Sediment Basin Design Criteria for Flocculated Sediment

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16. Abstract

There is increasing interest in controlling turbidity in construction site runoff using various chemical flocculation treatments. Flocculated sediment is likely to behave much differently that untreated sediment, however, which could suggest changes to sediment basin design. This project was initiated to characterize the effects of chemical flocculation on sediment properties and to evaluate how it might affect basin design. The project was conducted in three phases: laboratory studies, field-scale studies under controlled conditions, and monitoring on active construction sites. In a laboratory column study, flocculated sediment was found to largely settle 1 m (3.2') within several minutes, with similar or better sediment removal rates for unflocculated sediment settling after an hour. The addition of polyacrylamide (PAM) shifted the particle size distribution to larger sizes for all but one soil, which was mostly sand with little clay. The uniformity coefficient was greatly reduced, primarily due to a shift from smaller to larger particle sizes. In field tests, the best flocculation system was a combination of fiber check dams and a jute liner, with PAM applied to the liner material. It is important to note that the ditch was lined with a geotextile, so the only source of sediment was that which was added to the water and the loading was much lower than typical on a construction site. Basin configurations (2:1, 1:2, and 2:1 with rising floor) did not change water quality at the outlet for flocculated sediment but the 1:2 configuration reduced sediment at the outlet compared to the 2:1 configurations for unflocculated sediment. There was evidence that passive treatment using PAM reduced sediment delivery to basins at three construction sites, but generally the sediment loads in the ditches were too high for effective treatment. Using data from the laboratory tests, the calculated surface area requirement to attain similar sediment retention for current designs could be reduced considerably if the sediment is completely flocculated. However, in order to attain this condition, construction sites would have to be managed closely in order to ensure the sediment was flocculated prior to entering the basin.

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Executive Summary

This study involved a series of experiments at the laboratory, field, and construction site scales to characterize the effects of flocculation on suspended sediment and how that might influence sediment basin design. In the laboratory, experiments were conducted to evaluate how flocculation affects particle size distribution for different sediment sources around North Carolina. The effect of polyacrylamide (PAM) on particle size distribution and settling rates was also investigated. This information was used to calculate surface area requirements using current guidelines. Field testing under controlled conditions was also conducted to determine optimal treatment combinations for turbidity and sediment control in both the water conveyance and within the sediment basin. Ditch configurations included wattles, jute lining, and both, with and without PAM. Basin configurations included, all with porous baffles, of 2:1 (standard), 1:2 (horizontal), and 2:1 with the bottom sloped up toward the outlet. Monitoring was done on three active construction sites around the state in order to characterize the flocculation process under real conditions. We have the following conclusions from our investigation:

1. Flocculation clearly shifts the particle size distribution to large sizes and results in much faster settling. In theory, a system which produces well-flocculated sediment could allow basin surface areas to be 50% or less than current designs and still produce higher discharge quality.
2. Turbidity and total suspended solids (TSS) can be greatly reduced using PAM in water conveyances, with PAM applied to the ditch lining (jute) being the most effective. It is important to note that the turbidity in these controlled tests was much lower than commonly found in the field.
3. When the sediment is flocculated, the basin configuration did not influence sediment capture. With no PAM, the horizontal 1:2 configuration resulted in greater sediment capture than the others.
4. Attaining flocculation at the field sites was difficult, primarily because the sites underwent drastic changes over time and the treatment systems were usually compromised. Erosion and high sediment loading in the treatment systems were the primary issues.

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Introduction

Around 2 billion tons of soil eroded from the land of United States (US) is deposited in water bodies each year, making sediment the largest water pollutant (Clark et al., 1985). Construction activities are particularity problematic as they heavily disrupt native soil structure and vegetation cover, leaving exposed soil and disturbed land to erosion. The erosion rates on construction sites are approximately 5 to 450 Mg ha^{-1} per year, with erosion rates as high as 100 times greater than those crops lands and 1000 times greater than those of forest lands (USEPA, 2000; Pitt et al., 2007). Such sediment losses by erosion to streams can cause damage to aquatic organisms, habitat, and water-storage of reservoirs as well as carrying other nutrients and pollutants (Newcombe and MacDonald, 1991). In addition, off-stream erosion can adversely affect water conveyance and increase the cost of disinfection and clarification processes at water treatment plants (Le Chevallier et al., 1981).

The guidelines by US Environmental Protection Agency (USEPA) and state regulations require construction activities to minimize soil erosion and to install sediment control measures. Amendments in 1987 to the Clean Water Act labeled construction activities as "point sources" under the National Pollution Discharge Elimination System (NPDES), requiring improved erosion and sediment control practices and permitting programs for discharges from construction activities (USEPA, 2012). At state level, North Carolina (NC) enacted the Sedimentation Pollution Control act in 1973. This act requires that any construction site that disturbs greater than 1 acre must have an approved erosion and sedimentation control plan (NCDENR, 2002). In addition to this regulation, Fresh Surface Water Quality Standards in NC (Administrative code 15A NCAC 02B .0211) requires that the turbidity of discharged water to non-trout streams not exceed 50 nephelometric turbidity units (NTU) and not exceed 10 NTU to trout waters; for lakes and reservoirs not designated as trout waters, the turbidity shall not exceed 25 NTU.

The primary goal of the erosion and sediment control is to keep sediment within the boundaries of construction sites. When properly implemented, best management practices (BMPs) for erosion control (e.g., temporary mulch and erosion control blankets) and sediment control (e.g., silt fence and sediment settling basins) can be 80 to 90 % effective in sediment retention. However, the turbidity in water exiting sediment control measures is often in the range from hundreds to even thousands of nephelometric turbidity units (NTU), since fine sediments cannot be easily settled using gravity-based sediment control measures (Przepiora et al., 1997; Line and White, 2001, McCaleb and McLaughlin, 2008).

Research and demonstration projects have shown the potential for the use of flocculants to reduce total suspended solid (TSS) and turbidity in construction site stormwater. The most common flocculant is polyacrylamide (PAM), but others are being used (e.g., biopolymer). PAM is a water-soluble synthetic polymer made of repeating acrylamide and acrylate monomers. Commercially available PAMs vary in physical formulation (granule, solid block, emulsion), structure (linear vs cross-linked), molecular weight (low < 10^5 g mol^{-1}, medium 10^5 to 10^6 g mol^{-1}; high > 10^6 g mol^{-1}), net charge (anionic, cationic, or non-ionic), and charge density (low < 10 mol %, moderate 10 to 30 mol %, high > 30 mol %), which all affect their performance as a flocculating agent (Barvenik, 1994; McLaughlin and Bartholomew, 2007; Oliveira et al., 2010). High molecular weight, linear, moderately anionic PAMs have been found to be the most effective and non-toxic as a soil conditioner for erosion prevention in irrigation furrows and construction sites (Hayes et al., 2005; Sojka et al., 2007). When anionic PAM is in contact with turbid water, four mechanistic stages are involved in the flocculation reaction (Kitchener, 1972; Gregory, 1989): 1) diffusion of PAM molecules toward the solid/liquid interface, 2) adsorption of PAM molecules onto soil particles, 3) bridge formation between polymer molecules, and 4) formation and growth of flocs. The presence of Ca^{2+} in the water can shrink the electrical double layer surrounding soil particles and help bridge the anionic surfaces of soil particles and negatively charged PAM molecules, enhancing flocculation reaction (Sojka et al., 2007; Lee et al, 2000).

On construction sites, the key elements for successful turbidity control include a method to introduce flocculants into the flowing runoff water, mixing and contact time, followed by an impoundment to allow settling. Chemical flocculants can be added to stormwater either actively or passively. An active dosing system is configured as a small-scale water treatment plant implemented with a flocculant dosing device and a filtration device, but the costs associated with setup, filtering, and maintenance may limit its widespread use (USEPA, 2009). A passive dosing system relies on dissolution of solid flocculants (granule, solid blocks, etc.) into water flowing downhill , and it can be an inexpensive and effective method (McLaughlin et al., 2009b). There are many places to introduce PAM into the water passively, such as fiber check dams, rock check dams, drop inlets, slope drains, ditch lines, and riser barrels. Field tests on linear construction sites proved that fiber check dams reduced erosion relative to rock check dams, and when granular PAM was added turbidity was reduced even further (McLaughlin et al., 2009a,b). Kang et al. (2013) tested a range of check dam types applied with granular PAM (GPAM) in a drainage ditch and found that the GPAM applied to fiber check dams or rock check dams wrapped with an erosion control blanket reduced ditch effluent turbidity > 80 % relative to those check dams with no PAM treatment (> 350 NTU). Bhardwaj and McLaughlin (2008) tested a solid-block PAM (BPAM) installed in a corrugated pipe, and turbid water was pumped into the pipe and routed into a settling basin. They found that the passive dosing system using the BPAM reduced effluent turbidity by 78 to 88 % relative to untreated discharge.

The use of sediment basins is a common practice for sediment trapping at many construction sites as a final part of erosion and sediment control plan. During rain storms, sediment-laden runoff is temporarily retained in the basin to settle suspended particles and water is slowly discharged from the basin over a period of time. By law, a sediment basin or equivalent sediment control measures must be provided when attainable until final stabilization of the site as a part of Construction General Permit (USEPA, 2012). A number of factors need to be considered when designing a sediment basin: drainage area, basin size, energy dissipater such as baffles, surface outlet, and dewatering device (Goldman et al., 1986). In NC, temporary sediment basin should have drainage area less than 100 acre (40.5 ha) with a minimum volume of 1800 $ft^3\ s^{-1}$($51\ m^3\ s^{-1}$) for the disturbed area draining into basin (NCDENR, 2013). Length to wide (L/W) ratio affects the dead storage volume within a basin (Chen, 1975; Griffin et al., 1985) with a minimum of 2:1 typically recommended (Goldman et al., 1986; Haan et al., 1994; NCDENR 2013). However, these structures are less effective when turbulent water moves straight through to the outlet as a short-circuiting. Solid baffles of various designs, usually located near the inlet, have been recommended to minimize short-circuiting in sediment basins (Haan et al., 1994). An alternative system of porous baffles has been shown to be very effective in evenly distributing the inflow flow and reducing turbulence, thus allowing improved particle settling (Thaxton et al., 2004; Thaxton and McLaughlin, 2005; Bhardwaj et al., 2008). These baffle practices are required in all sediment traps and basins in NC (NCDENR, 2013).

Studies have shown that optimized surface outlets and dewatering devices can improve basin performance. A field study of sediment basins in NC found that basins with gravel surface outlets retained 50 % to 69 % of the incoming sediment during the 20-month monitoring period (Line and White, 2001). Engineered dewatering devices have been shown to improve sediment trapping by using a perforated riser (Fennessey and Jarrett, 1997) or a floating skimmer (Millen et al., 1997). The sediment basins installed properly with porous baffles, surface outlets, and dewatering devices can be highly effective in settling sand- and coarse silt-sized particles, but the low settling velocities of finer particles usually prevent their removal within typical 24 to 48 h retention times (Przepiora et al., 1997; Line and White, 2001, McCaleb and McLaughlin, 2008). One approach to settle fine suspended sediments is to make independent particles clump together before entering basin or during sedimentation. This type of sedimentation is often aided by the addition of flocculants which pull particles together. The most common flocculant is polyacrylamide (PAM), but others are being used (e.g., chitosan) (Sojka et al., 2007). The flocculation process involves the flocculants overcoming the forces which keep small particles separated and in suspension (Gregory, 1989). This process, known as destabilization, causes the particles to bind together to form flocs, which in turn settle out of water column. The key elements include a method to introduce the flocculant into the turbid water, mixing and contract time, followed by an impoundment to allow settling.

Dosing of dissolved PAM into pumped, turbid water at the inlet of sediment basins can reduce turbidity by 90 % or more in a sediment basin for borrow pit operation (Kang et al., 2013b). Because of the increased efficiency of the settling process due to flocculation, it is possible that sediment basin could be reduced in size relative to current requirements. Previous work has shown that the retention time for flocculated sediment can be much less when pumping turbid water into stilling basins (Bhardwaj and McLaughlin, 2008; Kang et al., 2013b). If this can be shown to be the case, the benefits of smaller basins include reduced installation costs, smaller land area, and easier maintenance. The optimum geometry of the settling basin may also be different when flocculation and the required porous baffles are included in the design.

Five objectives were proposed to determine the range of flocculated sediment characteristics important to settling and the impact those characteristics can have on basin design and the effectiveness of PAM use in field conditions:

1. Determination of particle characteristics (size, density, settling rate) of flocculated soils with different particle size distribution and mineralogy
2. Test relationships between flow, flocculant delivery method, and basin trapping efficiency.
3. Determine the influence of basin geometry and baffles on floc settling.
4. Characterization of particle sizes in untreated and treated (PAM) runoff on construction sites.
5. Validate the performance of the flocculation system (treatment with PAM + sediment basin) under field conditions

Study Methods

<u>Laboratory Analysis</u>

Particle size distributions, settling time, and settling velocity were first characterized in the laboratory to better understand the characteristics of flocculated sediments.

Particle Size distribution

A volume-based particle size distribution (PSD) was performed for five different soil materials (2-mm sieved) across physical regions of NC (Table 1) using the laser diffraction method (LD). All samples were prepared in suspensions (20 g L^{-1}) and subsamples were taken while being stirred by a magnetic bar. The main advantages of the LD technique for PSD determinations include: short time of analysis (5 to 10 min per sample), high repeatability, small size of sample needed (≤ 1 g), and a wide range of size fractions into which the entire range of particle sizes can be divided as a continuum (Eshel et al. 2004).

Table 1. Physical regions and textural information for the five construction site soils tested.

Soil ID	NCDOT division	Clay	Silt	Sand
			%	
Coastal plain sandy loam (CPSL)	1	20	14	66
Coastal plain loamy sand (CPLS)	2	5	14	81
Piedmont sandy clay loam (PSCL)	5	26	16	58
Piedmont silt loam (PSL)	8	26	59	15
Mountain clay loam (MCL)	14	28	27	45

Particle Size distribution for flocculated and unflocculated sediments
In order to see the effects of initial particle sizes on flocculation, we prepared sieved soil samples screened into three different sieve sizes: mesh no. 270 (<53 µm) – "Fine"; mesh no. 70 (53 to 210 µm) – "Mid"; mesh no. 10 (210 to 2000 µm) – "Coarse". Whole soil was sieved by mesh no. 10 (2000 µm) only. The test soil was a Piedmont clay loam with 41% sand, 22 % silt, and 37 % clay. For each of the size-aggregated soils, we prepared soil suspension at 2 g L^{-1} and added dissolved polyacrylamide (APS 705) at 10 mg L^{-1}.

Time Effects on Particle Size distribution curve
Briefly, we prepared a series of soil suspensions (2 g L^{-1}), added PAM (10 mg L^{-1}) at day 0 and let the samples sit at the lab bench for differing time frames (day 1, day 3, and day 6). For each day of analysis, the identical soil suspensions were stirred for a while to take subsamples for the LD analyzer.

Settling Time and Settling Velocity
Settling tube testing was conducted on the five different soil materials (Table 1) with and without PAM addition to characterize how the soil particles will behave under the influence of gravity. We added a given amount of sediment on the top of clear acrylic column and observed how the particles in the sediment settled over time. These empirical tests provided the settling characteristics specific to the sediment of interest and provided a basis for the rational design of gravity-based solid-liquid separation systems, such as sediment basins for construction sites (Wong and Piedrahita, 2000).

For our tests, we used a 1.25 m tall by 10 cm diameter clear plastic column (Fig. 1) installed with two sampling ports: upper sampling port (0.4 cm in diameter) located at 15 cm from the bottom and bottom drainage port (1.0 cm in diameter). We first filled the column with tap water up to a height of 1 m as measured from the sampling port. We prepared a soil suspension by weighing either 5 or 20 g of air-dried soil (2-mm sieved) and mixing it with 150 mL of tap water for 30 s. The suspension was poured into the top of column through a conical sample dissipater. The dissipater distributed the suspension evenly at the top of the water column with minimal turbulence. We obtained samples at the sampling port at 0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 10, 15, 30, and 60 min. After the final sampling, the settled sediment was carefully removed through the bottom drainage port. For all of the collected samples, total suspended solid (TSS) concentration was measured gravimetrically by filtering through

76 mm pre-weighted fiberglass filters (Environmental Express, Mt. Pleasant, SC) and drying for 24 h at 105 °C.

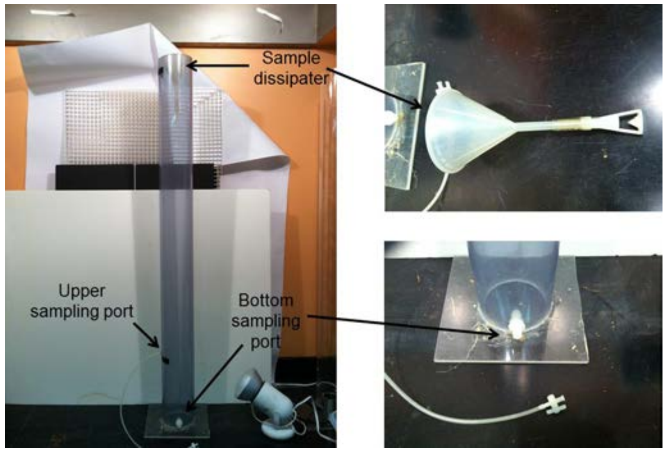


Figure 1. Apparatus used for the settling column experiment

A total of 40 settling tube tests were performed as a combination of five soil materials, two sediment loadings (5 g and 20 g) and two PAM levels (with and without PAM) in duplicates. Based on the water volume in the settling tube (9.2 L), volume-weighted TSS concentrations at time = 0 were 544 mg L^{-1} and 2,178 mg L^{-1} for 5 g and 20 g tests, respectively. For the PAM treatment (APS 705), we added 1 mL of 0.5 g PAM L^{-1} into the 150 mL of soil suspension and the PAM concentration in the settling column was 0.5 mg L^{-1}.

Ditch Tests

The study was conducted at the Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, NC. The experimental setup (Fig. 2) involved a 24-m ditch lined with a plastic tarp on a 7% natural slope and three straw wattles installed perpendicular to flow according to the guidelines by King and McLaughlin (2009). Straw wattles are one of the most common fiber check dams in NC and it is a tubular product (30 cm in diameter and 3.1 m in length) made of agricultural straw fibers encased in durable netting (ACF Environmental, Clayton, NC). They were spaced at 5 m apart with the top of each check dam even with the bottom of the check dam above it.

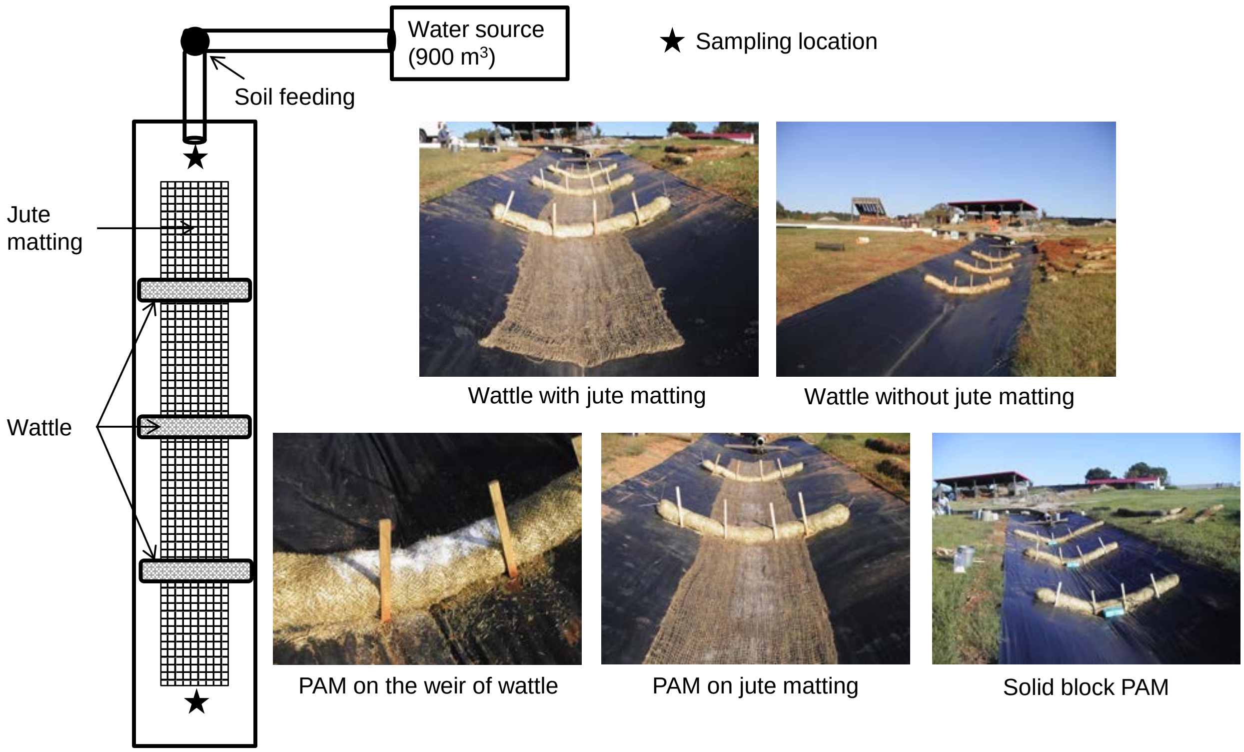


Figure 2. Ditch test layout consisting of excelsior wattle, jute matting, and polyacrylamide (PAM) application.

A ditch test consisted of three consecutive, simulated stormwater events coming into the entrance pipe of the ditch. The duration of each event was 28 min and water was introduced from a source pond through a 0.3-m diameter pipe (Fig. 1). Chemical properties of the pond water are presented in Table 2. Each storm event consisted of flow at 0.014 (0.5 cfs for 5 min), 0.028 (1 cfs for 3 min), 0.057 (2 cfs for 3 min), 0.028 (1 cfs for 3 min), and 0.014 $m^3 s^{-1}$ (0.5 cfs for 15 min), simulating an increasing and decreasing storm event over a 28-min period. The highest flow at 0.028 $m^3 s^{-1}$ (2 cfs) was similar to peak flows expected from a 0.45-ha construction site for a 2-year storm event in the area. The flows were regulated at a gate valve located in the pipe near water source pond. To generate turbid water, a total of 170 kg soil was added to the delivery pipe by hand during each 28-min storm event. The soil material used in this study (Table 3) was a sandy clay loam obtained from a local construction site and it was stored in an open shed without grinding before use. The soil was added in proportion to flow to achieve approximately 5,000 mg L^{-1} of sediment loading at all flows, which is within typical total suspended solid (TSS) concentration range found in construction site discharges in NC (Line and White, 2001; McCaleb and McLaughlin, 2008).

Table 2. Selected chemical properties of the pond water used for the ditch tests.

Parameter[a]	Value
pH	6.0
EC (dS m^{-1})	0.07
Turbidity (NTU)	3.0
TSS (mg L^{-1})	4.7
TOC (mg L^{-1})	7.1
Al (mg L^{-1})	0.8
Ca (mg L^{-1})	3.5
Fe (mg L^{-1})	0.3
K (mg L^{-1})	3.6
Mg (mg L^{-1})	2.4
Na (mg L^{-1})	5.2

[a] EC = electrical conductivity; TSS = total suspended solid; TOC = total organic carbon.

Table 3. Selected properties of the sediment used for basin tests.

Texture	Sand[a]	Silt[a]	Clay[a]	pH[b]	EC[c]
	g kg^{-1}	g kg^{-1}	g kg^{-1}		dS m^{-1}
Sandy clay loam	585	157	258	5.3	0.71

[a] Particle size analysis by hydrometer method.
[b] pH by a glass electrode at 1:1 water to solution ratio.
[c] Electrical conductivity (EC) by an EC meter.

A total of 6 ditch tests were performed to evaluate the flocculation efficacy of physically different two PAM formulations with and without jute matting (Table 4). The PAM formations were: 1) a granular PAM (GPAM) (APS 705, Applied Polymer Systems Inc., Woodstock, GA) and 2) a solid block PAM (BPAM) (APS Floc Log 706b, Applied Polymer Systems, Inc., Woodstock, GA). Both products are formulated from the same proprietary mixture of anionic polymers of different molecular weights and charge densities, and are certified by North Carolina Department of Environment and Natural Resources (NCDENR) for stormwater treatment for turbidity. The jute matting (Hanes Geo Components, Winston-Salem, NC) was 1.2 m wide and was installed in the ditch prior to the installation of the wattles. The treatments tested are shown in Table 4. The GPAM treatment consisted of 100 g applied to each wattle weir (middle 1 m) or the jute matting. When installing BPAM, we placed the attachment loop of the BPAM over the stake for wattles and laid it into the center of the ditch. Our experimental treatments enabled us to evaluate passive PAM treatment in terms of its formulation (granular vs block) and application area (wattle or jute matting). However, it is important to note that the BPAM dosing using three blocks was only adequate for the low-flow portion of the test, according to the guidelines from the manufacturer, which would call for 12 blocks for the highest flow.

Table 4. Experimental treatments for ditch test.

Treatment[a]	Erosion control product	PAM and applied area

1. No jute + No PAM	Wattle without jute matting	None
2. No jute + BPAM on wattle	Wattle without jute matting	Solid block PAM
3. No jute + GPAM on wattle	Wattle without jute matting	GPAM on the weir of wattle
4. Jute + No PAM	Wattle with jute matting	None
5. Jute + GPAM on wattle	Wattle with jute matting	GPAM on the weir of wattle
6. Jute + GPAM on jute	Wattle with jute matting	GPAM on jute matting

[a] GPAM = granular polyacrylamide; BPAM = solid block polyacrylamide.

Water samples were taken manually at the entrance (influent) and exit (effluent) of the ditch (Fig. 2). Twelve samples were obtained at each location during each test, collecting at least two samples for each flow. The water samples collected during tests were analyzed for turbidity using Analite NEP 260 turbidity probe (McVan Instruments, Melbourne, Australia), and TSS after filtering through 76 mm pre-weighted fiberglass filters (Environmental Express, Pleasant, SC) and drying for 24 h at 105 °C. For the turbidity measurement, sample was shaken for 10 s and turbidity reading was taken after 30 s of settling. Measured turbidity readings were corrected daily using a standard curve generated with formazin solutions of known turbidity.

