REBEKAH LILLIAN GLAZER
The Use of Polyacrylamide (PAM) to Reduce Erosion on Disturbed Piedmont Soils.
(Under the direction of DANIEL MARKEWITZ)

Land disturbing activities during urban development increase soil erosion and thus turbidity in surface waters. To combat this problem Best Management Practices (BMP) such as re-vegetation must be followed during construction. Recently, Polyacrylamide (PAM), a synthetic soil conditioner, has been accepted as a BMP in Georgia. This study tested whether spray applications of PAM in conjunction with hydroseed (a common means of grass re-vegetation) would improve erosion control from slopes. Rainfall simulations in the laboratory demonstrated that PAM could effectively reduce erosion and runoff. In field trials at three locations using PAM+hydroseed, hydroseed alone, and a control estimated total solids loss was 25, 10, and 9 Mg ha^{-1}, respectively, while total sediment accumulation at the lower plot edge was 8.3, 4.6, and 3.9 cm, respectively. Both treatments reduced erosion compared to the control but no significant differences were apparent between the two treatments. PAM had no added benefit in controlling erosion.

INDEX WORDS: Polyacrylamide, PAM, hydroseed, total dissolved solids, total solids, infiltration, rainfall simulation

THE USE OF POLYACRYLAMIDE (PAM) TO REDUCE EROSION ON DISTURBED PIEDMONT SOILS

by

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"If one advanced confidently in the direction of their dreams, and endeavors to lead a life which they have imagined, they will meet with a success unexpected in common hours."

--Henry David Thoreau

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CHAPTER 1

INTRODUCTION

Purpose of the Study

Field studies were conducted to assess the value of polyacrylamide for controlling surface soil erosion during urban and suburban development. Polyacrylimides (PAMs) are long-chained synthetic polymers that were first used as soil conditioners in the 1950's. These polymers, which come in a diversity of molecular weights and charge capacities, function by binding clays together. The exact mechanism of clay binding with PAMs is uncertain, but is partially due to both surface charge properties and physical entrapment of clays by the polymer. Regardless of the mechanism, the binding of clays serves to minimize soil crusting, thus maintaining soil infiltration, while also serving to enhance rates of clay flocculation. PAMs have been used in water treatment operations, in the mining industry, and in irrigated agriculture (Barvenik, 1994). Currently there is interest in extending the use of PAMs through the process of spray application on the soil surface for erosion control on lands that have been cleared for construction. Under these construction conditions, hydroseeding (a spray application of cellulose mulch and grass seed) is the most common erosion control technique applied. The objective of this study was to test the effectiveness of spray applications of polyacrylamide in combination with hydroseed, for controlling erosion on soils of the Georgia piedmont. Soils of this region are often clay rich and highly susceptible to erosion.

To determine the erosion control effectiveness of PAM relative to hydroseed and on untreated soils, PAM was tested in two different field trials and also under laboratory conditions using a rainfall simulator. Chapter two reviews literature regarding previous work with PAMs. Chapter three reports results of the initial field trial. During this initial trial, performed at two locations, little information was available regarding rates of PAM use for spray application, and so a relatively low application rate was used. Based on these results a higher application rate was tested in a second field trial at three separate locations, and in the laboratory using a rainfall simulator. Chapter 4 presents results of the second field trials and laboratory simulations. Chapter 5 presents concluding remarks regarding the results of these combined studies.

CHAPTER 2

LITERATURE REVIEW OF POLYACRYLIMIDE RESEARCH

In 1951 the American Association for the Advancement of Science held a symposium in Philadelphia introducing the idea that synthetic polymers may change the physical properties of soils (Deboot, 1993). The earliest studies of synthetic soil conditioners, similar to polyacrylimides (PAMs) available today, were begun over 51 years ago (Quastel, 1954). The first studies were done on a product named Krilium or hydrolyzed polyacrylonitrile (HPAN). This product, manufactured by Monsanto Co., was able to resist soil microbial breakdown, enabling the polymer to last longer than its predecessors (Martin,1953; Sherwood and Engibous, 1953). This early product was designed to change the physical properties of soil by stabilizing soil aggregates, improving seed germination, and increasing pore spacing (De Boodt, 1993). Krilium cost $1,500 ha^{-1} to broadcast and $5,000 ha^{-1} to plough in to the top 2 cm of soil (De Boodt, 1993), however, and for these reasons was not successfully marketed. On the other hand, Krilium did initiate further research regarding soil conditioners such as PAM.

PAM, in fact, is a generic term that refers to many different polymers of repeating monomer subunits. The properties of PAMs rely both on the size of the polymer and modification of the polymer subunits. PAMs on the market today differ from their earlier predecessors, most particularly due to their large size (Lipp and Kozakiewicz, 1991). PAM is a long chain organic polymer that is composed of acrylamide monomers. It is through the polymerization process that PAM can attain large size and thus high molecular weights. In its dry state, PAM is a brittle white solid with water contents of 5-15% and a density of 1.302 g cm^{-3}. PAMs are generally soluble in water and become more hygroscopic as the ionic character of the polymer increases. The ionic character is altered through modification of the subunits as illustrated in Figure 1 with the substitution of sodium formate (NaO) for the amide (NH_2) group. The dissociation of Na^+ leads to a negative charge on the PAM. The negatively charged or anionic PAMs are the most commonly used commercial products. The extent of subunit modification in the PAM is quantified as the charge density. For example, 20% charge density indicates a substitution of 1 in 5 NH_2 subunits. As a result of this substitution and Na^+ dissociation anionic PAMs possess carboxyl groups (COO^-) that can then bond with particle surfaces. PAMs can have molecular weights that vary from a few thousand g $mole^{-1}$ to 20 Mg $mole^{-1}$ and charge densities that range from 2-20% (Green, 2000). The most common molecular weight is 10-15 Mg $mole^{-1}$ and a charge density of 18-20% (Green, 2000).

The raw material for PAM is often natural gas (Sojka and Lentz, 1997). To produce a solution form of polyacrylamide an aqueous solution of the monomer acrylamide subunits are introduced into a stainless steel reactor with sodium bisulfite and ammonium persulfate. The temperature of the mixture is raised to 90°C and mixed thoroughly. Dry PAM is prepared as a free-flowing bead formed by aeotropically distilling water from inverse suspension polyacrylamides, collecting the filtration particles, and then drying the particle (LIPP 1991).

Polymer chemistry

Although studied for the last fifty years, the chemistry of the clay-polymer interaction is a largely descriptive science (Theng, 1982). The exact mechanism describing how PAM is attracted to soil colloids has many theories. Napper (1983), for example, suggested that at very low polymer concentrations, bridging flocculation is the predominant effect. Bridging flocculation of anionic PAM can be achieved either through electrostatic stabilization, i.e. when the net charge of the dispersion media is equal but opposite in charge to the particles, or through steric stabilization, i.e. where polymer molecules are physically adsorbed to the surface of the soil particles. In the case of anionic PAMs that have a net negative charge, as do clay particles, cation bridging is thought to be a critical process (Napper, 1983). Napper has designated the order for flocculation potency of cations to serve as cation bridges as $K^{+}>Ca^{2+} = Mg^{2+}$.

Another mechanism for polymer-clay interaction, as suggested by Lipp (1991), indicates that anionic PAMs contain carboxyl groups that have many interactions with divalent cations, which may also be considered a form of cation bridging. In addition to interacting with positively charged cations, however, these same carboxyl groups may form hydrogen bonds with oxygen during hydrolysis. Processes of cation bridging and hydrogen bonding can be sensitive to the pH of the solution media (Napper, 1983). For example, titration to pH 4 will protonate functional carboxyl groups lowering repulsion between PAM and other negative charge surfaces (Lipp, 1991). This reduced repulsion may then allow closer interaction, and therefore an unprotonated carboxylic anion on the PAM may bond with a surface hydroxyl of a clay particle through a cation-bridge, or there may be formation of a hydrogen bond between the C=O group of the polymer and the clay surface hydroxyl (Stutzmann, 1977).

The extent of bonding in PAMs may vary with the charge or molecular weight of the PAM. At high molecular weight the above reaction between the carboxyl group and a cation may cause high viscosity even in initially dilute aqueous PAM solutions (Lipp, 1991). This high viscosity indicates that with the mass and volume of a high molecular weight PAM, saturation of the charge locations cannot take place. Since polymer molecules become adsorbed to many particles (aggregation), there can be a decrease of bonding possibilities between the polymer and protonated clay crystal sites with increasing adsorbtion (Stutzmann, 1977). The capacity to bond along many sites, however, is exactly why a small amount of PAM may flocculate a large amount of clay particles. The polymer chain extends with the degree of hydrolysis and will bond much easier with the edge surface of the clay particles (Stutzmann, 1977). The broken edge of a clay particle may expose aluminum ions that also will bond to polyacrylamide (Ben-Hur, 1992). These ions would otherwise be unavailable to the polymer because of the small pore space of clay soils.

Polyacrylamide as a soil conditioner

Applied as a soil conditioner, PAM generally reduces erosion by improving soil structure through the binding of clay aggregates. For example, Mitchell (1986) showed in soils from the desert Southwest that PAM applied in dilute solution to irrigation water increased infiltration up to 57% in the first four hours of rainfall. Similarly, Zhang and Miller (1996) studying furrow erosion under rainfall simulation, observed increases of 65% in infiltration and 73 % in reduction of total erosion. Levy and Agassi (1995) found similar results in the rainfall simulator and recorded an improvement in final infiltration rate of 260%.

Much research with PAM has focused specifically on the use of PAM for controlling soil erosion in irrigated agricultural soils. Sojka and Lentz (1996) found that PAM used in irrigation water carried a reduced amount of sediment, pesticides, phosphorus and reduced biochemical oxygen demand. Helalia and Letey (1988) working with clay rich soil under rainfall simulation found that clay flocculation increased in the presence of PAM at concentrations of 10 mg L^{-1}. Later, Lentz et al. (1992) working in bean fields on silt loam in Idaho demonstrated reduced erosion and increased net infiltration after repeated applications of PAM. PAM concentration of 10 g m^{-3} reduced mean sediment load by 97% compared to the control and a residual irrigation reduced the mean sediment load by 50% (Lentz et al. 1992). Levy et al. (1991), in another irrigation experiment, added PAM (20 kg ha^{-1}) to irrigation water over a clay loam vertisol and found a decrease in water runoff of 50-70% over the control. This study also concluded that the cotton yield was increased from the decrease in erosion.

Beyond showing increases in soil infiltration, and thus reduced erosion rates, Chaudhari and Flanagan (1998) found grass emergence and growth to be better on PAM treated slopes in Indiana. Runoff volume and sediment loss were much reduced on these 35% slopes. Also studying emergence, Cook and Nelson (1986) showed that alfalfa treated with PAM in solution emerged days earlier from aggregated soil than with granular PAM through seven rain events. Shainberg and Levy (1994) showed a final infiltration rate ten times greater than a control that had a cultivated soils prone to surface sealing. An additional economic benefit of PAM is that it is easily placed into irrigation water (Ben-Hur, 1994; Lentz et al, 1992; Mitchell, 1986) or can be placed directly into irrigation ditches as a floc logs, i.e. a mass of PAM that is compressed into a brick and slowly dissolves into solution.

