ABSTRACT

WHITLEY, KIMBERLEY DAIL. Evaluation of Polyacrylamide for Improvement in Soil Infiltration and Field Evaluation of Hydromulches for Water Quality and Vegetation Establishment. (Under the direction of Dr. Richard McLaughlin and Dr. Joshua Heitman).

Erosion control on construction sites remains a key issue for water quality protection. Erosion control strategies can focus on reducing rainfall impact through addition of groundcover, or soil treatment to improve runoff water quality. Our first objective was to evaluate hydromulches (i.e. groundcover) for erosion control and vegetation establishment, a key for sustained erosion control. Five groundcovers were evaluated on a 2.88:1 fill slope in Kinston, NC. Treatments included: (1) straw + tackifier; (2) straw + polyacrylamide (PAM) + tackifier; (3) 70/30 wood/ paper fiber blend; (4) wood fiber; and (5) hydroblanket bonded-fiber matrix. Total suspended solids (TSS), turbidity and runoff volume were recorded for each of five sampling events. Biomass estimates were recorded 2 mo post-planting. There were no significant treatment differences in runoff, turbidity, TSS, or biomass ($p=0.5594$, $p=0.3862$, $p=0.6760$, and $p=0.1495$, respectively). Overall, TSS and turbidity values were extremely low compared to values typically found on construction sites. Treatment of soil with PAM has been shown to improve runoff water quality and infiltration. However, the appropriate application rate and method still remains unclear. Our second objective was to analyze how variations in PAM rate, water volume applied with PAM, straw cover, drying time, and mixing method affect runoff water quality. A clay loam subsoil packed to 1.5 g cm^{-3} bulk density was used in rainfall simulation tests at a 5% slope. Treatment combinations were applied as either randomized complete block or 2x2 factorial designs. Time to runoff, runoff volume, TSS, and turbidity were recorded. Results indicate both application water volume and ground cover effects. When PAM rates were low (i.e. 4.4 kg ha^{-1}), treatments

receiving the largest water volume application resulted in lower turbidity and TSS values ($p=0.0425$ and $p=0.015$). Higher application volumes produced less viscous PAM solutions and may have provided deeper penetration. Bare soil treatments, despite addition of PAM, always resulted in higher turbidity and TSS values, as well as shorter time to runoff and larger runoff volume. Effectiveness of PAM was improved when the straw cover was increased from 2,100 to 4,800 kg ha^{-1}, or roughly 50% to 100% cover. The PAM + 100% cover treatment resulted in significantly lower turbidity and TSS values than did PAM + 50% cover ($p=0.0187$ and $p=0.0237$). There were no significant differences for PAM mixing method (sump pump vs. trolling motor), even though viscosity was different, or allowing the soil to dry for 3-5 days. Overall, research suggests a limited relationship between ground cover and grass establishment, but that PAM, when applied with ground cover and appropriate water volume, may improve water quality of runoff.

Evaluation of Polyacrylamide for Improvement in Soil Infiltration and Field Evaluation of Hydromulches for Water Quality and Vegetation Establishment.

by
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A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Soil Science

Raleigh, North Carolina

2011

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BIOGRAPHY

Kimberley D. Whitley was born November 18, 1986 in Elizabeth City, North Carolina and was raised in the small town of Hertford, located in northeastern North Carolina. After graduating as valedictorian from Perquimans County High School in May 2004, Kim attended North Carolina State University. Graduating summa cum laude, she received her B.S. in Agronomy with a concentration in Soil Science in December 2008. Following graduation, Kim decided to further her education and began graduate school in Soil Science at N.C. State under the direction of Dr. Rich McLaughlin and Dr. Josh Heitman.

ACKNOWLEDGMENTS

As I come to the end of this chapter in my life, there are many people to which I owe thanks. First I would like to thank God for never giving me more than I can handle, even though sometimes I think he's pushing it. Secondly, I would like to thank my committee members Dr. Rich McLaughlin, Dr. Josh Heitman, and Dr. Rich Cooper. Your guidance and support are what has allowed me to achieve my goals both as a student and a researcher. I would also like to thank Joy Smith for the long, frustrating hours in which she helped me to analyze my data, Brenda Penny who helped with my seed testing, and Rob Austin who assisted me with some digital imaging. In regards to Jamie Luther, Melanie McCaleb, Matt Haynes, Craig Callis, and Virginia Brown, thanks for sweating with me in the heat, freezing with me in the cold, and for all the fun memories. You all are amazing people and without you, I could have never been successful. Finally, to my friends and family (my Mom in particular), thanks for standing behind me all the way, tolerating my mood swings, and loving me nonetheless. I love you all.

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CHAPTER 1: LITERATURE REVIEW

Erosion & Hydromulch

Whether it results from agricultural practices, urban runoff, construction, or forest activities, sedimentation is "one of the most widespread pollutants affecting assessed rivers and streams, [and is] second only to pathogens (bacteria)" (US EPA, 2009b). It is also important to note that from the list above, erosion from construction sites is an important contributor of sedimentation. Common erosion rates include "…forest lands los[ing] an average of 0.36 metric t ha^{-1} (1 t ac^{-1}) per year; agriculture…an average of 5.5 m t ha^{-1} (15 t ac^{-1}) per year, while construction sites average 73.3 m t ha^{-1} (200 t ac^{-1}) per year" (Faucette et al., 2006). The United States Environmental Protection Agency (US EPA, 2009b) validates this statement and goes even further stating that "sediment runoff rates from construction sites are 10 to 20 times greater than those of agricultural lands, and 1,000 to 2,000 times greater than those of forest lands." Such runoff results in both onsite and offsite damage, especially in terms of water quality. As a result, the Clean Water Act was implemented in 1972. This act set the foundation for the NPDES (National Pollutant Discharge Elimination System) permitting program and allowed both the EPA and state governments to regulate water effluent guidelines (US EPA, 2009a). In December of 2005, the EPA implemented the revised version of the Stormwater Phase II Final Rule. This rule requires all small MS4 (regulated municipal separate storm sewer system) operators to develop, implement, and enforce a stormwater pollution plan for all sites of disturbance greater than or equal to an acre using best management practices (BMP's) (US EPA, 2009b).

In order to prevent erosion on disturbed areas, short-term temporary ground covers such as erosion control blankets (ECB's), hydromulches, and straw mulches are often

applied. However, the ground covers are only temporary, with long-term erosion control and runoff reduction being accomplished through the establishment of dense vegetative cover (Benik et al., 2003a. and Faucette et al., 2006). To facilitate the establishment of vegetative cover, the North Carolina Department of Transportation (NC DOT) has recommended practices which account for the variation in climatic conditions and topography across the state as well as in soil characteristics across individual construction sites (NC DOT, 2009). Soils found on construction sites have been subject to cut and fill operations, which result in low fertility, subsurface horizons being brought to the surface (Benik et al., 2003a). Such excavation and variation in site conditions results in the need to use grass mixtures. Mixing seed from different grass species provides some insurance of vegetation establishment, since it is unlikely that all of the species present will be susceptible to the same stresses (Emmons, 1995). Although the combination varies depending on the region of the state, the majority of NC DOT grass mixtures consist of tall or hard fescue, Kentucky bluegrass, bermudagrass, and centipedegrass (NC DOT, 2009).

Tall fescue grows best in the piedmont and mountains, but can be successfully maintained on silt loams of the coastal plain. It is considered low maintenance in that it is both drought and cold tolerant, exhibits good disease resistance, and can tolerate low fertility, as well as moderate traffic. With such tolerances, it follows that tall fescue can survive on a wide range of soil conditions including infertile sand, compacted clay, and both alkaline and saline soils. Suitable pH ranges vary from 4.7 to 9.5 (Hannaway et al., 2009). One disadvantage of tall fescue is that damaged or bare areas have to be re-seeded, a direct result of its bunch-type growth habit (Bruneau, 1985 and Emmons, 2005).

Hard fescue, like tall fescue, is a drought tolerant, bunch-type grass and exhibits good disease resistance. Hard fescue is well adapted to shade and "poor soils" and is commonly used for erosion prevention/soil stabilization (Emmons, 2005 and Turgeon, 1996).

Commonly grown in conjunction with fescue, Kentucky bluegrass is well-known for its rhizomatous growth habit which allows for traffic and pest tolerance, as well as a quick recovery time (Bruneau, 1985). Although it may become dormant during periods of high temperatures, Kentucky bluegrass is very drought tolerant and will recover quickly with the return of cool, moist weather (Emmons, 2005). That being said, it grows best in the mountains of North Carolina, but can also be grown in the Piedmont. It, however, does not perform well in the Coastal Plain. Kentucky bluegrass "prefers fertile, limed, well-drained soil in sun or light shade" (Bruneau, 1985). Its optimum pH range is between 6 and 7 (Emmons, 2005).

Bermudagrass, known for its aggressive growth establishment and recuperative potential, has both a stoloniferous and rhizomatous growth habit (Emmons, 2005). Bermudagrass grows well on most soil types, except those that are poorly drained. Like the other varieties discussed above, it too is very drought tolerant. Bermudagrass is not shade tolerant, but when grown in full sunlight will form "a dense, durable surface" (Bruneau, 1985).

Centipedegrass is considered a "low maintenance" turf due to the fact that little fertilizer is required once vegetation has become established (Bruneau, 1985). Although it will develop on a wide range of soil conditions, it grows well on acidic, infertile soils (Emmons, 2005). Centipedegrass is more sensitive compared to the other grasses in that it "does not tolerate traffic, compaction, high soil pH, high soil phosphorus, excessive thatch,

drought, or heavy shade" (Bruneau, 1985). It also has a low salt tolerance (Emmons, 2005). Furthermore, centipedegrass has a stoloniferous growth habit and is slow to become established (Bruneau, 1985).

After determining the proper mixture of grass species to use on a site, members of the DOT must consider which BMP (temporary or permanent) will best facilitate long-term slope stabilization in terms of vegetation re-establishment. Due to the rising prices and high failure rate of straw mulch, the use of hydromulches is now of high interest in terms of erosion control and vegetation establishment (B. Blackburn; personal communication; 2010). The Erosion Control Technology Council (ECTC, 2009) defines hydraulic erosion control products, also known as "hydromulches", as "…manufactured, temporary degradable, pre-packaged fibrous material[s] that [are] mixed with water and hydraulically applied as a slurry designed to reduce soil erosion and assist in the establishment and growth of vegetation." However, the majority of research on hydromulches focuses on their ability to control erosion and subsequent water quality. The studies that have examined hydromulches in terms of vegetation establishment have had varying and somewhat inconclusive results.

Dougherty et al. (2008) tested the effects of wheat straw, erosion control blankets, and two types of hydromulch in comparison to a bare soil treatment for differences in runoff and sediment yield. One type of hydromulch was made from recycled cotton gin trash (Geoskin^{TM}) and the other was unspecified. The hydromulch treatments were applied in two ways: (1) hydromulch in conjunction with lime, fertilizer, and seed and (2) hydromulch applied following incorporation of fertilizer, lime, and the addition of seed. One of the hydromulch treatments (i.e. the unspecified hydromulch as a slurry) had to be excluded from the trial due to problems with the sample barrel. The results indicated that the wheat straw

treatment and the Geoskin^{TM} pre-mixed slurry treatment had the lowest mean and total runoff volume (i.e. 78.2 L, 782 L and 91.5 L, 915 L respectively). The two hydromulch treatments not applied as a pre-mixed slurry ranked second in terms of low runoff volume (129.8 L, 1298 L and 239.4 L, 2394 L), followed by the erosion control blanket (246.4 L, 2464 L) and the bare soil plot (313.6 L, 3136 L). When evaluated for sediment yields, the wheat straw treatment, hydromulch not applied as a slurry, and the erosion control blanket exhibited the lowest mean and total sediment yield followed by the Geoskin^{TM} and the bare treatments.

Megahan et al. (2001) evaluated cutslope erosion on forest roads in Idaho. Three erosion control treatments, dry seeding, hydroseeding plus mulch and terracing with hydroseeding plus mulch, were tested. The study road varied in soil properties; certain areas contained deep alluvial soils, others had terraces, and some places were shallow to bedrock. Dry seeding on deep alluvial soils and hydroseeding with mulch resulted in the largest reduction in erosion rates (1.7 t $ha^{-1}ac^{-1}$ and 7.1 t $ha^{-1}ac^{-1}$) in comparison to the control (16.4 t $ha^{-1}ac^{-1}$). Dry seeding on soils that were shallow to bedrock and terraces that received both hydroseeding and mulch treatments also reduced erosion rates, but were not considered statistically significant. This study also analyzed cost-effectiveness of the treatments and concluded that "unit area costs for dry seeding average about 10 percent of costs for hydroseeding + mulch" (Megahan et al., 2001).

Holt et al. (2005) compared traditional wood and paper hydromulches to cottonseed hulls, as well as three types of hydromulch made from cotton gin by-products (abbreviated as "COBY" treatments). All mulches were applied at two rates: 1121 kg ha^{-1} or 2242 kg ha^{-1}. However, the rate effect proved to be insignificant (p=0.181). Results of this study indicated a relationship between time to runoff and total sediment loss from the catch samples. In the

case of the paper mulch, this treatment had the longest time to runoff (20.3 minutes) and produced the highest sediment yield (35,400 kg ha^{-1}). The wood mulch treatment had the second highest time to runoff (17.6 minutes) and corresponding second highest erosion rate (28,900 kg ha^{-1}). The COBY treatments did reveal lower erosion rates (i.e. COBY green—18,600 kg ha^{-1}, COBY red—16,000 kg ha^{-1}, and COBY yellow—21,200 kg ha^{-1}) but were not considered statistically different from the paper or wood hydromulches. The cottonseed hulls exhibited the lowest erosion rate of 6,100 kg ha^{-1}.

Benik et al. (2003b) examined the effects of five different erosion control products on the side of a sedimentation basin in Minnesota for runoff and erosion rates and vegetative growth. The trials were conducted under both fall and spring conditions. The spring application resulted in little to no vegetation establishment and the fall application produced good vegetative growth. The five treatments included: 1) bare soil, 2) straw mulch, 3) bonded fiber matrix hydromulch (BFM), 4) straw/coconut blanket, and 5) wood-fiber blanket. All plots received a slow-release fertilizer and were seeded with a DOT mixture before the mulch was applied. Runoff amounts were statistically greatest for the straw mulch treatments during the spring trials and the bare soil treatment during the fall trials. Erosion rates were highest for both the bare treatment and the straw mulch despite the season. However, it is important to note that the erosion rates were significantly lower during the fall trials as a result of improved vegetation establishment. Overall, the erosion control products "performed well in reducing soil erosion" and for the spring trials "the ratio for erosion from erosion control product to that from bare plots was approximately 1:100" (Benik et al., 2003b). However, no statistical differences were noted between the BFM and ECB treatments. This study also evaluated the five erosion control products for overall vegetation establishment. Out of all of

the treatments, the straw-mulch and bare soil plots had the highest above-ground biomass and the BFM plots had the lowest. Despite being seeded with a DOT mix, weeds were the dominant vegetation present on all plots.

One of the few studies which evaluated mulches specifically for vegetation growth included four types of compost blankets, two hydromulches, and a bare soil control (Faucette et al., 2006). After three months, there were no significant differences between the control and the hydromulched treatments. There was, however, 2.75 times more vegetation present in the composted plots as compared to the hydromulch plots. There were no differences between hydromulched and composted plots in vegetative cover at twelve months and both were higher than the control, indicating that vegetative establishment had increased in the hydromulch plots. Faucette et al. (2006) also documented that the weed biomass in the hydromulch plots was considerably higher than that of the composted or control plots. It was concluded that "compost applications will provide a greater vegetation cover in the short term and less invasive weed growth in the long term relative to hydroseeding".

Two separate studies in Kentucky evaluated different types of mulch materials (some hydraulically applied and some mat mulches) for vegetation establishment and cost-effectiveness. The first study conducted in 1984-1985 tested four mat mulches (AMEX—a mat consisting of plastic mesh and curled wood fibers, GULF STATES—a nylon mesh mat interwoven with paper strips, JUTE—mesh mat made from jute fiber, and VERYOL—straw mulch mat) and two hydromulches (CONWED—made from hardwood fiber and HANSFORD—combination of fescue hay fibers and a binder to hold seed in place) (Ringe and Graves, 1985). During the first year (1984) all mulching treatments exhibited an increase in vegetation establishment when compared to the control, but there were no significant

differences among the treatments. Effects were still observed in the second year (1985), but no significant differences remained between the control and the mulched plots.

The second study in 1987 also tested four types of mat mulches and two hydromulches (Ringe and Graves, 1987). They were composed of the same types of material, but had different names (i.e. EXCELSIOR, HYDROMULCH 1, HYDROMULCH 2, JUTE, and STRAW). Just like the first study, all treatments resulted in significantly greater vegetation establishment compared to the bare soil control, and no differences were found among the ground covers.

Both studies evaluated the cost/effectiveness ratio (CER) of the various mulch treatments, relating the installation costs to the vegetation establishment improvement. The ratio was defined as CER=ICM/PI, where PI= [(CVM-CVC)/CVC](100), CVM is coverage percent obtained with a particular mulch, CVC is coverage percent using the control, PI is percent improvement in coverage due to mulch type, and ICM is the installation cost of a particular mulch.

In both studies, the hydromulches proved to be the most cost-effective. For example, in the 1987 study the ratios for HYDROMULCH 1 and HYDROMULCH 2 were much lower than those for EXCELSIOR, PAPER, JUTE, and STRAW; 0.13 and 0.14 versus 1.27, 1.51, 1.58, and 1.71, respectively. The studies also acknowledged that hydromulches might not serve as the best choice in areas that receive concentrated water runoff, such as drainage paths.

McLaughlin and Brown (2006) evaluated whether four types of mulch groundcovers had improved vegetation establishment with the addition of polyacrylamide (PAM) under simulated and natural rainfall conditions. The four groundcovers consisted of straw, straw

erosion control blanket, and wood fiber and mechanically bonded fiber matrix (MBFM) hydromulch. With or without the addition of PAM, the treatment that yielded the best vegetative cover was the straw. It was noted that grass seed on the bare plots tended to wash into low spots and the seed on the MBFM plots had trouble emerging through areas where the hydromulch had been applied more thickly. Both scenarios resulted in "spottier growth" in comparison to the straw and ECB treatments. However, in terms of water quality, the MBFM treatment showed a greater reduction in turbidity than the straw. Overall, the addition of PAM significantly reduced turbidity under all treatments, but did not provide a "consistent benefit" for improving ground cover.

Benik et al. (2003a) evaluated five different erosion control products for their capability to establish vegetation and reduce both runoff and erosion control. The five products included a wood fiber blanket, a straw blanket, a straw/coconut blanket, a hydraulically applied bonded fiber matrix, and a disk-anchored straw mulch. A large storm hit early on in the study and resulted in a failure of the BFM plots forcing them to be re-classified as "bare-treatment plots." Of the treatments that were left, the product that produced the most vegetative cover and had the least amount of runoff was the straw-mulch. The bare treatment produced the opposite effect and had the greatest runoff volumes, sediment yields, and the lowest amount of vegetative biomass. They found that the bare plots often produced a sediment yield ten times greater than any of the blanket treatments, with no significant differences occurring amongst the blanket treatments.

Overall, the majority of the literature only analyzed hydromulches for differences in total runoff and erosion rates. Very few studies actually evaluated hydromulches for vegetation establishment and those that did rarely found any significant differences among

treatment types, with the exception of two studies (McLaughlin and Brown, 2006, and Benik et al., 2003a) in which the straw mulches yielded the greatest vegetative cover. There also have not been many studies that only compare different types of hydromulches; many of the studies compare a hydromulch to erosion control blankets and bare soil plots. Finally, little research has been conducted in North Carolina. In order to make informed decisions on ground cover choices, additional research is needed to suggest when and where each type of ground cover will be the most successful in establishing vegetation and restraining erosion. Based on the literature, it is hypothesized that plots receiving straw mulches will produce greater amounts of vegetation.

Polyacrylamide

Polyacrylamide (PAM) includes a broad class of polymers composed of repeating acrylamide and acrylate chains (Lee et al., 2010 and Sojka et al., 2007). These polymers vary by chain length, type and number of functional groups, conformation (i.e. linear vs. cross-linked), and form (i.e. aqueous solutions, emulsions, and dry forms). PAM can be cationic, anionic, or nonionic, with linear, anionic PAMs commonly selected for environmental application due to their low aquatic toxicities (Sojka et al., 2007). In addition, such PAMs typically weigh 12-15 Mg mol^{-1}, contain 150,000 monomer segments per molecule, have negative charge densities of 8-35%, and contain 0.05% acrylamide monomer or less (Roa-Espinosa et al., 1999 and Sojka et al., 2007).

The homopolymer found in anionic PAMs used for erosion control and infiltration management are copolymerized by splicing amide functional groups and replacing them with protons like Na^{+}. These ions freely dissociate in water resulting in negative charge sites along the homopolymer chain (Sojka et al., 2007). When PAM is in contact with water and soil

particles, cationic electrolytes from the water are attracted to the negative charge sites on the soil (Vacher et al., 2003). Those cations, in turn, attract the negatively charged PAM molecules via Coulombic and van der Waals forces, creating what is commonly known as "cation bridges" (Lee et al., 2010). These "cation bridges" thus allow particles with opposing charges to be "bridged" together and is the basis for PAM's ability to settle suspended solids whether these solids are in a water treatment plant or in runoff from construction sites (McLaughlin and Bartholomew, 2007). Typically, the longer, less-coiled PAM molecules are more strongly adsorbed to soil particles. However, soils that contain high amounts of organic matter experience less PAM sorption despite chain length (Sojka et al., 2007).

Following the publication of the interim PAM-use conservation standard by the US NRCS in 1995, PAMs were soon commercialized for erosion control in the United States. In 2007, it was estimated that one million hectares of irrigated cropland in the US were PAM-treated and its use is expected to grow due to both state and federal water quality mandates (Sojka et al., 2007).

Effects on Seedling Emergence & PAM in Conjunction with BMP's

Previous research on PAM covers an array of topics ranging from seedling emergence and crust formation prevention, to implementation with best management practices (BMPs) on construction sites.

Rapp et al. (2000) evaluated how soil sodicity, phosphogypsum, PAM, and raindrop impact energy affected crust impedance, evaporation, and subsequent cotton and onion seedling emergence on two soils (hamra—mixed, loamy, typic Rhodxeralf and loess—mixed, silty loam, calcic Haploxeralf). For the PAM treatment, a 500 $\mu g\ mL^{-1}$ anionic PAM mixture was sprayed on the surface of 2L plastic pots that had been packed with soil to a bulk

density of 1.25 g cm^3. In addition, phosphogypsum, commonly used to increase electrolyte concentrations of soil solutions, was applied to the soil surface at a 5 t ha^{-1} rate prior to simulated rainfall. The PAM and phosphogypsum treatment stabilized soil surface structure, reduced surface seal formation, and increased onion seed emergence in the loess soil. No significant differences were observed for seedling emergence in the hamra soil.

Similar findings exist for other vegetable and grass seedling emergence. Wallace (1987) planted tomato and lettuce seeds in pots filled with two soil types (slightly calcareous sandy loam and a slightly saline clay loam). Following seeding, 50 mL of a 20 mg L^{-1} anionic PAM solution was applied to half of the pots, leaving the others as controls. The slightly calcareous sandy loam soil was found to be most responsive to the PAM addition in that the pots receiving the PAM mixture had accelerated seedling emergence and increased seedling dry weights. Despite the overall lower seedling emergence rates of the clay loam soil, seedling emergence and dry weights were greater in comparison to the controls (Wallace, 1987).

The development of surface crusts and diminished seedling emergence in rangelands prompted a two-year evaluation of PAM on several species of grass (i.e. blue panicgrass, King Ranch bluestem, sideoats grama, plains bristlegrass, and 'salado' alklai sacaton) in southcentral New Mexico (Rubio et al., 1992). PAM solutions were prepared by dissolving equivalent rates of 0, 10, 20, and 40 kg ha^{-1} in 10 L of water. The 10 L PAM solutions were then applied to 3 m x 2 m plots using water cans and seedling emergence was observed 30 days following the first rain event. During the first year of the study, seedling emergence for both blue panicgrass and sideoats grama increased quadratically as PAM rates increased. King Ranch bluestem was unaffected by the addition of PAM and plains bristlegrass did not

emerge in any of the plots. Similar trends developed during the second year with blue panicgrass and sideoats grama responding positively to the addition of PAM. Once again, King Ranch bluestem, as well as 'salado' alklai sacaton, did not illustrate improved seedling emergence with the addition of PAM.

The use of PAM in conjunction with other erosion control/best management practices on construction sites has also been studied. Hayes et al. (2005) applied two different kinds of PAM at 10.5, 5.2, 1.5, and 0.76 kg ha^{-1} rates to plots both with and without grass seeding and straw mulching. The plots were located on three different NC DOT construction sites. Polyacrylamide was mixed with water and applied with pressurized garden sprayers on the first site and with sprinkler cans on the second and third. On the first and second sites, the application of seed/mulch greatly reduced turbidity and sediment loss in comparison to the bare soil or PAM only treatments, thus illustrating the importance of ground cover. On the second site, the addition of PAM did reduce turbidity for all events at the $p < 0.10$ level. The third site, located in the Coastal Plain and composed of a sandy fill soil, exhibited higher total runoff values over all 7 events for those plots treated with PAM. It was hypothesized that this was due to PAM clogging the soil pores and resulting in more runoff. Hayes et al. (2005) suggest that the results from this study indicate that the manufacturer-recommended rates for PAM application were too low to be used on steep slopes likes those commonly found on construction sites.

A similar study by McLaughlin and Brown (2006) evaluated the use of PAM in conjunction with straw, straw erosion control blanket (ECB), hydraulically applied wood fiber, and hydraulically applied mechanically bonded fiber matrix (MBFM). Polyacrylamide was mixed and applied with a hydroseeder at a rate of 19 kg ha^{-1}. Treatments were evaluated

in both field plots and under a rainfall simulator, with the exception of the ECB treatment only evaluated on field plots. As in the previous study, the application of some sort of ground cover (straw, ECB, and MBFM) significantly reduced erosion and improved runoff water quality and once again, the addition of PAM did not provide consistent reductions in turbidity. Results from the rainfall simulator indicated that there was a significant PAM effect for turbidity in the bare soil and straw treatments, but not for the wood fiber or MBFM. However, it is noted that although turbidity was decreased with the addition of PAM in the bare soil treatment, the average turbidity value for bare soil + PAM was still high, especially in comparison to the other groundcover treatments (McLaughlin and Brown, 2006).

Factors Affecting PAM Performance

In reviewing the literature, PAM has been shown to be affected by a number of factors including temperature, electrolyte concentration, pumping method, etc. Such variation in performance is critical to understand as the use of PAM for erosion control in irrigated agriculture increases.