Selected samples during the first storm were analyzed for particle size distribution via a laser diffraction particle size analyzer (LS 13 320 Series, Beckman Coulter, FL). The analyzer determines volumetric particle size distribution by measuring the pattern of light scattered by the particles in the sample. Each particle's scattering pattern is characteristic of its size and the analyzer gathers the patterns by each constituent particle in the infinitesimal size interval (Agrawal et al., 1991). The analyzer had a detection range between 0.04 µm and 2 mm.

For statistical analysis, analysis of variance (ANOVA) was performed using the PROC GLM Procedure in SAS (Version 9.3; SAS Institute, Cary, NC). The three main treatment factors were PAM, jute mattering, and storm event with turbidity and TSS as repeated measurements. Statistical differences between treatment means were tested with Duncan's multiple range test and the Waller-Duncan *k*-ratio *t* test at a probability level of 0.05 (SAS, 2011).

Basin Design

The study was conducted at the Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, NC. The experimental setup (Fig. 3) involved a 24-m ditch lined with a plastic tarp and three straw wattles installed perpendicular to flow identical to the layout aforementioned ditch test without jute lining. The water exiting the check dams was routed into a sediment basin with one of the three different basin geometries: 1) standard basin, 2) horizontal basin, and 3) standard basin with ramp (Fig. 4). The standard basin was 2:1 in the L/W ratio (9 m:4.5 m) with 0.9 m in depth and two porous baffles were installed at 3 m and 6 m from the entrance. The horizontal basin was modified by simply moving the inlet and outlet to the long side of the basin while the basin storage volume remained the same. The purpose of horizontal basin was to promote greater energy dissipation by introducing wider baffle and thus redistribute the flow across a larger cross-sectional area. The second modified design was the same standard 2:1 basin but had a bottom floor sloped toward the outlet like a "ramp" rising up. We hypothesized that the sloped bottom in the ramp structure may intercept more suspended particles and reduce settling distance during sedimentation. This hypothesis was based on the observations of Bhardwaj and McLaughlin (2008) who found substantial suspended particle losses near the surface outlet, probably due to settling onto a sloped basin wall.

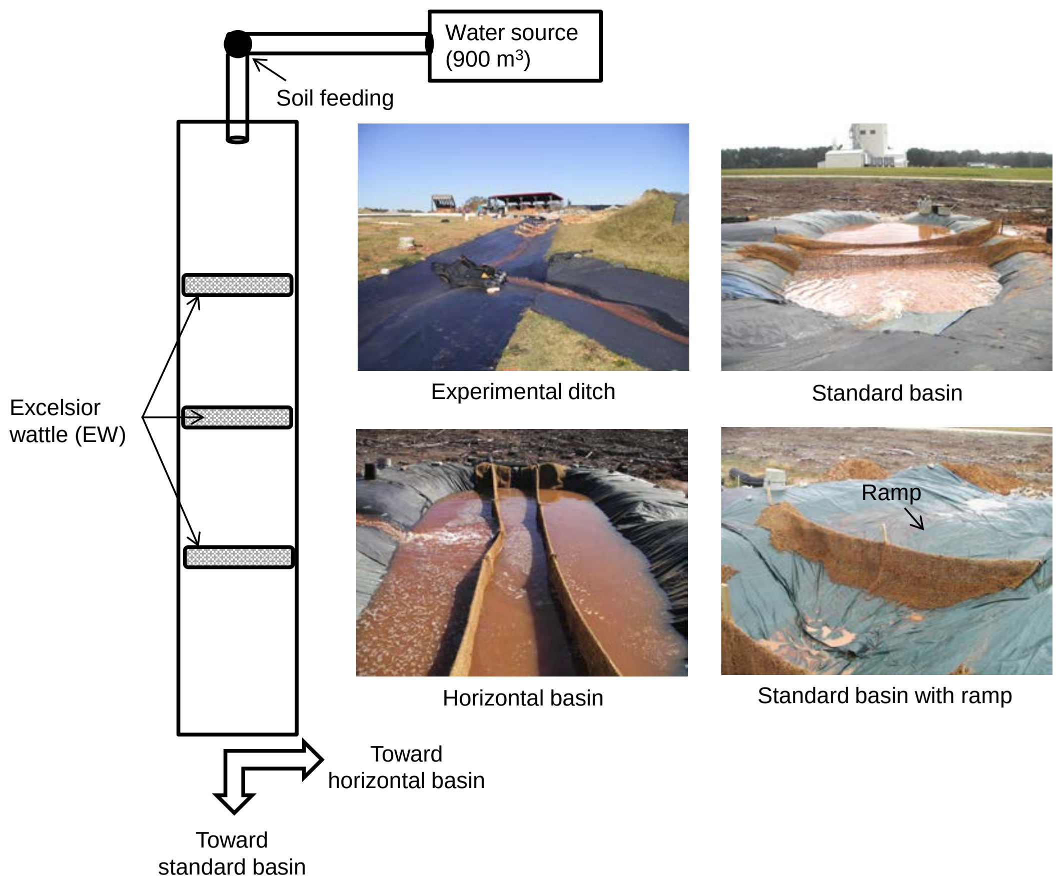


Figure 3. Layout of experimental ditch and settling basin.

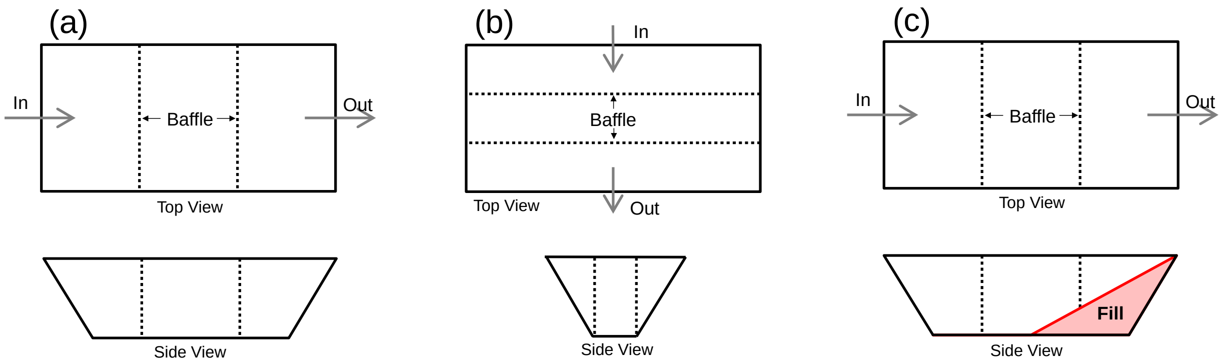


Figure 4. Sediment basin geometry tested in this study: (a) standard 2:1, (b) horizontal 1:2, and ramp on standard 2:1 (Length to width). Basin depth was 0.9 m in all cases.

A basin test consisted of a simulated stormwater event coming into the entrance pipe of the ditch installed with three excelsior wattles followed by one of the three aforementioned sediment basin geometries. A total of 18 basin tests were conducted to evaluate the performance of three different sediment basin geometries with and without PAM treatment in the upstream check dams in three-replicated trials. For the PAM treatment, 100 g of granular PAM (APS 705, Applied Polymer Systems Inc., Woodstock, GA) was applied to the weir (spillway) of each check dam. Water sampling and analyses followed same protocols as in ditch test. Selected samples from the standard and horizon basin tests were analyzed for particle size distribution via a laser diffraction particle size analyzer (LS 13 320 Series, Beckman Coulter, FL).

For statistical analysis, analysis of variance (ANOVA) was performed using the PROC GLM Procedure in SAS (Version 9.3; SAS Institute, Cary, NC). The two main treatment factors were PAM and basin geometry with turbidity and TSS as repeated measurements. Statistical differences between treatment means were tested with Duncan's multiple range test and the Waller-Duncan k-ratio t test at a probability level of 0.05 (SAS, 2011).

Field Tests

Three different sediment basins, located on North Carolina Department of Transportation (NCDOT) highway construction sites were instrumented and studied for this project.

The first site was located just north of Goldsboro, North Carolina along Interstate 795 in Wayne County. The project involved the construction of a four-lane divided freeway that will ultimately create a US-70 bypass around Goldsboro (project # : R-2554). This site is referred to as the Goldsboro site throughout this document.

The second site was located near the intersection of Interstate 40 and Interstate 77 near Statesville, North Carolina in Iredell County (Project #: I-3819). The project involved improvements to the interchange between I-40 and I-77 and is referred to as the Statesville site.

The final site was located near Rolesville, North Carolina in Wake County. The project involved extensions and widening of US 401 and some new construction (project #: R-2814). This site is referred to as the Rolesville site.

A sediment basin at each site was selected for study. Each basin contained coir baffles and a skimmer outlet installed according to NCDOT specifications. All basins were designed for a 10-year storm run-off event from their respective watersheds. Individual watersheds at each site varied considerably over the course of the study period. An ISCO 6700 series sampler (ISCO, Lincoln, Neb) was installed at the entrance and exit to each basin. The sampler at the entrance recorded stage within the 12 in plastic corrugated entrance pipe to each basin. The stage was used with Manning's Equation to calculate the flow rate through the pipe and an average value was recorded every five minutes. Located within each sampler were 24 bottles in which, during sampling events, four 200 mL samples were composited. Each sample was flow-weighted for 1000 gallons. The sampler at the exit of the basin recorded stage at the exit of the 4 in pipe leaving the basin (dewatering through the skimmer). Samples were pulled under the same program as the entrance.

Samples were analyzed for turbidity using the Analite nephelometer (model 152, McVan Instruments, Melbourne, Australia). Samples were shaken for 10 seconds and a turbidity reading was taken after another 30 seconds. Samples that were above the instrument limits of 3,000 NTU were diluted so that readings could be less than 3,000 NTU. The value was then multiplied by the dilution factor to determine the turbidity. Readings were corrected against formazin turbidity standards (HF Scientific, Ft. Meyers, Fla.) each day.

Every fourth sample from each sampling event was also analyzed for Total Suspended Solids (TSS) by the filtration method (Clesceri et al., 1998). A subsample was taken from the samples while they were being rapidly stirred on magnetic plates. The subsample was then filtered through 76 mm pre-weighted fiberglass filters (Environmental Express, Pleasant, SC) (Fig. 5) and dried for 24 h at 105 °C.

Selected samples from the entrance and exit, as well as, samples taken from the watershed were analyzed for particle size distribution via a laser diffraction particle size analyzer (LS 13 320 Series, Beckman Coulter, FL). The analyzer had a detection range between 0.04 µm and 2 mm.

Statistical analysis consisted of using Jmp10 (Version 10.1, SAS Institute, Cary, NC) to test for differences in mean based on the factors of location (entrance or exit of the basin) and the presence of PAM. Turbidity and TSS were both tested using Tukey's Honest Significant Difference (HSD) at a probability level of 0.05. The same test was used for PSA samples, testing for differences between mean particle volumes at the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles.

Figure 5. Vacuum filter device – TSS.

Results and Discussion

Laboratory Tests

Figure 6 shows two different ways in describing PSD data. In all soil types, there were multiple-modal distributions in the PSD (Fig. 6a) and these are indicative of multiple gap-graded particle size distribution in the analyzed samples. Civil engineers often use a range of coefficients to describe the uniformity vs. the well-gradedness of soils (Peck et al. 1974; ASTM D 2487, 1994). The coefficients are often calculated based on the PSD by sieve analysis on a mass basis, but we have examined our data measured on a volume basis in the similar manner. A wider band in the PSD indicates the well-gradedness while normal distribution without multiple peaks (modals) is indicative of the uniformity of particles. Our results showed that mountain clay loam (MCL) was relatively uniform in particle size and poorly graded ($C_u = 4$) compared to Coastal Plain and Piedmont soils (Table 6).

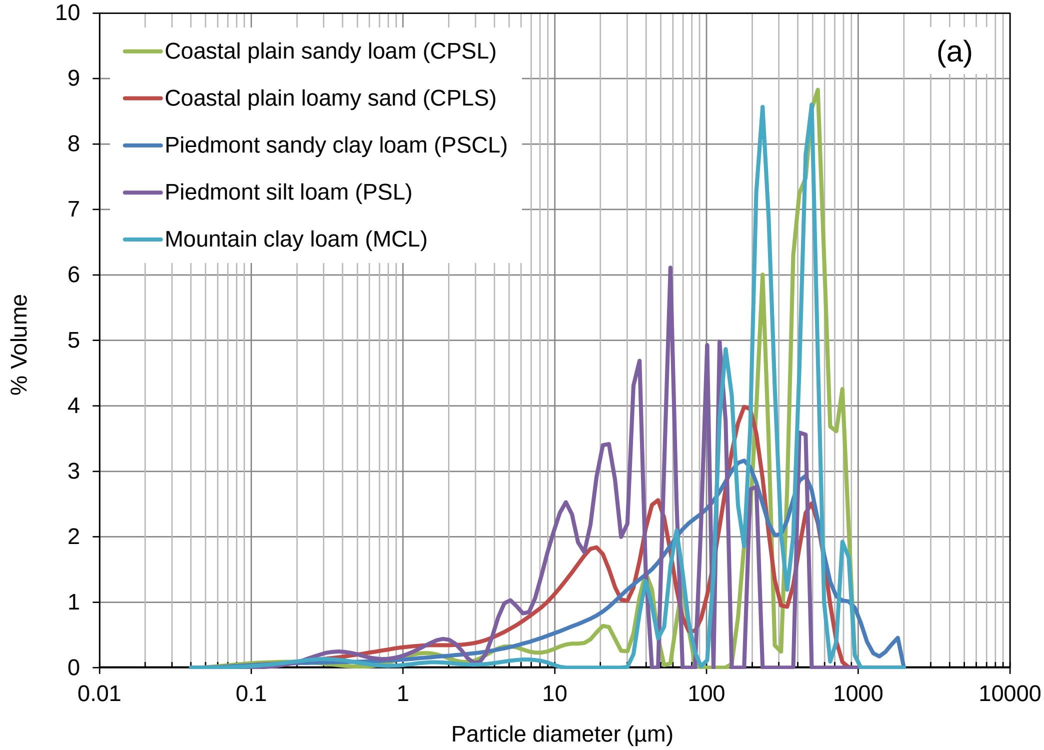
1) The Uniformity coefficient: $C_u = D_{60}/D_{10}$,

   Soils with $C_u \leq 4$ are considered to be "poorly graded" or uniform; when the particles are distributed over a wide range, termed "well graded".

2) The coefficient of gradation: $C_c = (D_{30})^2/(D_{60} \times D_{10})$,

   For well-graded soils, $C_c \approx 1$.

3) The sorting coefficient: $S_o = (D_{75}/D_{25})^{0.5}$,
The larger S, the more well-graded the soil.



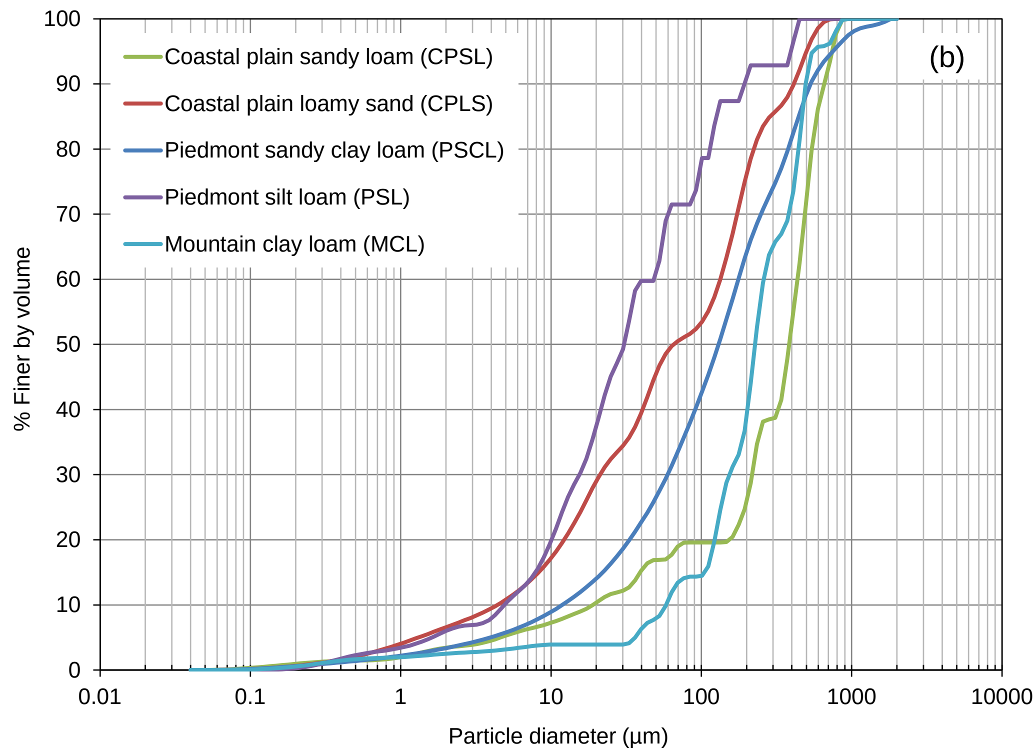


Figure 6. Particle size distribution n in the suspensions of unflocculated sediments: (a) absolute volume percent in Y-axis and (b) cumulative volume percent in Y-axis.

Table 5. Summary of particle size distribution data of unflocculated sediments.

Parameter	Coastal plain sandy loam (CPSL)	Coastal plain loamy sand (CPLS)	Piedmont sandy clay loam (PSCL)	Piedmont silt loam (PSL)	Mountain clay loam (MCL)
			µm		
Mean	392	151	245	81	299
Mode	568	185	185	60	517
D_{10}	21	5	13	5	64
D_{25}	215	18	50	13	148
D_{30}	218	21	59	15	154
D_{50}	422	72	143	34	250
D_{60}	436	134	177	48	257
D_{75}	566	213	343	104	458
D_{90}	721	454	586	213	542
Uniformity C_u	20.8	26.7	13.6	9.6	4.0
Gradation C_c	5.2	0.7	1.5	0.9	1.4
Sorting S_o	1.6	3.4	2.6	2.8	1.8

Particle size distribution affected by initial particle sizes and flocculant addition

During our preliminary tests, we measured the shift in floccuated sediment particle size distribution to coarser sizes. In order to see the effects of initial particle sizes on flocculation, we prepared sieved soil samples screened into three different sieve sizes: mesh no. 270 (<53 µm) – “Fine”; mesh no. 70 (53 to 210 µm) – “Mid”; mesh no. 10 (210 to 2000 µm) – “Coarse”. Whole soil was sieved by mesh no. 10 (2000 µm) only. The test soil was a Piedmont clay loam with 41% sand, 22 % silt, and 37 % clay. For each of the size-aggregated soils, we prepared soil suspension at 2 g L^{-1} and added dissolved PAM at 10 mg L^{-1}.

The PSD data showed that the size-aggregated samples with no PAM (i.e., unflocculated sediments) showed that mean diameter of the size-aggregated samples increased with increasing sieve opening sizes (Fig. 7). Overall, the flocculated sediments increased mean particle diameter up to five times compared to unflocculated sediments. It was notable that all flocculated sediments showed similar particle size distribution pattern with bi-modal peaks and more uniform distribution. The uniformity coefficient for flocculated sediments (Table 7) confirmed this observation in that the values of C_u decreased ≤ 4.7 compared to those of unflocculated sediments (8.5 to 12.4). The PSD curves presented in cumulative volume (% Finer in volume) further demonstrated the particle size growth to coarser fractions (Fig. 8). The particle size growth was more pronounced in the fine group, implying the reason why PAM has been so effective in removing turbidity (fine suspended sediments).

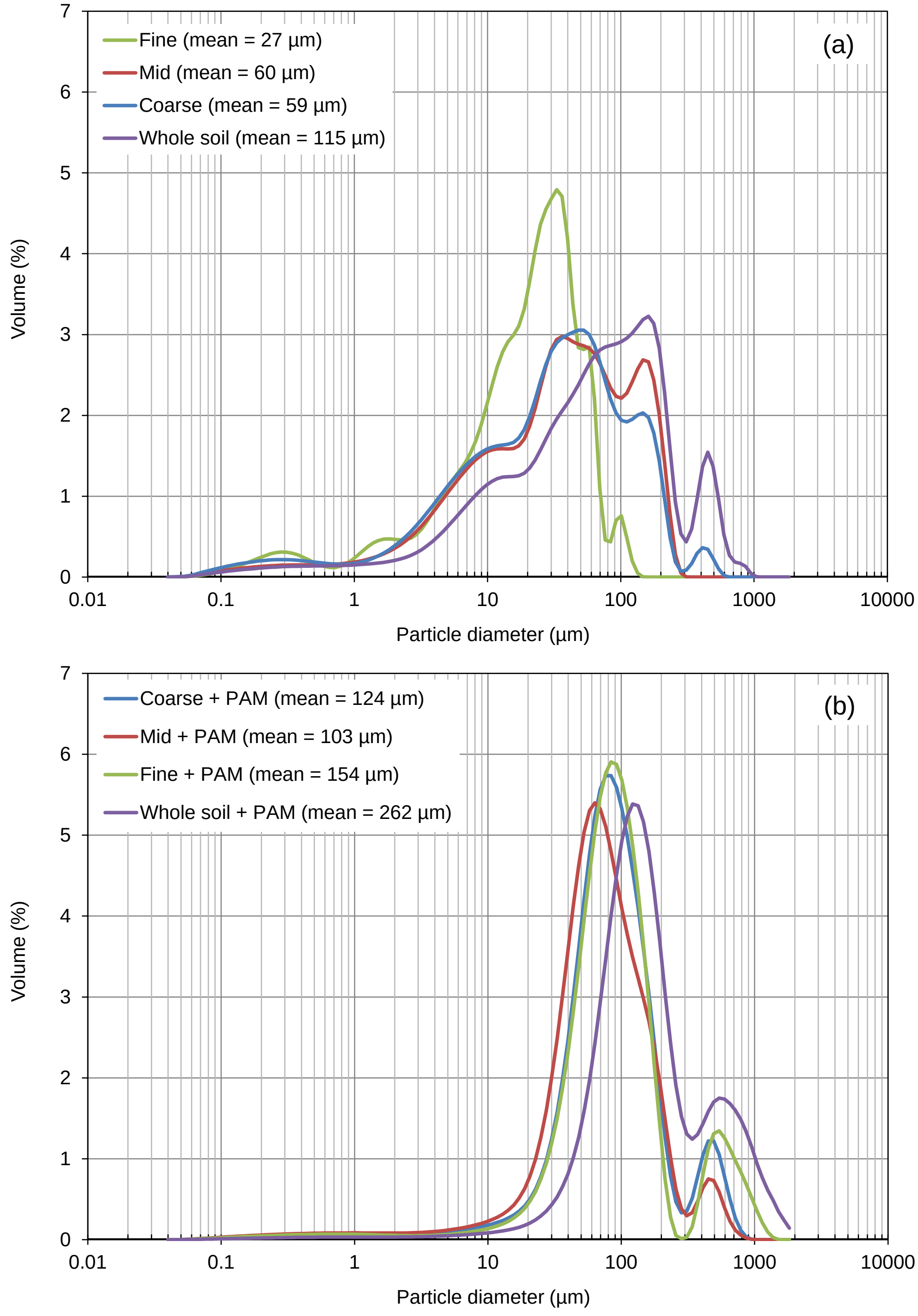
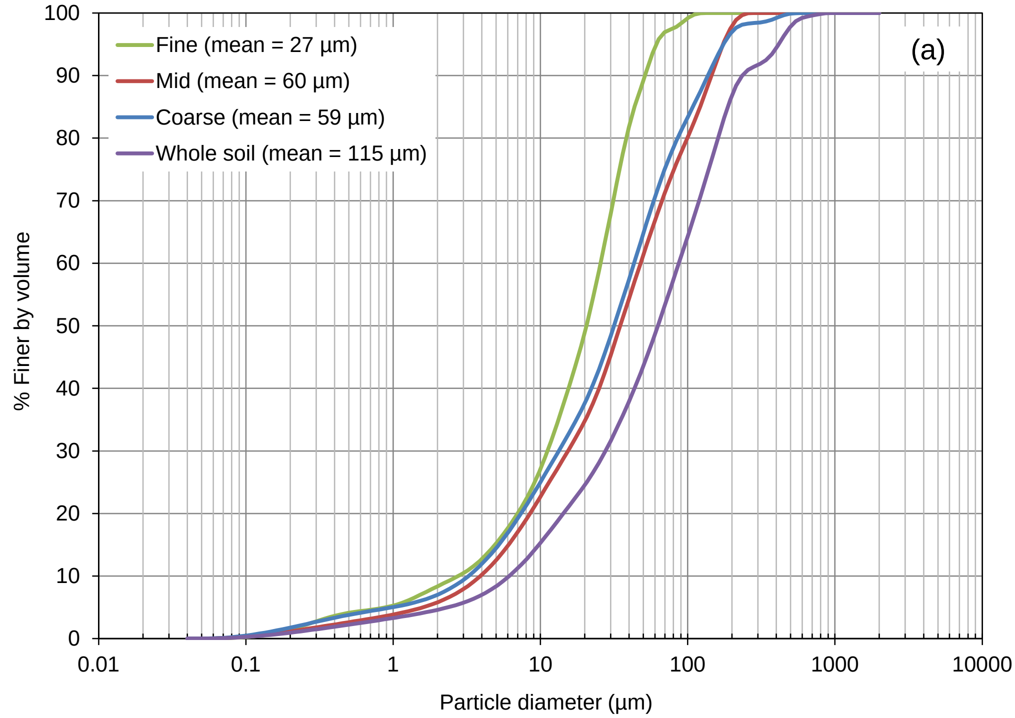


Figure 7. Volumetric particle size distribution in the suspensions of size-aggregated sediments (piedmont clay loam) affected by polyacrylamide (PAM) treatment: (a) unflocculated and (b) flocculated sediments. Fine, Mid, and Coarse groupings correspond to sieve opening size: mesh no. 270 (<53 µm) – Fine; mesh no. 70 (53 to 210 µm) – Mid; mesh

no. 10 (210 to 2000 µm) – Coarse. Whole soil was sieved by mesh no. 10 (2000 µm) only. Mean diameters are given in figure legends.