Using a rainfall simulation, Flanagan and Chaudhari (1999) tested for a reduction in soil loss using dry soils, wet soils, and very wet soils that had been treated with PAM against untreated controls. In all cases the PAM treated soil had a significantly reduced amount of runoff than the control. Also using rainfall simulation, Roa-Espinosa et al., (2000) found a 93% reduction in sediment yield with a PAM/mulch/seed mix applied on dry soil and a 77% sediment yield reduction when PAM was applied on moist soil. Green et al. (2000) tested a variety of soils that differed in clay content and chemical exchange characteristics, treated with a variety of PAMs that varied in charge density and molecular weight. In this study, they generally found a 3 to 5 fold increase in infiltration rate. The interaction of clay content or exchange chemistry with PAM type was weak, however, and did not seem to substantially alter performance.

Despite many of these promising results with PAM in agricultural systems, some researchers believe that there is still not enough conclusive information regarding the proper application of PAM or its cost effectiveness. For instance, Mitchell (1986) argues that PAM will increase initial infiltration on swelling soils, but may not effect net infiltration since subsoil swelling halts water entry in ongoing irrigation. Similarly, Nadler and Letey (1989) found that removing organic matter from the soil, severely disrupting the aggregates, or saturating the soil with Ca or Na did little to aid in PAM adsorption. Also, if PAM is applied only to the exterior of the aggregates, the untreated areas exposed during a rain event may break down or crust over (Ben-Hur and Letey, 1989; Malik and Letey, 1991; Letey, 1994). Most do agree, however, that anionic polymers, such as PAM, have great potential for stabilizing soil if they can be applied at low rates and at low cost (Nadler, et al. 1996; Sojka and Lentz, 1996).

Environmental considerations

Environmentally, anionic PAM (as opposed to cationic PAM) has been found to have a very low rate of toxicity in mammalian (e.g. slight eye irritation under certain test conditions) and aquatic environments (e.g. LC_{50} values > 100 mg L^{-1}) (Barvenik, 1994). The U.S. EPA has listed PAM under the category of “Acceptable Drinking Water Additives” and PAM meets “ANSI/NSF” standards for drinking water (Barvenik, 1994). These regulations rate PAM safe for application as an agricultural amendment, as it will break down over time (Barvenik, 1994). The low toxicity levels of PAM allow it to be used in addition to, or in the place of, organic amendments currently used in agriculture (Wallace et al., 1986).

Research need

The current research focuses on the expanded use of polyacrylimides as a spray application on steep slopes cleared for construction. Only a small body of literature is available on this topic for a limited number of soils and situations (Chaudhari and Flanagan, 1998; Stoddard, 1998; Flanagan and Chaudhari, 1999; Roa-Espinosa et al., 2000; Glazer and Markewitz, 2001). There is currently a lack of research on spray application methods for PAM and little field research is available to assess the added benefits for erosion control from PAM usage, compared to commonly used hydroseeding techniques. The current study hopes to fill some of these gaps.

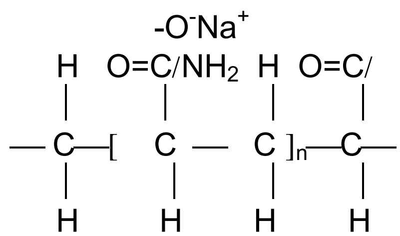

Figure 2.1: Repeating monomers of acrylamide in polyacrylamide. The Na^+ formate (O-Na^+) at the top of the figure substitutes for the amide group (NH_2) creating an anionic surface charge.

CHAPTER 3

A FIELD TRIAL USING LOW APPLICATION RATES OF POLYACRYLAMIDE (PAM) TO REDUCE SOIL EROSION FROM DISTURBED PIEDMONT SOILS

Introduction

Recently, the Manual for Erosion and Sediment Control in Georgia (GSWCC, 2000) has developed more restrictive best management practices (BMP) for urban land-disturbing activities. These more restrictive BMPs have been adopted due to increasing urban development of slopes and highly erodable soils in the Piedmont. In the Upper Chattahoochee River, such development has led to a six-fold increase in average suspended sediment concentrations (1993-1998) from upstream to downstream of the Atlanta metropolitan area (Frick and Buell, 1999).

Current BMPs include installation of silt fences, sediment basins, proper construction exits, as well as other structural and vegetative measures. Unfortunately, current BMPs have failed to reduce the problem of soil erosion sufficiently. Improper installation of existing structural BMPs (mainly silt fences) is one reason for the insufficient protection while the limited use of BMPs other than silt fences is also a contributing factor. Polyacrylamide (PAM) is a lesser known and a lesser used BMP that might provide great benefit for minimizing sediment delivery to streams. Government regulatory agencies recently approved the use of PAM as an acceptable BMP.

The objective of this study was to test the efficacy of low application rates of PAM for minimizing erosion on recently disturbed construction sites.

Background

Early studies of synthetic soil conditioners were begun over 51 years ago (Quastel, 1954). Recently, much has been written on the use of PAM, one of many types of synthetic soil conditioners, on irrigated agricultural soils (Helalia and Letey, 1988). Despite promising results with PAM in agricultural systems some researchers still believe that there is not enough conclusive information regarding the proper application of PAM or its cost effectiveness (Mitchell, 1986; Nadler, et al. 1996). Most do agree, however, that anionic polymers, such as PAM, have great potential for stabilizing soil if they can be applied at low rates and at low cost (Nadler, et al. 1996).

PAM is a water-soluble organic polymer. Applied as a soil conditioner, PAM functions by improving soil structure through the binding of clay aggregates in the soil to long chain synthetic molecules (Mitchell, 1986). The process of binding clay particles together through the use of PAM increases pore space and water infiltration rates, and reduces soil crusting and rill erosion (Zhang and Miller, 1996). Helalia and Letey (1988) showed that when applied to clay rich soil PAM increased the soil infiltration rate. Clay rich southeastern soils, similar to those present in the Georgia piedmont, are particularly susceptible to rill erosion as a result of poor structural stability (Miller and Baharuddin, 1987).

Environmentally, anionic PAM (as opposed to cationic PAM) has been found to have a very low rate of toxicity in mammalian and aquatic environments (Barvenik, 1994). The U.S. EPA has listed PAM under the category of “Acceptable Drinking Water Additives” and PAM meets “ANSI/NSF” Standards for drinking water (Barvenik, 1994). These regulations rate PAM safe for application as an agricultural amendment, as it will break down over time (Barvenik, 1994). The low toxicity levels of PAM allow it to be used in addition to, or in the place of, organic amendments currently used in agriculture (Wallace et al., 1986).

Methods

Five research sites with three different experimental treatments have been placed in the field. The experimental design is an incomplete, randomized block with site locations serving as blocks. Site locations include Watkinsville ARS, Park Creek in Woodstock, GA, and three sites near Ball Ground, GA. The Park Creek and Ball Ground sites were recently cleared of forest and prepared for residential development or power line installation. All slopes were engineered and graded by a bulldozer prior to treatment. At four sites experimental treatments were: (1) PAM with hydroseed (i.e. mulch and seed sprayed from a water tank), and a silt fence; (2) hydroseed and a silt fence; and (3) a silt fence alone as a control. The ARS plots are on the back of an earthen dam and thus contain a half PAM plus hydroseed treatment instead of a silt fence only control. The locations have varying slopes and soil types. In this paper only results from

Park Creek and ARS are reported.

Plot size for each treatment is approximately 10 m x 12 m. At the ARS and Park Creek locations, applications of PAM 630 (Applied Polymer Systems, Norcross, GA) were sprayed on the plots at a rate of 150 ml ha^{-1}. This application rate is 100-fold less than current recommendations but little information is available regarding spray application of PAM on construction slopes thus a conservative approach was taken for the first two locations. The Ball Ground locations have received the recommended rates of PAM. A type C silt fence with wire back was placed at the bottom edge of each plot. Meter sticks were placed in front of the silt fence to estimate the volume of sediment runoff reaching the bottom edge of the plot. Rainfall intensity and amount were measured at each site with a HOBO data logger and tipping rain gage. To estimate vegetative grass cover we cut the grass in a defined area from a number of locations in the plots on a periodic basis. Using this information we quantified the percent cover of grass and bare soil over time in each plot.

In addition to the plot level measurements, within each plot three 1-m wide by 3-m long defined area samplers were installed. The samplers are enclosed on all sides and drain into 120-L containers to estimate surface water and sediment runoff. Nephelometric turbidity units (NTU) of the collected waters were analyzed in the laboratory (Clesceri et al., 1998). Samples with NTU>200 were diluted as necessary. Measured turbidities were converted to total suspended solids (TSS) in mg L^{-1} using a regression (TSS in mg L^{-1} =0.7147*NTU – 1.1523) based on kaolin standards (N=5) of known concentration. Total solids were also measured by oven drying a known volume of sample water (Clesceri et al., 1998). These defined area samplers provide greater precision in estimating rainfall vs. runoff relationships as well as a means to quantify sediment loads in the runoff waters.

Finally, along with the above measurements, we have quantified some general chemical and physical properties of the surface soil at each site to correlate with PAM effectiveness. Chemical properties include soil pH in water and salt (2:1 water or 0.01 M $CaCl_2$ to soil {v/w}), and base cation (Ca, Mg, and K) concentrations (double acid extraction followed by measurement on atomic absorption). Physical properties include soil particle size analysis for sand, silt, and clay following the hydrometer method (Gee and Bauder, 1986).

Results and Discussion

Sand, silt, and clay contents of the upper 0-5 cm of soil from the ARS and Park Creek locations were substantially different (Table 3.1). ARS had clay contents of ~19% while those at Park Creek were ~7%. In both locations soils were from cut and fill operations and thus represented a mixture of local soils and fill material. The TSS measurements from ARS and Park Creek ranged over a four-month period that was marked by a record drought in the state. Regardless, for the available rain events TSS measurements at both locations ranged between 5 and 1100 mg L^{-1} (Figure 1 and 2). At both locations TSS decreased in runoff waters during the period of measurement by >20-fold. The effect of PAM on runoff water TSS was minimal at both locations when compared to hydroseed treatments although PAM+hydroseed and hydroseed treatments were clearly superior to the control at Park Creek (Figure 2).

In this low application rate study with PAM no differences in effectiveness were apparent between the sites despite differences in particle size distributions. Other work with a rainfall simulator (Green et al., 2000) also indicated that off-the-shelf PAMs may function similarly across soils with 13 to 57 % clay. The higher clay content soil of the ARS site did, however, have the highest measured TSS (~1100 mg/L) after the first rainfall event. Although the measured TSS at both sites during the first rainfall events likely exceeded enforcement standards for a National Pollution Discharge Elimination System (NPDES) permit. The NPDES permit limits TSS discharge into a warm water stream at a 25 NTU increase up to a 25-year 24-hour rainfall event (GDNR, 2000). The PAM+hydroseed and hydroseed treatments applied to the slopes probably did not reduce sediment entrained in runoff water below this limit. This does not indicate, however, that all sediments would reach local stream waters. In fact, PAM may provide some benefit to erosion control by continuing to act as a flocculent in sediment enriched waters even if washed down slope. PAM has not been approved for direct application into stream waters, however, and thus PAM inputs to streams would not be acceptable.

Conclusion

The low application rates of PAM used in the first two field trials did not show a marked improvement in reducing erosion. These applications were well below recommended rates, however, thus we are currently performing field trials with 100-fold higher rates or ~15 L ha^{-1} (1.5gal ac^{-1}) of PAM. PAM has a proven effectiveness as a flocculent and thus maintains promise as an effective BMP for controlling erosion although continued research for spray applications on constructions sites is required.

Table 3.1. Particle size analysis for 0-5 cm soils at the sites used for the low application rate PAM treatments.

