Final Report

NCDOT Research Project HWY-2007-02

Stilling Basin Design and Operation for Water Quality Field Testing

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16. Abstract

Many construction projects involve the need to pump turbid water from borrow pits or other excavations into stilling basins or sediment bags prior to discharge. The design and operation of these basins needs to be optimized to provide the best water treatment prior to discharge. This project was designed to provide an evaluation of stilling basin designs and polyacrylamide (PAM) injection to minimize turbidity in discharged water. A Piedmont subsoil was mixed with water in a large holding pond which served as a source of the turbid water which was pumped into the stilling basin. Initial turbidities were in the range of 250-400 nephelometric turbidity units (NTU) in the source basin. Physical changes to the open basin, both with porous baffles and distribution along the bottom, significantly reduced turbidity or total suspended solids in the stilling basin, but the highest reduction was only 25%. Chemical treatment with PAM reduced turbidity and TSS by up to 88% and 84%, respectively, with little effect from the baffles or bottom spreader. Both types of PAM dosing systems worked well. There was some evidence that flocs formed after PAM treatment were intercepted by the dam slope. The porous baffle with 10% open pore space was significantly more effective than the baffle with 45% open pore space, but only when no PAM was added. The PAM treatments were highly effective and should be relatively simple and economical to use to reduce turbidity in pumped water.

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Executive Summary

Stilling basins are often ineffective in capturing fine sediment which may be present in pumped construction site water. These fine materials settle as such slow rates that typical retention times of 24 h or more are insufficient, even under ideal settling conditions. This study examine two options for improving efficiency: physical alterations to improve settling conditions and chemical treatments to flocculate the suspended sediment. The physical variables included porous baffles of different types (pore size, material) and the distribution of incoming flow along the bottom of the basin. The chemical treatments included polyacrylamide in solution pumped into the water pump intake or pumping the turbid water over a solid block of polyacrylamide (PAM).

Tests were conducted of various combinations of these variables under controlled conditions at the Sediment and Erosion Control Research and Education Facility (SECREF) at North Carolina State University. A Piedmont subsoil was mixed with water in a large holding pond which served as a source of the turbid water which was pumped into the stilling basin. Initial turbidities were in the range of 250-400 nephelometric turbidity units (NTU) in the source basin. The main findings were as follows:

1. Physical changes to the open basin, both with porous baffles and distribution along the bottom, significantly reduced turbidity or total suspended solids in the stilling basin, but the highest reduction was only 25%.
2. Chemical treatment with PAM reduced turbidity and TSS by up to 88% and 84%, respectively, with little effect from the baffles or bottom spreader.
3. Both types of PAM dosing systems worked well.
4. There was some evidence that flocs formed after PAM treatment were intercepted by the dam slope.
5. The porous baffle with 10% open pore space was significantly more effective than the baffle with 45% open pore space, but only when no PAM was added.

Recommendations:

Turbidity and suspended solids in pumped water may not be treated sufficiently in open stilling basins. The addition of porous baffles provides some improvement, but treatment with PAM will usually be required to meet water quality targets. A simple PAM pumping system which injects a solution into the water pump intake works very well. An even simpler approach, pumping the turbid water over a PAM log, may also work very well. However, the latter system lacks any control over dosing rates, and although it is unlikely to result in toxicity issues it might be less acceptable to regulatory agencies. When PAM is used, one porous baffle should be installed primarily to catch any floating flocs which may be produced.

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Stilling Basin Design and Operation for Water Quality: Field Testing

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Chapter 1. Polyacrylamide Dosing Systems Compared With and Without Coir Baffles

Abstract: *Stilling basins are often ineffective in reducing turbidity and total suspended solids (TSS) in water containing fine sediments. This study determined the effectiveness of two polyacrylamide (PAM) dosing systems to flocculate suspended materials and the influence that porous baffles have on the two systems. Turbid water was generated by injecting soil into pond water flowing into a mixing basin for 30 min. Turbid water containing mostly fine suspended sediments was pumped from the surface of the mixing basin to a test stilling basin with physical and chemical treatments. The physical treatments were either an open basin or one with three porous baffles of 900 g m^{-3} coir matting. The chemical treatment was either passive using a PAM block or active using a PAM solution injected into the water pump intake at 4 mg L^{-1} in the pumped water. The passive treatment involved pumping turbid water over the PAM block at the basin entrance, dissolving the PAM as the water flowed over the block. Sampling for turbidity and total suspended solids (TSS) was done at 5 min intervals at the inlet, outlet weir, and 4 surface and bottom points inside the basin. In laboratory screening for PAM formulation and dose, tests conducted with whole soil resulted in greatly reduced turbidity while those with only the suspended fraction had a much lower turbidity reduction. In the stilling basin, detention times of 1.5 or 24 h both had no effect on turbidity or TSS at the outlet. The turbidity of untreated discharges ranged from 220-260 nephelometric turbidity units (NTU), while both active and passive dosing significantly decreased the turbidity by 66-88%. Porous baffles had little effect compared to the PAM treatment. The active PAM treatment significantly reduced TSS at the outlet by up to 80%, but the 45-65% reduction by the passive system was not significantly different from the untreated tests. Patterns within the basins indicated that suspended flocs in PAM treated water may have been intercepted and removed by the sloped dam wall, a phenomenon not observed in the untreated water.*

Introduction

Construction activities are a major contributor of suspended solids and sediments to surface waters, with sediment loads as high as 2000 times that of wooded lands and 10-20 times that of agricultural lands (Owen, 1975). Urban erosion related pollutants impose net damage costs that have been estimated to be from $ 192 million to 2 billion per year (Clark et al., 1985; Paterson et al., 1993). Suspended solids in surface waters detrimentally affect aquatic biota, facilitate the transport of organic and inorganic pollutants, and decrease the aesthetic value of lakes and rivers (Novotny and Chesters, 1989; Pitt, 1995). Increased turbidity reduces the amount of light penetrating the water, clogs fish gills, smothers fish eggs, decreases feeding rates of fish, alters water chemistry, and reduces photosynthesis and overall productivity of the community. These changes that can occur in a water body may alter the composition of an aquatic community (Wilber, 1983). High turbidities interfere with chlorination, requiring higher chemical treatment rates and increased costs for drinking water treatment (Le Chevallier et al., 1981).

In an effort to reduce the sediment coming from construction activities, North Carolina enacted the Sedimentation Pollution Control act of 1973. Federal and state regulations now require developers to design sediment and turbidity control programs for construction sites (United States Environmental Protection Agency (USEPA), 1992; North Carolina Department of Environment and Natural Resources (NCDEHNR), 1995). These regulations provide that any land disturbing activity that covers one or more acres must submit an erosion and sedimentation control plan. This plan must include Best Management Practices (BMPs), structural or non-structural, that reduce non-point source inputs to receiving waters (NCDENR, 2004). In addition to this regulation, North Carolina Administrative Code 15A NCAC 02B .0211 states that the turbidity in the receiving waters adjacent to a site must not exceed 50 NTU in streams not designated as trout waters and 10 NTU in streams, lakes or reservoirs designated as trout waters. In lakes and reservoirs not designated as trout waters, the turbidity must not exceed 25 NTU. If the receiving waters already exceed these levels, runoff from a construction site must not increase turbidity further. However, the standard control measures have been shown to be ineffective in controlling the elevated levels of turbidity in the waters discharged from the construction sites.

Przepiora et al. (1997) observed turbidities of 120- 3200 NTU from two construction sites during a 1 year period. Suspended clay and silt particles escape detention by the standard control structures due to their low settling velocities (Haan et al., 1994; Wu et al., 1996), regardless of basin shape (Simons and Senturk, 1992) unless residence time is increased or aggregation is induced by natural or artificial means (Chen, 1975). Line and White (2001) found that sediment traps on active construction sites in North Carolina retained 59-69% of sediment entering them, but very little of the clay sized particles were retained. Consequently, the turbidity ranged from 100 – 15,000 NTU in the discharged water. McCaleb and McLaughlin (2008) found turbidities often exceeded the instrument limit (30,000 NTU) in discharges from sediment traps on construction sites.

Stilling basins are impoundments designed to treat the turbid waters encountered on construction sites by converting flows from supercritical to subcritical, which creates a hydraulic jump and increases the residence time. Energy dissipaters within the basin, such as baffles, can play an important role providing particles an increased opportunity to settle under non-turbulent conditions. Turbulence within the water column contributes to prolonged suspension (Graf, 1971; Goldman et al., 1986). Millen et al. (1997) demonstrated that turbulence likely maintains particles suspended much longer than expected in basins. Baffles also increase the hydraulically effective width as ‘the width over which the flow is uniformly distributed' (Chen, 1975). Porous baffles have been shown to reduce turbulence and improve sediment capture in sediment basins (Thaxton et al., 2004; Thaxton and McLaughlin, 2005), suggesting they might be helpful in stilling basins as well.

Many construction projects need to pump turbid waters from burrow pits or other excavations into stilling basins prior to discharge. These waters may contain very fine suspended sediments, too small to settle under normal conditions. Chemical treatment using coagulants or flocculants would promote the coagulation of fine suspended sediments into floccules and enhance their settling and trapping in the basins. Many coagulants like alum and gypsum (Harper and Herr, 1992), molding plaster (Przepiora et al., 1998) and $CaCl_2$ (Robbins and Brockway, 1978) are effective for reducing turbidities in either storm waters or waste water treatment operations. Often the quantity of these coagulants required for effective flocculation is very high or the discharged water has to be monitored for changes in water chemistry due to pH effects or ions ($SO4^{2-}$, Cl^{-1} etc.) released.

Polyacrylamide has been found to be an effective chemical flocculent (Peng and Di, 1993, Qian et al., 2004) without aquatic toxicity at typical treatment concentrations (<10 mg L^{-1}). There are different physical forms of PAM (powder, block, emulsion) which can be used to treat turbid waters with different dosing methods in order to achieve flocculation and to reduce turbidity in stilling basins. Emulsions are less desirable because the emulsifying agents will often remain in the discharged water.

The objective of this study were to evaluate the effectiveness of two relatively simple PAM dosing systems for turbidity control in stilling basins and the potential for further improvements using porous baffles.

MATERIALS AND METHODS

The study was conducted at the Sediment and Erosion Control Research and Education Facility on the North Carolina State University Lake Wheeler Field Laboratory in Raleigh, NC. The experimental setup consisted of a series of basins which were used to test a number of turbidity reduction options for pumped construction site water (Fig. 1). Water from a source pond (~ 900 m^3) was delivered to a mixing pond (80 m^3) through a pipe (dia. = 0.3 m) with a control valve for regulating the flow (Fig. 1). An inlet "T" was located approximately half of the distance between the source pond and the mixing pond, to allow the introduction of soil into the pipe. The soil was obtained from a large stockpile brought to the Field Laboratory as excess soil from nearby construction sites. The selected properties of soil and water used for the tests are provided in Table 1 and 2, respectively. The turbidity for tests was generated by releasing water from the source pond into the mixing pond at a fixed rate of 20 L s^{-1} (0.7 cu. ft. s^{-1}) while adding soil (23 kg min^{-1}) to the pipe at a controlled rate for 0.5 h. Approximately 700 kg of soil was added to the flow. The turbid water from the mixing basin was then pumped into a stilling basin (22 m^3) where all chemical and physical treatments were tested (Fig. 1). The stilling basin was 7.0 m long x 4.9 m wide x 0.8 m deep at the top of the outlet weir, and 5.1 m long x 2.0 m wide at the bottom. The soil used for the tests had sandy clay loam texture (Table 1) and produced turbidity in the range of 150-400 NTU in the mixing basin. A settling time of 5 min. was provided between turbidity generation in the mixing basin and pumping of water into the test basin to allow the settling of large particles. The heavy particles (predominantly sand and coarse silt) do not contribute much to turbidity and may not be present when pumping out standing or accumulated water from an excavation. The water from the mixing basin was pumped to the stilling basin using a gasoline pump (51 mm outlet; Hypro C-35, Waterford, WI) at the rate of 4 L s^{-1}, which provided a detention time of 1.5 h. The pump flow was calibrated before each test.

Figure 1-1. Layout of the experiment showing the mixing basin (top) and the open stilling basin with no baffles (bottom).

Table 1-1: Selected physico-chemical and mineralogical characteristics of soil used.

Characteristics†	Value
Physico-chemical	
Clay (%)	25.0
Silt (%)	18.8
pH	4.70
EC (dS m^{-1})	0.10
Fe_{OX} (mmol kg^{-1})	8.9
Fe_{CBD} (mmol kg^{-1})	357
Al_{CBD} (mmol kg^{-1})	92
Mineralogical	
Fine clay (< 1 μm)	
Kaolinite (%)	87
Gibbsite (%)	5.8
Vermiculite (%)	7.7
Coarse clay (1-2 μm)	
Kaolinite (%)	78
Quartz (%)	8.4
Mica (%)	4.9
Vermiculite (%)	4.9
Gibbsite (%)	3.9

† EC, electrical conductivity; Fe_{OX}, ammonium oxalate extractable iron; Fe_{CBD} and Al_{CBD}, citrate bicarbonate dithionite extractable iron or aluminum.

