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Evaluation of Turbidity Reduction Using Polyacrylamide with Linear Sediment Control Best Management Practices

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EVALUATION OF TURBIDITY REDUCTION USING POLYACRYLAMIDE WITH LINEAR SEDIMENT CONTROL BEST MANAGEMENT PRACTICES

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ABSTRACT

Accelerated erosion and highly turbid stormwater runoff from construction sites are known to cause a variety of environmental and economic problems. To reduce turbidity and keep eroded sediment on site, this research was conducted to evaluate the potential for turbidity reduction using polyacrylamide (PAM) flocculants with sediment control best management practices (BMPs).

Previous research has shown significant turbidity reduction when applying granular PAM to linear sediment control BMPs. Numerous studies indicate that PAM loses efficacy if it becomes wet and then dries. This makes PAM reapplication a necessary part of maintaining sediment control BMPs using PAM and suggests that further research is warranted.

The longevity of PAM when it is applied and reapplied to sediment tube ditch checks was evaluated. No statistical differences were observed between freshly applied PAM and PAM which endured a three-, five-, or ten-day waiting time between reapplication and runoff event. However, the two trials of the ten-day test yielded the highest effluent turbidities that were observed.

Research on a South Carolina Department of Transportiation (SCDOT) construction site analyzed the impact on turbidity of rock ditch checks (RDCs) and rock ditch checks with washed #57 stone on the upstream face (RDC-WS), both with and without granular PAM. It was observed that RDCs alone tended to increase turbidity of runoff between 116% and 282%. For RDC-WS the observed increase to turbidity was smaller, between 3% and 43%. Both types of check were treated with 100 grams of

granular Applied Polymer Systems Silt Stop® #705 PAM and turbidity reduction of runoff was consistently observed, though it varied between 12% and 67% for average turbidity and between 46% and 82% for peak turbidity.

Based on these results, when PAM is used with sediment control BMPs, it should be reapplied after every rain event of 0.5 inches or greater, or every 5 days if no such event occurs. This should ensure effective PAM is constantly present to reduce turbidity of runoff during a storm event.

DEDICATION

I dedicate this thesis to my parents, Kent and Kathryn. They gave me life, raised me well, and have been an endless source of love and support. They taught me the value in hard work and education. They also instilled in me a passion for science and the beauty of the natural world. Without all these gifts, my work on this project would not have been possible.

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CHAPTER ONE

INTRODUCTION

Construction sites frequently experience greatly accelerated rates of erosion due to land disturbance and removal of ground cover. These rates are typically 1,000 to 2,000 times that of forested lands and 10 to 20 times that of agricultural lands (EPA, 2005) and have been estimated to be as high as 35 to 45 tons per acre per year (USGAO, 1998). The impact of accelerated erosion due to construction and land development has been estimated to have a direct cost of over two billion dollars. Much of this cost is associated with damage to water storage, treatment, and conveyance facilities, reduced navigation capacity of waterways, and harm to commercial fisheries. That figure does not attempt to include biological or aesthetic costs (Clark, 1985).

When it rains on bare soil, particles are detached and transported by runoff. Sand particles (diameter between 1 mm and 0.1 mm) settle out in a matter of seconds or minutes, but small colloid particles (dia < 0.0001 mm) can stay in suspension for hundreds of days under natural conditions (McLaughlin and McCaleb, 2014). This means that larger particles are easily removed by conventional sediment control practices, and small particles are very difficult to remove. These small suspended particles cause runoff to have high turbidity, often thousands of Nephelometric Turbidity Units (NTUs). Turbidity is an optical measurement which directly measures light scattered by a water sample. It is common to consider turbidity to be an indirect measurement of suspended matter in a water sample. High turbidity caused by suspended sediment is disruptive to natural systems and harmful to organisms in a variety of ways (EPA, 2012). In order to remove sediment and reduce turbidity, it is necessary to use flocculation.

Flocculation is the process of small particles sticking together to form large particles, or "flocs," which settle faster and are more easily removed (Auckland Regional Council, 2004). Flocculation is necessary to settle small sediment particles within a reasonable amount of time to prevent them from being transported off construction sites. Anionic polyacrylamide (PAM) is the preferred flocculant material for environmental applications due to low aquatic toxicity and past research which has shown it can be very effective at turbidity reduction (Sojka et al., 2007). Traditional sediment control best management practices (BMPs) in South Carolina are designed to remove 80% of total suspended solids, but are ineffective at reducing turbidity caused by fine suspended particles (Bhardwaj and McLaughlin, 2008, Berry, 2012). Therefore it is desirable and necessary to research how PAM can be used with sediment control BMPs in order to reduce turbidity of stormwater runoff.

PAM can be applied to BMPs through active or passive systems. Active systems require energy inputs to cause PAM and turbid runoff to mix. Passive systems cause runoff to mix with PAM as it flows across and through sediment control practices, without an additional energy source. One passive method of introducing PAM into sediment control systems is the spreading of dry granular PAM on sediment control structures, such that runoff will come into contact and mix with the PAM. Research has shown significant turbidity reductions from such an approach, in both controlled and construction site settings (Berry, 2012, McLaughlin et al., 2009).

Numerous studies indicate that when PAM becomes wet during a runoff event and then is allowed to dry, it loses efficacy (Berry, 2012, McLaughlin, 2006, Zech, 2014). This makes it necessary to re-apply PAM after runoff events in order to ensure treatment of the next event. There is limited research about this re-application. If PAM is applied to a sediment control practice, it will not maintain its efficacy indefinitely. How many days make up an acceptable wait time before another PAM application is of particular interest and will be explored by this research.

The majority of research with PAM has been done in controlled field testing environments at universities and research experiment stations. This is desirable because it enables many factors to be controlled which are otherwise unpredictable. However, it is also necessary to explore how PAM can be integrated into construction site sediment control BMPs under actual site and storm conditions. This has been done to some extent, but not in the state of South Carolina. Such an investigation is another point of interest for this research.

The main objectives of this research project are the following.

1. Investigate turbidity measuring instruments and establish a knowledge base of how they work and compare.
2. Conduct controlled experiments to explore the longevity of applied granular PAM, with respect to turbidity reduction, when it is exposed to environmental conditions.
3. Monitor turbidity of stormwater runoff on an active South Carolina Department of Transportation (SCDOT) construction site.

4. Investigate PAM’s ability to reduce turbidity of stormwater runoff on an active SCDOT construction site.
5. Produce recommendations to SCDOT about the use of PAM on ditch check applications on construction sites and how often it should be re-applied to ensure effective turbidity reduction.

CHAPTER TWO

LITERATURE REVIEW

Erosion

Erosion is the process of detachment, transport, and deposition of sediment on Earth's surface. Natural erosion is a slow process driven by water, wind, or ice which detaches sediment. It is then transported and later deposited through sedimentation. Human and animal activities can significantly accelerate erosion (Johns, 1998). One of the leading anthropogenic causes of accelerated erosion is construction. Construction projects disturb soils and remove ground cover, leaving them highly susceptible to erosion. Erosion rates from construction sites typically are 10 to 20 times greater than agricultural lands and 1,000 to 2,000 times greater than those of forested lands (EPA, 2005). Without proper controls these erosion rates can be as high as 35 to 45 tons per acre per year (USGAO, 1998).

These high erosion rates have a variety of negative impacts on water bodies and ecosystems that present a monetary cost to humans and are harmful to a variety of organisms. Costly impacts of erosion to human beings come in the form of damage to water storage and conveyance facilities and reduced navigation capacity of waterways as they are filled with deposited sediment. There is also a cost associated with damage to commercial fisheries. When eroded sediment is deposited it can destroy spawning areas, food sources, and habitat for aquatic species and other species which rely on them. Sediment can also cause direct physical harm to fish, crustaceans, and other aquatic wildlife. The cost of sediment related damages from accelerated erosion is estimated to be between $3.0 billion to $3.5 billion, with only about $1.0 billion to $1.2 billion coming from cropland erosion. This estimate does not include biological or aesthetic damages (Clark, 1985).

A large portion of eroded soil is made up of fine particles which stay in suspension for a long time and can be transported great distances. Suspended sediment is sometimes estimated using the optical measurement of turbidity as a proxy. The negative ecological impacts of suspended sediment and turbidity are described in greater detail in the next section.

Turbidity

Turbidity is the optical measurement of scattered light resulting from the interaction of an incident light beam with particulate matter in a liquid sample. It approximates the amount of suspended matter in the sample and is a frequently used parameter to assess water quality (Sadar, 2002). High turbidity is associated with cloudy or even opaque water. Low turbidity is associated with clear water.

It is common to measure turbidity using the nephelometric technique (Henley et al., 2000; Lloyd, 1987). This technique uses a turbidity probe which consists of a light beam and a light detector. The light beam sends light into a sample where it is scattered by suspended solids in the sample. Some of the scattered light then strikes the photodiode detector which converts the amount of light it detects into nephelometric turbidity units (NTUs). This detector is oriented such that it detects light which is scattered at a 90 degree angle from the incident light beam (EPA, 1993). If more particles are suspended then more light will be scattered and detected, so the turbidity will be represented by a larger value in NTUs. This test is a direct measurement of scattered light and an indirect measurement of suspended solids. It is comparable in validity to fecal coliform bacteria tests as an indicator of contamination of drinking water (Lloyd, 1987), a commonly used and trusted test for that purpose.

A high level of turbidity in water is harmful to natural systems in several ways. Suspended particles are darker and absorb heat which leads to higher water temperatures. This corresponds to lower dissolved oxygen levels since warm water holds less dissolved oxygen than cold water. High turbidity also inhibits light penetration which limits photosynthesis and its associated dissolved oxygen production. This impact on photosynthesis also disrupts food webs that rely on primary consumers that eat plant material. Suspended solids can also interfere with the gill function in fish species which inhibits their respiration, growth, and reproduction. When particles settle they can interfere with fish eggs and benthic macroinvertebrate species (EPA, 2012).

The suspended sediments that are a primary cause of high turbidity can also be harmful due to their ability to transport biological and chemical contaminants. Organic chemicals are known to adsorb to clay and silt sized particles (LaGrega, et al., 2001). These small particles are the ones most likely to be suspended and contribute to turbidity. They are also slower to be deposited than larger sand particles so they have the potential to transport contaminants great distances. This adsorption and transport process is also problematic with respect to biological contaminants. Fecal coliform bacteria, specifically *Escherichia coli*, are known to be more likely to attach to fine clays than coarse sand

(Tempel, 2011). These fecal bacteria can live for months outside of their hosts' bodies (Burton et al., 1987) and can therefore cause contamination of drinking and recreational waters at distant locations where finer sediment may be deposited.

In response to these harmful impacts of highly turbid stormwater runoff, EPA established non-numeric and numeric Effluent Limitation Guidelines (ELGs) on December 1, 2009. The numeric limit for turbidity was set at 280 NTU. Several parties filed petitions against the 280 NTU limit and successfully identified deficiencies in the dataset EPA used when making the rule. On December 10, 2012 EPA entered into a settlement agreement and temporarily stayed the numeric turbidity limit. In February of 2014, final revisions were made to the rule which withdrew the numeric turbidity limit and monitoring requirements (EPA, 2014). The threat of a numeric limitation, as well as an interest in maintaining waters of the United States, generated an elevated interest in research related to turbidity reduction.

Turbidity Meter Reporting Units

A variety of turbidity meters, or "turbidimeters," are currently available in order to measure turbidity in both laboratory and environmental settings. Due to differences in instrument design, different meters often do not yield equivalent results when measuring natural waters (Gray and Glysson, 2003). Each meter may respond differently to the color, particle size distribution, or particle concentration in a water sample. This creates a situation where measurements made with different meters or in different environments may not be comparable.

The traditional measurement unit of turbidity is the NTU, described previously. In response to the realization that not all NTU readings were equivalent, it was determined that data need to be reported in more specific, “information-rich,” measurement units (USGS, 2004). The U.S. Geological Survey (USGS) combined with the American Society for Testing and Materials (ASTM) to create a suite of units for storing and reporting turbidity which are based on instrument design. These units are described in Table 2.1.

Table 2.1: Instrument specific turbidity units established by USGS and ASTM (USGS, 2004).

Reporting units corresponding to different turbidity instrument designs [nm, nanometers; °, degree]		
Detector geometry	**Light Wavelength**	
	White or broad band (with a peak spectral output of 400-680 nm)	**Monochrome** (spectral output typically near infrared, 780-900 nm)
Single Illumination Beam Light Source		
At 90° to incident beam	Nephelometric Turbidity Unit (NTU)[a]	Formazin Nephelometric Unit (FNU)[b]
At 90° and other angles. An instrument algorithm uses a combination of detector readings, which may differ for values of varying magnitude.	Nephelometric Turbidity Ratio Unit (NTRU)	Formazin Nephelometric Ratio Unit (FNRU)
At 30°± 15° to incident beam (backscatter)	Backscatter Unit (BU)	Formazin Backscatter Unit (FBU)
At 180° to incident beam (attenuation)	Attenuation Unit (AU)	Formazin Attenuation Unit (FAU)
Multiple Illumination Beam Light Source		
At 90° and possibly other angles to each beam. An instrument algorithm uses a combination of detector readings, which can differ for values of varying magnitude.	Nephelometric Turbidity Multibeam Unit (NTMU)	Formazin Nephelometric Multibeam Unit (FNMU)

[a] Use of NTU: limited to instruments that comply with EPA Method 180.1 (U.S. Environmental Protection Agency, 1993).

[b] Use of FNU: pertains to instruments that comply with ISO 7027, the European drinking-water protocol (International Organization for Standardization, 1999), which includes many of the submersible turbidimeters that are in common use in the USGS for onsite measurements.

The conventional “NTU” is now reserved for instruments designed to comply with EPA Method 180.1, which utilizes the 90 degree detector angle of the Nephelometric technique and a light wavelength of 400 to 680 nm. Other reporting units now exist to describe instruments which use different wavelengths of light and different detection angles.

Coagulation and Flocculation

Small colloid particles (dia < 0.0001 mm) can take hundreds of days to settle out of suspension under natural conditions (McLaughlin and McCaleb, 2014). This makes them significant contributors to turbidity. This settling time can be greatly decreased through a process of coagulation and flocculation by chemical agents. Coagulation refers to the destabilization of colloids by neutralizing the repulsive forces that keep them apart. Flocculation is the process of these small particles sticking together and building up into larger "floc" particles which settle much faster. Colloids typically have a negative surface charge so chemicals which introduce positive charges into the system are necessary for coagulation and flocculation (Auckland Regional Council, 2004). The rate of flocculation depends on the frequency of particle collisions and how often particles stick together when they collide. Then number and nature of particle collisions depends on mixing energy or turbulence, mixing time, pH, temperature, number of particles present, type of flocculant, and amount of flocculant (McLaughlin and McCaleb, 2014).

A variety of flocculants have been used successfully to remove solids in different water treatment industries. Alum, gypsum, molding plaster, and calcium chloride have been effective for turbidity reduction in stormwater and wastewater. However, they require large doses which make it necessary to monitor for pH changes and the presence of residual ions in the finished water (Bhardwaj and McLaughlin, 2008). Research has shown that anionic polyacrylamide (PAM) is an effective flocculant of suspended sediment particles which has low aquatic toxicity. For these reasons, it is a preferred chemical treatment in environmental applications. It may seem counterintuitive that a negatively charged polymer is successful at flocculating negatively charged particles. The process is able to occur due to cation bridging with positively charged ions that are common in aquatic systems, typically Ca^{2+} (Sojka et al., 2007). In some applications gypsum ($CaSO_4$) is applied with PAM to provide the necessary cations (Rabiou, 2005).

Polyacrylamide Background

Polyacrylamide (PAM) is a generic term which refers to a broad range of compounds. There are hundreds of PAM varieties which vary in polymer chain length and shape as well as in number and type of functional groups. Linear chain PAM is typically water soluble whereas PAM with cross linking chains typically is not. PAM can be chemically manipulated to be cationic, anionic, or nonionic. Anionic PAM is commonplace in environmental applications due to extremely low aquatic toxicity when compared to nonionic and cationic PAM. PAM for environmental applications typically has a molecular weight of 12-15 Mg mol^{-1} and have over 150,000 monomer units per molecule (Sojka et al., 2007). In addition to low aquatic toxicity, it has also been found that the presence of anionic PAM does not reduce microbial metabolic potential of soil or affect bacterial structural diversity, richness, or evenness (Entry, et al. 2013). Some common uses of anionic PAM include drinking water treatment, sewage sludge dewatering, drilling mud, paper manufacturing, clarification of juices and drinking water, thickening of animal feed, and coating of paper used in food packaging (Sojka et al., 2007). The use of PAM for water quality improvement, erosion prevention, and sediment control is of particular interest in order to protect water bodies and meet current and potential future environmental regulations.

In the 1990s water soluble anionic PAM was identified as highly effective at preventing erosion and increasing infiltration when used with furrow irrigation. PAM was applied either as a liquid of known concentration from 1-10 ppm or in granular form using the "patch method." This involves spreading 15-30 grams of PAM in the first meter or two of a furrow. A sticky patch of PAM forms which releases PAM into the irrigation water as it passes over it. Using PAM in this way stabilizes the soil surface structure and substantially reduces soil loss. In research conditions, this reduction was seen to be as high as 94% (Lentz et al., 2002). Since the detachment of particles is reduced, fewer particles are deposited elsewhere. This means fewer pores are clogged, causing an increase in infiltration. Research has also shown reduction in erosion and increase in infiltration when using PAM with sprinkler irrigation, both as a soil pre-treatment and when mixed with irrigation water (Sojka et al., 2007).

PAM was first used to prevent erosion related to construction activities for the building of roads and runways during World War II (Wilson and Crisp, 1975). This initial use involved high application rates and substantial cost. The comparatively recent successes with low rate PAM application in irrigation led to a renewed interest in use of PAM on construction sites for erosion prevention and sediment control (Sojka et al., 2007).

Erosion Prevention BMPs and Polyacrylamide

In most cases, the end goal of erosion prevention is to establish vegetation which will keep soil in place. With that in mind, the simple act of applying seed to the ground is an essential Best Management Practice (BMP) to prevent erosion. A variety of other BMPs exist to keep soil in place before vegetation is established, hold seed in place, and to encourage vegetation to grow quickly (SCDHEC, 2005).

Rolled erosion prevention materials are one way to achieve these goals. They come in large rolls which can be spread out over disturbed areas to reduce soil loss. Erosion control blankets (ECBs) are made of natural fibers like straw, excelsior, and coir. Excelsior fiber consists of curled wood fibers while coir is made from the fibers of coconut husks. ECB has the benefits of facilitating vegetative growth and naturally biodegrading over time. Its use is limited by the moderate flow velocities that it can withstand. For higher velocity slope stabilization applications, turf reinforcement matting (TRM) is the appropriate rolled erosion prevention material. TRM is typically made of a plastic mesh and comes in varying levels of strength depending on the velocity it needs to withstand.

The spreading of straw or mulch on the ground surface is another BMP for erosion prevention. This provides ground cover, but without the structural netting that gives rolled materials their shape. For large sites, spreading ground cover in this way would be time consuming and impractical. Hydroseeding and hydromulching address this issue by speeding up the process, but at higher cost. This involves large machines that mix seed, organic materials, and tackifying agents and spray the mixture onto slopes that need to be stabilized. Liquid PAM is one of the common tackifiers used with hydroseeding operations.

Erosion prevention with PAM generally involves applying PAM to the ground surface, either with or without the previously mentioned erosion prevention BMPs. PAM has shown benefits in the erosion prevention field in some cases. However, the presence of ground cover is consistently a more important factor than the inclusion of PAM.

Soupir et al. (2004) investigated total suspended solids (TSS) of runoff during simulated storm events at a construction site on Virginia Tech's campus. The study considered dry PAM and three different concentrations of liquid PAM applications compared to straw mulch and hydroseeding. Practices were applied directly to soil on plots of fill material, graded at a 5% slope. On average, the material was 22% sand, 32% silt, and 46% clay. Straw mulch was most effective at reducing TSS concentration and total load, by 92% and 91% respectively. Hydroseeding and dry PAM (20.17 kg ha^{-1}) were the next most effective, but with reductions of 50% or less. Hayes et al. (2005) explored the use of PAM at rates of up to 10.5 kg ha^{-1} combined with grass seeding and straw mulching on NCDOT construction sites. On 50% and 20% slopes, sediment loss and turbidity were decreased by up to 83% and 75% by the use of seed/mulch. PAM alone did not cause a significant reduction and PAM added to the seed/mulch did not differ statistically from the seed/mulch alone. In general, the greatest benefit observed was from mulching and seeding (Hayes et al., 2005).

McLaughlin and Brown (2006) conducted a similar study which considered four different types of ground cover (straw, straw ECB, wood fiber, and mechanically bonded fiber matrix), both with and without PAM, on slopes of 4, 10, and 20 percent. The study used natural rainfall and a growing period of 36 days to test vegetation establishment on the 4 percent slope. Simulated rainfall on soil boxes tested the 10 and 20 percent slope. For all treatments and conditions, the ground covers consistently reduced turbidity and sediment loss. The addition of PAM improved those reductions in some cases. The use of PAM did show a significant improvement in the establishment of vegetative cover for the 36 day test on 4% slope with natural rainfall conditions. More recently, Babcock and McLaughlin (2013) conducted a study using simulated rainfall on soil boxes at 18 percent slope. The treatments involved straw and hydromulch, each with and without PAM. PAM application with straw was done in both granular and liquid form. PAM improved the water quality of runoff for both ground covers but not always to a statistically significant level. Hydromulch with PAM provided the lowest runoff turbidity, between 62 and 151 NTU. Straw with PAM performed as well or better than hydromulch alone, suggesting it might be a cost effective alternative to hydromulch.

Studies on erosion prevention with PAM have shown that PAM was significantly more effective at TSS and turbidity reduction during initial storm events than in subsequent events when no re-application was present (Soupir et al., 2004; McLaughlin and Brown, 2006; Babcock and McLaughlin, 2013). Rabiou (2005) explored this phenomenon by keeping the overall application rate constant and comparing it to a “split” application where half the dose was applied initially and the second half applied halfway through the simulated storm event. The result was a significant reduction in soil detachment and loss for the split application. This suggests a potential benefit to re-application when PAM is used as an erosion prevention measure.

Sediment Control BMPs and Polyacrylamide

It is impracticable to attempt to stop all erosion from occurring during land disturbing activities. This is why downstream sediment control measures are a critical part of sustainably managing a construction site. Sediment control BMPs consist of a variety of ditch check structures and ponding structures which seek to reduce velocity of runoff and encourage settling of suspended particles. The end goal of sediment control is to keep any eroded sediment on-site and discharge clean water.

Ditch checks are made of a variety of materials. For high flow velocity applications, rock ditch checks are necessary. Rock ditch checks can be made of large stone or large stone lined with smaller stone to encourage sediment trapping. In many water conveyance channels, ditch checks can be made of fibrous material enclosed in tubular netting. These checks are called sediment tubes, sediment logs, or wattles. The most common materials are straw, mulch, excelsior, and coir. Excelsior fiber consists of curled wood fibers and coir is made from the fibers of coconut husks. These fiber ditch checks have the advantage of lower cost and easier installation compared to traditional rock structures. They also can be used on tight linear roadway projects where space is limited (McLaughlin et al., 2009).

The last line of defense in sediment control is the sediment basin. A sediment basin is a pond or excavated retention area that is designed to contain runoff from a construction site for a length of time, usually several days, in order to let suspended sediment settle. Some states now require porous baffles and surface withdrawal from sediment basins in an effort to utilize the full basin volume and discharge less turbid water. In South Carolina, basins are often designed to trap at least 80% of sediment based on a calculation involving watershed and sediment characteristics, basin size, and soil type (SCDHEC, 2005).

Neither ditch checks nor sediment basins significantly reduce turbidity of stormwater runoff (Bhardwaj and McLaughlin, 2008; Berry, 2012). However, research has shown that the introduction of PAM to these practices can reduce turbidity. PAM for sediment control comes in three main physical forms: granular powder; liquid solution; and solid blocks. Its use is separated into active and passive treatment systems. Active treatment involves using energy inputs, usually pumping, to inject PAM into turbid water. Passive treatment introduces PAM into the system without energy inputs in such a way that runoff comes in contact with PAM as it moves naturally through the on-site sediment control practices.

Some active treatment systems pump turbid water out of basins and into mixing tanks containing PAM to remove sediment prior to discharge. This creation of a small scale, usually portable, water treatment plant adds significant cost but can be very effective. Some systems promise 90% turbidity reduction (Smits et al., 2014). When strict regulations need to be met, systems like this can be useful to ensure compliance. Active treatment can also be simpler. Pumping liquid PAM into a channel or basin to mix with turbid runoff is also considered an active application. Active treatment of this nature has the advantage of being able to apply a specific dose of PAM to a system. In comparison, many passive treatment methods do not offer this level of precision (Bhardwaj and McLaughlin, 2008). The added cost of equipment and energy inputs for active systems have led to substantial research towards finding effective passive treatment options.

Some passive systems have been developed which attempt to dose variable amounts of PAM in response to a rain event without the use of a power source. In New Zealand, a system was developed which catches rainfall and directs it into bucket. The bucket floats on a reservoir of liquid PAM. As the rain bucket fills, its increased weight results in displacement and causes the PAM to rise. As the PAM level rises, it enters a pipe which directs it into the stormwater treatment system (Auckland Regional Council, 2004). Garbrecht et al. (2011) conducted research at Oklahoma State University that sought to dose liquid PAM in response to stage of water behind a flow control structure, rather than rainfall. They developed a system in which a series of floats rise and actuate float valves which open and allow liquid PAM to flow from an elevated storage tank. Both systems avoid using an external power source so they are technically passive systems. However, compared to other passive treatment methods, they have a higher level of complexity that may inhibit their adoption at a large scale.