Site	Location	Sand	Silt	Clay
	County	----------%----------		
Watkinsville, ARS	Oconee	50	31	19
Park Creek	Cherokee	86	7	7

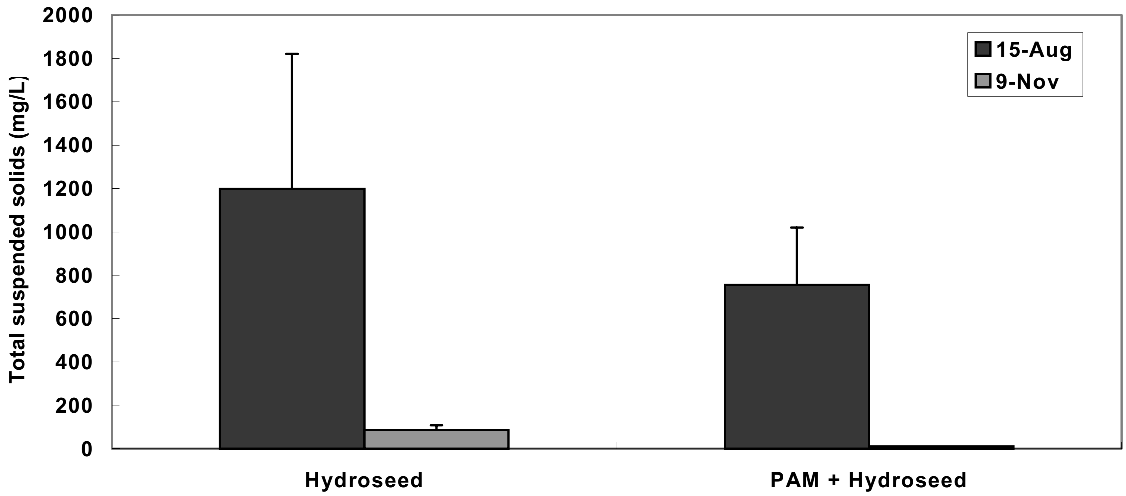

Figure 3.1. Turbidity of runoff waters collected from defined area samplers (N=2/plot) at the Agricultural Research Station (ARS) in Oconee County, GA. Treatments are a low application rate of PAM+Hydroseed and Hydroseed alone. Error bars equal one standard deviation.

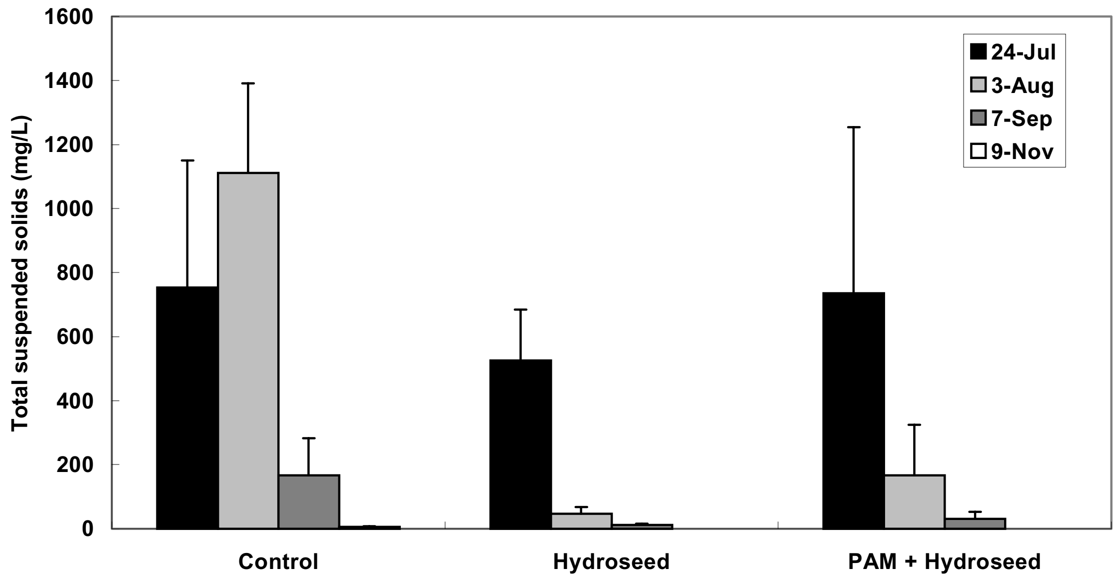

Figure 3.2. Turbidity of runoff waters collected from defined area samplers (N=3/plot) at the Park Creek location in Cherokee County, GA. Treatments are a low application rate of PAM+Hydroseed, Hydroseed alone, and a bare soil control. Error bars equal one standard deviation.

CHAPTER 4

EFFECT OF POLYACRYLAMIDE (PAM) ON SOIL EROSION FROM STEEP PIEDMONT SLOPES

Introduction

Soils of the piedmont region of Georgia, USA were known for rapid rates of erosion during the first half of the 20th century when much of the area was cleared of forest cover for agriculture (Trimble, 1974). Although soil erosion has decreased as forests have re-grown, the region is once again challenged by land clearing activities for suburban development (Wear, 1999). Unlike the earlier clearing for agriculture, which generally remained on gentler slopes (<10%), clearing for development often engineers and bares slopes of >20 %. Minimizing erosion from these slopes during construction is a critical regional issue that is receiving much public attention.

Currently, guidelines for controlling erosion require coverage of bare slopes within seven days (GSWCC, 2000). This is a mandatory law required by the Environmental Protection Division (EPD) of Georgia. Hydroseeding, a combination of cellulose mulch with grass seed and fertilizer sprayed onto slopes from a water cannon, has received increasing use, although delays in grass emergence due to drought or downslope movement of mulch leave room for improvement. Polyacrylimide, (PAM), a class of long chained synthetic polymers, has been tested as a soil conditioner to help reduce soil erosion (Sojka and Lentz, 2000). PAM functions by stabilizing soil aggregates, reducing soil crusting, and thus increasing soil water infiltration, reducing runoff and erosion (Ben Hur, 1992, Zhang and Miller, 1996).

Currently, revegetation through hydroseeding costs approximately $1,200/ac ($2,965/ha). If PAM is added to the hydroseed mixture, the cost is increased to only $1,400/ac ($3,459/ha). This increased cost is contrasted with fines of up to $2,500/day required by the Georgia EPD if revegetation is unsuccessful and erosion and sedimentation violations are incurred. Thus, if PAM can be successfully applied through spray application it may provide a cost effective tool for erosion control on construction sites.

At present, most research and use of PAM has been in irrigated agriculture on coarser textured soils with the placement of PAM in the advance stream during furrow irrigation (Mitchell, 1986; Lentz et al., 1992). Much less is known, however, about the value of surface spray applications of PAM on large steep slopes like those found on construction sites (Chaudhari and Flanagan, 1998; Flanagan and Chaudhari, 1999; Roa-Espinoza et al., 2000) with few studies on high clay content soil similar to those found in the piedmont region of Georgia (Zhang and Miller, 1996).

The objective of this study was to test the value of spray applications of PAM in conjunction with hydroseeding for controlling erosion of steep slopes. The three treatments used in this study are similar to previous work (Glazer and Markewitz, 2001) although application rates of PAM are higher in the current investigation. The treatments include PAM+hydroseed, hydroseed alone, and a control. Although previous research has investigated PAM only treatments (Rao-Espinozo et al., 2000) it was felt that this was impractical since re-vegetation is required. Thus this study is specifically interested in testing whether PAM+hydroseed is more effective in controlling erosion than hydroseed alone.

Materials and Methods

Two approaches were simultaneously used for this research. The largest component of the research was based on the use and measurement of field plots. In addition, laboratory analysis using a rainfall simulator was also undertaken.

Rainfall Simulator Experiments

For rain simulation, a solenoid operated variable intensity simulator was used (Miller and Baharuddin, 1986). The simulator has a single rotating spray nozzle (Teejet 30 WSQ Spraying Systems Inc., Wharton IL) mounted four meters above a table. The solenoid was controlled with a computer to deliver rain for two seconds and shut off for two seconds. This rainfall rate of approximately 60 mm hr^{-1} at 22 kPa is comparable to a one-year return rain event in Georgia (Elijay, GA, Griffin.peachnet.edu).

Soils used to fill the rainfall pans were collected from Ball Ground, GA and Kaolin, GA. The Ball Ground soils were collected within the AB horizon during field site installation as described below. The Kaolin soils were collected from a kaolin mine and come from a depth of 5 to 35 meters. Both soils were air dried and sieved to 6 mm. The 0.36 m long by 0.2 m wide pans were packed with a layer of cheesecloth, plastic mesh, 2.5 cm of coarse river sand and 12 cm of sieved Ball Ground or Kaolin soils (Miller and Baharuddin, 1987). Two pans with differing treatments were placed on a 9% slope side by side and rained on simultaneously.

The treatments for the rainfall simulator studies included a bare soil control, a soil sprayed with PAM, and a soil covered with hydroseed. Treatments were rained on in pairs of control vs. PAM or PAM vs. hydroseed. The PAM used in this study was in an anionic PAM powder form (Stockhausen Greensboro, NC) with a molecular weight of 7 Mg $mole^{-1}$ and 30% charge saturation. To create an emulsion for spray application 18.75 g of the powdered PAM was mixed with 300 ml of 0.5 *M* HNO_3, 30 g of gypsum ($CaSO_4{*}2H_2O$), and 15 L of water. This mixture was left sitting for two days and mixed twice with a paddle fitted to a hand drill. The emulsion was sprayed on to the pans with a spray wand from a 2 L bottle pressurized with CO_2. The application of five one-second passes over a pan achieved an approximate rate of 45 kg-PAM ha^{-1}. Hydroseed applications of 10 g, 70 g, or 110 g were established using Soil Cover cellulose mulch by Terra-Mulch (Buffalo Grove, IL). The cellulose mulch was saturated and placed on the pans in an even layer but to varying thickness. In addition to these treatments the moisture conditions of the soil were also varied prior to rainfall simulations. In the first case soil pans were sprayed with PAM or covered with hydroseed and allowed to dry for 24 hours prior to rainfall. In the second case applications were applied and rainfall was begun within the hour.

Measurements from the rainfall simulation consisted of water and sediment runoff. To estimate runoff 400 ml beakers were placed below the spigot at the lower end of each pan. During a simulation, beakers were changed every five minutes. Water runoff volume was measured on each beaker by measuring the total weight of the beaker and subtracting the beaker tare weight. In cases were volume runoff was <100 ml the water was evaporated in a 105°C oven and total sediment (coarse and fine) was estimated by weight. If >100 ml of runoff was available a 100 ml aliquot was removed from the beaker after vigorous mixing and 45 seconds of settling. Based on Stokes' law (Jackson, 1972) the estimated settling time separated coarse from fine material. After separation, each fraction was estimated by weight after evaporating all water. An assumed constant concentration of fines in the entire solution was then used to estimate the concentration of total fines and total coarse material. Contents of water and sediments were summed over the entire period of collection to estimate total runoff. Finally, average rain intensity was estimated using a 178-cm^2 bucket placed next to the runoff pans.

Site Characteristics for field trials

The city of Ball Ground, Georgia lies in the piedmont region of Cherokee County, Georgia. The topography is undulating and proceeding northward evolves into the rolling foothills of the southern Appalachian Mountains. The predominate soil association in this county is Tallapoosa-Madison-Hayesville, and is generally found on steep slopes, defined by gravely rock fragments on the surface and throughout the soil solum. Slopes in the area range from two to thirty percent with elevation ranging up to 335 m. The surface soil layer of these series are generally a brown fine sandy loam eight centimeters thick underlain by 20 cm of brown fine sandy loam. The subsoil is often a yellow-red silty-clay loam about 24 cm thick. The parent material is mica-schist and gneiss-saprolite (USDA, 1973).