Table 1-2: Selected chemical characteristics of pond water used for the turbidity tests.

Parameter†	Value	Parameter†	Value (mg L^{-1})
pH	6.00	Al	0.77
EC (dS m^{-1})	0.07	Ca	3.52
Turbidity (NTU)	3.00	Fe	0.28
TSS (mg L^{-1})	4.73	K	3.56
TOC (mg L^{-1})	7.10	Mg	2.35
NO_3 (mg L^{-1})	0.64	Na	5.25
NH_3 (mg L^{-1})	0.59	Mn	0.15
PO_4 (mg L^{-1})	0.02	Zn	0.03

† EC, electrical conductivity; TSS, total suspended solids; TOC, total organic carbon.

The stilling basin was filled, after approximately 90 min of pumping, and allowed to overflow through the 1 m wide spillway. In-basin sampling began at that point, and pumping of turbid water was continued for 40 min to determine the effects of treatments on turbidity of water exiting the basin. Water sampling was accomplished using six automatic samplers (Teledyne ISCO 6712 portable sampler, Lincoln, NE) installed at the inlet (in pipe), and at 2.2 m(bottom and surface), 3.6 m (bottom and surface), and 7.0 m (outlet) from entrance. The middle two positions had two samplers each, one 0.1 m above the bottom and the other 0.1 m below the surface. The sampler intakes within the basin were placed on the downstream side of each baffle, or at that same position when baffles were not installed. The sampling at the entrance was started from the time when pumping into the stilling basin was started while at the other locations it was started only once the basin was filled and water started flowing over the spillway. Water from the spillway passed through a flume where it was sampled with an automatic sampler. The automatic sampler at the exit was equipped with a bubbler flow module (Teledyne ISCO 640) to confirm the flow rate in the outlet flume during the test. The stilling basin was lined to prevent erosion of the basin bottom.

The testing included physical and chemical treatments for controlling turbidity. The physical treatments tested were porous baffles made of 900 g m^2 coir material. Four 150 x 150 mm sections of the coir roll were sampled and thread diameter and opening size were measured at four random points each. From these measurements, we determined the coir material had an average thread diameter of 4.6 mm, 65 mm openings, and an overall 46% open space fraction. Three baffles in the basin were installed at 2.2, 3.6, and 4.9 m from the entrance. The first two baffle positions coincided with the location of sampler intakes in the basin, which were placed just downstream of each baffle. The baffles were 0.81 m tall (0.01 m above the outlet level) and were spread across the entire width of the basin. For tests without baffles, the sampler intakes remained in the same positions on the baffle supports. The chemical treatments included two methods of introducing PAM: a passive dosing system using a solid block (APS Floc Log 706b, Applied Polymer Systems Inc., Woodstock, GA, USA), which dissolved as the pumped water flowed over it, and an active dosing system in which a concentrated solution made from a powder form (APS Silt Stop 705, Applied Polymer Systems Inc., Woodstock, GA, USA) was injecting into the turbid water at the pump intake. The two polymer products are formulated from the same proprietary mixture of medium and high molecular weight anionic polyacrylamide and are certified by North Carolina Department of Environment and Natural Resources (NC DENR) for storm water treatment for turbidity. Both products were effective in flocculating this soil in laboratory screening tests (see below). The PAM solution was made by dissolving 705 powder in water (1.0 g L^{-1}) and injecting it directly into the intake hose of the turbid water pump using a variable speed, peristaltic pump. The peristaltic pump was calibrated to maintain 4 mg 705 L^{-1} at the pumping rate used in the tests. The floc log contained 3.4 kg PAM active ingredient and the dosage rate, as determined by the manufacturer, was < 2.0 mg L^{-1}. The PAM block was covered with metal hardware cloth with 100 mm^2 openings to keep the block from eroding excessively from the pump discharge water pressure. The treatments were initiated as soon as the water began to be pumped into the stilling basin. Water sampling occurred at 5 min intervals and with at least 8 samples at each sampling point in the basin for each test.

The laboratory screening test involved mixing 2 g of soil in 100 mL water, then dosing them with 0, 0.5, 1.0, 5.0, and 10.0 mg PAM L^{-1} using the APS 705 powder in solution. Additional tests were conducted on the fine fraction by mixing soil with 4 L of water until the turbidity after 5 min of settling was > 500 NTU. The supernatant, designated "high turbidity," was decanted and tested in the same manner as the 2 g soil tests. In addition, the decanted water was diluted to a lower turbidity ("low turbidity") and tested. When the tests showed the fine fraction maintained a much higher turbidity after PAM treatment than the whole soil, we added 2 g soil to the 1, 5, and 10 mg PAM L^{-1} high turbidity solutions to see if this addition would reduce turbidity.

Two additional tests were conducted with an open stilling basin and two pumping rates, 0.25 L s^{-1} and 4.0 L s^{-1}, which provided for detention times of 24 and 1.5 h, respectively. Samples were taken after the stilling basin began to overflow at 15 min for the 24 h pumping rate test and composited with four samples per bottle. For the 1.5 h pumping rate, samples were taken every 5 min after flow was initiated at the stilling basin outlet, and they were no composited. Only the surface water samplers were used for these tests, which were designed to determine the effect of detention time on stilling basin efficiency.

The water samples collected during the tests were analysed for turbidity by shaking them for 10 s and taking a turbidity measurement after 30 s using an Analite NEP 260 turbidity probe (McVan Instruments, Melbourne, Australia). The 30 s delay was used to reduce variations produced by the turbulence in the bottle. Measured turbidity readings were corrected daily using a standard curve generated with formazin solutions of defined turbidity.

Soil clay mineralogy (< 2 μm) was determined by x-ray diffraction analysis (XRD) (Whittig and Allardice, 1986). The soil was chemically and physically dispersed for mineralogical analysis (Kunze and Dixon, 1986). X-ray diffraction patterns were obtained for Na-saturated, K-saturated, Mg-saturated and Mg glycerol-saturated samples (25 and 550^{0}C). The patterns were interpreted by integrating the peak area for each clay mineral. The X-ray diffraction analysis was semi-quantitative in nature and provides relative proportion (± 15%) of clay minerals in the soil samples. Soil pH was determined using a pH electrode with distilled water and a 1:1 soil to water ratio. Electrical conductivity (EC) was determined using an EC meter (EC Testr, Oakton Instruments, Vernon Hills, IL). Extractable soil iron and aluminium were determined by ammonium oxalate and citrate bicarbonate-dithionite (CBD) extraction. Ammonium oxalate extraction was done to determine the amount of amorphous and organically bound Fe and Al. Citrate bicarbonate-dithionite extracts all forms of iron oxide: crystalline and non-crystalline (Jackson et al., 1986). The particle size distribution was determined using the hydrometer method (Gee and Bauder 1986).

Statistical Analyses

A repeated measure analysis of variance (MANOVA) with interactions was used to determine significance of treatment effects on outlet water using SAS PROC GLM (Cody and Smith, 1997). A completely randomized design was used with chemical treatment (PAM solution, PAM block, No PAM dosing) and physical treatment (baffles or no baffles) of water as main treatment factors, and turbidity and TSS with time at the basin exit as the repeated variable. Statistical significance was determined by Tukey's comparative analysis of log transformed data (Steel and Torrie, 1960). The variability of relative values was calculated by using delta method (Oehlert, 1992). Statistical significance was defined as $P \leq 0.05$ using SAS v. 9.1 and JMP v. 7.0 (SAS Institute, 2005; Cary, NC, USA).

Results

Preliminary screening of the soil with PAM solution indicated that the PAM significantly reduced turbidity using the standard whole-soil procedure (Fig. 2). The optimal dose was 5 mg L^{-1}, which reduced turbidity from >400 NTU to < 5 NTU. When only supernatant was tested, the reduction in turbidity was considerably less than with whole soil, and doses above 0.5 mg L^{-1} did not further reduce turbidity regardless of the initial level of turbidity. Adding soil to the supernatant solutions previously dosed with PAM did reduce turbidity at the 5 and 10 mg L^{-1} concentrations. This phenomenon suggests that a portion of the whole soil was not reactive to the PAM we used, but that the flocs formed by the reactive portion of the soil could pull the non-reactive portion out of solution. This may explain some of the results of the field-scale testing, as discussed later.

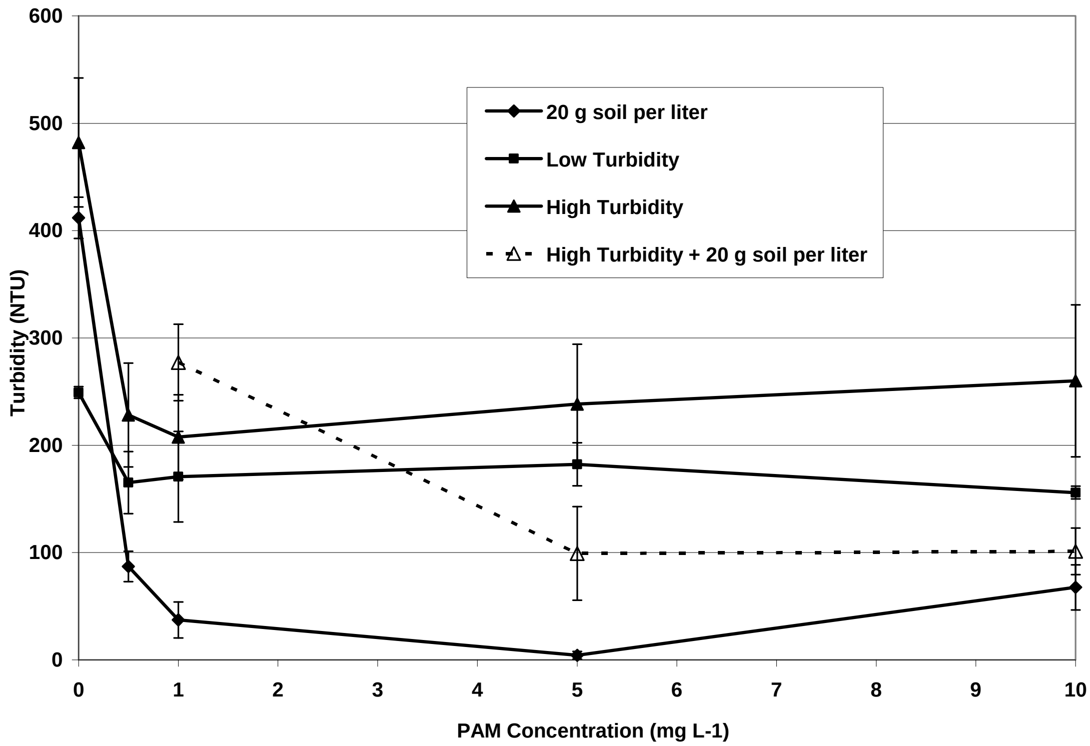

Figure 1-2. Turbidity in laboratory screening tests for soil, turbid water, and turbid water plus soil at different PAM concentrations.

Neither turbidity nor TSS was reduced in the open stilling basin (no baffles) tests at 1.5 and 24 h detention times (Figs. 3, 4). This suggests that the suspended materials were very resistant to settling in a stilling basin representing those typically used for that purpose. Assuming a 1.5 h detention time and a 0.8 m settling depth, the grain size which would settle in the basin would be approximately 0.006 mm as estimated by Stoke's Law. This is at the low end of the silt size class, which means that little of the clay fraction (25% in this soil) would be expected to settle in the 1.5 h detention time. For the 24 h detention time, the same calculation results in a size of 0.0015 mm, a coarse clay size, so again little of the clay fraction in the soil would be trapped. Clay and silt fractions are the greatest contributors to turbidity of runoff water from a disturbed area. Previous tests in this basin also showed that the clay fraction is very resistant to baffle treatments in basins, regardless of the improvements in flow characteristics for settling (Thaxton and McLaughlin, 2005).

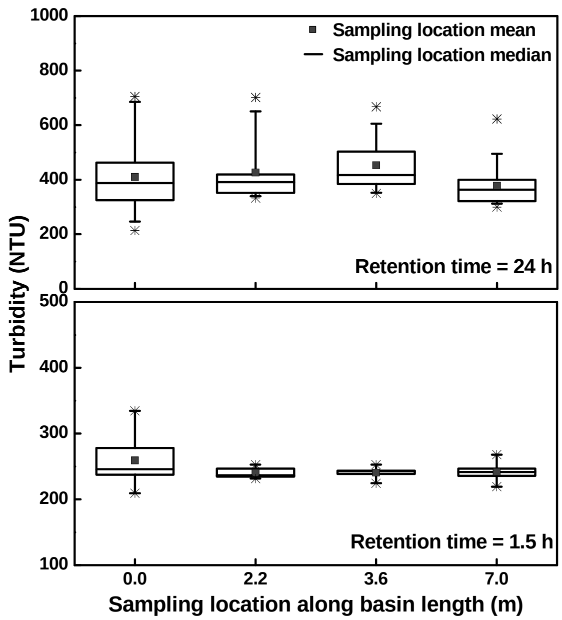

Figure 1-3. Turbidity measured at four surface points in the open stilling basin during tests with 24 and 1.5 h retention times and no PAM. The 7 m point is the spillway outlet.