Many passive applications of PAM forego the infrastructure and cost necessary to dose specific amounts of PAM in direct response to a storm event. Instead, PAM blocks and/or granular powder are strategically placed in sediment treatment systems to maximize contact with runoff and encourage good mixing. McLaughlin (2006) showed a

50-80% reduction of turbidity when simulated runoff of 400 to 600 NTU flowed across PAM blocks and then settled in various basin configurations at the North Carolina State University Sediment and Erosion Control Research and Education Facility. The basins alone did not significantly treat turbidity, and reductions were attributed to the effect of PAM. Bhardwaj and McLaughlin (2008) compared passive block treatment to an active treatment that involved pumping of liquid PAM into runoff as it entered a basin. Both treatments significantly reduced turbidity by 66 to 88% and were not significantly different from each other. A study was conducted in Ontario which compared passive treatment to tank-based active treatment. The passive treatment took place in a channel with rock ditch checks outfitted with solid PAM blocks and areas of jute netting sprinkled with granular PAM. The active treatment pumped turbid water into a mixing tank containing solid PAM blocks, followed by a settling tank. Both treatments significantly reduced turbidity, respectively by 88% and 92% (Toronto and Region Conservation, 2010).

Zech et al. (2014) monitored a sediment basin in Franklin County, Alabama which used passive treatment in the form of PAM blocks positioned upstream of a sediment basin. Typical inflow turbidities were high, from several thousand to 10,000 NTU. Outlet turbidity was observed to decay exponentially from around 1000 NTU to under 280 NTU over several days as the basin slowly dewatered through a surface skimmer. However, PAM blocks are not effective if they become wet and then dry out or if they become buried by sediment, so block placement is very important (McLaughlin, 2006; Zech, 2014). They are also less effective under cold water conditions

(McLaughlin, 2006). Having the correct number of blocks of the right kind of PAM was also an issue observed by Zech at the Alabama site. The issue of blocks being used once and then drying out must be addressed by keeping them moist or replacing them after storm events. The application and re-application of granular PAM to conventional BMPs has the potential to address the desiccation issue of PAM blocks while reducing the total amount of PAM that is necessary.

McLaughlin et al. (2009) used PAM in conjunction with fiber ditch checks (FDCs) as a sediment control measure to treat runoff on two roadway projects in North Carolina. Substantial reduction in sediment load and turbidity was seen when comparing the FDCs to traditional BMPs (narrow sediment traps and rock ditch checks), and also when comparing FDCs with granulated PAM to FDCs alone. At the first site, average turbidity was 3813 NTU for the rock BMPs, 202 NTU for the FDCs, and 34 NTU for the FDCs with PAM. At the second site, average turbidity was 867 NTU for the rock BMPs and 115 NTU for FDCs with PAM. Kang et al. (2013) then explored PAM and BMPs in a controlled field setting with simulated stormwater runoff. The three treatments were FDCs, rock ditch checks, and rock ditch checks wrapped in erosion control blanket (ECB). They found that PAM reduced turbidity by greater than 75% for all practices. They also found that PAM with FDCs or rock checks wrapped in ECB reduced numeric turbidity significantly, respectively to less than 57 and 90 NTUs.

Berry (2012) looked at different passive treatment methods of introducing PAM to a series of five sediment tubes in a triangular channel under simulated runoff conditions. Sediment tubes with no PAM did not treat turbidity and showed an average discharge turbidity of 3104 NTU. When sprinkling PAM on the tubes prior to each storm simulation, average turbidity was reduced to 202 NTU after three tubes and 82 NTU after five tubes. When applying PAM once and then simulating multiple storms, reduction was present but did not happen as quickly. Average turbidity was 289 NTU after four tubes and 61 NTU after five tubes. Granular PAM in a permeable bag at each sediment tube only reduced average discharge turbidity to 915 NTU after five tubes.

Berry also explored the desiccation of PAM and its effect on turbidity reduction. Several days after the final runoff simulation of his tests, he performed an additional runoff simulation on the same set of logs. This simulated construction site activity in which a there is often a dry period before the next rain event. In the treatment involving multiple storm simulations and no reapplication, this delayed run discharged an average turbidity of 1283 NTU. In the treatment with reapplication prior to each run, the delayed run discharged an average turbidity of only 100 NTU. This treatment was statistically the same as all previous runs for that treatment. These results suggested a need for PAM re-application on construction sites.

Current Specifications for Polyacrylamide Use

PAM is included in many state specifications for construction site practices, but with variable levels of detail. Some states only mention PAM as a soil stabilizer and erosion prevention supplement. Others recommend the use of PAM for sediment control as well as erosion prevention. Alabama and North Carolina no longer recommend using PAM for soil stabilization and erosion prevention, as there is strong evidence support that

PAM has greater benefits when used for sediment control (ALDOT, 2012; NCDOT, 2013). All specifications share language which says to follow manufacturer's recommendations, only use approved varieties of PAM, and to capture flocculated material prior to discharge into natural systems. Some states go into greater detail. For example, Florida recommends the use of PAM in the following four ways (FDOT, 2013).

1. Apply soil-specific polymer surrounding an area drain and cover the soil with a layer of jute fabric.
2. Install polymer logs inside and/or upstream of water conveyance devices to treat runoff after it has moved through a rock barrier.
3. Place the polymer logs so that runoff within a drainage channel having check structures will flow over and around them. The number of logs is determined by the flow rate of the water. Longer mixing times will have the best reduction of turbidity
4. Cover rock check structures with jute fabric that has been applied with a site-specific polymer powder.

More examples of how states have chosen to describe the use of PAM for sediment control can be found at the resources in Table 2.2.

Table 2.2: Erosion and sediment control manuals which describe the use of PAM.

State	Link to Resource
South Carolina	https://www.scdhec.gov/environment/water/swater/docs/BMP-handbook.pdf
North Carolina	http://portal.ncdenr.org/web/lr/publications
Alabama	http://www.dot.state.al.us/conweb/doc/Specifications/2012_GASP.pdf
Florida	http://www.dot.state.fl.us/rddesign/Hydraulics/files/Erosion-Sediment-Control.pdf
Tennessee	http://tnepsc.org/TDEC_EandS_Handbook_2012_Edition4/TDEC%20EandS%20Handbook%204th%20Edition.pdf
Georgia	http://www.gaepd.org/Documents/esc_manual.html
Pennsylvania	http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-87860/363-2134-008.pdf
South Dakota	http://sddot.com/resources/manuals/E&SControlSW.pdf
Washington	http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/SS2014.pdf

North Carolina has specific BMP details which include PAM, for example "Wattle with PAM" and "Temporary Rock Silt Check Type A with Excelsior Matting and PAM." North Carolina specifies 4 ounces of PAM be applied to each BMP at installation and then reapplied after every rain event of 0.5 inches or greater (NCDOT, 2008).

CHAPTER THREE

COMPARISON OF TURBIDIMETERS

ABSTRACT

Before turbidity research could be conducted, an investigation of turbidity meters, or "turbidimeters," and their reporting units was necessary. The following meters were investigated, listed with their range of operation.

- Hach 2100AN Laboratory Turbidimeter, 0-10,000 NTUs
- Campbell Scientific OBS500 Turbidimeter, 0-4,000 NTUs
- McVan NEP Analite Turbidimeter, 0-3,000 NTUs

The Hach and McVan turbidimeters were designed to meet the EPA 180.1 Standard and therefore report in the well-known reporting units of Nephelometric Turbidity Units (NTUs). The Campbell Scientific OBS500 turbidimeters reported in three sets of instrument specific turbidity units. One of these units was the Formazin Nephelometric Ratio Unit (FNRU), a reporting unit which used an instrument algorithm to report results using multiple light detectors. FNRU was designed to be the best representation of turbidity by the instrument throughout its range**.**

A procedure using Formazin standard solutions of varying concentrations showed that OBS500 FNRUs were statistically the same as Hach NTUs, and that both were the same as the standard values. Testing with stormwater samples showed differences in the readings from each instrument, but were predictable by a power curve relationship. These differences were attributed to the different physical workings of the instruments as well as different ranges of calibration and recommended operation. In the shared range

of 0 to 4,000 NTUs, both instruments and sets of units provided meaningful results for turbidity analysis.

INTRODUCTION

Three different turbidity meters, or "turbidimeters" were used for different aspects of this research. These meters and their ranges of use are as follow:

- Hach 2100AN Laboratory Turbidimeter, 0-10,000 NTUs
- Campbell Scientific OBS500 Turbidimeter, 0-4,000 NTUs
- McVan NEP Analite Turbidimeter, 0-3,000 NTUs

Each meter has its strengths and weaknesses and together they are able to meet turbidity measurement needs in a wide range of applications. The Hach is a benchtop laboratory turbidimeter that is accurate within a large range. The OBS500 units have the benefit of being robust and portable. They are easily mounted in the environment for real-time measurements and can record large amounts of data using Campbell Scientific dataloggers. The McVan is a portable unit with a handheld display. It can be taken into the field for measurements that can be seen immediately, but it is not designed to make and record unattended measurements.

The standard reporting unit for turbidimeters which are designed to meet EPA Standard 180.1 is the Nephelometric Turbidity Unit (NTU). This refers to a white or broad band (400 to 680 nm) light wavelength and a detector oriented 90 degrees from the incident beam (USGS, 2004). The Hach and McVan meters were both designed for this standard and report readings in NTUs. Campbell Scientific utilizes three instrument design specific turbidity units (TUs) which were established by the USGS and ASTM (USGS, 2004). See Table 2.1 for more information about instrument design specific turbidity units.

The TUs that Campbell uses are the Formazin Nephelometric Unit (FNU), Formazin Backscatter Units (FBU), and Formazin Nephelometric Ratio Unit (FNRU). The FNU refers to measurements taken with a detector oriented 90 degrees from a monochrome (780-900 nm) incident light beam. These are also referred to as “side scatter” measurements. The FBU refers to measurements taken with a detector oriented 30 degrees from a monochrome incident light beam. These are also referred to as “back scatter” measurements (USGS, 2004). Side scatter measurements operate within a few inches of the probe lenses and are most accurate in a low turbidity range (below 500 NTU). Back scatter measurements operate within a range of up to 18 inches, depending on water clarity, and provide higher accuracy in the higher turbidity range (above 900 NTU), where side scatter is not as accurate. The FNRU unit involves an instrument algorithm programmed to weigh its numeric output towards the sensor reading that is most appropriate for the turbidity that is present (Campbell Scientific, 2013). For example, the following observations were made during laboratory procedures. At a turbidity of 100 NTU, the FNRU reading is the same as the FNU reading. At a turbidity of 1200 NTU, The FNRU reading is the same as the FBU reading. At intermediate values where it is appropriate, the FNRU reading is a value which draws influence from both sensors. The FNRU was designed to give a best estimate of turbidity throughout the range of the instrument, with consideration given to both light detectors utilized by the OBS500.

The three turbidimeters that have been described were created for a common purpose but vary in exactly how they work and in their reporting units. Accordingly, it was anticipated that there would be variation between observations made by the different meters. In this study, variation was also observed between field readings and laboratory readings from the Campbell OBS500 turbidimeters. This was not surprising given the inconsistency of field conditions, but warranted investigation. In order to understand the variation in measurements between instruments and between field and lab conditions, the following three objectives were established.

1. Compare the reporting units of the Campbell OBS500 turbidimeter in order to understand how they relate to each other.
2. Compare readings from turbidimeters in order to understand how they relate to each other.
3. Compare field readings and laboratory readings for the Campbell OBS500 unit in order to understand the variation that field conditions can have on turbidity measurements.

These matters had to be explored in order to have meaningful results which could be compared to each other and to past and future research. In order to achieve this goal, the following procedures were carried out.

PROCEDURES

Formazin Testing

The three turbidimeters involved in this study were used to measure a series of dilutions of Hach 4,000 NTU Formazin standard in order to compare their performance. Readings for the OBS500 and McVan instruments were recorded by putting each probe into 1000 mL of Formazin in a 4000 mL beaker. Care was taken to orient the probes to minimize possible interference by the walls of the beaker. A sample of the Formazin was then transferred to a Hach vial and the reading was recorded.

The first readings were taken using 1000 mL of Hach 4000 NTU Formazin standard solution. Then 500 mL of Formazin was removed and stored for future use and 500 mL of deionized water was added to the beaker to return the total volume to 1000 mL, but with a turbidity of 2000 NTUs. A second set of readings were taken. Dilution and additional readings continued in this manner until a Formazin standard of 15.6 NTUs was created and readings were taken. All Formazin standards were then stored in the original bottle or amber glass bottles and labeled for future reference.

Stormwater Sample Testing

Each stormwater sample that was obtained was tested for turbidity using the Hach benchtop turbidimeter and total suspended solids using Standard Method 2540 B (APHA, 2005). The following was then carried out with the remaining volume of the sample in order to obtain laboratory readings with the OBS500 turbidimeter. The sample was agitated by inverting and shaking the sample bottle for 5 seconds, and then pouring it into a 4000 mL beaker. The beaker was then gently agitated by hand, the OBS500 probe was submerged, and turbidity readings were recorded. The 4000 mL beaker had an inner diameter of about 7 inches and the sample volume of 500 mL had a depth of about 1 inch. This was the largest data collection vessel possible which ensured adequate depth of the sample to submerge the optical sensors of the OBS500 probe. All laboratory turbidity readings from the OBS500 were recorded so that they could be compared to field observations made at the same time the sample was taken.

Statistical Analysis

Statistical calculations were performed using JMP statistics software (SAS Institute Inc., Cary, NC, USA). Analysis of Variance (ANOVA) tests were used to develop 95% confidence intervals to compare turbidimeter readings to the Formazin standard.

RESULTS AND DISCUSSION

Formazin Testing

The procedure was carried out as described above and the readings obtained for each meter were plotted against the Formazin standard value. These observations were then split into two figures. Figure 3.1 was created to show the three different readings given by the OBS500 turbidimeter compared to the Formazin standard. A "1:1 Relationship" line was included to show where readings would be if they were the same as the standard solution.

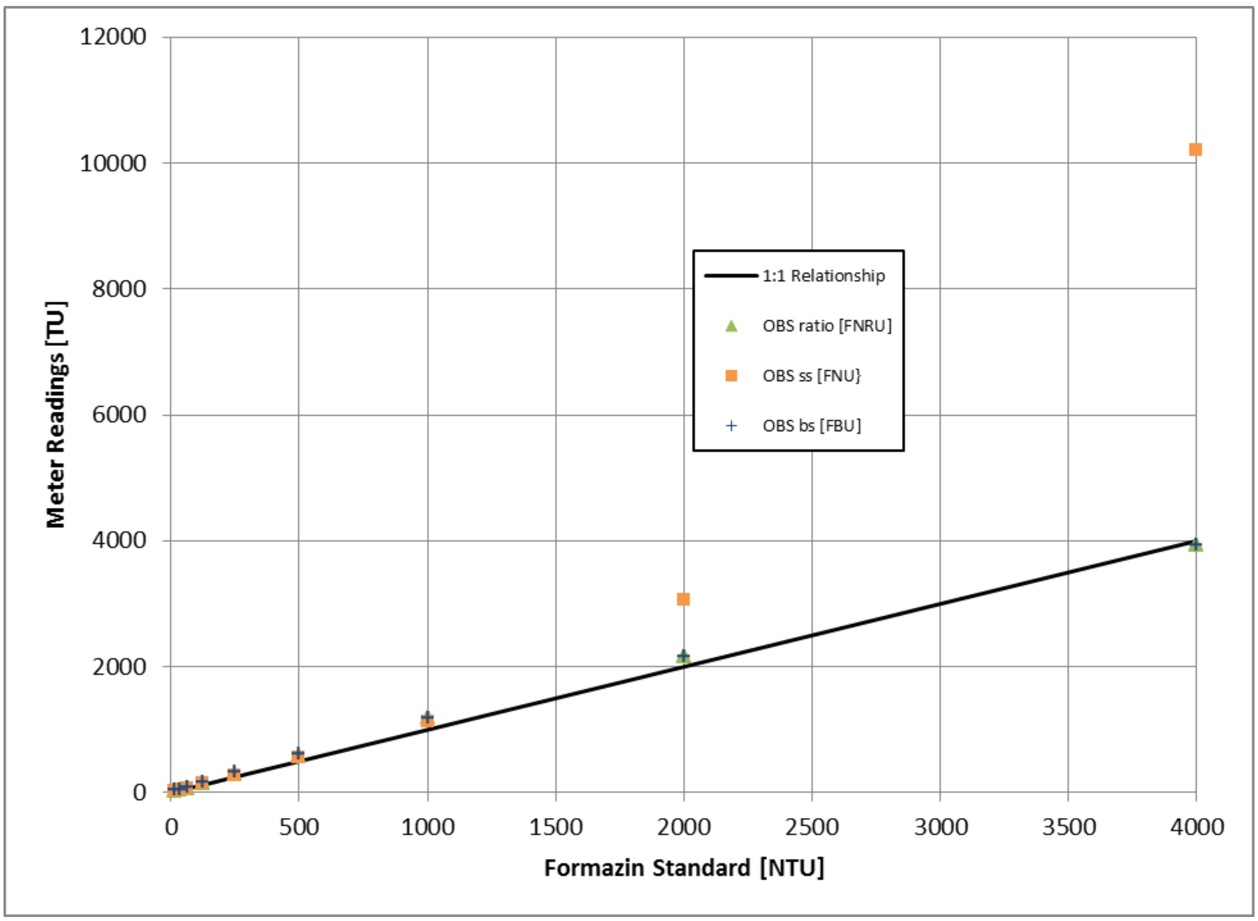

Figure 3.1: OBS500 readings for Formazin standard solutions.

The three readings behaved much the way that they were described by the manufacturer, Campbell Scientific. The FNU readings did a poor job measuring high turbidity and accordingly the FNRU reading weighed its result entirely toward the FBU reading. It appeared that both FBUs and FNRUs were good approximations of the Formazin standard. For the purposes of this study, the FNRU readings were chosen as the primary reporting unit for the OBS500. They were designed to be the best estimate of turbidity throughout the range of the instrument (Campbell Scientific, 2013), and the results of this procedure supported that suggestion.

Figure 3.2 was created in order to compare the three turbidimeters to the Formazin standard and to each other. It also includes the “1:1 Relationship” in order to provide a point of comparison for the observations to the Formazin standard.

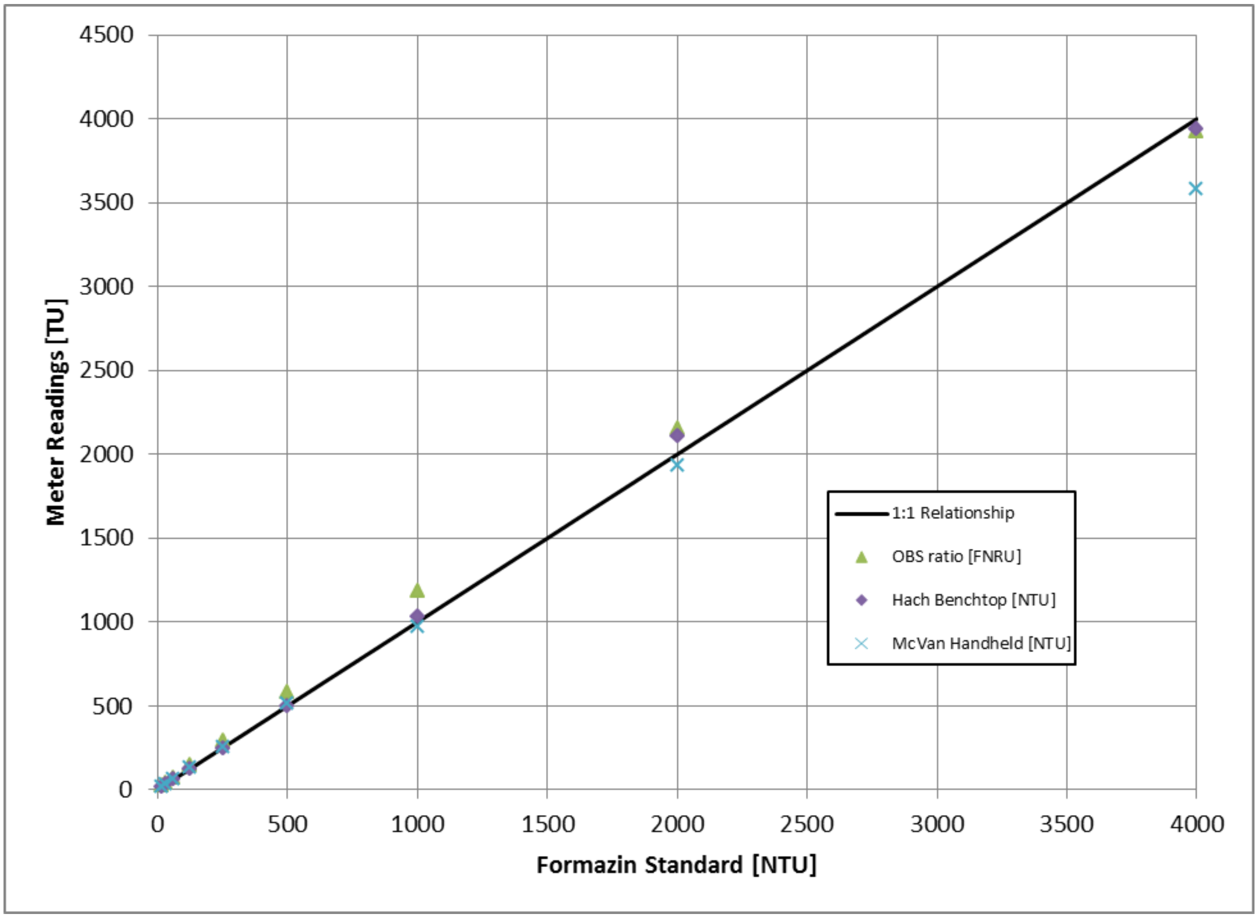

Figure 3.2: Readings of the three turbidimeters for Formazin standard solutions.

In order to test how close the readings were to the standard, 95% confidence intervals were established for the slope of the best fit line for the data from each turbidimeter. A slope of one indicated a perfect fit to the standard, so the inclusion of one in the 95% confidence interval was determined to be an indication of readings very close to the standard. The confidence intervals are shown in Table 3.1.

Table 3.1: 95% confidence intervals for the slope of the best fit line for turbidimeter readings.

Turbidimeter	**Units**	**Lower 95%**	**Upper 95 %**	**Is 1 included?**
OBS500	FNU	2.132	3.178	NO
OBS500	FBU	0.937	1.041	YES
OBS500	FNRU	0.943	1.051	YES
Hach 2100	NTU	0.967	1.027	YES
McVan	NTU	0.872	0.936	NO

Based on the slope criteria, the OBS500 readings in FBU and FNRU and the Hach readings in NTU were considered to be equivalent to the Formazin standard. The McVan instrument provided a close approximation but overall it under predicted turbidity due to low observed values in the high standard turbidity range. This was expected because the McVan's range of use only goes up to 3,000 NTU. In that range, the slope of the McVan dataset was not significantly different than one. The OBS500 FNU readings were not a good approximation of the standard but this was not surprising, as they are meant to be accurate at a low turbidity range.

Stormwater Sample Testing

It is not uncommon for meters which are calibrated with Formazin to give different readings when used on real world samples (Gray and Glysson, 2003; Resler, 2011). For this reason, and because they are the two primary meters used in this study, it was desired to investigate how the OBS500 turbidimeter readings compared to Hach benchtop readings. This was done by comparing OBS500 readings from the construction site, referred to as field readings, to laboratory Hach measurements. These Hach measurements were made using samples obtained by the ISCO 6712 portable samplers.

The samples were pulled at known times and turbidity field readings were taken every minute, so field readings were paired with runoff samples. The assumption was made that the sample contained water very similar to that which had been measured by the on-site OBS500 turbidimeter at the same minute. This assumption would have to be re-evaluated based on the results but was considered reasonable for an initial comparison of the instrument readings.

It was quickly observed that some OBS500 field readings were not similar to the Hach laboratory readings. In order to investigate this, OBS500 readings were taken in the laboratory, as described in the Procedures section. The OBS500 laboratory readings had a much more predictable relationship to the Hach readings than did the OBS500 field readings. Figure 3.3 shows the complete dataset for OBS500 field and lab readings compared to Hach lab readings.

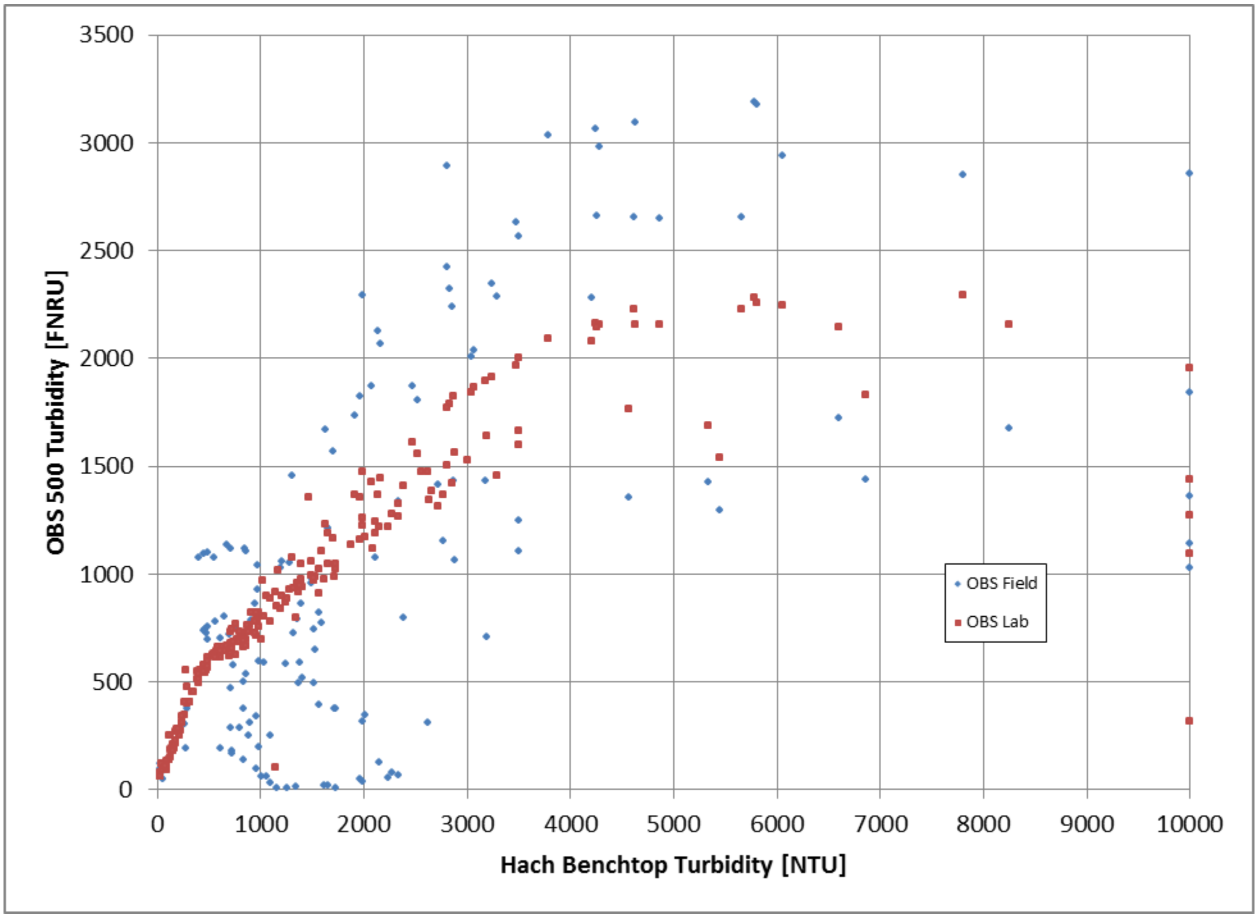

Figure 3.3: OBS500 Field (n=149) and Lab (n=218) readings compared to Hach Lab readings.