Table 6. Summary of particle size distribution in the suspensions of size-aggregated sediments (piedmont clay loam) with and without polyacrylamide (PAM) treatment.

	Fine (<53 µm)		Mid (53 to 210 µm)		Coarse (210 to 2000 µm)		Whole soil (< 2000 µm)	
Parameter	No PAM	PAM	No PAM	PAM	No PAM	PAM	No PAM	PAM
				µm				
Mean	27	154	60	103	59	124	115	177
Mode	34	88	38	73	55	88	169	116
D_{10}	3	35	4	26	4	33	7	34
D_{25}	10	58	13	46	11	56	23	92
D_{30}	11	59	29	46	13	56	28	94
D_{50}	22	90	38	73	35	87	69	105
D_{60}	26	96	48	79	43	93	87	160
D_{75}	38	139	89	121	76	136	152	274
D_{90}	56	444	159	195	151	225	258	513
Uniformity C_u	8.5	2.8	12.0	3.1	10.8	2.8	12.4	4.7
Gradation C_c	1.6	1.0	4.4	1.0	1.0	1.0	1.3	1.6
Sorting S_o	1.9	1.5	2.6	1.6	2.6	1.6	2.6	1.7



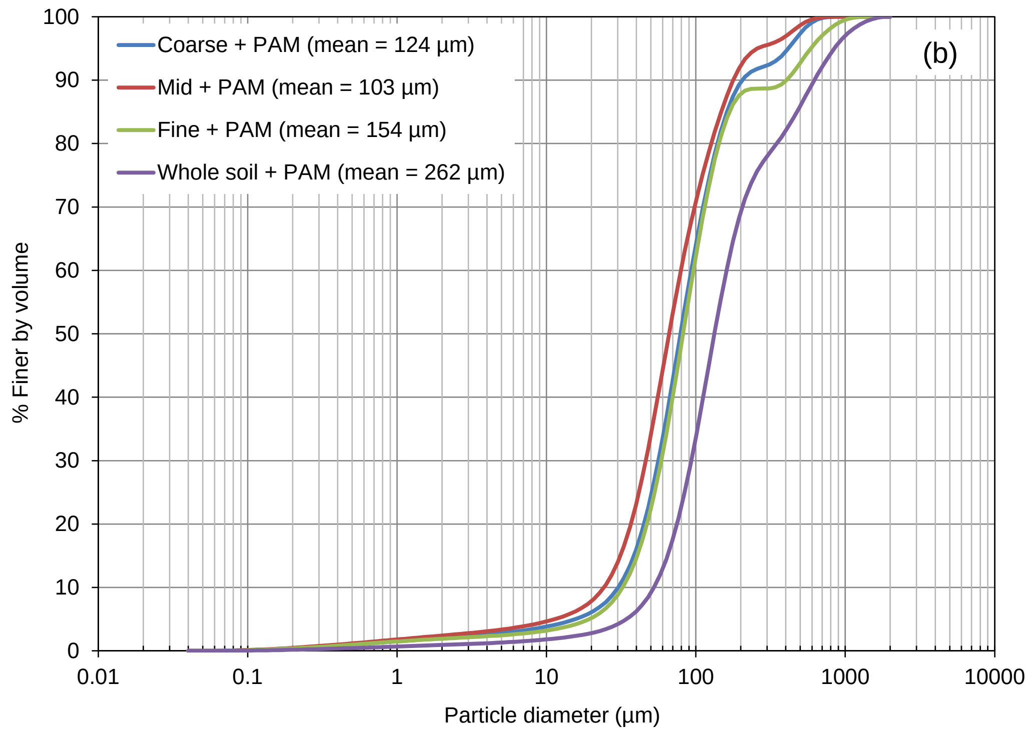


Figure 8. Particle size distribution curves in the suspensions of size-aggregated sediments (piedmont clay loam) affected by polyacrylamide (PAM) treatment: (a) unflocculated and (b) flocculated sediments. Fine, Mid, and Coarse groupings correspond to sieve opening size: mesh no. 270 (<53 µm) – Fine; mesh no. 70 (53 to 210 µm) – Mid; mesh no. 10 (210 to 2000 µm) – Coarse. Whole soil was sieved by mesh no. 10 (2000 µm) only. Mean diameters are given in figure legends.

Time Effects on Particle Size Distribution Curve of Flocculated Sediments

During this project, we observed that PSD of flocculated sediments changed over time (Fig. 9). Briefly, we prepared a series of soil suspensions (2 g L^{-1}), added PAM (10 mg L^{-1}) at day 0 and let the samples sit on the lab bench for up to six days. For each day of analysis, the identical soil suspensions were stirred for a while to take subsamples for the LD analyzer. The greatest mean particle diameter occurred immediately after flocculating and over time it shifted to finer particle sizes (Fig. 10). This is likely due to a change from a loose structure to a more compressed structure in the flocs as void spaces are reduced. This likely also occurs in sediment basins, particularly as large amounts of sediment accumulates. Presumably, the particle density increase also results in faster settling rates, although we did not measure that. The shape and band of PSD were relatively changed (bi-modal) but the second highest peak in the coarser fraction (500 to 700 μm) tended to decrease in a greater extent over time compared to the first peak (Fig. 9a).

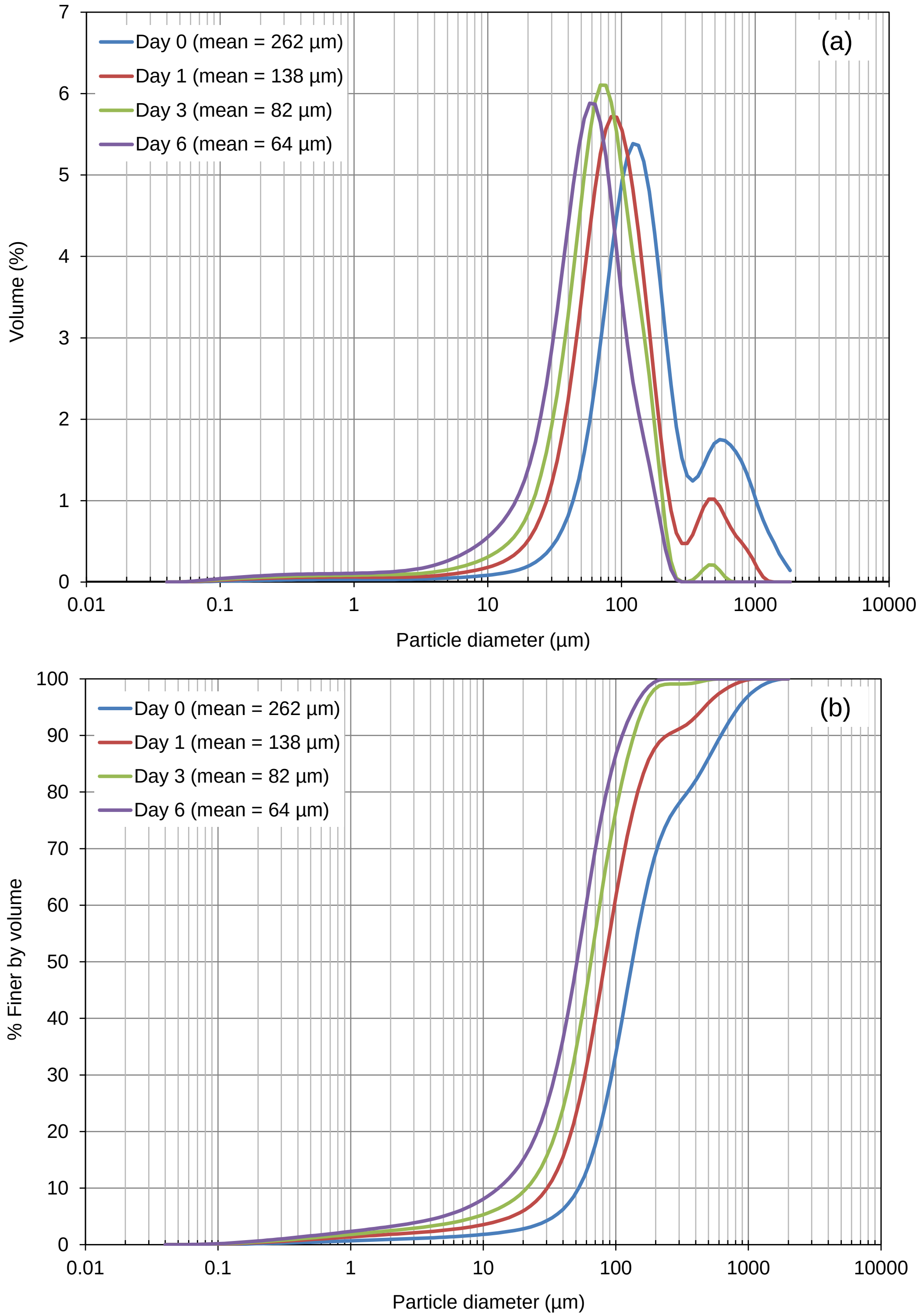


Figure 9. The effects of storage time on the particle size distribution of flocculated sediments.

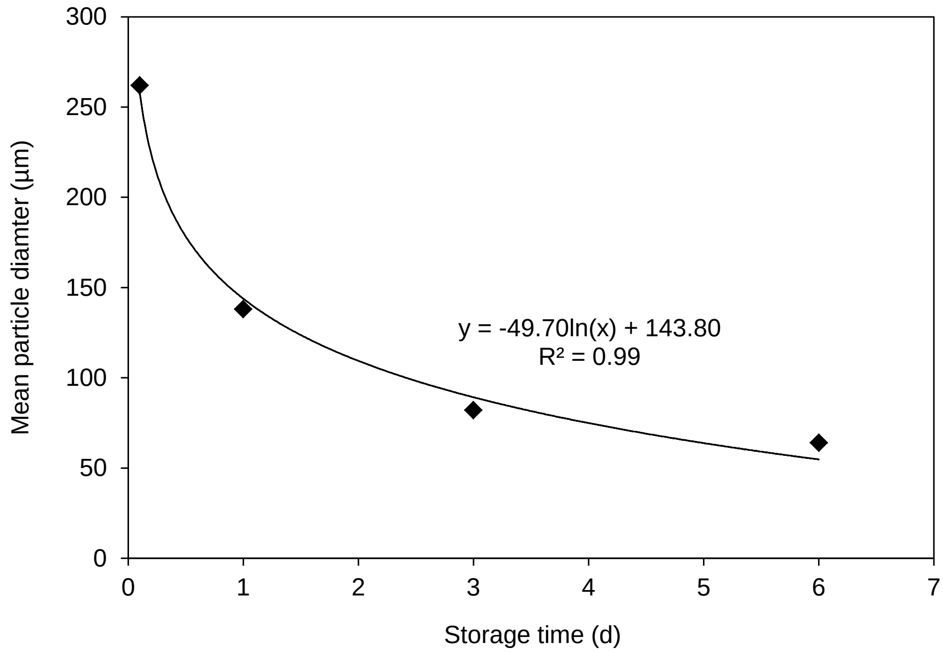


Figure 10. The relationship between sample storage time and mean particle diameters of flocculated sediment.

Settling tube experiment

1) Mass balance of settling tube experiment

Without flocculant, s 88 to 90 % of sediment added at 5 g and 69 to 93 % of sediment added at 20 g settled in 60 min(?). Among the five soil materials tested, Coastal Plain sandy loam (CPSL) had the lowest settled fraction during the 1-h settling period at both sediment loading (5 and 20 g) (Table 8). Flocculated sediments by PAM increased settled fraction up to 93 to 97 % in only 10 min settling time. The greatest improvement by PAM was observed with CPSL at 20 g (26 %) followed by piedmont clay loam (PCL) at 5 g (22 %). Overall chemical treatment of PAM applied at 0.5 mg L^{-1} achieved more than 90 % of sediment removal efficiency in all soil types tested. However, the pattern and rate of settling was quite different for sediment with and without PAM.

Table 7. Mass balance summary of settling tube experiment

Sediment loading	PAM	Sediments in tube[a]	Soil material[b]				
			CPSL	CPLS	PSCL	PSL	MCL
5 g	No PAM	Settled (g)	4.42	4.46	4.78	3.58	4.48
		Suspended (g)	0.58	0.54	0.22	1.42	0.52
		Settled fraction (%)	88	89	96	72	90
	PAM	Settled (g)	4.65	4.83	4.73	4.70	4.64
		Suspended(g)	0.35	0.17	0.27	0.30	0.36
		Settled fraction (%)	93	97	95	94	93
20 g	No PAM	Settled (g)	13.77	18.70	18.77	17.86	18.69
		Suspended (g)	6.23	1.30	1.23	2.14	1.31
		Settled fraction (%)	69	93	94	89	93
	PAM	Settled (g)	18.92	19.47	19.29	19.35	19.36
		Suspended (g)	1.08	0.53	0.71	0.65	0.64
		Settled fraction (%)	95	97	96	97	97

a Cumulative mass during the 1-h settling period.
b CPSL, Coastal Plain sandy loam; CPLS, Coastal Plain loamy sand; PSCL, Piedmont sandy clay loam; PSL, Piedmont sandy loam; MCL, Mountain clay loam.

The TSS concentrations in the samples collected from the upper sampling port (1 m travel distance from top) for the two sediment loading rates (5 g and 20 g) are shown in Figures 11-21. For most of the soils,, sediment flocculated by PAM arrived earlier at the 1 m sampling point and the TSS was much higher in the first few minutes than for unflocculated sediment (no PAM). However, the flocculated and unflocculated Coastal plain loamy sand (CPLS) had relatively similar TSS settling curves. This is likely to due to the high sand content (81 %) and lowest clay content (5%), thus less of the total soil was being affected by chemical treatment. Shorter tailing in TSS curves was evident in flocculated sediments, even for the CPLS, indicating that the total mass settled was much greater at earlier settling times .

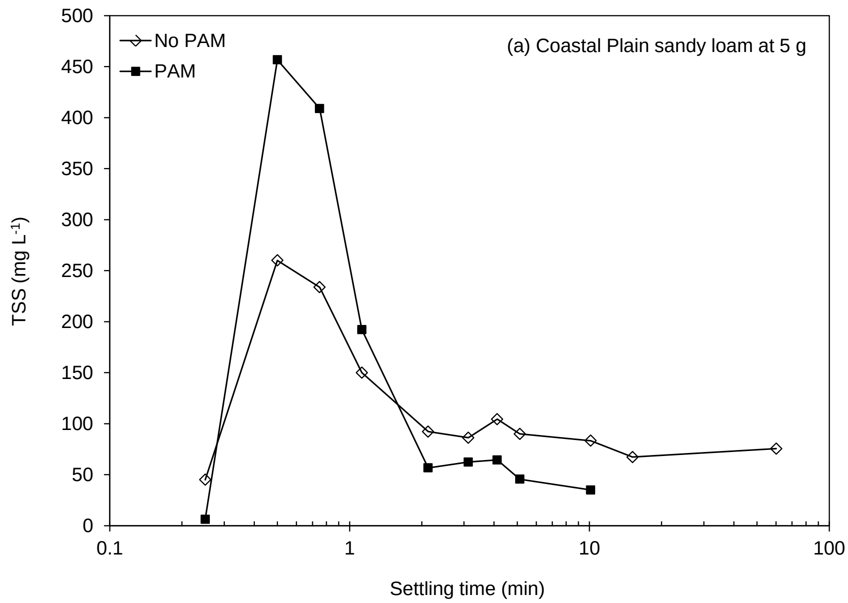


Figure 11. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (5 g of Coastal Plain sandy loam added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

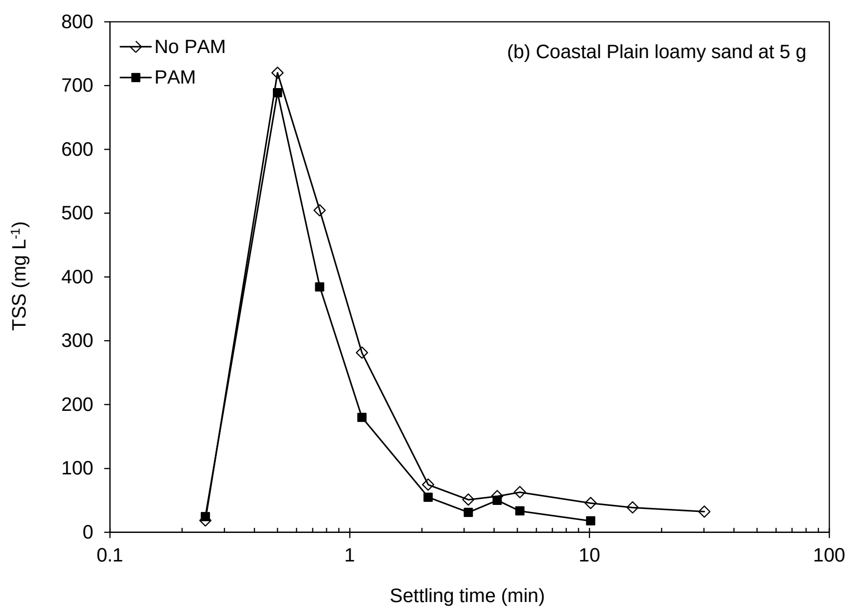


Figure 12. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (5 g of Coastal Plain loamy sand added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

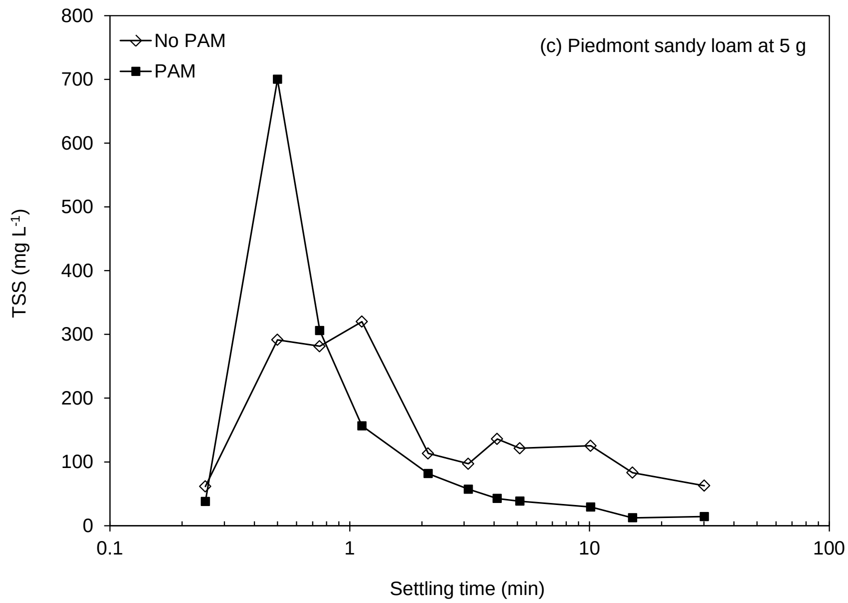


Figure 13. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (5 g of Piedmont sandy loam added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

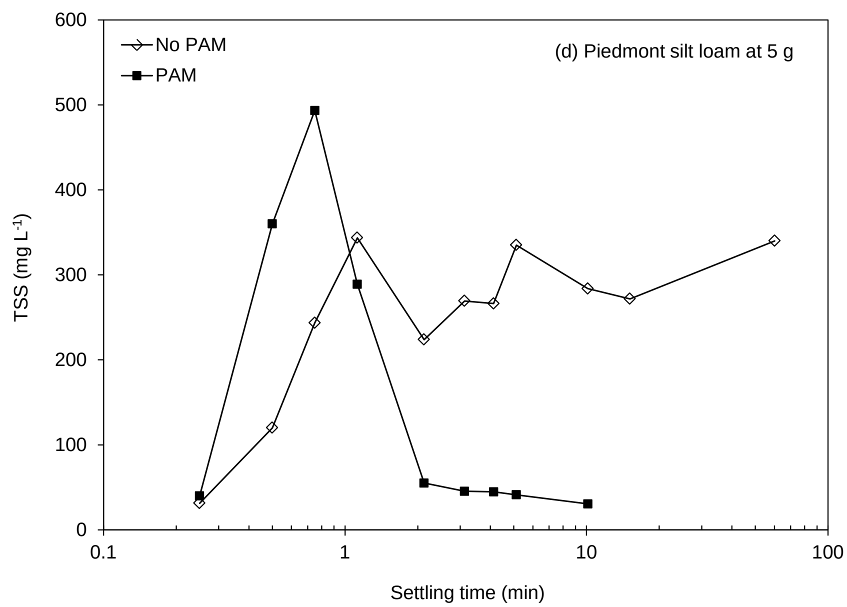


Figure 14. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (5 g of Piedmont silt loam added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

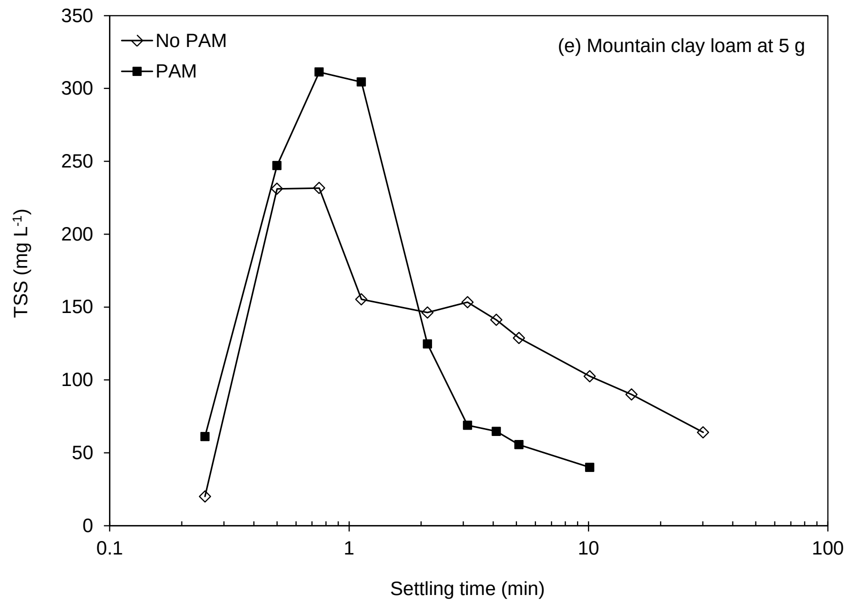


Figure 15. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (5 g of Mountain clay loam added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

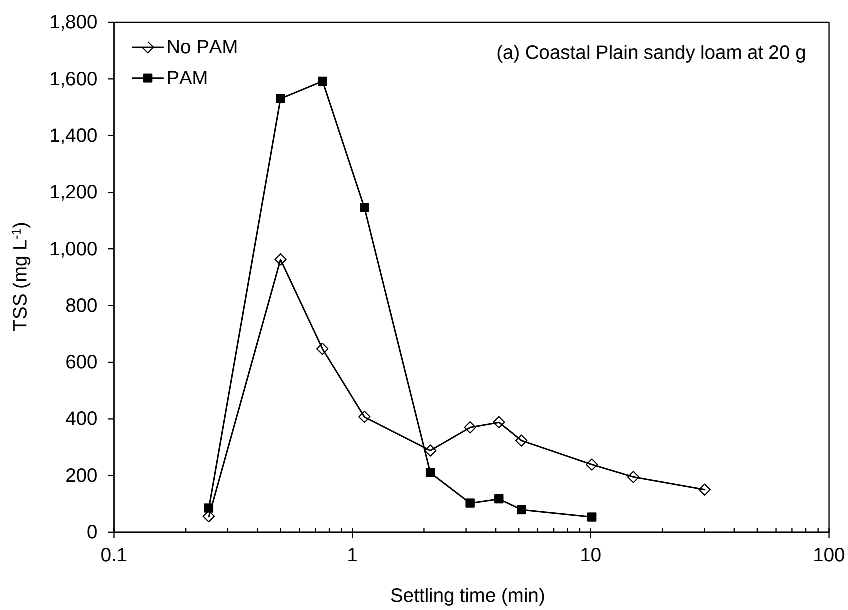


Figure 16. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (20 g of Coastal Plain sandy loam added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

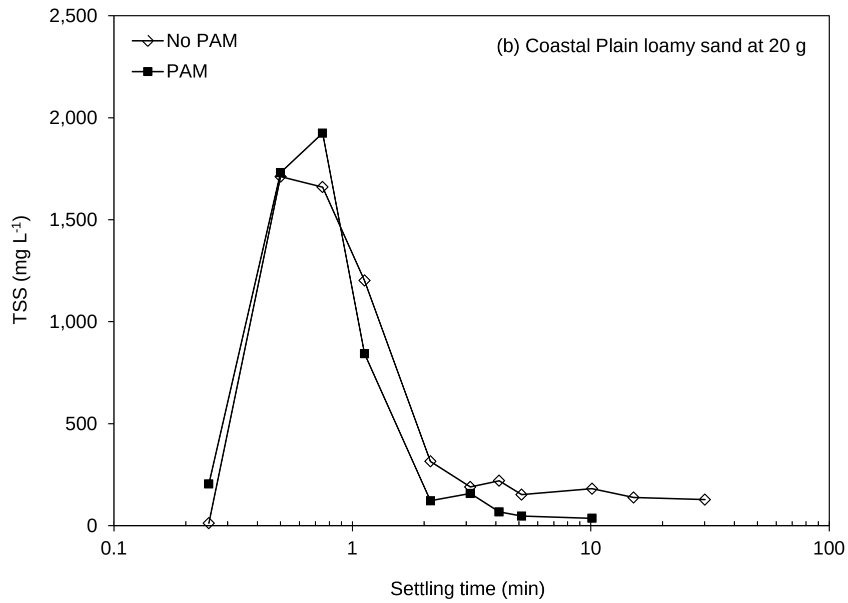


Figure 17. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (20 g of Coastal Plain loamy sand added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