The 50-year average rainfall in the region of Ball Ground is 152.2 cm per year (Elijay, GA, Griffin.peachnet.edu). Rainfall is relatively evenly distributed with all months receiving greater than 10 cm of rain. March and December receive the greatest rainfall averaging 16.5 cm of rain.

Due to soil disturbance and mixing during installation of power lines, it was not possible to identify the exact soil series on each of the Ball Ground research sites. Further at one site (designated Ball Ground 1) the slope was engineered with cut and fill material and is not representative of the local soils. Particle size analysis from the other two sites (Ball Ground 2 and 3), however, relates most closely to the Tallapoosa soil series in that there was relatively high sand and mica content.

Plot Design

Plots for all research trials were located in a transmission line right-of-way that was being installed by Georgia Power. The portion of the transmission line with plot installations ran between Ball Ground and Dawsonville, GA. The right-of-way paralleled portions of the Etowah River and crossed Cons Creek close to the Ball Ground 1 plot location (Photo 4.1).

The general plot design was consistent across all locations and is depicted in Figure 4.1. All plots included three defined area samplers randomly placed in each treatment to collect runoff water and sediment. The defined area samplers were 1 m wide x 3 m long x 0.2 m thick. The lower meter of the sampler was triangular to divert all runoff into a PVC pipe. Varying lengths of PVC pipe were connected to the defined area samplers in order to direct runoff water and sediment to 143 L containers that were stabilized by rebar outside the lower boundary of the plot. Above each defined area sampler there was a 2 m piece of edging staked in and shaped like a half moon, to divert rainwater from digging out the sides. At the lower boundary of each plot there was a type C silt fence. Five metal meter sticks with 1 mm gradations were placed approximately every one-meter along the bottom silt fence to measure the height accumulation of sediment. A buffer strip of grass, silt fence, or straw blanket was placed between the treatment plots. A Hobo data logger and tipping bucket rain gauge (Onset, Bourne, MA) were placed in an open location at each site. Finally, grass growth was assessed qualitatively by visual inspection.

Ball Ground 1 (BG1) was installed in November 2000. The slope chosen was a large slope engineered with cut and fill material on an incline of approximately 50% (i.e. a 2:1 grade) that had been stabilized prior to this study. The overall plot size was 15 m tall by 35 m wide or 525 m^2 total with each treatment plot being 10 m wide along the slope by 12 m upslope (120 m^2). Due to prior seeding of the slope at this location, plots were re-cleared by removing the upper 5 cm of soil with a bulldozer. Grass buffer strips were left above and between each of the treatment plots. Due to the season of installation, a hydroseed mixture containing 9 kg fescue per acre (*Festuca arvenensis*) and 9 kg of rye per acre (*Secale cereale*) was sprayed on the PAM+hydroseed treatment and hydroseed alone treatment.

The second Ball Ground site (BG2) was installed in January 2001. The slope at this site was 29 % (i.e. a 3.5:1 grade). This hill slope was smaller than the first site with an overall plot size of 12 m by 30 m (360 m^2) with the treatment plots of 9 m wide by 10 m tall (90 m^2). This site had been recently harvested of all vegetation and a substantial depth (~20 cm) of topsoil was removed. Due to the small area of slope and the lack of any vegetation, silt fence was used to create buffers between the plots. Care was taken to ensure that runoff created along the side buffers bypassed the lower silt fence where sediment accumulation was being measured. A fourth piece of silt fence was placed along the upper boundary to define the plot dimensions. The grass mixture used in this location contained 9 kg of fescue and 5 kg of rye.

The third site, Ball Ground three (BG3), was installed in March 2001. This site was harvested of timber three days prior to plot installation. This site had a 33 % slope (i.e. a 3:1 grade). The overall plot size here was 20 m by 40 m (800 m^2) with each treatment being 12 m wide by 18 m tall (216 m^2). This slope was large but did not have any vegetation due to the recent clearing. In order to buffer each treatment, a 1.5 m strip was hydroseeded and covered with an Excelsior straw blanket (Justin Seed company, Justin, Texas). The grass mixture used in the hydroseeder at this location was 9 kg of fescue, 5 kg of rye, and 9 kg of bermuda grass (*Cynodon dactylon*).

Application of treatments

At each location, treatments of PAM+hydroseed, hydroseed alone, and control were randomly assigned to one of the three plots. Prior to hydroseed application, PAM was applied to the bare surface soil of the appropriate plot. PAM used in the field trials was Silt Stop 634 from Applied Polymer Systems (Norcross, GA). The exact constituency of this PAM is unknown but is probably in the range of 15-20 Mg $mole^{-1}$ with a charge density of 20 to 30 %. This is an emulsion form of PAM and was applied at a rate of 14 L-emulsion ha^{-1}. A 190 L water tank with a three horsepower motor and a small mixing apparatus was used to apply the PAM. Based on plot size, an appropriate amount of water and emulsion mixture was sprayed on each plot, total liters of water ranged from ~50 to 100 L. This amount of water would only create a 2 mm wetting front assuming 50 % porosity in the surface soil. To maintain consistency among the treatments a similar amount of water was sprayed on the other plots. In fact, the control and hydroseed plots were sprayed prior to adding PAM to the tank to avoid PAM contamination. Following the PAM application, hydroseed was sprayed on the PAM+hydroseed and hydroseed alone plots. Approximately five 27 kg bags of cellulose mulch (70/30 recycled paper and wood), 68 kg of 19-19-19 fertilizer, and 6 kg CaO as liquid lime, along with the seasonal grass mixes stated above, were combined in a 3400 L water tank and sprayed evenly on the two plots. At BG1, BG2, and BG3 a Finn hydroseeder (Finn, Fairfield, OH) was used for this purpose.

Soils analyses

Samples were taken from the top 0-5 cm of soil. Soils were collected using a trowel in two transects running along the lower and upper portions of the plots. Soil analyses included particle size (Gee and Bauder, 1986), pH in both water and salt (Thomas, 1996), exchangeable cations, and exchangeable acidity (Thomas, 1996). Effective cation exchange capacity was estimated using the sum of cations method.

Rainfall

A Hobo shuttle (Onset Corp, Bourne, MA) was used to download data from the recording tipping rain gauges. The tipping rain gauges measure 0.0254 cm increments of rainfall. To estimate the total amount of rainfall between collection periods I simply summed all rainfall events. In addition, there was interest in quantify the greatest intensity rainfall within any runoff or sediment collection period. To quantify rainfall intensity I used a minimum of 10 minutes to sum total rainfall but quantified a cm hr^{-1} rainfall rate.

Runoff water

To determine runoff volume from the defined area samples, the height of water within each collection container was recorded. Heights were converted to liters of water using a regression developed for the specific containers used in this study (regression not shown). To obtain a sample for sediment analysis the containers were mixed well using a large paddle to ensure re-suspension of all particles and then a 250 ml sample was immediately collected by submerging a polypropylene bottle into the container. After the sample collection the containers were emptied, rinsed with a pressurized stream of water from a backpack sprayer, covered, and replaced to collect the next rain event.

The 250 ml samples from the containers were transported back to the lab and analyzed for total suspended solids (TSS) and total solids (TS) concentrations. To measure TSS the 250 ml bottle was shaken vigorously and left to settle for five minutes to remove all sand sized particles from the upper 2.5 cm of the water column. After settling, a 10 ml sample was pipetted off the top of the water column and mixed with 90 ml of DI water. The TSS of this diluted sample was estimated using the Hach 2100P portable turbidity meter (Loveland, CO). The Hach turbidity meter has an upper range of 800 nephlometric turbidity units (NTU) and thus the sample dilutions were usually necessary. The recorded NTU value was converted to mg L^{-1} based on a standard curve using kaolin standards. The kaolin standards were made using mined kaolin (Kaolin, GA). Standard solutions of 0, 10, 20, 100, and 200 mg L^{-1} were dispersed using a salt solution of KCl and sonicated for 30 minutes in a sonicating bath. In addition to these kaolin standards, calibration solutions of the same mg L^{-1} concentrations of formazine were used periodically. After the removal of the turbidity sample from the original 250 ml, the remaining sample was evaporated in a 65°C oven to estimate total solids in the sample. The oven dried weight of the bottle and sediment minus the tare weight of the bottle was used to estimate TS (Clesceri, 2000).

To estimate the total loss of sediments from the slope on a per unit area TS concentrations were multiplied by the volume of collected runoff water and divided by the area of the defined area samplers (2.5 m^2).

Hillslope sedimentation

As a further and independent estimate of total sediment movement from the slope among the treatments, measurements were taken at each ruler attached to the sediment fence at the base of the slope. The initial height of sediment at each ruler was subtracted from all subsequent readings such that sediment accumulation was being recording and not absolute sediment height. Height accumulations were not always unidirectional as periodically heavy rains moved sediments vertically along the fence. Even more rarely, rains would dislodge the lower portion of the silt fence creating a loss of sediment. In these few instances readings were reinitiated and additional accumulations of sediment were added to that accumulated up to the sediment loss event.

Results

Rainfall simulation

The rainfall simulation used paired comparison for two soil pans at a time. Each simulation was run in replicate. Results are reported for PAM vs. a control and PAM vs. a hydroseed covered tray. In addition, in the PAM vs. hydroseed comparisons no differences were found for the differing levels of hydroseed and thus only results from the 110 g of hydroseed cover are reported.

Ball Ground soils used for the rainfall simulation were collected from BG2 and thus had approximately 14 % clay content (Table 4.1). In the PAM treatments (applied at 40 kg ha^{-1}) less runoff and total sediment were recovered during simulated rain events under both the 24 hr and 1 hr drying times when compared to the bare soil control (Table 4.2). The PAM (with only 1 hr of drying time) generated both more runoff (1.97 cm) and sediment (195 kg ha^{-1} of total solids). Interestingly, the control treatment generated less sediment when the surface soil was still wet (1 hr drying time) compared to initiating rainfall with a dry surface (24 hr drying time). It is possible that a wet surface helped minimize available energy for slaking soil aggregates. In the PAM vs. hydroseed comparison, PAM performed well under both the 24 hr and 1 hr drying times. In both cases runoff and total solids were virtually absent. The hydroseed did not perform as well as the PAM, although runoff and total solids were low under both conditions (Table 4.2).

The same experiment using the kaolin soil generated relatively similarly results despite the higher clay content of these soils (Table 4.1). The control after 24 hrs of drying again generated the most runoff and total solids with values decreasing for the control under the 1 hr drying condition (Table 4.3). The PAM treatment performed relatively well on both drying conditions, although again generated more runoff with only 1 hr of drying time (Table 4.3). The trials with the PAM vs. hydroseed comparisons generated no runoff in either scenario.

The generally good performance of PAM under these rainfall simulations is consistent with previous observations for similar simulated rainfall studies (Ben-Hur and Lety, 1989; Levy and Agassi, 1995; Green et al., 2000). The mechanisms minimizing runoff are not assessed in this study but probably relate to improved aggregate stability (Nadler et al., 1996). Importantly in this study, however, it is demonstrated that a hydroseed cover is as effective in reducing runoff and sediment loss as is PAM, and thus the field trials are required to more fully assess the value of PAM in reducing erosion when hydroseed is already in use.