Bjorneberg (1998) evaluated how dry powder (Superfloc A836) and inverse oil emulsion (Pristine) formulations of PAM and their corresponding viscosities varied with temperature, concentration, and pumping. Flow tests involving six different PAM concentrations and four flow rates were used to determine whether or not the Superfloc A836 was a Newtonian fluid. Under constant temperature and concentration, a Newtonian fluid will have a constant viscosity. Pristine was not analyzed due to handling difficulties as a result of its high viscosity. Results indicate that PAM behaves as a Newtonian fluid at concentrations of 100 mg L^{-1} or less and as a non-Newtonian fluid at concentrations greater than or equal to 400 mg L^{-1}. At high concentrations, PAM viscosity decreased as water flow

rate increased; likely due to the PAM molecules orienting themselves with laminar flow lines as shear rate increased. Viscosity tests were also performed and analyzed the effect of concentration, temperature, and pumping on PAM viscosity. At low concentrations (i.e. 0-24 ppm), both PAM formulations had viscosities similar to that of water, exhibiting only a 5% increase in fluid viscosity for every 10 ppm PAM increase, relative to water. In comparing the higher concentrations, undiluted Pristine (300,000 ppm) and Superfloc (2400 ppm) experienced a 20% and 15% decrease in viscosity, respectively, as temperature was increased from 20 C to 30 C. Pumping effects were also noted using the Superfloc (2400 ppm) PAM. Pumping through a centrifugal pump one time reduced viscosity 15-20%, whereas being pumped through five times resulted in a 50-60% decrease in viscosity. There were no significant differences in circulating the PAM through the pump five versus ten times. Bjorneberg (1998) suggested these reductions in viscosity were the result of shearing of the PAM molecules as they are circulated through the centrifugal pump. Such shearing may be expected to reduce the effectiveness of PAM for erosion control and surface stabilization. MacWilliams (1978) and Tolstikh et al. (1992) had similar findings. They documented that high-speed agitation of PAM solutions results in shearing of PAM molecules, especially ones with higher molecular weights and longer chain lengths. Such shearing was assumed from reductions in solution viscosity.

Roa-Espinosa et al. (1999) also noted differences in PAM solution viscosity when evaluating various application methods of PAM field plots under moist and dry soil conditions. The PAM used in this experiment was anionic, high molecular weight, and granular in formulation. Using a garden sprinkler, 2.25 g of PAM was mixed in 5 L of water (corresponding rate of 22.5 kg ha^{-1}) and applied to the appropriate plots. The PAM-mix

solution was prepared the night before the test was conducted and it was noted that the solution viscosity decreased throughout the next day. Possible explanations for this decrease include: photolytic and/or oxidative interaction, UV degradation, or some other reaction occurring with the PAM-water mix. They also noted that PAM effectiveness in controlling sediment yield was reduced as viscosity decreased.

Fitzpatrick et al. (2004) further supports the temperature and PAM efficacy research described above. At colder temperatures (i.e. 6-15 C) flocs, or loose aggregates of fine particles that are of sufficient size and weight to settle out of suspension, took longer to form and were smaller than those formed at higher temperatures. However, the flocs that formed under colder temperatures were not as readily disrupted and were more capable of reformation. Increases in viscosity as a function of increasing PAM concentration have also been documented. It was noted that as more viscous PAM solutions are applied to soils, narrow pores experience restricted fluid movement and therefore, infiltration in those smaller pores is reduced (Muller et al., 1979; Malik and Letey, 1992; Letey, 1996).

Effects on Soil Infiltration

Another well-studied aspect of PAM is its ability to improve infiltration in soils. Studies investigating the effect of various polymers on infiltration, hydraulic conductivity, soil structure, etc. began as early as the 1980's. Those studies and others published since then typically focus on infiltration as a function of various factors: surface aggregate stability and seal formation; the amount of time it takes to initiate runoff as well as total runoff volume; soil type; electrolyte source; PAM formulation (i.e. granular vs. liquid), molecular weight, concentration, and charge density; and electrolyte source and concentration (Sojka et al., 2007).

Vacher et al. (2003) evaluated both low and high molecular weight PAMs at increasing concentrations on boxes packed with soil from three Australian mine sites. The boxes were placed under a rainfall simulator where infiltration, surface hardness, and erosion were recorded for each treatment. Despite the PAM formulation, molecular weight, or charge density, as the application rate of PAM increased from low to high (i.e. 5-10 kg ha^{-1} to 40 kg ha^{-1}), so did the amount of total infiltration. The application of PAM was also found to decrease surface hardness in comparison to the controls. On the contrary, it was noted that as the soils dried over time, the higher application rates of PAM (i.e. 40 kg ha^{-1}) tended to increase surface hardness.

Vacher et al. (2003) also demonstrated that the amount of soil eroded was significantly less for the PAM treated boxes in comparison to the controls, with the high molecular weight PAMs being more effective in reducing erosion on the soils with lower clay contents. As clay content decreases within a soil, the distance between potential clay bonding sites increases thus, making it harder for the short-chain, low molecular weight PAMs to bridge the clay particles together. In the soils with higher clay contents, the differences in effectiveness based on molecular weight diminished due to the fact that the average distance between clay particles was shorter. Charge density also affected PAM performance, with the higher charge density PAMs being more efficient at reducing sediment loss in the soils with higher clay contents. Higher charge densities are the result of more substitution along the PAM homopolymer chain. More substitution allows for more cation bridges to be formed between clay particles. Therefore, the higher the charge density of a particular type of PAM, the more potential it has to flocculate clay particles and stabilize soil structure.

Soils with low clay contents do not always experience improved infiltration rates (Ajwa and Trout, 2006). When sandy loam soils were packed into soil columns and various rates of PAM were applied as a solution, infiltration rates decreased with increasing PAM concentrations. Such low infiltration rates were attributed to increases in solution viscosity as a function of increasing PAM concentration. Unless the type and amount of PAM applied can adequately stabilize surface aggregates and structure to the point where the viscosity of the PAM solution is no longer an issue, infiltration will be reduced.

Polyacrylamide formulation (i.e. granular vs. liquid) has also been investigated for its effects on runoff and sediment loss (Soupir et al., 2004 and Peterson et al., 2002). One study (Soupir et al., 2004) applied liquid PAM, dry PAM, wood/paper hydromulch, straw mulch, and a bare control to field plots on a construction site, with each treatment being evaluated for runoff, erosion (TSS), nitrogen and phosphorus. Of all the PAM treatments, the liquid PAM formulation applied at the lowest concentration (i.e. 1.68 kg ha^{-1}) was found to most effectively reduce runoff, likely due to the preservation of soil structure. The dry and liquid, high concentration PAM treatments (i.e. 20.17 kg ha^{-1} and 6.73 kg ha^{-1} , respectively) appeared to clog soil pores and reduced infiltration, resulting in high volumes of runoff. During the first round of testing when the soils started out as dry, all treatments reduced TSS in comparison to the control, with the straw mulch and granular PAM noted as performing the best. One month later, when the second round of testing was performed, the greatest reduction in TSS occurred in the straw mulch plots. The PAM treated plots appeared to have little PAM remaining and were not as effective during the second round of rainfall simulation. Another study (Peterson et al., 2002) compared dry vs. dissolved PAM formulations on field plots in conjunction with two different kinds of electrolyte sources. The

plots were subject to three separate rainfall simulations, with all treatments applied at the beginning of the first simulation. All PAM treatments consisted of anionic Magnafloc 336, applied at a rate of 60 kg ha^{-1}. Dissolved PAM in conjunction with either electrolyte source (i.e. SoilerLime and Nutra-Ash) proved to most effectively reduce runoff and sediment losses overall, with the most dramatic effect occurring during the first rainfall simulation. Although the dry PAM applications decreased soil infiltration due to the migration of PAM granules into pore spaces and enlarging upon wetting, these treatments did reduce sediment losses.

Electrolytes & PAM

As in the previous study, the use of an electrolyte source in conjunction with PAM has become another parameter of interest in trying to improve soil infiltration (Flanagan et al., 1997; Jian et al., 2003; Flanagan et al., 2002; Lee et al., 2010). By increasing the electrolyte concentration of a soil, more ions such as Ca^{2+} and Mg^{2+} are present in the soil solution. These small ions, with the exception of Na^{+} which has a large hydrated radius, help reduce the electrical double layer surrounding charged clay particles and promote flocculation (Sojka et al., 2007).

Flanagan et al. (1997) applied simulated rainfall to an easily dispersed silt loam soil that was divided into rill and interrill plots. Two primary factors were assessed in the study: type of simulated rainfall (tap water, deionized water, tap water + 10 ppm PAM) and soil amendment (5 t ha^{-1} Fluidized Bed Combustion Bottom Ash (FBCBA) and 20 kg ha^{-1} PAM applied as a solution and allowed to dry). On the interrill plots, the addition of the FBCBA with DI water proved to be the only treatment that significantly improved infiltration. Both the FBCBA and tap water served as electrolyte sources, but the higher concentration of electrolytes present in the FBCBA likely promoted more flocculation and stabilization of the

surface soil structure. None of the PAM treatments (i.e. PAM + DI water and PAM + tap water) significantly improved infiltration. The opposite effect occurred on the rill plots in that the only treatment that proved to be effective in increasing infiltration was the 10 ppm PAM mixed with tap water applied as simulated rainfall. The addition of FBCBA or 20 kg ha^{-1} PAM alone did not result in increased infiltration rates. Flanagan et al. (2007) suggest that the lack of improved infiltration with the addition of the FBCBA was likely due to loss of the applied material via erosion and concentrated flow, and that PAM applied in simulated rainfall may have potential for use in irrigated agriculture.

The use of gypsum as an electrolyte source is also common (Jian et al., 2003; Flanagan et al., 2002; Lee et al.; 2010). Jian et al. (2003) mixed granular PAM (20 kg ha^{-1}) in the upper 5cm, as well as surface applied various amount of granular PAM and gypsum to both a silt loam and sandy clay soil. The PAM + gypsum surface treatments proved to be most effective in increasing infiltration, followed by surface application of gypsum only, the control treatments, and finally the treatment that mixed the granular PAM within the upper 5mm of the soil surface. The addition of gypsum in conjunction with PAM reduced the repulsion forces between the negative charge sites on the PAM polymer. This resulted in shorter, more coiled PAM molecules with a lower solution viscosity. The lower solution viscosity prevented clogging of the soil pores, reduced surface seal formation, and aided in stabilization of the surface aggregates, thus improving infiltration. The addition of gypsum alone also resulted in higher infiltration by simply preventing the dispersion of clay particles and reducing seal formation. Although the incorporation of granular PAM into the surface of both soils was found to reduce sediment loss, the long tails of polymer clogged soil pores and prevented infiltration.

Flanagan et al. (2002) also evaluated PAM (80 kg ha^{-1}) and PAM + gypsum (80 kg ha^{-1} and 5 Mg ha^{-1}, respectively) under simulated rainfall. The PAM and PAM + gypsum treatments reduced runoff by 40% and 52% respectively across all simulations in comparison to the control. These data agree with the previous study by illustrating that the addition of gypsum increased the electrolyte concentration of the soil, reduced clay dispersion, and gave the PAM + gypsum treatment a slight advantage over PAM alone. The PAM and PAM + gypsum treatments were also noted to significantly reduce sediment losses.

Lee et al. (2010) also found that PAM in conjunction with gypsum reduced cumulative runoff and sediment loss. Two soils, Hoberg and Brussels, were collected at two different depths (i.e. 0-30 cm and 30-60 cm), resulting in four different soil samples for testing. Both soils had silt loam surface textures but the Brussels soil had a finer subsurface texture. All samples were packed into 0.3 x 0.3 x 0.15 m test beds at a 20% slope and placed underneath a rainfall simulator. In addition to soil type, various surface treatments were applied: dry gypsum (2 t ac^{-1}), liquid PAM (20 kg ha^{-1} and 40 kg ha^{-1}), liquid PAM + gypsum (20 kg ha^{-1} and 5 Mg ha^{-1}, respectively). All treatments were analyzed for time to initial runoff, cumulative runoff, and cumulative sediment loss in comparison to a bare soil control. Overall, the PAM + gypsum treatment performed the best, significantly increasing the time to initial runoff and decreasing cumulative runoff and sediment loss. The only exception where this trend did not exist, was with one of the Hoberg soil samples which had a high organic matter content. Organic matter functional groups typically possess a negative charge. When these negative charges interact with the negative charges found on PAM homopolymer chains, repulsion ensues and PAM sorption decreases (Lu et al., 2002). The PAM + gypsum treatments, as well as the PAM only treatments both reduced sediment losses, but they noted

that the PAM + gypsum performed slightly better. And as was observed in the previous studies described above, more concentrated PAM only treatments (i.e. liquid PAM applied at 40 kg ha^{-1}) appeared to clog soil pores and increased cumulative runoff.

Despite the numerous studies testing whether or not PAM or PAM in combination with an electrolyte source improves infiltration, very few studies have actually attempted to track PAM distribution in soils. This is due to the fact that very little desorption of PAM occurs after it comes into contact with soil particles (Lu and Wu, 2003). Lu and Wu (2003) applied PAM solutions via ponded or drip application to 5.2 cm diameter soil columns. The columns were filled with two soil types, a Hanford sandy loam and an Imperial silty clay, both with organic matter removed. The soils were packed to bulk densities of 1.68 g cm^{-3} and 1.33 g cm^{-3}, respectively. PAM solution concentrations applied ranged from 10-40 mg L^{-1}. Forty-eight hours after PAM application, the columns were opened and divided in sections. Samples were collected in 1cm increments and analyzed in order to determine the amount of PAM present. Polyacrylamide content was determined using the modified N-bromination method. In general, it was determined that PAM is only able to move to a depth of one-eighth to one-half of the wetting front, with the majority of it being concentrated near the surface. However, this may vary depending on the salt concentration and texture of the soil at hand, with higher salt concentrations and finer textures resulting in more PAM sorption towards the soil surface. PAM distribution based on application method and initial soil moisture content also produced different results. When applied slowly as a drip, PAM was able to penetrate slightly deeper in the column. Therefore, if deeper PAM penetration is desired, drip or trickle irrigation should be used. However, if the primary concern is the stabilization of the surface structure, furrow and flood irrigation methods would be preferred. Initial moisture content

also affects PAM movement in that the higher the water content, the deeper the PAM is transported down through the profile.

In summary, numerous aspects of PAM have been researched including temperature and mixing effects, how PAM performs as an addition to typical BMP's, etc. PAM has also been evaluated for infiltration improvements via surface aggregate stability and sealing effects. However, throughout the literature a specific PAM rate, application volume, and coverage rate is never specified for optimum PAM performance in terms of infiltration and water quality. Furthermore, differences in viscosity are detected but evaluation of those effects on PAM performance has not been thoroughly investigated. These "gaps" in the literature thus serve the basis for the PAM infiltration study.

CHAPTER 2: FIELD EVALUATION OF HYDROMULCHES

Introduction

As described in Chapter 1, sediment is one of the main pollutants affecting rivers and streams (US EPA, 2009b). Since erosion from construction sites can be a significant contributor, the Clean Water Act of 1972 and the Stormwater Phase II Final Rule require construction site managers to reduce erosion as a part of their stormwater pollution plans. Due to the frequent failure and rising price of straw mulches, there has been more interest in other temporary ground covers such as hydromulches as an erosion control alternative (B. Blackburn; personal communication; 2010). Most research focuses on how hydromulches control erosion and affect water quality (Benik et al., 2003a; Benik et al., 2003b; Dougherty et al., 2008; Emmons, 1995; Faucette et al., 2006; Megahan et al., 2001; Ringe and Graves, 1987). However, little research exists that examines how hydromulches facilitate vegetation establishment, usually the ultimate goal for slope stabilization.

The objective of this study was to evaluate a variety of hydromulches for erosion control and vegetation establishment at different sites around N.C. Because of limitations on site availability, the results from only the first site are reported here.

Materials & Methods

The site, evaluated from 11/2009 to 1/2010, was a fill slope that was part of a borrow pit operation located on a DOT site near Kinston, N.C. The soil was topsoil which had been stockpiled and applied as a surface layer on the fill material at a 2.9:1 slope facing east. It was predominantly sandy loam and loamy sand in texture, with an average bulk density of 1.53 g cm^{-3} (Table 1). Following a preliminary hydromulch evaluation (Appendix 1) and seed testing (Appendix 2), the following treatments were selected: straw + tackifier (WCM;

Enviroblend, Profile Inc., Chicago, IL); straw + PAM (705, Applied Polymer Systems, Woodstock, GA) + tackifier; 70:30 wood fiber/cellulosic blend (WCM; Enviroblend, Profile Inc., Chicago, IL); wood fiber hydromulch (WM; Conwed Fibers 1000, Profile Inc., Chicago, IL); and bonded fiber matrix (BFM; Hydroblanket BFM, Profile Inc., Chicago, IL). The PAM used was a proprietary blend of linear, anionic polyacrylamides (PAM). The area was divided into 20 plots 3 m wide and 9 m from top to bottom of the slope. Each treatment was replicated 4 times and arranged in a randomized complete block design (Fig. 1).

Hydromulches were applied using a hydroseeder (TurfMaker 420, TurfMaker Corp., Rowlett, TX) and were applied at the following manufacturer-recommended rates: 70:30 wood fiber/cellulosic blend—2800 kg ha^{-1}, wood fiber hydromulch—2240 kg ha^{-1}, bonded fiber matrix—3920 kg ha^{-1}, straw treatments—3360 kg ha^{-1}, PAM—22.4 kg ha^{-1}, and tackifier—560 kg ha^{-1}. The hydromulches were also mixed at manufacturer recommended rates: 70:30 wood fiber/cellulosic blend—48 g L^{-1}, wood fiber—36 g L^{-1}, bonded fiber matrix—48 g L^{-1}.

The area selected had been fertilized and temporarily seeded with rye grain 2-3 weeks prior to installation. The slope was cultivated in order to kill the germinating rye. Due to the fact that the slope had been temporarily seeded, the existing straw was incorporated. When the soil was sampled any remaining surface residue was scraped away. Following the use of the cultipacker to kill the germinating rye, lime (280 kg) and additional fertilizer (6.4 kg) were applied to meet DOT recommendations (NCDOT, 2008a). The slope was re-seeded by DOT with a blend of centipede (*Eremochloa ophiuroides*; 11 kg ha^{-1}), Bermudagrass (*Cynodon dactylon*; 40 kg ha^{-1}), and tall fescue (*Festuca arundinacea*; 57 kg ha^{-1}).

Our procedure to determine hydromulch application rates was by calibrating the spray rate (seconds per liter) of the hydromulcher and spraying for the appropriate time (½ from the top, ½ from the bottom of plots) to achieve the desired mulch rate, based on the amount of mulch and volume of water in the tank. The amount of mulch and water added to a tank was calculated to exceed the amount needed for all of the plots to avoid running out, with the excess applied outside of the plots. During the application of HM, however, not enough water was added to the tank as a result of a miscalculation, and the tank ran dry after the third plot. More water was added to finish the last plot, but to check on the resulting application rates, samples of the applied mulch were obtained. Four samples were collected from each plot using a 7.62 cm diameter metal ring and then composited. Collective samples were then used to estimate actual HM application rates. In order to separate sediment from the mulch, the samples were placed in water, where most of the sediment settled on the bottom and the mulch floated on top. The mulch was collected, oven dried, and weighed. Based on the weight of the oven-dried mulch and the area of the metal ring (i.e. 45.6 cm^2), the mulch application rate could be estimated.

On each plot, two 1.2 m pieces of edging were inserted into the soil in the plot center in a "V" formation to direct water flow into a 10.2 cm diameter pipe, which then flowed into a 38 L container. The open end of the "V" was 1.2 m across, and the outlet into the pipe was 1.5 m from the bottom of the slope. The end of the pipe that collected water from the plots was placed 1.5 m from the bottom of the plots in order to accommodate the collection container, making the runoff collection area 7.6 m x 1.2 m. A 12 V bilge pump was placed inside each 38 L container and pumped excess water into a 378.5 L tank. Flow from the pump was divided with half going into the container and the other half flowing onto the

ground in order to prevent overflow in the large tubs during heavy runoff events (Fig. 2). The idea behind this set up was that the majority of the sediment would settle in the first container and excess water would accumulate in the 378.5 L container. Sediment from the small tub was deposited into the larger one, and mixed. Subsamples were taken in order to determine turbidity and TSS, and depth was recorded in each tub to determine the overall volume of runoff. Each tub was calibrated such that increments of depth corresponded to a particular runoff volume (Fig. 3). Rainfall data was estimated from the NC Climate Office Multi-Sensor Precipitation Estimates system, which combines radar and rain gauge data to provide an estimate of precipitation amounts for any location (State Climate Office of North Carolina, 2009).

Biomass was also determined for each treatment. Using scissors and a square grid (Fig 4.), vegetation was clipped from 20 cm x 20 cm squares. The grid was placed onto each plot 3 times; once towards the top, a second time towards the middle, and a third time towards the bottom. Three randomly selected squares were clipped at each sample location, for a total sample of nine squares per plot. The samples were collected, oven-dried and weighed. Using the weight of the samples along with the calculated area of the nine squares, biomass was estimated for the total plot area.

A second site, installed in Asheboro, N.C. (Appendix 3) experienced an intense rainstorm (15.2 cm within three days) approximately three weeks after installation. This resulted in severe rill and gully erosion, as well as slope failure (Figs. 5, 6). This site was abandoned with no data collected.

Data Analysis

Field evaluation for hydromulches tests were random complete block designs, designed to determine the best mulch type(s) in terms of reducing erosion and facilitating the most vegetation establishment. All data were analyzed using SAS software and the "proc mixed" procedure (SAS version 9.2, SAS Institute, Cary, NC).

Results & Discussion

Overall, there were no significant differences among straw, straw + PAM, or types of hydromulch using α=0.05 for percent runoff, turbidity, TSS, or biomass (Table 2). There were only significant differences between events ($p<0.0001$), which was expected considering that each rainfall event consisted of different rainfall amounts and intensities (Table 3). To be more specific, event 1 had the highest amount of rainfall (i.e. 99 mm), but exhibited the lowest amount of runoff (~5%). Such a high infiltration rate is likely due to the sandy texture of the soil. Following the first event, runoff rates actually increased, which was not expected. Typically, as more vegetation becomes established, soil structure improves allowing for more infiltration. The first sampling event occurred in November and subsequent events continued through mid-December. During this time frame temperatures decreased, resulting in increased soil moisture contents (i.e. from 0.2 m^3 m^{-3} to 0.4 m^3 m^{-3}) (State Climate Office of North Carolina, 2009). These conditions may have been why the runoff rate relative to rainfall increased in sampling events 2-5 (Table 4).

There was also a significant interaction effect for percent runoff (i.e. $p=0.0193$; Table 2). This was likely due to the variation in runoff for the BFM and straw+PAM treatments. Specifically, the BFM had the most runoff in events 1-3 and the lowest for event 4. The

straw+PAM treatment was the inverse, having the lowest runoff in event one and higher values for events 2 and 3.

Despite no significant differences among the treatments, certain trends are apparent in the data: 1) The BFM plots typically result in the most runoff, followed by the straw only plots, in four of the five rainfall events, 2) BFM plots also exhibited the highest turbidity values and the straw + PAM plots had the lowest in three of the five events, and 3) The straw + PAM plots had the lowest TSS values for three of the five events (Table 4). Turbidity and TSS values were higher for event 5 relative to all of the other events, even though there was no evidence of increased erosion and the vegetation was well-established. During this time period, lots of grading was occurring onsite, likely generating large amounts of dust which settled in the runoff collection vessels.

The estimate of the amount of hydromulch applied was universally higher than the spray calibration estimate of application rate (Table 5). This may have been a result of soil materials which were not removed through the separation method we used. Generally, when we spray hydromulch we have a considerable amount of mulch left in the tank once the liquid runs out, suggesting that the application would be less than expected rather than more.

Conclusions

No significant treatment differences were observed on Site 1, likely due to the sandy loam/loamy sand soil texture and resulting high infiltration capacity. Because relatively little runoff was generated (5–20% of rainfall), there was little erosive energy to distinguish one treatment from another. However, certain trends were observed: 1) The BFM hydromulch typically resulted in the most runoff, followed by the straw only plots (in 4 of 5 events), 2) The BFM and straw + PAM plots had the highest and lowest turbidity values, respectively

(in 3 of 5 events), and 3) The straw + PAM plots had the lowest TSS values (in 3 of 5 events). Higher treatment averages for turbidity and TSS in the 5th event was likely due to windblown sediment from nearby grading activities.

CHAPTER 3: PAM INFILTRATION STUDY

Introduction

In addition to reducing erosion, PAM has been shown to affect the infiltration rates of various soil types (Lee et al., 2010; Sojka et al., 2007; Ajwa and Trout, 2006; Jian et al., 2003; Vacher et al., 2003; Flanagan et al., 2002; Flanagan et al., 1997). The majority of research typically focused on infiltration as a function of surface aggregate stability and seal formation, the amount of time it takes to initiate runoff, total runoff volume, PAM formulation/concentration, and electrolyte concentration (Sojka et al., 2007). However, the effects of application rate and method have not been fully explored in previous research.

Increased PAM concentration in solution, as well has higher molecular weight PAMs, result in increases in solution viscosity (Letey, 1996; Malik and Letey, 1992; Muller et al., 1979). Such high viscosities are believed to be capable of clogging narrow soil pores and reducing infiltration (Bhardwaj et al., 2010)

Temperature, mixing methods, and amount of mixing have also been shown to affect viscosity (Roa-Espinosa et al., 1999; Bjorneberg, 1998; Letey, 1996; Malik and Letey 1992; Tolstikh et al., 1992; Muller et al., 1979; MacWilliams, 1978). Bjornberg (1998) found that pumping a PAM solution through a centrifugal pump one time and five times resulted in 15-20% and 50-60% reductions in solution viscosity, respectively. Such reductions in viscosity were attributed to shearing of the PAM molecules as they were forced through the pump impeller (Bjorneberg, 1998; MacWilliams, 1978; Tolstikh et al., 1992). Shearing a large PAM molecule into smaller molecules could potentially affect its performance in surface stabilization and erosion control, although this has not been explored previously.

The objective of this study was to analyze how variations in PAM rate, concentration, amount of straw coverage, drying time, and mixing method affect runoff and water quality for a clay loam soil under simulated rainfall conditions.

Materials and Methods

Rainfall Simulator Study

Five treatment factors were varied in this study: PAM rate, application volume, PAM mixing method (i.e. sump pump vs. trolling motor), amount of straw coverage (i.e. 2100 kg ha^{-1} vs. 4800 kg ha^{-1}), and whether or not the boxes were allowed to dry 3-5 days before being placed underneath the rainfall simulator. Using the same wooden boxes and clay loam soil as that of the preliminary HM evaluation (1 m x 0.2 m) (Appendix 1), boxes were packed with 15.6 kg of soil and tamped down to a depth of 5 cm in order to achieve a bulk density of 1.5 g cm^{-3}. Based on our standard recommended PAM application rate of 22 kg PAM ha^{-1} (McLaughlin, 2006), and the calculated area of each box (i.e. 0.2 m^2), each box received 0.44 g PAM as a baseline rate. Additional rates of 45 kg ha^{-1} and 91 kg ha^{-1} were included, either in the same volume or at the same concentration, to determine whether higher PAM rates and/or application volumes could penetrate deeper within the profile, help preserve soil structure, and offer benefits in terms of improved infiltration.