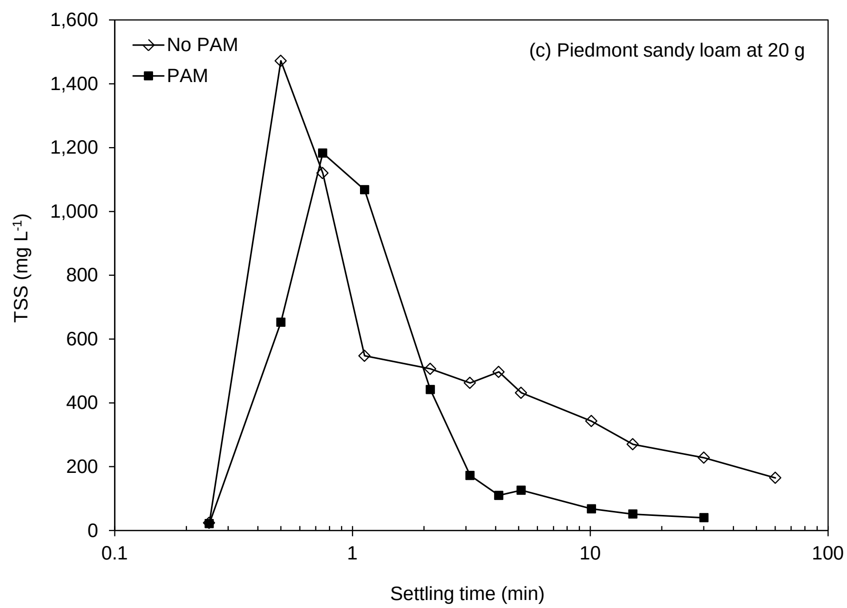


Figure 18. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (20 g of Piedmont sandy loam added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

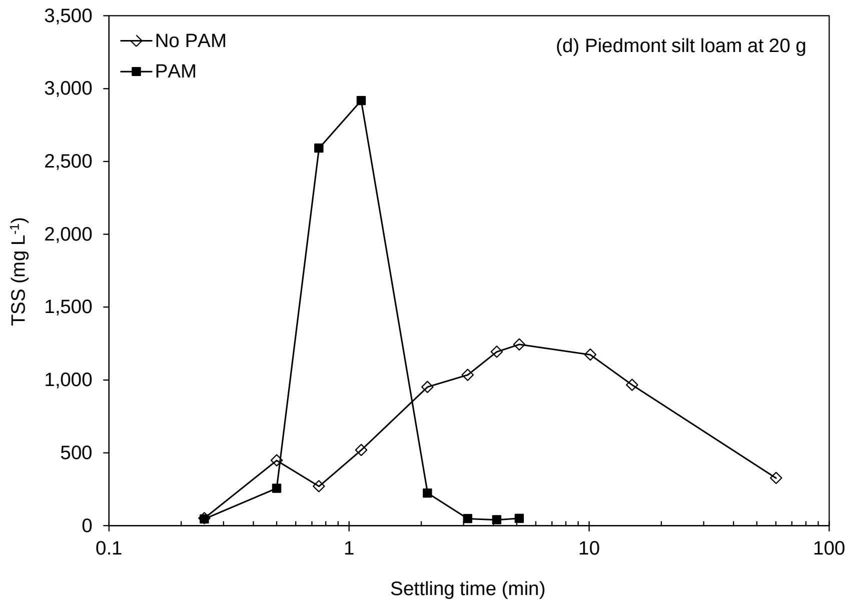


Figure 19. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (20 g of Piedmont silt loam added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

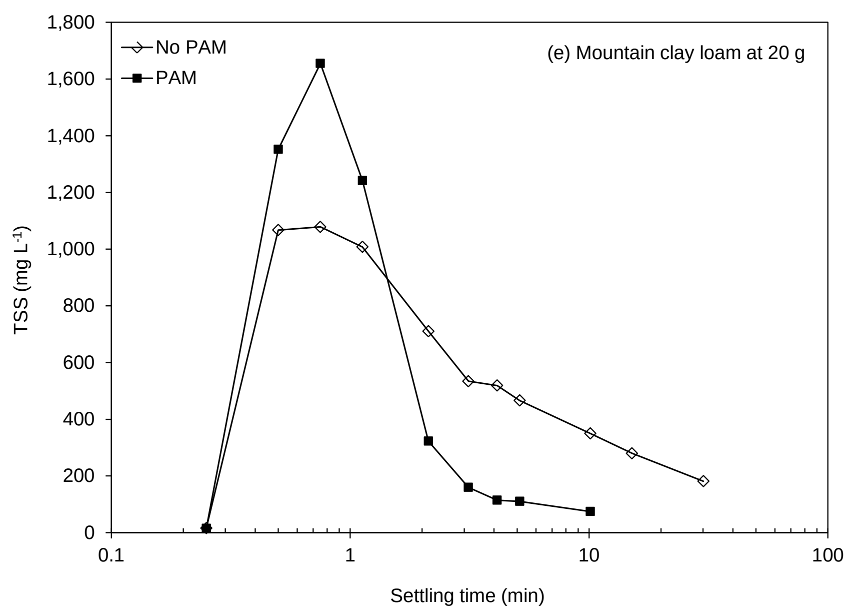


Figure 20. Total suspended concentration (TSS) concentrations at the sampling port of settling tube (20 g of Mountain clay loam added) with and without polyacrylamide (PAM) addition as a function of settling time. Note a logarithmic scale on X-axis.

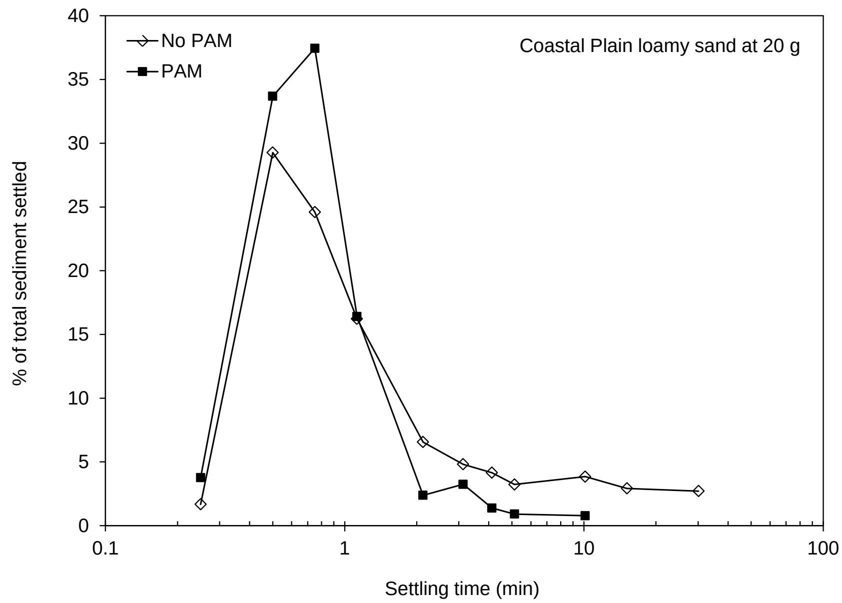


Figure 21. Percent of total sediment settled with and without polyacrylamide (PAM) addition in Coastal Plain loamy sand. Note a logarithmic scale on X-axis.

2) Settling velocity curve

An informative way of displaying the settling column data is to construct a settling velocity curve (Fig. 22). The X-axis of this curve is settling velocity (V_s) and the Y-axis is the mass fraction of solids that has a settling velocity less than or equal to the value on the X-axis.

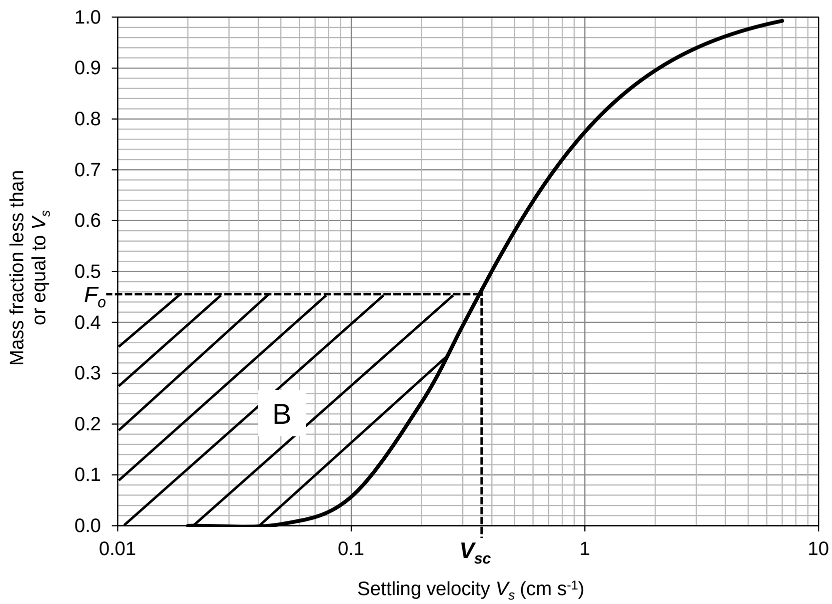


Figure 22. An example of settling curve to display settling velocity data.

The overflow rate (OFR), which is a volumetric flow rate (Q) entering basin divided by the surface area, is one of key parameters for sediment basin deign. From the settling curve, one can choose an OFR that is known as the terminal settling velocity or design settling velocity (V_o) and then estimate theoretical sediment removal efficiency of the basin by (Reynolds and Richards, 1996):

$$\eta = (1 - F_o) + 1/V_o \int_0^{Fo} V dF \qquad [1]$$

where η is the removal efficiency as a fraction of influent suspended solids removed and F_o is the value on the Y-axis corresponding to V_o (Fig. 22). By integration, eq.[1] can be written as:

$$\eta = (1 - F_o) + B/V_o \qquad [2]$$

where B is the area of the settling curve shown in Fig. 22 and is equal to the integral in eq.[1]. Thus, by using settling curves, we can calculate theoretical sediment removal efficiency of basins as a function of settling velocities. Samples withdrawn from the bottom of sampling tube at times ($t_1, t_2, t_3, \ldots, t_n$) represent the settled solid along the length of the tube between time t_{n-1} and t_n. The values of V_s were calculated by:

$$V_s = D/(t_n - t_{n-1}) \qquad [3]$$

where D is the water depth of the settling tube. Opening the sampling port causes the water level in the settling tube to drop. Similar to the approach employed by Wong and Piedrahita (2000), we made corrections for the dropping water level by calculating the average velocity at which the water level drops (v_i):

$$v_i = q / A_s \qquad [4]$$

where q = volumetric effluent flow rate during sampling (the volume of sample divided by sampling duration) and A_s is the surface area of the settling tube. The dropping water level (L_d) was calculated by:

$$L_d = v_i \times t_p \qquad [5]$$

Where t_p is the duration of each sampling event (s). Finally adjusted V_s was calculated by subtracting cumulative L_d at time = n from the D:

$$\text{Adjusted } V_t = (D - L_d) / (t_n - t_{n-1}) \qquad [6]$$

The interpretation of the settling curves requires the understanding of type I settling, which assumes discrete particle settling (i.e., particles fall independently of each other) in low-concentration solutions (Haan et al., 1994). We assumed our pre-mixed sediments with and without PAM do not contribute to further flocculation during their travels in the settling tube. From the Stokes equation for laminar flow and constant temperature, the settling velocity of a discrete particle is defined as:

$$Vs = \frac{1}{18}\frac{g\, d^2\, (\rho_f - \rho_w)}{\mu} \qquad [7]$$

where
V_s = terminal settling velocity of a particle
g is the gravitational constant
d is the diameter of particle
ρ_f is the density of water
μ is the viscosity of water (cm^2/sec).

Particles that arrive at the sampling port had an average settling velocity of (Fig. 23):

$$V_o = \text{distance travelled / time of travel} = Z_o/t_o \; [8]$$

On the assumption that another particle added at distance, Zp, had terminal velocity less than the particle in surface, but arrived at the same time, the terminal velocity of the another particle is

$$V_s = Z_p/t_o \qquad [9]$$

Where Vs is less than Vo but arrives at the sampling port at the same time. By setting the travel time for both particles are equal, we can derive:

$$t_o = Z_o/V_o = Z_p/V_s \qquad [10]$$

$$V_s/V_o = Z_p/Z_o \qquad [11]$$

Based on these relationships, following generalized statements can be made:
1) All particles having settling velocity greater than V_o, will arrive or pass the sampling port in time t_0.
2) Particles that have settling velocity (V_s) less than V_o will arrive or pass the sampling port provided its initial settling point is below Z_p.
3) If the soil suspension is uniformly mixed and entered to the top of setting tube at the same time, the fraction of particles that will arrive or pass the sampling port in time to will be $V_s/V_o = Z_p/Z_o$, which is equivalent to the removal efficiency of sediment.

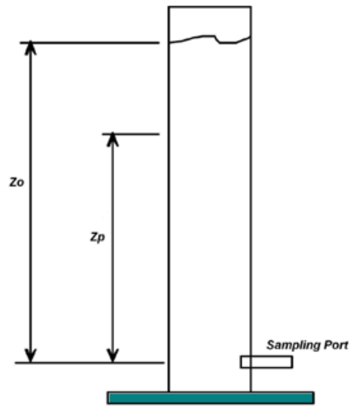


Figure 23. A schematic of the settling tube used in this study. Zo and Zp indicate the travel distance of particles (adapted from Samdani and Kapoor, 2013).

Figures 24 - 28 shows the settling velocity curves for the five different soil materials with and without PAM treatment. In order to calculate B in eq.[2], measured data were fitted with TableCurve 2.0 (Jandel Scientific, San Rafael, CA) and the area of B in Fig. 22 was calculated by a curve area calculator (Tutorvista, 2013). The TableCurve 2.0 is a least-square curve-fitting program to find best equation for empirical data (Scientific, J. 1994). The fitted equations for each of the settling curves are summarized in Table 9. The settling curves in Figs. 24-28 showed that flocculated sediments by PAM can have enhanced V_p as they were added in the middle of column (Z_p). For instance, the curve appeared to shift to the right that was higher V_s range. The Y-axis, mass fraction less than or equal to V_s that represents the suspended sediment fraction, was much lower with PAM treatment up to 2 to 4 cm s^{-1}, which was dependent on the soil type. These results suggest that when chemically-assisted settling is used, the OFR (or design settling velocity) can increase substantially. The increase in OFR can be translated to greater volumetric flow rate that can be treated with a given surface area or reduced surface area for a basin.

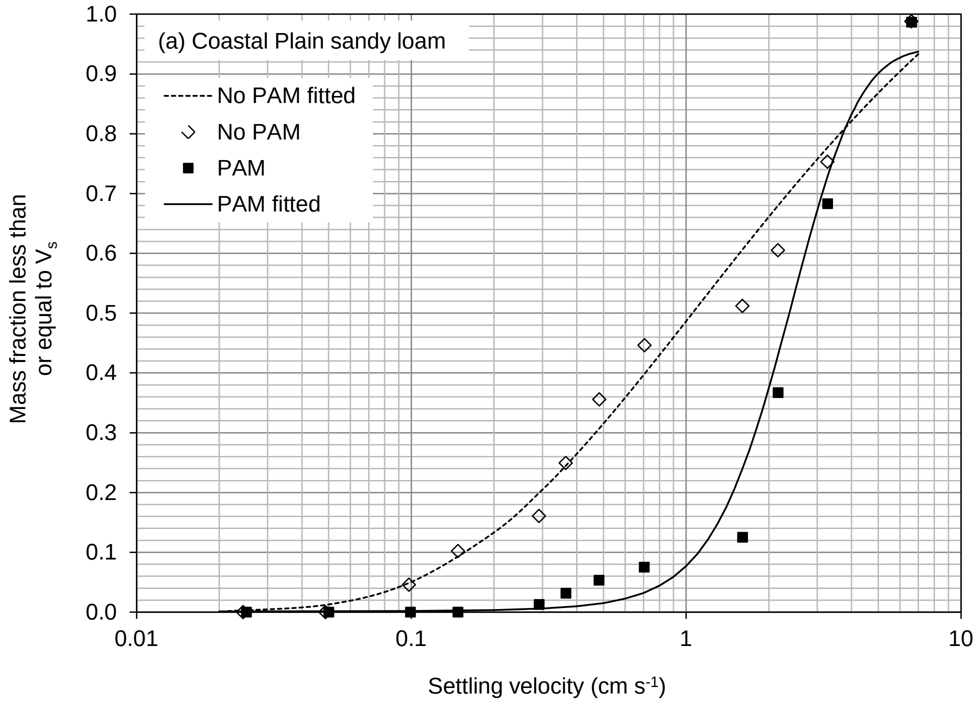


Figure 24. Settling curves of Coastal Plain sandy loam added at 20 g showing measured and fitted data.

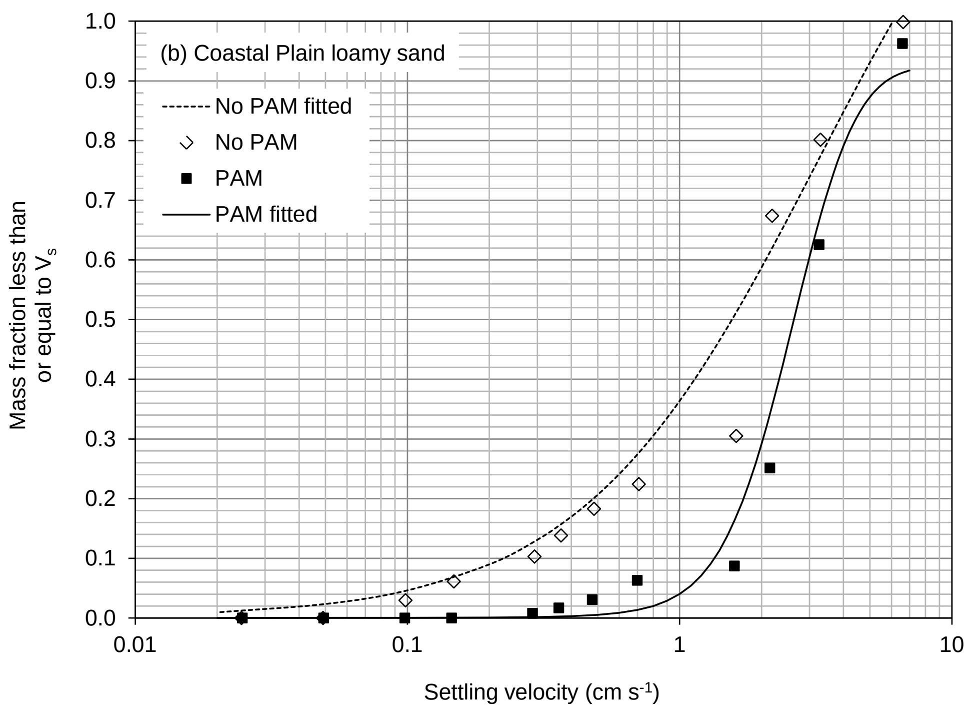


Figure 25. Settling curves of Coastal Plain loamy sand added at 20 g showing measured and fitted data.

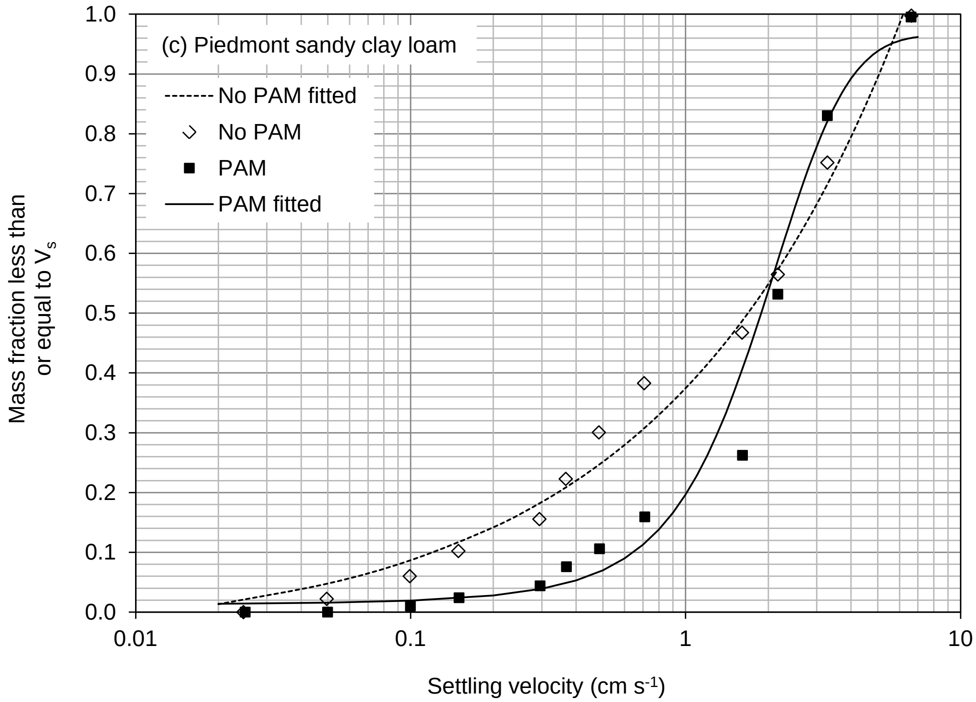


Figure 26. Settling curves of Piedmont sandy clay loam added at 20 g showing measured and fitted data.

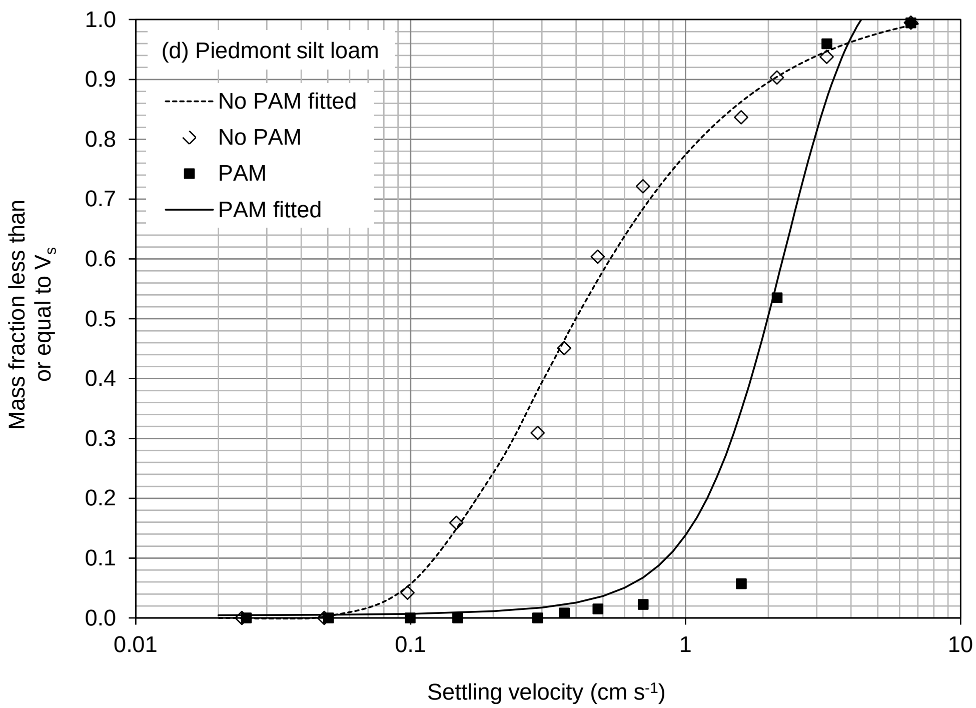


Figure 27. Settling curves of Piedmont silt loam added at 20 g showing measured and fitted data.

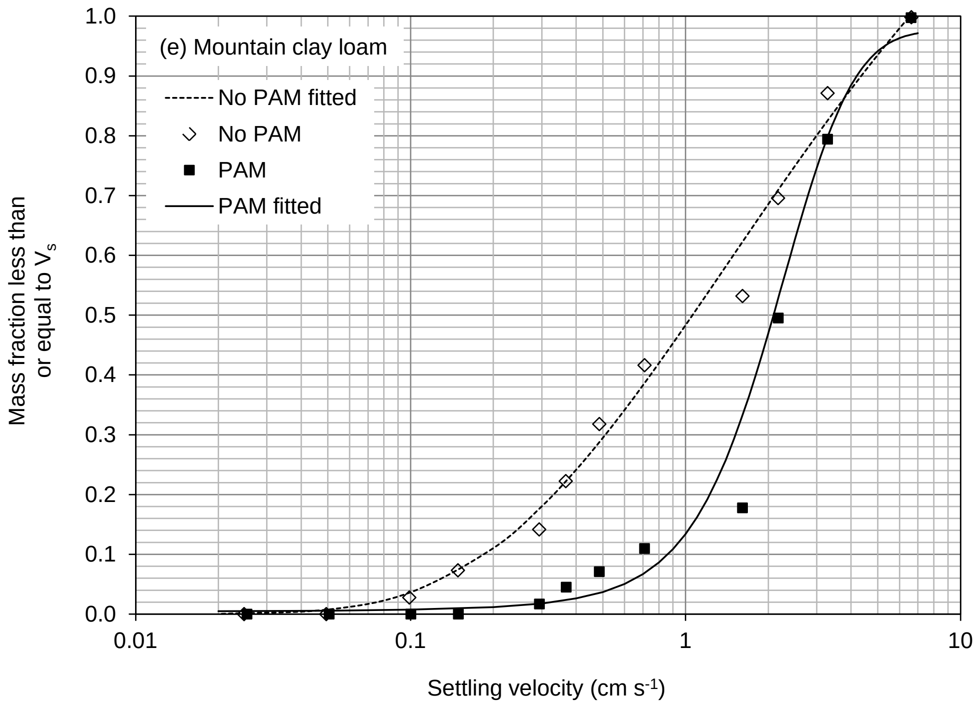


Figure 28. Settling curves of Mountain clay loam added at 20 g showing measured and fitted data.