From Figure 3.3 it was apparent that the field data varied from laboratory data in two main ways. The first was a larger scatter of the data points. This was attributed to the non-homogeneous nature of stormwater runoff coming from watersheds containing multiple types of land use (CDRPC, 2003). The area draining to this channel was 7 acres with approximately 2.25 acres of road. The rest was a mix of impervious surface and open grassy cover. These different kinds of land use each contribute differently to runoff volume and sediment load, so it was not expected that runoff coming into the channel from the piped stormwater system would be a homogeneous mixture. Therefore, even if the sampler pulled a sample at the exact same moment the OBS500 took a reading, it would not necessarily be true that the runoff at the meter and runoff at the sampler intake (several feet away) were the same. Additional variation in field measurements compared to Hach measurements can be attributed to the time difference in the moment of sampling. The ISCO samples and OBS500 field turbidity readings were taken at times with precision of one minute. Turbidity conditions at fixed locations in the channel could change quite a bit during one minute.

The second peculiarity in the field turbidity readings was the presence of several points which had high Hach benchtop turbidity (over 1000 NTU) and low OBS field turbidity (below 100 FNRU, often below 25 FNRU). This is a large discrepancy which could be due to a factor other than natural variation in flow or variation due to a time difference between samples. One possible explanation is that the meter took a reading in very clear water but when the sampler pulled a sample, the suction caused deposited sediment to be pulled into the sample bottle.

In this comparative procedure, it was observed that both instruments operated in such a way that they stayed in their recommended range of use. The OBS500 never gave readings above 4,000 FNRUs, and the Hach gave values all the way up to 10,000 NTUs. Numerically, this is a large discrepancy between the two units. However, from a functional perspective, a turbidity of several thousand TUs represents turbid water and the potential for environmental problems if that water is discharged into natural systems. This difference in the units does not imply ambiguity in the overall condition of a water sample. Rather, it is simply a reflection of how the instruments are physically different and how the instrument specific units respond differently to highly turbid water samples.

In order to investigate the relationship of the instruments and units in their shared turbidity range, observations greater than 4,000 NTU were removed from the dataset. Figure 3.4 shows linear regression for both the OBS500 field and lab datasets compared to the Hach measurements.

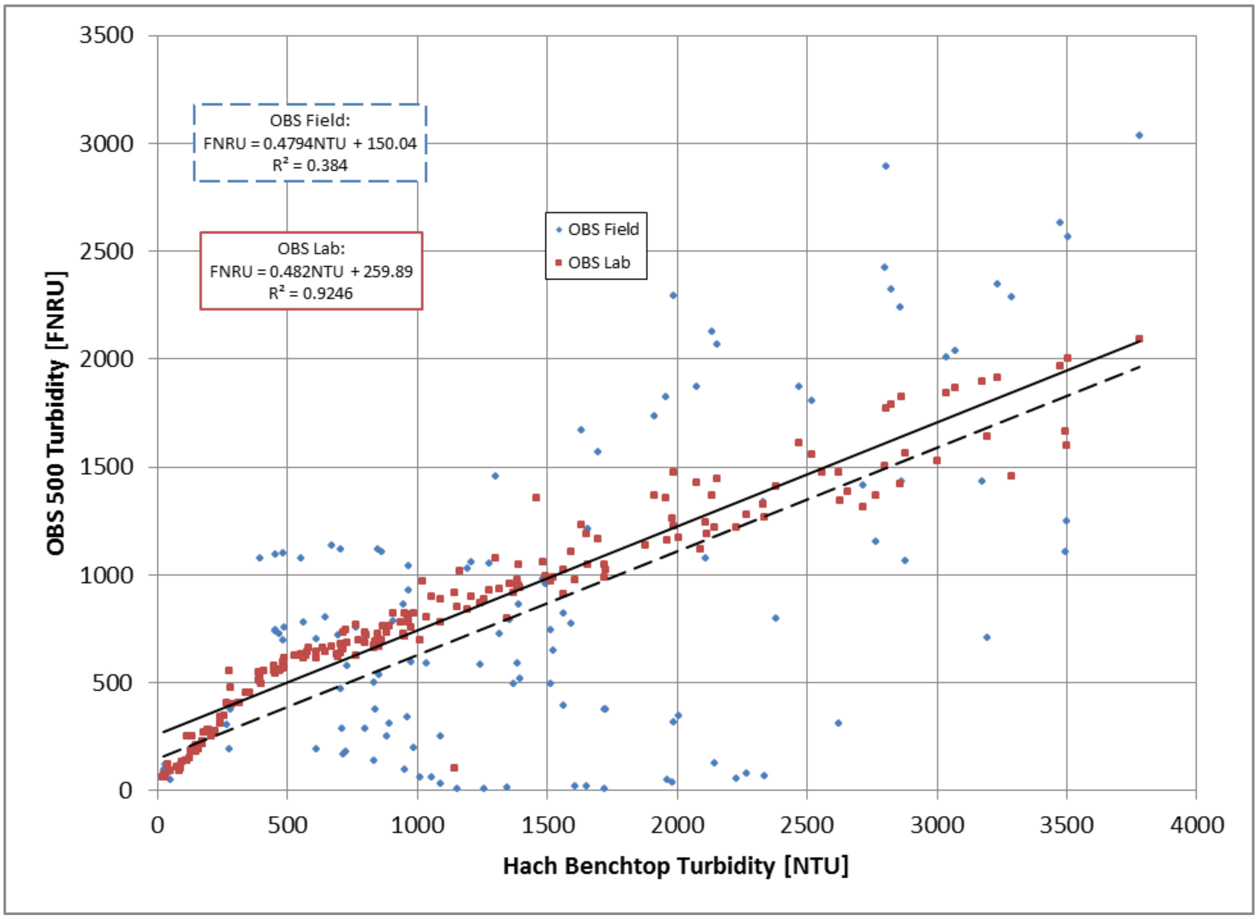

Figure 3.4: Linear regression for OBS500 Field (n=126) and Lab (n=195) readings compared to Hach Lab readings, values greater than 4,000 NTU removed.

A strong linear relationship ($R^2 = 0.9246$) was found between OBS500 laboratory readings and Hach laboratory readings. However, the data fell around the line in a manner suggesting that a linear relationship may not be the best fit. Other relationships were explored. Figure 3.5 shows a power relationship fit to the OBS500 lab readings only.

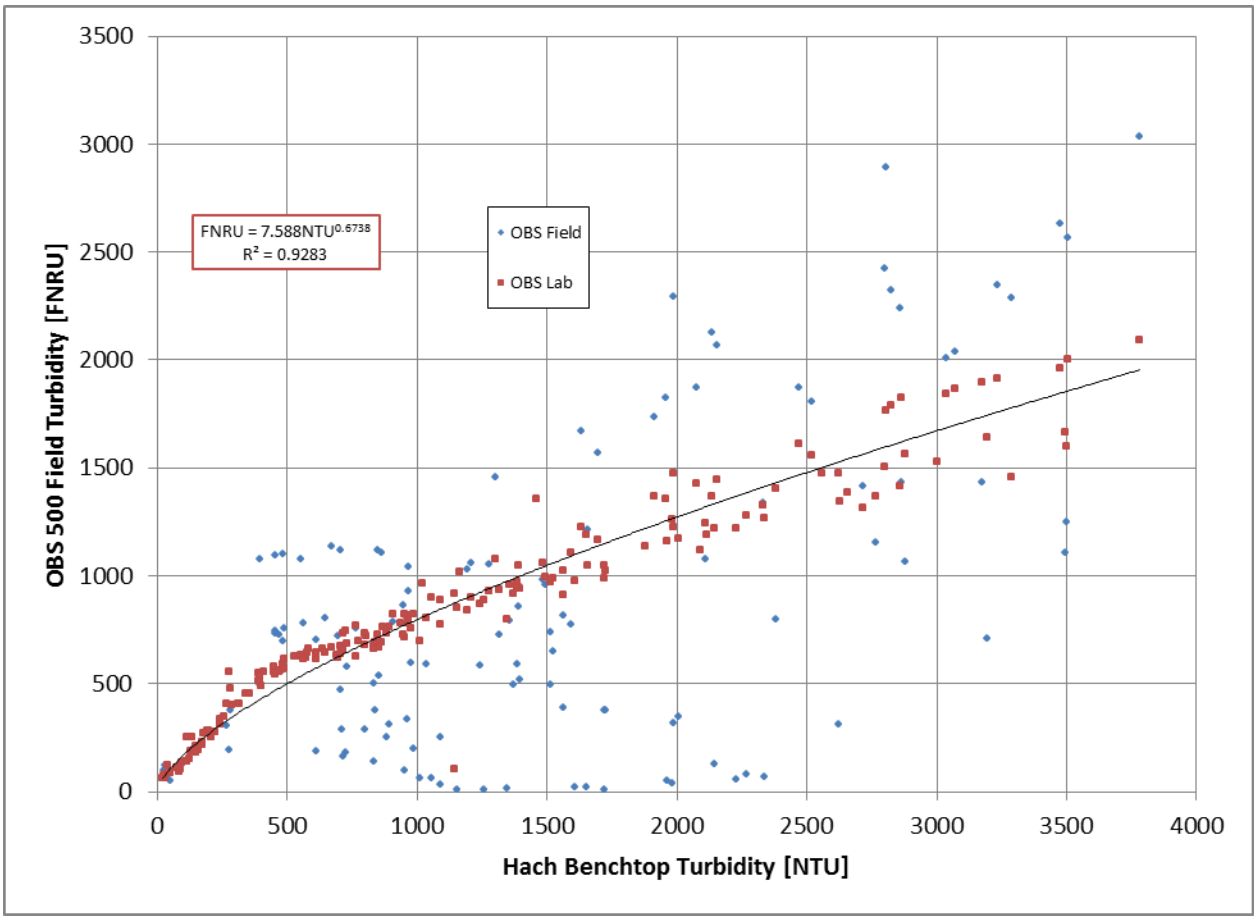

Figure 3.5: Power curve relationship for OBS500 Lab (n=195) readings compared to Hach Lab readings, values greater than 4,000 NTU removed.

Though the R^2 values were similar, the power relationship curved to visually fit the observations better than the linear relationship. There was an apparent change in the relationship around 500 NTUs which was not captured particularly well by either a linear fit or a power curve. This was around the range of turbidities where the FNRU algorithm moved away from the side scatter and began to consider back scatter turbidity readings as well.

Thus far, field and lab readings from the OBS500 have been compared to Hach benchtop readings. Figure 3.6 was created to investigate the extent to which the field and lab readings related to each other.

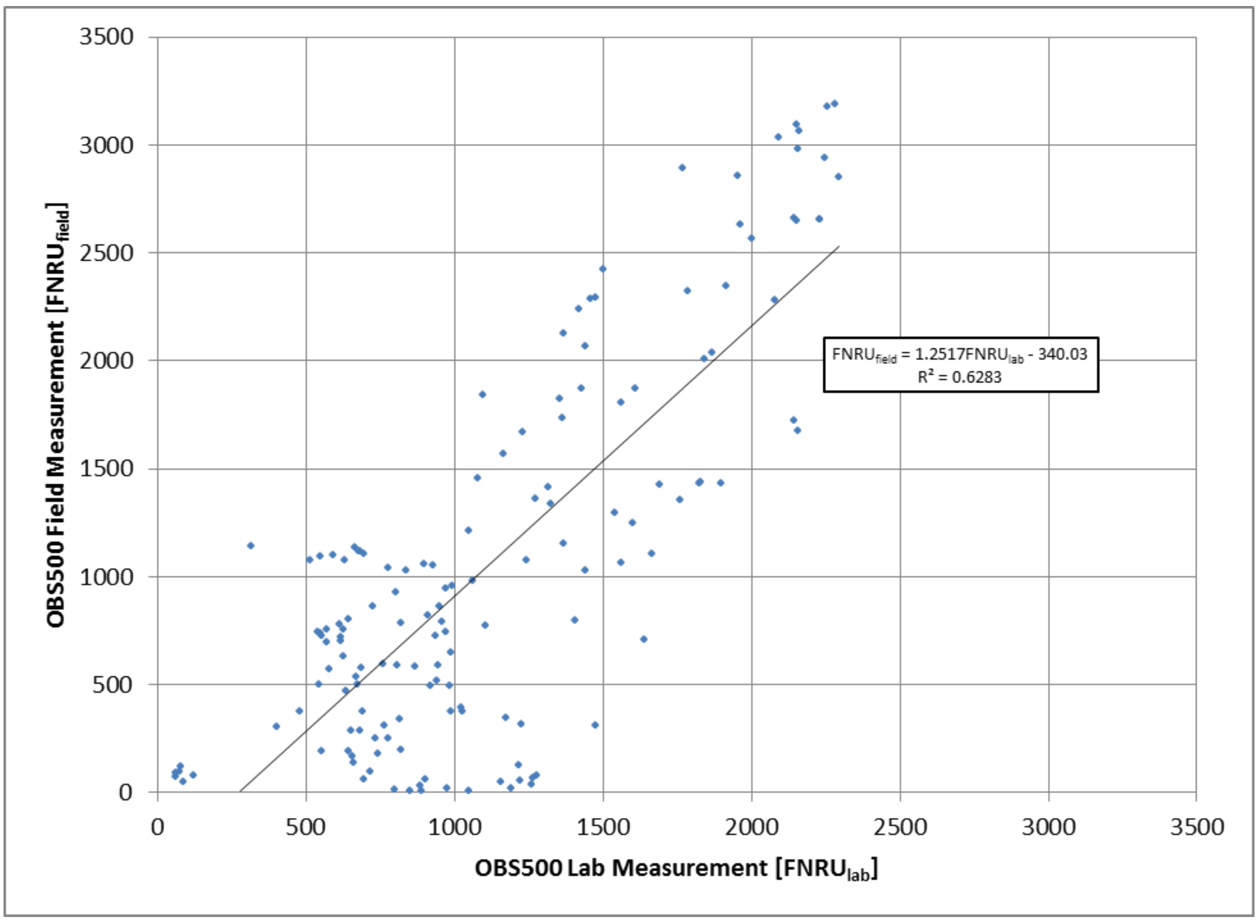

Figure 3.6: Comparison of OBS500 Field and Lab measurements (n=149).

A linear trend line was fit to the data but the correlation was not strong. This inconsistency between field and lab readings using the same instrument was attributed to the sources of variation discussed previously, non-homogeneous stormwater flows and discrepancy between the runoff present at time of meter reading and present in the sample.

CONCLUSIONS

This investigation of different turbidimeters and units led to some important conclusions about how they work and their utility for this research. The Campbell OBS500 units worked as advertised by Campbell Scientific. Both FBUs and FNRUs produced accurate results in the Formazin test. FNRUs were chosen as the primary reporting unit after the Formazin test and proved to be a useful representation of turbidity from the OBS500 throughout the stormwater sample tests. In the Formazin test, the OBS500 FNRU, OBS500 FBU, and Hach NTU produced results statistically similar to each other and to the Formazin standard values.

Stormwater sample testing showed that OBS500 turbidity readings in a laboratory setting were best related to Hach turbidity readings by a power curve relationship with an R^2 value of 0.9283. Significant variation was observed between OBS500 field readings and laboratory readings using samples which were collected at the same minute. This was attributed to non-homogeneous stormwater runoff and discrepancy between the runoff present at time of meter reading and present in the sample. .

CHAPTER FOUR

LONGEVITY OF POLYACRYLAMIDE FOR TURBIDITY REDUCTION OF SIMULATED STORMWATER

ABSTRACT

Accelerated erosion and highly turbid stormwater runoff from construction sites are known to cause a variety of environmental and economic problems. In order to reduce turbidity and keep eroded sediment on site, this research was conducted to evaluate the potential for turbidity reduction using polyacrylamide flocculants with sediment control best management practices.

Significant turbidity reduction has been observed when applying granular PAM to sediment tubes in both research and construction site settings. It has also been documented that when PAM gets wet and then dries, this desiccation dramatically decreases turbidity reduction capacity. This makes reapplication of PAM to sediment control practices necessary. However, there is a lack of research on the longevity of PAM in construction site environments. If PAM is re-applied to sediment tubes, how long can it remain on the tubes and still reduce turbidity when a runoff event occurs?

This question was explored through tests where simulated stormwater runoff was directed down a channel across four 20-inch excelsior sediment tubes. The tubes had an initial application of 100 grams of Applied Polymer Systems Silt Stop® #705 PAM to each tube before the first run for each test. PAM was strategically reapplied after runoff events in order to investigate the effect on turbidity reduction of different time intervals between PAM reapplications and subsequent runoff events. These tests showed average

effluent turbidities between 82 NTU and 477 NTU and percent turbidity reductions between 78% and 96%.

Results and statistical analysis from this study suggested that the turbidity reduction capacity of PAM when it is first applied is no different than it is after a three-, five-, or ten-day waiting period between reapplication and a runoff event. Though not statistically different, the two runs of the ten-day waiting period showed average effluent turbidities of 324 and 477 NTU, the two highest observations of any treatment.

It was observed that environmental conditions at the outdoor test site played a significant role in the turbidity reductions that were seen. Tests which saw frequent rain between runs had the lowest effluent turbidities (109 and 82 NTU) and highest percent reductions (96% in both cases).

Based on the observations that were made, it is recommended that PAM should be reapplied every 5 days in order to ensure turbidity reduction of runoff during a storm event. Also, the results from this study provided further evidence to support the common theory that PAM loses efficacy if it gets wet and then dries. Therefore, reapplication of PAM is necessary to ensure treatment.

INTRODUCTION

Construction sites frequently experience greatly accelerated rates of erosion due to land disturbance and removal of ground cover. These rates are typically 1,000 to 2,000 times that of forested lands and 10 to 20 times that of agricultural lands (EPA, 2005) and have been estimated to be as high as 35 to 45 tons per acre per year (USGAO, 1998). The impact of accelerated erosion due to construction and land development has been estimated to have a direct cost of over two billion dollars. Much of this cost is associated with damage to water storage, treatment, and conveyance facilities, reduced navigation capacity of waterways, and harm to commercial fisheries. That figure does not attempt to include biological or aesthetic costs (Clark, 1985).

When it rains on bare soil, particles are detached and transported by runoff. Sand particles (diameter between 1 mm and 0.1 mm) settle out in a matter of seconds or minutes, but small colloid particles (dia < 0.0001 mm) can stay in suspension for hundreds of days under natural conditions (McLaughlin and McCaleb, 2014). This means that larger particles are easily removed by conventional sediment control practices, and small particles are very difficult to remove. These small suspended particles cause runoff to have high turbidity, often thousands of Nephelometric Turbidity Units (NTUs). Turbidity is an optical measurement which directly measures light scattered by a water sample. It is common to consider turbidity to be an indirect measurement of suspended matter in a water sample. High turbidity caused by suspended sediment is disruptive to natural systems and harmful to organisms in a variety of ways (EPA, 2012). In order to remove sediment and reduce turbidity, it is necessary to use flocculation.

Flocculation is the process of small particles sticking together to form large particles, or "flocs," which settle faster and are more easily removed (Auckland Regional Council, 2004). Flocculation is necessary to settle small sediment particles within a reasonable amount of time to prevent them from being transported off construction sites. Anionic polyacrylamide (PAM) is the preferred flocculant material for environmental applications due to low aquatic toxicity and past research which has shown it can be very effective at turbidity reduction (Sojka et al., 2007). Traditional sediment control best management practices (BMPs) in South Carolina are designed to remove 80% of total suspended solids, but are ineffective at reducing turbidity caused by fine suspended particles (Bhardwaj and McLaughlin, 2008, Berry, 2012). Therefore it is desirable and necessary to research how PAM can be used with sediment control BMPs in order to reduce turbidity of stormwater runoff.

Studies have shown significant turbidity reductions when applying granular PAM to sediment tubes in both research and construction site settings (Berry, 2012; McLaughlin et al., 2009). Berry (2012) conducted research on turbidity reduction using a series of five sediment tubes in a triangular channel under simulated runoff conditions. Sediment tubes alone did not reduce turbidity, and the channel discharged water with an average turbidity of 3104 NTU. Granular PAM was introduced to the system by sprinkling it on the tubes and through a separate treatment using permeable bags placed in the flow path. Sprinkling PAM on the tubes was the more effective treatment, reducing turbidity to an average of 202 NTU after three tubes and 82 NTU after five tubes.

Berry (2012) also explored longevity of PAM and found that if PAM becomes wet and then dries, it is no longer as effective. This desiccation effect was observed in other PAM research as well (McLaughlin, 2006; Zech, 2014). In Berry's longevity tests, an average discharge turbidity of 1283 NTU was present during runs after the sediment tubes were allowed to dry out. When PAM was reapplied to the used and dried tubes prior to the runoff simulation, average discharge turbidity was reduced down to only 100 NTU. This showed a need for reapplication of PAM and research about how often to reapply it. If PAM is re-applied, for how long is it still effective and ready to reduce turbidity of runoff? In order to explore the longevity of PAM, the following objectives were established.

1. Analyze how length of time between PAM re-application and runoff event impacts PAM's effectiveness.
2. Compare the extent of turbidity reduction of re-applied PAM after various numbers of days to that of freshly applied PAM on new sediment tubes.

PROCEDURES

Experimental Site

The Clemson University sediment control test channel at the LaMaster Dairy was utilized for this research. The triangular channel's dimensions are 185 feet in length with a top width of 12 feet, an average depth of 1.65 feet, and on a 7% slope (Berry, 2012). The channel was lined with 50 mil HDPE plastic to prevent scouring and erosion. Figure 4.1 shows a schematic of the channel with its maximum of five sediment tubes in place. Figure 4.1 also shows the sampling locations used in this research. Berry (2012) showed that, when sprinkling PAM before each run, turbidity was reduced to below 280 NTU after just three sediment tubes. PAM was reapplied before each run in this testing so the relevant observations were expected to be present after four tubes and the fifth was omitted to save material costs. A GeoHay® ditch check was put in place at the fifth location, downstream of the portion of channel used for research. This provided a final sediment control prior to discharging effluent. Figure 4.2 shows a test in the channel with the four sediment tubes.

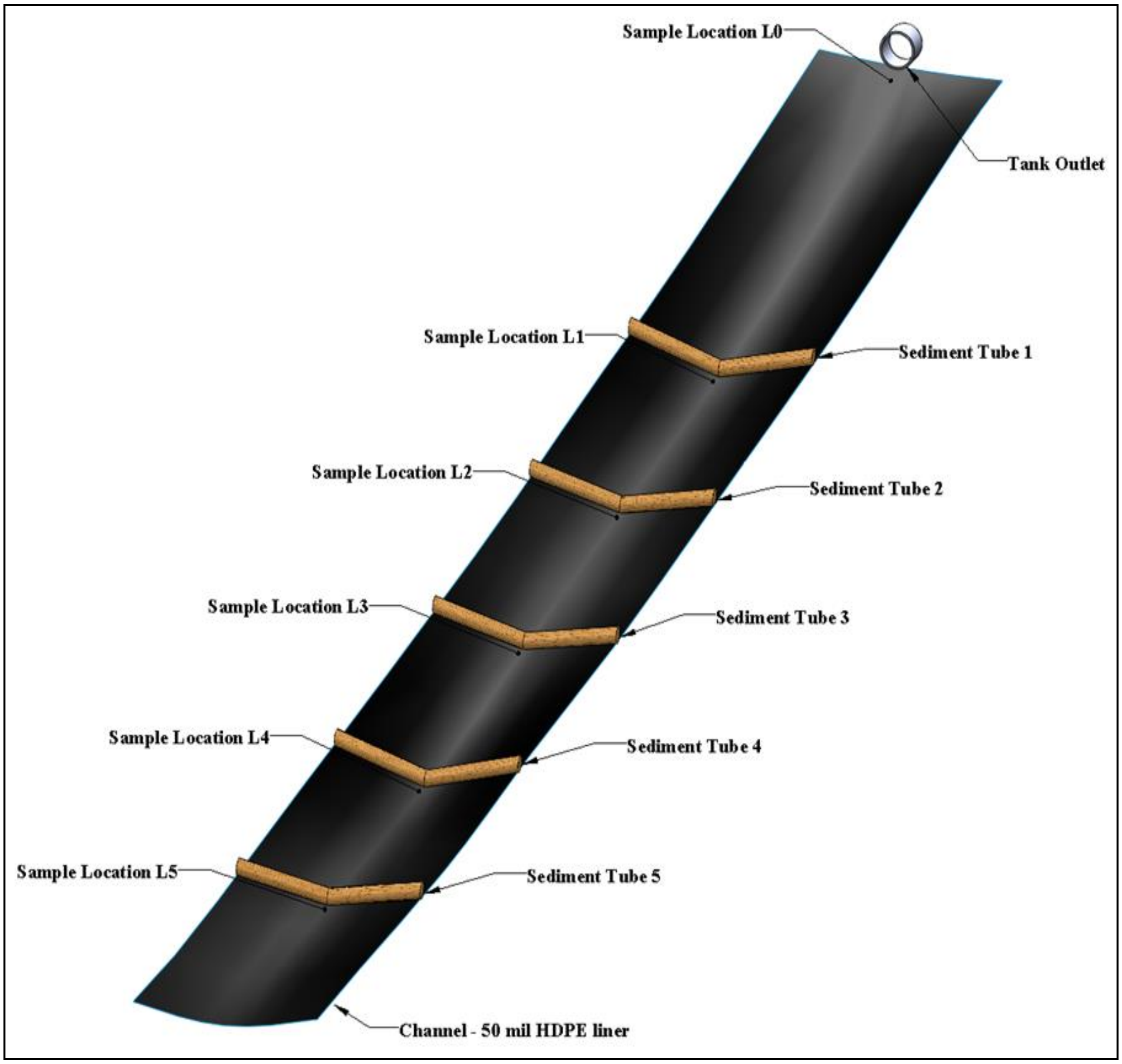

Figure 4.1: Design schematic of the test channel, sample locations labeled (Berry, 2012).