All PAM (APS 705, Woodstock, GA) treatments were mixed as stock solutions in 114 L trash cans for at least two hours or until all PAM was dissolved. Stock solutions had a concentration of 2.2 g L^{-1}. The first treatment was originally designed to apply enough of the PAM solution to penetrate a depth of at least 2 mm (application volume of 0.01 ML ha^{-1}), assuming 50% porespace. However, the solution was found to be too thick to be applied evenly over the soil box surfaces using a 15 L, piston pump backpack sprayer (425, Solo Inc.,

Newport News, VA) (Fig. 7). Rather than exiting the nozzle as a spray, it dribbled out in a thick stream. Stock solutions were then mixed at a concentration of 1.1 g L^{-1}, which allowed for even spray application, resulting in a calculated penetration with the first treatment designed to penetrate a depth of at least 4 mm (i.e. 0.02 ML ha^{-1} application volume). Other treatments were further diluted for penetration depths of at least 8 mm, 16 mm, and 32 mm (0.04 ML ha^{-1}, 0.08 ML ha^{-1}, and 0.16 ML ha^{-1} application volumes, respectively).

The two mixing methods for the stock solutions were either a 1/6 horse power, centrifugal sump pump or a trolling motor (Fig. 8). The purpose of using both a trolling motor (less shearing potential) and sump pump (more shearing potential) was to evaluate whether or not mixing method affected PAM performance.

Straw coverage rates were also varied in order to determine their effect on PAM performance in terms of erosion and turbidity reduction. Typical recommendations for straw applications range from 1-2 tons ac^{-1} (2,242-4,483 kg ha^{-1}) (NCDENR, 2006). Coverage rates used in this experiment were based on visual estimates (i.e. 50% coverage vs. 100% coverage) and corresponded to 0.96 kg ha^{-1} and 2.18 kg ha^{-1}.

In applying PAM treatments to the boxes and allowing them to dry 3-5 days before simulating rainfall, we hoped to determine whether or not drying allowed more time for PAM molecules to interact with the soil, thus stabilizing surface structure and improving infiltration. It is highly likely that the soil will dry to some degree after the application of PAM and mulch before the next rainfall. Previous rainfall simulator studies have not tested PAM applications which were allowed to fully dry before the simulation was initiated. The boxes were left in the sun during the summer and usually covered at night to prevent dew or unexpected night rainfall events from re-moistening the soil.

As mentioned previously, all treatments were applied using a backpack sprayer and were replicated three times within each test. The sprayer was calibrated using the 1.1 g L^{-1} stock solution. We determined that the sprayer retained 20 mL of the solution at the point when it ceased to spray. This was likely due to the mechanics of the backpack. Therefore, we added an additional 20 mL of the test solution to each tank.

Rainfall simulations were conducted by randomly placing each box in one of four locations under the simulator on a stand that had a 5% slope (Fig. 9). Water for the rainfall simulator came from a local well which was constantly fed into a 113.5 L trashcan or 378.5 L tub (Fig. 10). To provide a constant pressure during simulations, a well pump was used to pump water from the trashcan or tub via a hose to a Fulljet 1/2HH-SS50WSQ nozzle located 3 meters above the boxes. Rainfall was applied at a pressure of 28 kPa to provide approximately 70 mm h^{-1} rainfall and a median diameter drop size of 1.9 mm as shown by Humphry et al. (2002). Following the third test, a windscreen was installed on three sides of the rainfall simulator in order to sustain an even, conical distribution of raindrops (Fig. 11). Rainfall distribution was also checked with rain gauges on a regular basis to ensure an even rainfall distribution (Productive, 2010) (Figs. 12, 13, 14).

At the lower end of each box the runoff was directed into a rubber hose that funneled the runoff into a collection tub. The collection tubs were covered with plastic in order to exclude rainfall (Fig. 15). Rainfall was applied for approximately 40 minutes or until each box produced runoff. The amount of time it took to achieve runoff and the total volume of runoff was recorded. Subsamples were taken from each of the runoff collection tubs and analyzed for turbidity and TSS.

Treatments are listed in Table 6. Note that T1 (Test 1) was not included in the analysis due to a design flaw and T6 (Test 6) was used to verify that allowing the boxes to dry for 3-5 days resulted in similar starting moisture contents among treatments.

Viscosity/PAM Effectiveness Measurements

After mixing PAM with the sump pump, trolling motor, and on a stir plate in the lab, differences in PAM viscosity were noticeable in that the PAM mixed with the trolling motor and the stir plate were more difficult to apply uniformly with the backpack sprayer. In order to determine whether or not viscosity differences were actually present, the following samples were taken to the Food Science laboratory at N.C. State University for viscosity analysis: 1) 1 mg L^{-1}, 2 mg L^{-1}, 4 mg L^{-1}, and 8 mg L^{-1} lab mixed (with a magnetic stir plate); 2) 1100 mg L^{-1} lab mixed; 3) 1100 mg L^{-1} mixed with sump pump; 4) 1100 mg L^{-1} lab mixed and pumped through backpack with strainer intact (Fig. 16). Samples were analyzed using a rheometer and viscosity was measured as a function of shear rate (H.S. Melito, personal communication, 2010).

To test the effect of different mixing methods on turbidity reduction, 200 mL solutions of 1, 2, 4, and 8 mg PAM L^{-1}, mixed by each method, were added to 250 mL plastic containers followed by 10 g of the same clay loam soil used in the box tests (Fig. 17). The samples were then shaken for thirty seconds and supernatant turbidities were read one minute later. This was done in order to determine whether or not any differences in mixing methods, which had different levels of shear, affected PAM performance as measured by turbidity reduction.

Data Analysis

Rainfall simulator tests 2 through 9 (abbreviated T2-T9) were all random complete block designs. Simulations T10 through T12 were 2x2 factorial, random complete block designs to further explore the trends evident in T2-T9 and the differences detected in viscosity measurements of the two mixing methods used in the field. All data were analyzed using SAS software and the "proc mixed" procedure (SAS version 9.2, SAS Institute, Cary, NC). For certain tests (i.e. T8, T9, T10, T11, and T12) the data were log transformed in order to improve normality. Differences were considered significant only if α values were less than or equal to 0.05.

Viscosity measurements were used to confirm our observations with the backpack sprayer and were not replicated for statistical analysis.

Results and Discussion

Rainfall Simulator Study

Volume Effects

In Test 2 all treatments received the same amount of PAM (i.e. 22 kg ha^{-1}) and were allowed to dry, but varied in the amount of water in which the PAM was applied (i.e. 0.02 ML ha^{-1}, 0.04 ML ha^{-1}, or 0.08 ML ha^{-1}). Significant treatment effects were evident for TSS and runoff time ($p=0.015$ and $p=0.0001$). Applications using higher water volumes had runoff initiation sooner, but had lower TSS values (Figs. 18, 19). There were no significant differences in turbidity, runoff volume, or erosion rate for Test 2 ($p=0.2996$, 0.1149, and 0.1875, respectively). Despite the lack of significance in regards to runoff volume, it appears that treatments receiving higher application volumes also result in higher runoff volumes (Fig. 20). It was also observed that the treatments receiving greater application volumes

appeared to seal and crack (Fig. 21). This sealing effect (Bhardwaj et al., 2010) may have resulted in greater runoff volumes, but because PAM was present in the solution, there was enough stabilization of the aggregates to result in lower TSS values.

When the experiment was conducted again but with PAM which had been mixed with a trolling motor to reduce shearing of the PAM molecules, the solution was found to be too viscous to spray from the sprayer. The solution was diluted 50% and this resulted in an acceptable spray pattern, although the application volumes were twice that of Test 2. In this experiment (Test 4), there was a significant treatment effect for turbidity (Fig. 22; $p=0.0425$), but not for TSS or erosion rate ($p=0.0625$ and $p=0.6339$). Once again the treatment receiving the highest water volume, or lowest PAM concentration, resulted in the lowest turbidity values. The trend is remarkably similar to Test 2, although the turbidities tended to be higher in Test 4 at the same application volume, probably because the PAM applied was cut in half due to the dilution. Application volume did not have significant effects on runoff volume ($p=0.0980$) but, as in Test 2, treatments receiving more water volumes tended to have higher runoff volumes (Fig. 23). The effects of mixing method were further explored in other tests.

The effect of maintaining PAM concentration while also increasing application volume was also tested for both sump and trolling motor mixing methods. There were no significant effects on any variable with increasing application volume of identical PAM solutions mixed with a sump pump, although a trend toward reduced turbidity was evident (Test 3; Figure 24). The PAM mixed with a trolling motor and applied at the same rate but twice the volume due to the higher viscosity, had a declining trend in TSS with increased application volume, with the highest volume being significantly lower than the other two (Test 5; Fig. 25). No other effects were significant, although a declining trend was evident

for turbidity as well as runoff volume (Test 5; Figs. 26, 27). Perhaps in applying higher concentrations of PAM solutions, there is enough PAM present to counteract the surface sealing effect evident in Test 2 and Test 4, allowing for greater infiltration.

In a factorial test to isolate the effects of concentration and volume (Test 10), neither had a significant impact on turbidity, TSS, or erosion rate ($p=0.9858$, 0.9407, and 0.2600, respectively). Significant differences among treatments did occur, however, in time to runoff and runoff volume ($p=0.0066$ and $p=0.0116$, respectively). Despite being allowed to dry 3-5 days before being tested, boxes receiving 0.08 ML ha^{-1} of water had a faster time to runoff and a greater volume of runoff compared to 0.04 ML ha^{-1} (Figs. 28, 29). Allowing the boxes to dry should have resulted in all boxes having similar starting moisture contents, as shown from an earlier test with similar average temperatures (Table 7). There may have been an effect on the soil physical properties. As noted above, it was observed that treatments receiving higher volumes and allowed to dry for 3-5 days before rainfall simulation appeared to crack at the soil surface (Fig. 21). Once again, the higher application volumes may have created surface seals that reduced infiltration rates.

In another factorial test, PAM rate and water volume were kept the same (i.e. 22 kg ha^{-1} PAM and 0.04 ML ha^{-1} water), but the mixing method (i.e. trolling motor vs. sump pump) and whether or not the PAM treatments were allowed to dry before being tested were varied. Neither mixing method nor drying time significantly affected turbidity, TSS, time to runoff, runoff volume, or erosion rate values ($p=0.2433$ and 0.1148, $p=0.54$ and 0.8659, $p=0.9694$ and 0.7472, $p=0.8774$ and 0.3221, $p=0.7159$ and $p=0.6517$, respectively). Although not significant, the "wet" boxes did appear to have slightly lower turbidity values (Fig. 30). However, when two different tests with identical treatments except for drying were

compared (Test 7 vs. Test 8), time to runoff occurred more quickly when the boxes were not allowed to dry (Fig. 31). However, despite the faster time to runoff, turbidity, TSS, and erosion rates were significantly lower (Figs. 32, 33, 34).

Coverage Effects

Because the turbidity values for the tests were relatively high compared to previous experiments in our rainfall simulator, and jar tests indicated that the PAM was effective with this soil, we investigated the straw application rate as a possible reason. The straw had been applied based on visual estimation of typical coverage. When this application rate was actually measured by removing the straw and weighing it, the rate was approximately 2,100 kg ha^{-1} (1,900 lb ac^{-1}), which is at the low end of recommended rates (2,000-4,000 lb ac^{-1}). When the straw application rate was increased to a visually assessed "100%" cover, the application rate was measured at 4,800 kg ha^{-1} (4,300 lb ac^{-1}), slightly above the recommended rates. These two straw application rates were further tested to determine their effects on runoff with and without PAM.

Runoff turbidity was not significantly different between low straw with no PAM (0-2,100), low straw with PAM (22-2,100), and high straw with PAM (22-4,800) (Test 8; Fig. 35). All three treatments resulted in significantly lower turbidity than the bare soil with PAM treatment, illustrating that PAM alone is not an effective treatment. When the bare soil + PAM (22-0) treatment is dropped out, both straw application rates with PAM resulted in significantly lower turbidity than the 50% straw alone (0-2,100) (Fig. 36). Similarly, all three treatments had significantly lower TSS in the runoff compared to the bare soil + PAM treatment (22-0), which was at least 20X higher than the others (Fig. 37). However, the low straw alone (0-2,100) had significantly higher TSS than the high straw + PAM treatment.

There were no significant differences in time to runoff or runoff volume, although the low straw alone (0-2,100) had the longest time to runoff and least volume (Figs. 38, 39).

When the data for Test 8 were log transformed due to variability in the data, two other treatment differences became significant: 1) The 50% cover + PAM (22-2,100) treatment had lower turbidity values than the 100% cover only treatment (0-4,800) ($p=0.0166$) and 2) 100% cover + PAM (22-4,800) had lower turbidity values than the 100% cover only treatments (0-4,800) ($p=0.0049$) (Table 8). In fact, this pair-wise analysis showed that only the 50% straw + PAM and 100% straw + PAM were not significantly different. Differences in erosion rates also became significant, with the bare + PAM treatment (22-0) having the highest erosion rate in comparison to the other treatments (Fig. 40).

Tests comparing PAM on bare soil (22-0), 100% cover alone (0-4,800), and 100% cover + PAM (22-4,800) showed again that PAM alone is not a viable treatment, although the treatment effects were not always significant. Turbidity was more than five times higher for the bare soil + PAM (22-0) treatment compared to 100% cover (0-4,800), but only the 100% cover + PAM (22-4,800) turbidity was significantly lower (Test 9; Fig. 41). Even greater differences in TSS and erosion rate were evident, but no statistical differences were found (Figs. 42, 43). Time to runoff was significantly faster for the bare soil + PAM (22-0) treatment compared to both 100% cover treatments (Fig. 44). No significant differences in runoff volume were found, although the bare soil + PAM (22-0) treatment resulted in more than double the volume from the other treatments (Fig. 45). In these tests, the soil was allowed to dry after PAM application but this did not appear to have much effect compared to the previous tests, which had rainfall simulations soon after PAM application (Test 8 vs. Test 9).

A factorial experiment was conducted to determine differences among the 50% vs. 100% cover treatments, and whether or not the addition of PAM added any extra benefit (Test 12). Significant treatment differences, as well as an interaction effect, did occur in regards to turbidity ($p[PAM]<0.0001$, $p[cover]<0.0001$ and $p[PAM*cover]=0.0004$). The following were statistically significant: 1) Boxes receiving PAM (22 kg ha^{-1}) had lower turbidity values than those not receiving PAM ($p<0.0001$), 2) The PAM+50% coverage (22-2,100), PAM + 100% coverage (22-4,800), and 100% coverage only (0-4,800) treatments had lower turbidity values than the 50% coverage only (0-2,100) treatment ($p<0.0001$), and 3) The PAM + 100% coverage treatment (22-4,800) resulted in lower runoff turbidity in comparison to the PAM + 50% coverage treatment (22-2,100) ($p=0.0187$) (Fig. 46). There were no significant differences between the PAM + 50% coverage treatment (22-2,100) vs. the 100% coverage treatment (0-4,800) or the 100% coverage (0-4,800) vs. the PAM + 100% coverage treatment (22-4,800) ($p=0.0968$ and $p=0.3200$, respectively).

The 50% coverage treatment produced significantly higher erosion than the 50% + PAM (22-2,100), 100% coverage (0-4,800), and 100% + PAM (22-4,800) treatments (Fig. 47). There were no significant differences between the 50%+PAM (22-2,100) and 100% coverage (0-4,800) treatments, 50% + PAM (22-2,100) and 100% + PAM (22-4,800) treatments, nor the 100% (0-4,800) and 100% + PAM (22-4,800) treatments ($p=0.3520$, 0.2686, and 0.8403, respectively). This data from this test illustrated the importance of good ground cover, even when PAM is applied. Despite there being no significant differences amongst the latter two, treatment averages demonstrate that applying PAM to the 100% coverage treatment may further reduce erosion.

The following treatment differences for TSS were also statistically significant: 1) The addition of PAM (22 kg ha^{-1}) resulted in lower TSS values than treatments receiving no PAM ($p=0.0015$), 2) The PAM + 50% coverage (22-2,100), PAM + 100% coverage (22-4,800), and 100% coverage only (0-4,800) treatments all performed better than the 50% coverage only (0-2,100) treatment($p=0.0003$, $p<0.0001$, and $p<0.0001$, respectively), 3) The PAM + 50% coverage (22-2,100) treatment had lower TSS values compared to the 100% coverage (0-4,800) treatment ($p=0.0495$), and 4) The PAM + 100% coverage (22-4,800) treatment reduced TSS in comparison to the PAM + 50% coverage (22-2,100) treatment ($p=0.0237$) (Fig. 48). Despite not qualifying as a significant treatment difference, the PAM + 100% treatment had lower TSS values on average than the 100% coverage treatment ($p=0.6488$).

No significant differences were evident for time to runoff ($p[PAM]=0.5924$, $p[cover]=0.6273$, $p[PAM*cover]=0.1920$) and runoff volume ($p[PAM]=0.9681$, $p[cover]=0.0607$, $p[PAM*cover]=0.3129$). Although not significant, the 100% coverage treatment (0-4,800) did produce lower runoff volumes than the 50% coverage treatment (0-2,100) (Fig. 49). Greater coverage reduced raindrop impact and degradation of soil structure. This allowed for more water to infiltrate and resulted in lower volumes of runoff. When PAM was applied, these factors also reduced losses of PAM due to erosion, which occurred in boxes with no ground cover.

These results demonstrate both the importance of coverage in reducing erosion rates, as well as how the addition of PAM will only improve turbidity values if adequate cover is already present.

Viscosity Measurements

The rheometer was not able to detect differences among the low concentration samples (i.e. 1, 2, 4, or 8 mg L^{-1}). However, differences were apparent among the 1100 mg L^{-} concentration samples (Fig. 50). The 1100 mg L^{-} samples are ranked most viscous to least viscous as follows: 1100 mg L^{-} lab mixed with stir plate, sump pump, and lab mixed followed by pumping through backpack with strainer intact (Fig. 50). Based on this data, the sump pump mixing method may be shearing the PAM molecules into shorter chain lengths (Bjorneberg, 1998). In addition, the PAM molecules may also have been sheared when forced through the strainer in the backpack sprayer nozzle.

The potential shearing effect of the trash screen was evident in tests for turbidity reduction. Although all PAM turbidity values were still low relative to the control, the turbidities for the PAM pumped through the backpack sprayer with the screen intact were higher than solutions dripped through the strainer, run through the sprayer without the strainer, or just tested after mixing (Table 9). After these tests were performed, the trash strainer was removed from the backpack sprayer wand before PAM treatments were applied (i.e. Test 7-Test 12 did not have the strainer intact). Upon removal of the strainer, turbidity and TSS values were expected to be lower. However, this was not the case, so it is unlikely that removal of the strainer had any treatment effect. As shown in previous tests, even when the PAM molecules may have been sheared during mixing, this did not affect the parameters measured.

Conclusions

Overall, the PAM infiltration data (Test 2, Test 4, and Test 10, specifically) illustrate that higher water volumes, or lower PAM concentrations, typically produce lower turbidity

and TSS values, but higher runoff volumes. However, the opposite occurs when the same concentration of PAM is applied in greater volumes. More specifically, treatments receiving greater PAM application rates and concentrations (Test 5 and Test 10, specifically) typically had lower runoff volumes. When applying lower PAM concentrations, greater amounts of liquid are applied to each box. The force from the backpack sprayer wand in conjunction with greater water volumes appeared to create surface seals. There was enough PAM present to reduce turbidity and TSS values, but the seals, in turn, resulted in greater runoff volumes. When PAM is applied at higher rates and concentrations (as in Test 5 and Test 10), conceivably there is enough PAM present to preserve the surface structure and counteract the sealing effect, thus producing lower runoff volumes and maintaining lower TSS and turbidity values.

Despite variation, there do not appear to be any significant differences in terms of PAM performance when mixed with a sump pump or a trolling motor, nor does it appear to matter if PAM treatments are allowed to dry. There was only one instance in which the "wet" boxes resulted in significantly lower turbidity and TSS values than those that were allowed to dry (i.e. Test 7 vs. Test 8).

Although not always statistically significant, trends in runoff time and volume convey the importance of starting moisture content. Boxes with higher starting moisture contents have more total pore space occupied with water and once rainfall ensues, are more likely to experience faster runoff initiation and higher runoff volumes.

The importance of adequate coverage is also very evident throughout the data. The bare soil treatments, despite the addition of PAM, always resulted in higher turbidity and TSS values, as well as faster times to runoff and more runoff volume. Such differences did

not always qualify as significant, likely due to variability in the data, but the trends are evident. It is likely that the force of raindrop impact eroded the PAM from the soil surface and created surface seals despite the addition of PAM (Bhardwaj et al., 2010). Adequate cover reduces raindrop impact and prevents surface seals from forming. This allows for better preservation of soil structure and subsequently, more infiltration. Results also indicate that PAM can further improve infiltration and water quality if adequate coverage is already present.

In terms of PAM mixing methods, mixing with an impeller-type pump such as a sump pump resulted in lower solution viscosity, suggesting shearing occurred (Bjorneberg, 1998; MacWilliams, 1978; Tolstikh et al., 1992). Pumping the PAM solution through a metal strainer under pressure also resulted in a lower solution viscosity, possibly due to physical shearing of the PAM molecules. However, it does not appear that the lower viscosity PAM solutions significantly reduced PAM effectiveness for erosion and turbidity control for the soil we tested.

CHAPTER 4: CONCLUSIONS & FUTURE RESEARCH

Hydromulch Study

- There were no significant differences in turbidity, TSS, % runoff, or biomass in the hydromulch study. This was likely due to the sandy soil texture and resulting high infiltration capacity.
- Hydromulch research should continue across the state of N.C. in order to determine how various mulches perform on different soil types and landscape positions. Based on these results, it would be useful to develop a decision matrix in order to aid NC DOT officials in determining which mulches perform best on different soil types/under various conditions, as well as which ones are more cost-effective.
- Soil moisture probes, although expensive, may also prove beneficial in monitoring how soil moisture changes over time, as well as how it affects hydromulch performance and vegetation establishment.
- Methods for determining hydromulch application rates via a hydroseeder should be investigated further in order to assure application rates are in accordance with manufacturer recommendations.

PAM Infiltration Study

- At the same PAM application rate, application in higher volumes produced greater runoff volumes, but had lower TSS and turbidity values. Greater application volumes appeared to result in surface sealing which generated more runoff. However, the applied PAM reduced erosion, resulting in lower turbidity and TSS values.

- When PAM solutions were applied at greater concentrations, conceivably there was enough PAM present to counteract the sealing effect and preserve soil structure. This allowed for more infiltration, and despite high application volumes, resulted in lower runoff volumes.
- Despite detecting viscosity differences among PAM solutions mixed with a sump pump and a trolling motor, there were no significant differences in PAM performance. Allowing the soil to dry after PAM application usually did not have a treatment effect, with the exception of the treatment comparison in Test 7 vs. Test 8.
- Without a ground cover to protect against raindrop impact, high erosion rates will occur in spite of PAM application at the rates tested, as the bare+PAM treatments consistently resulted in significantly higher TSS and turbidity values.
- Coverage is crucial in reducing raindrop impact, preventing surface sealing, and allowing for more infiltration. Despite proving to be statistically significant, treatment means illustrate that PAM will offer an additional benefit in terms of turbidity and TSS, but only if adequate coverage is already present.
- Other soil types, landscape positions, and slopes should also be investigated as these factors may alter PAM performance.
- The effects of the treatments on moisture content should be investigated further for potential impacts before rainfall simulation.

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TABLES & FIGURES

Table 1. Particle size distributions and bulk density readings for site 1 in Kinston, N.C.

Plot #	PSA				ρ_b
	clay	silt	sand	Texture	
	----------%		----------		---g cm^{-3}---
1	20	12	68	SCL	1.60
2	14	10	76	SL	1.45
3	4	15	81	LS	1.63
4	5	20	75	SL	1.40
5	5	15	80	LS	1.59
6	5	17	78	LS	1.53
7	4	14	82	LS	1.58
8	6	19	75	SL	1.40
9	5	17	78	LS	1.43
10	5	20	75	SL	1.59
11	4	13	83	LS	1.49
12	5	14	81	LS	1.37
13	4	10	86	LS	1.60
14	5	14	81	LS	1.50
15	4	9	87	LS	1.51
16	5	14	81	LS	1.58
17	5	13	82	LS	1.60
18	2	12	86	LS	1.53
19	4	13	83	LS	1.54
20	4	13	83	LS	1.59

Table 2. ANOVA output for site 1 (Kinston, N.C.; 2009).

Kinston ANOVA Output					
Parameter	**Effect**	**Num df**	**Den df**	**F Value**	**Pr > F**
Turbidity (NTU)	type	4	15	1.11	0.3862
	event	4	15	16.20	<.0001
	type*event	16	15	1.82	0.1274
TSS ($mg\ L^{-1}$)	type	4	15	0.59	0.6760
	event	4	60	12.01	<.0001
	type*event	16	60	1.46	0.1469
Runoff (%)	type	4	15	0.77	0.5594
	event	4	15	66.03	<.0001
	type*event	16	15	3.01	0.0193
Biomass ($kg\ ha^{-1}$)	type	4	15	1.98	0.1495

Table 3. Total precipitation for site 1 (Kinston, N.C.; 2009).

Sampling Event (Dates)	**Total Precipitation**	**Peak Intensity**
	-------mm-------	-----mm hr^{-1}-----
1 (11/3-11/11)	99	13
2 (11/11-11/17)	39	6
3 (11/17-11/24)	53	11
4 (11/24-12/7)	50	6
5 (12/7-12/14)	48	14

Table 4. Site 1 treatment means for % runoff, turbidity, and TSS (Kinston, N.C.).

Kinston Treatment Means					
Mulch Type	Sampling Event (total rainfall in mm)				
	1 (99)	2 (39)	3 (53)	4 (50)	5 (48)
	----------Turbidity (NTU)----------				
BFM	83.7	40.0	36.2	37.8	45.4
70/30	76.1	41.0	10.0	20.1	114.2
Straw	62.8	19.8	6.6	21.5	87.4
Str. + PAM	30.7	17.5	3.7	14.3	49.6
Wood	62.0	14.6	8.3	18.7	116.2
	----------TSS (mg L^{-1})----------				
BFM	96.4	140.4	112.6	71.9	254.6
70/30	87.0	145.0	69.1	85.0	623.5
Straw	56.2	195.6	89.3	89.7	280.2
Str. + PAM	123.2	104.2	48.8	38.7	427.0
Wood	203.7	258.2	56.7	43.5	328.5
	----------Runoff (% of precipitation)----------				
BFM	10.0	18.9	11.5	9.6	21.1
70/30	4.8	10.5	8.5	10.5	16.2
Straw	6.2	13.7	9.2	12.6	18.5
Str. + PAM	0.8	12.5	8.6	12.1	15.0
Wood	3.1	9.1	7.1	11.8	16.9
	----------Biomass (kg ha^{-1})----------				
BFM	14.9				
70/30	17.9				
Straw	17.6				
Str. + PAM	15.5				
Wood	17.5				

Table 5. Hydromulch application estimates for site 1 (Kinston, N.C.; 2009).