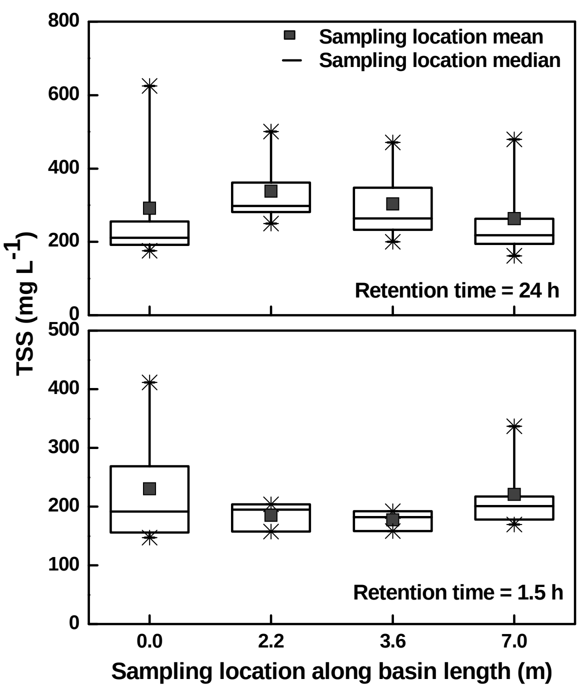

Figure 1-4. Total suspended solids measured at four surface points in the open stilling basin tests with retention times of 24 h and 1.5 h and no PAM. The 7 m point is the spillway outlet.

Active Dosing of PAM

The addition of baffles alone did not have a substantial effect on turbidity, although there were significant reductions at the 2.2 m surface and exit points (Fig. 5). The retention time of 1.5 h clearly was not sufficient to settle the fine sediment in suspension as previously discussed. The treatment with PAM solution, however, dramatically reduced turbidity. The test run with PAM and no baffles had the highest average turbidity (362 NTU) in the mixing basin (point 0.0 on x-axis), but this was reduced to 53 NTU by the first sampling point and 40 NTU at the outlet. The turbidity after treatment was similar to the test run with PAM and baffles, which had an initial turbidity much lower. The discharge turbidity was < 50 NTU, which is a common value cited for allowable turbidity for discharges into surface waters (US EPA, 2003; NCDENR DWQ, 2004; Peeler, 2005).

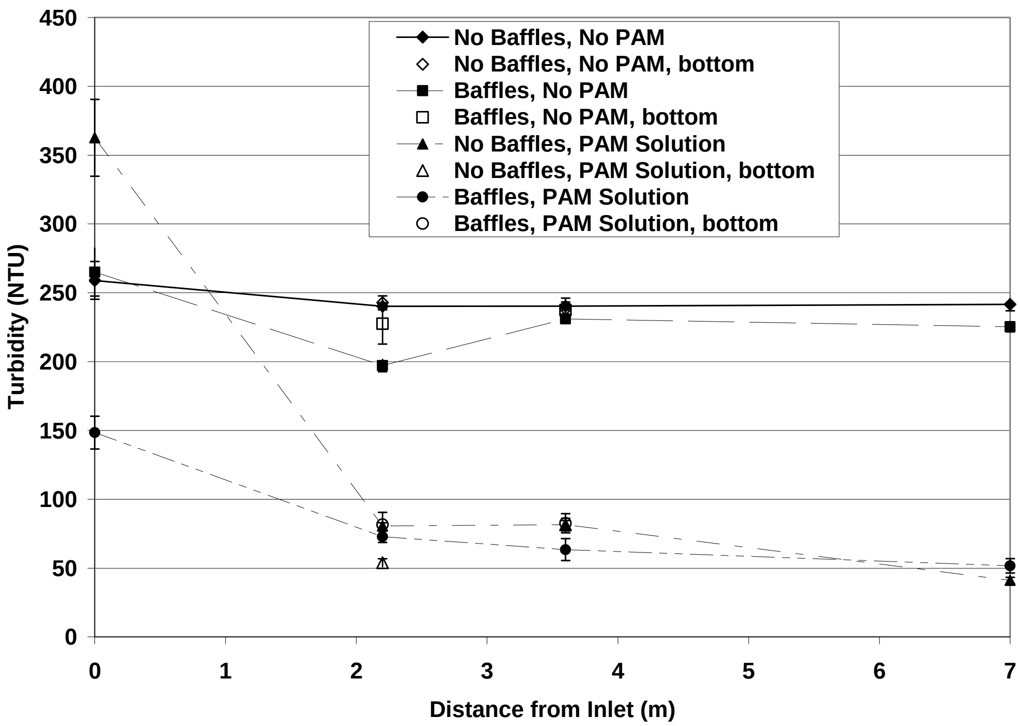

Figure 1-5. Turbidity at different points in the stilling basin as affected by porous baffles and dosing with PAM solution. The 7 m point is the outlet spillway.

In all of our tests with PAM treatments, a substantial reduction in turbidity and TSS occurred at the exit point, even if no reduction was evident within the basin. It is possible that flocs passing through the baffles intercepted the 2:1 (width:height) slope of the outlet dam. This could suggest that basins receiving chemically flocculated water should be designed to have a progressively shallow area prior to a surface discharge.

The pattern for TSS was somewhat different than that for turbidity. The initial TSS for all four tests was similar (~ 240 mg L^{-1}, Fig. 6), as opposed to the more than two-fold range for turbidity (Fig. 5). This may have been a reflection of the differences in individual batches of soil used for each test, some of which may have had more fine clays than others. Total suspended solids in the open basin with no PAM varied considerably but remained unchanged at the exit. The introduction of porous baffles produced a pattern of high TSS at the bottom and lower TSS near the surface within the basin at the first three sampling points, which would be expected based on improved settling characteristics, but there was little difference after that. Thaxton and McLaughlin (2005) found that suspended sediment was greatly reduced by porous baffles, but whole soil was added to the incoming water flow instead of only suspended sediment after removing the heavy sediment in a mixing basin. The improvement in hydraulics that porous baffles produce is not sufficient to settle the fine fraction, as was noted in Thaxton and McLaughlin (2005).

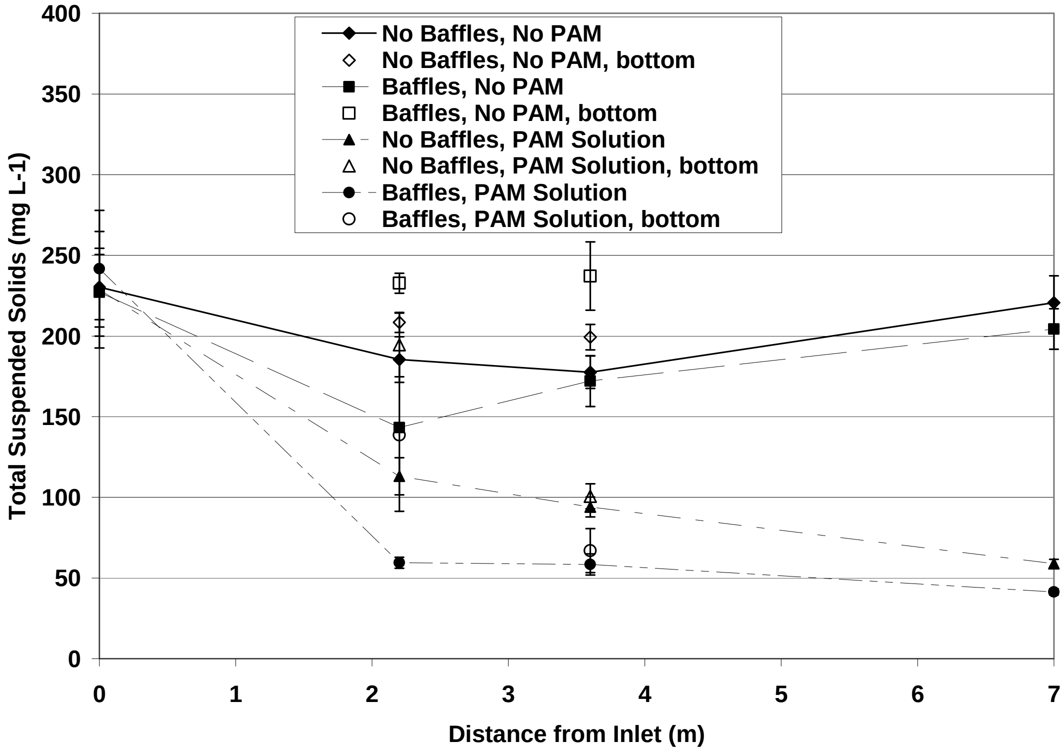

Figure 1-6. Total suspended solids at different points in the stilling basin as affected by porous baffles and dosing with PAM solution. The 7 m point is the outlet spillway.

The addition of PAM in the open basin produced a drop in TSS after the first sampling point at 2.2 m, with the bottom having much higher TSS than the surface (Fig. 6). However, after that point TSS was similar throughout the basin and only declined further from the last sampling point (bottom) to the outlet (surface). It is likely that some of the suspended flocs were trapped on the 2:1 sloping dam as the water moved toward the dam spillway. The baffles produced a more dramatic initial drop in TSS with the PAM treatment, although this also did not change after the first baffle all the way to the outlet. This supports the conclusions of Thaxton and McLaughlin (2005) that most of the beneficial effects of porous baffles occur with the first baffle. In this study, the additional turbulence and mixing which the first baffle created between the hose discharge and the baffle might have improved floc formation.

Some of the differences in patterns between turbidity and TSS in the basin are likely an artefact of the methods for measuring each. Turbidity was measured by shaking the sample bottle to resuspend sediment, then waiting 30 s to take a measurement. This would allow any flocs formed to settle to some degree. Total suspended solids are from a complete sample, so all material captured in the sampling process is measured. A sample with more suspended solids might not have a higher turbidity under these conditions. The suspended sediment remaining after PAM treatment was not responsive to additional PAM of the same type (data not shown), and adding more PAM beyond the flocculation optimum usually increases turbidity due to increased viscosity and other factors (McLaughlin and Bartholomew, 2006).

Passive Dosing of PAM

Adding the PAM by passing the pumped water over a solid PAM block reduced turbidity significantly relative to the untreated water (Fig. 7), similar to dosing with dissolved PAM (Fig. 4). The PAM treatment in the open basin reduced turbidity from 290 NTU at the entrance to 62 NTU at the outlet, with very little change within the basin until the last interval, as noted for the active dosing results. The effects of baffles were more significant in the passive dosing than the active dosing of PAM. When the PAM block treatment was combined with baffles the turbidity was reduced to as low as 37 NTU at the basin exit from the initial 314 NTU. The relative improvement in turbidity reduction with the PAM block that the baffles provided over the open basin may have also been the result of the high turbulence in the first cell. Because the PAM has to both dissolve and react with the sediment particles, this mixing zone might be important for solid PAM uses. In addition, the evenly distributed flow provided by the porous baffles (Thaxton et al., 2004) may provide more a more uniform flocculation process by preventing short circuiting.