Table 8. Fitted settling curves using measured settling tube data for five different soil materials and polyacrylamide (PAM)

Soil material	PAM	Best fit equation	R2
Coastal plain sandy loam (CPSL)	No PAM	ln y = 0.33 – 1.05/x0.5	0.98***
	PAM	ln y = -0.06 – 6.81 e-x	0.98***
Coastal plain loamy sand (CPLS)	No PAM	y^{-1} = 0.66 + 2.09/x	0.97***
	PAM	ln y = -0.07 – 8.52 e-x	0.98***
Piedmont sandy clay loam (PSCL)	No PAM	y = -0.05 + 0.42 x0.5	0.99***
	PAM	ln y = -0.03 – 4.33 e-x	0.98***
Piedmont silt loam (PSL)	No PAM	ln y = 0.03 – 0.29/x	0.99***
	PAM	ln y = 0.07 –5.57 e-x	0.94***
Mountain clay loam (MCL)	No PAM	ln y = 0.47 – 1.19/x0.5	0.99***
	PAM	ln y = -0.02 –5.40 e-x	0.98***

Simulation of removal efficiency and surface area requirement for sediment basin

Table 10 shows surface area requirements of sediment basins presented in Goldman et al. (1986). Using the relationship between fall velocity and particle size, they estimated the basin surface area (A_s) as a function of Q and V_s assuming a surface area adjustment factor of 1.2 (Mills and Clar, 1976):

$$A_s = 1.2\ Q/V_s \quad [12]$$

Table 9. Surface area requirements (SARs) of sediment basins (adapted from Goldman et al. (1986)).

Particle size		Settling velocity		SAR	
mm		ft/sec	cm/sec	ft^2 per ft^3/sec discharge	m^2per m^3/sec discharge
0.5	coarse sand	0.19	5.8	6.3	20.7
0.2	medium sand	0.067	2.0	17.9	58.7
0.1	fine sand	0.023	0.7	52.2	171
0.05	coarse silt	0.0062	0.19	193.6	635
0.02	medium silt	0.00096	0.029	1250	4101
0.01	fine silt	0.00024	0.0073	5000	16404
0.005	clay	0.00006	0.0018	20000	65617

In NC, the surface area of sediment basins is required to be 325 ft^2 per ft^3/sec (1427 m^2per m^3/sec discharge) to achieve more than 75 % of sediment removal efficiency on most soils (NCDENR, 2013). Corresponding particle size for 0.01 acre/cfs in Table 10 is close to 0.04 mm (40 µm), which has been adopted as a design particle size for sediment basins in NC with a minimum efficiency of 70 % during the 2-yr peak runoff event. Using the information in Figs. 24-28, Table 9 and Table 10, we compared simulated theoretical sediment removal efficiency between unflocculated and flocculated sediments as a function of surface area (SA) requirement for sediment basin (Figs. 29-33).

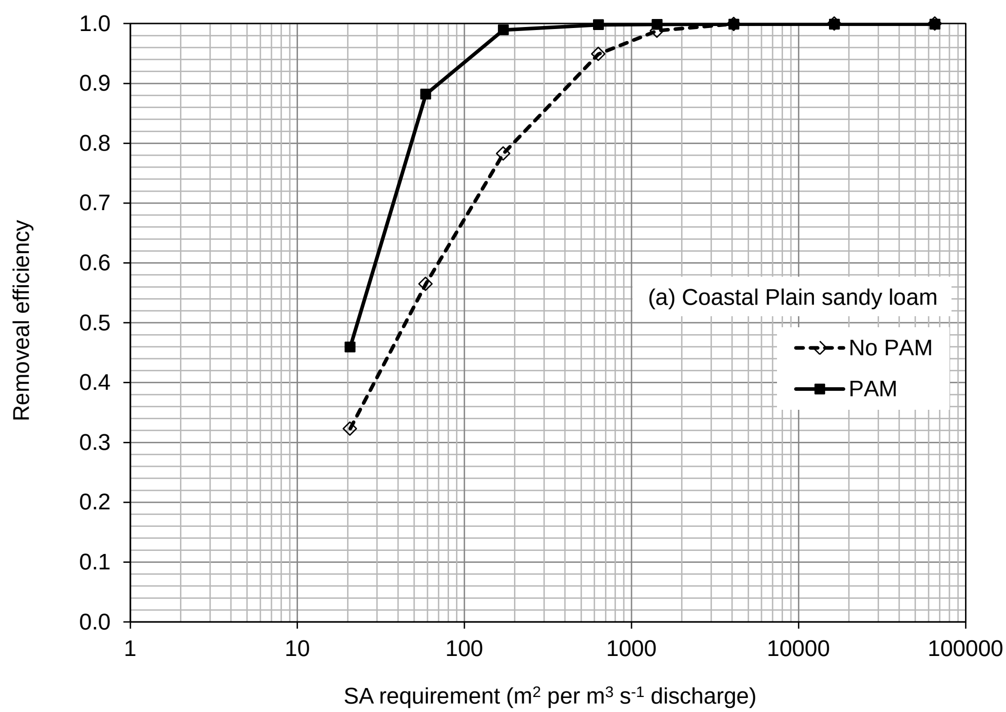


Figure 29. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Coastal Plain sandy loam as a function of surface area requirement.

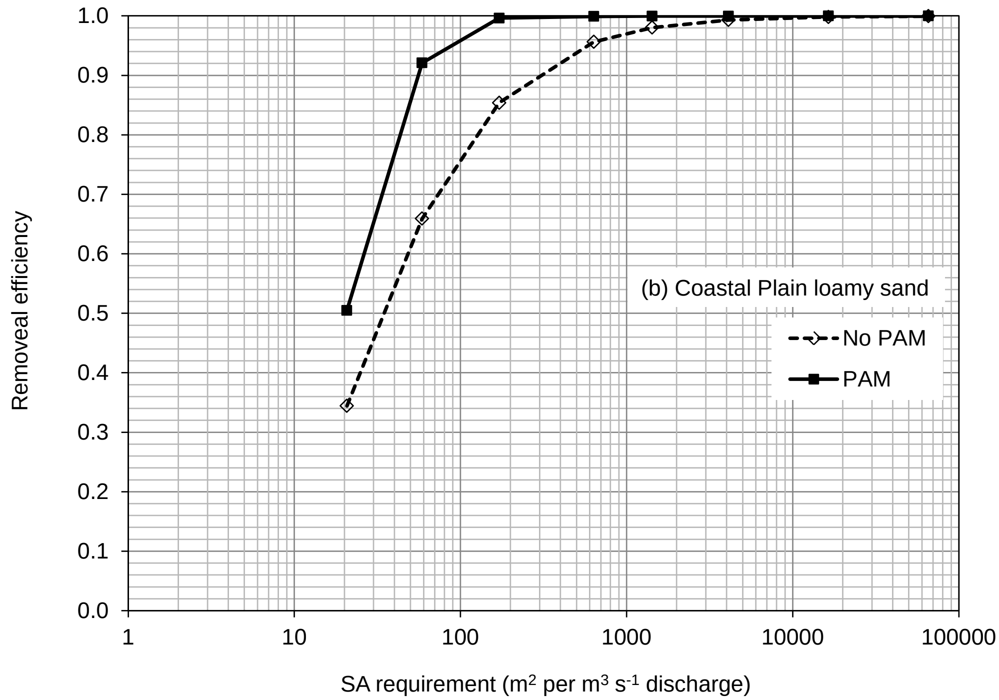


Figure 30. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Coastal Plain loamy sand as a function of surface area requirement.

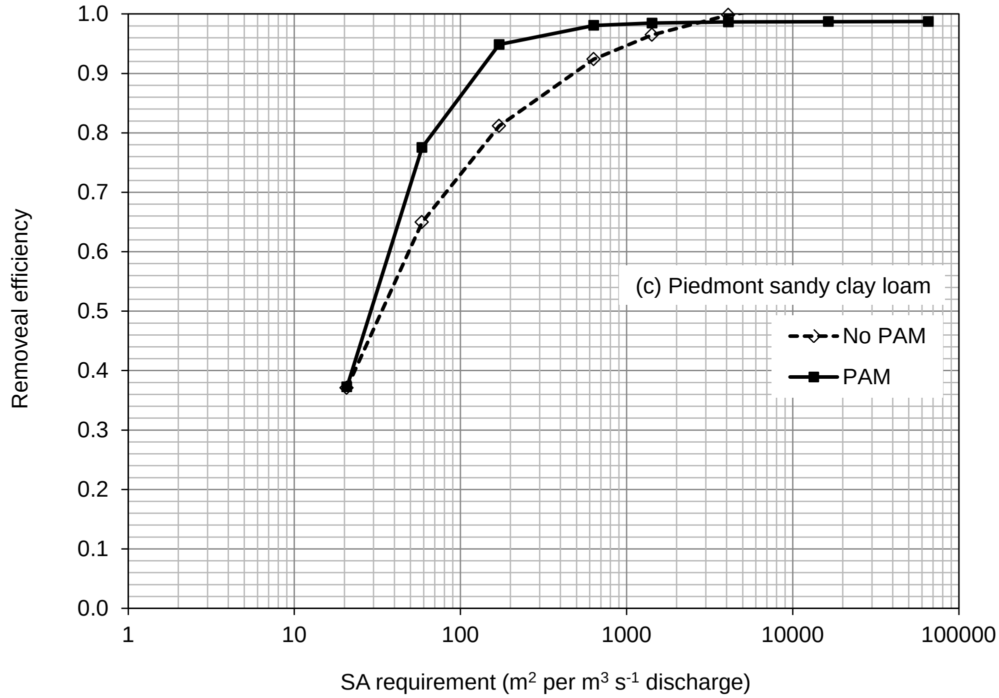


Figure 31. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated Piedmont sandy clay loam (PAM) as a function of surface area requirement.

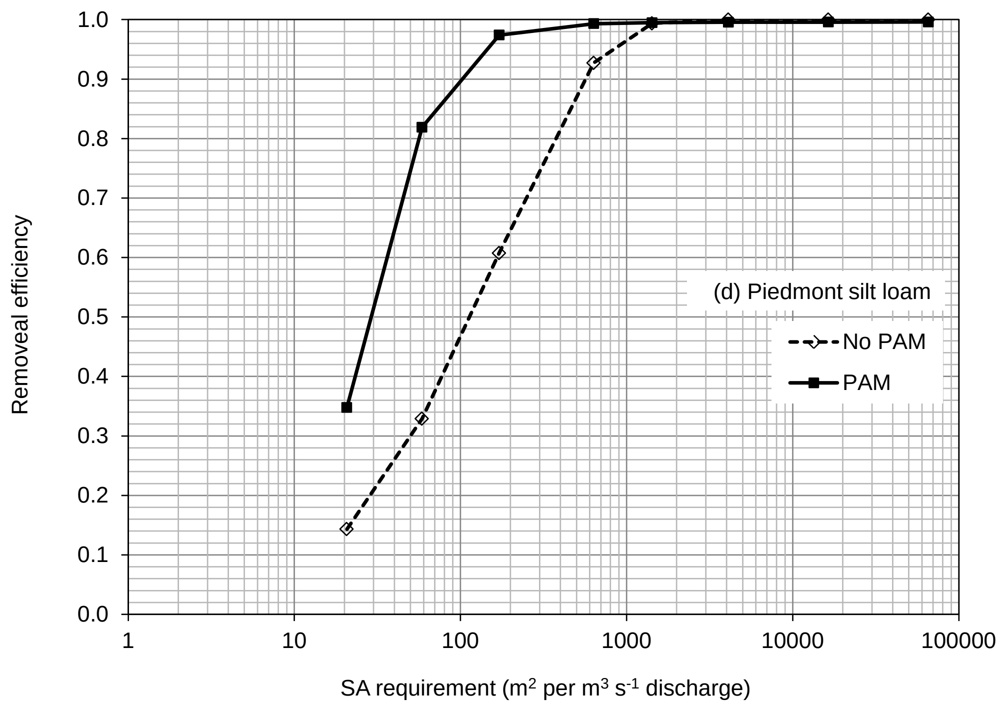


Figure 32. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Piedmont silt loam as a function of surface area requirement.

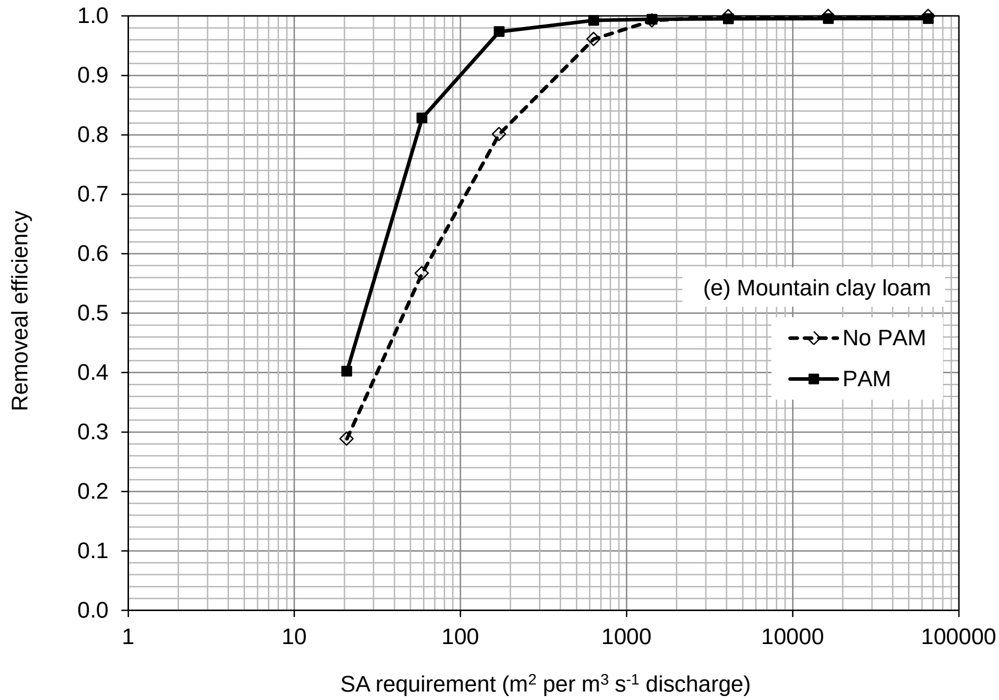


Figure 33. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Mountain clay loam as a function of surface area requirement.

Well flocculated sediment can result in substantially reduced SA requirements. For instance, in meeting 75 % of sediment removal efficiency, flocculated sediments required 2 to 4-fold less SA than those of unflocculated sediments. This relationship is critical in practical standpoint since the basins receiving flocculated sediment (refer to as "flocculated sediment basin" hereafter) could be reduced in size theoretically, taking up much less space in construction sites. Another aspect of flocculated basins is that they would require less detention time, which is closely related to the determination of basin surface area. When the sediment removal efficiency data are plotted with OFR or design settling velocity (V_o), flocculated sediment basins can increase their capability in treating 2 to 4-fold greater runoff volume than conventional sediment basins since they require less retention time (Figs. 34 - 38). The sediment removal efficiency data presented are likely to be useful as a reference in selecting right basin size for flocculated sediments.

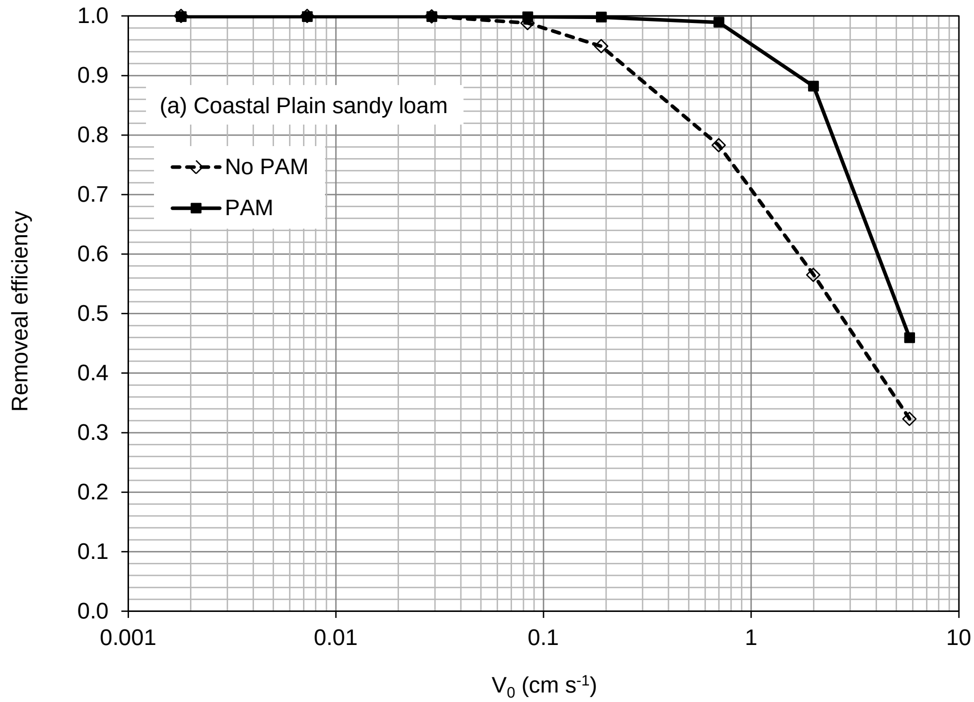


Figure 34. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Coastal Plain sandy loam as a function of design settling velocity (Vo = overflow rate).

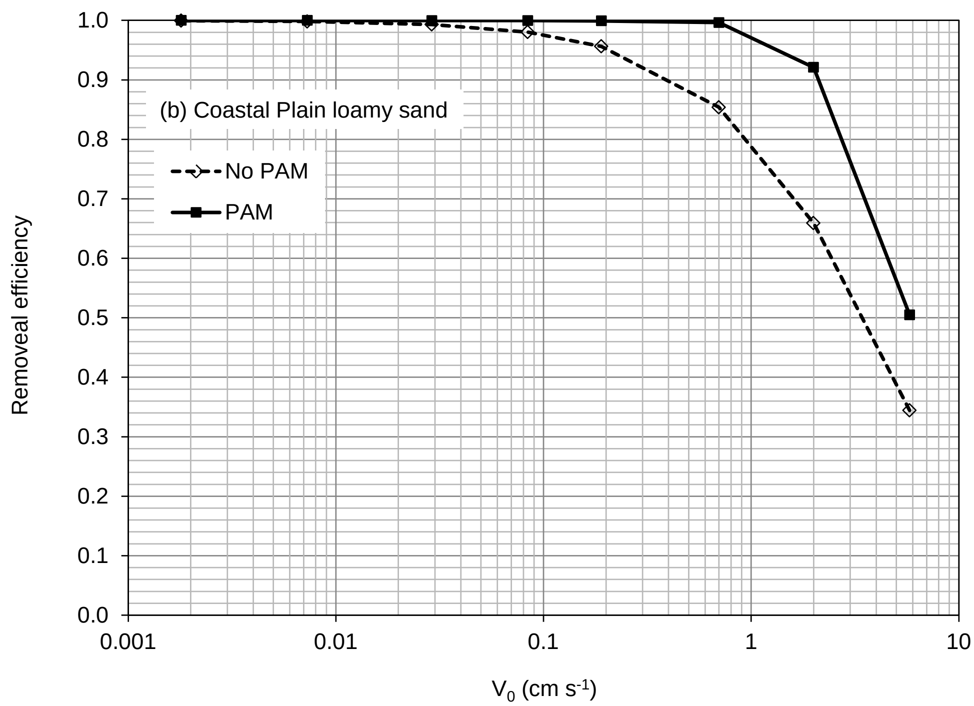


Figure 35. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Coastal Plain loamy sand as a function of design settling velocity (Vo = overflow rate).

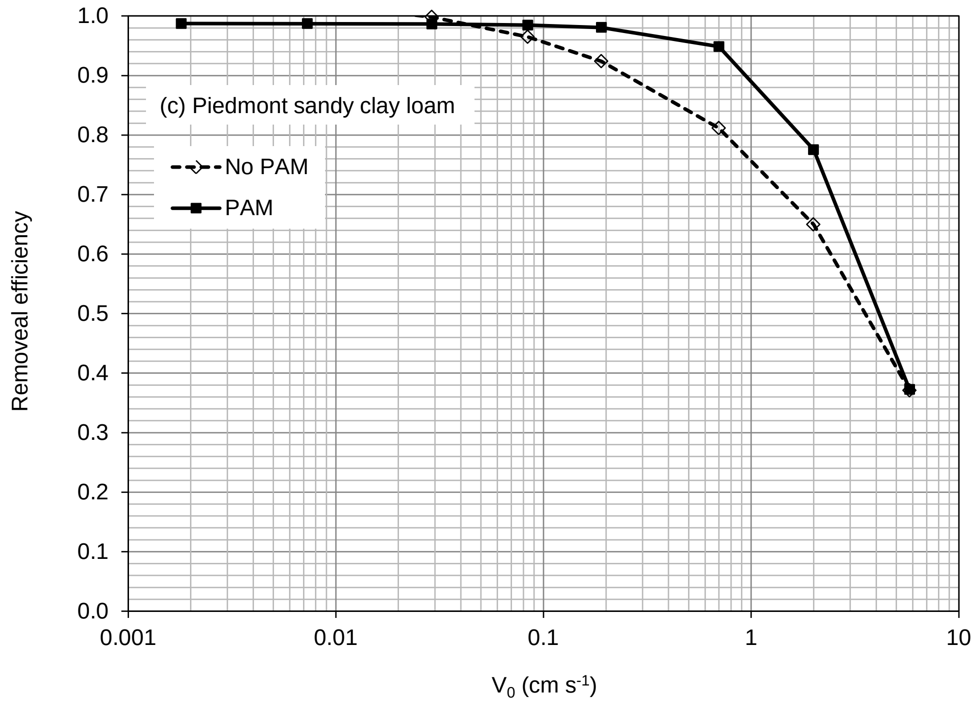


Figure 36. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Piedmont sandy clay loam as a function of design settling velocity (Vo = overflow rate).

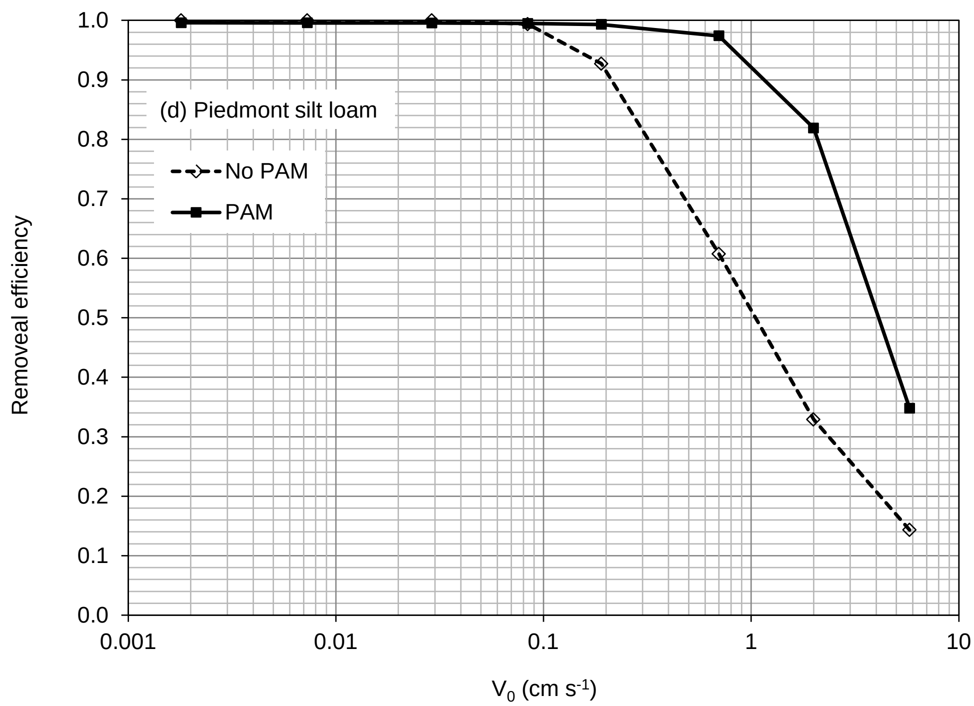


Figure 37. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Piedmont silt loam as a function of design settling velocity (Vo = overflow rate).