Mulch Type	Sample #	HM subsample weight	Manufacturer-recommended rate	Estimated HM rate based on subsample	Difference between actual and recommended rates
		----g----	----------kg ha^{-1}----------		-------%-------
wood fiber	1	6.71	2240	3672	164
	2	8.39	2240	4591	205
	3	12.64	2240	6917	309
	4	11.83	2240	6474	289
BFM	1	17.31	3920	9472	242
	2	7.66	3920	4192	107
	3	10.06	3920	5505	140
	4	11.22	3920	6140	157
wood/paper blend	1	6.83	2800	3738	133
	2	6.5	2800	3557	127
	3	10.22	2800	5593	200
	4	9.27	2800	5073	181

Table 6. Polyacrylamide (PAM) infiltration box test descriptions.

Test #	Treatment #	Amount of PAM	Vol. H_2O mixed with PAM	Straw Coverage	Mixing Method (sump/tr. motor)	Boxes (dry/wet)	PAM conc.
		----g----	----mL----	----%----			----mg L^{-1}----
T2	1	0.44	400	0.5	sump	dry	1100
T2	2	0.44	800	0.5	sump	dry	550
T2	3	0.44	1600	0.5	sump	dry	275
T3	1	0.44	400	0.5	sump	dry	1100
T3	2	0.88	800	0.5	sump	dry	1100
T3	3	1.6	1600	0.5	sump	dry	1100
T4	1	0.44	800	0.5	tr. motor	dry	550
T4	2	0.44	1600	0.5	tr. motor	dry	275
T4	3	0.44	3200	0.5	tr. motor	dry	137.5
T5	1	0.44	800	0.5	tr. motor	dry	550
T5	2	0.88	1600	0.5	tr. motor	dry	550
T5	3	1.6	3200	0.5	tr. motor	dry	500
T7	1	0.44	400	0.5	sump	dry	1100
T8	1	0.44	400	0	sump	wet	1100
T8	2	0	0	1	sump	wet	0
T8	3	0.44	400	0.5	sump	wet	1100
T8	4	0.44	400	1	sump	wet	1100
T9	1	0.44	400	0	sump	dry	1100
T9	2	0	0	1	sump	dry	0
T9	3	0.44	400	1	sump	dry	1100
T10	1	0.44	800	0.5	sump	dry	550
T10	2	0.44	1600	0.5	sump	dry	275

Table 6. (continued)

T10	3	0.88	800	0.5	sump	dry	1100
T10	4	0.88	1600	0.5	sump	dry	550
T11	1	0.44	800	0.5	tr. motor	wet	550
T11	2	0.44	800	0.5	tr. motor	dry	550
T11	3	0.44	800	0.5	sump	wet	550
T11	4	0.44	800	0.5	sump	dry	550
T12	1	0.44	800	0.5	tr. motor	wet	550
T12	2	0.44	800	1.0	tr. motor	wet	550
T12	3	0	800	0.5	tr. motor	wet	0
T12	4	0	800	1.0	tr. motor	wet	0

Table 7. Box moisture contents from Test 6 of PAM infiltration study. (Note: Test 6 was only used as a moisture content check).

T6 Moisture Contents

Treatment (PAM rate in kg ha^{-1}, water rate in ML ha^{-1})	Box #	Sample 1	Sample 2	Sample 3	Avg. for each box	Overall trt. Avg.	Avg. minus the 3rd box
		----------%----------					
22-0.02	1	4.07	3.67	4.02	3.92	8.76	7.07
	2	4.39	12.48	13.78	10.22		
	3	13.20	13.19	10.05	12.15		
22-0.04	1	4.92	5.97	9.46	6.78	5.92	
	2	6.25	5.86	6.88	6.33		
	3	4.77	5.12	4.05	4.64		
22-0.08	1	2.85	3.06	2.96	2.96	6.04	
	2	5.04	6.03	5.54	5.54		
	3	4.70	12.00	12.15	9.62		

Table 8. Differences of least squares means for Test 8 of PAM infiltration study (log transformed).

Differences of Least Squares Means			
Trt.	**Trt.**	**t value**	**Pr > |t|**
0-0-1	0.44-400-0	-5.12	0.0022
0-0-1	0.44-400-0.5	3.29	0.0166
0-0-1	0.44-400-1	4.34	0.0049
0.44-400-0	0.44-400-0.5	8.41	0.0002
0.44-400-0	0.44-400-1	9.46	<.0001
0.44-400-0.5	0.44-400-1	1.05	0.3325

Table 9. Supernatant turbidities for PAM effectiveness based on application method and concentration.

PAM Turbidity		
Trt.	**PAM rate**	**Supernatant Turbidity**
	---ppm---	---NTU---
Control	0	2091.0
Sump pump (backpack w/ screen)	1	1459.7
	2	327.5
	4	85.7
	8	39.8
Sump pump (backpack w/o screen)	1	250.0
	2	84.3
	4	62.6
	8	28.5
Sump pump (trickled through backpack screen w/ pipette)	1	107.4
	2	82.9
	4	43.3
	8	27.6
Sump pump (not pumped through backpack)	1	228.2
	2	83.7
	4	42.4
	8	28.0

Table 10. Tetrazolium test summary for seed used in preliminary hydromulch evaluation.

TZ Seed Testing		
Seed Type	**Number of Viable Seeds (out of 50)**	**Notes**
Hard Fescue	3	• Low number of viable seed indicates seed deterioration. • Endosperms look flaccid/"mealy" which also indicates seed deterioration.
Lespedeza	0	• A few seed had stained radicles, but the rest of the seed was not stained; indicates storage deterioration. • Even the few seed that were stained were not fully stained.
Millet	0	• Root tips were not fully stained→indicates seed deterioration. • Plumules and radicles are also not stained or not fully stained. • Embryos were dead; seed likely deteriorated from an extended storage period.
Tall Fescue	42	• Overall seed health and viability was good. • This seed was not received from DOT. It was purchased from a local dealer.
Kentucky Bluegrass	0	• Seed deterioration was present. • Embryos and endosperms look flaccid and "mealy".

Table 11. Germination rates for tall and hard fescue varieties as a function of contact time with lime and fertilizer.

Fescue (Tall + Hard) Germination Rates						
Treatment	**Days after Treatment**				**Total seeds that germinated**	**% Germination at the end of the study**
	(7 days)	**(14 days)**	**(21 days)**	**(28 days)**	--# out of 10--	----%----
30 min. control	3	6	0	1	10	100
30 min. treated	5	2	1	0	8	80
1 hr. control	3	6	0	0	9	90
1 hr. treated	2	7	0	0	9	90
2 hr. control	7	2	0	0	9	90
2 hr. treated	6	3	0	0	9	90
4 hr. control	7	2	0	0	9	90
4 hr. treated	4	6	0	0	10	100
8 hr. control	1	7	2	0	10	100
8 hr. treated	5	3	1	0	9	90

Table 12. Particle size distributions and bulk density readings for site 2 (Asheboro, N.C.).

Plot #	PSA				ρ_b
	clay	silt	sand	Texture	
	----------%----------				---g cm^{-3}---
1	30	60	10	SICL	1.35
2	34	61	5	SICL	1.18
3	31	64	5	SICL	1.39
4	37	59	4	SICL	1.28
5	32	61	7	SICL	1.40
6	23	73	4	SIL	1.22
7	31	65	4	SICL	1.26
8	25	68	7	SIL	1.36
9	43	55	2	SIC	1.32
10	22	66	12	SIL	1.13
11	37	58	5	SICL	1.33
12	20	68	12	SIL	1.18
13	32	56	12	SICL	1.31
14	14	81	5	SIL	1.13
15	33	62	5	SICL	1.57
16	16	79	5	SIL	1.17
17	29	64	7	SICL	1.31
18	13	75	12	SIL	1.13
19	36	57	7	SICL	1.29
20	16	58	26	SIL	0.98

Figure 1. Site 1 (Kinston, N.C.) after set-up was complete. (Note: tarps were removed following the first rain event).

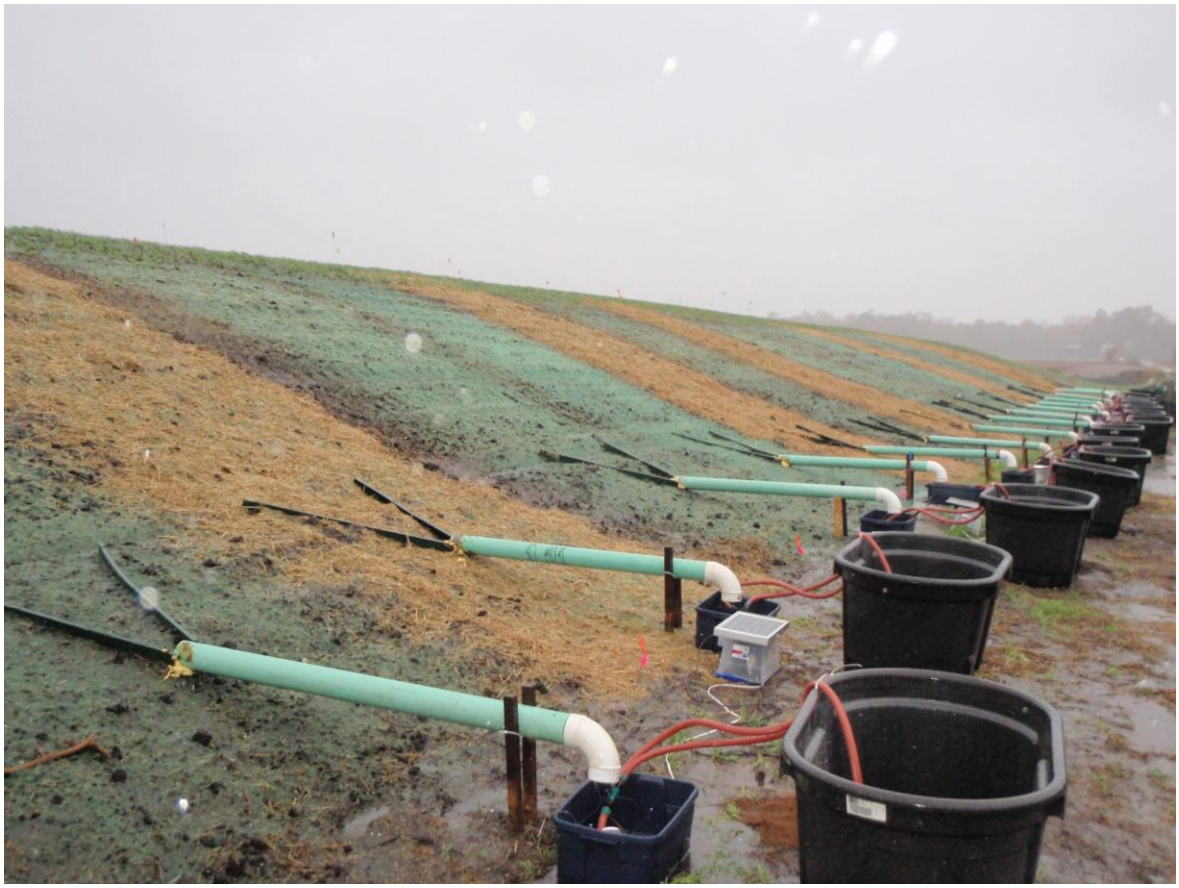

Figure 2. Runoff collection setup at site 1. Two 1.2 m pieces of edging used to direct water flow into a 10.2 cm diameter pipe, which then flowed into a 38 L container and pumped (split flow) into a larger 378.5 L container.

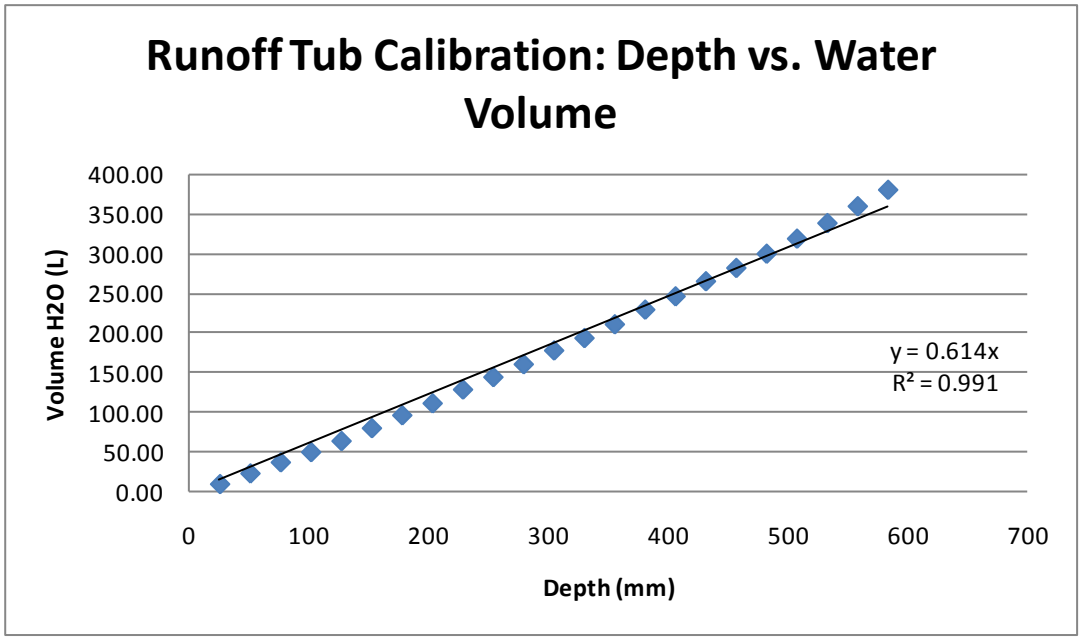

Figure 3. Equation used to convert runoff depths to volumes for site 1.


Figure 4. Biomass sampling at site 1 (Kinston, N.C.).

Figure 5. Severe rill and gully erosion at site 2 (Asheboro, N.C.).

Figure 6. Example of plot failure at site 2 (Asheboro, N.C.).

Figure 7. Backpack sprayer used to apply PAM treatments in infiltration study.


Figure 8. Sump pump (left) and trolling motor (right) used to mix PAM for infiltration study.

Figure 9. Boxes placed on stands at a 5% slope underneath the rainfall simulator for PAM infiltration study.

Figure 10. Well pump and container used to supply water to the rainfall simulator (113.5 L trashcan—left and 378.5 L tub—right).

Figure 11. Windbreaker installed on three sides of the rainfall simulator used in the PAM infiltration study.

Figure 12. Rain gauges used to check for rainfall distribution in PAM infiltration study.

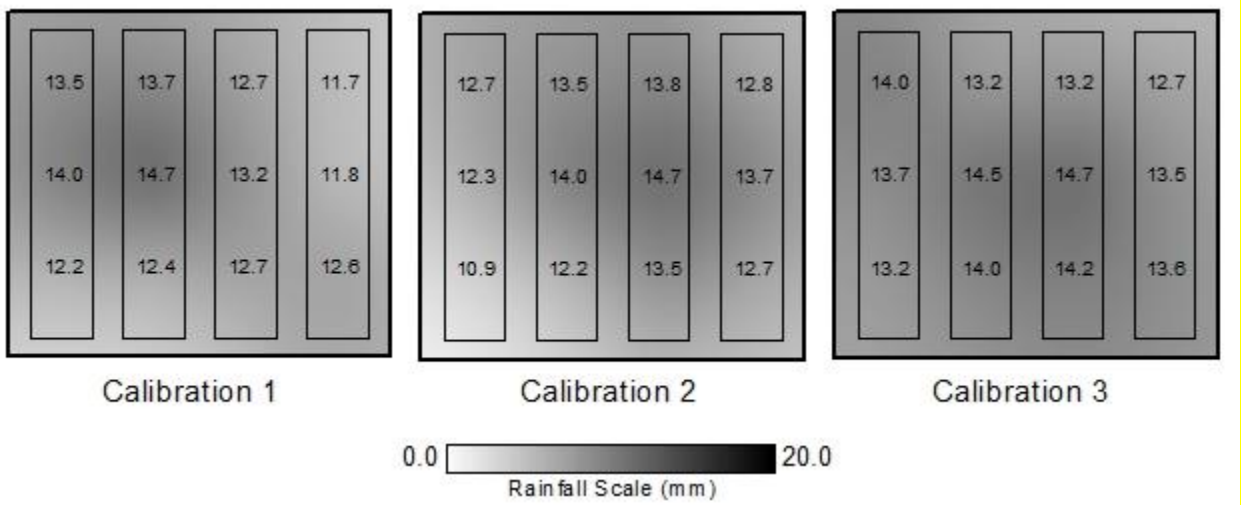

Figure 13. Rain gauge calibration. Values indicate rain gauge location (shown inside boxes) as well as rainfall distribution.

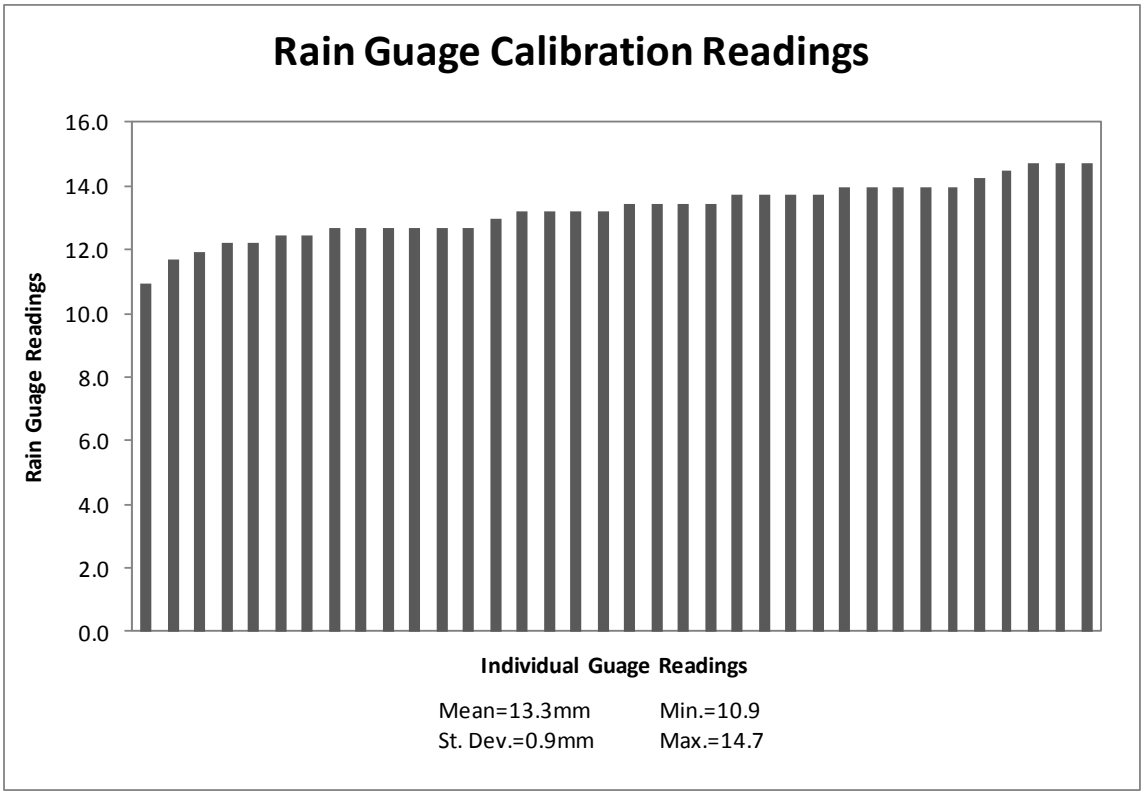

Figure 14. Rain gauge measurements (from 3 calibrations).

Figure 15. Boxes and runoff collection tubs used in PAM infiltration study.

Figure 16. Trash strainer located within backpack sprayer wand used to apply treatments in PAM infiltration study.

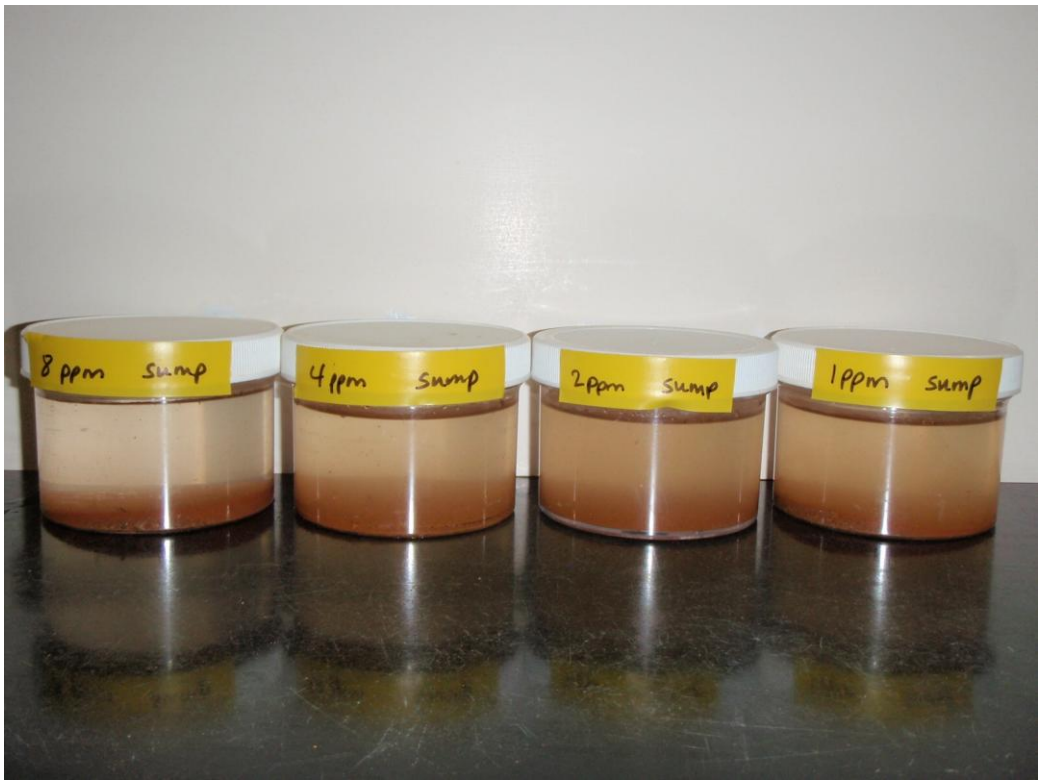

Figure 17. PAM clear jar tests used to evaluate PAM effectiveness via supernatant turbidity measurements.

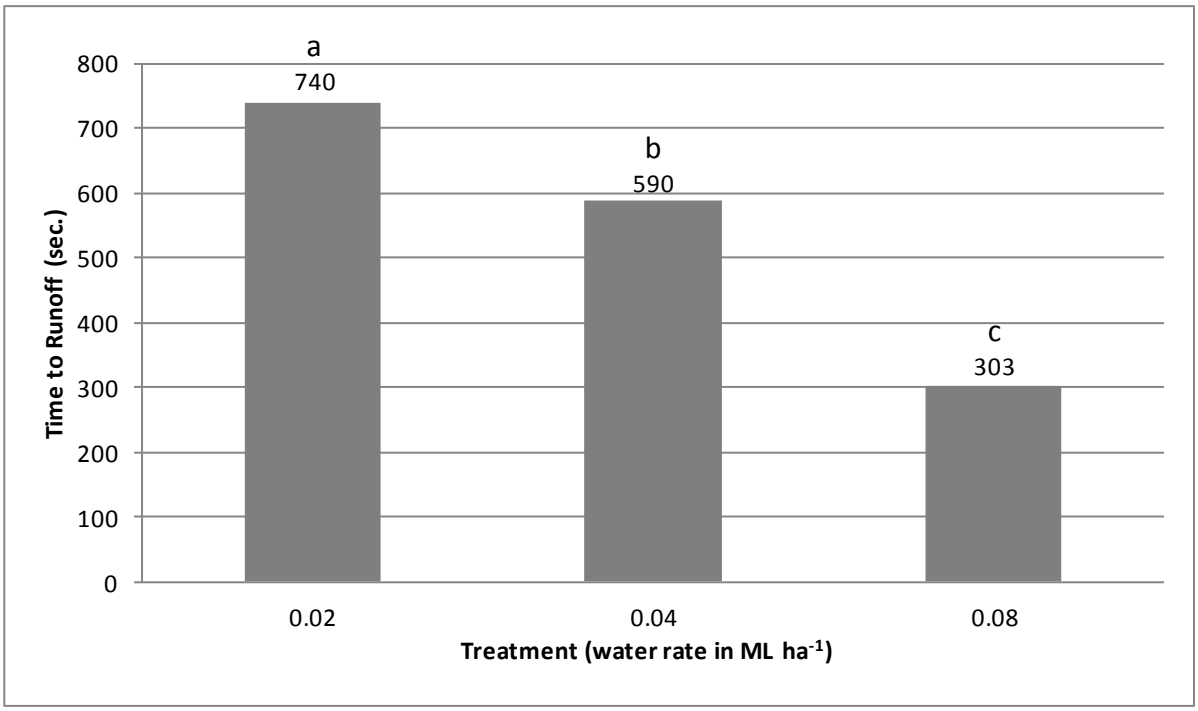

Figure 18. The effect of application volume on time to runoff for PAM mixed with a sump pump, applied at 22 kg ha^{-1}, and allowed to dry for 3-5 days prior to rainfall simulation (Test 2). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

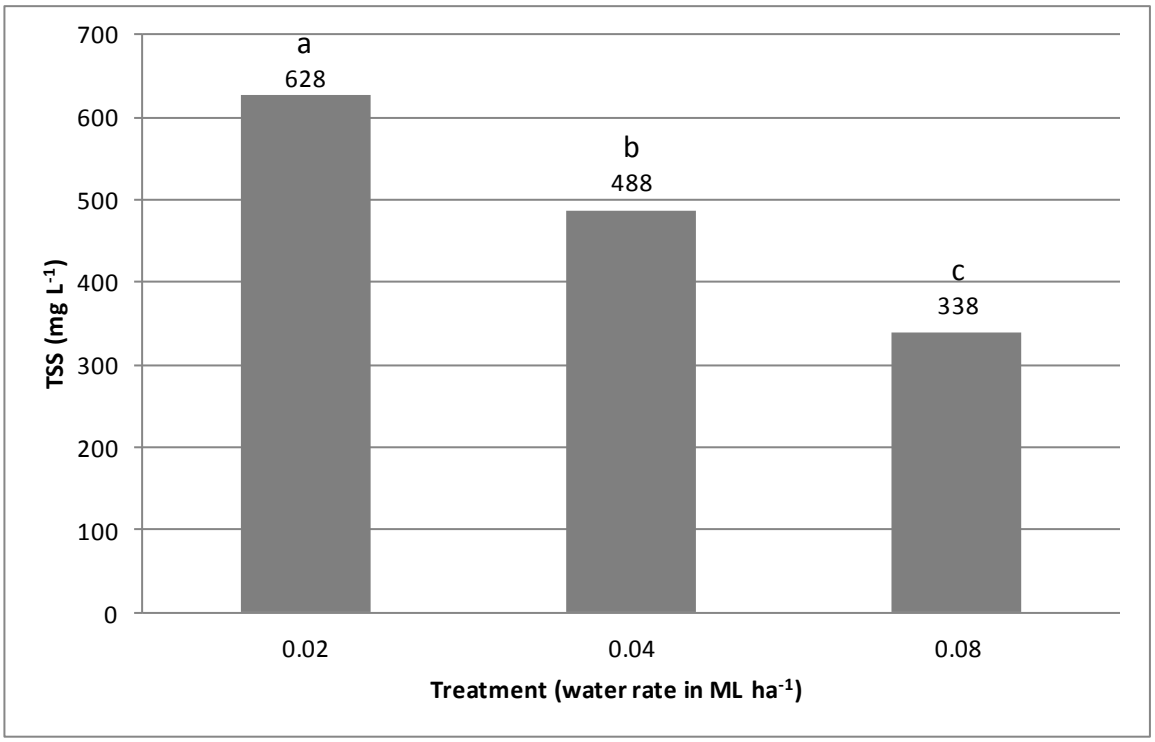

Figure 19. The effect of application volume on TSS for PAM mixed with a sump pump, applied at 22 kg ha^{-1}, and allowed to dry for 3-5 days prior to rainfall simulation (Test 2). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