Figure 4.2: Experimental setup during testing. On left, the channel below the tank. On right, the tank mid-discharge.

A 4800 gallon collapsible tank with a 6-inch gate valve outlet was in place at the top of the channel. This tank was filled with water from a nearby pond. Once full, the tank was connected to a recirculation pump. The recirculation pump withdrew water from the bottom of the tank and discharged it through a PVC pipe manifold in the center of the tank, visible in Figure 4.2. Kaolinite clay was introduced in order to create simulated stormwater runoff. Kaolinite was chosen because it is naturally occurring clay that is easily suspended in water and represents the silt/clay fraction that would be found in a South Carolina Cecil soil (Berry, 2012). For this research, Paragon®, a trade name for kaolinite clay used by IMERYS Minerals Company, was acquired from the Langley, SC mine. Table 4.1 shows the particle size distribution of this product.

Table 4.1: Particle Size Distribution for Paragon® (IMERYS Minerals, 2012).

PARTICLE SIZE		
Median	(microns)	1.1
+325 Mesh	(% retained)	0.3
PERCENT PASSING		
% < 20	(microns)	98
% < 10	(microns)	94
% < 5	(microns)	84
% < 2	(microns)	65
% < 1	(microns)	52
% < 0.5	(microns)	36
% < 0.2	(microns)	14

The amount of clay added for each test varied in an effort to reach the target turbidity range for the simulated stormwater, 1800-2200 NTUs. Initially, one 50 pound bag was added and allowed to mix for several minutes. The turbidity was checked using an Analite NEP 160 display with NEP 260 handheld probe turbidity meter with a range of 0 to 3,000 NTU (McVan Instruments, 2012). Additional clay was added gradually until the desired turbidity range was achieved. The amount of clay introduced for each test varied between 50 and 100 pounds.

The tank discharged over the course of 12 minutes with decreasing flow rate over time. Calibration was performed so that this variable flow rate was known, and the results are shown in Figure 4.3 (Berry, 2012). The peak flow rate was 1.91 cfs and the average flow rate over the 12 minutes was 0.72 cfs (Berry, 2012). This decreasing flow rate resembled the falling limb of a runoff hydrograph and was considered an approximation of a natural runoff event.

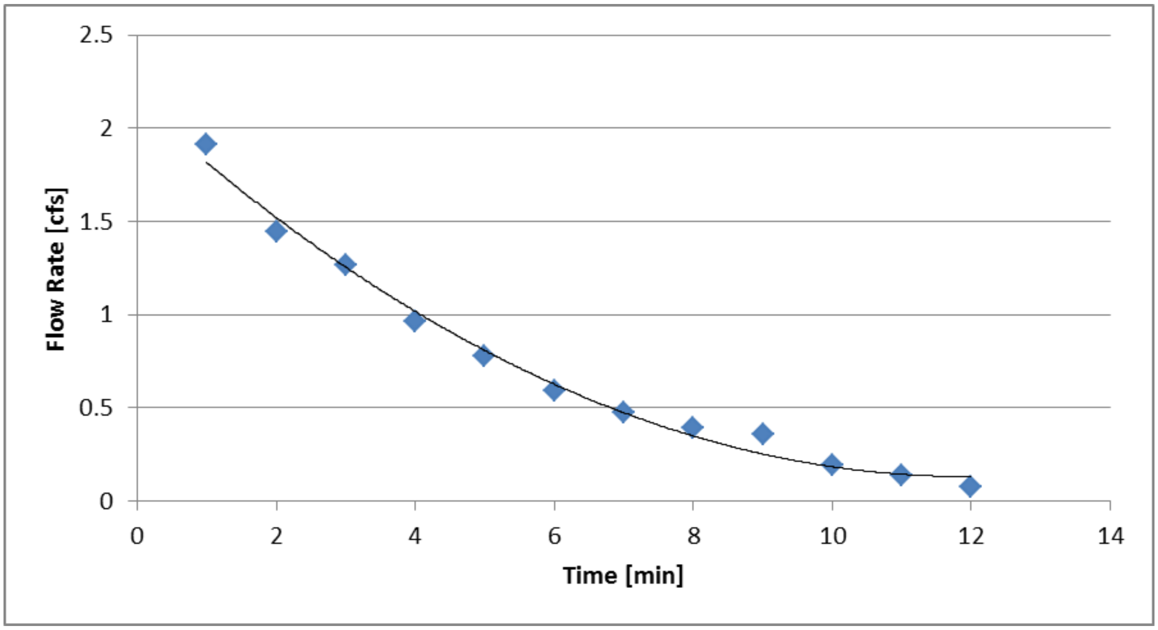

Figure 4.3: Variable flow rate measured during 12 minute tank discharge (Berry, 2012).

Five ISCO 3700 samplers were programmed with a time-based sampling protocol to collect samples during the simulated runoff event (Teledyne ISCO, 2012). Samples were taken at the tank outlet and on the downstream side of each sediment tube. Sampling began when the simulated runoff reached each sampling location, and samples were taken every four minutes until water was no longer present. The samplers used ISCO 1640 liquid level actuators to sense the presence of flow and activate the sampling program.

Longevity Testing of PAM

Laboratory testing indicated that Applied Polymer Systems (APS) Silt Stop® #705 was the PAM variety most well suited to the kaolinite clay (Berry, 2012). All PAM applications followed the sprinkle method of 100 grams of APS #705 graular PAM per sediment tube (NCDOT, 2008). PAM was sprinkled on the upstream side and top of each sediment tube, as shown below in Figure 4.4, in order to facilitate contact with the runoff.

Figure 4.4: Hatching showing areas of PAM application by the sprinkle method (Berry, 2012).

This experimental design was created to simulate activity on a construction site. Sediment tubes and PAM are installed before a storm. PAM is reapplied after the storm and remains on the tubes until the next storm event. PAM continues to be reapplied after events until eventually the tubes become damaged or full of sediment and are replaced. These activities were simulated through tests described as follows.

Three different storm intervals of interest were established in order to test the longevity of reapplied PAM. Historic data on storm occurrence from the South Carolina Department of Natural Resources were used to determine these intervals. The number of days each year with greater than or equal to 0.1" of rain varies regionally from 70 to 95 in South Carolina. The number of days each year with greater than or equal to 0.5" of rain varies regionally from 30 to 48 (SCDNR, 2014). These figures equate to recurrence of 0.1" or greater rain events every 3.8 to 5.2 days and 0.5" or greater rain events every 7.6 to 12.2 days. Five days was used as the average number of days between storm events based on these figures and professional judgment. Three days was used to represent instances where consecutive storms occurred more frequently than the average. Ten days was used to consider a dry period where storms were less frequent than the average. Ten days also provided an interval approximately equivalent to the frequency of 0.5" rain events.

An experimental procedure was developed to analyze the impact that number of days between PAM reapplication and a rain event, or "wait time," had on PAM's capacity for turbidity reduction. Each test consisted of three runoff simulations, or "runs" with reapplication of PAM in the manner described as follows. All tests started with a new set of four 20-inch excelsior sediment tubes anchored in the channel and a PAM application. The first run was simulated, followed by a reapplication of PAM. The number of days for the specified wait time passed and a second run was simulated, followed by another reapplication. The specified number of days passed again and a third and final run was simulated. These separate tests for the three different time intervals established seven different treatments for comparison, as described below in Table 4.2.

Table 4.2: Treatment designations used for statistical comparison.

Treatment	Wait Time [days]	Run Number
f	0	1
A2	3	2
A3	3	3
B2	5	2
B3	5	3
C2	10	2
C3	10	3

Wait times of 0, 3, 5, and 10 days were given alphabetic designations of "f," A, B, and C in order to have treatment names involving a letter and a number instead of two numbers. Treatment "f" was chosen for the wait time of 0 days because these are all first runs on a new set of sediment tubes. Treatment "f" includes the first run from every test that was conducted. The lower case "f" ensured that there would never be ambiguity on a statistical figure that referred to treatment "f" and included a letter "F" indicating significance. The run designations of 2 and 3 referred to whether that treatment contains data from the second or third overall runs for a given wait period.

Six total tests were conducted for the following reasons. The first two tests were three-day tests. These produced similar results showing effective turbidity reduction. It was determined that these two tests would be a sufficient representation of the three-day wait time and that time and resources should be spent on tests for the five- and ten- day wait times. Three five-day tests were conducted in order to represent the five-day wait time. Finally, one ten-day test was conducted in order to see if it would have results similar to the tests of shorter wait time.

Sample Analysis

A Hach 2100AN Laboratory Turbidimeter was used to measure turbidity of all samples following Standard Method 2130 B (APHA, 2005). The Hach has a range up to 10,000 NTUs with the following accuracy specifications (Hach, 2012).

±2% of reading plus 0.01 NTU from 0-1000 NTU
±5% of reading from 1000 NTU to 4,000 NTU
±10% of reading from 4,000 NTU to 10,000 NTU

Each sample was agitated by inverting and shaking the sample bottle for 5 seconds or until sediment was visually evenly suspended. The sample was then transferred into a Hach turbidimeter vial. The vial was then wiped clean, carefully inverted 10 times, and placed into the turbidimeter. After turbidity analysis, samples were analyzed for TSS using Standard Method 2540 B (APHA, 2005).

Statistical Analysis

Statistical calculations were performed using JMP statistics software (SAS Institute Inc., Cary, NC, USA). Analysis of Variance (ANOVA) tests were used to detect significant differences at the $\alpha=0.05$ confidence level. Fisher's Least Significant Difference (LSD) comparison t-test was used to identify specific differences when they were present.

RESULTS AND DISCUSSION

Analysis of Turbidity Data

Appendix A contains the two datasets that are relevant to this analysis. Table A.1 shows the turbidity measurements from the analyzed samples as well as average turbidity at each location and percent reduction for each test. Table A.2 shows temperature and rainfall data relevant to the days that runs occurred and periods of time between runs. Tables 4.3 and 4.4 were created to respectively show arithmetic mean turbidities and percent reduction calculations at each location for each treatment that was specified in the Procedures section.

Table 4.3: Mean turbidity at each sample location for each treatment.

	Treatment Turbidity [NTU]						
Location	f	A2	A3	B2	B3	C2	C3
L0	2153	2659	2081	2013	2232	2839	2194
L1	1602	1375	1598	1111	1634	2224	1662
L2	829	557	595	499	744	812	993
L3	452	335	259	393	459	608	733
L4	214	109	82	153	284	324	477
n =	6	2	2	3	3	1	1

Table 4.4: Percent reduction calculations at each sample location for each treatment.

	Treatment Reduction [%]						
Location	f	A2	A3	B2	B3	C2	C3
L0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
L1	25.6%	48.3%	23.2%	44.8%	26.8%	21.6%	24.2%
L2	61.5%	79.0%	71.4%	75.2%	66.7%	71.4%	54.7%
L3	79.0%	87.4%	87.6%	80.5%	79.5%	78.6%	66.6%
L4	90.1%	95.9%	96.1%	92.4%	87.3%	88.6%	78.2%
n =	6	2	2	3	3	1	1

The data in Table 4.3 shows that the poorest turbidity reductions, in terms of numeric effluent turbidity from the channel, were present for the runs of the ten-day test (treatments C2 and C3). These treatments respectively had final turbidities of 324 and 477 NTU. Prior to further speculation, more robust statistics were employed to identify specific areas of significant difference among the tests.

A statistical model was developed using JMP software to describe the relationship of least squares (LS) mean turbidity to treatment and location in the channel. All means discussed beyond this point should be regarded as LS mean turbidities. Fisher's LSD test was utilized to develop letters and symbols which show significant difference or similarity. In all statistical figures, the presence of a common letter or symbol means that two values are not significantly different. The first analysis compared the treatments in the most general sense by comparing the overall mean turbidity (all locations combined) for each treatment. Overall means for each treatment were compared and a null hypothesis was established that the mean for each treatment was equal. The ANOVA test returned a P-Value = 0.5449, so the null hypothesis was not rejected. There was not statistical evidence that any of the treatment means were different. Figure 4.5 shows these overall means. All of them share the letter “A,” indicating no significant differences.

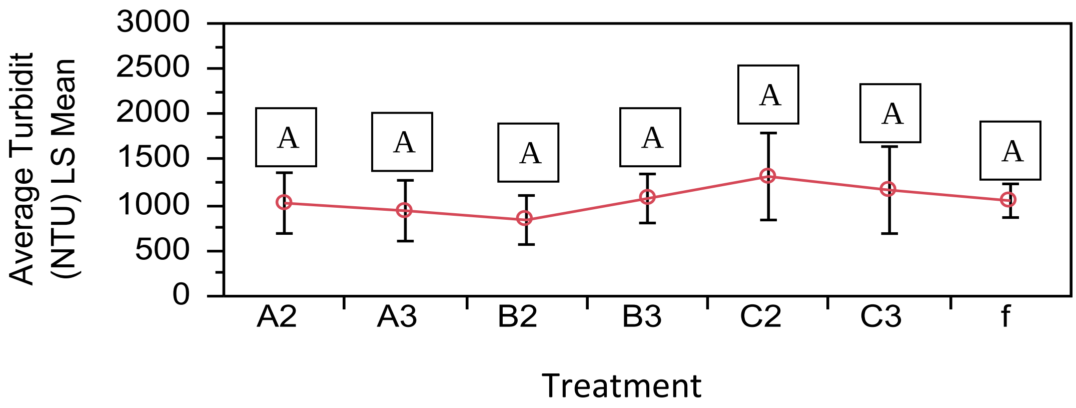

Figure 4.5: Overall LS mean turbidity for each treatment.

The next analysis was with respect to the effect of location on turbidity. Overall means at each location were compared and a null hypothesis was established that the mean at each location was equal. The ANOVA test returned a P-Value < 0.0001, so the null hypothesis was rejected. There was evidence that some difference was present between the means. Figure 4.6 illustrates this.

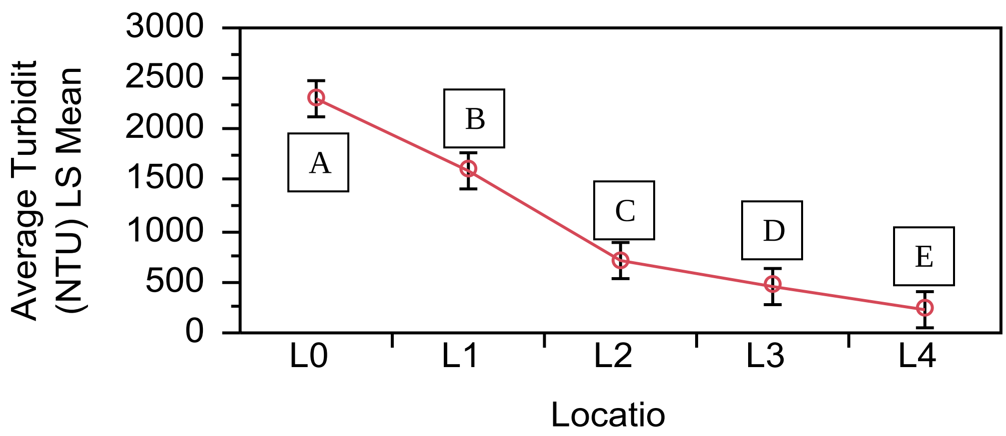

Figure 4.6: LS mean turbidity at each sample location, all treatments combined.

These results showed that significant difference was present for all locations. This was expected because the PAM treatment was intended to cause a reduction in turbidity. Berry (2012) showed significant difference between the locations L0, L1, L2, and L3, but not between L3 or L4. He also included a L5 after a fifth sediment tube which was also not significantly different. In his testing, target treatment was achieved by L3. Treatment may have continued through L4 for this research due to the prescribed wait times.

Analysis to this point has established that overall mean turbidity did not change between treatments and did change between locations. It was then desired to evaluate whether the treatments were statistically the same at all locations in the channel. If they were not the same, the reason for the difference had to be evaluated. This led to an analysis which compared the variation in order of the means at each location for each treatment. If a difference was present in this order of the means between locations, then some treatments behaved differently. A null hypothesis was established that the order of the mean turbidities for the treatments at a given location was the same at all locations. The ANOVA test returned a P-Value = 0.0171, so the null hypothesis was rejected. There was evidence that some difference was present in the order of treatment means between one or more locations. In order to better understand this statement, consider Figure 4.7, which shows mean turbidities for each treatment at each location. Some of the lines cross each other. Therefore the mean turbidities for each treatment are not staying in the same order at different locations.

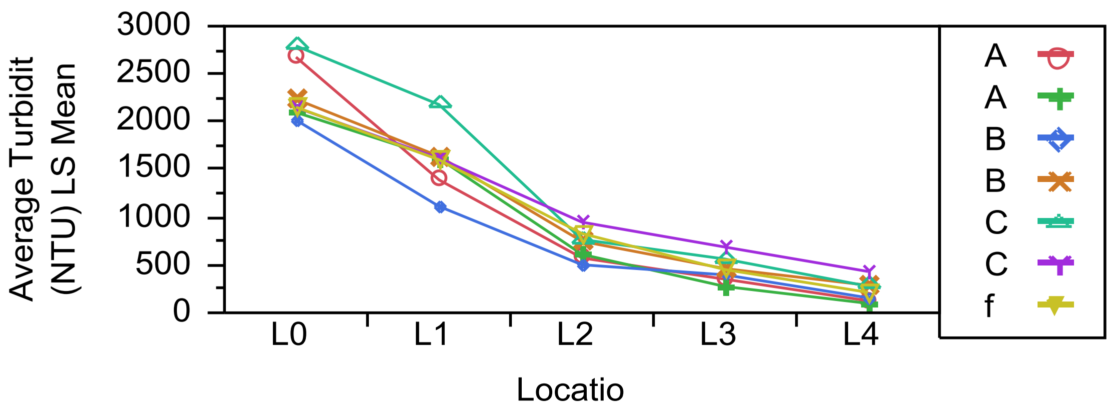

Figure 4.7: LS mean turbidity for each treatment at each location.

Fisher's LSD test was used to analyze mean turbidity for every combination of location and treatment. This made it possible to see, at a given location, which treatments were different from the others. The "f" treatment, which represented the first runs on new sets of sediment tubes, was used as a baseline for comparison for the following reason. It was reasoned that if a re-application treatment performed statistically the same as a first application of PAM with no wait time between application and runoff event, then a drop in efficacy did not occur due to the re-application and wait time. Therefore, the Fisher's LSD test results were used to compare the means for each treatment to the "f" treatment at the same location. Due to the large number of factors being compared, letters and symbols were not added to Figure 4.7. Instead, the results of Fisher's LSD test are shown below in Figure 4.8. This figure can be used to determine differences between any "Levels," which specify location as well as treatment, by identifying common letters between levels. The presence of any common letter means they are not statistically different.

Level																															Least Sq Mean
L0,C2	A																														2793.7836
L0,A2	A	B																													2675.6936
L0,B3	A	B	C		E																										2235.5264
L1,C2		B	C	D	E	F	G	H																							2179.2336
L0,f			C		E																										2152.5694
L0,C3	A	B	C	D		F			I																						2148.5336
L0,A3			C	D	E		G																								2097.9020
L0,B2			C	D	E	F	G	H																							2017.1931
L1,B3				D		F	G	H	I	J																					1638.2208
L1,C3					E		G	H		J	K																				1617.2836
L1,A3						F		H	I	J	K	L																			1615.1520
L1,f									I	J																					1601.6806
L1,A2										J	K	L																			1391.6020
L1,B2											K	L	M																		1114.2986
L2,C3												L	M	N	O	P			S			V									948.4336
L2,f													M	N			Q		S					X							829.1083
L2,C2													M	N	O	P	Q	R		T	U		W		Y			\	]	^	767.0336
L2,B3													M	N		P	Q		S					X							747.4708
L3,C3													M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	688.0336
L2,A3														N	O	P	Q	R	S	T	U	V	W	X		Z	[	\	]		611.5270
L2,A2														N	O	P	Q	R	S	T		V	W	X	Y	Z	[	\			573.8770
L3,C2													M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	[	\	]	^	562.7003
L2,B2														N	O	P	Q	R	S	T	U	V		X	Y	Z	[			^	502.9708
L3,B3															O			R		T	U	V	W		Y	Z	[	\	]	^	462.2819
L3,f															O	P		R			U	V	W		Y	Z			]	^	451.9000
L4,C3																	Q	R		T	U		W	X	Y	Z	[	\	]	^	432.4336
L3,B2															O	P		R		T	U	V	W		Y	Z	[	\	]	^	397.0819
L3,A2															O	P		R		T	U	V	W		Y	Z	[	\	]	^	351.6770
L4,B3																		R		T	U		W		Y	Z	[	\	]	^	288.1708
L4,C2																			S			V		X		Z	[				278.5336
L3,A3																		R		T	U		W		Y	Z	[	\	]	^	275.4020
L4,f																				T							[	\			214.0806
L4,B2																							W					\	]		156.9931
L4,A2																					U								]	^	125.5770
L4,A3																									Y					^	98.7936

Figure 4.8: Fisher’s LSD test for LS mean turbidity of each treatment at each sample location.

Comparison of the letters and symbols in Figure 4.8 identified a total of six instances of significant difference between treatment runs and first runs, within given locations. These were present at three different channel locations and will be explained starting at the top of the channel. None of the differences raised any concerns about a decrease in the efficacy of PAM with respect to any of the wait times tested.

At the tank outlet (location L0), treatments A2 and C2 were significantly larger than the “f” treatment. This was due to inconsistency in the turbidity of the simulated stormwater. The goal was to create stormwater with a turbidity of 1800 to 2200 NTU. On some occasions the tank outlet had a higher turbidity. This was because too much sediment was present in the tank and suspended in the water. One possible reason for this is that too much sediment may have been added by the researcher during the mixing phase. Another possible reason could be an increasingly high amount of residual sediment in the tank becoming re-suspended during the mixing phase. Mixing was not perfectly uniform in the tank, and sediment accumulated in dead zones. It is reasonable to surmise that a large chunk of deposited sediment could come loose and re-suspend, leading to a higher turbidity. Inconsistency in the simulated runoff does not indicate poor turbidity reduction by the PAM. The PAM was not yet present in the system.

After the first sediment log (location L1), there were two instances of significant difference. Mean turbidity for treatment B2 was significantly lower than the “f” treatment at L1. This instance of “better” treatment was not concerning. It was likely due to a higher than average amount of PAM being present in the sample that was taken. This could have been due to fortunate good mixing in the turbulent water. Mean turbidity for treatment C2 was significantly higher in turbidity than the fresh run average at L1. This was not surprising since the runoff sampled at L1 flowed from L0, which also had significantly higher mean turbidity for treatment C2, as discussed in the previous paragraph.

The final two instances of significant difference were present after the last sediment log (L4). The mean turbidities for both three-day treatments (A2 and A3) were significantly lower in turbidity than the "f" treatment at L4. These instances of greater turbidity reduction were explained by an evaluation of weather conditions at the site during the test. Table A.2 in Appendix A shows that for both three-day tests (treatment letter A), significant rain occurred during the waiting periods between PAM reapplications and runoff events. The test channel was oriented such that it did not receive runoff from surrounding areas, but rain falling directly on the channel did have an impact on the tests.

For the test starting on November 13th, 0.17 inches and 0.59 inches of rain, respectively, fell during the waiting periods. For the test starting on December 3rd, 0.85 inches and 1.08 inches of rain, respectively, fell during the wait periods. For the December 3rd test, some rain actually occurred on every day of the test. This frequent rain and the short three-day waiting period for these tests meant that the PAM never had a chance to dry. It has been observed in multiple studies that desiccation after initial use makes PAM less effective in future treatments (Berry, 2012, McLaughlin, 2006, Zech, 2014). With every subsequent run, more PAM was added to the system of four sediment tubes. Some of it bound to soil particles and was washed away, but it was observed in all tests that a significant amount of PAM stuck to the sediment tubes and formed gelatinous patches. The significantly greater reductions seen in treatments A2 and A3 were attributed to this increased amount of PAM in the system which experienced very little, if any, reduction in efficacy due to desiccation.