Field trials

Soil - The soils from the three field trials differed sightly in both chemical and physical characteristics. More particularly, Ball Ground 1 differed from Ball Ground 2 and 3, which shared greater similarity. Ball Ground 1 that was an engineered slope composed of cut and fill material, had a lower content of clay and a lower cation exchange capacity than BG2 or BG3 (Table 4.1). BG2 and

BG3 that were installed on natural slopes shared greater similarities with surface soil characteristics of the Piedmont region. These characteristics include acidic pH, i.e. <4.5, low ECEC, i.e. <4 $cmol_c$ kg^{-1}, and clay contents of 10 to 20 %. Despite similarities in clay contents of BG2 and BG3, the sites did differ by two-fold in silt contents.

Rainfall – amount and intensity - BG1 received almost no precipitation in the first three months after site installation, with an input for this three-month period of 0.94 cm (Figure 4.2). In mid February the average monthly rainfall amount of 14 cm was reached, but this dropped again when March produced only 7.1 cm of rain. The most significant rain fell in mid April, with a total of 38.2 cm, well above the 14 cm average for the month. Despite these relatively small rainfall amounts this first location did see four intense periods of rain. On February 16^{th} 1.4 cm of rain fell in a ten-minute time span, on April 18^{th} 2.16 cm of rain fell in ten minutes, on April 19^{th} a ten-minute period yielded 2 cm of rain, and on April 20^{th} 1.14 cm of rain fell in ten minutes.

The second location, BG2, had the most rain activity. The first three months after this location was installed, it received close to the average amount of rainfall for each month. January rains at BG2 totaled 11.8 cm, February 9.3 cm, and March 17.7 cm (Figure 4.2). The rain continued into the beginning of April but ended after the second week, achieving only 4.4 cm of rain for the month. Although rainfall amounts were higher at this location, there was only one intense ten-minute storm on January 19^{th} yielding 0.48 cm of rain.

Ball Ground 3 was installed in March and was left *in situ* until the beginning of May. This location did not receive the heavier rains observed at BG2 accumulating only 8.7 cm of rain over the one and half month period (Figure 4.2). Similarly, no intense events per ten-minutes were observed at this site, but on April 3, it did rain steadily for 8 consecutive hours.

Water runoff volume - Water runoff during the above periods of rainfall was estimated at each location using the defined area samplers and the total volume of runoff collected under the different treatments (Fig. 4.3-4.5). At BG1 runoff amounts from the three treatments ranged up to 1.4 cm (Fig. 4.3). Runoff was in fact relatively consistent during the first five rainfall events while the runoff from the final event was diminished both in absolute amount and as a percent of rainfall. Among the treatments there was a general trend of lower runoff in the PAM+hydroseed treatments compared to the control and hydroseed alone treatments.

At BG2 higher total runoff volumes per collector were observed (Fig. 4.4), a response consistent with the heavier rainfall inputs at this site (Fig. 4.3). During the largest rainfall events up to 4 cm of runoff were collected. Runoff also varied temporally at the site in response to rainfall with values decreasing during the lighter rainfall of March but increasing to its highest values again in April when intense rains were apparent (Fig. 4.4). There was no clear pattern in runoff response at this site and in fact the control plot often had the lowest runoff amount. The control plot at this site appeared to vary somewhat in surface soil sand content from the two treatment plots although particle size fractions were not quantified on each plot. After the intense rains in April, the final rainfall event in May was of lesser quantity and runoff was similarly much smaller.

At BG3 there were only four runoff events. Total runoff was similar to amounts at BG2 ranging up to 4 cm (Figure 4.5). The three initial runoff events at BG3 were of a similar order of magnitude while the final event in May was up to five-fold lower with maximum runoff <0.5 cm. The low runoff volume in May was consistent with rainfall inputs. At BG3 there was a general trend of decreasing runoff with treatment intensity such that PAM plus hydroseed was lower than hydroseed that was lower than control.

Water runoff sediments - At all sites and for all treatments, sediments in runoff waters from the defined area samplers were quantified for total suspended sediments (TSS) and for total sediments (TS). All sites shared similar ranges for TSS with values being between 100 and 8000 mg L^{-1} although BG1, the sandiest site, responded with the lowest TSS values on average, ~2000 mg L^{-1} (Fig. 4.3-4.5). TS, on the other hand, differed among the sites with BG1 having values up to 90,000 mg L^{-1} while BG3 had no values over 27,000 mg L^{-1}. All sites shared some similarity is temporal trends with values for both TSS and TS decreasing with time although each site had different response features.

At BG1 TSS concentrations decreased sharply after the first two runoff events, with values being an order of magnitude less during the third and fourth event (Fig. 4.3). No strong patterns among the treatments were apparent at this site for TSS, and in fact results were anomalous during the first runoff event with TSS of the control being much lower than either hydroseed or PAM+hydroseed. In the case of TS the opposite result was observed with TS of the control being consistently higher than the other treatments and TS concentrations in the control remained elevated throughout the period of study.

BG2 differed from BG1 in that TSS concentrations did not change abruptly after some time but appeared to decrease gradually through the period of study (Fig. 4.4). Results for TS concentrations did not have a gradual character but were more erratic with a spike in concentration to >30,000 mg L^{-1} during the February 17th collection. More generally, concentrations for this site were <10,000 mg L^{-1}. For both of these measures, however, there was no apparent response to the treatment with control, hydroseed, and PAM+hydroseed having similar concentrations of sediment in runoff water and similar temporal responses.

Finally, BG3 (that had only four runoff events) had no discernible temporal trends although concentrations of both TSS and TS were lowest in the final runoff collection (Fig. 4.5). TS values were lower on average at BG3 than either BG1 or BG2. At the BG3 location the PAM+hydroseed treatment was consistently lowest for the TSS and TS concentrations. Conversely, concentrations in the hydroseed treatment often exceeded the control for TSS concentrations although TS concentrations were most often below the control.

Total sediment mass movement was estimated at each treatment on each site by multiplying the above runoff volumes by the sediment concentrations and summing over all dates (Figure 4.6). The general patterns in these data are the same as above, with greater differences among treatments at BG1 and BG3 than observed at BG2. The statistical analysis of the treatments across all blocks are based on the cumulative sediment losses and are discussed further below.

Sediment at the silt fence - Height measurements for the amount of sediment that traveled to the silt fence were recorded at five rulers during each runoff collection. The average of these rulers by treatment, date, and location are reported in Figure 4.7. These sediment measures are more integrative of all hill slope processes taking place in the treatment plot, such as rill erosion, compared to the defined area samplers. This is due to the unhindered flow of water over the entire slope compared to the defined area samplers that restrict downslope flow to a two-meter distance (Fig. 4.1). In some cases, ruler measurement decreased from one period to the next in response to lateral movement of sediment along the silt fence. Height increments across all sites ranged from 2 cm to 13 cm on all plots. At BG1, more sediment moved downslope on the control treatment during all dates than on the hydroseed treatment, and both of these plots showed more movement of sediment than the PAM+hydroseed treatment. At BG2 there is little difference between the three treatments. At BG3 the hydroseed treatment seems to control erosion better than the PAM+hydroseed treatment or control. There was a large storm at this location that overwhelmed the silt fence in front of the control treatment and appeared to have overflowed the PAM+hydroseed treatment at the beginning of April. A new height measurement was initiated and added to the previous total but clearly more measurement error was incurred at this site.

Discussion

The main objective of this study was to test whether PAM+hydroseed was more effective in controlling erosion than hydroseed alone, with both being compared to a bare soil control. To assess this hypothesis from the above data, the total sediment mass movement that was accumulated at each treatment on each site (i.e. the final point in Figure 4.6) was used as the measurement unit of interest. A one-way ANOVA was then performed on the mean mass movement for the three plots for each treatment using sites as a blocking factor. A similar analysis was performed on the cumulative height estimates at the base of each plot (Table 4.4).

The average sediment yield from the control plots (25.1±13.8 Mg ha^{-1}; mean±SD) exceeded that from the hydroseed (9.7±6.1 Mg ha^{-1}) or PAM+hydroseed (9.4±7.9 Mg ha^{-1}) plots (Table 4.4). Despite these large differences the overall ANOVA was not statistically significant ($P>0.2$). Values for the all means test in Table 4.4 indicate that the hydroseed and PAM+hydroseed more nearly differed from the control than from each other. The results for cumulative height were similar with the control (8.3±4.1 cm) exceeding hydroseed (4.6±2.8cm) or PAM+hydroseed (3.9±1.5). Again all means of comparison indicated the hydroseed and PAM+hydroseed differed more from the control than each other. These results indicate that PAM+hydroseed did not improve the sediment erosion control beyond that achieved with the hydroseed only treatment.

Knowing how PAM binds to soil, it is important to note that the clay soils of the Georgia piedmont have low activity clays (i.e. kaolinite) and a low CEC (Miller and Baharuddin, 1986; Goldberg et al., 1988; Levy, 1997). Although the pH of these soils does seem low enough to aid in adsorption of the polymer to the soil particles, the low CEC and relative high sand content in surface soils may be a hindrance to bonding with the polyacrylamide. Malik and Letey (1991) found that large polymer molecules with molecular weights of 0.2 to 15 million Mg $mole^{-1}$ did not penetrate well into sandy California soils, which may be a further consideration for cut and fill operations having a high sand content. In addition, at BG1 the absence of rain for three months may have caused the PAM to photodegrade, decreasing its effectiveness. Sojka et al. (2000) found that PAM breaks down quickly in irrigation ditches.

The findings presented here do differ with conclusions from other recent studies on the effectiveness of spray applications of PAM (Stoddard, 1998; Chaudhari and Flanagan, 1998; Flanagan and Chaudhari, 1999; Rao-Espinosa et al., 2000). In each of these studies PAM was interpreted to be effective in comparison to a control but PAM was generally not compared directly to hydroseed treatments. In Roa-Espinosa et al. (2000), however, it was determined that a PAM+mulch treatment was the most effective at reducing erosion to 13 %

of that in the control while PAM treatments reduced runoff to ~40% of that found in the control. No mulch only treatment was available to test its effectiveness in the absence of PAM.

Chaudhari and Flanagan (1998) and Stoddard (1998) did include a PAM plus grass seed treatment in some portion of their studies and both interpreted an increased rate of grass growth in the presence of PAM. The grass on both the hydroseed and PAM+hydroseed plots of this study generally grew thick near the end of the study to effectively hold soil in place. In some cases there was an accumulation of grass inside the silt fence due to seed and mulch being washed down slope. Based on visual assessments of percent grass cover through the study period on all the plots, no clear difference was apparent in the success of grass germination and re-vegetation between the hydroseed and PAM plus hydroseed treatments. The last rains from all the locations generally demonstrate the effect of the grass having grown over the plot. In a number of cases, although a significant volume of water was collected, the amount of TSS and TS in solution decreased to the Georgia stream water standard of 25 NTU (GWSCS, 2000). In the control plots spikes in sediment are apparent through out the study after periods of prolonged rain (Figure 4.3-4.5).

An important difference between these previous studies and the current study is that this study has endeavored to apply PAM at a large plot scale. A number of the previous studies only used defined are samplers for the entire treatment assessment. For example, Stoddard (1998) used six 1 m^2 defined area samplers. The exclusive use of such samplers probably provides a level of application and measurement accuracy greater than that which could be obtained when treating a large plot. Clearly in the current study there was a fair extent of inter-site variability. The use of large plots may also have made applying a sufficient amount of water difficult. PAM generally needs to infiltrate soils to a few millimeters depth (>3 mm) to effectively coat the soil aggregates (Zhang and Miller, 1996). The amount of water used in the current study was limited by the size of the water tank and was estimated to only infiltrate ~2 mm.