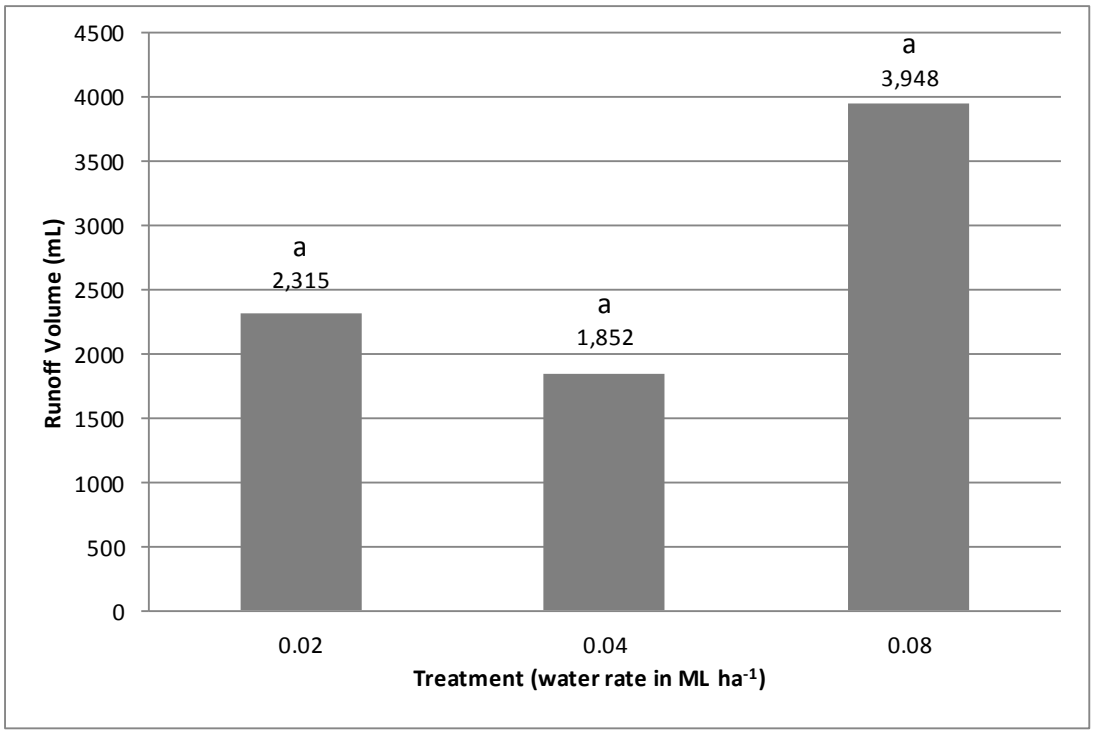

Figure 20. The effect of application volume on runoff volume for PAM mixed with a sump pump, applied at 22 kg ha^{-1}, and allowed to dry for 3-5 days prior to rainfall simulation (Test 2). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

Figure 21. Illustration of surface seal formation when using large application volumes. Treatments include 22-0.08 (left) and 22-0.04 (right). Treatment units are kg ha^{-1} PAM and ML water ha^{-1}, respectively.

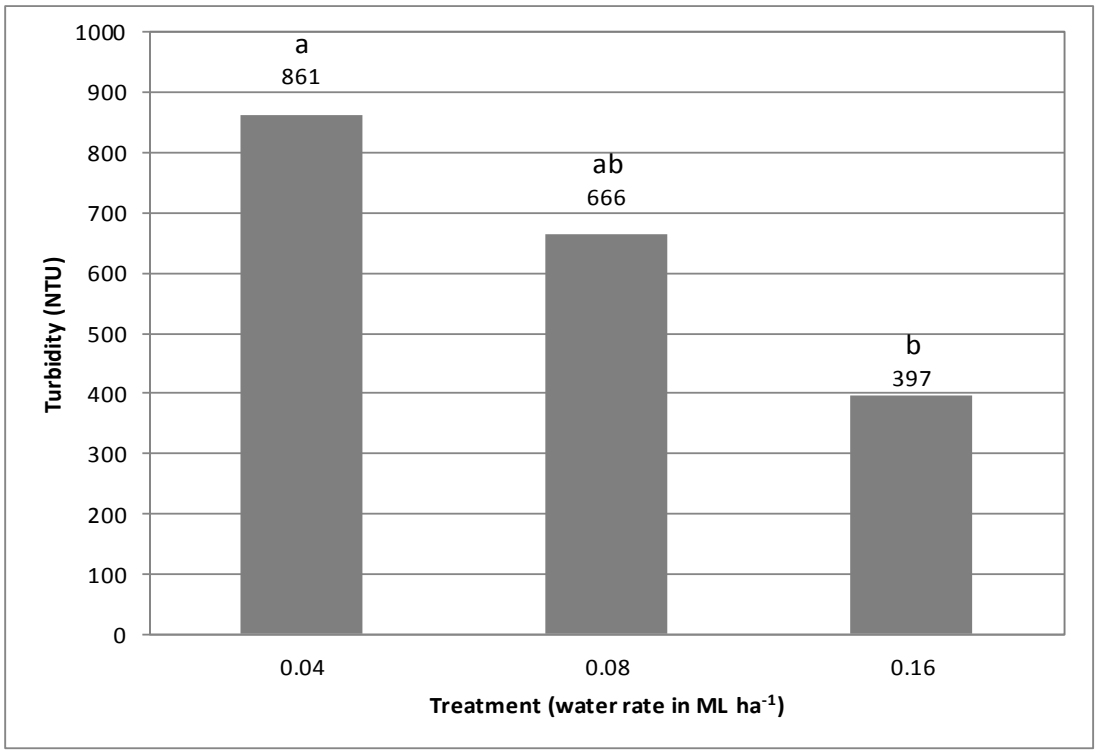

Figure 22. The effect of application volume on turbidity for PAM mixed with a trolling motor, applied at 22 kg ha^{-1}, and allowed to dry for 3-5 days prior to rainfall simulation (Test 4). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

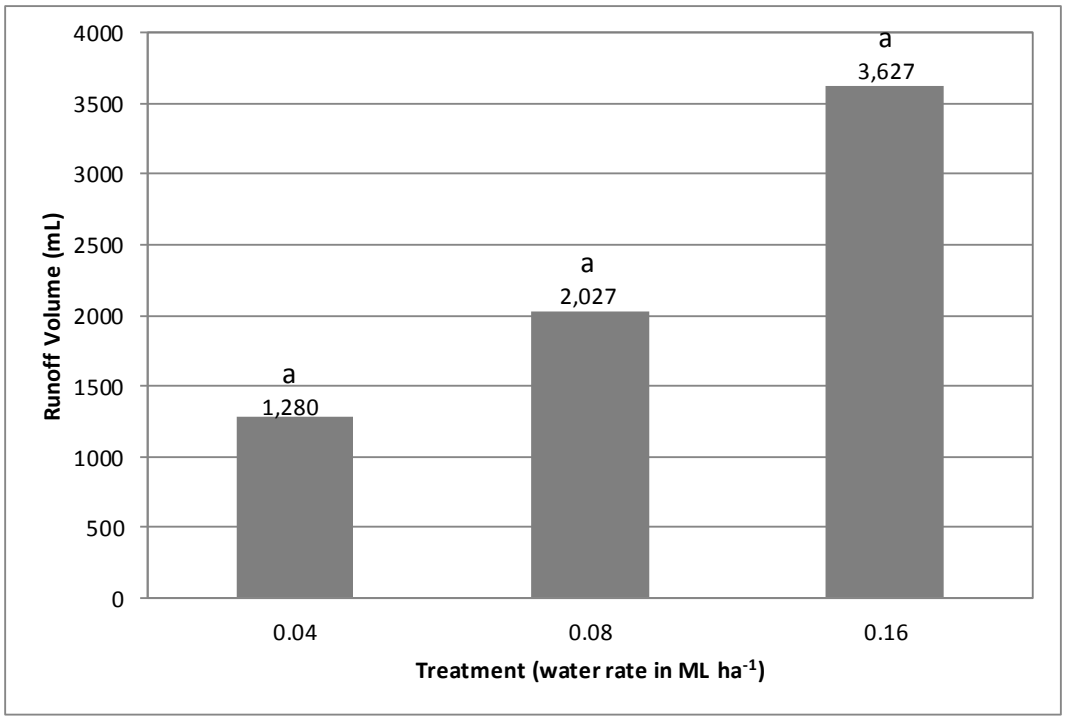

Figure 23. The effect of application volume on runoff volume for PAM mixed with a trolling motor, applied at 22 kg ha^{-1}, and allowed to dry for 3-5 days prior to rainfall simulation (Test 4). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

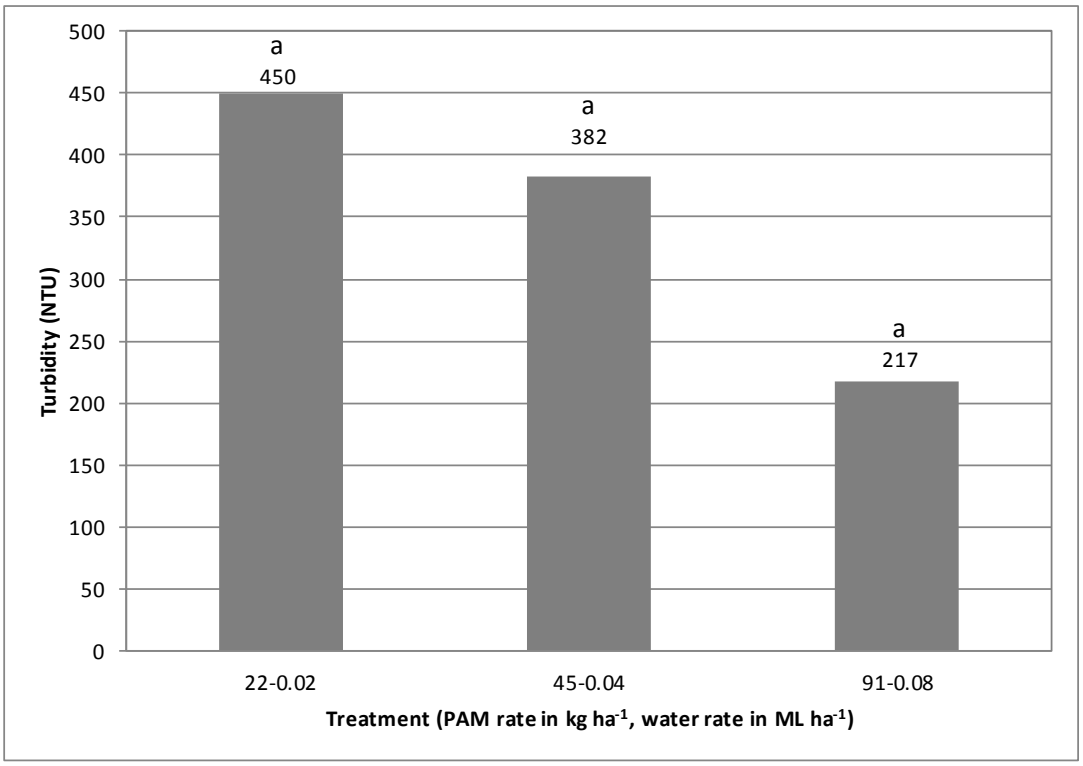

Figure 24. The effect of PAM rate and application volume on turbidity for PAM mixed with a sump pump and allowed to dry for 3-5 days prior to rainfall simulation (Test 3). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

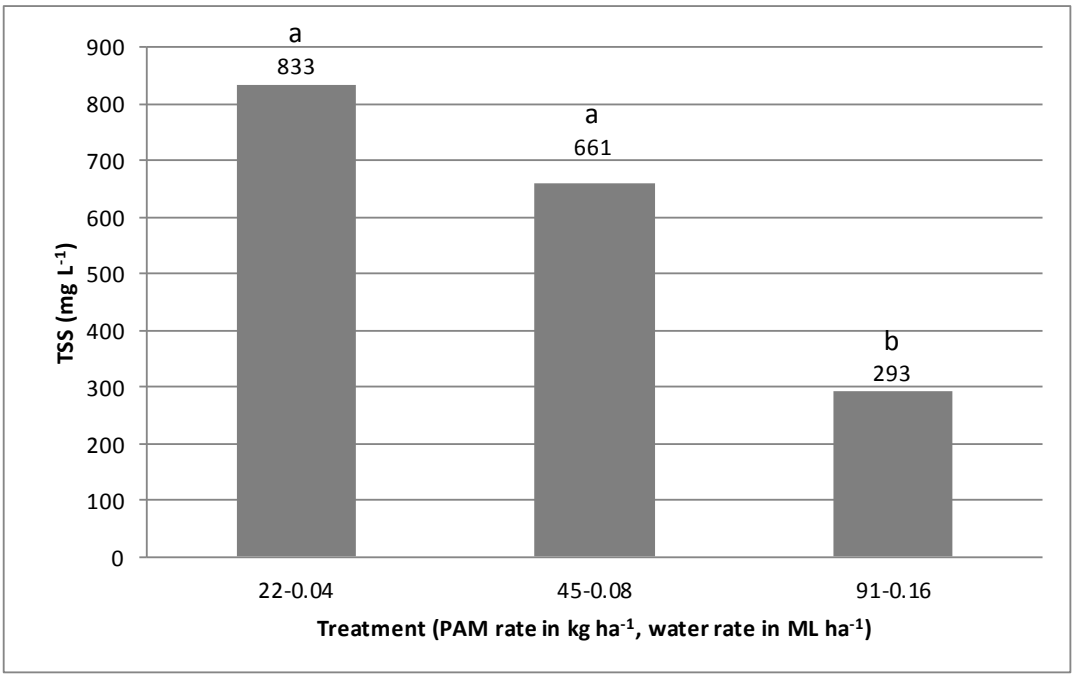

Figure 25. The effect of PAM rate and application volume on TSS for PAM mixed with a trolling motor and allowed to dry for 3-5 days prior to rainfall simulation (Test 5). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

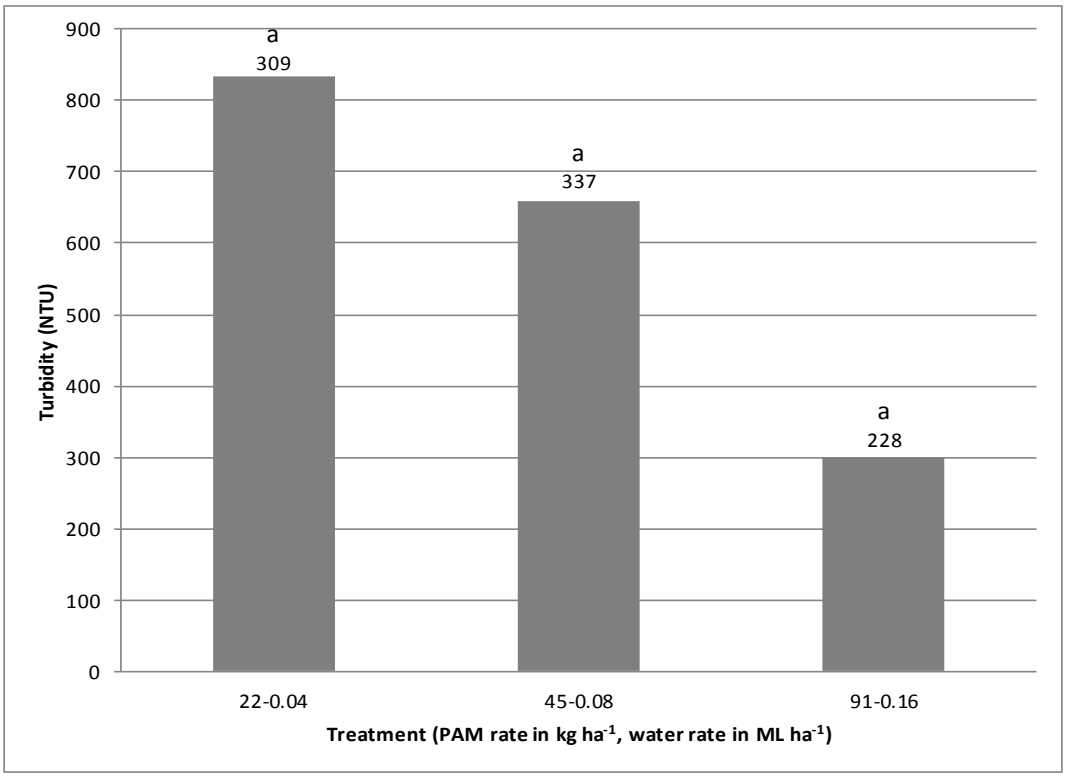

Figure 26. The effect of PAM rate and application volume on turbidity for PAM mixed with a trolling motor and allowed to dry for 3-5 days prior to rainfall simulation (Test 5). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

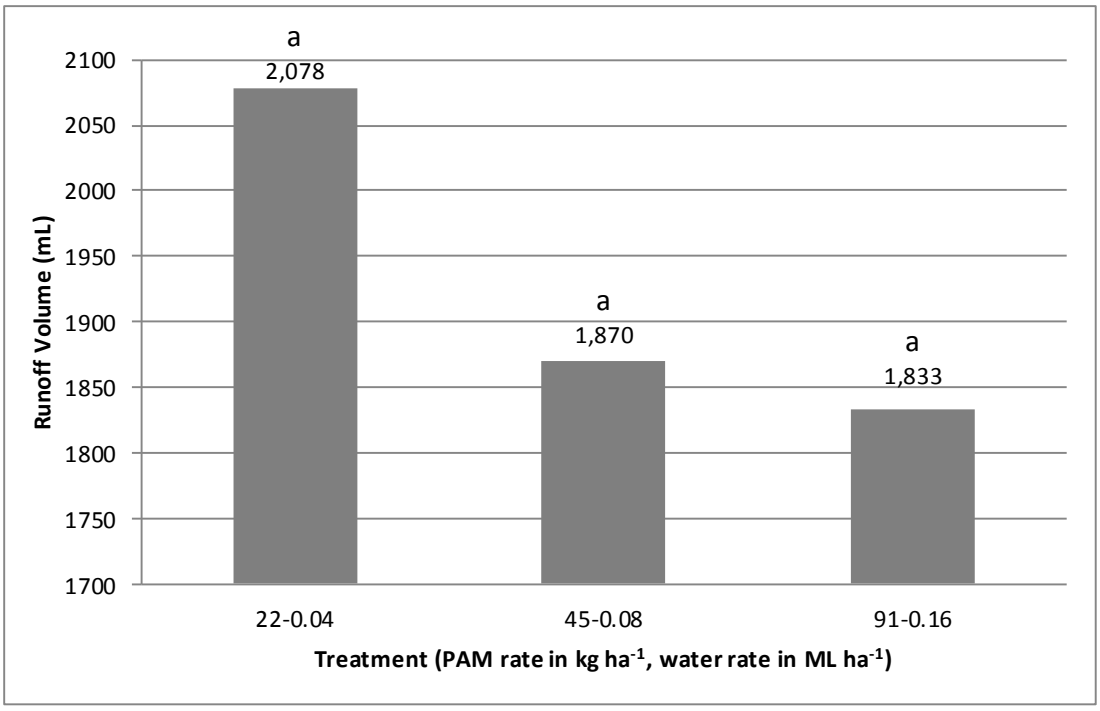

Figure 27. The effect of PAM rate and application volume on runoff volume for PAM mixed with a trolling motor and allowed to dry for 3-5 days prior to rainfall simulation (Test 5). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

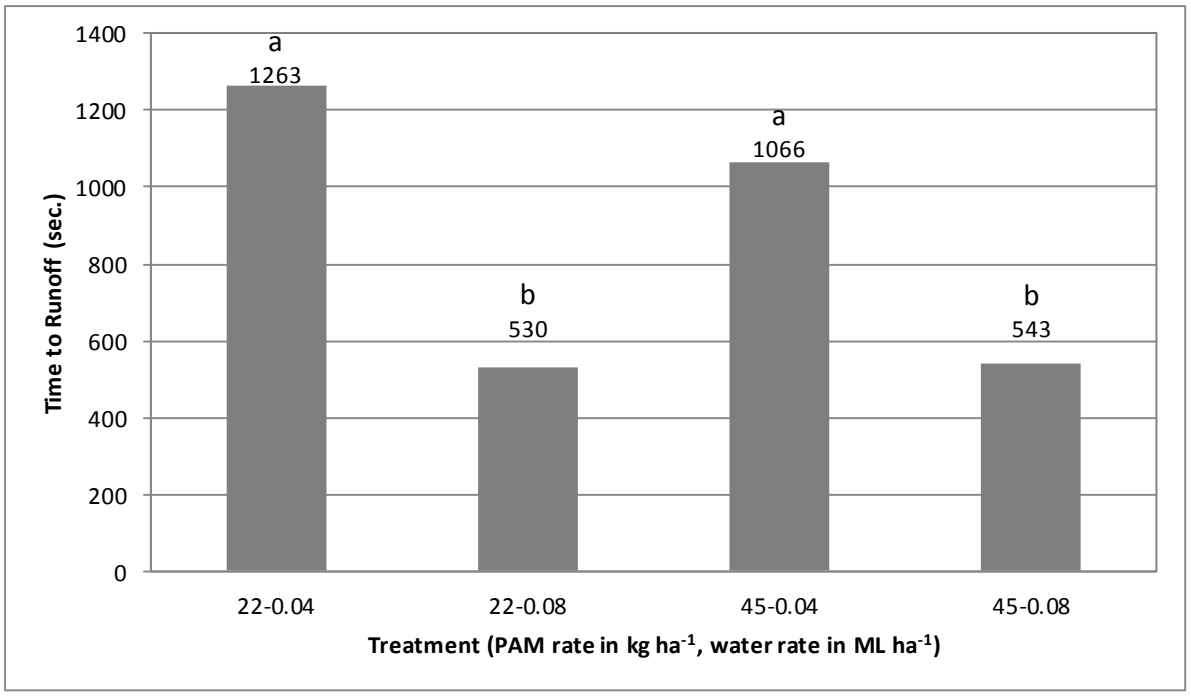

Figure 28. The effect of PAM rate and application volume on time to runoff for PAM mixed with a sump pump and allowed to dry for 3-5 days prior to rainfall simulation (Test 10). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

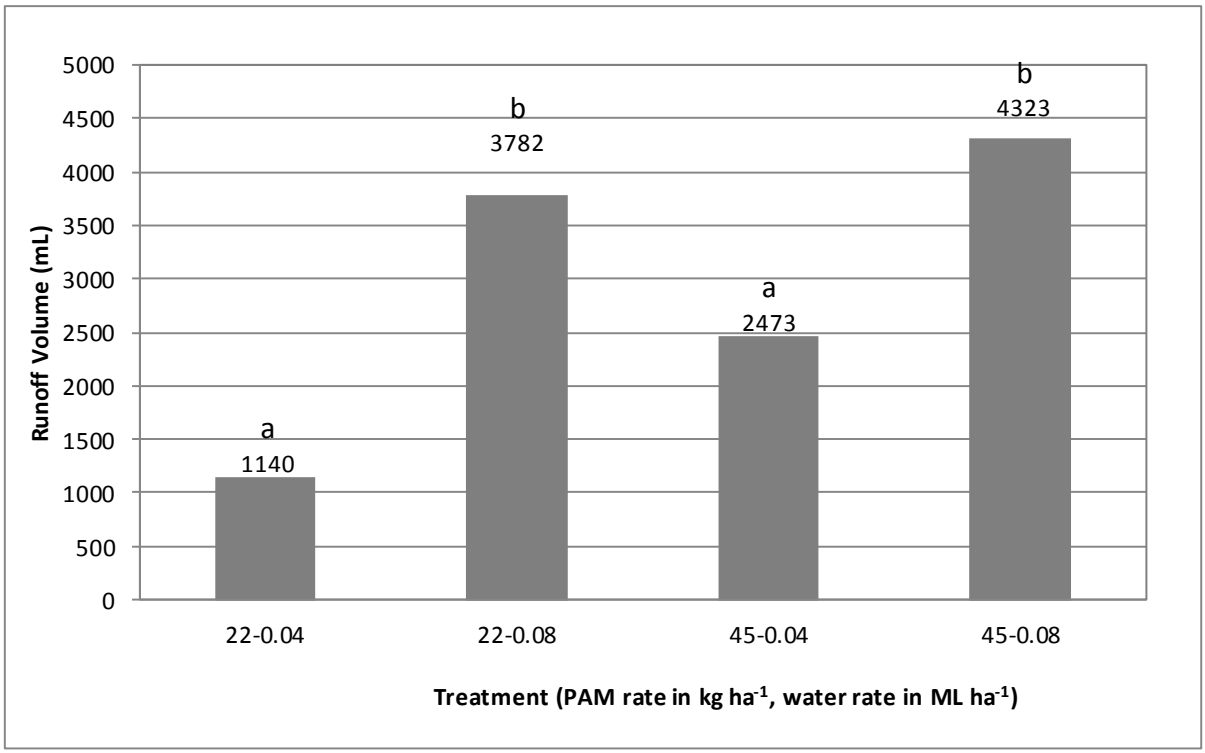

Figure 29. The effect of PAM rate and application volume on runoff volume for PAM mixed with a sump pump and allowed to dry for 3-5 days prior to rainfall simulation (Test 10). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