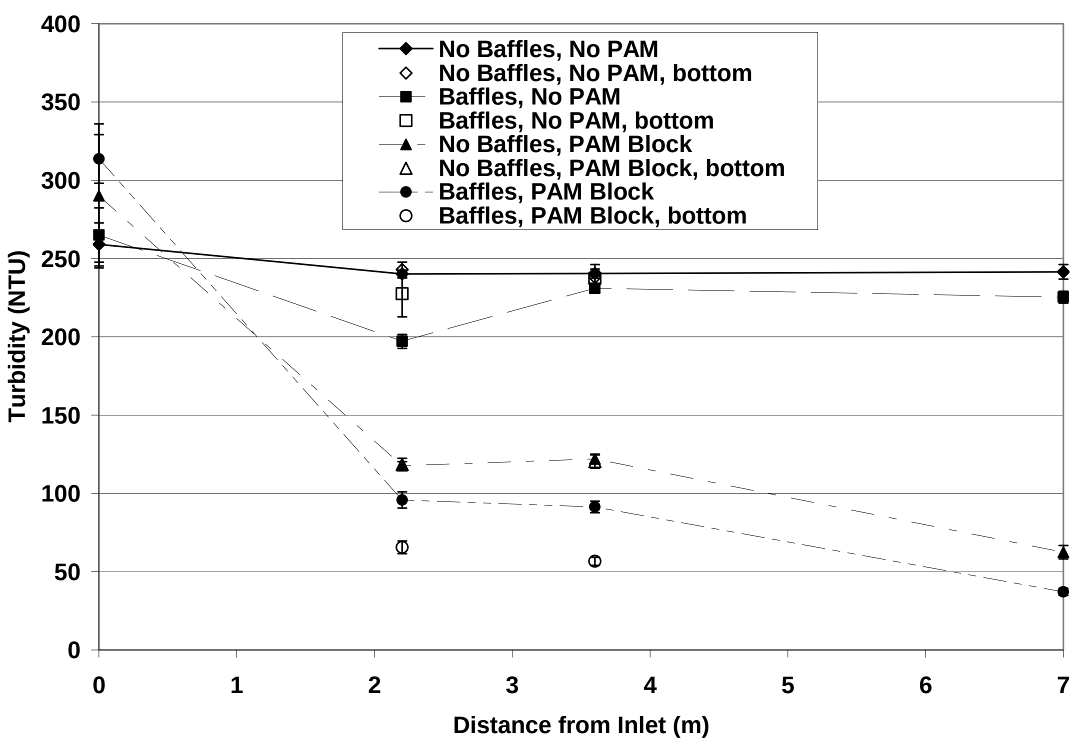

Figure 1-7. Turbidity at different points in the stilling basin as affected by porous baffles and dosing with a solid PAM block. The 7 m point is the outlet spillway.

The effect of any treatment on TSS was hard to detect within the basin but was evident at the outlet (Fig. 7). Samples from within the open and baffled basins had relatively high TSS in spite of the PAM treatment, in contrast to the turbidity response, most likely a result of the measurement technique, as noted previously. The actual dose of PAM that resulted from discharging water over the PAM log was not measured, but filtering times for TSS determination in these samples were often noticeably longer than for samples from the PAM solution tests with comparable levels of turbidity. Because PAM increases the viscosity of water in proportion to its concentration, this would suggest higher concentrations were present with the solid block treatment system.

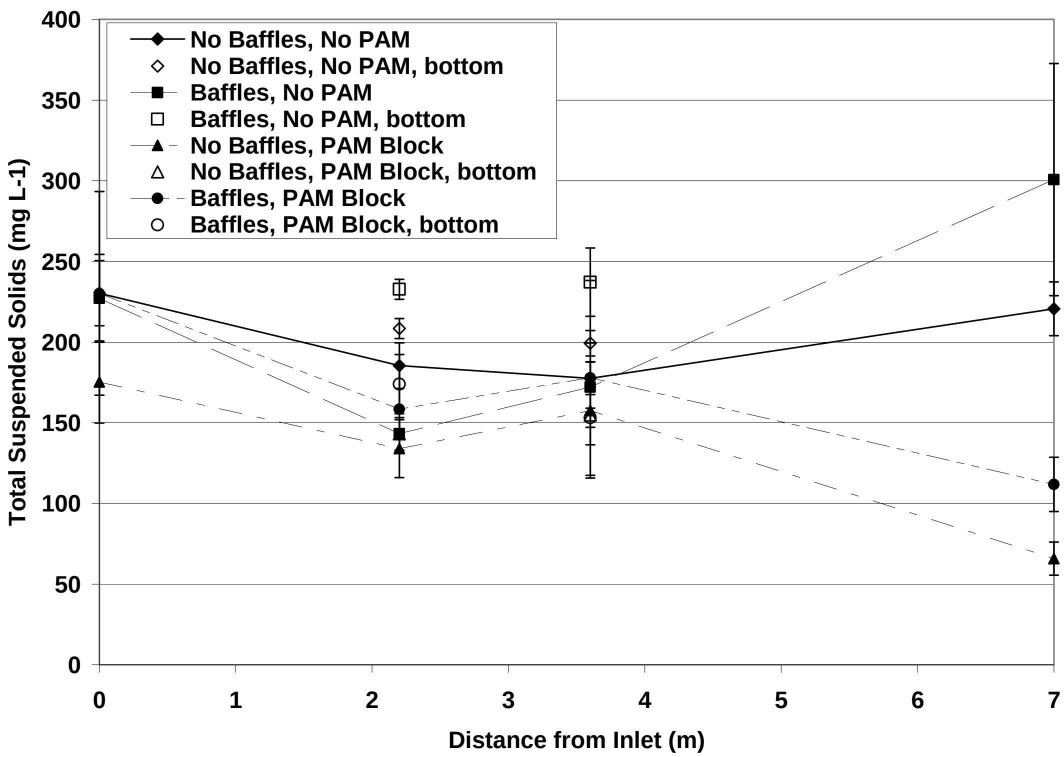

Figure 1-8. Total suspended solids at different points in the stilling basin as affected by porous baffles and dosing with a solid PAM block. The 7 m point is the outlet spillway.

The overall effect of the porous baffles on these fine, suspended particles was not significant when used alone (Table 3). Adding PAM in either form, with or without porous baffles, significantly reduced turbidity, however. The active dosing system with baffles had a lower turbidity reduction mostly because the average inlet turbidity (158 NTU) was much lower than the other treatments. The passive PAM dosing treatment reduced TSS by a substantial amount but this was not statistically greater than the tests conducted with no PAM. Total suspended solids at the inlet for all six tests was not significantly different ($\alpha = 0.05$), so we also compared the actual TSS values at the exit. Polyacrylamide significantly reduced TSS at the outlet, with the active dosing with baffles providing the lowest concentration. It is not clear why the passive dosing with baffles system was significantly less effective for TSS than the other three PAM systems, because it actually generated the lowest turbidity among all treatments (Fig. 7).

Table 1-3: Reduction in turbidity and TSS and exit TSS at the basin outlet as affected by PAM treatment and presence of porous baffles. Numbers within a column followed by a different letter are significantly ($\alpha = 0.05$) different.

PAM Treatment	Porous Baffles	Turbidity Reduction (%)	TSS Reduction (%)	Exit TSS (mg L^{-1})
None	No	8 c	5 b	220 c
None	Yes	14 c	17 ab	301 c
Active	No	88 a	75 a	68 a
Active	Yes	66 b	80 a	40 a
Passive	No	78 a	65 ab	66 a
Passive	Yes	88 a	45 ab	111 b

† PAM, polyacrylamide.
‡TSS, total suspended solids .

Both systems which included PAM dosing reduced turbidity, but none of the four systems reduced turbidity as much as the laboratory screening test with this soil at similar initial turbidity and PAM concentrations (Fig. 2). The field tests did reduce turbidity more than the screening tests performed with the supernatant, however. Although in both cases the soil was allowed to settle for five minutes prior to PAM dosing, it is likely that the settling was more complete in the test cups than in the mixing basin. The action of the pump may have also maintained more of the coarse material in the water column. As a result, the coarser fraction in the soil, which was more reactive to the PAM, may have been pumped into the stilling basin to some extent and helped to flocculate the less reactive fraction. This would explain why the turbidity in the stilling basin tests with PAM was intermediate between the screening tests with whole soil and supernatant at similar doses. This also suggests that screening tests to determine the best PAM and dose should be conducted with the type of water expected to be treated. These tests should either be conducted with the whole soil if there is little settling expected prior to treatment or with only the fine material remaining suspended after settling.

Recommendations:

- Both PAM dosing systems (liquid at intake, log at pump hose outlet) worked well in reducing turbidity and TSS significantly.
- When dealing with fine, suspended sediment, the use of porous baffles alone will not affect turbidity. However, one baffle is recommended when PAM is used to catch floating flocs.
- Increasing retention time from 1.5 h to 24 h did not improve turbidity reduction.
- When PAM is used, there is no evidence of turbidity or TSS removal beyond the first baffle, except just before the outlet, possibly through interception with the dam.
- The latter two findings suggest that much smaller stilling basins can be installed when PAM is used. A progressively shallow bottom might enhance floc interception and removal.

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Chapter 2: Effects of Bottom Inlet, Baffle Pore Size, and Polyacrylamide on Stilling Basin Performance

Abstract. *Surface water pumped from construction sites frequently contains high levels of turbidity and suspended sediment which is not effectively removed using gravity-based systems. This study assessed the effects of modifying a permanent pool stilling basin with energy dissipaters and with the addition of polyacrylamide (PAM) on turbidity and suspended sediments. Turbidity was generated by injecting soil into flowing water at a fixed rate and mixing for 30 min in a mixing basin. Turbid water containing only suspended sediment was pumped from the surface of the mixing basin to the test basin with physical and chemical treatments. Three energy dissipater treatments were tested: bottom inlet level spreader (BILS; impermeable fabric installed with 40 mm opening from the basin bottom), coir baffles (900 g m^{-2} coir fabric with 0.45 open space fraction (OSF), and Pyramat baffles (synthetic fabric with 0.10 OSF). The tests were run either with or without PAM dosing by passing the flow over a solid PAM block at the stilling basin inlet. A single treatment run included: 30 min adding soil to water flowing into a turbid water source basin, 5 min settling period, 90 min stilling basin filling, and sampling for 40 min once the basin was full. Sampling occurred every 5 min at the basin inlet, basin exit, and six surface and bottom grid points inside the stilling basin. The physical treatments (i.e., energy dissipation) reduced the turbidity and total suspended solids (TSS) of the water exiting the basin by up to 33% and 27%, respectively. The chemical treatment was much more effective regardless of the physical treatment, either in combination or alone, reducing turbidity and TSS up to 88 and 84%, respectively. The BILS enhanced the efficiency of the coir baffles and decreased that of Pyramat baffles in absence of PAM dosing, but had no effect with PAM dosing. The patterns of turbidity and TSS within the basin suggest that only one porous baffle is adequate for PAM-treated water, and that the reduction observed near the outlet was likely floc interception by the sloped wall of the basin outlet. This study provides a relatively simple, inexpensive approach to improving the function of stilling basins for treating turbid water.*

Keywords. *Bottom inlet, level spreader, silt fence, porous baffle, sediment, clay, coir, Pyramat, polyacrylamide.*

INTRODUCTION

Sediment is widely recognized as a leading pollutant of surface waters. In United States alone around 2 billion tons of eroded soil is deposited in water bodies every year (Clark et al., 1985). Construction activities are a major contributor to sedimentation with sediment loads as high as 2000 times that from forested lands to 10-20 times that of agricultural lands (Owen, 1975). Urban erosion related pollutants impose net damage costs that have been estimated to be from \$ 192 million to \$ 2 billion per year (Clark et al., 1985; Paterson et al., 1993). Suspended solids in surface waters are a serious water quality problem detrimentally affecting aquatic biota, facilitate transport of organic and inorganic pollutants, and decrease the aesthetic value of lakes and rivers (Novotny and Chesters, 1989; Pitt, 1995). Increased suspended sediment reduces the amount of light penetrating the water, harms fish gills, smothers fish eggs, decreases feeding rates of fish, increases water temperature, alters water chemistry, and reduces overall productivity of an aquatic community (Wilber, 1983). The disinfection and clarification processes at water treatment plants is also adversely affected, resulting in increased treatment costs (Le Chevallier et al., 1981).

Federal and state regulations require developers to design sediment and turbidity control programs for construction sites (USEPA, 1992; NC DEHNR, 1995). In an effort to reduce the sediment coming from construction activities, North Carolina enacted the Sedimentation Pollution Control act of 1973. This act requires that any land disturbing activity that covers one or more acres must have an approved erosion and sedimentation control plan. Further, the plan must include structural or non-structural management practices that reduce non-point source inputs to receiving waters, sufficient enough to prevent off-site sedimentation damage (NCDENR, 2004). In addition to this regulation, North Carolina Administrative Code 15A NCAC 02B .0211 states that the turbidity in the receiving waters adjacent to a site must not exceed 50 nephelometric turbidity units (NTU) in streams not designated as trout waters, and 10 NTU in water bodies designated as trout waters. If the receiving water already exceeds these levels, runoff from a construction site cannot increase turbidity further. However, the existing control measures are usually ineffective in reducing the elevated levels of turbidity in the waters discharged from the construction sites.

Turbidities of waters discharged from construction sites range from hundreds to thousands of NTU. Przepiora et al. (1997) observed turbidities of 120 to 3200 NTU from two construction sites during a one year period. Suspended clay and fine silt particles escape detention by the standard control structures due to their low settling velocities (Haan et al., 1994; Wu et al., 1996), regardless of particle shape (Simons and Senturk, 1992) unless residence time is increased or aggregation is induced by natural or artificial means (Chen, 1975). Line and White (2001) found the trapping efficiency of sediment traps located on an active construction site in North Carolina to range from 59 to 69%, with retention of only 43 per cent of the silt and 21 per cent of the clay sized particles. Consequently, fine sediment resulted in turbidity ranging from 100 – 15,000 NTU in the discharged water.