The information in Figure 4.8 was useful to make another important comparison. It was desirable to know whether 2^{nd} and 3^{rd} runs were statistically the same for each treatment. Figure 4.8 was evaluated for significant differences between Run 2 and Run 3 for each wait time and at each location. Three instances of significant difference were noted. Treatments C2 and C3 were different at L0, treatments A2 and A3 were different at L0, and treatments B2 and B3 were different at L1. These points of difference were also seen in the comparison of runs to treatment "f," discussed previously. The three statistically different observations were not only different from "f," but also different from the other run for that wait time at those respective locations. All other Run 2 and Run 3 mean turbidities were the same for a given wait time at all locations.

It was then desired to combine runs into treatments based only on wait time in order to see what effect this would have on significant differences. For example, treatments A2 and A3 were combined into a single treatment A. The overall means for each treatment were compared and no differences were found. This is illustrated in Figure 4.9. The means for each treatment were then plotted together in Figure 4.10. Letters representing similarity from Fisher's LSD test for the combined treatments are shown in Figure 4.11.

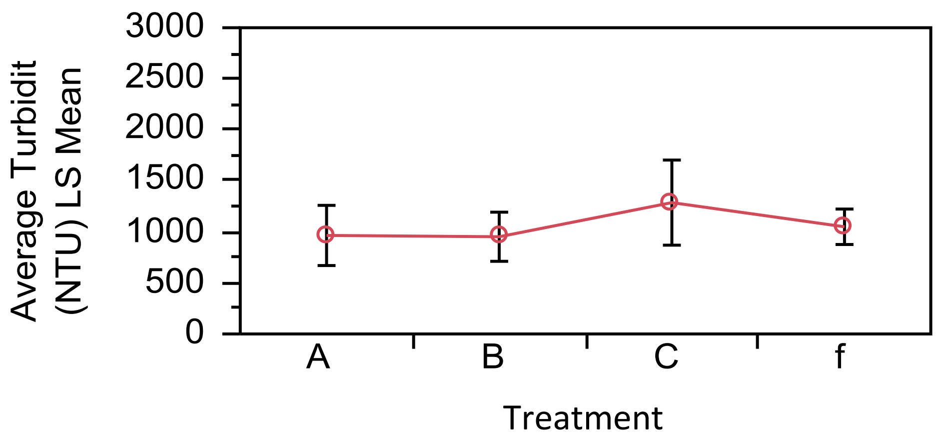

Figure 4.9: Overall LS means for combined treatments A, B, C, and f.

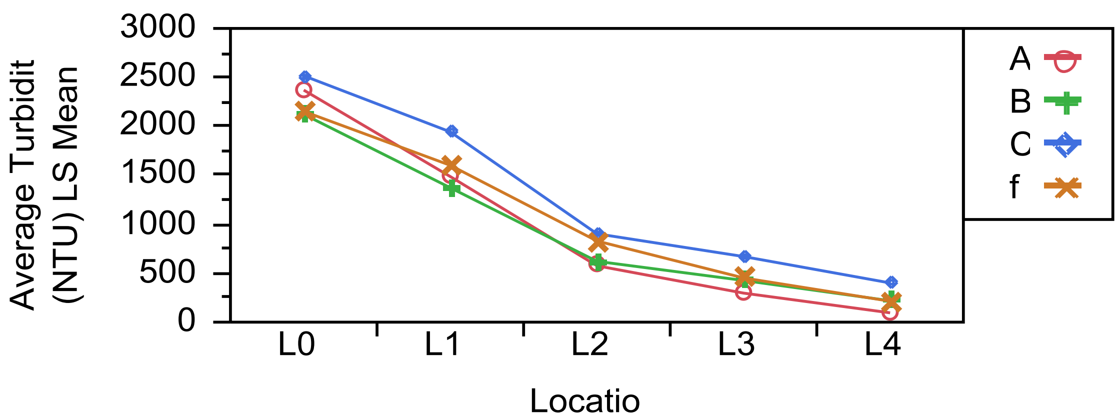

Figure 4.10: LS mean turbidity for each treatment at each location, combined treatments.

Level												**Least Sq Mean**
C,L0	A											2516.1250
A,L0	A	B										2370.0208
f,L0	A	B										2152.5694
B,L0	A	B										2122.5556
C,L1		B	C									1943.2250
f,L1			C	D								1601.6806
A,L1			C	D								1486.6000
B,L1				D	E							1372.4556
C,L2					E	F		H				902.7000
f,L2						F	G					829.1083
C,L3						F	G	H	I	J	K	670.3333
B,L2						F	G	H	I			621.4167
A,L2						F	G	H	I	J		575.9250
f,L3								H	I	J	K	451.9000
B,L3								H	I	J	K	425.8778
C,L4							G		I	J	K	400.4500
A,L3									I	J	K	296.7625
B,L4										J	K	218.7778
f,L4										J	K	214.0806
A,L4											K	95.4083

Figure 4.11: Fisher's LSD test for LS mean turbidity of each combined treatment at each sample location.

The only difference observed within a location was at L1. Mean turbidity for treatment B was lower than treatment "f," as well as the other treatments at L1. This was noted in the discussion of Figure 4.8 and was not considered problematic.

This statistical analysis considered the turbidity reduction of each treatment and compared them all to the first run "f" treatment to determine instances of significant difference. No differences were found which showed a statistically significant drop in turbidity reduction capacity of PAM with respect to reapplication period. All instances of significantly larger values occurred at L0 or L1. These differences were not present at locations further down the channel, after PAM was introduced to the runoff. The lack of meaningful significant difference meant that Figure 4.6, the combined average of all treatments for each location, can be considered a representation of all tests that were conducted. Table 4.5 shows the numeric LS mean turbidity values which make up Figure 4.6 and represent this set of tests. It also compares these results to the research of Berry (2012). His "reapplication" tests involved reapplying PAM prior to each run for five consecutive runs. His "one application" tests involved applying PAM and then running five consecutive runs.

Table 4.5: Overall mean turbidity at each location for this research compared to that of Berry.

	Location				
LS Mean Turbidity [NTU]	L0	L1	L2	L3	L4
Burkey's tests, from Figure 4.6	2290	1601	732	461	232
Berry's test with reapplication	2192	1311	412	202	126
Berry's test with one application	2388	1796	1010	581	289

The tests conducted in this research did not reduce turbidity to the extent that Berry's reapplication tests did. This was likely due to the wait times that were added for this study. Berry's reapplication tests did not involve any prescribed wait time so the PAM had less time to dry and lose efficacy. With more effective PAM in each run, it is not surprising greater turbidity reductions were observed in Berry's study with reapplication. However, this study did reduce turbidity beyond that of Berry's one application tests. This was likely due to the reapplication and accumulation of PAM in the system for this research. Some of it may have dried during the wait times and lost efficacy, but the presence of more total PAM was a reasonable explanation for the greater turbidity reduction.

Turbidity to TSS Relationship

For comparative purposes, samples were analyzed for TSS as well as turbidity. During Berry's research under the same conditions, the following relationship was found with an R^2 value of 0.8856, n = 418.

$$\text{Log(Turbidity)} = -1.42463 + 1.1892181*\text{Log(TSS)}$$

Data from this study were plotted in Figure 4.12. The best fit line was a similar log-log relationship with similar R^2 value.

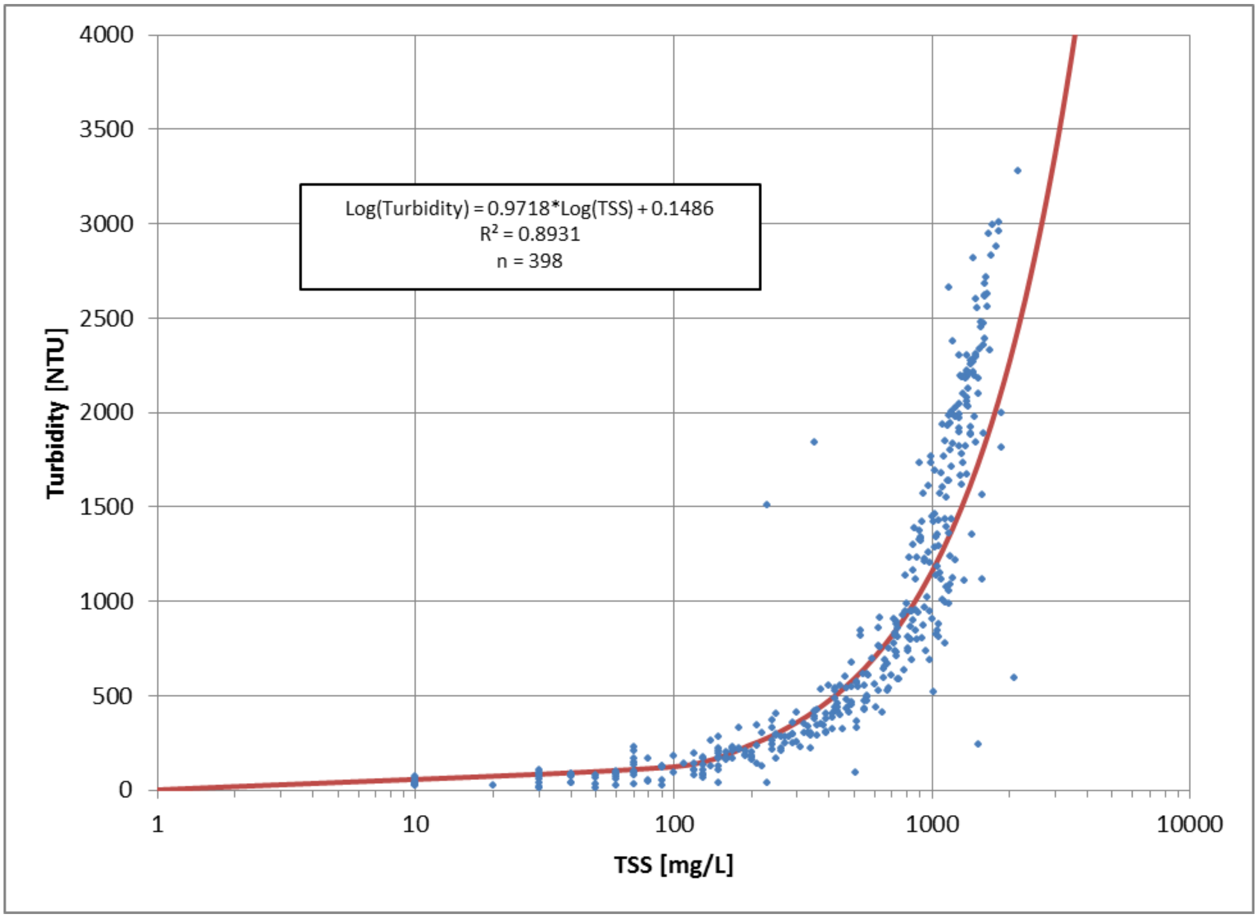

Figure 4.12: Relationship of TSS to turbidity for simulated stormwater runoff samples.

CONCLUSIONS

The statistical results from this chapter indicated that turbidity reduction capacity of PAM when it is first applied is no different than it is after a three-, five-, or ten-day waiting period between reapplication and a runoff event. However, due to limited time and resources, the ten-day trial was only conducted once. The two runs for the ten-day wait period showed the highest effluent turbidities from the channel, 324 and 477 NTU. Though not statistically different from the other tests, this suggests that ten days may be too long to expect PAM will maintain its turbidity reduction capacity. A more conservative recommendation was made to reapply PAM every five days in order to ensure turbidity reduction when a storm comes and a runoff event does occur. The five-day wait time (treatments B2 and B3) was evaluated by three separate tests so its statistical similarity to the first run (treatment "f") was regarded with greater confidence.

The mean turbidities observed in the channel were similar to previous research of Berry (2012) which was conducted under similar conditions. The greater turbidity reduction seen in Berry's tests appeared to be due to the lack of a prescribed waiting period. This effect of desiccation during the waiting period seen by comparing these tests and Berry's tests provides another observation in a research setting which supports the theory that PAM loses efficacy when it gets wet and dries.

CHAPTER FIVE

ENHANCEMENT OF LINEAR SEDIMENT CONTROL BEST MANAGEMENT PRACTICES WITH POLYACRYLAMIDE IN UPSTATE SOUTH CAROLINA

ABSTRACT

Accelerated erosion and highly turbid stormwater runoff from construction sites are known to cause a variety of environmental and economic problems. In order to reduce turbidity and keep eroded sediment on site, this research was conducted to evaluate the potential for turbidity reduction using polyacrylamide flocculants with sediment control best management practices.

Instruments were deployed at the top and bottom of a runoff conveyance channel in order to measure the change to turbidity as runoff traveled through a series of four rock ditch checks (RDCs). The effect on turbidity of RDCs with and without washed #57 stone added to the upstream face was quantified. Granular PAM was applied to both variations of the RDCs and its effect on turbidity was also quantified. Time weighted and flow weighted average turbidities were calculated at each location for each event. Peak turbidity at each location was also observed and considered a parameter of interest. Reductions for each treatment were then calculated.

RDCs alone showed an increase in average turbidity between 116% and 282%. The addition of PAM to RDCs consistently showed a decrease in average turbidity between 12% and 67%. RDCs showed an increase in peak turbidity between 31% and 92%. Peak turbidity was then decreased by the addition of PAM, by between 52% and 82%. RDC-WS showed an increase in average turbidity between 3% and 43% but did not affect peak turbidity in a consistent way. The addition of PAM to RDC-WS did show

a reduction of average turbidity between 51% and 63% and a reduction of peak turbidity by between 48% and 76%.

Based on this research, PAM can be used to reduce turbidity of runoff on construction sites. Turbidity reductions were consistently seen when granular PAM was used with RDC or RDC-WS. However, the extent of the reduction was variable. If reduction to a specific numeric standard is ever necessary or desired, this treatment may or may not be adequate, depending on the standard. Based on the observations made in this study, the specification to reapply granular PAM after every 0.5-inch rain event is effective.

INTRODUCTION

Construction sites frequently experience greatly accelerated rates of erosion due to land disturbance and removal of ground cover. These rates are typically 1,000 to 2,000 times that of forested lands and 10 to 20 times that of agricultural lands (EPA, 2005) and have been estimated to be as high as 35 to 45 tons per acre per year (USGAO, 1998). The impact of accelerated erosion due to construction and land development has been estimated to have a direct cost of over two billion dollars. Much of this cost is associated with damage to water storage, treatment, and conveyance facilities, reduced navigation capacity of waterways, and harm to commercial fisheries. That figure does not attempt to include biological or aesthetic costs (Clark, 1985).

When it rains on bare soil, particles are detached and transported by runoff. Sand particles (diameter between 1 mm and 0.1 mm) settle out in a matter of seconds or minutes, but small colloid particles (dia < 0.0001 mm) can stay in suspension for hundreds of days under natural conditions (McLaughlin and McCaleb, 2014). This means that larger particles are easily removed by conventional sediment control practices, and small particles are very difficult to remove. These small suspended particles cause runoff to have high turbidity, often thousands of Nephelometric Turbidity Units (NTUs). Turbidity is an optical measurement which directly measures light scattered by a water sample. It is common to consider turbidity to be an indirect measurement of suspended matter in a water sample. High turbidity caused by suspended sediment is disruptive to natural systems and harmful to organisms in a variety of ways (EPA, 2012). In order to remove sediment and reduce turbidity, it is necessary to use flocculation.

Flocculation is the process of small particles sticking together to form large particles, or “flocs,” which settle faster and are more easily removed (Auckland Regional Council, 2004). Flocculation is necessary to settle small sediment particles within a reasonable amount of time to prevent them from being transported off construction sites. Anionic polyacrylamide (PAM) is the preferred flocculant material for environmental applications due to low aquatic toxicity and past research which has shown it can be very effective at turbidity reduction (Sojka et al., 2007). Traditional sediment control best management practices (BMPs) in South Carolina are designed to remove 80% of total suspended solids, but are ineffective at reducing turbidity caused by fine suspended particles (Bhardwaj and McLaughlin, 2008, Berry, 2012). Therefore it is desirable and necessary to research how PAM can be used with sediment control BMPs in order to reduce turbidity of stormwater runoff.

The majority of research with PAM has been done in controlled field testing environments at universities and research experiment stations. This is desirable because it enables many factors to be controlled which are otherwise unpredictable. However, it is also necessary to explore how PAM can be integrated into construction site sediment control BMPs under actual site and storm conditions. That is the goal of this study.

In collaboration with the South Carolina Department of Transportation (SCDOT), this research was conducted on a linear construction project on SC Highway 9 in Boiling Springs, SC. Instruments were deployed at the top and bottom of a runoff conveyance channel in order to measure the change to turbidity as runoff traveled through a series of four rock ditch checks (RDCs). The objectives were to do the following at this site, as a representation of the upstate of South Carolina.

1. Evaluate the effect of RDCs on turbidity.
2. Evaluate the effect of RDCs with granular PAM on turbidity.
3. Evaluate the effect of RDCs with washed #57 stone added to the upstream face on turbidity.
4. Evaluate the effect of RDCs with washed #57 stone added to the upstream face and granular PAM on turbidity.

PROCEDURES

Experimental Site

In September of 2013, instrumentation was deployed in a runoff conveyance channel associated with the widening of SC Highway 9 in Boiling Springs, SC. The research channel ran parallel to Holden Drive, which runs perpendicular to and down-grade from Highway 9. The intersection is located at 5636 Boiling Springs Road. This location is shown in Figure 5.1 and Figure 5.2 below.

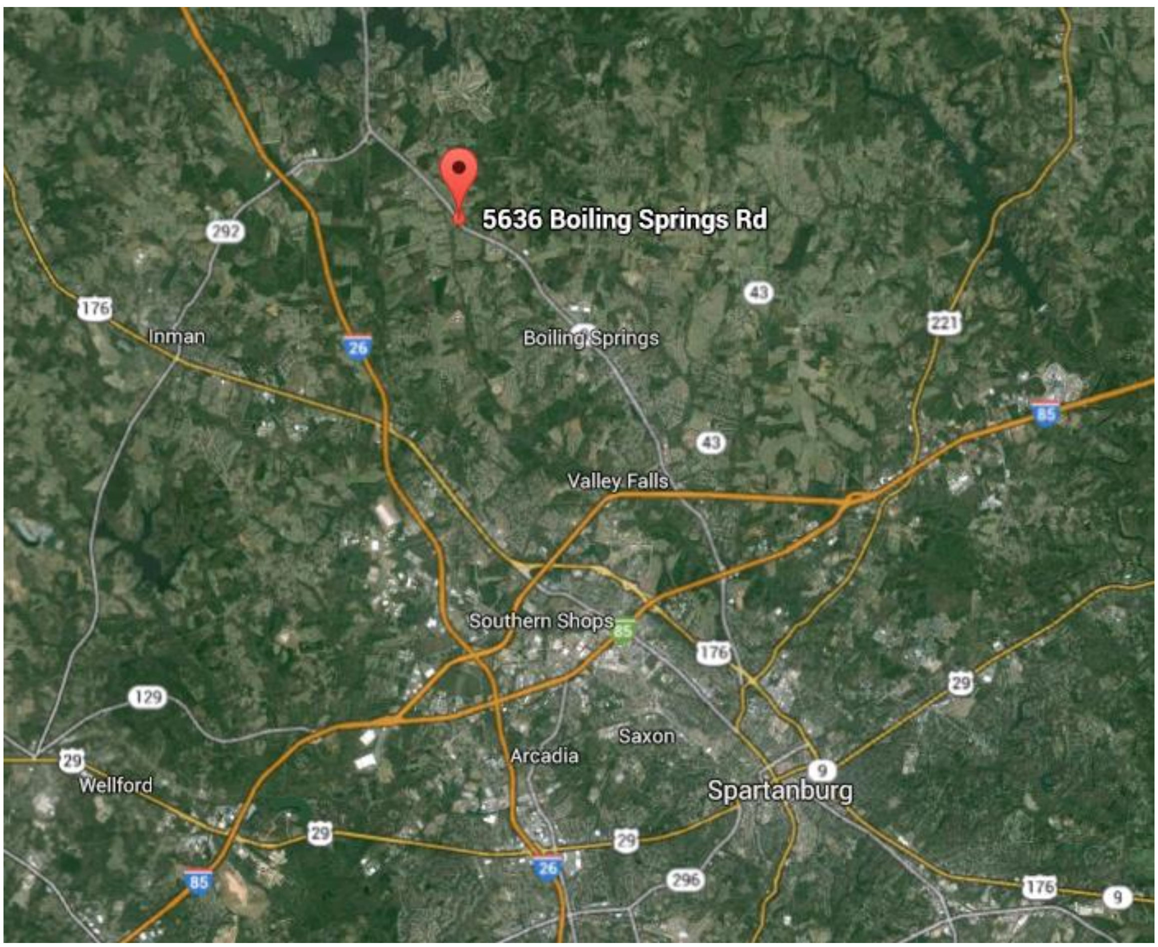

Figure 5.1: Location of experimental site.

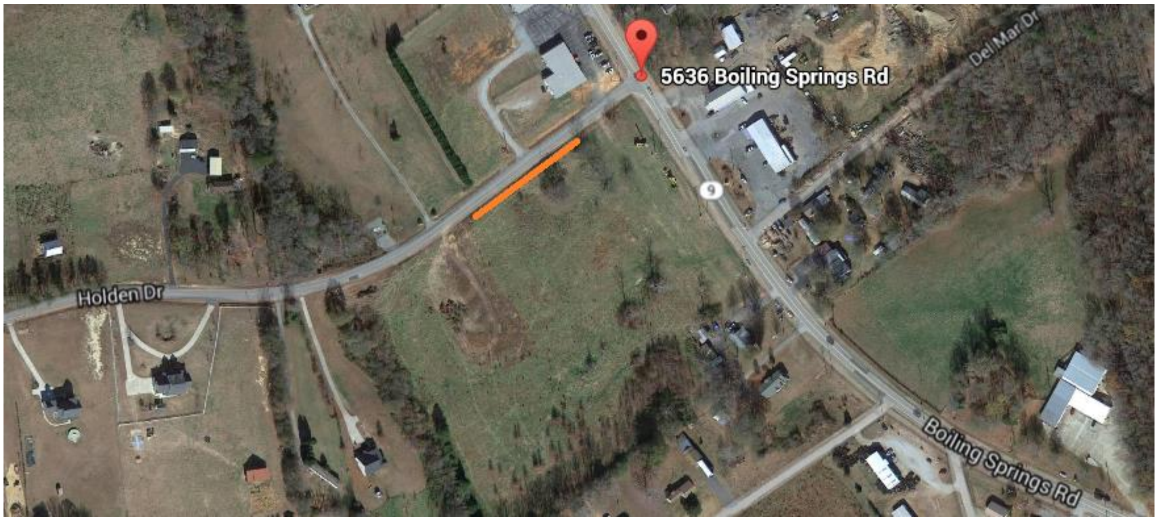

Figure 5.2: Location of experimental site, research channel shown in orange.

The channel had a slope of 5% and then flattened out at the bottom of the hill, before discharging into a sediment basin. The channel was lined with turf reinforcement matting in the center and erosion control blanket on the sides for stabilization. It received runoff that was piped from the project along Highway 9 and discharged through a 30-inch diameter concrete pipe at the top of the channel. The drainage area contributing runoff to the channel was 7 acres, with 2.25 acres of that being the road. Based on the NRCS Web Soil Survey, the area of interest was 90-95% Cecil sandy loam with small areas of other Cecil series soils also present. The sloped portion of the channel contained four rock ditch checks made of Class A rip rap, and the flat part of the channel contained two additional rock ditch checks. Instrument stations were established at the top and bottom of the sloped section, enclosing the first four rock ditch checks as the practices to be researched. The channel is shown in Figure 5.3 from the 30-inch pipe.

Figure 5.3: Research channel with instrumentation.

Instrumentation and Data Collection

Each instrument station consisted of a 6-inch Parshall flume with a Campbell Scientific CS451 pressure transducer to measure flow depth. From this depth, the flow rate through the flume was calculated using the following equation (Teledyne ISCO, 2011).

$$Flow\ [cfs] = 2.060H^{1.580}\ where\ H = head\ [feet]$$

The flumes were installed with 45 degree plywood wing walls. This can be seen in Figure 5.3, above. Installation involved digging into the channel to create a level place for the flume and walls, orienting them correctly, attaching the wing walls, and then backfilling with the excavated material. Also in the flume, a Campbell OBS500 turbidity meter was installed. A Teledyne ISCO 6712 Portable Sampler was installed at each station with its sampler intake anchored to the ground immediately downstream of the flume. Instruments were wired to a Campbell CR206x datalogger for logging and control purposes. These instruments were chosen so that real-time field turbidity data could be recorded and samples could be taken for laboratory analysis.

Data and sample collection was triggered based on presence of runoff through the Parshall flume. When the pressure transducer detected 0.1 feet of water, the turbidity meter started recording observations every minute, and the ISCO Sampler began a time based sampling protocol. The code for this programming can be found in Appendix B. The trigger depth of 0.1 feet was chosen for two reasons. The first is that 0.1 feet of depth in a 6-inch Parshall flume is equivalent to 0.05 cfs of flow and this is the smallest measurement in the recommended flow measurement range for the flume (Teledyne ISCO, 2011). This flow measurement is important for flow weighting calculations as well as general knowledge of the flow conditions in the channel. The second reason is that 0.1 feet of water is enough to expect that the ISCO intake strainer will be submerged and able to pull samples.

The ISCO sampling protocol is shown in Table 5.1 below. Samples of 500 mL were taken when the sampler was enabled and then every five minutes for the first thirty minutes of runoff. After this period, samples were taken every ten minutes. This protocol emphasized catching the “first flush” of sediment from a storm when turbidity is known to be high (Tempel, 2011). It also ensured sampling for the entirety of smaller storm events as well as a substantial initial portion of longer duration storm events. Even when samples were not being collected, real-time turbidity data was always collected when runoff was present in the channel.

Table 5.1: Time based ISCO sampling protocol.