Conclusions

The current study on steep slopes in the Georgia piedmont indicates that PAM+hydroseed did not perform better in reducing sediment erosion than the hydroseed alone treatment. Both were clearly superior to a bare soil control. These results strengthen the argument that vegetation must be placed on disturbed soils within a week's time to minimize the amount of soil loss. Whether PAM can add some additional measure of erosion control during short intervals prior to grass growth remains uncertain. Further, the current study measured sediment movement to the bottom of a slope and did not evaluate sediment transport to a stream. The capacity of PAM to flocculate clays may provide some additional benefits in preventing sedimentation to streams even as particles are moving down slope. Clearly no one product is likely to replace wise land clearing practices in the field but PAM likely deserve continued development of application methodologies in hopes of providing a new tool to protect our state waters.

Table 4.1: Soil chemical and physical analysis for soils from three locations in Ball Ground, GA. Samples were collected from Ball Ground 1 and 2 in January 2001 and from Ball Ground 3 in March 2001.

Site	Location	PHw[1]	pHs	Exch-Acid[2]	ECEC	Sand	Silt	Clay
	County			--$cmol_c$ kg^{-1}--		----------%----------		
Ball Ground 1	Cherokee	5.21	4.27	0.42	1.29	67	29	4
Ball Ground 2	Cherokee	5.03	4.10	1.68	3.33	71	15	14
Ball Ground 3	Cherokee	4.25	3.83	1.59	2.85	58	28	14
Kaolin	Kaolin					27	8	55

[1] pHw is pH in deionized water with a soil to solution ratio of 1 to 2 and pHs is salt pH in 0.01 *M* $CaCl_2$.

[2] Exchangeable acidity is measured by soil extraction with 1*M* KCl solution by titration with 0.02 *M* NaOH to pH 8.2. ECEC is estimated by the sum of cations method.

Table 4.2: Rainfall simulator experiments using polyacrylamide (PAM) and hydroseed treatments on soil collected from Ball Ground, GA. Values are an average of laboratory replicates.

Comparison	**Measured component**	**Drying time**	**Control**	**PAM 40 kg/ha**	**Hydroseed 110 g/pan**
PAM vs. Control	Runoff (cm)	24 hr	3.67	0.06	N/A
	TS (kg ha^{-1})		3382	0.05	N/A
	Runoff (cm)	1 hr	4.75	1.97	N/A
	TS (kg ha^{-1})		507	195	N/A
PAM vs. Hydroseed	Runoff (cm)	24 hr	N/A	0.07	0.38
	TS (kg ha^{-1})		N/A	0	3.1
	Runoff (cm)	1 hr	N/A	0	1.18
	TS (kg ha^{-1})		N/A	0	98.5

Table 4.3: Rainfall simulator experiments using polyacrylamide (PAM) and hydroseed treatments on soil collected from Kaolin, GA. Values are an average of laboratory replicates.

Comparison	**Drying time**	**Measured component**	**Control**	**PAM 40 kg/ha**	**Hydroseed 110 g/pan**
PAM vs. Control	24 hr	Runoff (cm)	1.78	0.18	N/A
		TS (kg ha^{-1})	4317	30	N/A
	1 hr	Runoff (cm)	1.75	1.60	N/A
		TS (kg ha^{-1})	165	143	N/A
PAM vs. Hydroseed	24 hr	Runoff (cm)	N/A	0.0	0.0
		TS (kg ha^{-1})	N/A	0	0
	1 hr	Runoff (cm)	N/A	0.0	0.0
		TS (kg ha^{-1})	N/A	0	0

Table 4.4. Results from all means comparison using the using the cumulative total solids collected from the defined area samplers and the cumulative total height accumulation measured at the silt. C is control; H is hydroseed alone; P is PAM+hydroseed.

Trt	Cumulative total solids	C vs H C vs P	H vs P	Cumulative sediment height	C vs H C vs P	H vs P
	kg ha^{-1}	*P*>F	*P*>F	cm	*P*>F	*P*>F
C	25114			8.31		
H	9719	0.16		4.56	0.20	
P	9416	0.16	0.97	3.86	0.14	0.78

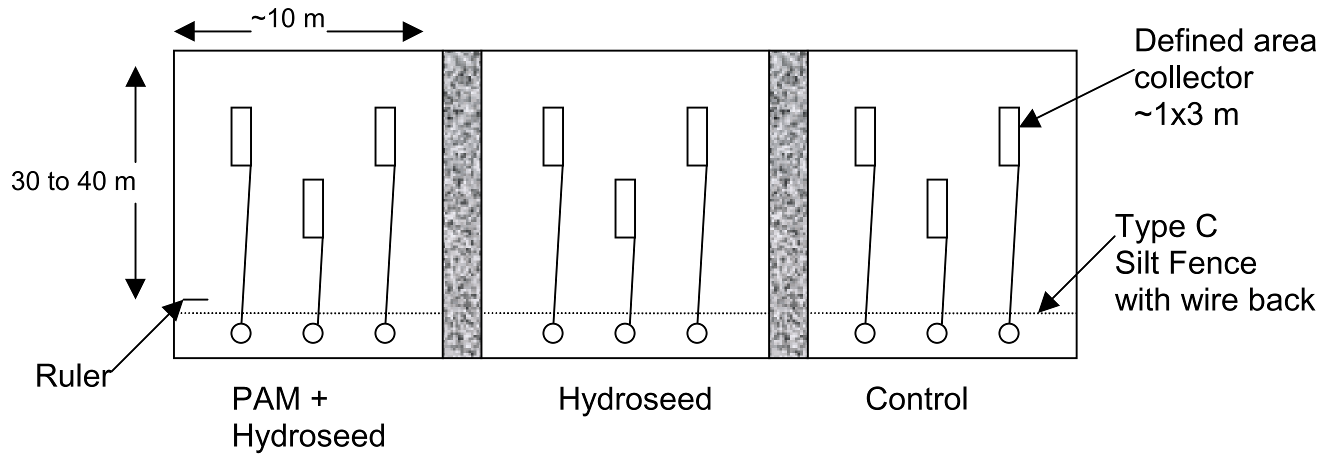

Figure 4.1: Diagrammatic presentation of plot design for Ball Ground, Georgia.

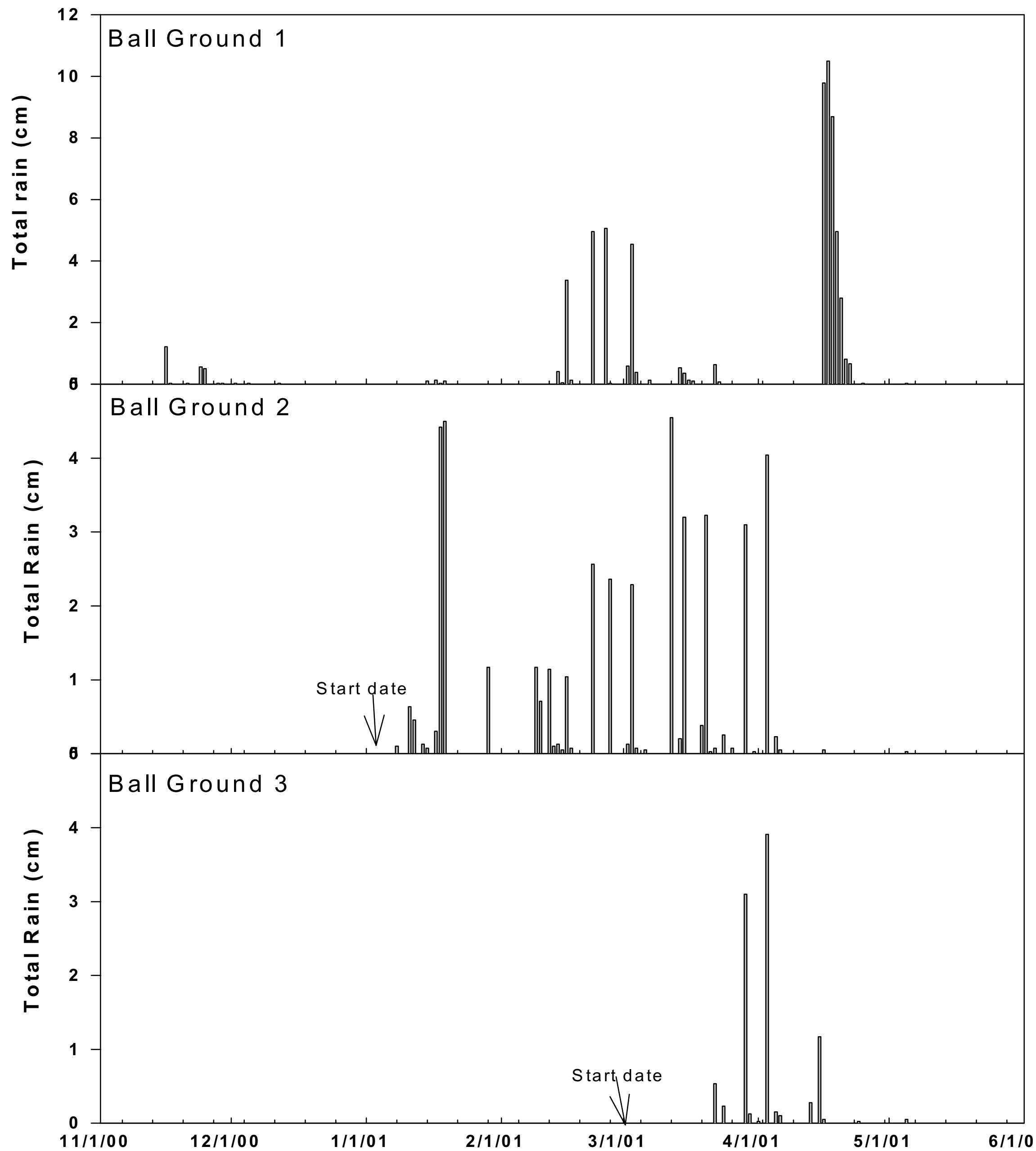

Figure 4.2: Rainfall data in cm per day for the three Ball Ground, GA. Data was collected at each location with a tipping rain gage bucket and datalogger.