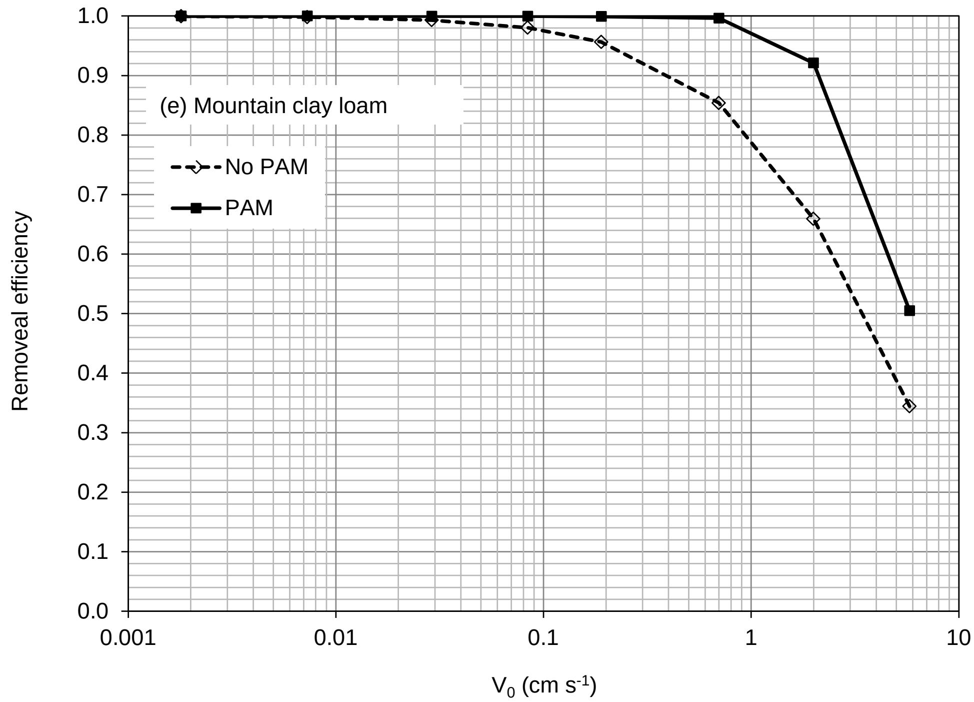
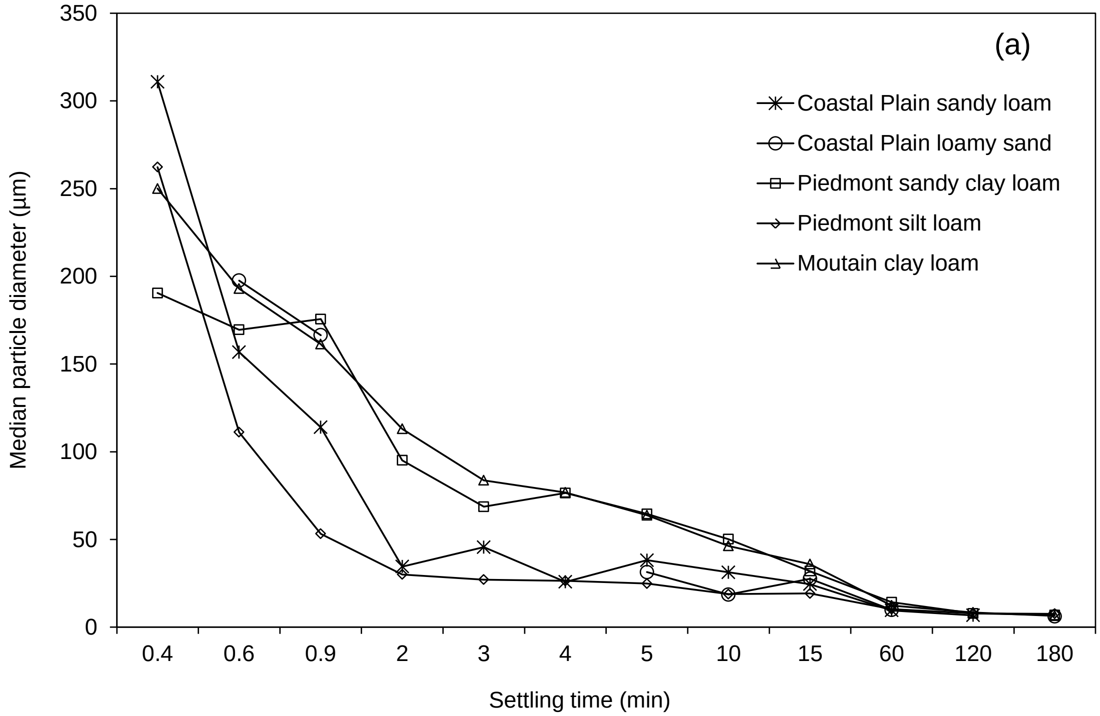


Figure 38. Simulated sediment removal efficiency between an unflocculated (No PAM) and flocculated (PAM) Mountain clay loam as a function of design settling velocity (Vo = overflow rate).

For the samples collected from the bottom of settling tube, particle size distribution was analyzed by a LD analyzer. Without PAM treatment, coarse particles (large mean diameter) traveled faster at the sampling port and there was continuous arrival of finer sediments over time (Fig. 39a). After the 1-h settling, the median particle diameters (D_{50}) were converged to 10 to 14 µm. The PAM treatment resulted in a fast removal of sediment from the water column, so after the 4-min mark there was not enough sediment to analyze for particle size distribution. Only the Coastal Plain sandy loam had enough suspended solids to analyze up to 4 min, most likely because the PAM did not flocculate this soil very well.



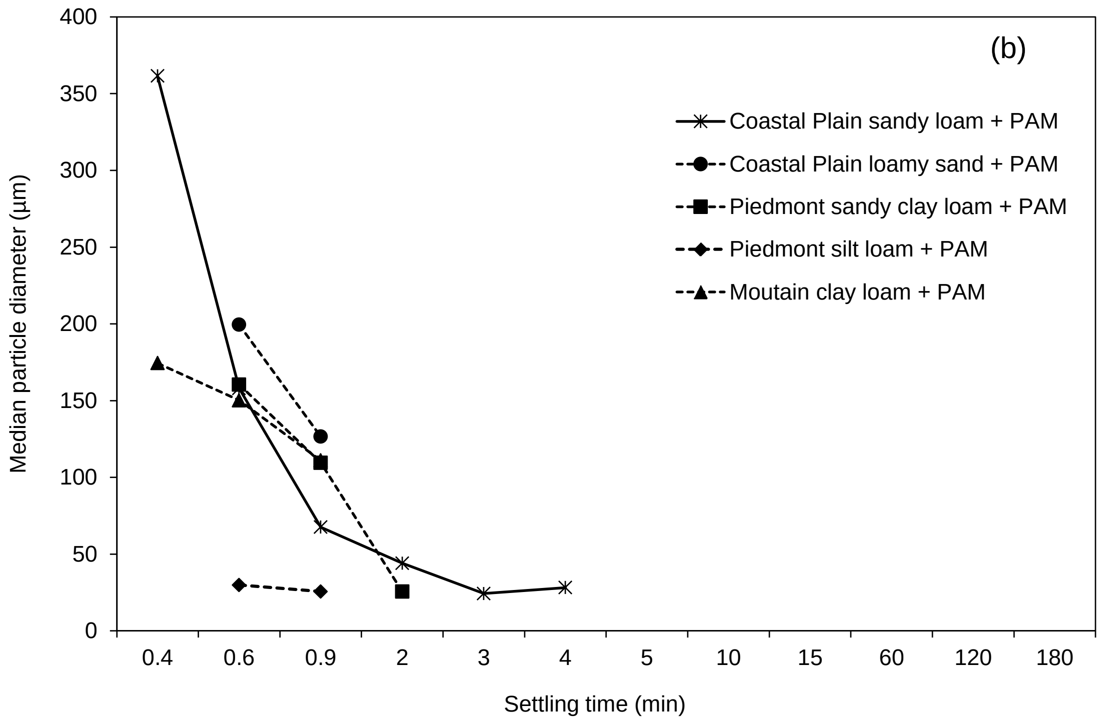


Figure 39. Comparison of mean particle diameter affected by polyacrylamide (PAM) treatment.

Summary and conclusions

Flocculated sediment tested with five different soil materials showed unique characteristics in their PSD and enhanced settling velocities in the settling tube experiments. To retain the current design for sediment capture, the surface area may be reduced by up to 2 to 4 times for well-flocculated sediment. Attaining good flocculation in the field has been demonstrated but only when the site is managed properly. Our simulated results on sediment removal efficiency and basin surface area requirement need to be validated in field-scale basin experiments to examine any interferences from flow regimes (e.g., turbulence) in the basin.

Ditch Tests

Turbidity

Two main treatments, PAM and event, significantly affected effluent turbidity while jute matting did not (Table 11). When averaged across three storm events, mean influent turbidity was 291 ± 11 NTU (mean ± std. error) and effluent turbidity varied from 96 to 298 NTU depending on treatments (Table 12). When comparing turbidity reduction between influent and effluent, PAM treatments reduced turbidity by 38 to 67 % depending on PAM formulations and applied areas. GPAM applied on jute matting performed the best (67 %) followed by GPAM applied on wattles with and without jute matting (58 to 60 %). The additional turbidity reduction with jute matting was likely to be attributable to the treated surface area where PAM molecules are attached to upon hydration. PAM granules applied on the weir of wattles had smaller surface area for the PAM molecules to attach to than those on jute matting. Without PAM treatment, there was no turbidity reduction regardless of the use of jute matting. This suggests that wattles and jute matting alone are not effective in reducing turbidity unless PAM is included. Note that this is under conditions where the only turbidity source is the water since the test ditch was lined with geotextile to prevent erosion. Previous work on construction sites demonstrated that wattles and lining greatly reduced turbidity by reducing ditch erosion (McLaughlin et al., 2009a).

Table 10. Significance of treatment main effects and interactions of PAM, jute matting, and storm events on runoff water quality.

	Pr > F	
Source	Turbidity	Total suspended solids
PAM	<0.0001	0.0058
Jute	0.9611	<0.0001
Storm	<0.0001	<0.0001
PAM × Jute	0.9719	0.0304
PAM × Storm	0.1389	0.3435
Jute × Storm	0.0821	0.8812
PAM × Jute × Storm	0.2712	0.6854

Table 11. Mean ditch effluent turbidity and total suspended solid (TSS) concentration averaged across three storm events and their reduction (%) relative to influent qualities.

	Turbidity		TSS	
Treatment	NTU[a]	Reduction %[b]	mg L^{-1}[a]	Reduction %[b]
No jute + No PAM	298 a	-2.5	1496 a	59.2
No jute + BPAM on wattle	179 b	38.5	1116 b	69.6
No jute + GPAM on wattle	115 c	60.4	1410 a	61.6
Jute + No PAM	298 a	-2.5	1198 b	67.4
Jute + GPAM on wattle	122 c	58.2	970 c	73.6
Jute + GPAM on jute	96 d	67.1	931 c	74.6

[a] Within a column, values followed by same letters are not significantly different ($P \leq 0.05$).
[b] Reduction % was calculated as [(influent – effluent)/influent × 100]. Negative % indicate a net increase in the water quality parameters (i.e., influent < effluent).

Overall, the passive dose of GPAM (96 to 122 NTU) outperformed that of BPAM (179 NTU) when examining the effluent turbidity between PAM treatments (Table 12). It is important to note that the BPAM treatment included only one block per wattle, sufficient for the lowest flow according to the manufacturer's recommendation (1 log/70 gallon min^{-1}), but at least 12 blocks would have been recommended for the peak flow. There were two observations which may also suggest issues with BPAM in this type of application. First, BPAM appeared to take longer to hydrate and start to release PAM compared to the GPAM. Secondly, the surface of BPAM tended to become coated with sediment over the course of several events, which reduced active surface for PAM to be dissolved into the runoff. On actual construction sites, we often observe that BPAM can be buried completely by sediment under high sediment loadings. We recommend that they be used in areas protected from heavy sediment such as in storm drains and slope drains with inlet protection to reduce sediment loads.

Effluent turbidity increased with successive events in all treatments (Fig. 40). Without PAM treatment, effluent turbidity during the first storm was < 250 NTU and it increased up to 350 NTU during the third storm. Such an increase was attributable to the continued sediment addition over storms and some scouring from accumulated sediment behind wattles and in the ditch bottom. Applying PAM reduced effluent turbidity as high as 84 % compared to no-PAM treatment during the first storm. BPAM performed well during the first two storms (<160 NTU), but during third storm its efficacy (272 NTU) was significantly lowered than GPAM (<188 NTU), indicating a limited dissolution of PAM in successive events. Within GPAM treatments, placing jute matting along with wattles provided additional benefits during the first two storms, but its efficacy was less during the third storm.

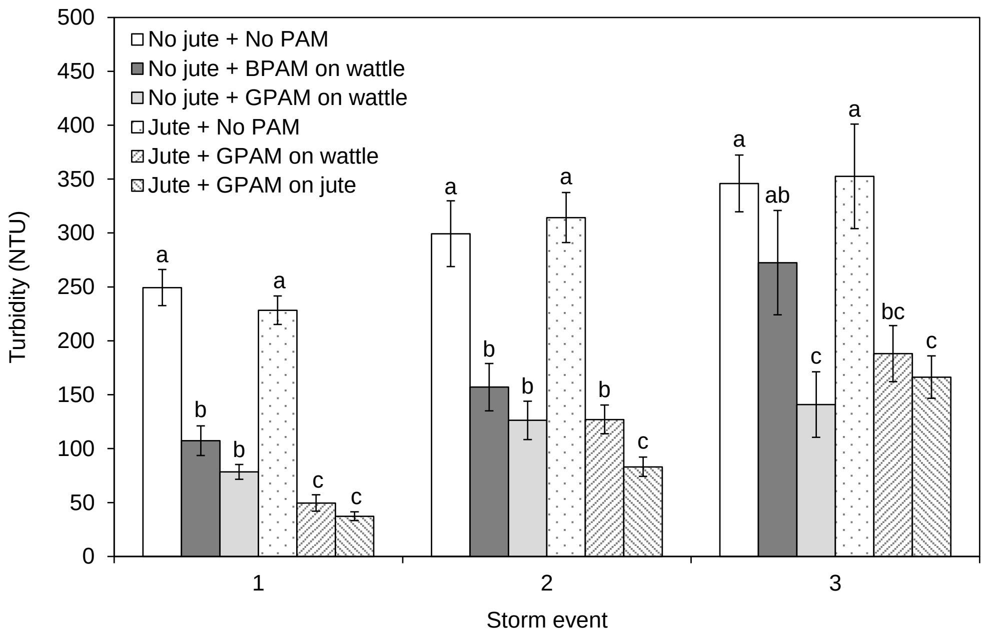


Figure 40. Mean turbidity in ditch effluents by storm events. BPAM is a solid block polyacrylamide (PAM) and GPAM is a granular PAM. Error bars represent standard error of the mean. Within a storm event, values followed by same letters are not significantly different ($P \leq 0.05$).

Total suspended solids

All three of the main treatments (PAM, jute, and storm) significantly affected TSS concentrations in effluent turbidity (Table 11). When averaged across three storm events, effluent TSS with no PAM ranged from 1198 to 1496 mg L^{-1} (Table 12), accounting for 59 to 67% reduction relative to influent TSS (3669 ± 150 mg L^{-1}). Adding jute matting was beneficial in reducing effluent TSS by 8 % in the untreated ditch test. Within PAM treatments, BPAM (1116 mg L^{-1}) performed better than GPAM in the absence of jute matting (1410 mg L^{-1}), but the use of jute matting with GPAM (< 970 mg L^{-1}) outperformed BPAM.

Similar to turbidity data, effluent TSS increased with successive storm events in all treatments (Fig. 41). TSS concentrations without jute matting showed that BPAM performed better than GPAM during first storm, but their difference was not significantly different afterward. Sediment accumulation and covering onto BPAM is likely to be attributable to the additional TSS reduction during the first storm, which, in fact, negatively affected the dissolution of PAM afterward. The use of jute matting improved overall sediment retention and the GPAM applied to jute matting performed the best during repeated storm events.

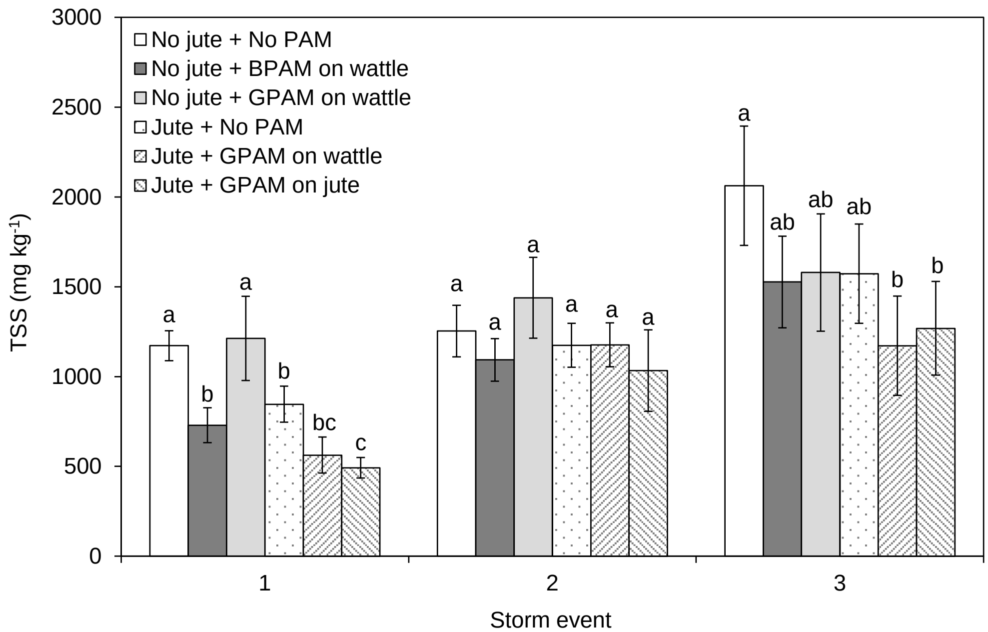


Figure 41. Mean total suspended solid (TSS) concentration in ditch effluents by storm events. BPAM is a solid block polyacrylamide (PAM) and GPAM is a granular PAM. Error bars represent standard error of the mean. Within a storm event, values followed by same letters are not significantly different ($P \leq 0.05$).

Characteristics of flocculated sediments

Figure 42 shows the relationship between TSS and turbidity in effluent samples. TSS concentrations and turbidity are common water quality parameters related to the amount of solids suspended in water, but the modes of quantification are different: TSS are determined by gravimetrically in solid mass per liter while turbidity is an optical property measured by the amount of light scattering as a function of the number of particles. The size, shape, composition and refractive index of particles are other factors which contribute to the amount of scattering (Sadar and Engelhardt, 1998). Turbidity has often shown a positive and linear correlation with TSS concentrations in natural waters (Earhart, 1984; Lewis, 1996; Pavanelli and Bigi, 2005), but it was not the case in this study. Our turbidity data are rather scattered and separated by the GPAM treatment within given TSS range ($R^2 = 0.22$). Various particle sizes and a wide range of TSS concentrations caused by repeated storm events and PAM treatments were likely to contribute to the lack of the linear relationship (Lowis, 1996; Hannouche et al., 2011).

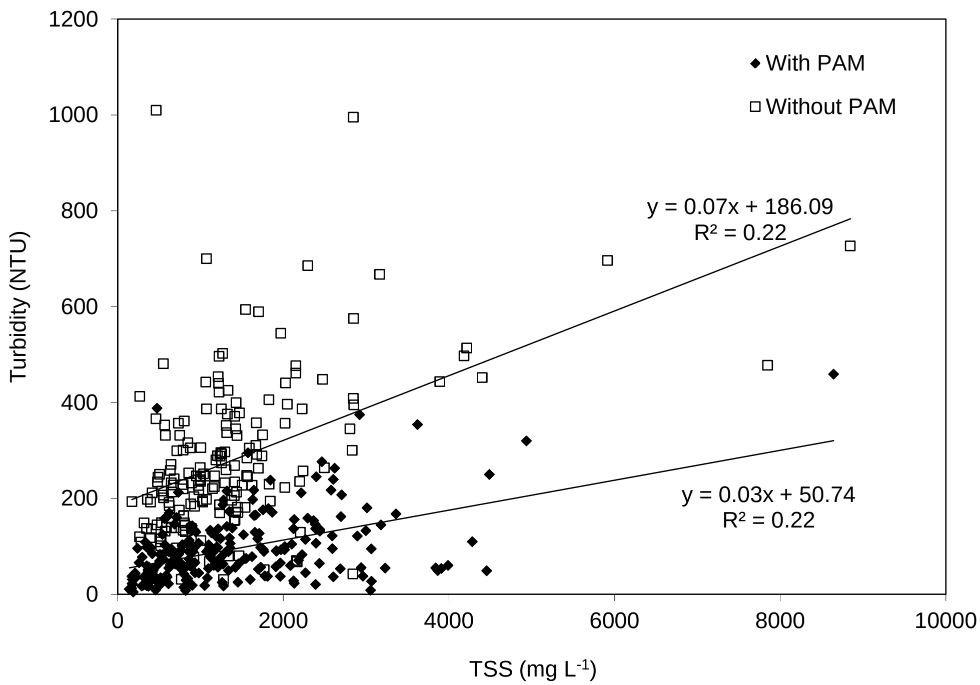


Figure 42. The relationship between total suspended solid (TSS) and turbidity in ditch effluents affected by granular polyacrylamide (PAM) treatment.

Our results infer a unique nature of flocculated sediments in the ditch effluent samples, showing lower turbidity in the similar TSS levels due to flocculation (Fig. 42). This explains why passive dosing of GPAM decreased effluent turbidity substantially, but not for the TSS. A comparison in volumetric particle size distribution between influent and effluent samples (Fig. 43) showed that GPAM treatment shifted particle size to coarser fraction with narrower size range and this is an indicative of particle size growth occurred as the stormwater flowed through. For example, when comparing median particle diameter (D_{50}), effluent sample from GPAM treatment (81 µm) was more than two-times greater than that of influent (33 µm).

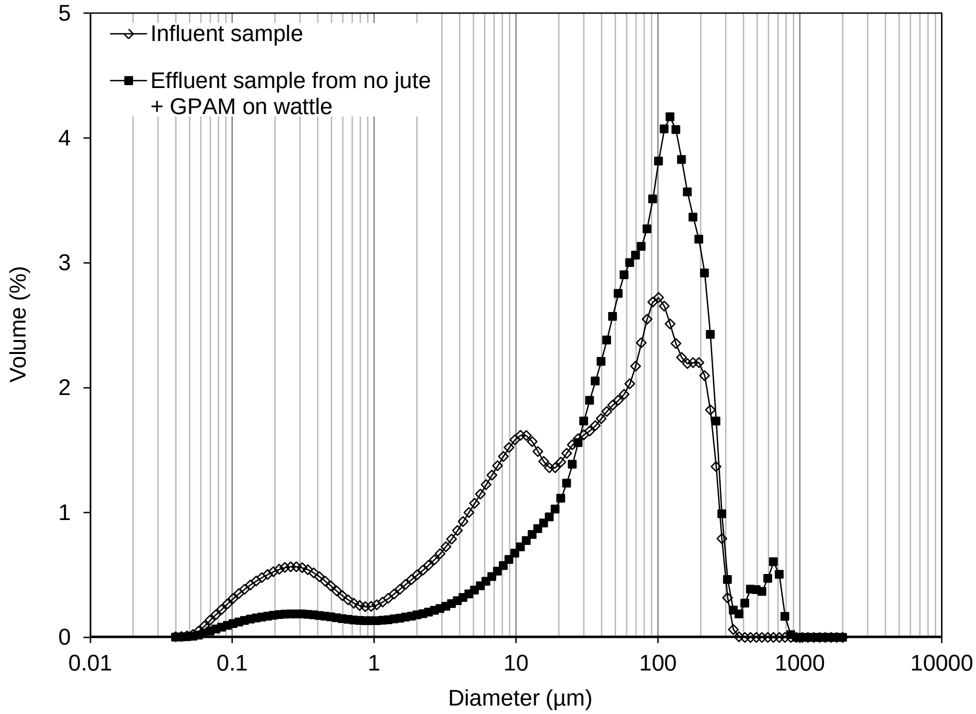


Figure 43. Change in volumetric particle size distribution before and after granular PAM (GPAM) treatment. Note a logarithmic scale on X-axis.

Volumetric particle size distribution between treatments showed that PAM treatment consistently increased the volume of sand-size fraction in the effluent samples as compared to untreated samples (Fig. 44). In particular, the effluents from GPAM treatment with jute matting contained the highest sand-size fraction in volume (> 87 %), which matched with the lowest turbidity reading (< 85 NTU). This is similar to turbidity removal efficiency by coagulation/flocculation processes in water treatment plant. For example, large compact flocs have higher settling rate, which in turn results in lower turbidity in treated water (Cheng et al., 2008). The effluents without jute matting showed relatively higher clay- and silt-size fraction, which resulted in greater turbidity (141 to 381 NTU) than those with jute matting. When compared by the values of D_{50}, GPAM applied on jute matting yielded the highest D_{50} (174 µm) in the effluent samples, which were about 10-fold greater than no PAM treatment without jute matting (Table 13). Diameters of the 10th percentile (D_{10}) and the 90th percentile (D_{90}) showed similar size growth by the PAM treatments as an indication of flocculation extent. The values of D_{10} (< 70 µm) was close to the particle size range contributing the most to turbidity (e.g., silt and clay; < 50 µm), and they were negatively correlated with turbidity in a logarithmic function (Fig. 45). This result emphasizes that removal silt- and clay-sized particles is a critical in reducing overall turbidity in construction site runoff (Przepiora et al., 1997).

