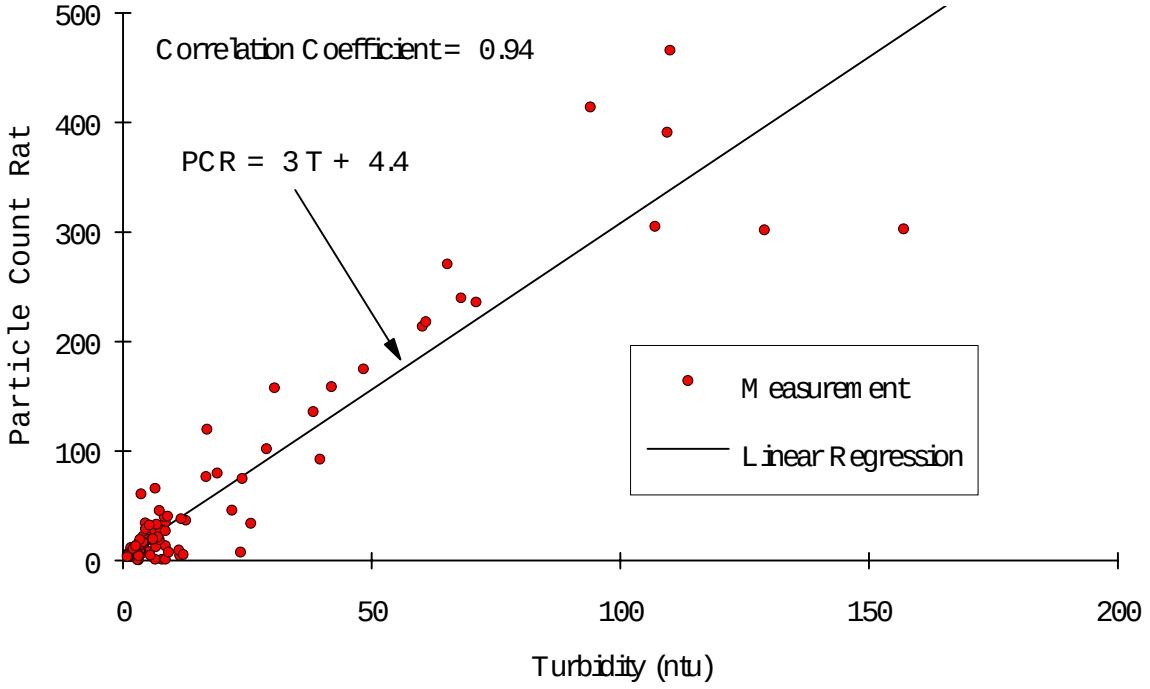


Figure 5-20. Particle Count Rate Versus Turbidity

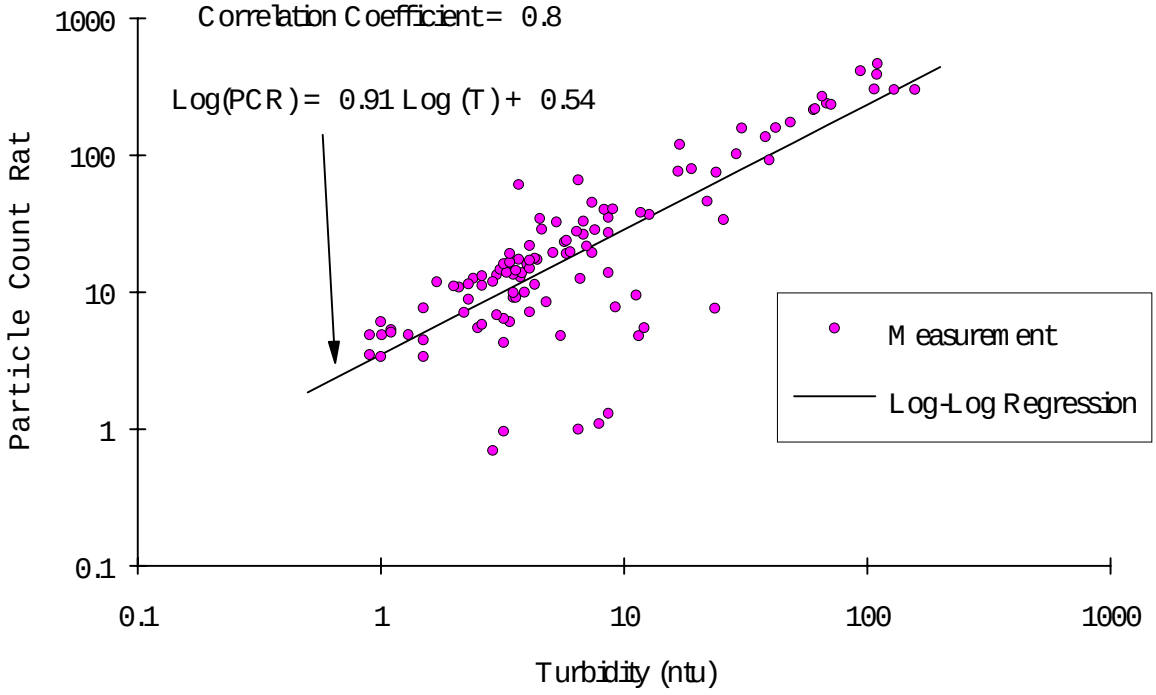
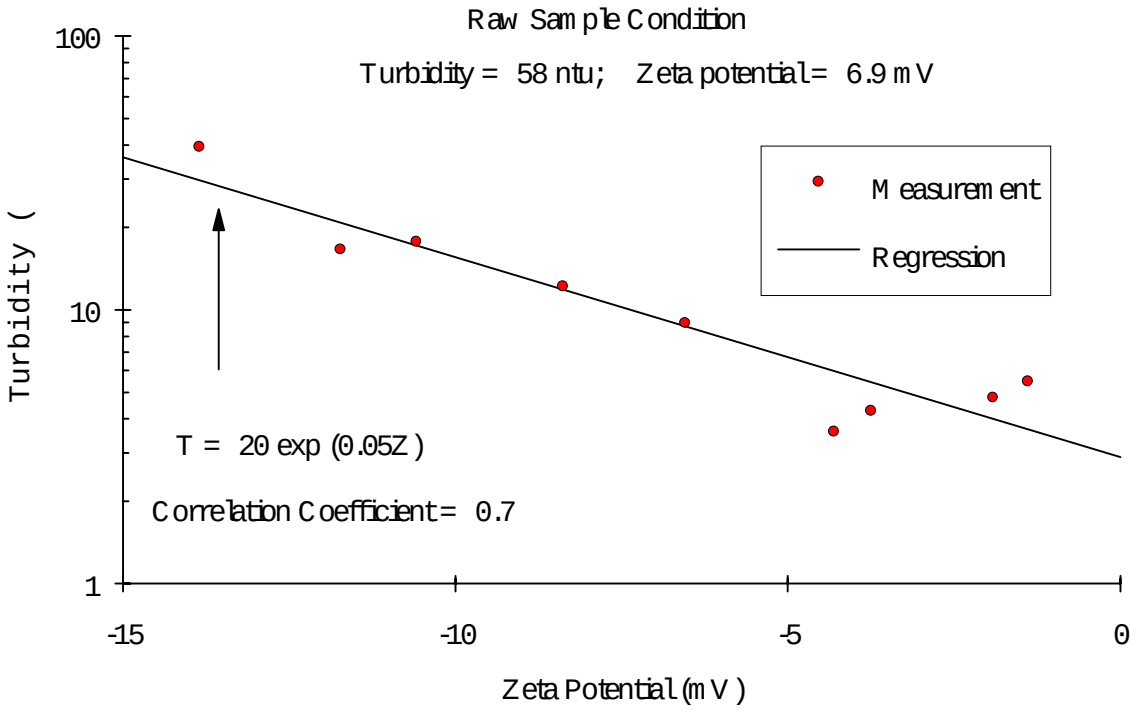


Figure 5-21. Particle Count Rate Versus Turbidity (log-log)

Zeta Potential

The relationship between zeta potential and turbidity is illustrated in Figure 5-22. It appears that the treatment is more effective when particles have less charge. A semi-log regression was performed based on test results. However, it was noted that in most CSO samples, zeta potential data fluctuated, which may be due to the varying charge characteristics of raw samples. The relationship between zeta potential and turbidity in CSO treatment is not as clear as in surface runoff treatment.



MC-5: MC Size Range = 53—75 µm; MC Concentration = 3 g/L
E-2: Ferric Chloride Concentration: 20—40 mg/L as Fe^{+++}
PE-5: Polyelectolyte 309C Concentration: 6—18 mg/L

Figure 5-22. Turbidity Distribution Versus Zeta Potential