Stilling basins are impoundments used on construction sites to settle suspended solids in turbid water being pumped from excavations. Baffles of various designs can be installed within the basin to dissipate flow energy and lengthen the flow path, providing suspended particles an increased opportunity to settle. Turbulence within the water column contributes to prolonged suspension (Graf, 1971; Goldman et al., 1986). Baffles installed in a pond increase sediment retention rates by reducing the flow energy and turbulence within the pond and increasing the hydraulically effective width defined by Chen (1975) as "the width over which the flow is uniformly distributed". Jarrett (1996) and Millen et al (1997) found that geotextile baffles reduce short circuiting and thus increase trapping effectiveness, although in an undersized pond baffles may not significantly improve total sediment capture (Rauhofer et al., 2001). In an evaluation of geo-textiles for sediment control, Barrett et al. (1998) concluded that sediment removal from highway construction sites was due to the formation of pools that formed behind the silt fabric fence and not by filtration by the geotextile material. Porous baffles have been found to be very effective at absorbing the inflow momentum, reducing turbulent energy and diffusing the incoming energy and flow velocity such that more of the pond volume participates in the sediment settling process (Thaxton et al., 2004). Evidence of an optimal open space fraction (OSF, area occupied by open pores divided by total area) of 5-10% was suggested by Thaxton et al. (2004) but not investigated further. Though the porous baffles increase the retention of coarser sediment, fine suspended sediment remain largely uncaptured (Thaxton and McLaughlin, 2005). Due to the size and nature of the suspended particles, the decrease in turbulence does not have significant effects on their settling (Holliday et al., 2003), especially without chemical treatment for flocculation.

The present study was undertaken to evaluate the interactions between baffle OSF, a bottom inlet level spreader, and polyacrylamide (PAM) dosing, on turbidity and TSS reduction in a stilling basin.

MATERIALS AND METHODS

The study was conducted at the Sediment and Erosion Control Research and Education Facility (SECREF) on the Lake Wheeler Field Laboratory in Raleigh, NC. The experimental setup consisted of a series of basins which were used to test a number of turbidity reduction options for pumped construction site water (fig. 1). Water from a source pond (~ 900 m^3) was delivered to a mixing pond (80 m^3) through a pipe (diameter = 0.3 m) with a control valve for regulating the flow (fig. 1). An inlet tee connection was located approximately half of the distance between the source pond and the mixing pond, to allow the introduction of soil into the water passing through the pipe. The soil was obtained from a nearby construction site and was stockpiled on site at the Field Laboratory. The turbidity for the study was generated by releasing water from the source pond into the mixing pond at a fixed rate of 20 L s^{-1} (0.7 cfs) while adding soil to the pipe at a controlled rate of approximately 23 kg m^{-1} (for a total amount of 700 kg). The turbid water from the mixing basin was then pumped into a test basin (22 m^3) where all chemical and physical treatments were tested. The test basin functioned as a stilling basin in the experimental setup. The soil used for the tests had sandy clay loam texture and was found in prior studies to be producing turbidity in the range of 250-400 NTU and TSS of 150-400 mg L^{-1} under the conditions employed in this study. The selected properties of soil and water used for the tests are provided in Tables 1 and 2, respectively. A settling time of 5 min was provided between turbidity generation in the mixing basin and pumping of water into the test basin to allow the settling of large particles.

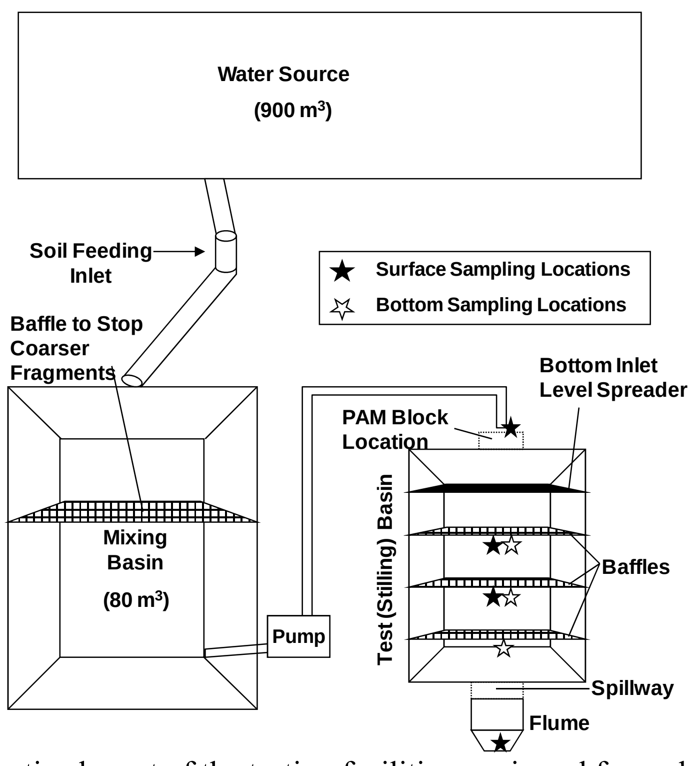

Figure 2-1. Schematice layout of the testing facilities as viewed from above. Not to scale.

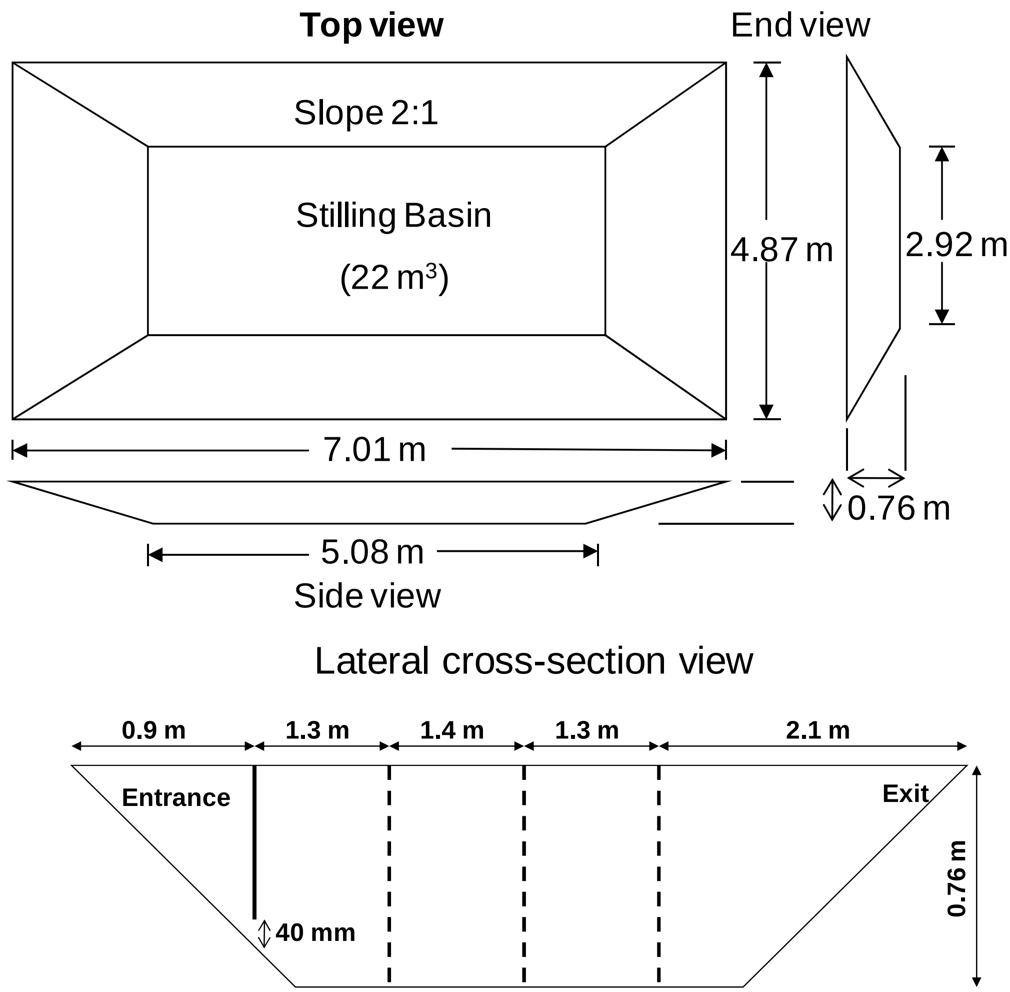

Figure 2-2. Detailed description of the stilling basin used in our tests.

Table 2-1: Selected characteristics of the soil used for turbidity tests.

Physico-chemical Characteristics†	Value
Clay (g kg^{-1})	250
Silt (g kg^{-1})	188
pH	4.70
EC (dS m^{-1})	0.10
FeOX (mmol kg^{-1})	8.9
FeCBD (mmol kg^{-1})	357
AlCBD (mmol kg^{-1})	92
Mineralogical	
Fine clay (< 1µm)	
Kaolinite (%)	87
Gibbsite (%)	6
Vermiculite (%)	7
Coarse clay (1-2 µm)	
Kaolinite (%)	78
Quartz (%)	8
Mica (%)	5
Vermiculite (%)	5
Gibbsite (%)	4

† EC, electrical conductivity; FeOX, ammonium oxalate extractable iron; FeCBD and AlCBD, citrate bicarbonate dithionite extractable iron and aluminum, respectively.

Table 2-2: Selected chemical characteristics of pond water used for the turbidity tests.

Parameter†	Value
pH	6.00
EC (dS m^{-1})	0.07
Turbidity (NTU)	3.00
TSS (mg L^{-1})	4.73
TOC (mg L^{-1})	7.10
NO_3 (mg L^{-1})	0.64
NH_3 (mg L^{-1})	0.59
PO_4 (mg L^{-1})	0.02
Al (mg L^{-1})	0.77
Ca (mg L^{-1})	3.52
Fe (mg L^{-1})	0.28
K (mg L^{-1})	3.56
Mg (mg L^{-1})	2.35
Na (mg L^{-1})	5.25
Mn (mg L^{-1})	0.15
Zn (mg L^{-1})	0.03

† EC, electrical conductivity; NTU, nephelometric turbidity units; TSS, total suspended solids; TOC, total organic carbon.

Particles in the size range of 20-50 μm would theoretically (Stoke's Law) have settled out of the turbid water during the mixing (30 min) and settling (5 min) periods, so most of the sediment in the turbid water being pumped would have been < 20 μm. Sand and coarse silt do not contribute much to turbidity and may not be present when pumping out standing or accumulated water from an excavation. The water from the mixing basin was pumped to the stilling basin using a gasoline pump (51 mm outlet; Hypro C-35, Waterford, WI) at the rate of 4 L s^{-1}, which provided a retention time of 1.5 h. The pump flow was calibrated before each test. The stilling basin was lined with polypropylene geotextile to prevent erosion of the basin bottom.

After approximately 90 min of pumping, the stilling basin was filled with turbid water and overflowing through the 1 m wide spillway. In-basin sampling began at that point, and pumping of turbid water was continued for 40 min to determine the effects of treatments on turbidity of water exiting the basin. Water sampling was accomplished using seven automatic samplers (Teledyne ISCO 6712 portable sampler, Lincoln, NE) installed at the inlet (in pipe), and at set distances from the inlet of 2.2 (bottom and surface), 3.6 (bottom and surface), 4.9 (bottom) and 7.0 m (outlet). The sampler intakes within the basin were attached to the middle support post on the downstream side of each baffle. The posts remained in place when no baffles were in place and the intakes remained in the same position. The sampling at the stilling basin inlet was started from the time when pumping was started while at the other locations it was started only once the basin was filled and water started running over the spillway. Water from the spillway passed through a flume where it was sampled with an automatic sampler equipped with a bubbler flow meter (Teledyne ISCO 640 bubbler module). The bubbler flow meter was also used to further confirm the pumping rate during the test.

The testing constituted physical and chemical treatments for controlling turbidity. The physical treatments tested included two types of porous baffles and a bottom inlet level spreader (BILS). The two types of baffles tested were: (i) coir baffles with thread diameter of 4.0 mm and OSF of 0.45 (fig. 3) and (ii) Pyramat (Propex Inc., Chattanooga, TN) baffles with thread diameter of 1.0 mm and OSF of 0.1 (fig. 4). The open space fraction of the baffles was determined by image analysis using ArcView GIS v.3.2 (ESRI, Redlands, CA). The BILS was an impervious geotextile installed to have 40 mm open space between lower end of fabric and basin bottom (fig.2). The BILS was included to determine if spreading the flow across the basin bottom could enhance settling by reducing the distance particles needed to fall. Three baffles in the basin were installed at 2.2, 3.6 and 4.9 m from the entrance. The position of the baffles coincided with the location of sampler intakes in the basin. The baffles were 0.8 m tall and were spread across the entire cross sectional width of the basin. The chemical treatment included dosing with PAM by directing the pumped, turbid water over a solid PAM block (Floc Log APS 706b, Applied Polymer Systems, Woodstock, GA) installed at the basin inlet. The PAM block was a proprietary mixture of medium and high molecular weight anionic polyacrylamide, certified by North Carolina Department of Environment and Natural Resources (NC DENR) for storm water treatment. The PAM release rate was estimated by the manufacturer to be 2.1 mg L^{-1} at pumping rates similar to the one used in this study. The PAM block was covered with galvanized hardware cloth (wire diameter = 1.6 mm) with 100 mm^2 openings to avoid disintegration as the water was discharged from the pump hose. The control treatment constituted an open basin with no chemical treatment of the pumped water.