Bottle #	Time Since Enable [min]	Bottle #	Time Since Enable [min]
1	0	13	90
2	5	14	100
3	10	15	110
4	15	16	120
5	20	17	130
6	25	18	140
7	30	19	150
8	40	20	160
9	50	21	170
10	60	22	180
11	70	23	190
12	80	24	200

Figure 5.4 shows the pressure transducer and turbidity probe mounted in the Parshall flume. The original plan was to mount the pressure transducer in the recessed cavity shown in Figure 5.4. However, in this orientation the probe consistently became buried by sediment and gave inaccurate readings. Vertical mounting with a metal bracket prevented this problem. At the top station, it was necessary to move the vertically mounted OBS500 turbidity probe to the downstream section of the flume to prevent its lenses from being buried. Care was taken to mount such that the lenses were facing downstream and had maximum amount of free space in front of them in which to take optical readings. The presence of the probe in the flume was an unavoidable source of

flow disturbance at times of high flow. However, no unusual measurements were observed at high flows that indicated this was an issue. Had such an unusual measurement occurred, the one-minute data interval limited the impact of any individual reading on the overall dataset.

Figure 5.4: Probes mounted in the Parshall flume.

A “base station” was also established at the site to record rainfall and enable telecommunication. This consisted of a Campbell CR1000 datalogger connected to a tipping bucket rain gage, a RF401 radio, and a cellular modem. Programming was established such that one could communicate with the system remotely over the internet using Campbell Loggernet software. Rainfall data was available by connecting to the CR1000 datalogger. Flow rate and turbidity data was available by communicating through the base station to the instrument stations using radio telemetry. Figure 5.5 shows the instrument station at the bottom of the channel which included the base station (white box and large antenna) and rain gage.

Figure 5.5: Instrument station and base station at bottom of the channel.

Background data was collected for runoff events on RDCs with no PAM treatment, followed by a period of PAM application and reapplication to evaluate turbidity reduction using PAM. Each PAM application involved the sprinkling of 100 grams of granular APS #705 PAM on the top and upstream face of the rock ditch check structures, such that runoff was likely to make contact. In February of 2014, washed #57 stone (average diameter approximately ¾-inch) was added to the upstream face of the RDCs so that this practice could be evaluated. After a period of background data collection, PAM was applied in the same manner. Figure 5.6 shows a RDC with washed #57 stone and PAM at the Highway 9 site. The picture was taken from downstream of the RDC.

Figure 5.6: Rock ditch check with washed #57 stone on the upstream face and PAM.

During periods of PAM treatment, PAM was reapplied as soon as possible after rain events which caused runoff and triggered the ISCO samplers. In addition to the reapplication of PAM, regular maintenance involved collecting sample bottles from the ISCO samplers and making sure all instruments were in working order. This included removal of sediment deposits and debris and rinsing of probes. Rinsing of the tip of the pressure transducer and lenses of the OBS500 after storm events was effective at preventing inaccurate “false zero” readings due to sediment accumulation.

Sample Analysis

A Hach 2100AN Laboratory Turbidimeter was used to measure turbidity of all samples following Standard Method 2130 B (APHA, 2005). The Hach has a range up to 10,000 NTUs with the following accuracy specifications (Hach, 2012).

±2% of reading plus 0.01 NTU from 0-1000 NTU
±5% of reading from 1000 NTU to 4,000 NTU
±10% of reading from 4,000 NTU to 10,000 NTU

Each sample was agitated by inverting and shaking the sample bottle for 5 seconds or until sediment was visually evenly suspended. The sample was then transferred into a Hach turbidimeter vial. The vial was then wiped clean, carefully inverted 10 times, and placed into the turbidimeter. After turbidity analysis, samples were analyzed for TSS using Standard Method 2540 B (APHA, 2005).

Statistical Analysis

Due to the relatively small sample size provided by storm events, a combination of descriptive statistics and statistical graphics were utilized to describe apparent trends in the relationship between turbidity parameters, flow characteristics, BMPs, and PAM.

RESULTS AND DISCUSSION

Initial Analysis of Turbidity Data

Turbidity readings were taken using Campbell OBS500 turbidimeters every minute while runoff was present in the channel. This created large datasets which were analyzed in several ways to look at how turbidity related to the addition of granular PAM, the presence of washed stone on the upstream face of the RDCs, and flow characteristics.

In order to perform this analysis, criteria for a "storm event" had to be established. It was difficult to create one clear rule to satisfy all storm events so professional judgment was used in order to establish storm events that most accurately portrayed the relationship of turbidity observations to storm and flow characteristics. This involved the consideration of two factors, the period of rainfall and the period of runoff in the channel.

The first criterion for a storm event was simply the period of time that it rained, inclusive of all readings shown by the rain gage in proximity to the bulk of the rain. This satisfied many events. It did not sufficiently define events which were long in duration with periods of greatly variable intensity. In this case, consideration was given to the period during which runoff occurred. In instances where it rained constantly but with variable intensity for one or more days, distinctly separate runoff events sometimes occurred. When this was the case, the rain contributing to these separate runoff events were considered separate storm events. A final criterion which applied to all storm events was that they must generate 0.1 feet of runoff in the Parhsall flumes in order to trigger data collection. Any rain event which did not generate at least 0.1 feet of runoff was not considered significant for this study.

For each storm event, several parameters were identified and calculated from the turbidity data. Time weighted turbidity was simply an average of the turbidity observations that were recorded. Since observations occurred every minute, they were already weighted evenly on a time basis. The standard of deviation from the time weighted average was calculated to estimate the variability of turbidity during the storm. Flow weighted turbidity was calculated using the following equation.

$$Flow\ Weighted\ Turbidity\ [FNRU] = \frac{\sum(Turbidity\ [FNRU] * Flowrate\ [cfs])}{\sum Flowrate\ [cfs]}$$

This calculation gave an average which gave stronger weight to turbidity values present at times of higher flow. The maximum turbidity was identified by determining the largest observation that was within the range of the instrument (0 to 4,000 NTU). There was one storm where the meter gave four readings above this range. At the recommendation of Campbell Scientific, these readings were noted and treated as 4,000 FNRU (Campbell Scientific, 2013). A calculation of "Max 10%" turbidity was performed by taking the average of the largest 10% of turbidity readings. This gave an estimate of peak turbidity that was a more general representation than the largest value alone. Lastly, the total number of turbidity data points from each instrument station at each storm was noted. Table 5.2 shows an example of these turbidity data parameters for one storm event.

Table 5.2: Example of turbidity parameters calculated for each storm event.

TOP	Turbidity Parameter	FNRUs		**BOTTOM**	Turbidity Parameter	FNRUs	**BMP**
1/11/2014	Average (Time) =	810		1/11/2014	Average (Time) =	286	RDC
1.34"	Std Deviation =	708		1.34"	Std Deviation =	160	w/ PAM
	Average (Flow) =	1048			Average (Flow) =	346	
	Max =	4000			Max =	730	
	10% Max =	2184			10% Max =	610	
	n =	506			n =	536	

Appendix C contains data like that shown in Table 5.2 for all storm events. It also chronologically portrays other relevant events that went on during the study, for example PAM applications and minor changes to the instrumentation.

Turbidity During Storm Events

In order to take a closer look at runoff characteristics and fluctuations in turbidity at the top and bottom of the channel, graphs of turbidity over time were created and plotted with flow rate. A moving average with an interval of three was applied to turbidity and flow data in order to remove the visible minute-to-minute variation in the datasets. Doing this smoothed the lines but did not change the overall shape of any datasets. Datasets from the top and bottom of the channel were displayed on the same graph for comparative purposes. The term "turbidigraph" was established for these illustrations. Turbidigraphs were created for all storms of 0.5 inches or greater for which data was collected at both top and bottom stations. These storms were also referred to as instances of "paired observations" and will be the focus of the majority of this analysis. These paired datasets enable the change in turbidity from top to bottom of the channel to be observed. Figures 5.7 and 5.8 show turbidigraphs for two storms which represent background information for rock ditch checks.

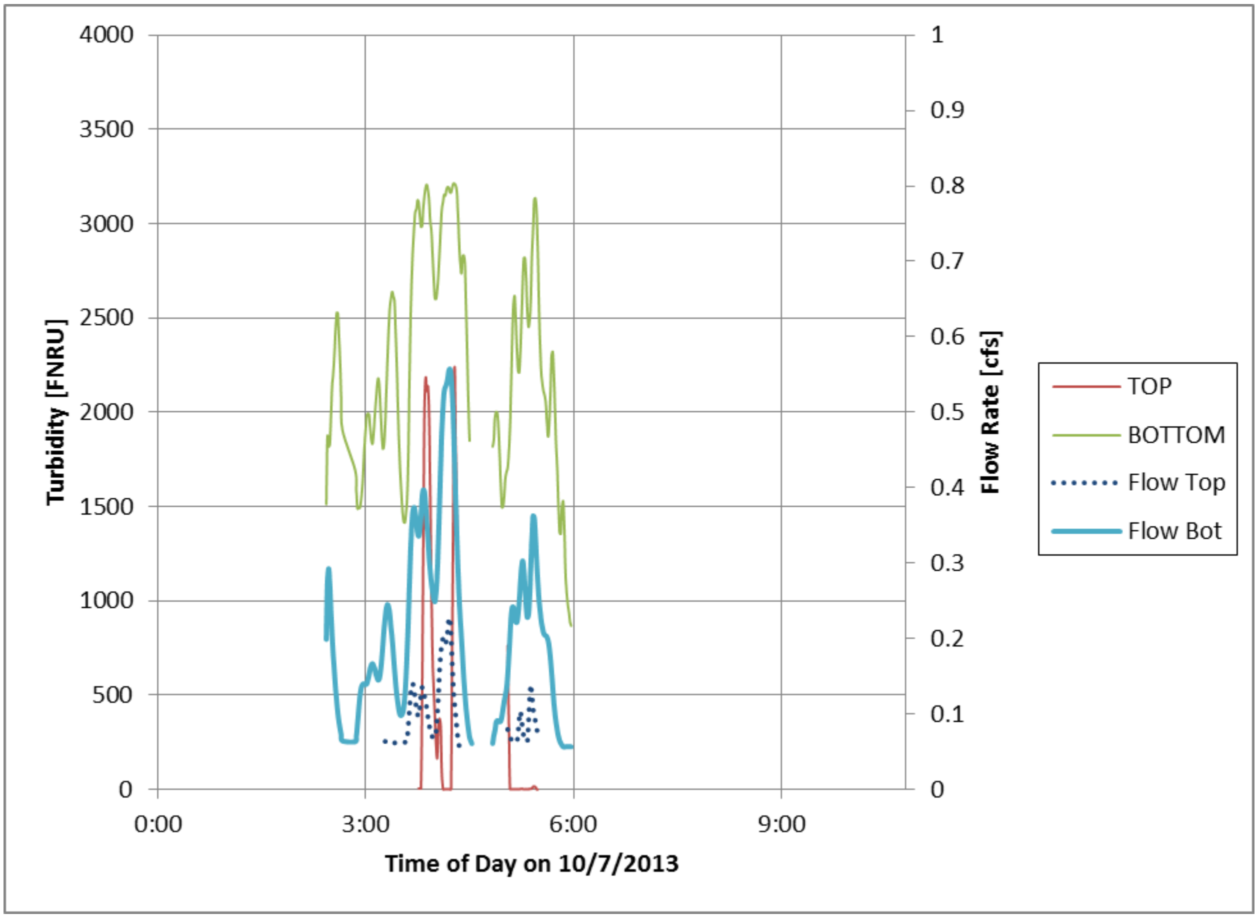

Figure 5.7: Turbidigraph for 2.1-inch storm event on October 7, 2013.

During the October 7th storm event it was clear from the raw dataset that the top station was buried in sediment during portions of the storm. This caused the turbidimeter to return false zero or near zero readings at times that flow was present in the channel, based on the depth measurement in the flume. For this reason, there were flat "false zero" portions in the turbidigraph for the top station in Figure 5.7. After this storm event the turbidimeter was remounted in the downstream part of the flume where it no longer became buried in sediment during storm events. This was an issue at the top station but not the bottom because of the proximity of the top flume to the culvert. There were no sediment control structures between the culvert and the flume so large sediment particles settled out at the entrance to the flume, burying the lenses of the turbidimeter.

The top and bottom datasets for the November 26th storm shown in Figure 5.8 had to be shifted due to a problem with the time stamps of the data points. The fall time change occurred on November 3rd, 2013. In the time between that date and the storm event, one of the loggers had been sent a program update with the new time stamp and the other had not. This was clear due to the unique peaks in flow which were present in the dataset. In order to show the datasets and their relationship to each other most clearly, the data from the top station was shifted forward by one hour. The time stamp problem was fixed and such a shift was not necessary for any other storm events.

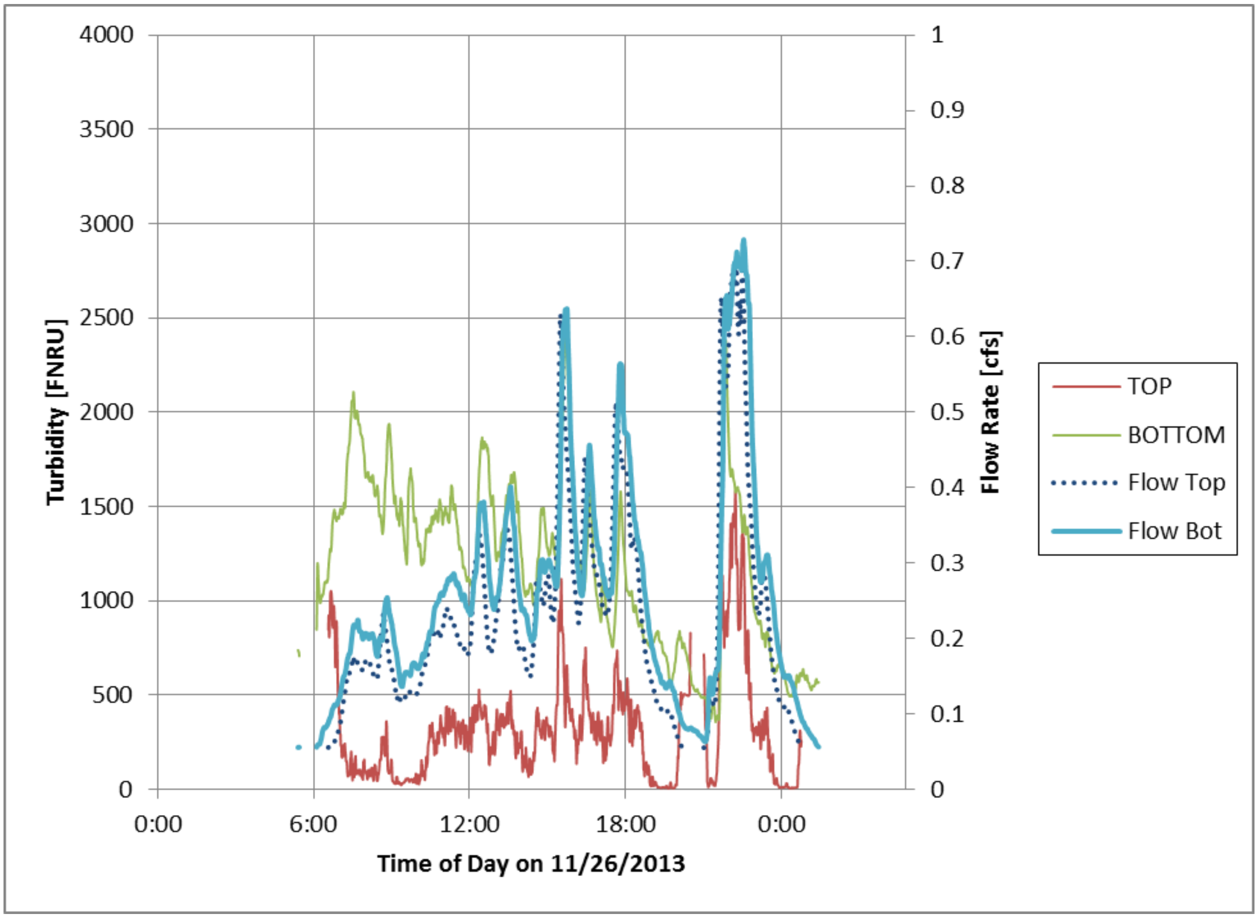

Figure 5.8: Turbidigraph for 3.53-inch storm event on November 26, 2013.

Two important observations were made from Figures 5.7 and 5.8. The most apparent was that turbidity at the bottom of the channel tended to be higher than at the top. Figure 5.8 showed this most clearly due to the long duration of the storm and the elimination of the burying problem at the top station. The October 7th storm had an incomplete dataset at the top station due to sediment burying but still supported the observation since the turbidities present at the top station were lower than turbidities at the bottom station at all times. The other important observation was that the bottom station tended to "turn on," indicating 0.1 feet of water in the flume, earlier than the top station did. This was the case for several storm events seen in the study and was an important realization with respect to dataset analysis of the next two storms.

PAM was applied to the RDCs for the first time on December 4th. The first two storm events that occurred were 0.15 inches on December 7th and 0.28 inches on December 8th. Both of these storms caused a small amount of data to be collected at the bottom station but none at the top station. This was a similar phenomenon to that of the bottom station turning on before the top in previous events. This was attributed to the difference in slope at the stations. The top station was immediately down grade of the culvert and was in the 5% slope channel. The bottom station was further down the channel at a location where the channel was beginning to flatten out. This meant that, for storms of low to moderate initial intensity, runoff was likely to pass the top station quickly and at a low level. That runoff would move more slowly through the bottom station and level in the bottom flume would rise to reach 0.1 feet before level in the top flume. For storms of high initial intensity, the flume levels reached 0.1 feet, and data collection began, at about the same time.

The consecutive days of runoff events continued with 0.49 inches on December 9th and 0.31 inches on December 10th. A turbidigraph was developed for the 0.49-inch event and is shown in Figure 5.9. There was not 0.1 feet of runoff in the channel at all times, so the turbidigraph lines are separated by periods where no data were collected.

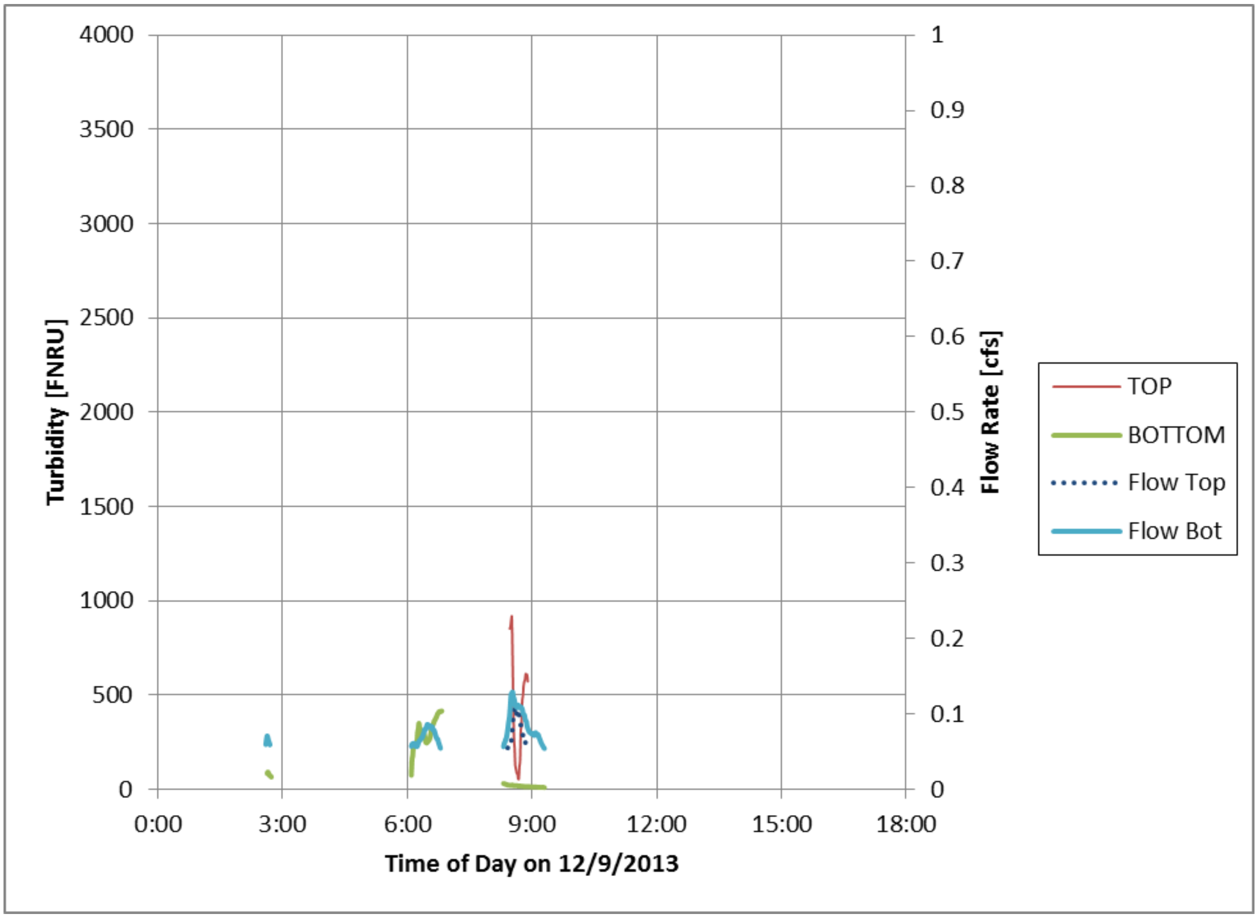

Figure 5.9: Turbidigraph for 0.49-inch storm event on December 9, 2013.

The dataset was small but it was noticeable that the spike in turbidity before 9:00 did not lead to any noticeable spike in turbidity at the bottom. This was an early indication of the impact of PAM treatment seen during future storm events.

On December 14th a rain event of 1.07 inches occurred two days after a PAM application. This would have been a great set of data for analysis except that the top station did not begin recording turbidity numbers until 0.77 cfs was already flowing through the flume. This was an isolated incident of level trigger at 0.1 feet failing to start turbidity data collection. This made overall turbidity analysis difficult and flow weighted analysis impossible. Fortunately, the sampler activated in response to the trigger and pulled samples every 5 minutes for 30 minutes during the period of missing turbidity data. This did not account for the entire range of missing data but did give an indication that there was a period of high turbidity at the top station early in the runoff event. The data from these samples were included in the turbidigraph shown below in Figure 5.10. This is somewhat visually apparent because this region has smoother curves due to the 5-minute data frequency, compared to the 1-minute frequency of real-time turbidity data. The portion of the curve at the top station from 12:24 to 12:54 is the portion approximated using the ISCO samples.

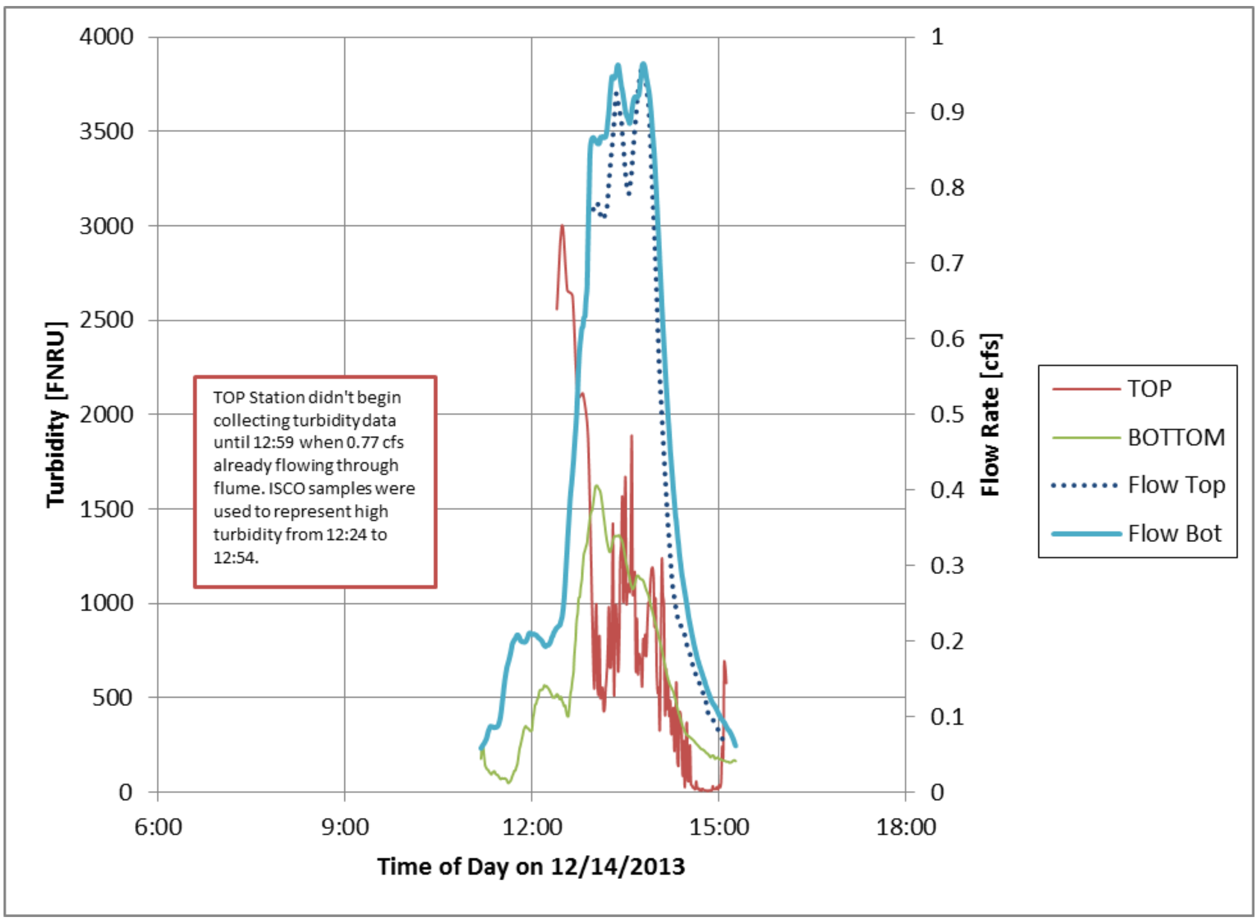

Figure 5.10: Turbidigraph for 1.07-inch storm event on December 14, 2013.