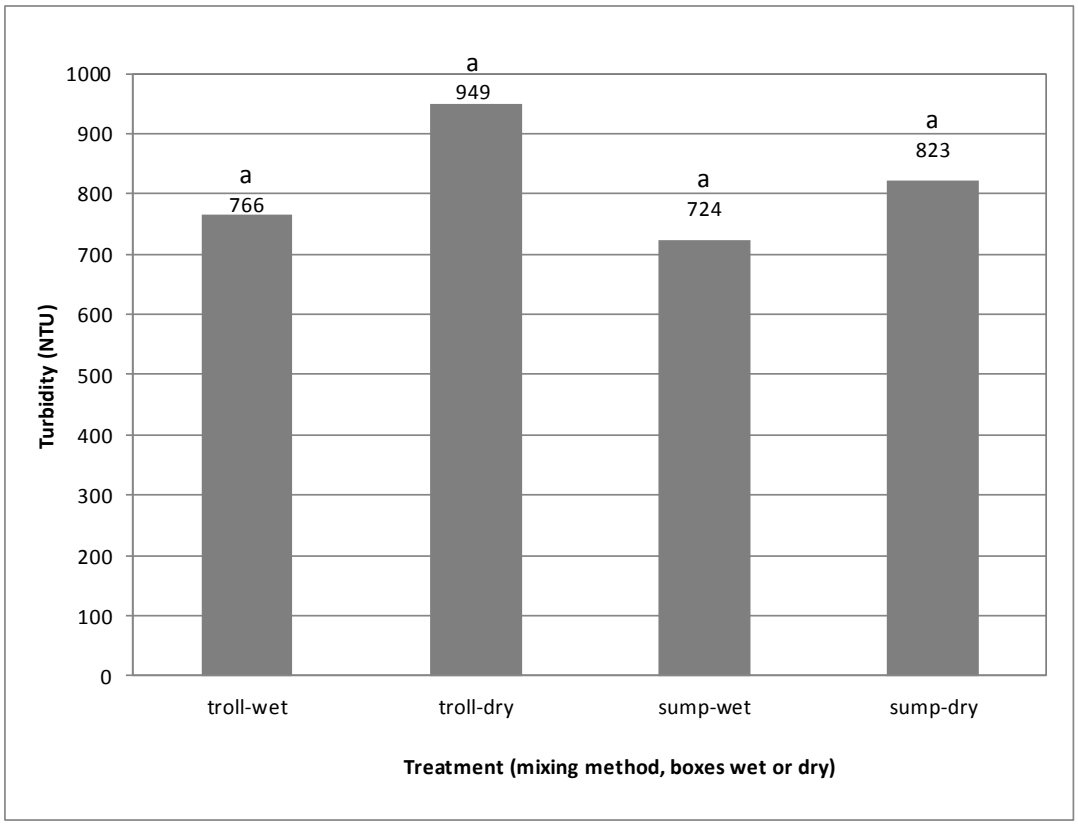

Figure 30. The effect of drying time (before rainfall simulation) and mixing method on turbidity for PAM applied at a rate of 22 kg ha^{-1} and with 0.04 ML ha^{-1} water (Test 11). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

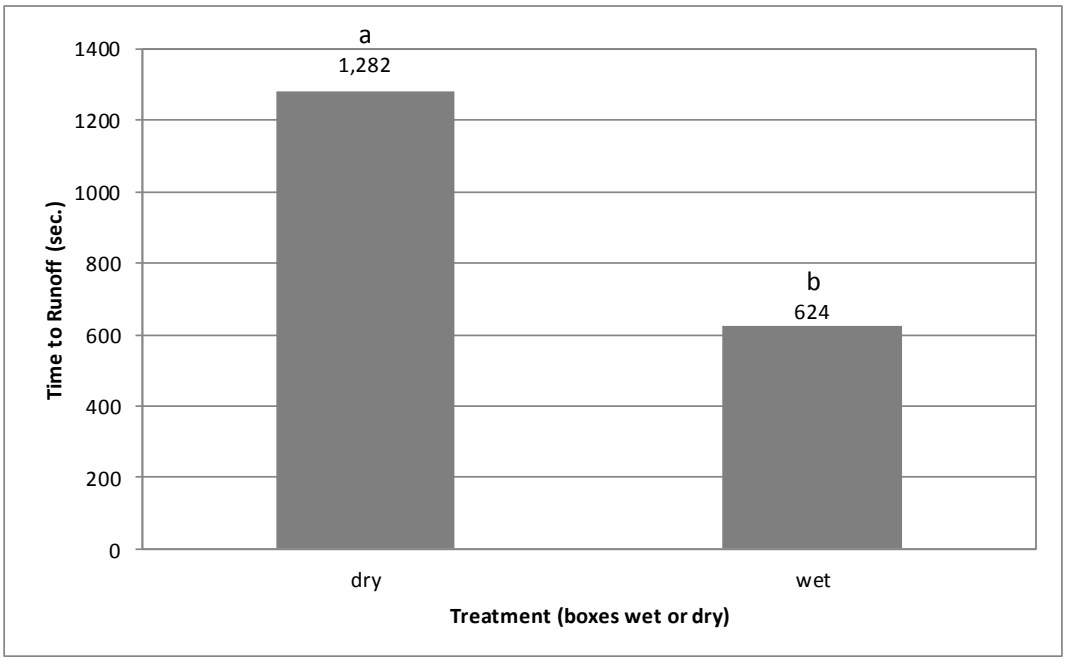

Fig. 31. The effect of drying time (before rainfall simulation) on runoff time for PAM applied at a rate of 22 kg ha^{-1} and with 0.02 ML ha^{-1} water (Test 7 vs. Test 8). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

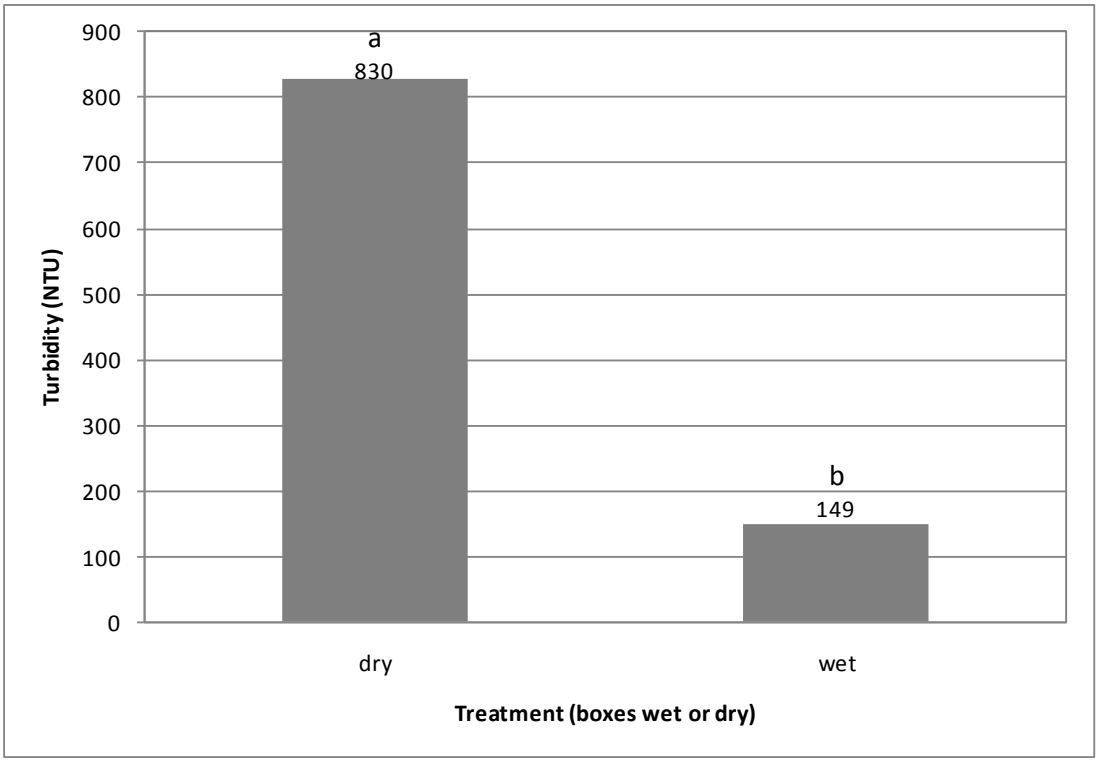

Figure 32. The effect of drying time (before rainfall simulation) on turbidity for PAM applied at a rate of 22 kg ha^{-1}, with 0.02 ML ha^{-1} water, and mixed with a sump pump (Test 7 vs. Test 8). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

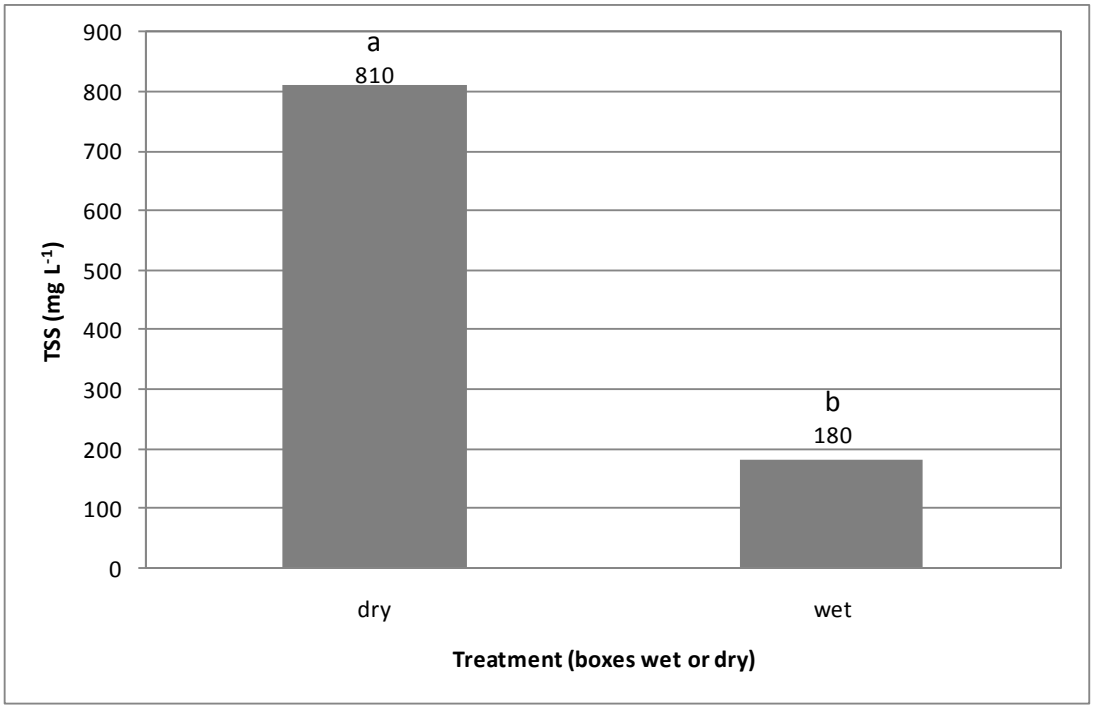

Figure 33. The effect of drying time (before rainfall simulation) on TSS for PAM applied at a rate of 22 kg ha^{-1}, with 0.02 ML ha^{-1} water, and mixed with a sump pump (Test 7 vs. Test 8). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

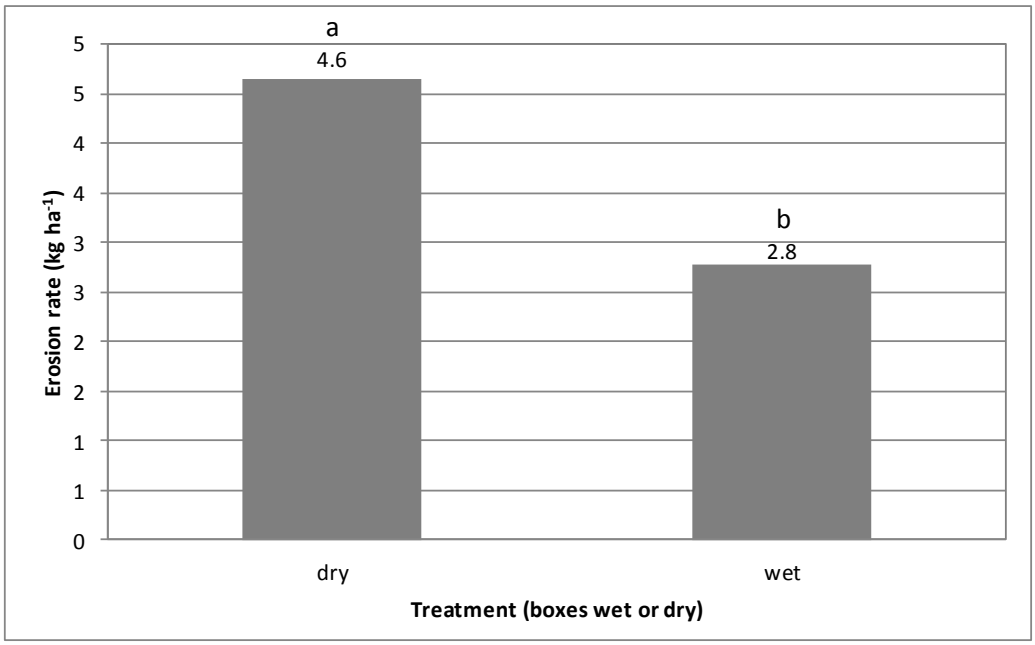

Figure 34. The effect of drying time (before rainfall simulation) on erosion rate for PAM applied at a rate of 22 kg ha^{-1}, with 0.02 ML ha^{-1} water, and mixed with a sump pump (Test 7 vs. Test 8). Data were log transformed. Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

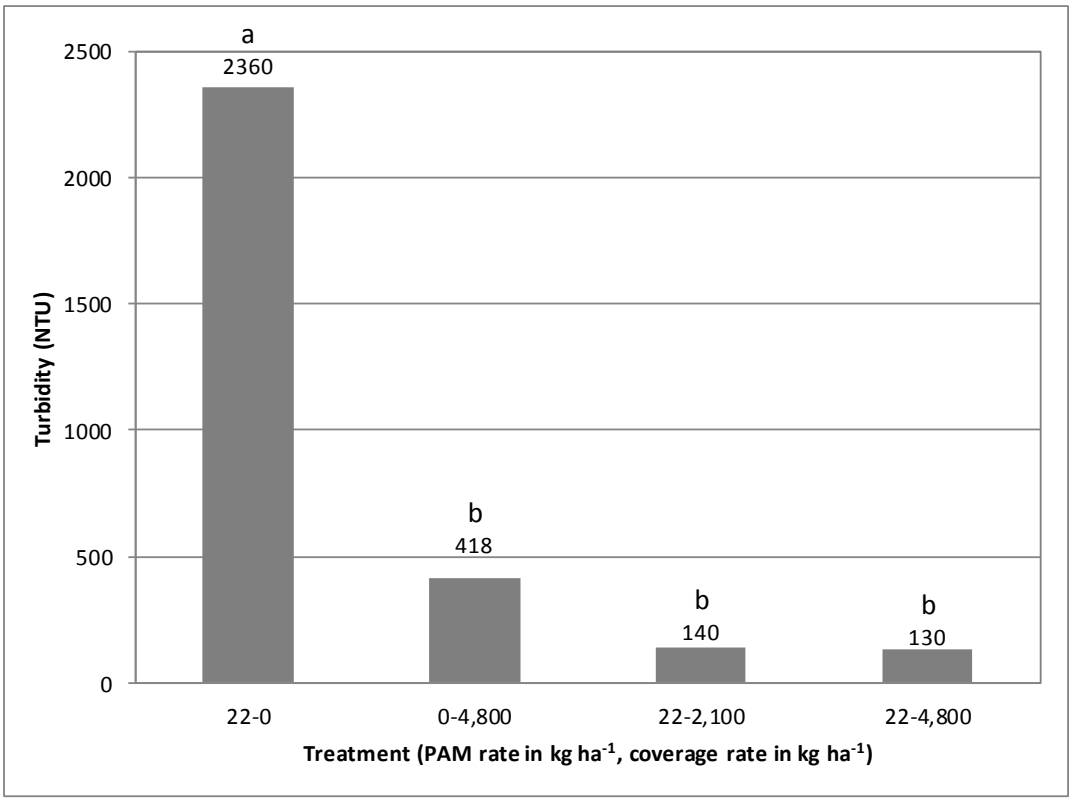

Figure 35. The effect of PAM rate and coverage rate on turbidity for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and not allowed to dry before rainfall simulation (Test 8). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

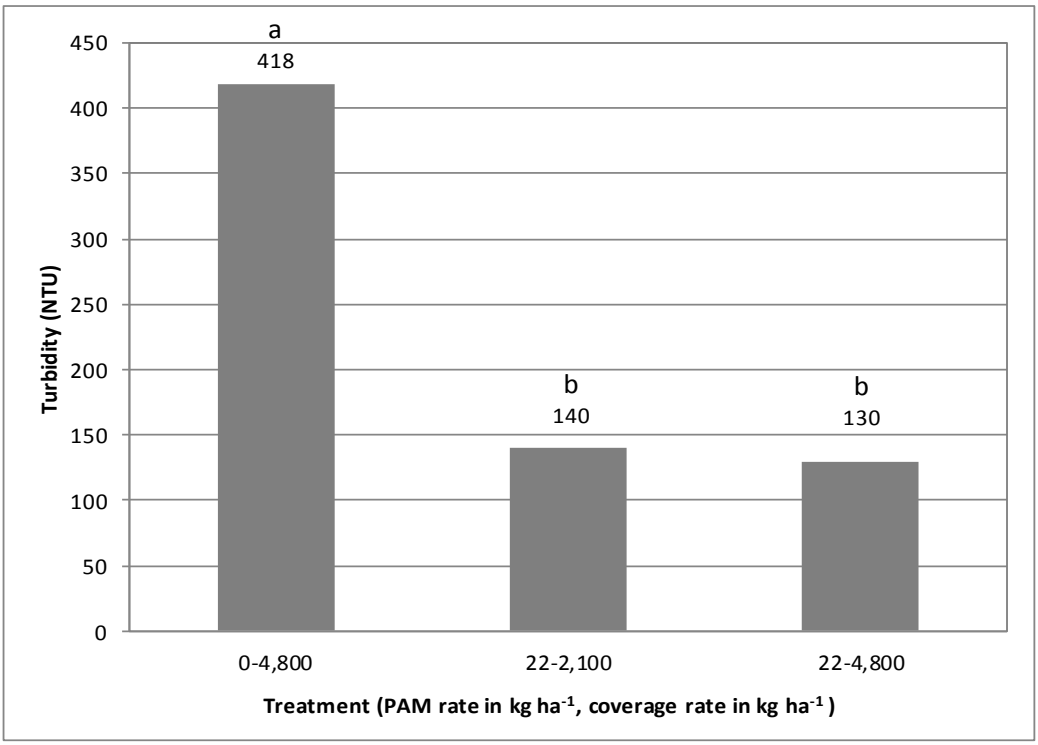

Figure 36. The effect of PAM rate and coverage rate on turbidity for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and not allowed to dry before rainfall simulation (Test 8). Turbidity values were analyzed without the 22-0 treatment. Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

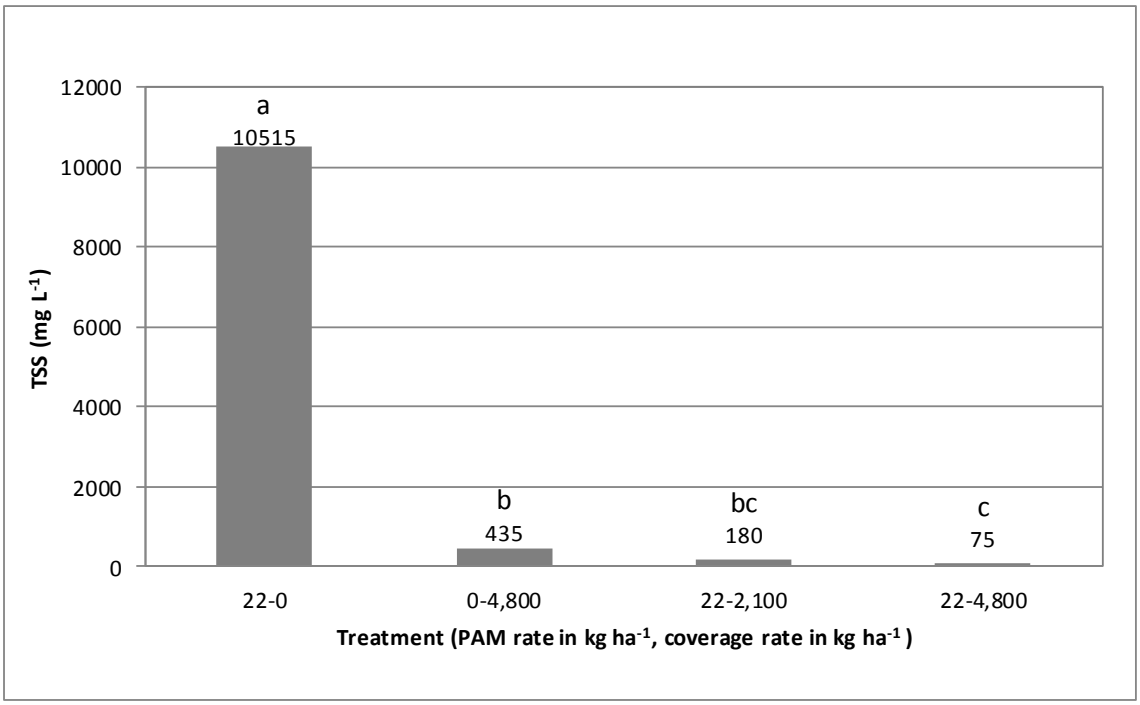

Figure 37. The effect of PAM rate and coverage rate on TSS for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and not allowed to dry before rainfall simulation (Test 8). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

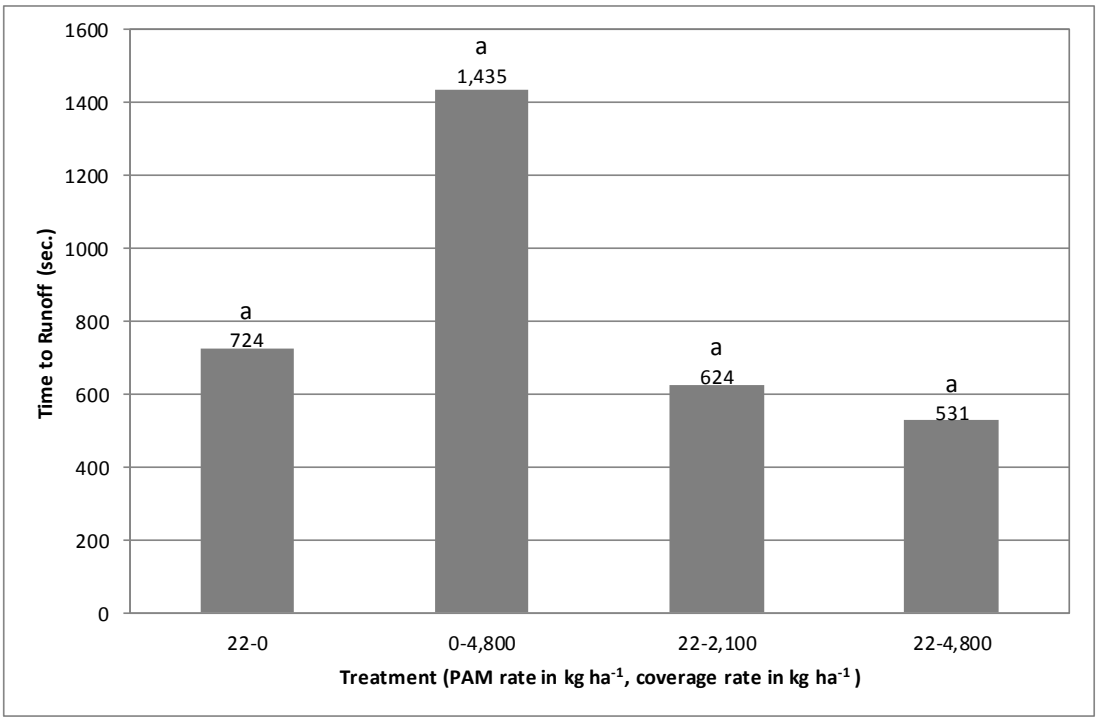

Figure 38. The effect of PAM rate and coverage rate on time to runoff for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and not allowed to dry before rainfall simulation (Test 8). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

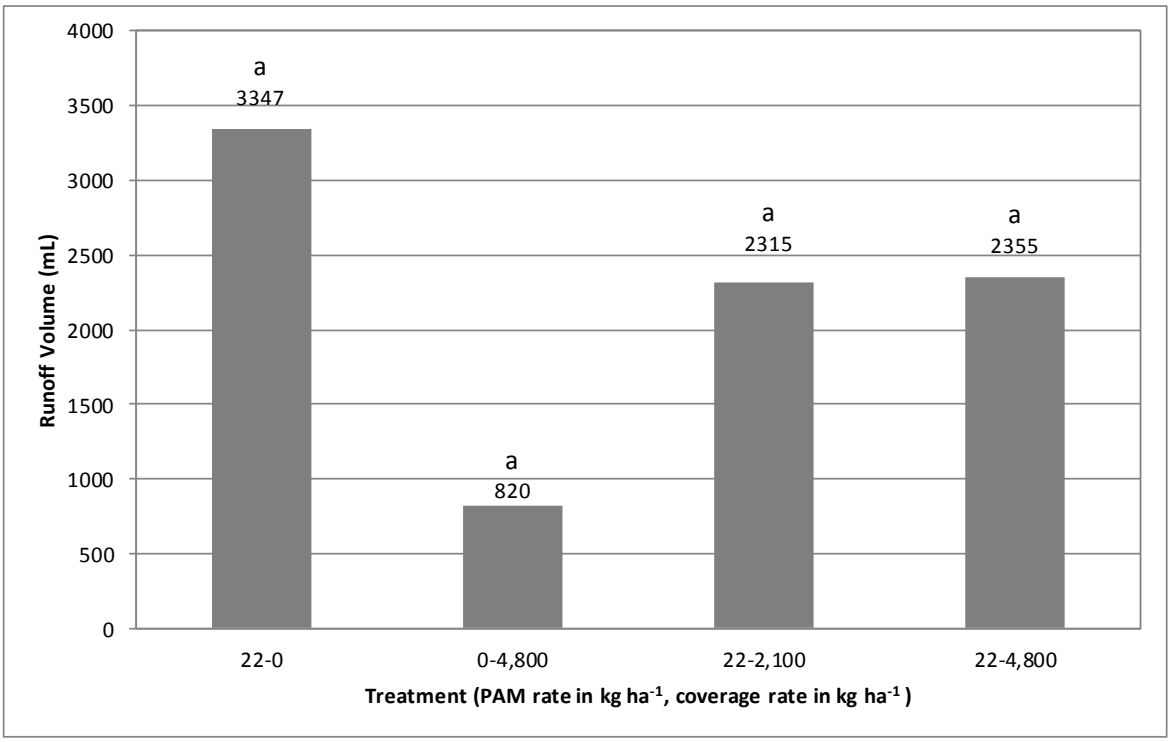

Figure 39. The effect of PAM rate and coverage rate on runoff volume for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and not allowed to dry before rainfall simulation (Test 8). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