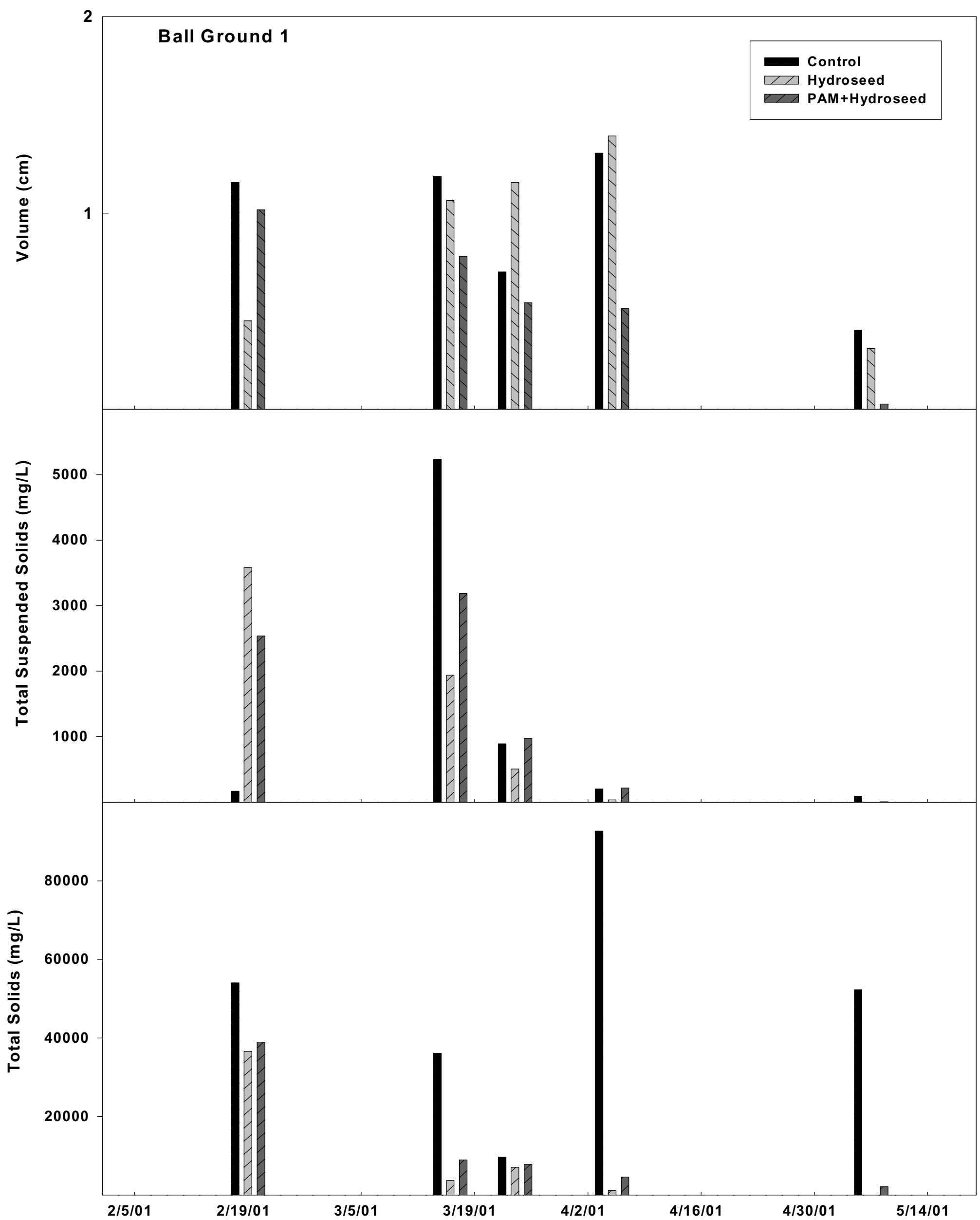

Figure 4.3: Volume of runoff water, total suspended solids, and total solids concentration in the runoff water for a control, hydroseed, and PAM+hydroseed treatments in Ball Ground, GA.

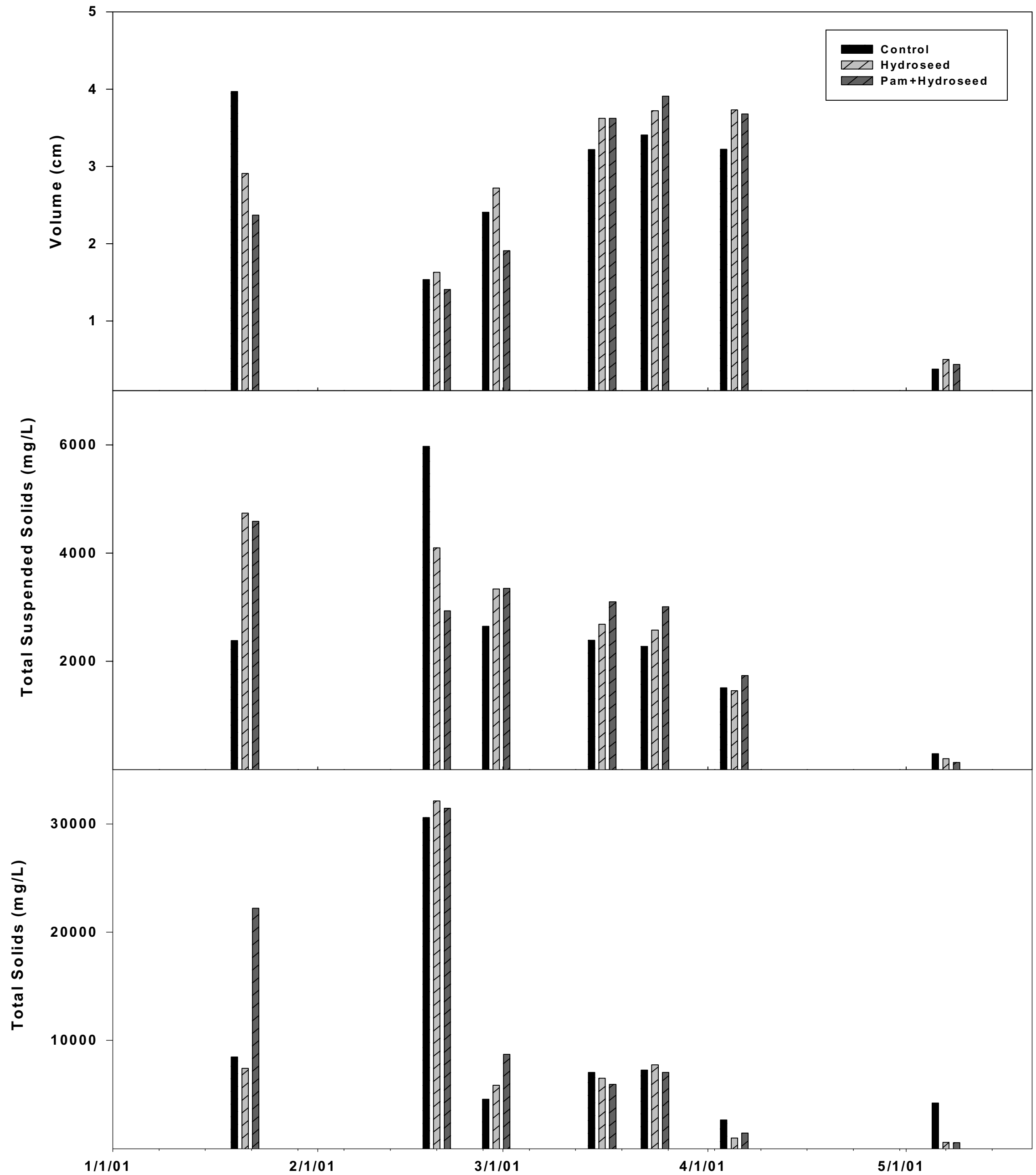

Figure 4.4: Volume of runoff water, total suspended solids, and total solids concentration in the runoff water for a control, hydroseed, and PAM+hydroseed treatments in Ball Ground, GA.

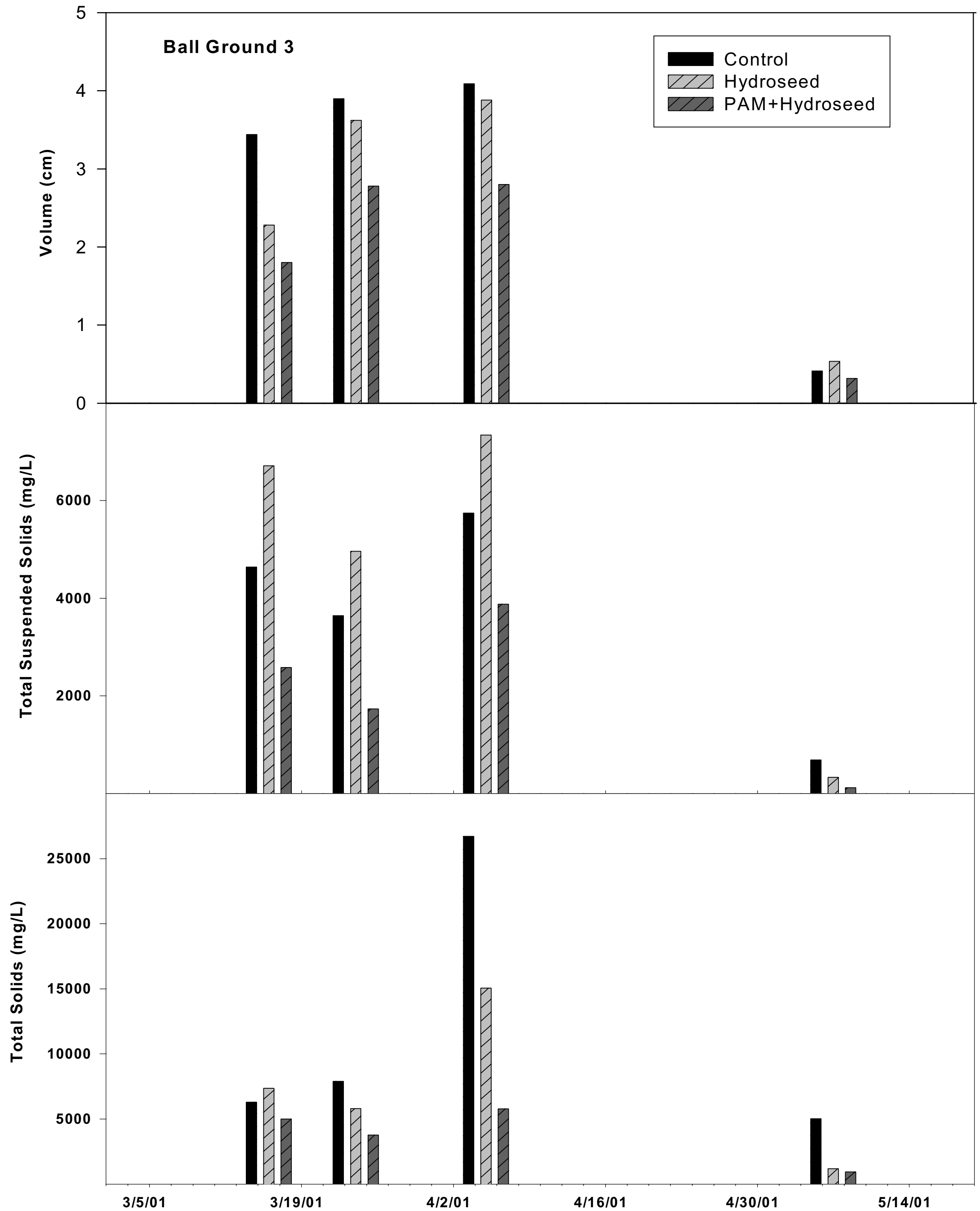

Figure 4.5: Volume of runoff water, total suspended solids, and total solids concentration in the runoff water for a control, hydroseed, and PAM+hydroseed treatments in Ball Ground, GA.