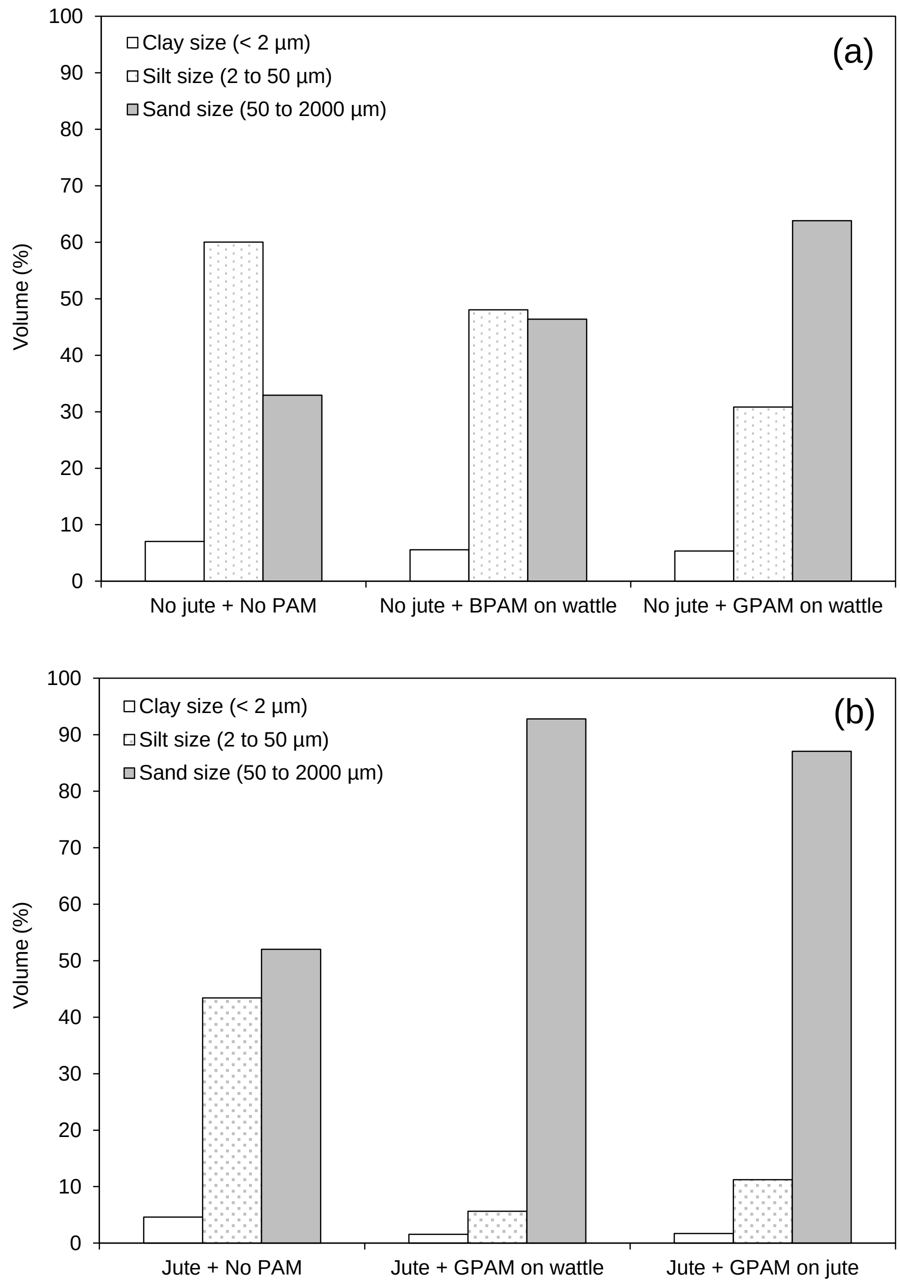


Figure 44. Volumetric particle size distribution in ditch effluents affected by polyacrylamide (PAM) application: (a) ditch with no jute matting and (b) ditch with jute matting. BPAM is a solid block PAM and GPAM is a granular PAM. The values in parentheses above bars are turbidity (NTU) and total suspended solid (mg L-1) in the sample.

Table 12. Summary of particle size distribution results in ditch effluent samples.

Diameter[a]	No jute + No PAM	No jute + BPAM on wattle	No jute + GPAM on wattle	Jute + No PAM	Jute + GPAM on wattle	Jute + GPAM on jute
	µm					
Mean	24.1	97.0	111.2	114.6	175.9	210.8
D_{10}	1.6	5.3	8.0	8.0	40.7	65.9
D_{25}	7.6	16.2	32.7	22.7	87.2	114.0
D_{50}	17.5	46.0	81.4	57.0	141.1	173.6
D_{75}	32.8	120.3	150.8	145.7	210.6	245.7
D_{90}	53.9	217.2	228.2	299.0	335.1	445.2

[a] D_{10}, D_{25}, D_{50}, D_{75}, and D_{90} are diameters corresponding 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentile, respectively, in volumetric particle size distribution.

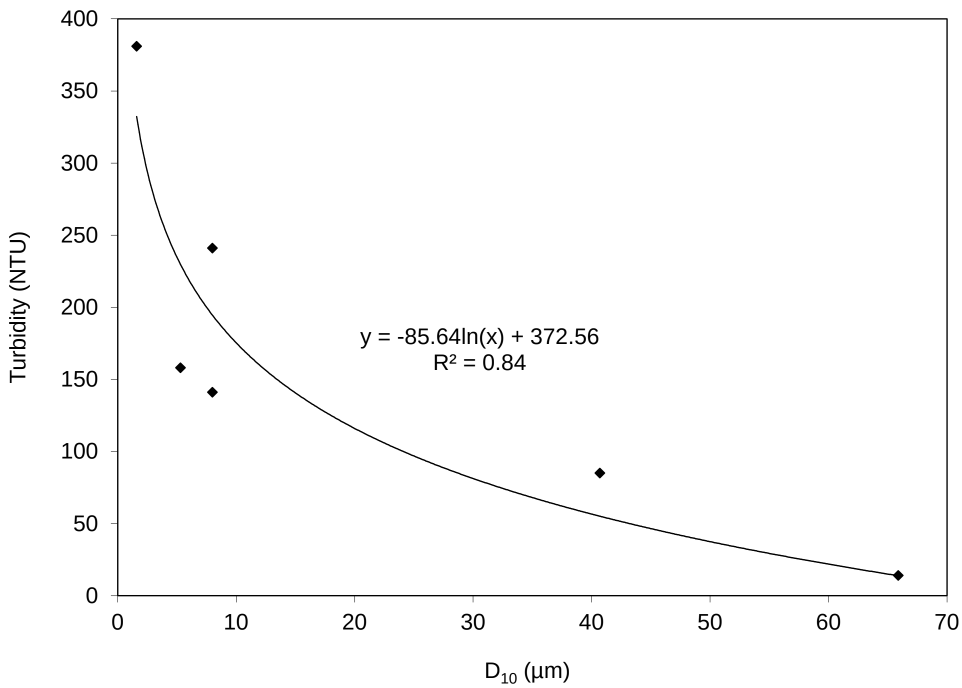


Figure 45. The relationship between particle size (10th percentile, D10) and turbidity in the ditch effluent samples.

Summary and conclusions

The major source of turbidity from construction- and development-related activities is fine suspended solids. These are so slow to settle that water containing them can remain turbid for days or weeks even if held in a settling basin. The passive dosing of GPAM on conventional fiber check dams or jute matting was a very effective system in controlling effluent turbidity. The use of BPAM for the ditch application was not as effective as GPAM but our tests did not include enough blocks to follow manufacturer recommendations at the highest flows. Sediment treated by the GPAM clearly were agglomerated and the aggregated flocs removed the fine sediments effectively out of suspension. This study suggests that construction site ditch with passive PAM dosing could be an effective turbidity control measure and perhaps facilitate subsequent settling of the flocculated sediments when conventional settling basins are in place.

Basin Design

Turbidity and TSS

The turbidity and TSS concentration in the ditch entrance varied considerably among tests due to the heterogeneity of the sediment being added. On average of three replicated trials, influent turbidity entering into the ditch was 291 ± 11 NTU (mean ± std. error) while the TSS was 3669 ± 150 mg L^{-1}. To compare the effects of PAM and basin geometry at the downstream sampling locations, turbidity and TSS data were normalized to the influent qualities (Fig. 46). As a combined sediment control system, most of TSS reduction (> 60 %) occurred at the ditch and turbidity reduction was dependent on the ditch PAM treatment. At the ditch exit, PAM treatment significantly affected turbidity while it was not a significant factor for TSS. For instance, turbidity at the ditch exit showed limited reduction without PAM treatment (<10 %) compared to those with PAM treatment (> 66%), suggesting that PAM treatment is essential step in removing turbidity at the ditch (Fig. 46). All ditch exit samples following the PAM treatment showed mean turbidity less than 100 NTU (Table 14). The effect of PAM treatment was not significant in reducing TSS at the ditch exit, accounting for > 67 % relative to influent regardless of PAM treatment. However, PAM significantly reduced TSS at the basin outlet for each of the three configurations.

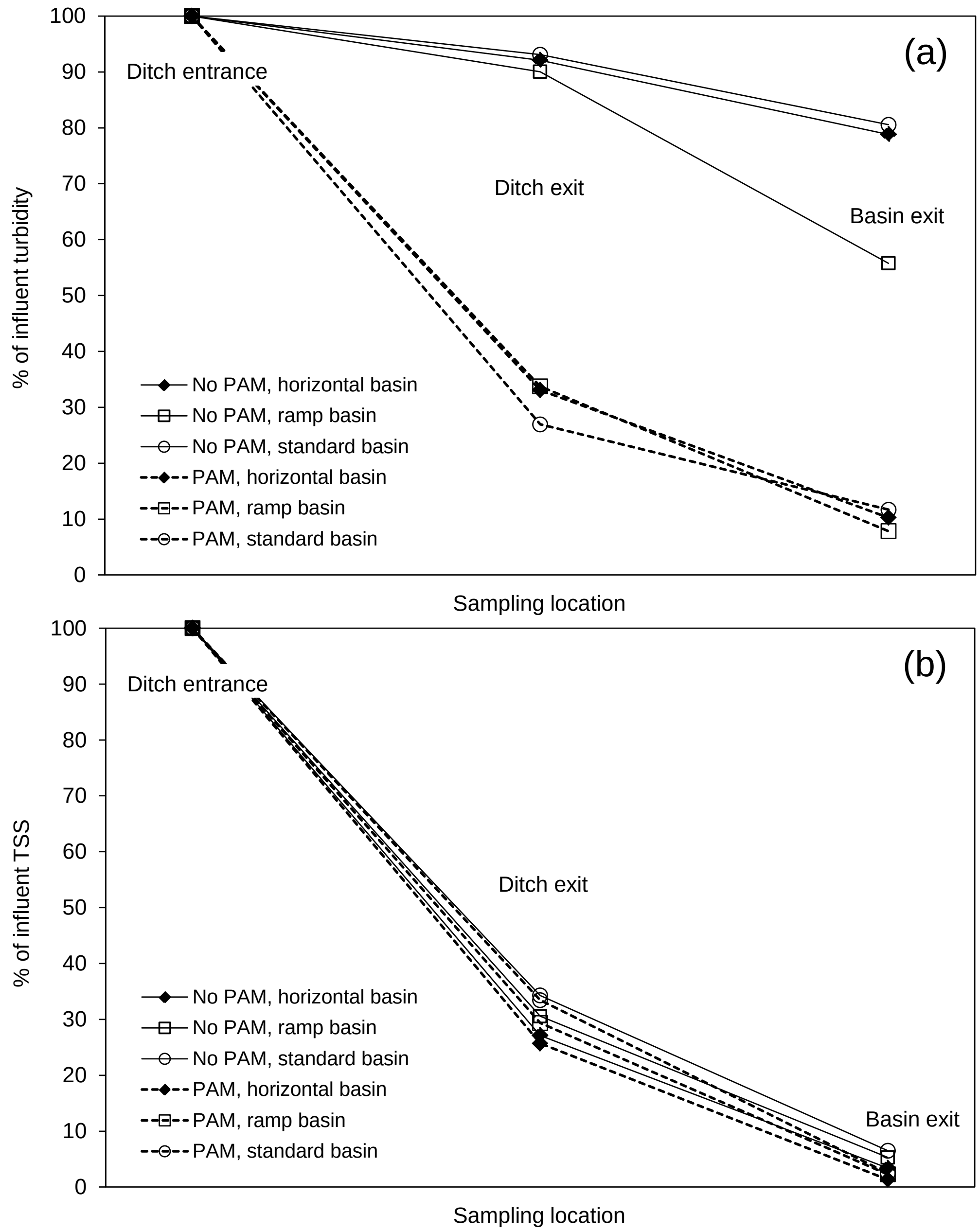


Figure 46. The effects of polyacrylamide (PAM) treatment and basin geometry on water quality: (a) turbidity and (b) total suspended solid (TSS) concentration.

Table 13. The effects of polyacrylamide (PAM) application and sediment basin geometry on turbidity and total suspended solid (TSS) concentrations in the water samples collected at ditch and basin exit.

		Turbidity (NTU)		TSS (mg L^{-1})	
PAM	Basin	Ditch exit	Basin exit	Ditch exit	Basin exit
None	Horizontal	268 ± 25 a	229 ± 27 a	995 ± 79 a	125 ± 3 b
None	Ramp	262 ± 24 a	162 ± 19 a	1121 ± 122 a	195 ± 14 a
None	Standard	271 ± 21 a	234 ± 22 a	1258 ± 107 a	239 ± 30 a
PAM	Horizontal	96 ± 20 b	30 ± 5 b	943 ± 84 a	49 ± 5 c
PAM	Ramp	98 ± 14 b	23 ± 4 b	1078 ± 80 a	84 ± 7 bc
PAM	Standard	78 ± 18 b	34 ± 5 b	1228 ± 78 a	91 ± 13 bc

We observed that the exit flow at the sediment basin began to overflow at 16 to 19 min once turbid water was introduced into the ditch. The results of ANOVA (Table 15) showed that both PAM and basin geometry significantly affected TSS at the basin exit while turbidity was only affected by PAM treatment. In the basin exit samples, there was a clear separation by PAM treatment for turbidity reduction (> 88 %) similar to its influence on the ditch exit samples (Fig. 47). Up to 90 % turbidity reduction was achievable in the basin exit when check dams were treated with granular PAM prior to entering into the sediment basin. The basin geometry was a not significant factor in controlling turbidity in flocculated sediment. With PAM treatment, the basin exit turbidity was maintained below 50 NTU regardless of the basin geometry (Fig. 47). However, the horizontal design resulted in significantly lower TSS when no PAM was applied to the check dams. In absolute terms, horizontal basin yielded the lowest TSS concentration (49 mg L^{-1}), followed by ramp (84 mg L^{-1}) and standard (91 mg L^{-1}) basins when PAM was applied to check dams (Table 14).

Table 14. ANOVA significance of treatment main effects and interactions of PAM and basin geometry on runoff water quality of basin exit samples.

	Pr > F	
Source	Turbidity	Total suspended solid
PAM	<0.0001	<0.0001
Basin	0.6161	0.0424
PAM × Basin	0.2448	0.1539

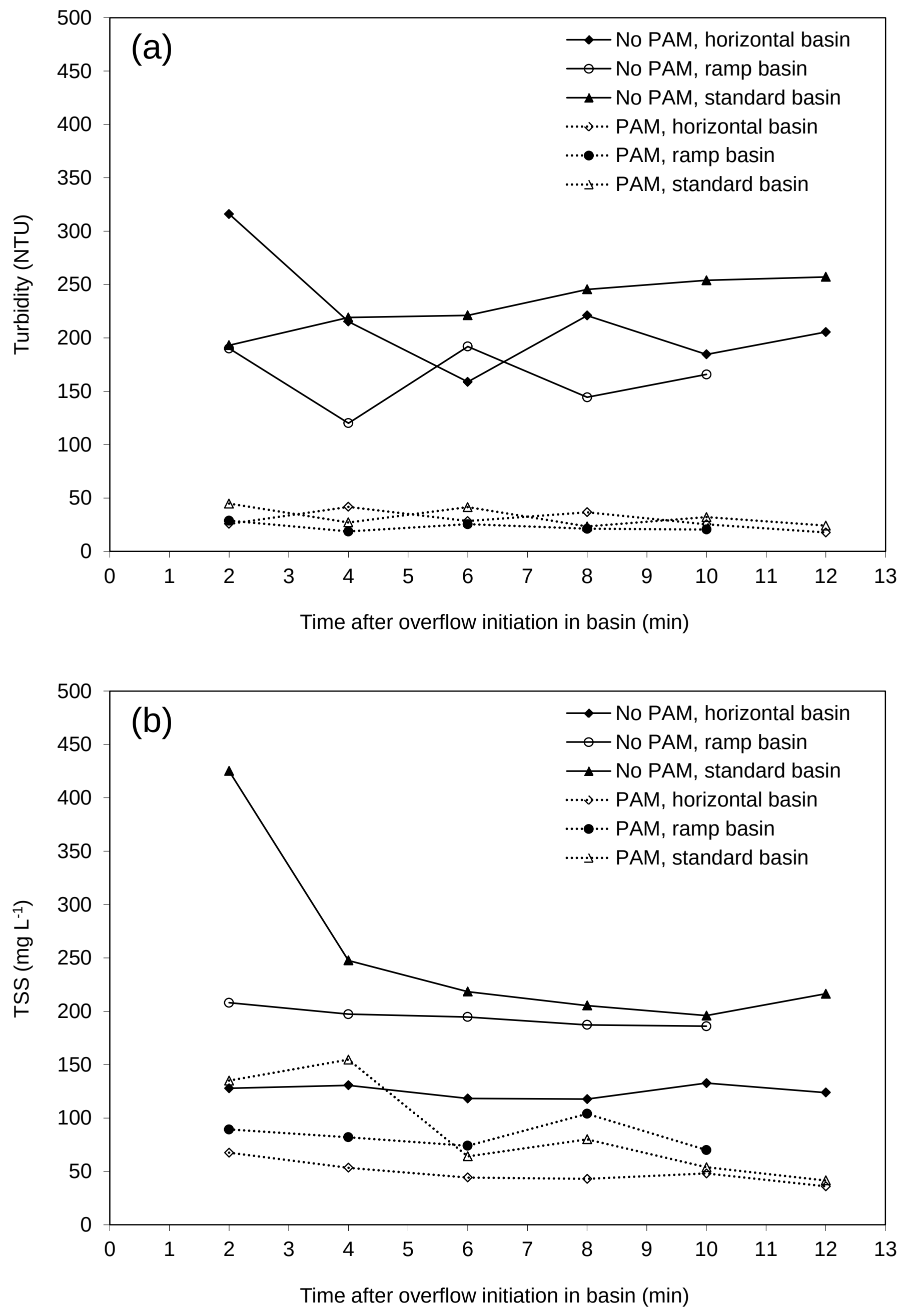


Figure 47. Basin effluent qualities affected by polyacrylamide (PAM) treatment and basin geometry: (a) turbidity and (b) total suspended solid (TSS).

Characterization of particle size distribution

In the design of sediment control measures, it is important to know how particle size distribution changes as sediment moves downstream or after significant deposition has occurred (Haan et al., 1994). Figure 48 shows the volumetric percentile of suspended sediments (% finer by volume) as a function of particle diameter at different sampling locations without PAM treatment. From both standard and horizontal basin tests, it was obvious that overall particle size decreased in order as the influent turbid water ran through check dams and sediment basin. For example, mean particle size diameter (91-99 µm) at the ditch entrance decreased to 73-78 µm at the ditch exit and 27 µm at the basin exit. When comparing the diameter of the 90th percentile in volume (D_{90}), check dams captured coarse- and medium sand-sized particles (>200 µm) and sediment basin retained down to coarse silt-sized particles (50 µm) in both basin geometries. It was also notable that as the extent of particle size difference by sampling locations became less at the smaller volume fraction (e.g., $D_{10}<D_{25}<D_{50}$). These results suggest that the sediment basin receiving unflocculated sediment is not effective enough to settle medium silt or finer clay particles (< 50 µm).

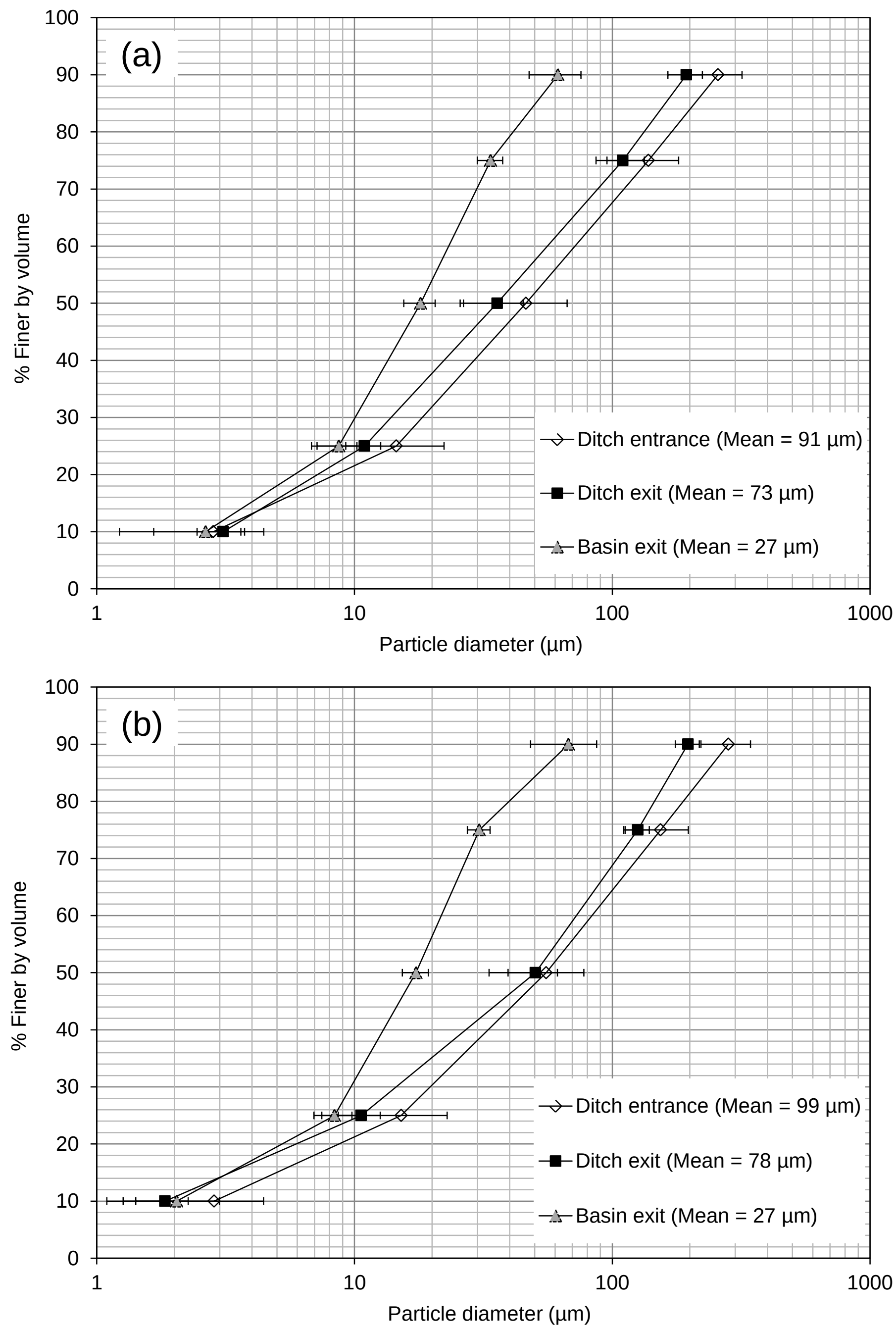


Figure 48. Particle size distribution curves of the suspended solid samples from ditch entrance, ditch exit, and basin exit without PAM treatment: (a) standard basin and (b) horizontal basin. Horizontal error bars represent standard error of the mean (n = 6). Mean diameters are given in figure legends.

Figure 49 shows the particle size distribution curves at the ditch exit samples affected by the ditch PAM treatment under standard basin tests. Flocculated sediments by PAM showed an increase in particle size particularly at D_{50}. This indicates that fine suspended particles were agglomerated into larger sizes by the flocculation, shifting overall particle size into coarser fraction. Particle size analysis for the basin exit samples with PAM treatment could not be run as there were not enough suspended solids to be analyzed. The laser particle size analyzer used in this study required a minimum 70 to 90 mg of suspended solid sample in 10 mL of water (Leithhold, L., personal communication, Nov 16, 2012). Turbidity and TSS data at the basin exit following the ditch PAM treatment indicated that most of suspended solids entered into the sediment basin were retained effectively, maintaining the TSS below 155 mg L^{-1} and turbidity below 45 NTU regardless of basin geometry (Fig. 50).

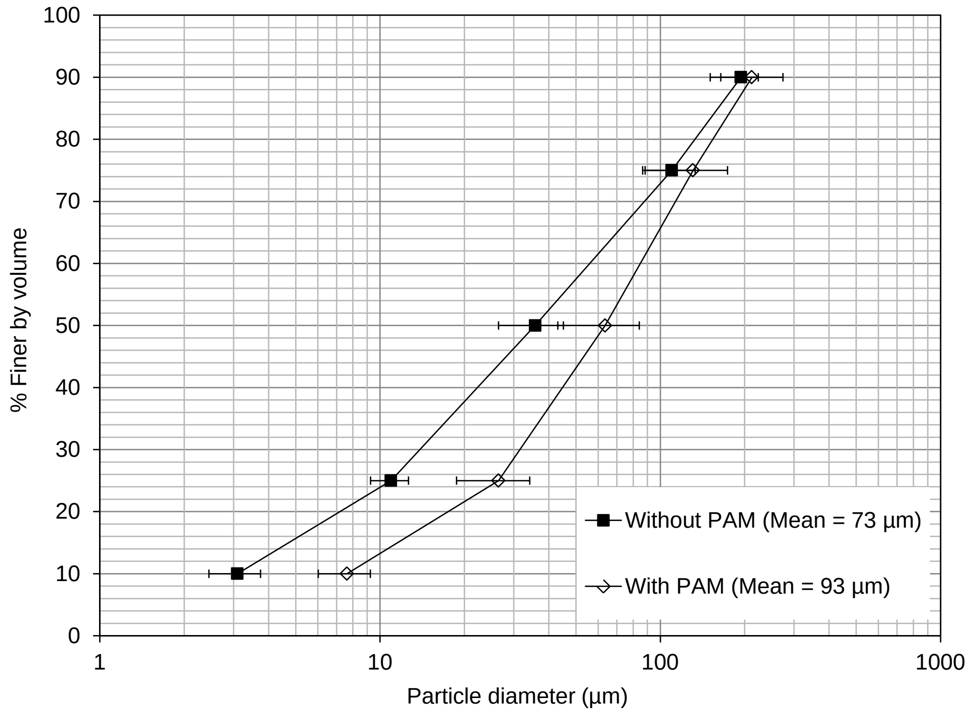


Figure 49. Particle size distribution curves of the suspended solid samples from ditch exit in the standard basin tests with and without polyacrylamide (PAM) treatment. Horizontal error bars represent standard error of the mean (n = 6). Mean diameters are given in figure legends.

The relationship between TSS and turbidity at the ditch exit samples confirmed that flocculated sediments by PAM were settled relatively well during our turbidity measurement that was taken after 30 s of settling (Fig. 50a). This result explains the reason why the PAM treatment reduced ditch exit turbidity substantially, but not for TSS. Turbidity has often shown a positive linear correlation with TSS concentrations in natural waters (Earhart, 1984; Lewis, 1996; Pavanelli and Bigi, 2005) and construction sediment basins (McCaleb and McLaughlin, 2008), but it was not the case in this study. Clearly the turbidity data at the ditch exit were separated by the PAM treatment with given TSS range, demonstrating a unique characteristic of flocculated sediments. Such a relationship was also found in the basin exit samples (Fig. 50b), suggesting that unsettled flocculated sediments existed in the basin exit samples in some extent.