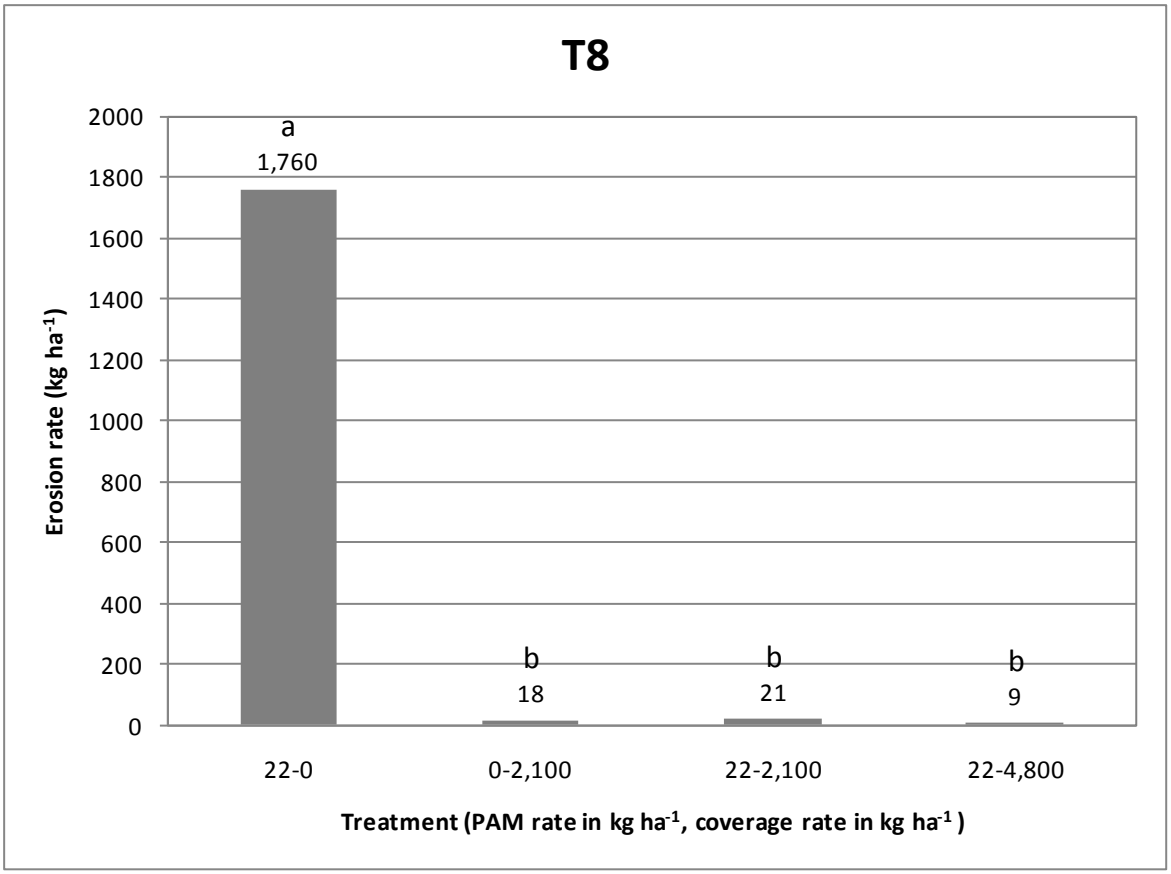

Figure 40. The effect of PAM rate and coverage rate on erosion rate for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and not allowed to dry before rainfall simulation (Test 8). Data were log transformed. Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

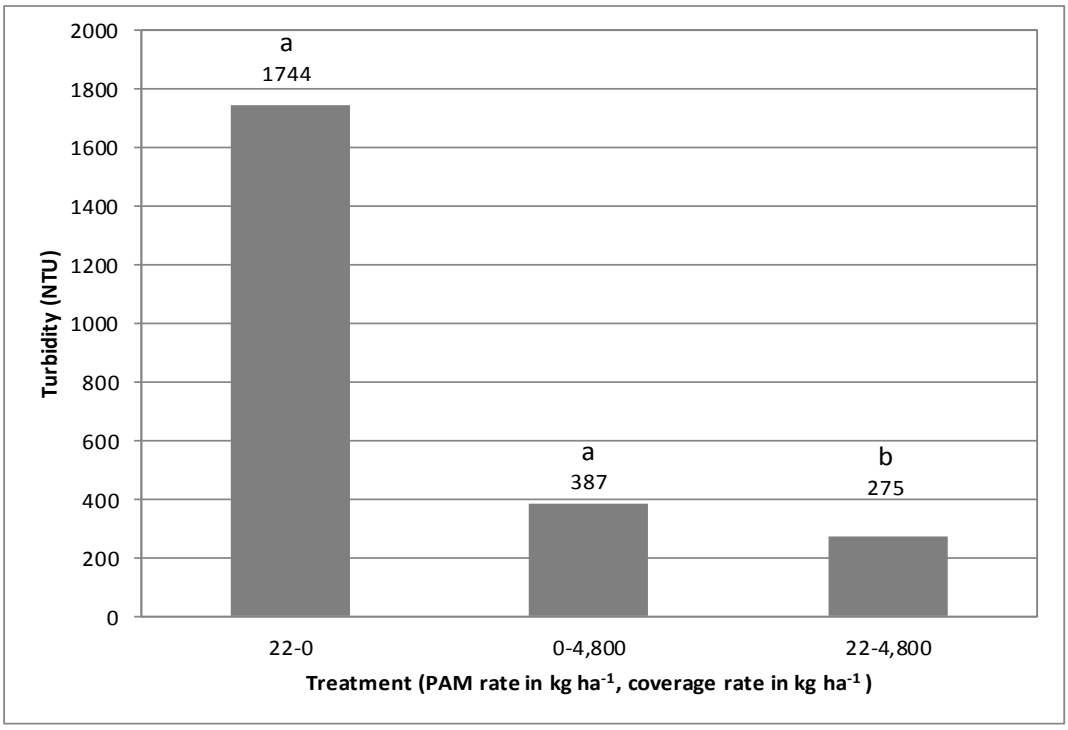

Figure 41. The effect of PAM rate and coverage rate on turbidity for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and allowed to dry 3-5 days before rainfall simulation (Test 9). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

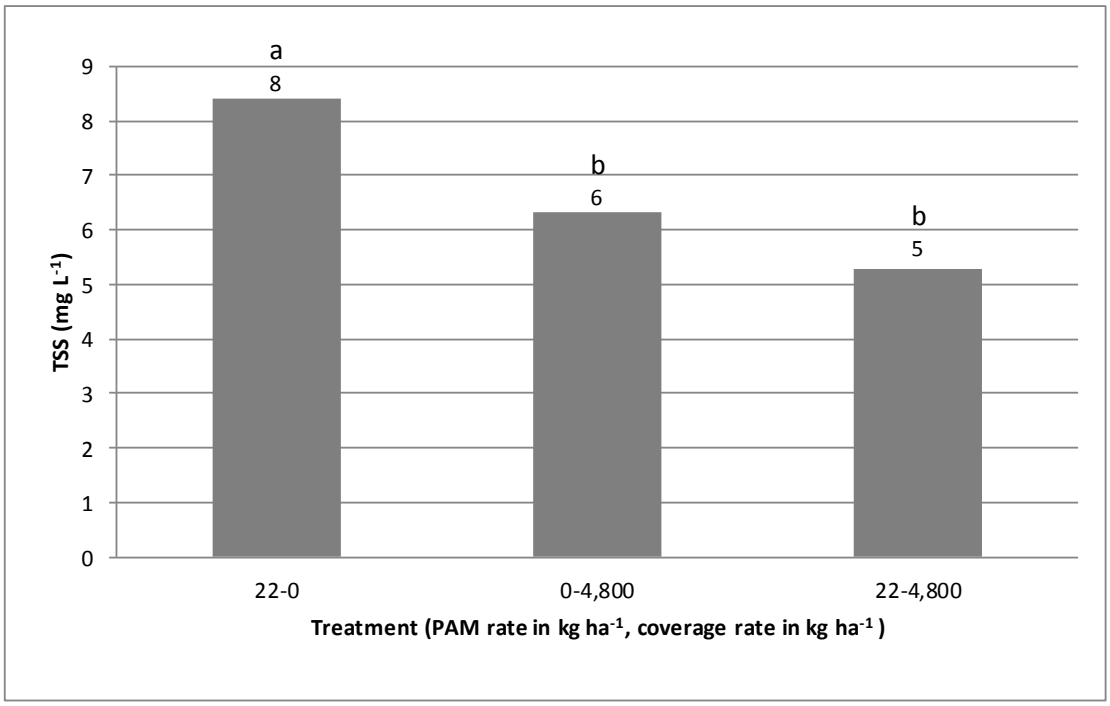

Figure 42. The effect of PAM rate and coverage rate on TSS for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and allowed to dry 3-5 days before rainfall simulation (Test 9). Significant differences (alpha $\leq$ 0.05) are indicated by different letters. Data were log transformed.

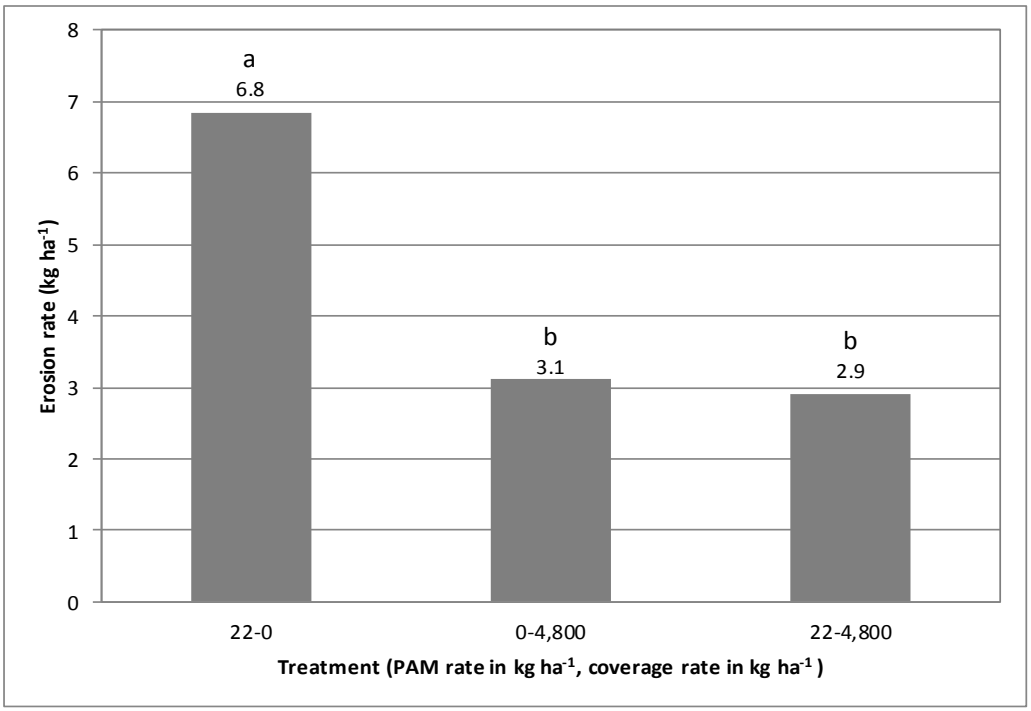

Figure 43. The effect of PAM rate and coverage rate on erosion rate for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and allowed to dry 3-5 days before rainfall simulation (Test 9). Significant differences (alpha $\leq$ 0.05) are indicated by different letters. Data were log transformed.

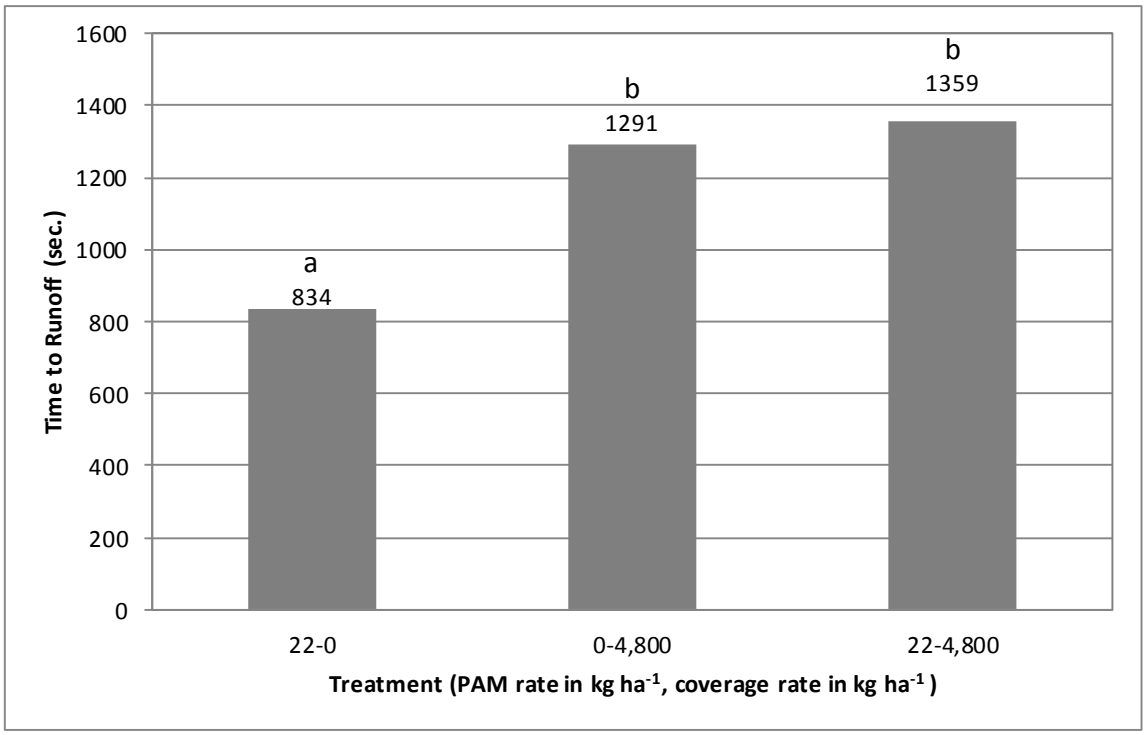

Figure 44. The effect of PAM rate and coverage rate on time to runoff for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and allowed to dry 3-5 days before rainfall simulation (Test 9). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

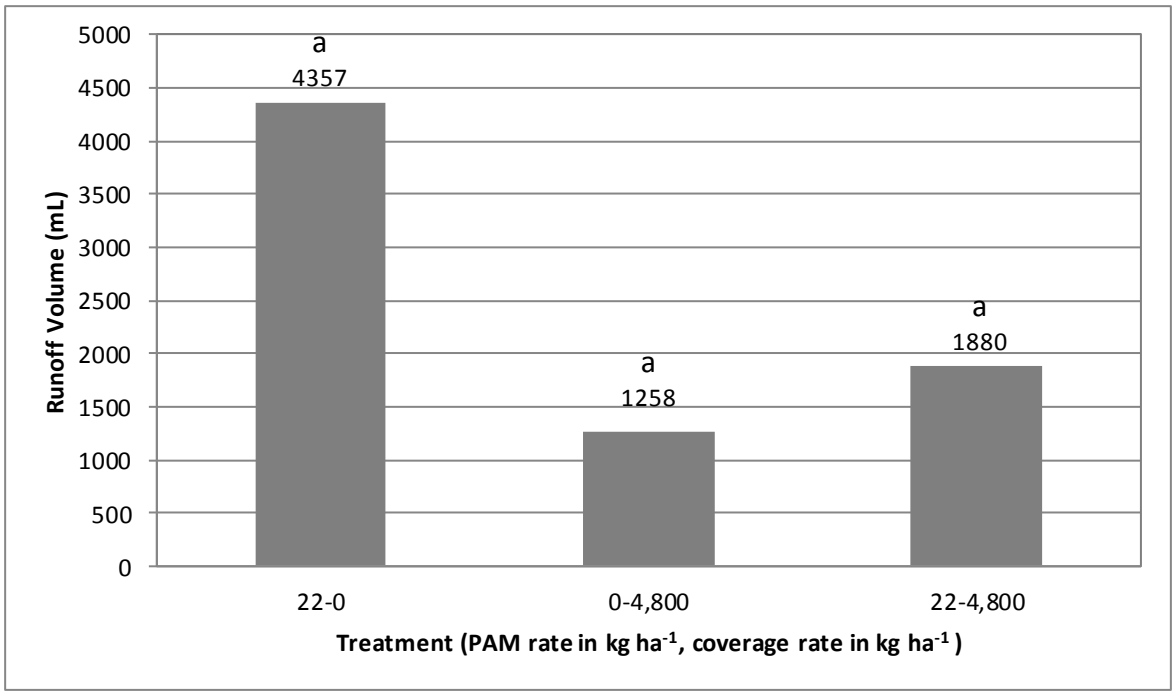

Figure 45. The effect of PAM rate and coverage rate on runoff volume for PAM applied with 0.02 ML ha^{-1} water, mixed with a sump pump, and allowed to dry 3-5 days before rainfall simulation (Test 9). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

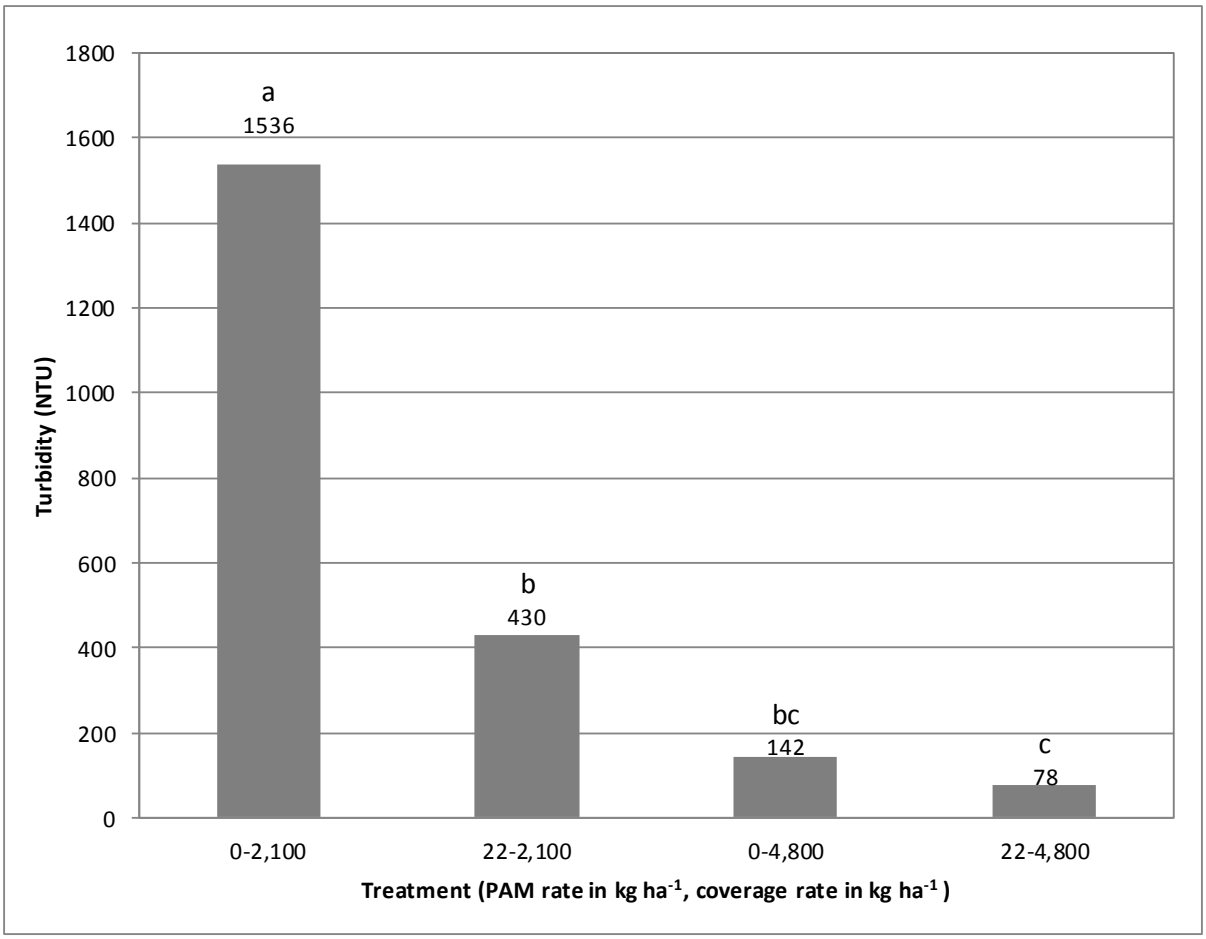

Figure 46. The effect of PAM rate and coverage rate on turbidity for PAM applied with 0.04 ML ha^{-1} water, mixed with a trolling motor, and not allowed to dry before rainfall simulation (Test 12). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

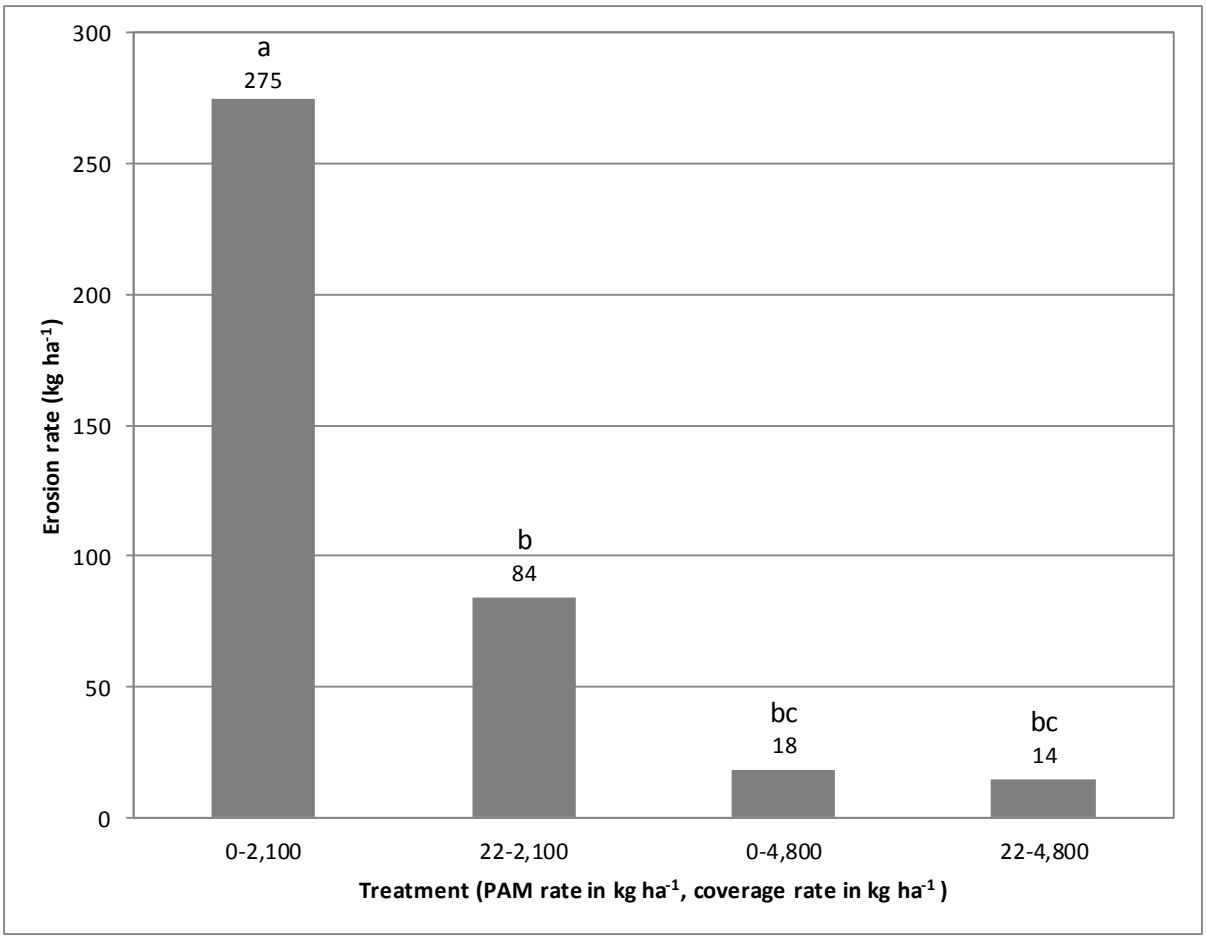

Figure 47. The effect of PAM rate and coverage rate on erosion rate for PAM applied with 0.04 ML ha^{-1} water, mixed with a trolling motor, and not allowed to dry before rainfall simulation (Test 12). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

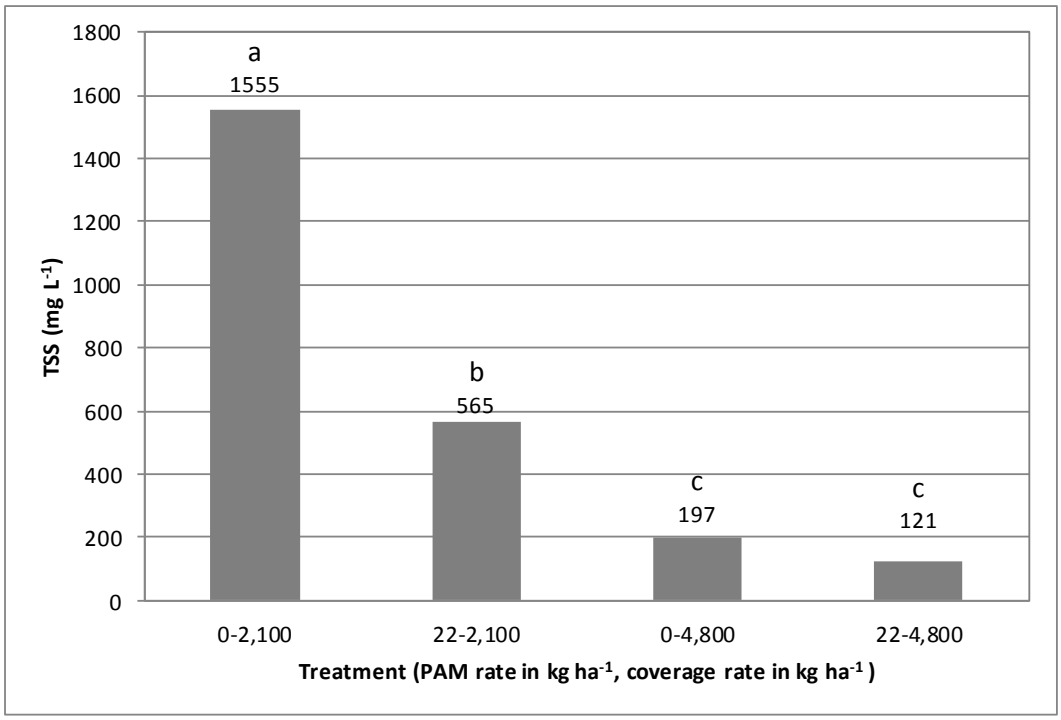

Figure 48. The effect of PAM rate and coverage rate on TSS for PAM applied with 0.04 ML ha^{-1} water, mixed with a trolling motor, and not allowed to dry before rainfall simulation (Test 12). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

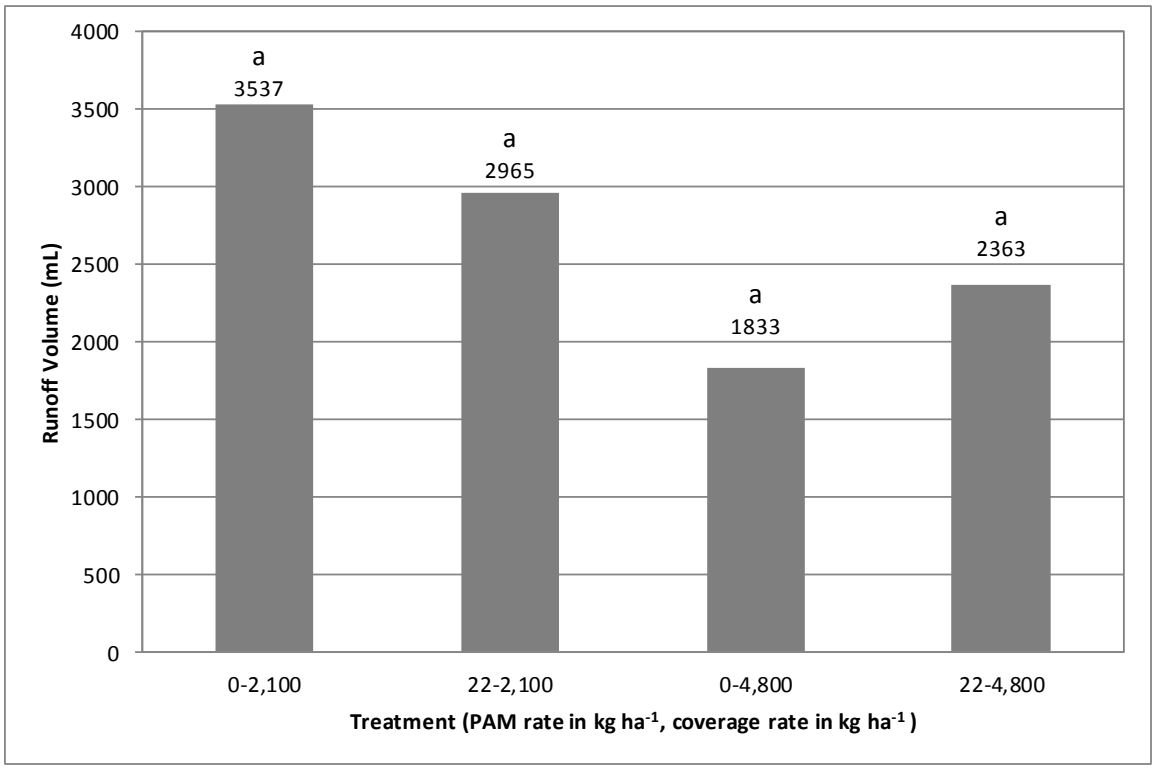

Figure 49. The effect of PAM rate and coverage rate on runoff volume for PAM applied with 0.04 ML ha^{-1} water, mixed with a trolling motor, and not allowed to dry before rainfall simulation (Test 12). Significant differences (alpha $\leq$ 0.05) are indicated by different letters.