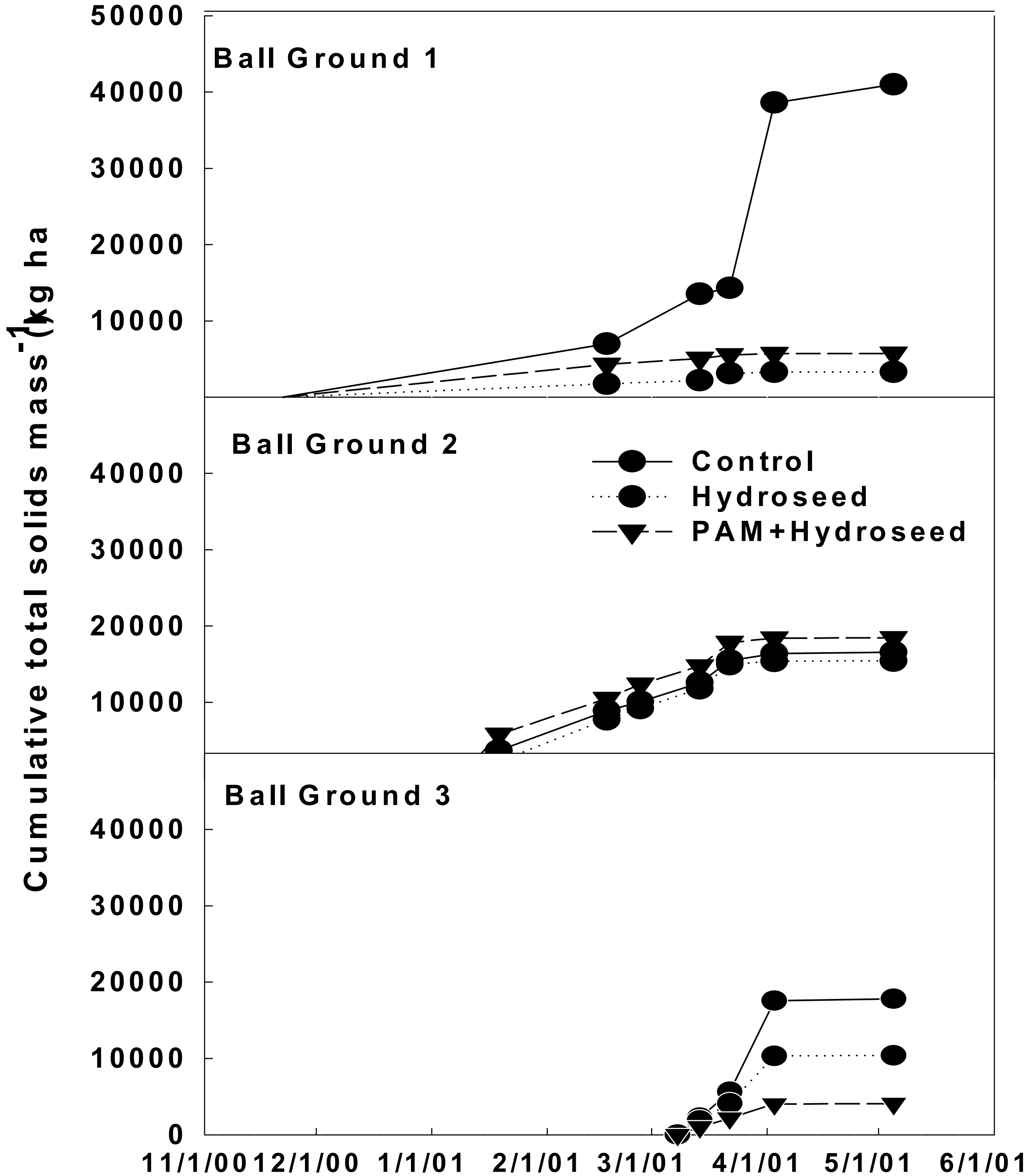

Figure 4.6: Total solids accumulation in runoff waters over the period of study for three Ball Ground locations under treatments of PAM+hydroseed, hydroseed alone, and a bare soil control.

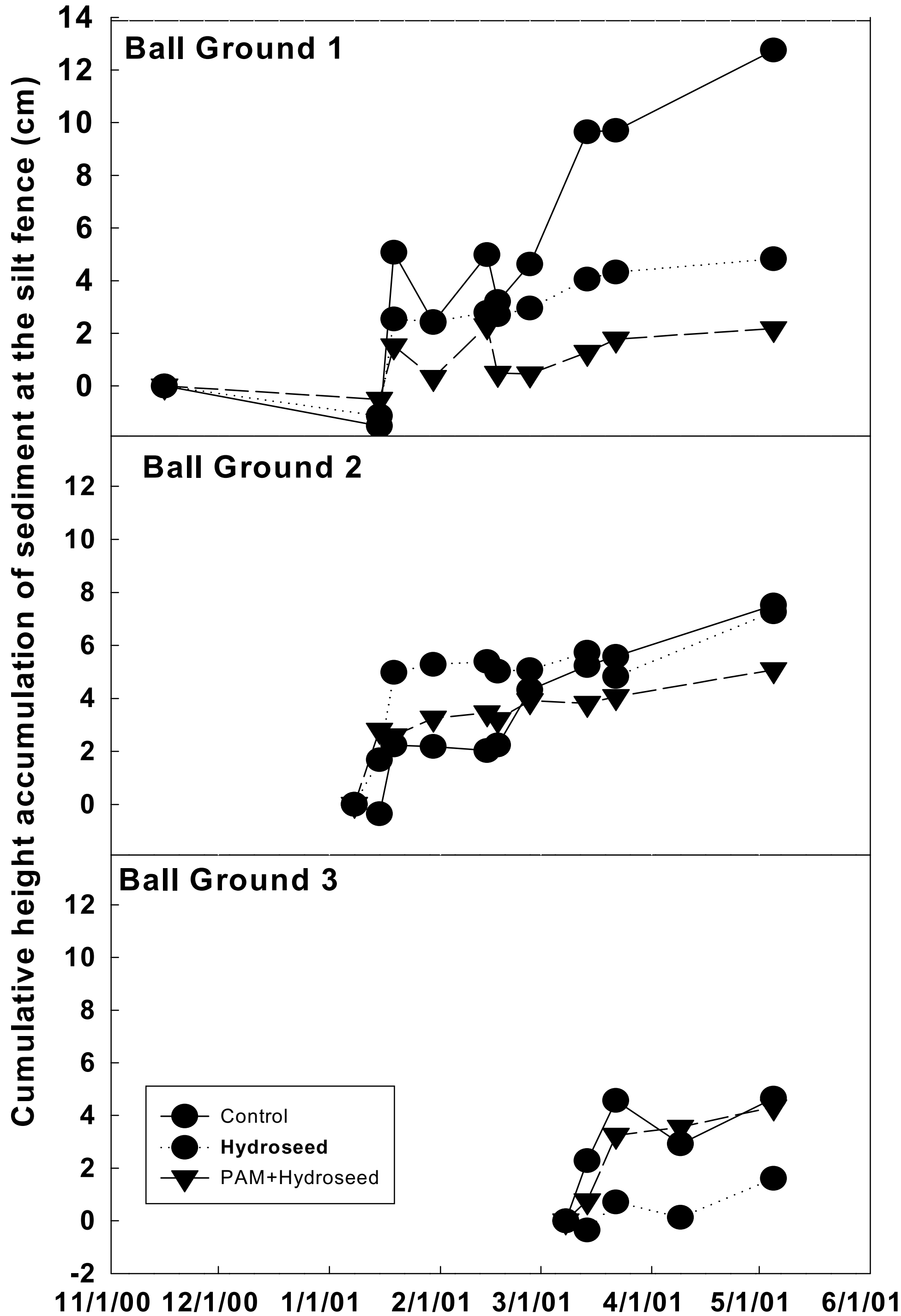

Figure 4.7: Total height accumulation of sediments along the silt fence at the base of each plot over the period of collection under treatments of PAM+Hydroseed, hydroseed alone, and a bare soil control.

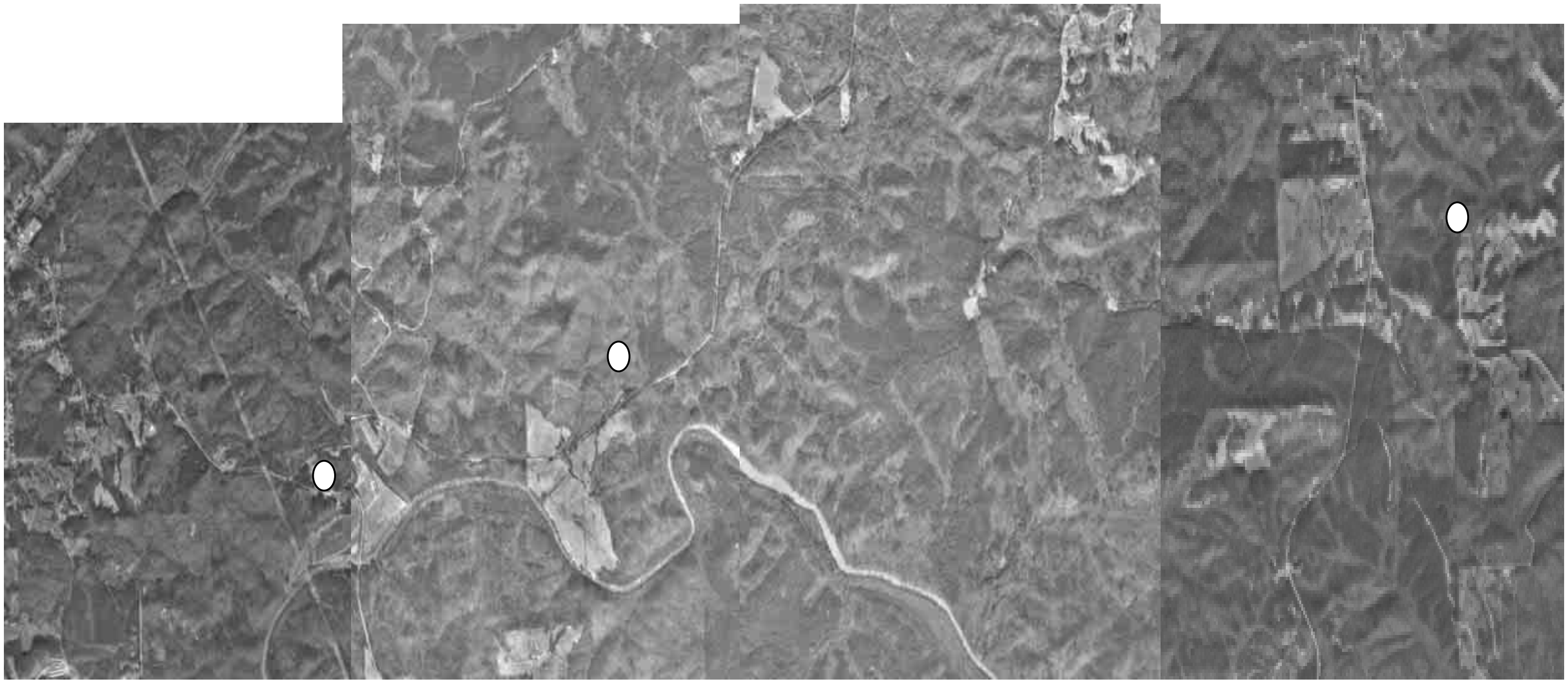

Photo 4.1: USGS digital orthophoto quadrangle (DOQ) of Ball Ground sites (http://gis1.state.ga.us/orthoview.htm). Each DOQ in the composite is a quarter-quadrangle of 3.75 x 3.75 minutes of latitude and longitude. Ball Ground 1 is on the left, then Ball Ground 2, with Ball Ground 3 on the far right of picture. The Etowah River is marked with an arrow below Ball Ground 1 and 2.

CHAPTER 5

SUMMARY AND CONCLUSION

The current study on steep slopes in the Georgia piedmont indicates that PAM+hydroseed did not perform better in reducing sediment erosion than the hydroseed alone treatment. Both were clearly superior to a bare soil control. These results strengthen the argument that vegetation must be placed on disturbed soils within a week's time to minimize the amount of soil loss. Whether PAM can add some additional measure of erosion control during short intervals prior to grass growth remains uncertain. Further, the current study measured sediment movement to the bottom of a slope and did not evaluate sediment transport to a stream. The capacity of PAM to flocculate clays may provide some additional benefits in preventing sedimentation to streams even as particles are moving down slope. Clearly no one product is likely to replace wise land clearing practices in the field but PAM likely deserve continued development of application methodologies in hopes of providing a new tool to protect our state waters.

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