It was important to take note of the incomplete dataset because it would have led to incorrect conclusions about the performance of PAM. The flow weighted and time weighted turbidities of the incomplete real-time dataset for the top station were artificially low because they excluded the first part of the storm, which was high in turbidity. This made it appear that PAM did nothing to treat turbidity and that turbidity was actually higher at the bottom of the channel after PAM treatment than at the top. Inclusion of the ISCO samples showed that this was not true, though the exact level of treatment could not be known with the certainty that a full dataset would provide. In Figure 5.10, the ISCO samples showed that the first portion of the storm was a time of high turbidity. The laboratory turbidity measurements of the ISCO samples were used as data points which represented a time block of five minutes. In this way, time weighted turbidity at the top station was calculated. This best estimate of the turbidity during the storm showed a reduction in time weighted turbidity from top to bottom of the channel (962 FNRU compared to 616 FNRU, time weighted turbidities). The reason for the instrument error which made this analysis necessary was unknown, but the problem did not occur again in this study.

On January 10^{th} and 11^{th}, it rained for the majority of both days, but with two clear instances of high intensity that generated runoff events. Each day had over 0.5 inches of rain and the events were considered separate since there was substantial time (over 16 hours) between the runoff events. Each day and its respective event are shown below in Figures 5.11 and 5.12.

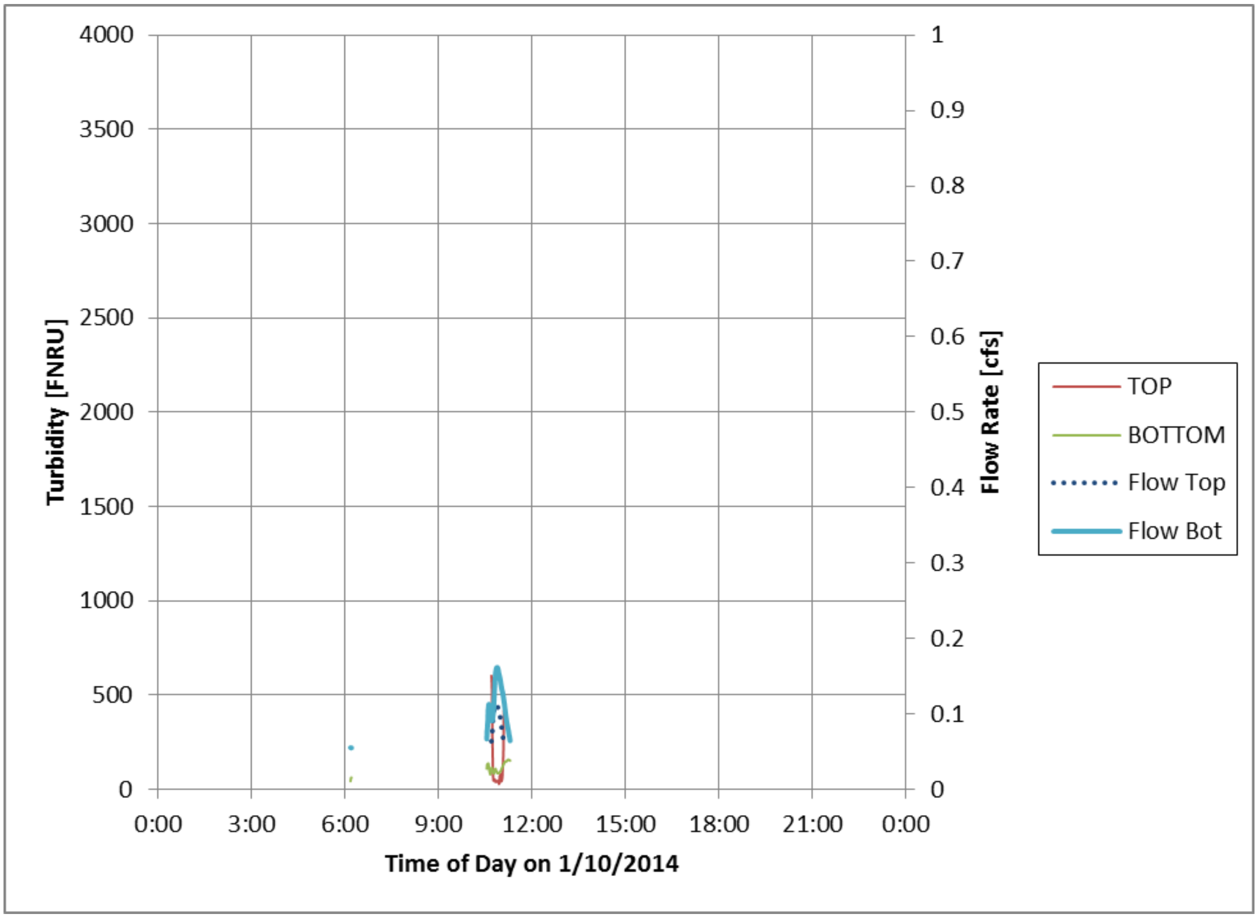

Figure 5.11: Turbidigraph for 0.68-inch storm event on January 10, 2014.

Figure 5.11 provided similar evidence for the effect of PAM on turbidity as did Figure 5.9, which represented the 0.49-inch storm on December 9th. It appeared that PAM in the channel caused peaks of inflow turbidity at the top of the channel to be reduced and not seen at the bottom of the channel. However, both of these turbidity datasets were small because of the characteristics of the storm. The rainfall on January 11th provided a look at PAM treatment during a more intense storm event.

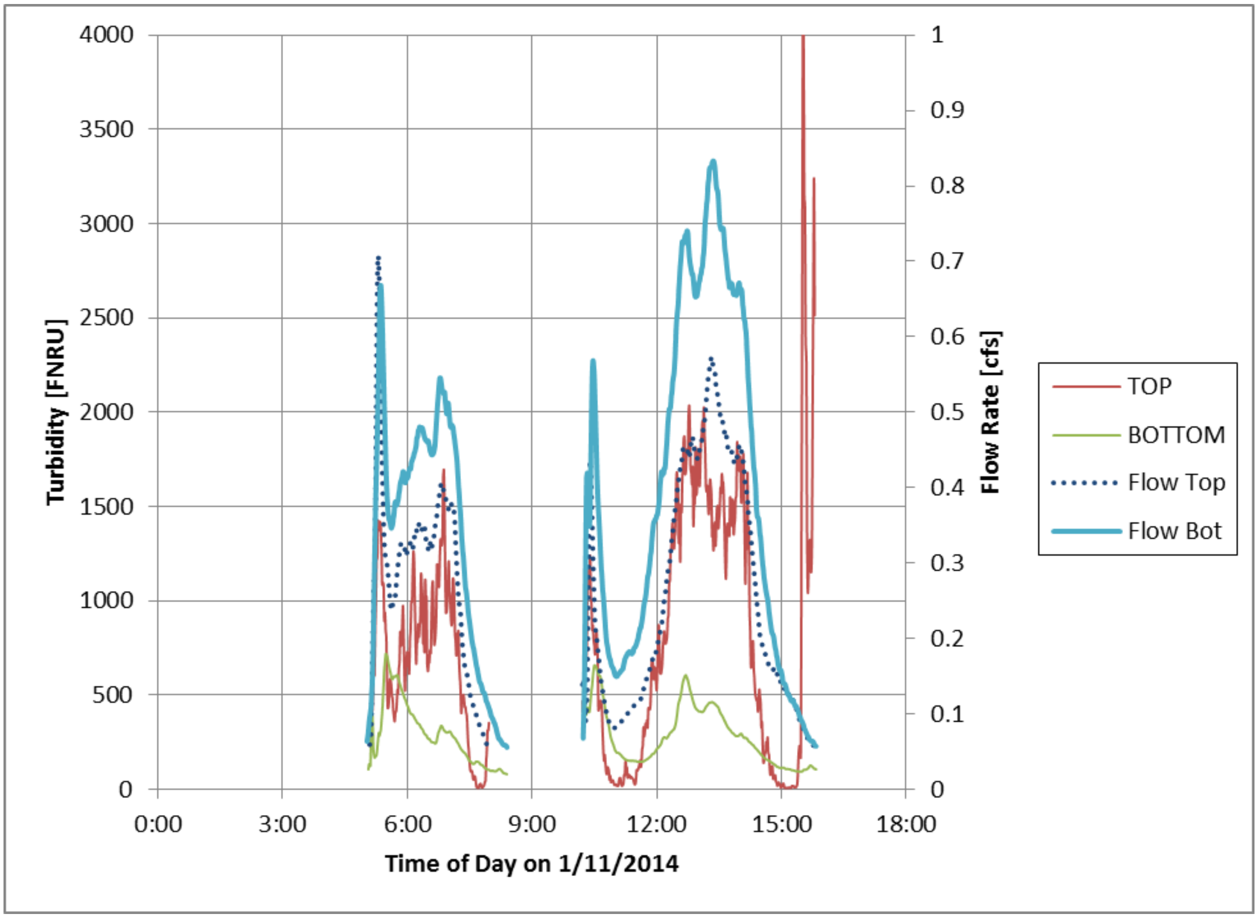

Figure 5.12: Turbidigraph for 1.34-inch storm event on January 11, 2014.

Figure 5.12 provided stronger evidence that PAM reduced turbidity in the channel. The top station experienced peaks of large increases in turbidity with substantial variation in the turbidity from minute to minute. The bottom station showed a response which followed the turbidity influx at the top, but reduced it substantially and showed much less variation. When compared to the background data in Figures 5.7 and 5.8, which showed an increase of turbidity in the channel, the effect of the PAM treatment in Figure 5.12 was even more apparent.

In mid-February the rock ditch check practices were altered by the addition of washed stone, also known as "#57 stone," to the face (RDC-WS) in order to investigate the effect on turbidity of runoff, both with and without PAM. This began with background observations during storms for RDC-WS without PAM. Turbidigraphs from these background storms are shown in Figures 5.13 and 5.14. The storm on February 21st shown in Figure 5.13 was the only instance of observed flows over 1.0 cfs, so its secondary y-axis scale was changed from that of all other turbidigraphs.

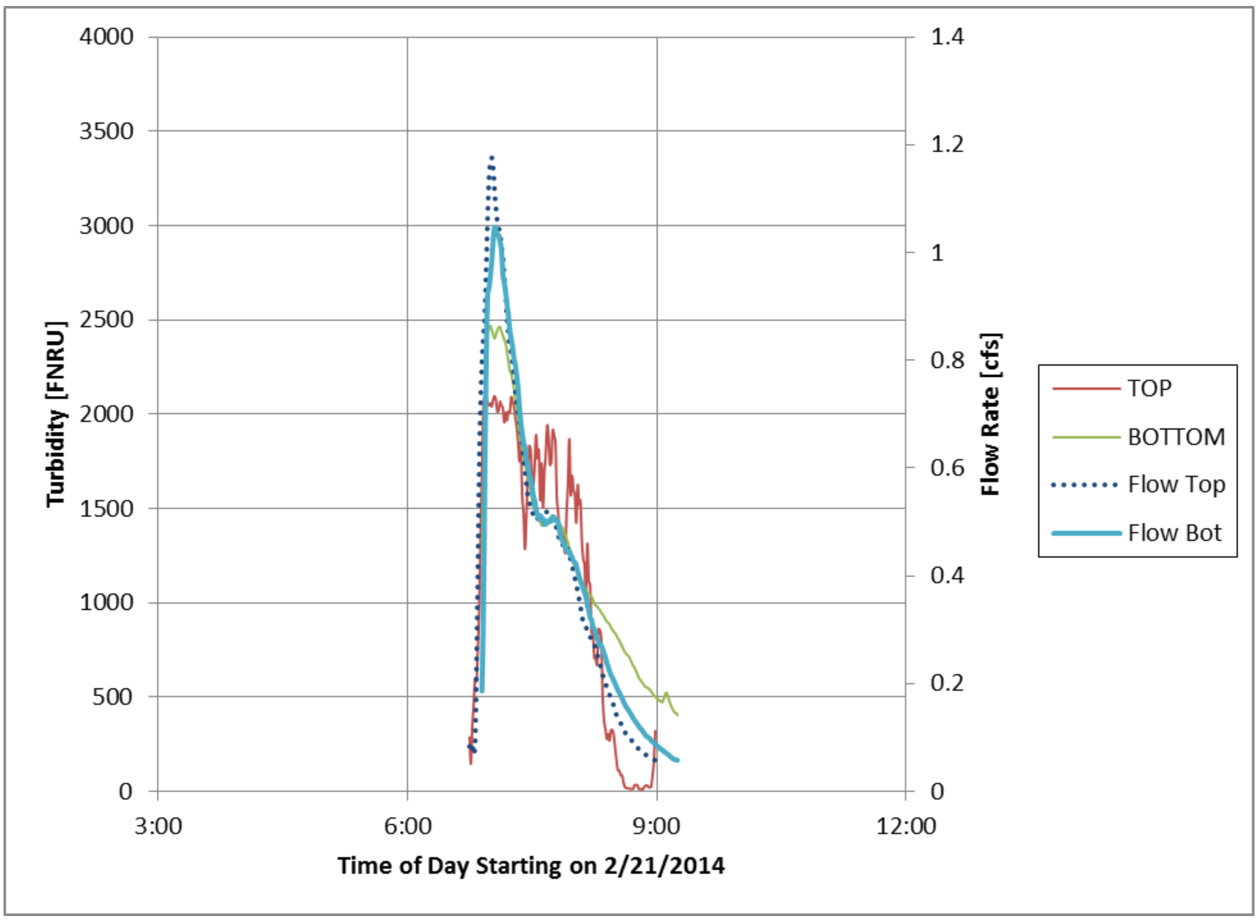

Figure 5.13: Turbidigraph for 0.8-inch storm event on February 21, 2014.

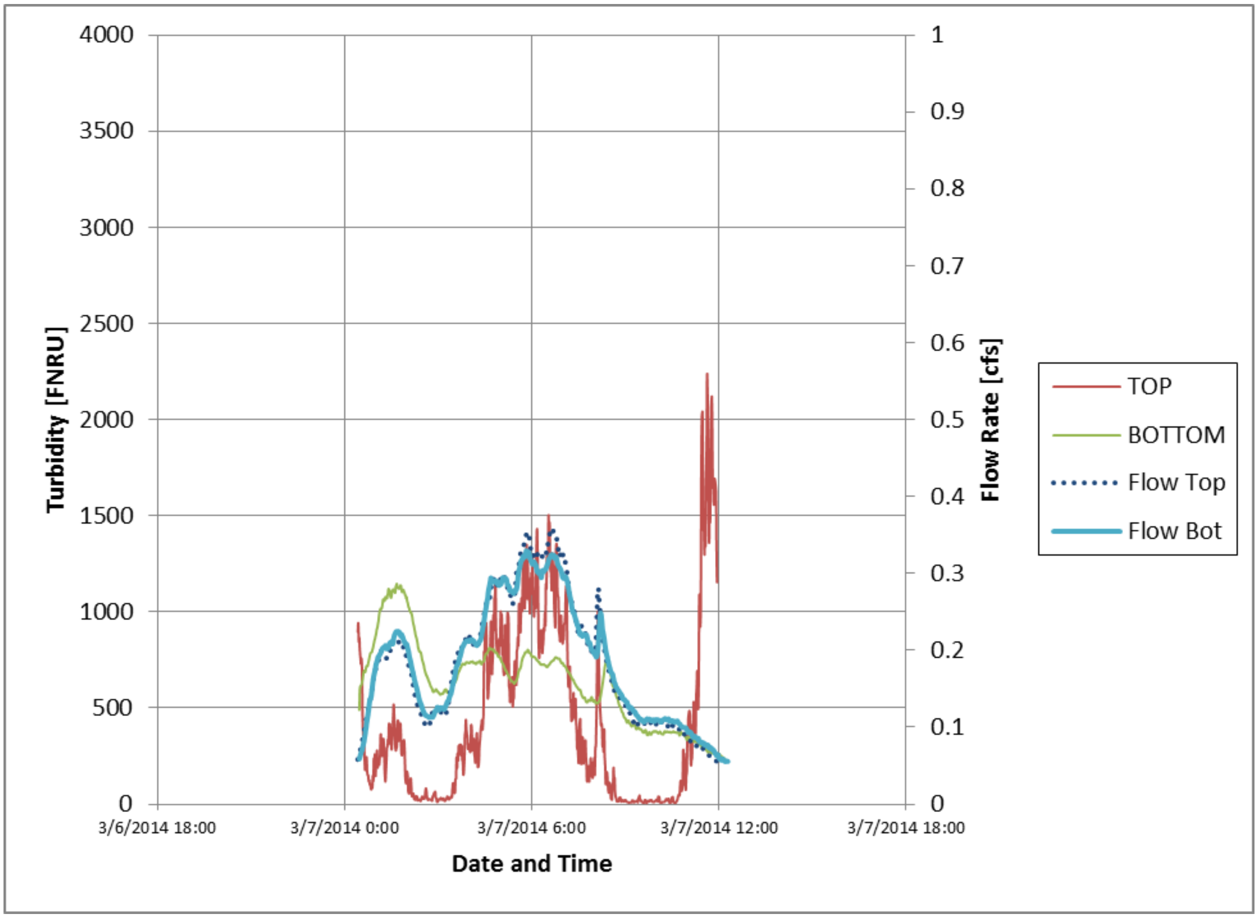

Figure 5.14: Turbidigraph for 1.91-inch storm event on March 7, 2014.

These background storms for the RDC-WS did not show the consistent increase in turbidity from top to bottom that was seen with RDCs alone. This was attributed to less turbulent flow due to the washed stone addition which caused less re-suspension and mixing of sediment particles with the runoff. There also may have been less sediment in the system due to sediment clean-out that occurred when the washed stone was added. The trend of turbidity at the bottom generally following that of the top, but with less variation, continued to be observed for the RDC-WS treatment.

Two storm events representing RDC-WS with PAM occurred on March 16th and April 7th. Their turbidigraphs are respectively shown in Figures 5.15 and 5.16.

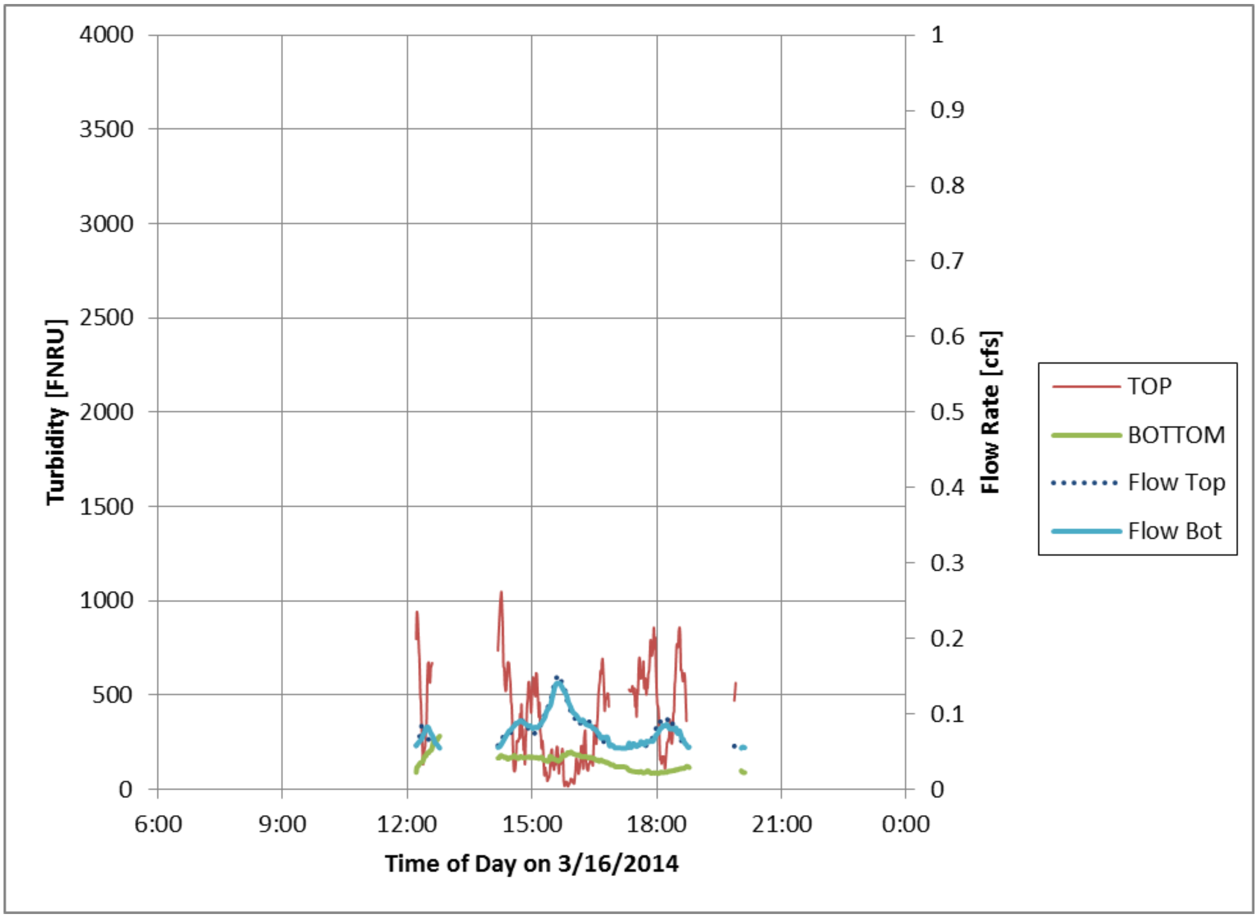

Figure 5.15: Turbidigraph for 1.14-inch storm event on March 16, 2014.

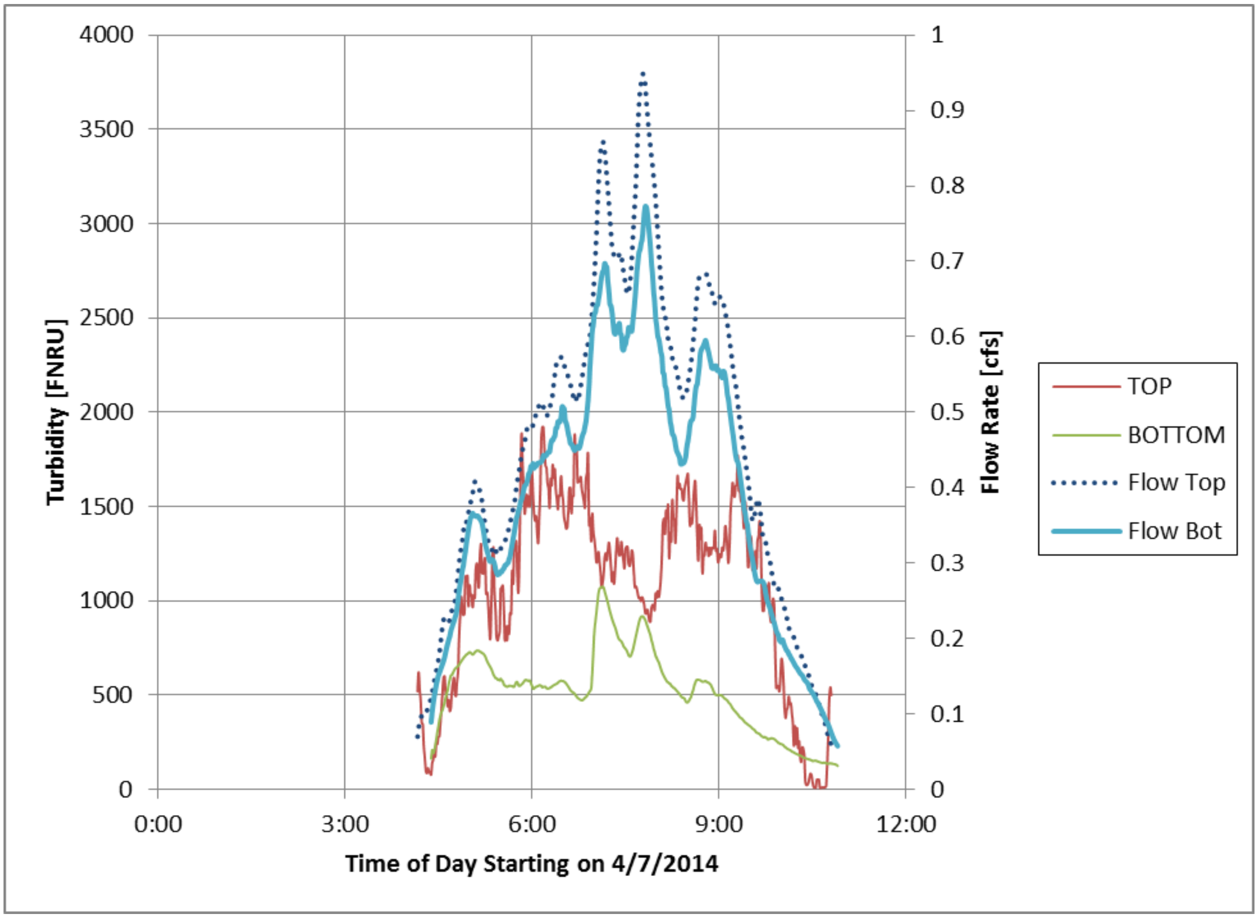

Figure 5.16: Turbidigraph for 2.06-inch storm event on April 7, 2014.

Similar to the RDC treatment with PAM, spikes in influent turbidity were reduced in the channel and not observed at the bottom station. With respect to the smoothing effect, it is important to consider the impact of instrument station location. In this study, the top station received runoff directly from a culvert. If there had been a rock check between the culvert and instrument station, it is possible that this would have caused the top station turbidity to be a smoother curve. Future research projects similar to this should consider instrument location carefully and researchers should keep in mind that any differences, for example BMPs upstream of instruments, will have an impact on results. This concludes the storm by storm turbidigraph analysis. Further analysis was then conducted using the calculated turbidity parameters that were listed in Appendix C.