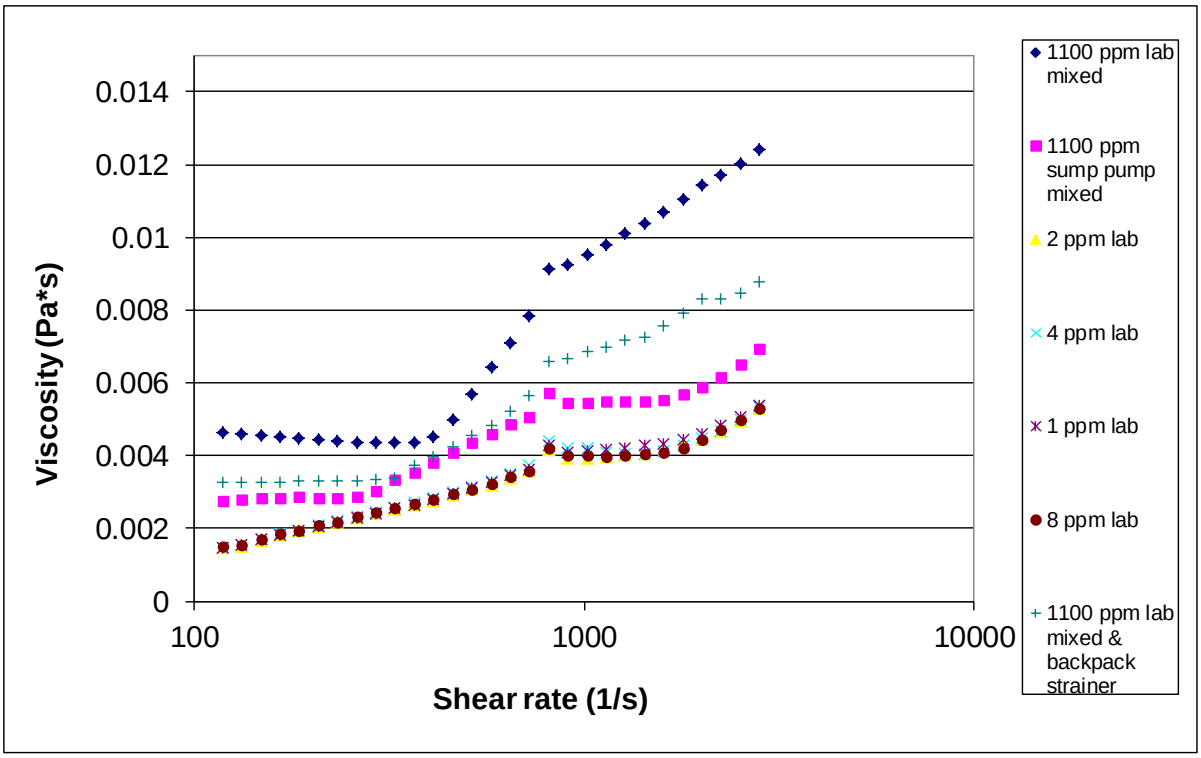

Figure 50. Viscosity measurements for PAM based on different mixing and application methods (NC State Food Science Lab). Units on the x-axis and y-axis are radians per second and Pascals multiplied by seconds, respectively.

Figure 51. Wooden boxes used in preliminary hydromulch evaluation, as well as PAM infiltration study.

Figure 52. “Fill-to” line drawn inside of boxes used in preliminary hydromulch evaluation and PAM infiltration study.

Figure 53. Turf Maker hydroseeder used in preliminary hydromulch evaluation and field plot testing.

Figure 54. Preliminary hydromulch evaluation boxes placed on hillslope at Lake Wheeler Training Facility in Raleigh, N.C.

Figure 55. Trenches dug during second round of preliminary hydromulch evaluation in order to keep boxes flush with the ground.

Figure 56. Examples of poor vegetation establishment during the second round of the preliminary hydromulch evaluation (left—CM, middle—FGM, right—straw).

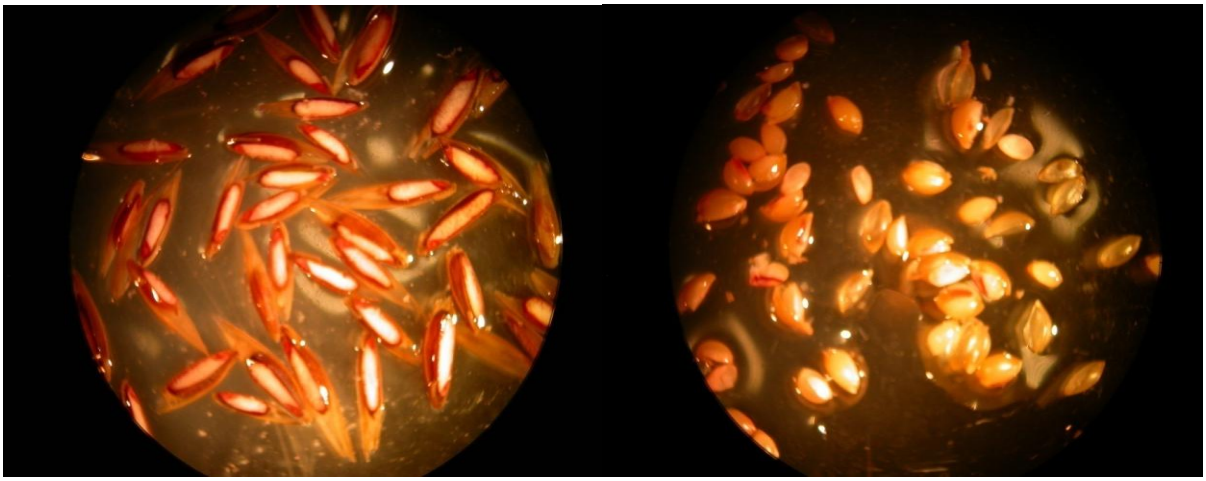

Figure 57. Images of tetrazolium (TZ) stain testing; tall fescue (top; classified as living) and millet (bottom; classified as dead).

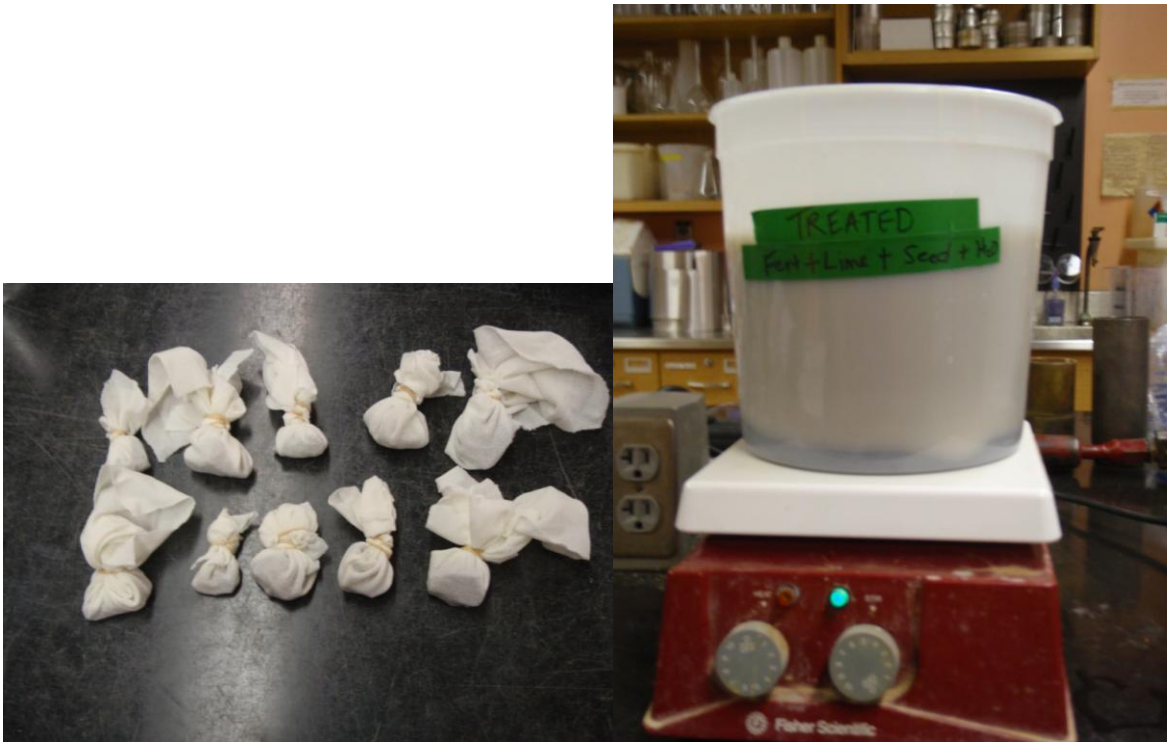

Figure 58. Permeable seed bags (left) and seed bags being mixed on a stir place with fertilizer and lime (right) according to NC DOT recommendations.


Figure 59. Site 2 in Asheboro, N.C.

APPENDICES

APPENDIX 1: PRELIMINARY BOX TEST

Introduction

The purpose of the preliminary box evaluation was to narrow down the list of hydromulches (HMs) to be evaluated as to the ones that produced good coverage and promoted the greatest vegetation establishment. Following the preliminary box evaluation, those HMs that performed the best would then be tested on field plots. Due to poor seed quality (shown in Appendix 2), no results in terms of HM performance were obtained.

Materials & Methods

Site

The site for testing was at the North Carolina State University Sediment and Erosion Control Research and Education Facility (SECREF) in Raleigh, N.C. The slope on which the boxes were placed was at 57%.

Soil Type

The soil used for the box tests was local subsoil from an unknown location that was purchased from American Soil & Mulch, located in Cary, N.C. This soil consists of 32% sand, 31% silt, 37% clay, and is classified as a clay loam. Analysis by the North Carolina Department of Agriculture and Consumer Services' Soil Testing Laboratory indicated a cation exchange capacity (CEC) of 10.4cmol$_c$/kg soil, a base saturation of 77%, and a pH of 5.3. The phosphorus, potassium, manganese, zinc, copper, and sulfur index values were, respectively: 12, 34, 163, 58, 40, and 232. These values indicate low fertility and no elemental toxicities within the soil.

Soil Boxes

The wooden boxes used for these tests are 39.5" long x 8" wide (1 m x 0.2 m) (Fig. 51). A "fill-to" line was marked on the inside of the boxes to a height of 2" (5 cm) (Fig. 52). On the

bottom of each box, nine holes were drilled with a 3/8" bit to allow for drainage. Each box had three lines of holes spaced equidistantly along the length, with three holes in each line.

In order to create a bulk density of 1.5 g cm^{-3} (a bulk density comparable to those commonly found on most construction sites), 34.2 lbs. (15.5 kg) of soil was added to each box and was tamped down in order to fill a volume of 633 in^3 (0.01 m^3) (the interior volume of the box denoted by the "fill-to" line).

Seeding & Fertilizing

Lime, fertilizer, and seed were added to each box based on NCDOT recommendations (NC DOT, 2008b). To be more specific, 560 kg ha^{-1} of 10-20-20 fertilizer and 4,480 kg ha^{-1} of pulverized dolomitic limestone were applied. After raking in the fertilizer and lime by hand, seed was applied at the following rates: 22.4 kg ha^{-1} Kentucky bluegrass, 84 kg ha^{-1} hard fescue, 11.2 kg ha^{-1} German or browntop millet, and 22.4 kg ha^{-1} sericea lespedeza.

Treatments

The eight cover treatments evaluated in this box screening include: straw and hydromulch tackifier (WM; Conwed Fibers 1000, Profile Inc., Chicago, IL); straw and hydromulch tackifier with 22.4 kg ha^{-1} granular, linear, anionic polyacrylamide (PAM; 705, Applied Polymer Systems, Woodstock, GA); cellulosic hydromulch (CM; Conwed Fibers Cellulose, Profile Inc., Chicago, IL); wood fiber hydromulch (WM; Conwed Fibers 1000, Profile Inc., Chicago, IL); wood fiber/cellulosic blend 70:30 (WCM; Enviroblend, Profile Inc., Chicago, IL); stabilized mulch matrix (SMM; Terra-Matrix, Profile Inc., Chicago, IL); bonded fiber matrix (BFM; Hydroblanket BFM, Profile Inc., Chicago, IL); and flexible growth medium (FGM; Flexterra FGM, Profile Inc., Chicago, IL).

Little information is available as to what actually is included in the mulches listed above. The only descriptions available are provided by the ECTC (2009) and Profile Products, Inc. (2010bcde) (Appendix 4).

The mulches were hydraulically applied to a 10' x 10' area using a TurfMaker 420 hydroseeder (TurfMaker Corp., Rowlett, TX) at a rate of 3360 kg ha^{-1} (Fig. 53). The three boxes representing one treatment were randomly placed inside the designated area. The mulches were mixed according to the individual manufacturer-recommended rates. Such rates were as follows: 50 g $L^{-1}$for the FGM, SMM, and BFM; 36 g L^{-1} for the WM; and 49 g L^{-1} for the WCM.

The "hydromulch tackifier" used on the straw plots was the wood fiber hydromulch and was applied at 1,120 kg ha^{-1}. It should also be noted that 2.24-4.48 Mg ha^{-1} (1-2 t ac^{-1}) of straw was applied to each box based on visual observations. Also, in order to prevent any one treatment (i.e. straw + tackifier + PAM) having a potential growth advantage over the other, 1.43 L of water was applied to the straw + tackifier treatments. This amount was applied because 1.43 L was the amount of water in the PAM + water solution applied per box to the straw + tackifier + PAM treatment.

In order to calibrate the rate of water being discharged from the hose on-site into the hydroseeder tank, the amount of time it took for the hose to fill a 5 gallon (19 L) bucket was recorded (i.e. 51 seconds). The amount of time the water hose should be turned on inside the tank could then be calculated based on the manufacturer-recommended mixing rates. After mixing, the same method was used to calibrate the rate of hydromulch being applied from the hydroseeder hose. It could then be calculated how long the 10' x 10' (3 m x 3 m) area should be sprayed.

Plot Setup

Upon application of all eight treatments, the 24 boxes were placed on the slope (Fig. 54). A random number table (Steel and Torrie, 1980) was used to arrange the boxes in a randomized complete block design. Two wooden stakes were installed at both bottom corners of each box in order to prevent movement of the boxes down the slope.

The boxes were exposed to natural rainfall events, but also kept moist by watering with a hose for 15-20 seconds daily to ensure grass growth.

Results & Discussion: Above-Ground Biomass

All treatments for the preliminary box test completed on 7/15/09 resulted in poor vegetation establishment. Following such poor results, it was determined that perhaps because the boxes were not flush with the ground, the force of the hydromulch was knocking the grass seed out of the boxes as it was applied. After re-evaluation of the application method, the test was repeated on 8/11/09. The second time, trenches were dug underneath the boxes so they were flush with the ground during mulch application (Fig. 55). Seed was also incorporated ~0.5-1" (1.3-2.5 cm) in order to assure that seed was not being splashed outside of the boxes. Despite the method modification, the second test also resulted in poor vegetation establishment.

Conclusions

Overall, the preliminary HM evaluation resulted in very poor vegetation establishment due to the low quality seed we had been provided (Appendix 2). The 100% cellulose mulch resulted in very poor coverage due to the fact that it tended to "ball up" and dislodge the soil as it was applied. This may have been due to the slope, but since this slope is similar to those we planned for field tests we decided to eliminate this hydromulch from our testing.

APPENDIX 2: SEED TESTING

Introduction

In a meeting with local DOT officials, it was determined that the list of hydromulches that were of interest was too long for the length and budget of the project. Therefore, it was decided upon that a preliminary box study would be performed in order to evaluate which types of hydromulches produced the greatest amount of vegetation (Appendix 1). Based on these results, hydromulches would be selected to use on future field sites. After obtaining such poor vegetation establishment in both rounds of the preliminary box study (Fig. 56), the seed were tested to determine whether or not they were viable. Following the TZ staining tests, it became clear how important seed vigor and germination is to any sort of testing.

Mixing of seed, lime, and fertilizer together in a hydroseeder tank is a common practice among contractors and other construction site workers (Profile, 2010a). Contractors prefer this method because it results in fewer passes over an area/slope. However, according to the literature there is some evidence that contact with salts (like those of fertilizers) can negatively impact germination (Rajput and Sen, 1990; Romo and Haferkamp, 1987). Instead of mixing all three components together, Dr. Rich McLaughlin from N.C. State University recommends putting the fertilizer and lime out first, incorporating it into the soil, then applying seed, and follow with mulch. This allows for better seed contact with the soil.

The objectives of this study were to 1) Determine whether or not the seed used in the preliminary box study were viable, and 2) Evaluate how seed contact time with lime and fertilizer affect germination rates.

Materials & Methods

Tetrazolium Stain (TZ) Testing

The following seed varieties were tested using a tetrazolium (TZ) staining solution in order to determine their viability: hard fescue, sericea lespedeza, millet, tall fescue, and Kentucky bluegrass (Tetrazolium, 1970; B. Penny; personal communication; 2009). The seed was obtained from various DOT officials, with the exception of the tall fescue which was purchased a month or two prior. Fifty seeds of each variety were imbibed in Petri dishes overnight and dissected the following day. After dissection, the seed were soaked overnight in a tetrazolium (TZ) staining solution inside of an 85˚F oven. The following day, the seeds were placed onto a Petri dish and analyzed under a microscope (Fig. 57). The tetrazolium staining solution stains the living/viable parts of a seed bright red. Based on the proportion of the endosperm that is stained as well as the intensity of the stain color, seed viability may be determined. The shoot, scutellar node, coleoptile, radicle, plumule, and cotyledonary tissue are all classified as critical seed parts important in classifying a seed as "dead" or "viable".

Seed Contact Time Testing

To simulate a hydroseeding mixture containing seed, lime and fertilizer, five permeable bags containing seed were placed in a container with tap water, fertilizer, and lime. The amount of fertilizer and lime was based on the following calculations. Assuming that a full hydroseeder tank (125 gal) receives one 23 kg bag of any given hydromulch, and that the hydromulch is applied at 3360 kg ha^{-1} rate, one hydroseeder tank will cover approximately 0.0068 hectares. If you multiply the 0.0068 hectare area to be covered by the DOT recommended fertilizer rate of 560 kg ha^{-1}, approximately 3.6 kg of fertilizer should be added to one full hydroseeder tank. Since these were lab tests, small buckets (Fig. 58) were filled with 3 liters of water. Using the

concentration above (i.e. 7.7 g L^{-1}), it was determined that 24 grams of fertilizer should be added to the 3 liters of water in the small buckets. A similar calculation was performed based on the DOT recommended lime rate of 4480 kg ha^{-1} (NC DOT, 2008b), and it was determined that 192 grams of pulverized dolomitic lime should be added to each bucket.

Each permeable bag contained 10 seeds and a rock to weigh down the bags into the solution (Fig. 58). Five bags, also containing 10 seeds and a rock, were placed inside another container with just tap water and served as the control. Each solution was continuously stirred using magnetic stirrers to simulate the agitation in hydroseeder tanks. A bag of seed was removed from each container at 30 minutes, 1 hour, 2 hours, 4 hours, and 8 hours. The seeds were placed on germination media in Petri dishes and put in a Hoffman germinator. The germinator was set to 16 hours of darkness and 8 hours of light. The temperature during the dark period was 15˚C to mimic nighttime and raised to 25˚C during the light period.

On 10/29/09 a mixture of tall and hard fescue was evaluated. Seeds were checked at days 7, 14, 21, and 28 and those that had germinated were counted and removed.

Results & Discussion

Tetrazolium Stain (TZ) Testing

Based on the results, all of the seed obtained from the DOT sources had indications of seed deterioration and were classified as “dead” (Table 10). This explains the low vegetation establishment noted in the preliminary box tests completed on 7/15/09 and 8/11/09. The only species that exhibited “good” overall seed health and viability was the tall fescue, which was purchased six months prior to testing from a local vendor.

Seed Contact Time Testing

On average, the tall and hard fescue varieties had mean germination rates of 92% regardless of exposure to the lime and fertilizer solution (Table 11). Placing the seed in contact with lime and fertilizer did not appear to have any effect on germination rates for a period of up to 8 hours.

Conclusions

The use of viable seed is critical in order for vegetation to be established. Although we do not know how the seed we used in the preliminary tests was stored, clearly the seed became non-viable during that period. This suggests that germination tests should be performed on all seed used to stabilize slopes to eliminate seed viability as a source of stand failure. Seed contact time with lime and fertilizer under simulated hydroseeder tank conditions did not appear to affect germination for a period of up to 8 hours. While it would still be better to incorporate lime and fertilizer for agronomic reasons, applying these along with seed and mulch did not appear to affect seed viability.

APPENDIX 3: SITE SETUP FOR ASHEBORO, N.C. (SITE 2)

Materials & Methods

Site 2 was a 2:1 slope located on a DOT construction site in Asheboro, NC (Fig. 59). The slope consisted of fill soil pack on top of bedrock to an average depth of 8-12" (20.3-30.5 cm). Plot setup was the same as on Site 1, with the exception that the plots were shortened to 8'x 20' each (2.4 m x 6.1 m). This was done in order to avoid having already present rills included in the plot areas. Treatments included: straw + tackifier, straw + PAM + tackifier, Flexterra (FGM), TerraMatrix (SMM), and Hydroblanket (BFM). Hydroblanket (BFM) was also used as the tackifier. The slope was predominantly silty clay loam in texture and had an average bulk density of 1.26 g cm^{-3} (Table 12).

Results & Discussion

Approximately three weeks after installation, the Asheboro site experienced 6" (15.2 cm) of rainfall within three days. On the third consecutive day, there was an intense 1" (2.5 cm) rainfall event, which resulted in massive rill and gully erosion, and the ultimate failure of the slope (Figs. 5, 6). Thus, no data were collected for site 2.

APPENDIX 4: HYDROMULCH DESCRIPTIONS

Hydromulch Type	Definition/Composition	Source
Fiber Reinforced Matrix (FRM)	A hydraulically-applied matrix containing organic defibrated fibers, cross-linked insoluble hydro-colloidal tackifiers, and reinforcing natural and/or synthetic fibers to provide erosion control and facilitate vegetation establishment on very steep slopes and designed to be functional for a minimum of 12 months.	(ECTC, 2009)
Bonded Fiber matrix (BFM)	A hydraulically-applied matrix containing organic defibrated fibers and cross-linked insoluble hydro-colloidal tackifiers to provide erosion control and facilitate vegetation establishment on steep slopes and designed to be functional for a minimum of 6 months.	(ECTC, 2009)
Stabilized Mulch Matrix (SMM)	A hydraulically-applied matrix containing defibrated organic fibers with, at a minimum, one of the following additives: soil flocculants, cross-linked hydro-colloidal polymers, cross-linked tackifiers. Utilized to provide erosion control and facilitate vegetation establishment on moderate slopes and designed to be functional for a minimum of 3 months.	(ECTC, 2009)
Hydraulic Mulch (HM)	A hydraulically-applied material(s) containing defibrated paper, wood and/or natural fibers that may or may not contain tackifiers used to facilitate vegetation establishment on mild slopes and designed to be functional for up to 3 months.	(ECTC, 2009)
Flexible Growth Medium (FGM)	Thermally Processed Wood Fibers . . . . .74.5% ± 3.5% Proprietary Crosslinked Hydro-Colloid Tackifiers and Activators . . . . . .10% ± 1% Proprietary Crimped, Interlocking Fibers . . . .5% ± 1% Moisture Content . . . . . 10.5% ± 1.5%	(Profile, 2010d)
Enviroblend Wood/Paper Fiber Mulch (WCM)	Thermally Refined® Wood Fibers (minimum) – 60% Cellulose Fiber (maximum) – 27% Proprietary Emulsifying Agents (TriFlo) – 1% ± 0.5% Moisture Content – 12% ± 3%	(Profile, 2010c)
Conwed Wood Fiber Mulch (WM)	Thermally Refined® Wood Fibers – 87% ± 3% Proprietary Emulsifying Agents (TriFlo) – 1% ± 0.5% Moisture Content – 12% ± 3%	(Profile, 2010e)