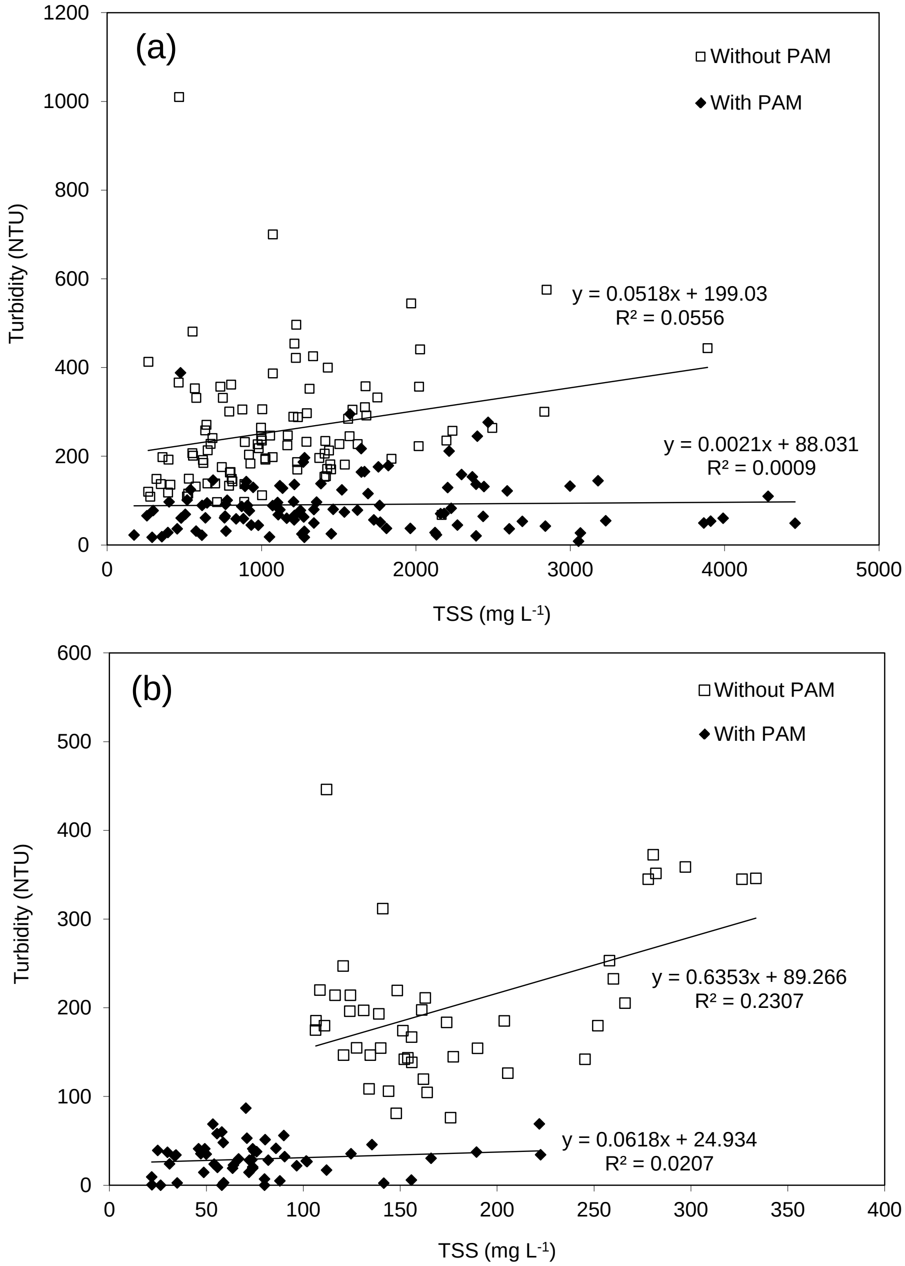


Figure 50. The relationship between total suspended solid (TSS) and turbidity with and without polyacrylamide (PAM) treatment: (a) ditch exit samples and (b) basin exit samples.

Implications on sediment basin size

The trapping efficiency of a basin is a function of the particle size distribution of the inflowing sediments, flow velocity, and basin size (Goldman et al., 1986). Under an ideal settling condition where a flow Q enters a basin of settling depth D, width W, and length L, a particle will travel horizontally at Q/WD (= 0.14 m s^{-1}) and will fall at a vertical velocity of V_s that is specific for each particle size: Q = 0.057 m^3 s^{-1} in maximum flow, W = 9 m, and L = 4.5 m at the standard basin geometry of this study. The basin surface area (A_s) can be estimated as a function of Q and V_s assuming a surface area adjustment factor of 1.2 (Mills and Clar, 1976; Goldman et al. 1986):

$$A_s = 1.2\ Q/V_s\ [1]$$

The eq.[1] defines the relationship between particle size to be captured and the surface area required for the basin. Using eq.[1], the V_s for the basin was estimated by 1.2 Q/A_s (= 0.0017 m s^{-1}) (Table 14). This means in theory the sediment basin used in this study can retain particles with the V_s equal to greater than 0.0017 m s^{-1} on the assumptions that it was designed in all key aspects (geometry, outlet location, rise design, etc.). By applying eq.[1] with the settling velocities V_s of various particle sizes, Goldman et al. (1986) calculated surface area requirements of sediment basins, which are plotted in Fig. 51. This figure clearly shows that the surface area required increases dramatically as the design particle size decreases to finer sizes in a logarithmic scale.

Our results demonstrated that the granular PAM applied to the check dam can lead flocculation reaction with sediment in runoff and shift overall particle size to coarser fraction before entering into a sediment basin. These results in addition to water quality benefits implied that sediment basin receiving flocculated sediments can be reduced in size. For instance, we interpolated particle diameter (46 µm) and surface area requirement (700 m^2 per m^3 s^{-1}) based on the V_s of 0.0017 m s^{-1} (Fig. 51). The estimated particle diameter of 46 µm was similar to the recommended design particle size (40 µm) for the sediment basins in NC (NCDENR, 2013) and the estimated surface area (700 × Q = 39.9 m^2) was close to actual surface area (40.5 m^2) employed in this study. By interpolation, the particle diameter of 46 µm corresponded to about 60th percentile (D_{60}) in the particle size distribution curve in the ditch exit samples without PAM treatment. At the same 60th percentile, flocculated sediments at the ditch exit showed increased its D_{60} at 74 µm (Fig. 51). When estimating surface area requirement with the flocculated sediment at D_{60} (74 µm), the surface area requirement decreased down to 400. This is translated that in absolute term unflocculated sediment required 40 m^2 of surface area while only 23 m^2 of surface area was required for flocculated sediment, reducing its surface area by 42 %. Smaller basins that perform nearly as well as large basins are likely to reduce construction costs by lowering installation costs, reducing the impact on construction activities, allowing placement within a right-of-way, and making it easier to access for maintenance.

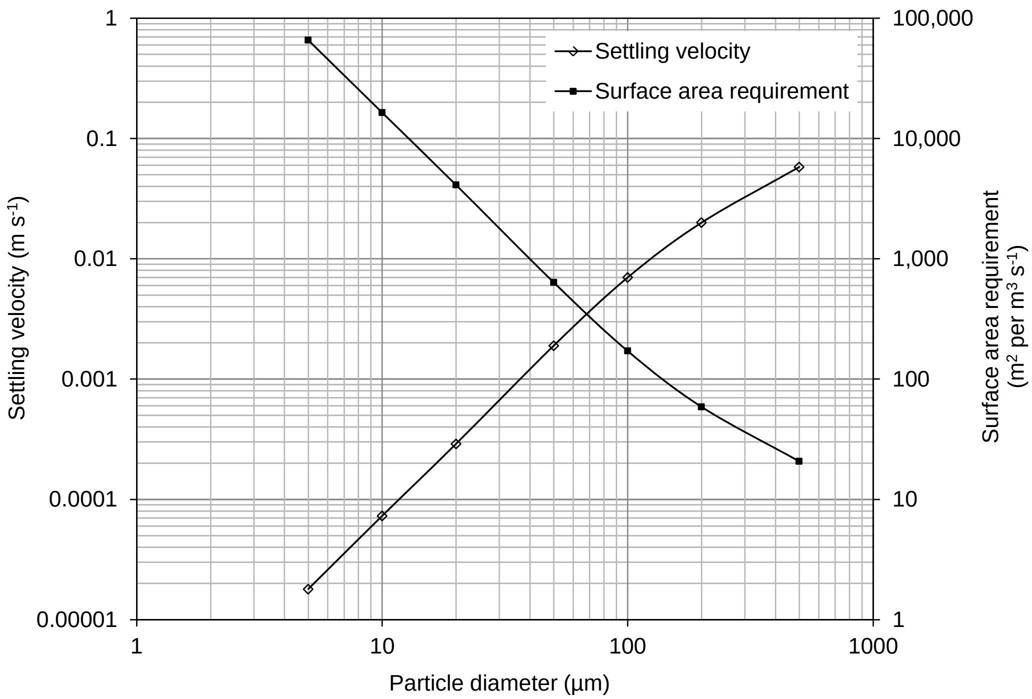


Figure 51. Surface area requirement (area to volumetric flow rate) of sediment traps and sediments as a function of particle size and settling velocity. Data were adapted from Goldman et al. (1986).

Summary and Conclusions

Our study showed that check dams could be effective in capturing coarse sediments, but the successful turbidity reduction requires a chemically-assisted settling of suspended particle through check dams and sediment basin. Within a sediment control system consisting of check dams + sediment basin, check dams functioned as a PAM-treatment zone by releasing PAM molecules and flocculating sediment, resulting in an increase in overall particle sizes. For the sediment basins receiving flocculated sediment, there was enhanced particle settling, lowering final effluent turbidity and TSS at given same retention time compared to those with unflocculated sediments. Our study suggests that granular PAM on check dams in construction ditches, often referred to as a passive treatment, could be effective measure in improving effluent quality from construction sites as well as in reducing and altering basin size and design economically.

<u>Field Tests</u>

Table 16 shows a summary of the monitoring periods and run-off events that were sampled at each site. Between 12 and 15 storms were monitored and more than 150 samples were collected at each of the sites. The range of rainfall at each site was similar with monitored storms ranging from very small storms (2-3 mm or 0.08-0.16 in) to storms that recorded 36 mm (1.4 in) or more of rainfall. At least half of the monitored storms at each site were greater than 13 mm (0.5 in) in rainfall.

Table 15. Summary of run-off events that were sampled during the monitoring period

	Location		
	Goldsboro	Statesville	Rolesville
Monitoring Period	9/2012 - 7/2013	2/2013 -5/2013	3/2012 - 8/2012
Total Run-off Events Sampled	15	12	12
Total Entrance Samples Collected	222	71	127
Total Exit Samples Collected	113	148	39
Rainfall Range (mm)	4 - 36	2 - 36	3 - 45

Water Quality

Figure 52 shows mean values of turbidity and Figure 53 shows mean values of total suspended solids (TSS) sampled at the entrance and exit of the sediment basins during the sampling period at each site. The sampling period was separated into two groups, samples obtained before the application of PAM (pre-PAM) and samples obtained after the application of PAM (post-PAM).

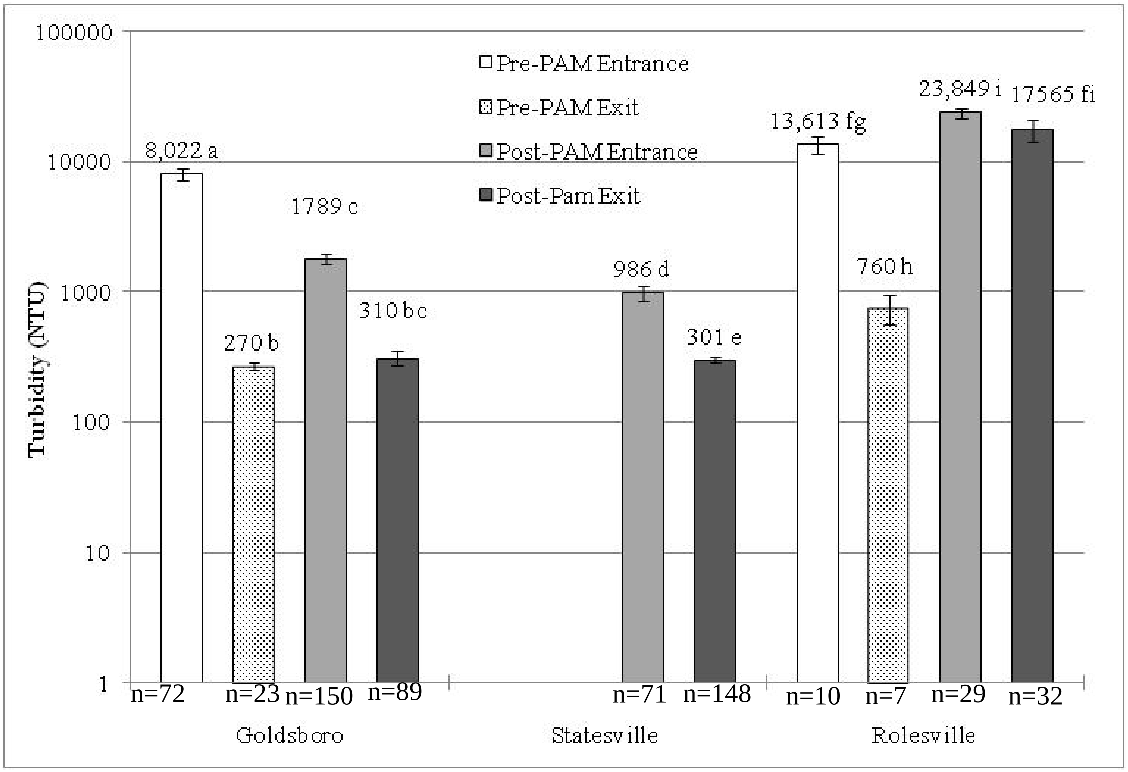


Figure 52. Mean turbidity for pre-PAM and post-PAM monitoring periods at the entrance and exit of each site's sediment basin

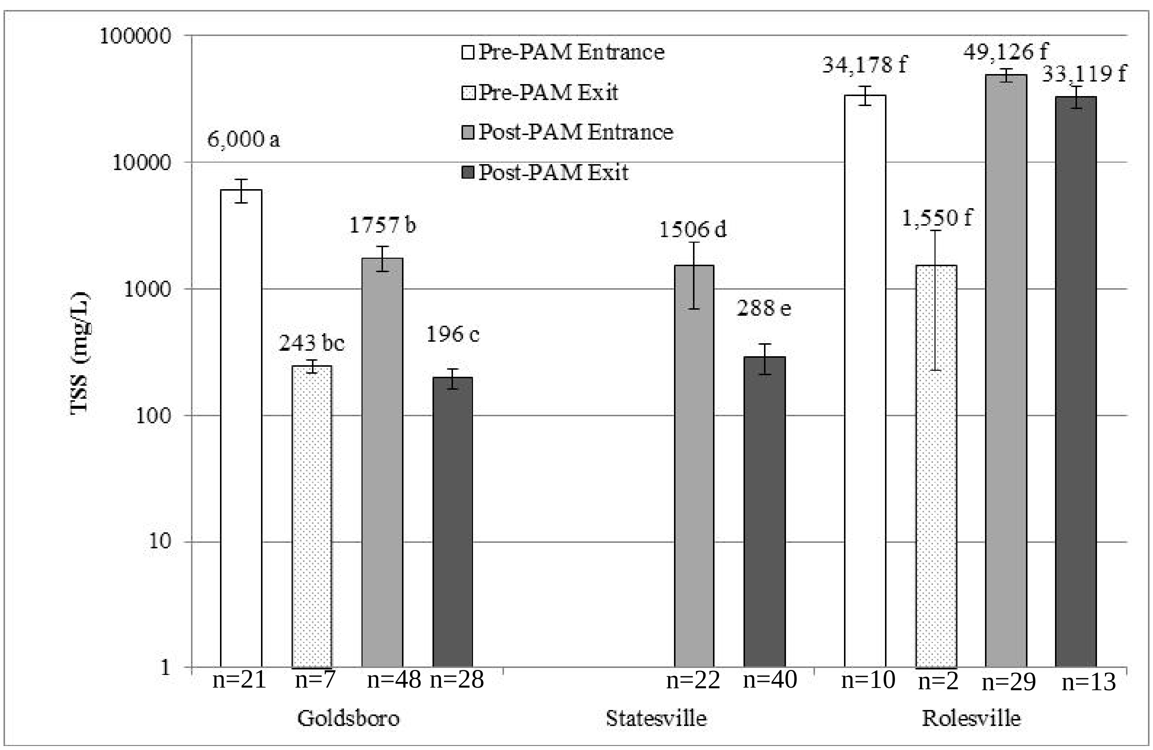


Figure 53. Mean TSS for pre-PAM and post-PAM monitoring periods at entrance and exit of each site's sediment basin

At the Goldsboro site, mean turbidity was significantly reduced between the entrance and the exit of the sampling basin by 97% during the pre-PAM sampling period. During the post-PAM sampling period, the reduction in turbidity between the entrance samples and exit samples decreased to 83%, however, this was mostly due to the lower turbidity entering the basin during the post-PAM period. The mean post-PAM entrance turbidity (1,789 NTU) was significantly lower than the mean pre-PAM entrance turbidity (8,022 NTU) indicating that treatment may have been occurring in the ditch before run-off arrived at the entrance of the sediment basin. No difference was found between exit samples taken during the pre-PAM and post-PAM sampling periods suggesting that there may be a lower bound to turbidity reduction that could be achieved at this location and with this sediment source. It is also important to note that site activities have a large effect on water quality and these were constantly changing over the course of monitoring.

Mean TSS values were also reduced between entrance and exit samples by 96% and 89% for the pre-PAM and post-PAM sampling periods respectively. Again, the reduction in efficiency during the post-PAM sampling period was due to the significantly lower TSS values sampled at the entrance of the basin rather than an actual decrease in the efficiency of the basin. PAM applied to check dams along the ditch leading to the entrance was lowering both turbidity and TSS before run-off reached the entrance of the basin. Similar to turbidity samples, no difference was found between the exit samples during the pre-PAM and post-PAM sampling periods suggesting that TSS reductions below those values may not be possible given the basin design.

Turbidity and TSS were reduced at the Statesville site by 69% and 81% respectively during the post-PAM phase. No pre-PAM sampling occurred at this site. Samples at the site were similar in turbidity and TSS to samples collected at the Goldsboro site, except that the reductions at Statesville between the entrance and exit samplers were statistically significant for both turbidity and TSS. The similarity in turbidity and TSS values at the exit of the Goldsboro and Statesville basins may be further evidence that the basins were basically functioning as well as can be expected and a floor may exist on how much turbidity and TSS can be removed. In our experience, often there is a turbidity source in sediment which does not respond to flocculation, even while the majority of the sediment is settled.

Turbidity and TSS values at the Rolesville site were higher than what was found at the other sites for both the pre-PAM and post-PAM sampling periods. A reduction of 94% and 95% between the entrance samples and the exit samples was observed during the pre-PAM period for turbidity and TSS samples respectively. Neither of the differences were found to be statistically significant. Reductions of only 26% and 33% were calculated for turbidity and TSS during the post-PAM sampling period, and again, neither of the reductions were found to be statistically significant. Rolesville received very high sediment inputs compared to the other two sites throughout both the pre-PAM and post-PAM sampling periods (Fig. 54). The site received very heavy sedimentation and the ditches and basin were found to be either full of sediment and needing maintenance or that there was evidence heavy disturbance from recent maintenance. This was especially true during June and July 2012, during the post-PAM period, when maintenance of the conveyances and basin was either requested or observed at the site at a rate of about every two storms. In both cases, the diversion filled with sediment or when that sediment is removed, the diversion is highly unstable and cannot function to dose runoff with PAM. There was no erosion control attempted at this site and the area was under constant disturbance. The very high turbidity and TSS values compared with the other sites are most likely related to those maintenance issues, underscoring the importance of maintenance and reducing sediment loads with other erosion BMPs before it reaches sediment basins.

Figure 54. Pictures showing deposition of sediment in ditches and sediment basin at Rolesville

Particle Size Analysis

Figure 55 shows data from the particle size analysis samples collected at the Goldsboro (Figure 55a) and Statesville (Figure 55b) sites. The figure shows the mean particle diameters for the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles (determined by volume). Samples were obtained from before PAM treatment locations, within the ditch but before the areas where PAM was applied, as well as the basin entrance after PAM treatments and the basin outlet. No pre-PAM location was sampled for the Statesville site.

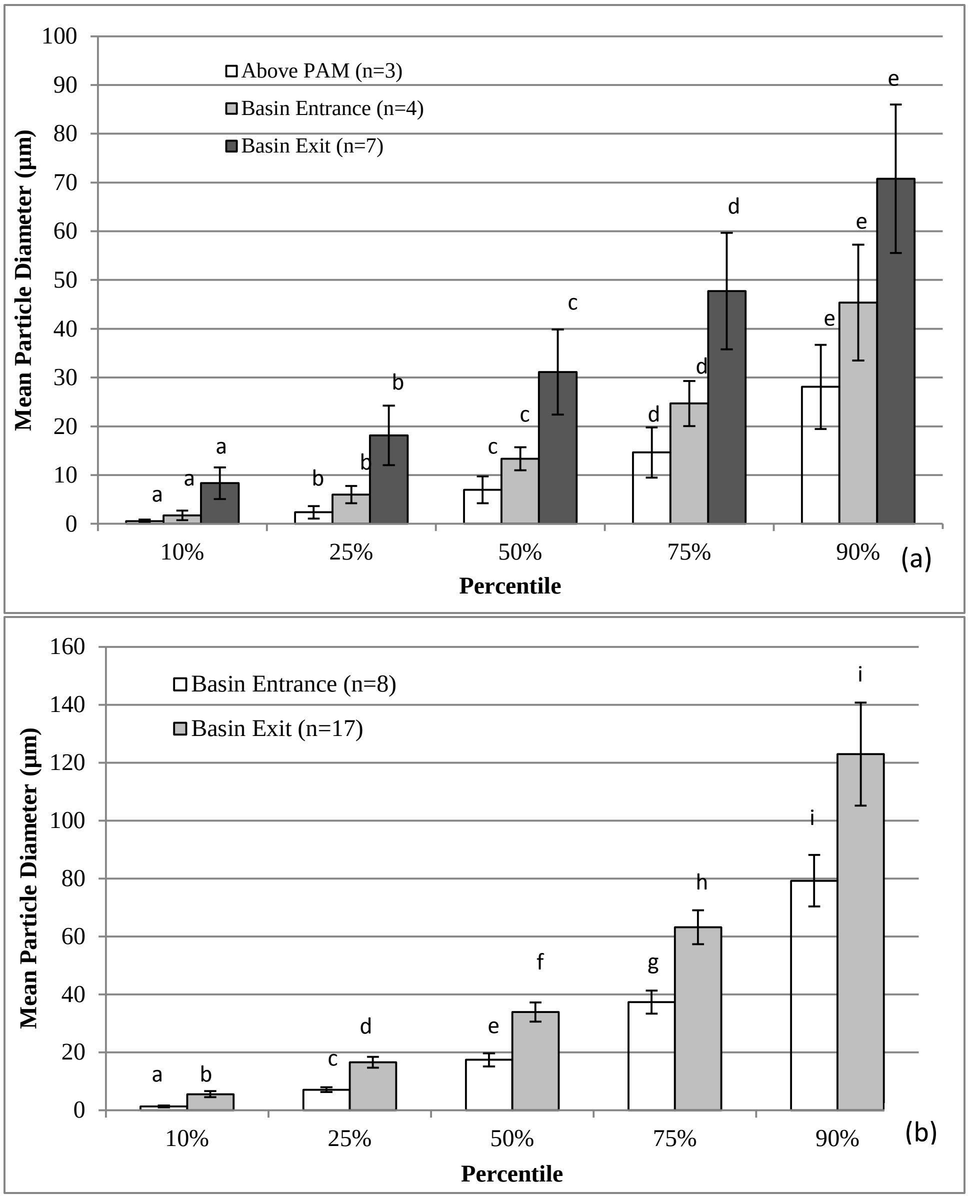


Figure 55. Mean Particle Size diameters for Goldsboro (a) and Statesville (b) sediment basins

The mean particle size generally increased as runoff moved through the system from the ditch to the entrance of the basin and finally to the exit of the basin. However, no statistically significant differences in means could be found for the Goldsboro site. Statesville particle sizes also showed the same trend of increasing particle size at the selected percentiles. In this case the differences among the means were found to be significant except for particles falling in the 90th percentile, where no difference was found. The increased particle size at the basin outlet would not be expected unless those particles were flocculated more than at the inlet, suggesting particle interactions in the basin that increased particle size.

Implementation and Technology Transfer Plan

1. Flocculating sediment was shown to significantly shift the particle size distribution to larger sized, greatly increasing settling rates for treated sediment.

2. Using current sizing formulas, sediment basins will capture much more sediment if it is flocculated. Conversely, attaining the current retention rate based on particle size could be achieved in basins with less than half the current surface area. This presumes the sediment is all flocculated prior to discharge into the basin. Monitoring on active construction sites demonstrated the difficulty in achieving thorough flocculation as sites are currently managed.

3. The design of the basin does not affect effluent water quality when the sediment is flocculated, but the 1:2 configuration did increase sediment capture for unflocculated sediment compared to the standard 2:1 geometry. This assumes functioning, porous baffles per current design specifications. The “sideways” configuration may be more easily fit onto sites with limited area.

4. Attempts to characterize flocculated sediment on active sites were usually thwarted by construction site activities that reduced or eliminated the flocculation potential of systems installed. Construction sites will have to be managed differently if the flocculation systems are to be successful.

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