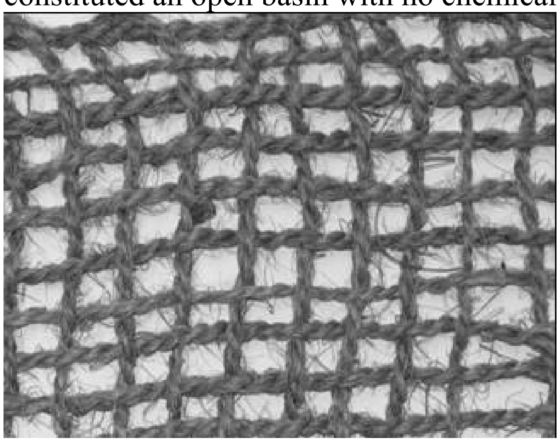

Figure 2-3. Example of the coir netting used as the first type of baffles.

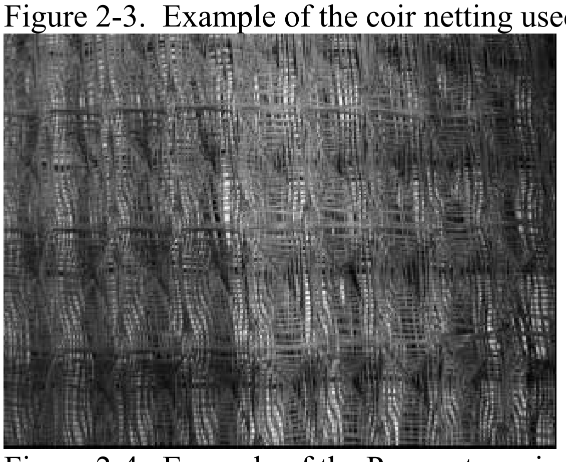

Figure 2-4. Example of the Pyramat erosion control blanket used as the second type of baffle.

The water sampling was done at 5 min intervals and constituted at least 8 samples at the designated points in the basin for each test. Each sample was treated as a replication for statistical analyses. The water samples collected during the tests were analysed for turbidity using Analite NEP 260 turbidity probe (McVan Instruments, Melbourne, Australia) and TSS after filtering through 76 mm pre-weighed fibreglass filters (Proweigh, Environmental Express, Mt. Pleasant, SC) and drying for 24 h at 105 ^{o}C. For turbidity measurement of each test samples, the apparent turbidity readings were corrected with standard curve generated using formazin solutions of defined turbidity. Turbidity and TSS reductions for each system were calculated from average inlet and outlet values. The sediment captured by the baffle material was calculated by sampling two 0.25 m^2 sections of each baffle after a test, drying them in an oven at 105 ^{o}C, and subtracting the weight of clean baffle material. Sediment captured by the baffles represented total sediment weight retained for all 3 baffles used in a test.

Each test was conducted one time with samples taken over the 40 minute test period being considered replications for statistical purposes. Between tests, sediment was removed from the stilling basin manually with shovels and the liner was rinsed with a hose and the water removed by opening a bottom outlet.

Clay mineralogy (< 2 μm) was determined by x-ray diffraction analysis (XRD) (Whittig and Allardice, 1986). The soil was chemically and physically dispersed for mineralogical analysis (Kunze and Dixon, 1986). X-ray diffraction patterns were obtained for Na-saturated, K-saturated, Mg-saturated and Mg glycerol-saturated samples (25 and 550 ^{o}C). The patterns were interpreted by integrating the peak area for each clay mineral. X-ray diffraction analysis is semi-quantitative in nature and provides relative proportion (± 15%) of clay minerals in the soil samples. Soil pH was determined using a pH electrode with distilled water and a 1:1 soil to water ratio. The electrical conductivity (EC) of soil (2:1 soil to water ratio) and water was determined using an EC meter (EC testr, Oakton Instruments, Vernon Hills, IL). Extractable soil iron and aluminium were determined by ammonium oxalate and citrate bicarbonate-dithionite (CBD) extraction. Ammonium oxalate extraction was done to determine the amount of amorphous and organically bound Fe and Al. Citrate bicarbonate-dithionite extraction determines both crystalline and non-crystalline forms of iron oxide (Jackson et al., 1986). The particle size distribution was determined by hydrometer method (Gee and Bauder, 1986).

STATISTICAL ANALYSES

A repeated measure analysis of variance (MANOVA) with interactions was used to determine significance of treatment effects using SAS PROC GLM (Cody and Smith, 1997). A completely randomized design was used with chemical treatment (PAM, No PAM dosing) and physical treatment (coir baffles, Pyramat baffles) of water as main treatment factors, and time as the repeated variable. The data was normalized using a power transformation (y1/3) for turbidity and log transformation for TSS. All figures show sample means and standard errors of untransformed data with significance being determined by Tukey's comparative analysis of the transformed data (Steel and Torrie, 1960). The variability of relative values was calculated by using the delta method (Oehlert, 1992). Statistical significance was defined as $P \leq 0.05$, unless otherwise indicated. SAS v. 9.1 (SAS Institute, 2005; Cary, NC) and JMP v. 7.0 (SAS Institute, 2005) were used for all analyses.

RESULTS AND DISCUSSION

TURBIDITY

The turbidity of the water in the control test changed very little between the entrance and the exit of the stilling basin (fig. 5). Similar findings have been shown for sediment basins on construction sites, with turbidity changing very little over time (Przepiora et al., 1998). The treatment with coir baffles had significantly lower turbidity than the control, but these reductions were relatively minor. The addition of the BILS to the coir baffles resulted in a significant turbidity reduction compared to coir baffles alone. The turbidity decreased from 227 to 155 NTU within 2.2 m and changed little from this point to the outlet. We did not test the BILS alone, but it appeared to significantly improve turbidity reduction when used with at least one coir baffle.

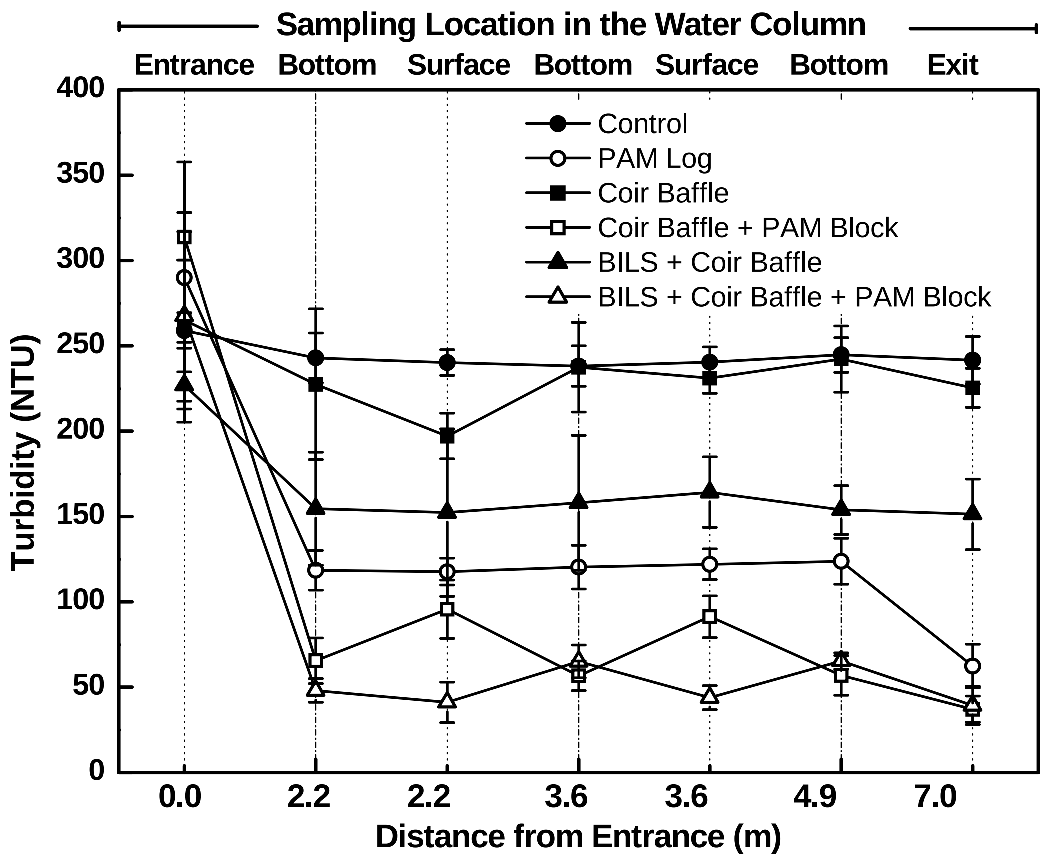

Figure 2-5. Treatment effects on turbidity within the stilling basin under with either no baffles or three coir baffles.

The greatest reduction in turbidity was achieved with PAM treatments. With no baffles, the turbidity dropped at the first sampling point and did not change until the water reached the outlet, where the turbidity dropped significantly. This could have been a result of the flocs being intercepted by the sloped (2:1) wall of the basin at the outlet. Turbidity was greater at the surface after the first and second coir baffle, but the BILS dampened that trend, and the two systems produced similar turbidity at the outlet. The Pyramat baffles, with or without the BILS, had no apparent effect on turbidity in the basin compared to the open basin control (fig. 6). When PAM was added, the BILS improved Pyramat performance within the basin, but turbidity was relatively similar among all three PAM treatments at the outlet. The Pyramat baffle + PAM treatment had a much higher initial turbidity and actually reduced it more after the first baffle compared to the other PAM treatments.

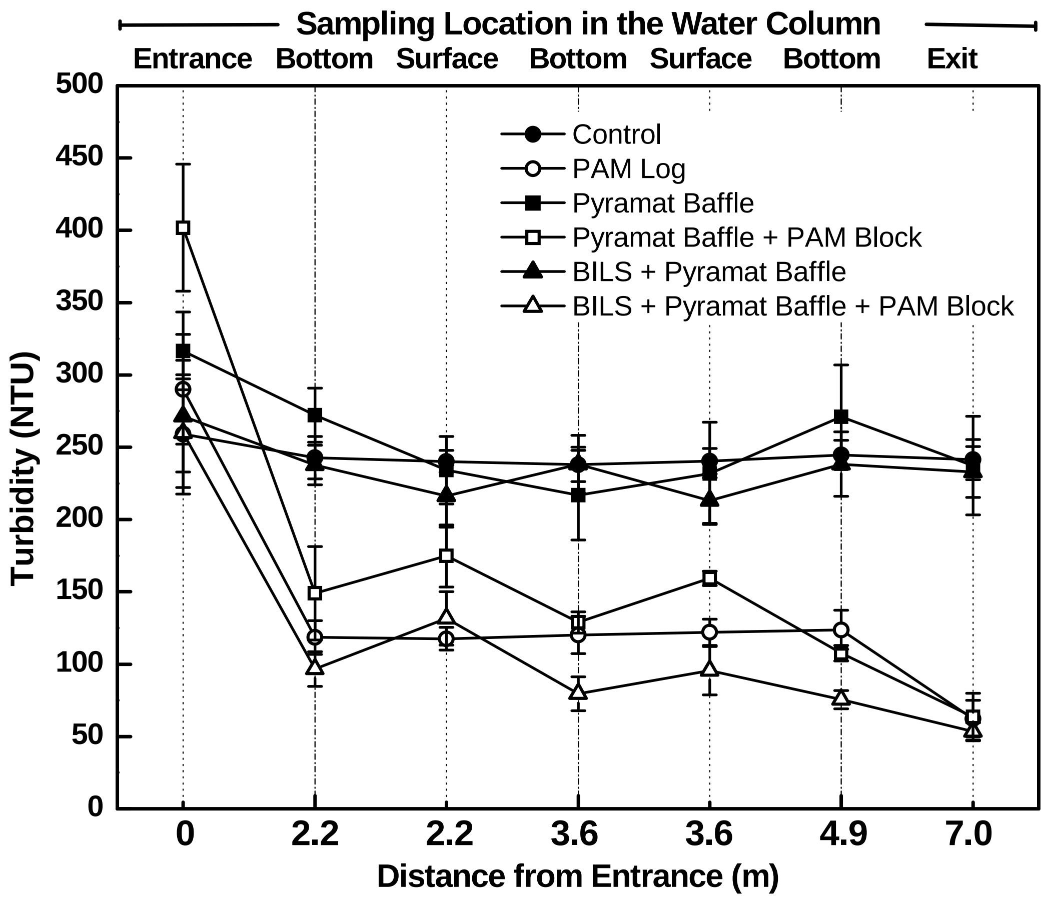

Figure 2-6. Treatment effects on the stilling basin with either no baffles or three Pyramat baffles.

Turbidity was significantly reduced compared to the open basin using any combination of physical barriers, with the optimal combination being the BILS + coir baffles, which reduced turbidity by 33% (table 3). The BILS significantly improved turbidity reduction for coir baffles but significantly impaired turbidity reduction for the Pyramat baffles. By comparison, however, the addition of PAM far exceeded the impacts of the physical treatments. Even with no baffles, PAM reduced turbidity by 78%, and this was significantly improved with all but the BILS + Pyramat baffles combination. This is likely the result of the improved settling characteristics within the basin (Thaxton et al., 2004; Thaxton and McLaughlin, 2005). The most significant changes in the turbidity were also produced within 2.2 m (first sampling location), indicating that the flocculation process was relatively complete once the water passed through the first baffle. There was a great deal of turbulence in the cell before the first baffle, enhancing mixing and contact between particles and PAM. Polyacrylamide dosing reduced the turbidity 54 to 78 % over the same treatments without PAM.

Table 2-3: Turbidity and total suspended solids (TSS) reduction in the stilling basin as affected by baffles, bottom inlet level spreader (BILS), and polyacrylamide (PAM). Numbers in a column followed by different letters are significantly different ($P<0.05$).

Treatment	Turbidity Reduction (%)		Total Suspended Solids Reduction (%)	
	No PAM	PAM	No PAM	PAM
No Baffle	6.7 d	78.4 b	4.2 d	62.4 bc
Coir	14.9 c	88.1 a	10.0 c	75.6 a
BILS + Coir	33.3 a	85.3 a	27.7 a	56.3 c
Pyramat	25.0 b	84.1 a	19.2 b	71.1 ab
BILS + Pyramat	14.2 c	79.4 ab	16.1 bc	83.6 a

Previous work suggests that this soil, with relatively high CBD-extractable Fe, should be well flocculated with anionic PAM (McLaughlin and Bartholomew, 2007). However, although the PAM did reduce turbidity significantly, the water continued to retain turbidity of about 50 NTU regardless of treatment combination. The work of McLaughlin and Bartholomew (2007) was conducted with whole soil, while these tests were conducted with only sediment remaining in suspension after a settling period. Recent laboratory testing has suggested that the fine fraction remaining is more difficult to flocculate than the whole soil (McLaughlin, unpublished data), possibly due to the presence of 2:1 clays, which are less reactive to PAM (Laird, 1997).

TOTAL SUSPENDED SOLIDS

The patterns of TSS in the basin were very different than for turbidity. The coir baffles, with or without the BILS, had somewhat higher TSS at the bottom and less at the surface when compared to the open control (fig. 7). This is consistent with the reduced turbulence and better flow characteristics that the porous baffles have been shown to provide (Thaxton et al., 2004). The addition of PAM reduced TSS at most sampling points, but the majority of the effect occurred after the final baffle, again suggesting interception by the sloped wall of the outlet dam. The patterns were similar in the Pyramat baffle treatments, with the differences between bottom and surface being even larger, although addition of the BILS tended to reduce the contrasts (fig. 8). The Pyramat baffles were somewhat more effective in enhancing the PAM effect for TSS within the basin, but these differences were largely not apparent at the outlet of the basin. The BILS also reduced TSS at several points in the basin and at the outlet, relative to Pyramat alone.

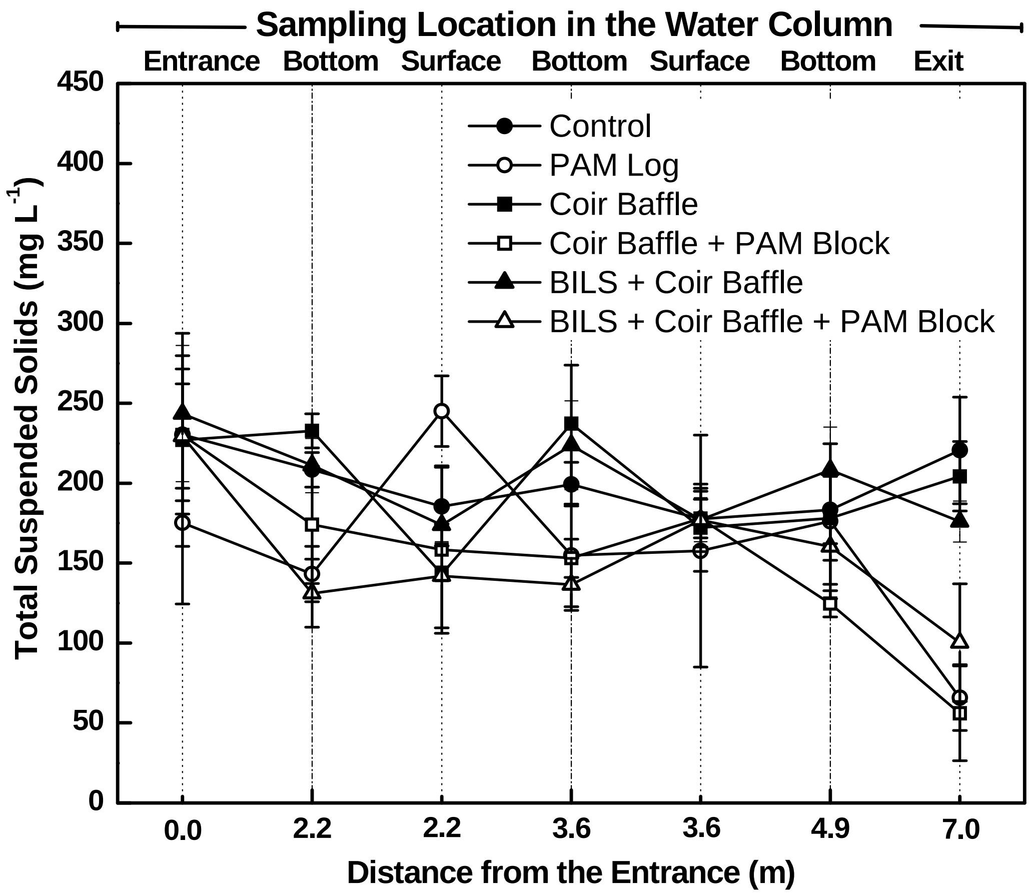

Figure 2-7. Treatment effects on TSS in the stilling basin with either no baffles or three coir baffles.

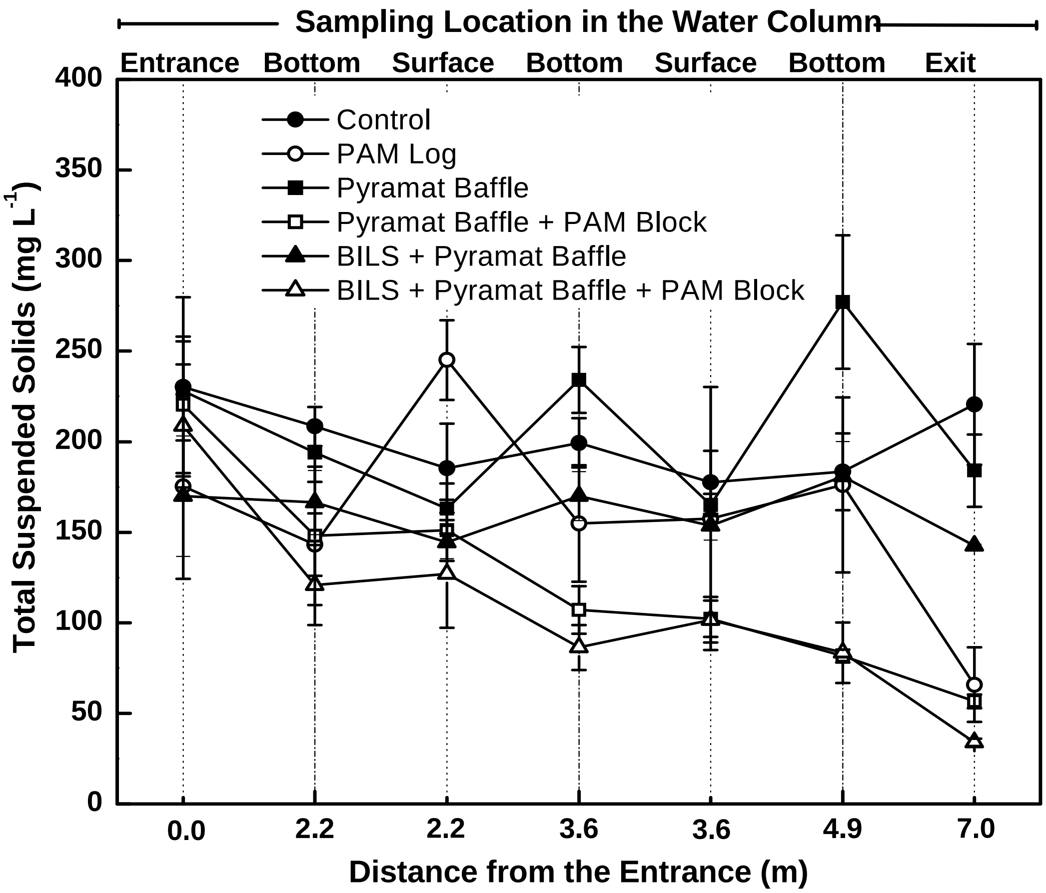

Figure 2-8. Treatment effects on TSS in the stilling basin with either no baffles or Pyramat baffles.

The physical treatments did significantly reduce TSS at the outlet compared to the 4% reduction in the open basin (table 3). As with turbidity, TSS was reduced much more by the PAM treatment than by the physical treatments, with 56-84% reduction at the outlet. The coir alone and BILS + Pyramat treatments significantly improved TSS reduction compared to the open basin. The BILS significantly reduced TSS capture in the coir baffle treatment with PAM, in contrast to the effect with no PAM. The BILS may improve TSS capture for the Pyramat baffle, but the effect was not significant in these tests.

The analysis of the overall treatment effects, measured as reductions in turbidity and TSS from inlet to outlet, suggests that the physical treatments were relatively ineffective compared to PAM. The open basin (control) reduced turbidity by only 7%, and adding the porous baffles only brought this up to 14 to 25% (table 3). However, dosing the water with PAM brought turbidity down by 78-88%, regardless of the physical layout of the basin, far exceeding the performance of any combination of physical system that were tested. Because the baffles improved turbidity and TSS reductions more in the untreated tests compared to the PAM treated tests, there was a significant interaction between baffles and PAM treatments (table 2-4). The addition of coir and Pyramat baffles reduced turbidity relative to the controls except in the Pyramat and BILS combination, which explains the significant interaction of BILS and PAM treatments. Among the PAM treatment combinations, only the coir alone and Pyramat with BILS significantly reduced TSS compared to PAM alone, again explaining the significant interaction between BILS and PAM. Because the BILS improved TSS reduction for the coir but not the Pyramat baffles, there was also a significant interaction among the baffle and BILS treatments.

Table 2-4: The general linear model (GLM) procedure repeated measure analysis of variance (MANOVA) for the effects of baffles (coir, Pyramat), polyacrylamide (PAM) dosing, and bottom inlet level spreader (BILS) on turbidity and total suspended solids (TSS). Probabilities (Pr) of effects which are <0.05 are considered significant

Source	Pr > F	
	Turbidity	TSS
PAM	<0.0001	0.0001
Baffle	0.1705	0.0198
BILS	0.3580	0.8409
Baffle × PAM	<0.0001	<0.0001
BILS × PAM	<0.0001	0.0430
Baffle × BILS	0.3333	0.0224
PAM × Baffle × BILS	<0.0001	<0.0001

Previous work has suggested that the primary effect of porous baffles on improving sediment settling is to reduce turbulence and velocities within the basin (Thaxton et al., 2004; Thaxton and McLaughlin, 2005). Those tests were performed using whole soil mixed into the inflow to the basin, as opposed to first settling the larger particles and pumping the turbid fraction into the basin, as in this study. Under the much lower sediment loads and smaller size sediments that we used, the relative contribution of the baffle material as a "filter" could have been important. However, without PAM, the coir and Pyramat baffles retained only 7 and 2% of the total sediment trapped in the basin, respectively (table 5). When PAM was added, this increased to 40 and 22%, respectively. The coir material retained more sediment in spite of the much higher OSF, probably because of the roughness (high surface area) of the coir threads relative to the smooth plastic of the Pyramat. The relative "stickiness" of the coir for the flocculated sediment may explain why the sediment capture rate increased more for the coir baffles than for the Pyramat baffles when PAM was added.

Table 2-5: Sediment capture effectiveness of the two baffles (coir, Pyramat) with and without polyacrylamide (PAM) treatment of turbid water.

Treatment	Coir Baffle	Pyramat Baffle
Open space fraction (OSF)	0.45 (± 0.03)	0.1 (± 0.02)
	Sediments fraction captured by baffles†	
Without PAM	0.07 (± 0.02)	0.02 (± 0.00)
With PAM	0.40 (± 0.05)	0.22 (± 0.06)
	Sediments fraction trapped in the basin† ‡	
Without PAM	0.10 (± 0.10)	0.19 (± 0.01)
With PAM	0.75 (± 0.33)	0.74 (± 0.09)

† Designates the fraction out of total amount of sediments entering the basin.

‡ Including the fraction on the baffles.

CONCLUSIONS

The objective of this study was to determine the effectiveness of different energy dissipaters in basins for settling fine, suspended particles, in presence or absence of PAM dosing. An open basin provided very little treatment, reducing turbidity and TSS by 7 and 4%, respectively. Adding the porous baffles significantly improved treatment, but reductions of only 15-25% were achieved. The addition of a device to spread the flow across the bottom of the basin further improved treatment for coir baffles but reduced treatment for Pyramat baffles. Dosing the water with PAM at the inlet had a much greater effect on turbidity and TSS, with reductions ranging from 78-88% and 56-84%, respectively, among all treatments. Adding porous baffles to the PAM treatment reduced turbidity compared to the open basin, but a bottom spreader did not improve this further. Compared to the open basin with PAM, TSS was significantly reduced with the coir baffle alone or the Pyramat baffle with the bottom spreader. Little of the trapped sediment was present on the baffles except when PAM was used, with the coir and Pyramat baffles trapping 40 and 22% of the sediment captured in the basin, respectively. Although the Pyramat had much smaller pores than the coir, the roughness of the coir fibers may have enhanced floc capture. A substantial portion of the reductions in suspended sediment by PAM occurred after the last baffle, probably as the flows encountered the sloping bank at the outlet. This suggests that having a progressively more shallow basin, in conjunction with porous baffles to reduce turbulence, may improve sedimentation rates for chemically flocculated systems.

ACKNOWLEDGEMENTS

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Chapter 3. Aquatic Toxicity Testing Results

The chemical treatment of stormwater should always be accompanied with testing to be sure that it will not result in adverse effects in the receiving water. There are a great variety of tests commonly used, involving fish, aquatic insects, algae, and other species. Acute toxicity, usually measured as deaths over a 24-48 h period, may be the most widely applied. In the case of anionic polyacryamide (PAM), however, acute toxicities are relatively high compared to the effective dose rates for turbidity and suspended solids removal. A more conservative measure is the chronic toxicity, as measured by adverse effects on an organism over a prolonged period of exposure. One of the most common of these is a 7-day *Daphnia* or *Ceriodaphnia* test. These small (1-2 mm) aquatic organisms feed on suspended plankton and are common to most fresh waters. They can reproduce asexually over the 7 day period, and the number of neonates produced is a measure of the level of stress that is brought about by the test chemical. In North Carolina, point dischargers such as factories and wastewater treatment plants have to have their discharges tested every 5 years using the 7-day *Ceriodaphnia* reproduction test. Since this is already an accepted test in this state, we decided to use it to determine the potential toxicity of PAM.

Materials and Methods

The aquatic toxicity tests were conducted at Meritech Environmental Laboratories, Inc., Reidsville, NC. They are certified by the NC Division of Water Quality to run the standard 7-day chronic toxicity test using *Ceriodaphnia dubia* as the test organism. This is the standard test for aquatic toxicity for discharges into stream from sources such as wastewater treatment plants, manufacturing, and similar dischargers. The test consisted of a set of 10 organisms individually housed in small wells (15 mL depressions in plastic trays). They received new test solutions on days 3 and 5, with final evaluation on day 7. The test solutions were mixed using natural lake water, which contains the algae that the Ceriodaphnia feed on. At the end of 7 days, survival and reproduction were both recorded and compared to the controls. *Ceriodaphnia* will asexually produce 20-30 offspring (neonates) during this period under optimal conditions, but produce less when stressed.

The tests were conducted included turbidity and several PAMs separately and in combination. Turbidity was generated using soil samples from a borrow pit near Lumberton. This material contains 15-20% montmorillinitic clays which are less reactive to PAM and more likely to remain in suspension. Turbidity solutions were generated by adding soil to a 4-L beaker and mixing thoroughly, then decanting the supernatant after a 5 min settling time. The supernatant was mixed with lake water to dilute it to initial turbidities of 50, 125, 250, 500, and 1,000 NTU. This was repeated on days 3 and 5 when the test solutions were replaced. A lake water control was included in the treatments.

Two PAMs were tested: APS 705 (Applied Polymer Systems, Woodstock, GA), a proprietary mixture of linear, anionic PAM, and NALCO 9907 (NALCO, Chicago, IL), a linear, cationic PAM. These were chosen because the former is commonly used in the state and it can flocculate this soil, and the latter is even more effective on this soil but it is generally more toxic to aquatic organisms. These were both made into stock solutions of

500 mg L^{-1} using distilled water and later diluted with lake water to bring the concentrations into the desired range. For APS 705, the range included 0, 0.5, 1.0, 5.0, 10, and 50 mg L^{-1}. For 9907, the range included 0, 0.25, 0.5, 1.0, 2.0, and 5.0 mg L^{-1}.

Additional tests were conducted which combined 500 NTU turbidity with the two PAMs in the range of concentrations described above. This was intended to test whether the reaction of the suspended sediment and PAM would change the toxicity of either one. The PAMs were added to 500 NTU lake water and mixed, with the resulting solution being added to the tests wells while continuously stirring. The *Ceriodaphnia* were then added to each well. In addition to the two PAM previously mentioned, we also included a third PAM, N300 (NALCO, Chicago, IL), which is a non-ionic PAM previously found to be less toxic to *Ceriodaphnia* than the anionic PAMs. This product had also be shown to be effective in reducing turbidity with this soil.

Results

The effect of the PAMs and turbidity on reproduction is shown in Figure 3-1. As expected, the cationic 9907 had a greater effect on reproduction compared to similar concentrations of the anionic 705. The first substantial effect for 9907 was at the 1 mg L^{-1} dose while it was 5 mg L^{-1} for 705. Turbidity began to have effects at the 125 NTU level and reduced reproduction to zero or nearly zero at the higher levels.

The survival curves for *Ceriodaphnia dubia* were not as steep as the reproduction curves, suggesting they are able to survive under conditions in which they have reduced reproduction (Figure 3-2). The 9907 PAM began to show toxicity at the 2 mg L^{-1} concentration, while 705 PAM had no substantial toxicity even as high as 50 mg L^{-1}. Turbidity was completely toxic at 500 and 1,000 NTU, with some toxicity apparent at the 250 NTU level.

The combinations of turbidity (500 NTU) and PAM were unsuccessful, with 100% mortality in all combinations. Since all tests were run simultaneously, we did not know that 500 NTU was totally toxic to *Ceriodaphnia dubia*. This partially explains why these tests failed. In addition, for some reason the turbidities were not substantially reduced with the addition of the PAMs. We had expected turbidity to be reduced, as it had in previous tests with this soil, and this would result in reduced impacts on the organisms. The technician running the test observed that the organisms became attached to the flocs, which would kill them as they are filter feeders which swim in the water column for food. Future tests will be done with only the supernatant after any flocs have formed.

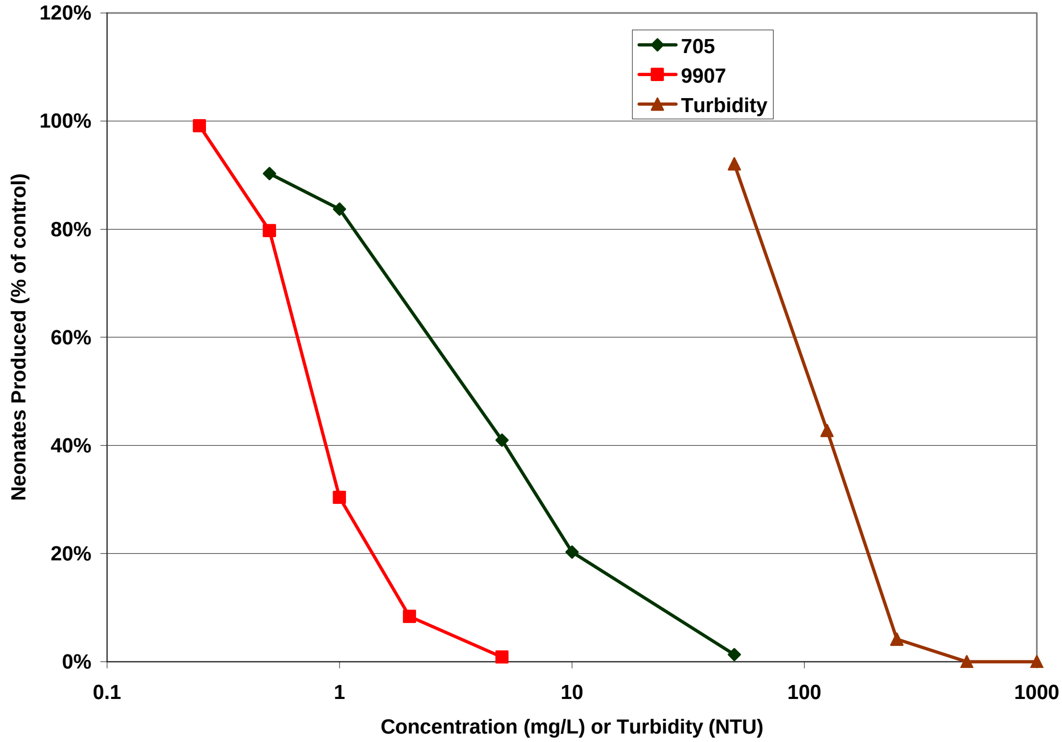

Figure 3-1. The effect of PAM and turbidity on the 7-day reproduction of *Ceriodaphnia dubia*.

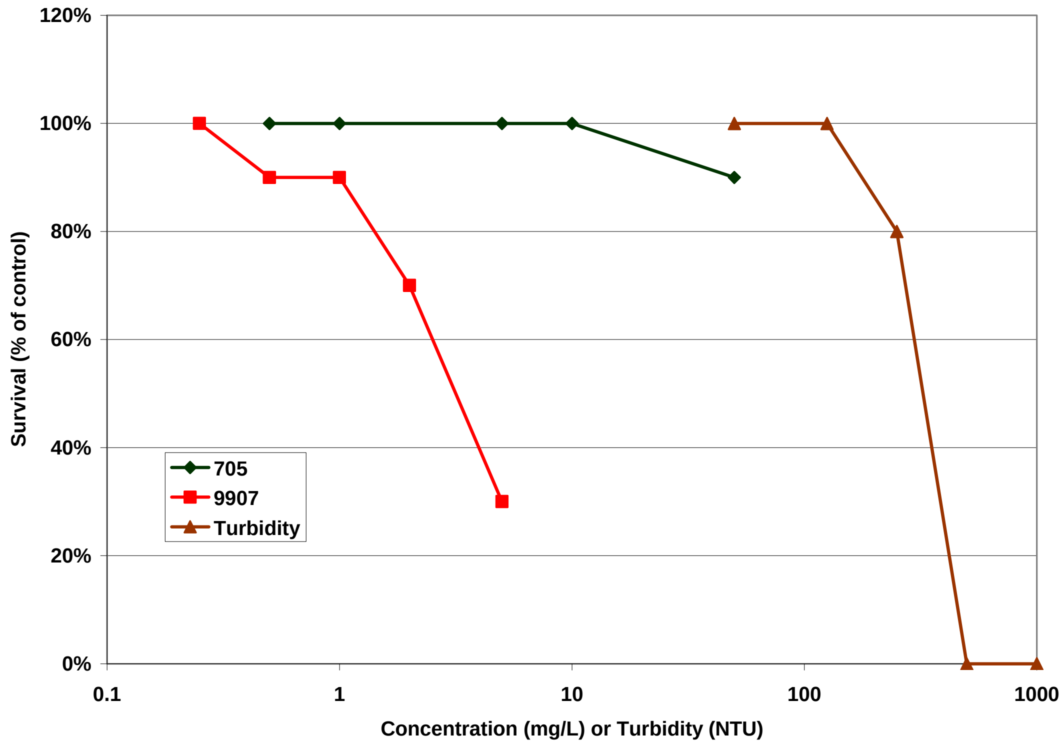

Figure 3-2. The effect of PAM and turbidity on 7-day survival of *Ceriodaphnia dubia*.