Analysis of Turbidity Parameters

In order to investigate trends in the effect of PAM on BMPs, several turbidity reduction calculations were performed. Tables 5.3 and 5.4 were created to show a summary of the relevant turbidity parameters which were used in the calculations, for RDC and RDC-WS respectively. Turbidity reduction was measured by a term called "FNRU Red." which was defined as turbidity at the top of the channel minus turbidity at the bottom of the channel, measured in FNRUs. This nomenclature was created in order to concisely label tables of results. A positive "FNRU Red." meant there was a decrease or reduction in turbidity as runoff traveled down the channel. A negative "FNRU Red." meant there was an increase in turbidity as runoff traveled down the channel. Hypothetically, a "FNRU Red." of zero would indicate that turbidity was exactly the same at the bottom of the channel as it was at the top. "FNRU Red." terms were calculated for the time weighted average turbidity, flow weighted average turbidity, peak turbidity, and top 10% peak turbidity. Percent reduction was then calculated as "FNRU Red." divided by the initial turbidity at the top of the channel, and multiplied by 100. These calculations are shown below in Table 5.5 for RDC and Table 5.6 for RDC-WS.

Table 5.3: Summary of turbidity parameters from Appendix C for the rock ditch check (RDC) dataset.

Date	Rainfall [in]	BMP	Location[a]	PAM? (Y/N)	# Days Since Applied	# Storms Since Applied[b]	Rainfall Since Applied [in][c]	Avg FNRU (time)	Standard Deviation	Avg FNRU (flow)	Peak FNRU	Peak FNRU (top 10%)	Number of Observations n =
9/21/2013	3.1	RDC	B	N				2122	744	2411	3210	3029	211
9/25/2013	0.88	RDC	B	N				1355	263	1402	1877	1816	96
10/7/2013	2.1	RDC	T	N				1047	820	1040	2364	2352	22
10/7/2013	2.1	RDC	B	N				2258	622	2547	3242	3186	186
11/26/2013	3.53	RDC	T	N				310	299	443	1845	1019	1049
11/26/2013	3.53	RDC	B	N				1185	443	1317	2421	1953	1168
12/7/2013	0.15	RDC	B	Y	3	0	0.23	37	20	38	57	57	4
12/8/2013	0.28	RDC	B	Y	4	1	0.38	190	70	188	320	299	28
12/9/2013	0.49	RDC	T	Y	5	2	0.66	457	298	395	1039	970	30
12/9/2013	0.49	RDC	B	Y		2	0.66	162	149	142	420	404	89
12/10/2013	0.31	RDC	T	Y	6	3	1.15	213	174	245	707	525	63
12/10/2013	0.31	RDC	B	Y		3	1.15	391	179	451	645	624	61
12/14/2013	1.07	RDC	T	Y	2	0	0	962	602	N/A[d]	3004	N/A[d]	136
12/14/2013	1.07	RDC	B	Y		0	0	616	471	957	1635	1473	248
1/10/2014	0.64	RDC	T	Y	9	0	0.29	158	230	126	848	744	27
1/10/2014	0.64	RDC	B	Y		0	0.29	113	34	111	161	159	49
1/11/2014	1.34	RDC	T	Y	10	1	0.93	810	708	1048	4000	2184	506
1/11/2014	1.34	RDC	B	Y		1	0.93	286	160	346	730	610	536

a: T = top, B = bottom of channel

b: Number of storms leading to runoff events

c: Includes all rainfall, not just rain associated with runoff events

d: Partial dataset, see discussion and turbidigraph

Table 5.4: Summary of turbidity parameters from Appendix C for the rock ditch check with washed stone (RDC-WS) dataset.

Date	Rainfall [in]	BMP	Location[a]	PAM? (Y/N)	# Days Since Applied	# Storms Since Applied[b]	Rainfall Since Applied [in][c]	Avg FNRU (time)	Standard Deviation	Avg FNRU (flow)	Peak FNRU	Peak FNRU (top 10%)	Number of Observations n =
2/21/2014	0.8	RDC-WS	T	N				1124	797	1621	2286	2178	137
2/21/2014	0.8	RDC-WS	B	N				1231	625	1671	2473	2435	144
3/7/2014	1.91	RDC-WS	T	N				438	496	535	2653	1551	692
3/7/2014	1.91	RDC-WS	B	N				627	224	688	1163	1065	711
3/16/2014	1.14	RDC-WS	T	Y	5	0	0.05	390	272	343	1140	899	260
3/16/2014	1.14	RDC-WS	B	Y		0	0.05	146	42	150	283	219	305
4/7/2014	2.06	RDC-WS	T	Y	4	0	0.01	1058	516	1216	2104	1822	401
4/7/2014	2.06	RDC-WS	B	Y		0	0.01	517	223	598	1086	926	394

a: T = top, B = bottom of channel; b: Number of storms leading to runoff events; c: Includes all rainfall, not just rain associated with runoff events

Table 5.5: Turbidity reduction calculations for the rock ditch check (RDC) dataset.

Date	Rain [in]	BMP	Location[a]	PAM? (Y/N)	# Days Since Applied	# Storms Since Applied[b]	Rainfall Since Applied [in][c]	FNRU Red. (Avg, Time)	FNRU Red. (Avg, Flow)	FNRU Red. (Peak)	FNRU Red. (top 10% Peak)	% FNRU Red. (Avg, Time)	% FNRU Red. (Avg, Flow)	% FNRU Red. (Peak)	% FNRU Red. (top 10% Peak)
9/21/2013	3.1	RDC	B	N											
9/25/2013	0.88	RDC	B	N											
10/7/2013	2.1	RDC	T	N				-1211	-1507	-878	-834	-116%	-145%	-37%	-35%
10/7/2013	2.1	RDC	B	N											
11/26/2013	3.53	RDC	T	N				-875	-874	-576	-934	-282%	-197%	-31%	-92%
11/26/2013	3.53	RDC	B	N											
12/7/2013	0.15	RDC	B	Y	3	0	0.23								
12/8/2013	0.28	RDC	B	Y	4	1	0.38								
12/9/2013	0.49	RDC	T	Y	5	2	0.66	295	253	619	566	65%	64%	60%	58%
12/9/2013	0.49	RDC	B	Y		2	0.66								
12/10/2013	0.31	RDC	T	Y	6	3	1.15	-178	-206	62	-99	-84%	-84%	9%	-19%
12/10/2013	0.31	RDC	B	Y		3	1.15								
12/14/2013	1.07	RDC	T	Y	2	0	0	346	N/A[d]	1369	N/A[d]	36%	N/A[d]	46%	N/A[d]
12/14/2013	1.07	RDC	B	Y		0	0								
1/10/2014	0.64	RDC	T	Y	9	0	0.29	45	15	687	585	28%	12%	81%	79%
1/10/2014	0.64	RDC	B	Y		0	0.29								
1/11/2014	1.34	RDC	T	Y	10	1	0.93	524	702	3270	1574	65%	67%	82%	72%
1/11/2014	1.34	RDC	B	Y		1	0.93								

a: T = top, B = bottom of channel

b: Number of storms leading to runoff events

c: Includes all rainfall, not just rain associated with runoff events

d: Partial dataset, see discussion and turbidigraph

Table 5.6: Turbidity reduction calculations for the rock ditch check with washed stone (RDC-WS) dataset.

Date	Rain [in]	BMP	Location[a]	PAM? (Y/N)	# Days Since Applied	# Storms Since Applied[b]	Rainfall Since Applied [in][c]	FNRU Red. (Avg, Time)	FNRU Red. (Avg, Flow)	FNRU Red. (Peak)	FNRU Red. (top 10% Peak)	% FNRU Red. (Avg, Time)	% FNRU Red. (Avg, Flow)	% FNRU Red. (Peak)	% FNRU Red. (top 10% Peak)
2/21/2014	0.8	RDC-WS	T	N				-107	-50	-187	-257	-10%	-3%	-8%	-12%
2/21/2014	0.8	RDC-WS	B	N											
3/7/2014	1.91	RDC-WS	T	N				-189	-153	1490	486	-43%	-29%	56%	31%
3/7/2014	1.91	RDC-WS	B	N											
3/16/2014	1.14	RDC-WS	T	Y	5	0	0.05	244	193	857	680	63%	56%	75%	76%
3/16/2014	1.14	RDC-WS	B	Y		0	0.05								
4/7/2014	2.06	RDC-WS	T	Y	4	0	0.01	541	618	1018	896	51%	51%	48%	49%
4/7/2014	2.06	RDC-WS	B	Y		0	0.01								

a: T = top, B = bottom of channel

b: Number of storms leading to runoff events

c: Includes all rainfall, not just rain associated with runoff events

There was significant variability in the observed turbidity reductions due to a wide variation in storm and flow characteristics. However, observations were made and trends were present which provided insight on the performance of RDC with and without washed stone, and with and without PAM application.

In order to analyze the effect of PAM treatment on turbidity, Figure 5.17 was created. It shows percent turbidity reductions (flow weighted average) plotted against storm size and assigned symbols based on the amount of rain that occurred between PAM application and the storm of interest. Both RDC with and without washed stone were included in Figure 5.17 in order to increase sample size and attempt to evaluate whether PAM treatment made an impact on turbidity reduction. Other figures were created which plotted numeric change in turbidity, instead of percent reduction, and number of runoff events prior to storm of interest, instead of total rainfall. The same general trends were apparent in those figures as can be seen in Figure 5.17. Percent reduction and total rainfall were determined to be the most descriptive datasets. Percent reduction was chosen because it standardized the data and kept the x-axis within the same order of magnitude. Total rainfall was chosen because the number of runoff events omitted information about rain that occurred, but did not cause substantial runoff.

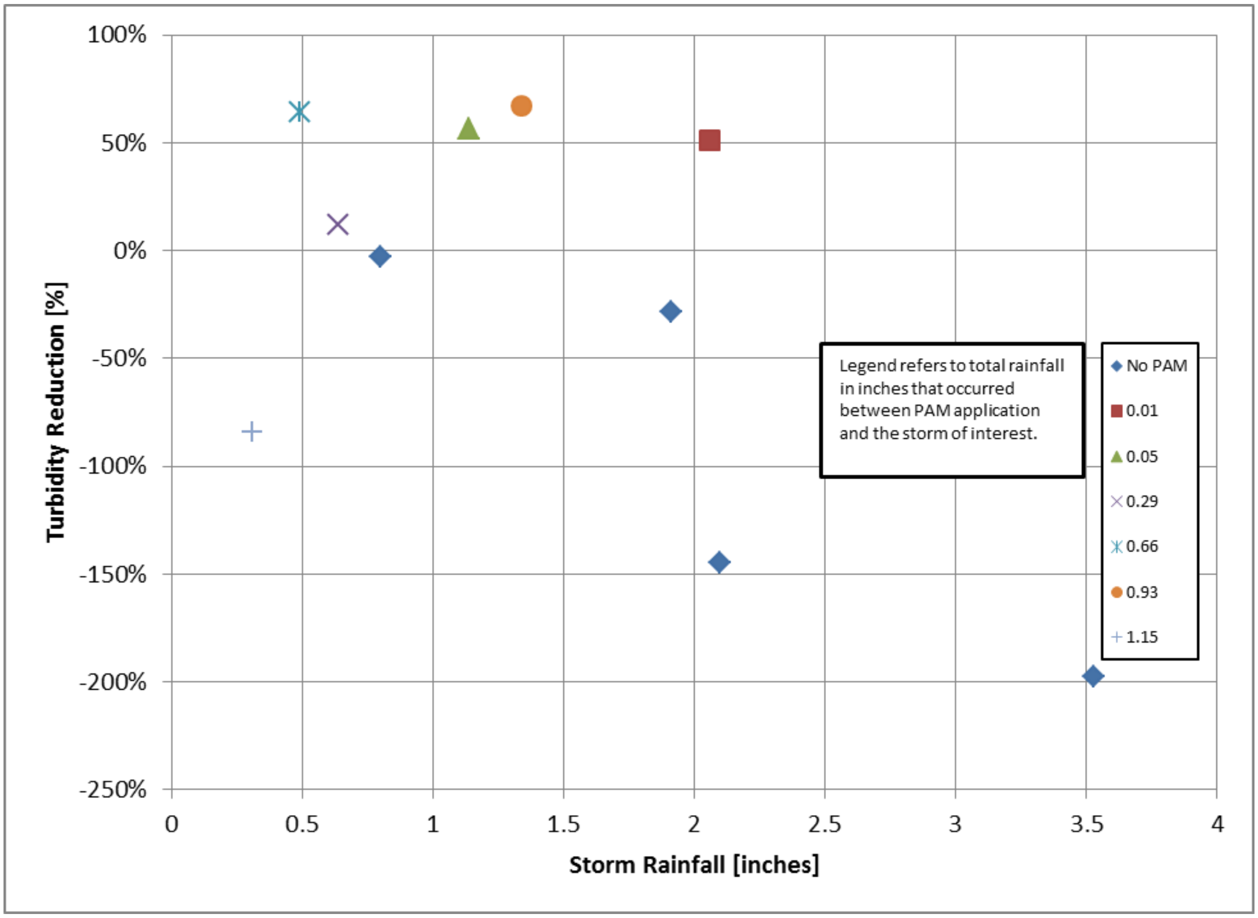

Figure 5.17: Percent turbidity reduction plotted with storm size and rainfall since PAM applied.

Figure 5.17 was useful in making several observations. First, the points of turbidity increase (indicated by negative reduction) were considered. Four of them were associated with storms that had no PAM treatment. The fifth took place during the period of PAM treatment but had experienced 1.15 inches of rainfall and three separate runoff events prior to the event of interest (refer to Table 5.3). Rain had been occurring periodically for several days so the post-rain event trip to the site for PAM reapplication and maintenance had not yet occurred. This storm event confirmed the necessity of PAM reapplication. In further discussion, the results of this storm were omitted from the PAM treatment. After that amount of rain and several runoff events, PAM was no longer present in the system, and the results were not indicative of the performance of PAM.

The points of turbidity reduction all took place during times of PAM application. Unfortunately, many of the PAM application storms were smaller than the background storms. If this were consistently the case, it would be hard to make many meaningful observations. Fortunately, a very useful comparison could be made by considering the three points which lie around the 2-inch storm size, in the middle of Figure 5.17. These three storms had similar size but behaved very differently with respect to turbidity. Considering the information from Tables 5.5 and 5.6, the practices associated with each point were identified. From lowest to highest physical position on Figure 5.16, these points represent RDC, RDC-WS, and RDC-WS with PAM. This suggests that RDC alone cause an increase in turbidity, RDC-WS cause an increase to a lesser extent, and that the addition of PAM was necessary in order to cause turbidity reduction.

For the discussion of reduction ranges, average turbidity will be discussed as a range including both flow and time weighted average turbidities. Peak turbidity will be discussed as a range including both peak and top 10% peak turbidities. As mentioned previously, the storm on December 10th had multiple storms and over an inch of rain between the most recent PAM application and day of storm, so it was not considered to be part of the PAM treatment.

RDC alone showed an increase to average turbidity between 116% and 282% with average final turbidities between 1317 and 2547 FNRU. Peak turbidity increased between 31% and 92% and final peak turbidities were observed between 1816 and 3242

FNRU. This means that RDC showed runoff exiting the channel with at least twice the turbidity that it had entering. This was attributed to the turbulent flow of runoff over rock checks causing re-suspension of fine sediment particles. If a turbidity limit was to be put in place, this behavior of RDC would be very problematic. The addition of PAM to the RDC showed a reduction in average turbidity between 12% and 67% with average final turbidities between 38 and 957 FNRU. Peak turbidity decreased between 46% and 82% with final peak turbidities between 57 and 1635 FNRU.

Reduction calculations for the storm on December 14th, which had an incomplete dataset at the top station (refer to discussion of Figure 5.10), were approached with caution. The reduction of the peak observation was included but calculations which relied on the incomplete top dataset were omitted (average flow weighted turbidity, 10% max peak turbidity). High values from the bottom station for that storm were included in the final observed ranges (957 FNRU average and 1635 FNRU peak) since the dataset from the bottom station was complete and those high numeric turbidities are of interest.

RDC-WS showed an increase in average turbidity between 3% and 43% with average final turbidities between 627 and 1621 FNRU. Peak turbidity varied between an increase of 8% and a decrease of 56% and average final peak turbidities were between 1065 and 2473 FNRU. The addition of PAM showed a decrease in average turbidity between 51% and 63% with final turbidities between 146 and 598 FNRU. Peak turbidity decreased between 48% and 76% with final peak turbidities between 219 and 1086 FNRU.

During this study, PAM was reapplied after periods of rain which caused runoff events. After the fact, this was compared to the specification to reapply after every 0.5-inch rain event which is used in North Carolina by NC State University and NCDOT (McLaughlin et al., 2009; NCDOT, 2013). Observations made support it being an effective rule for reapplying PAM. In December of 2013 there was a period of four consecutive days of rain and small runoff events. PAM had been applied prior to this long period of rain and was not applied again until after it was over. This provided an interesting point of comparison to the 0.5-inch reapplication specification. The first two days were 0.15-inch and 0.28-inch events, respectively. On the third day, 0.49 inches of rain fell, and turbidity reduction was observed. This indicated that effective PAM was still present in the system. This was followed by a 0.31-inch event on the fourth day for which no reduction in turbidity was observed. In fact, an increase in turbidity was seen similar to that of RDC without PAM. It appeared that the 0.49-inch storm event, considered to essentially be 0.5 inches, provided sufficient runoff to utilize all the PAM. Therefore, the 0.5 rule dictated reapplication of PAM at the appropriate time.

Turbidity to TSS Relationship

For comparative purposes, samples were analyzed for TSS as well as turbidity. The results are shown in Figure 5.18. The best fit line was a linear relationship with a slope of 1.1113 and an R^2 value of 0.9417.

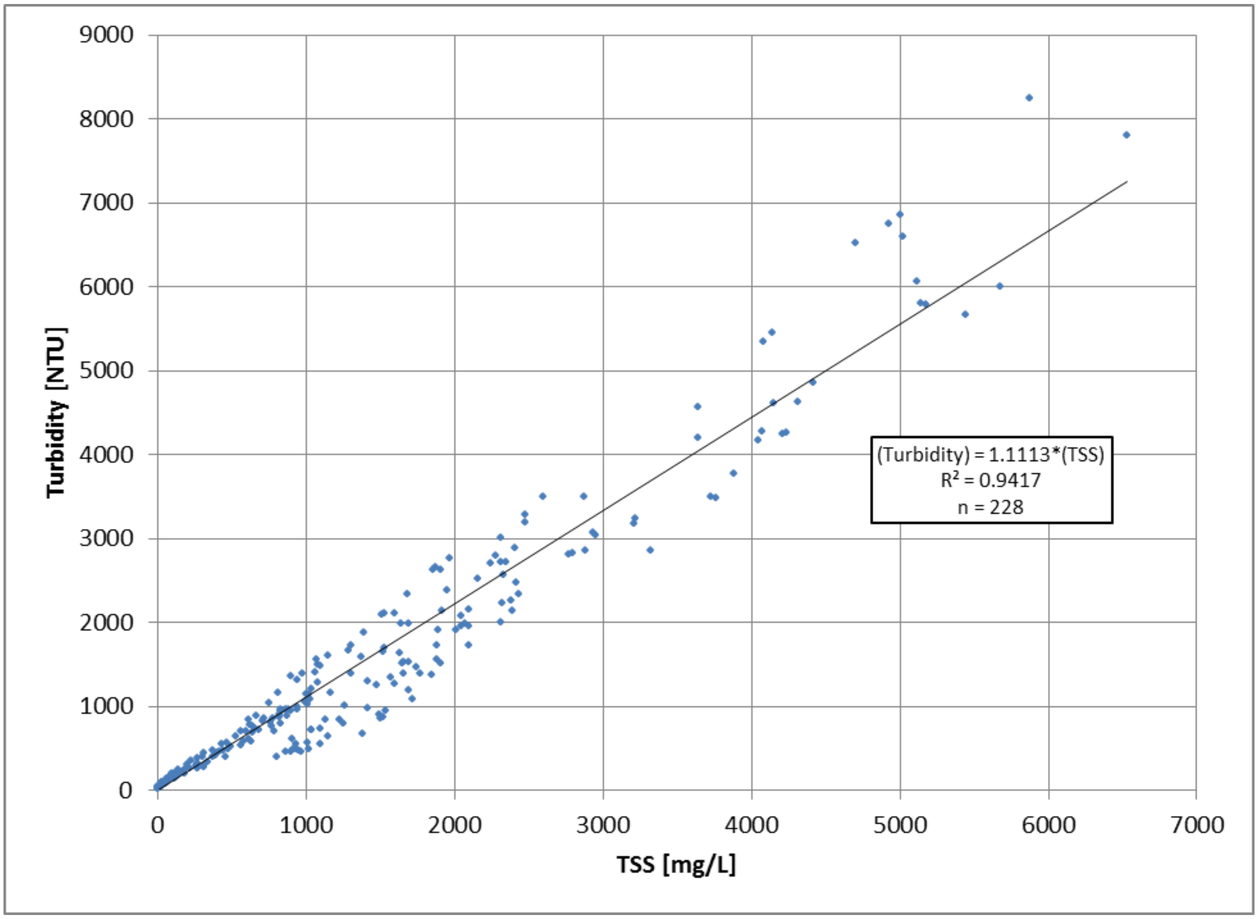

Figure 5.18: Relationship of TSS to turbidity for stormwater samples from the Highway 9 site in Boiling Springs, SC.

CONCLUSIONS

This analysis evaluated the impact on turbidity of rock ditch checks (RDCs) and rock ditch checks with washed #57 stone on the upstream face (RDC-WS), both with and without granular PAM. The results and conclusions should be considered relevant to the Upstate of South Carolina and the representative Cecil series soils present at the site. Statements of turbidity reduction refer to both time and flow weighted average turbidities. Statements with respect to peak turbidities refer to the maximum turbidity deserved as well as an average maximum taken of the top 10% of observations for each storm.

RDC alone showed an increase in turbidity between 116% and 282% with average final turbidities between 1317 and 2547 FNRU. Peak turbidity increased between 31% and 92% across the four RDCs and peak final turbidity values between 1816 and 3242 FNRU were observed. The addition of PAM reduced turbidity across the RDCs, consistently causing turbidity to decrease instead of increase. Average reductions in turbidity for RDC with PAM varied from 12% to 67% with final average turbidities ranging from 38 to 957 FNRU. Peak turbidity was reduced by PAM treatment, varying between 46% and 82% with peak final turbidity values between 57 and 1635 FNRU. A variety of storm sizes, durations, and intensities were observed and were shown in the turbidigraphs that were developed. The wide ranges in observed turbidities were attributed to these variable storms and the runoff flow characteristics.

RDC-WS showed an increase in average turbidity between 3% and 43% with average final turbidities between 627 and 1621 FNRU. Peak turbidity varied between an increase of 8% and a decrease of 56% and average final peak turbidities were between 1065 and 2473 FNRU. The addition of PAM showed a decrease in average turbidity between 51% and 63% with final turbidities between 146 and 598 FNRU. Peak turbidity decreased between 48% and 76% with final peak turbidities between 219 and 1086 FNRU.

Based on this research, the use of PAM on construction sites can reduce turbidity. PAM with either RDC or RDC-WS consistently showed turbidity reductions. However, the extent of both percentage reduction and numeric reduction varied quite a bit based on storm and runoff flow characteristics. Therefore, if it is ever necessary or desired to meet a specific numeric limit, granular PAM applied to RDC or RDC-WS may or may not be adequate to meet such a limit. Downstream sediment traps or ponds could potentially help achieve this goal by giving the runoff additional settling time after PAM is introduced. The observations made during periods of PAM application in this study generally support the reapplication specification used by NCSU and NCDOT, which is to reapply PAM after every 0.5-inch rain event.

CHAPTER SIX

SUMMARY CONCLUSIONS

An evaluation of turbidimeters was performed in order to obtain understanding needed to monitor turbidity of stormwater runoff using a variety of instruments. Most relevant to this study, Campbell OBS500 and Hach 2100 turbidimeters were investigated. The meters gave accurate readings compared to Formazin standard solutions and statistically similar readings to each other. When testing stormwater samples obtained in the field, OBS500 readings were no longer the same as the Hach, but in their shared range of operation (0 to 4,000 NTU) they were related by a power curve relationship with an R^2 value of 0.9283.

The longevity of PAM with respect to turbidity reduction was tested under simulated runoff conditions. Treatments were created such that different periods of time between PAM reapplication to 20-inch excelsior sediment tubes and runoff simulations were evaluated. Statistically, no significant differences in turbidity reduction of PAM were observed between first applications of PAM and PAM which had been reapplied to sediment tubes and endured a three-, five-, or ten-day waiting period before the runoff event. However, the test involving two runs for the ten-day waiting period yielded the two highest mean turbidities of test channel effluent, 342 and 477 NTU. Therefore it was recommended that PAM be reapplied at least once every five days to ensure turbidity reduction when a runoff event occurs.

Research on a South Carolina Department of Transportiation (SCDOT) construction site analyzed, relevant to the Upstate of SC, the impact on turbidity of rock ditch checks (RDCs) and rock ditch checks with washed #57 stone on the upstream face (RDC-WS), both with and without granular PAM. RDCs alone showed an increase in average turbidity between 116% and 282%. The addition of PAM to RDCs consistently showed a decrease in average turbidity between 12% and 67%. RDCs showed an increase in peak turbidity between 31% and 92%. Peak turbidity was then decreased by the addition of PAM, by between 46% and 82%. RDC-WS showed an increase in average turbidity between 3% and 43% but did not affect peak turbidity in a consistent way. The addition of PAM to RDC-WS showed a reduction of average turbidity between 51% and 63% and a reduction of peak turbidity between 48% and 76%.

These observations led to a recommendation of using PAM on construction sites, since PAM consistently caused turbidity reductions to some extent. However, the extent of both percentage reduction and numeric reduction varied based on storm and runoff characteristics. Therefore, if it is ever necessary or desired to meet a specific numeric limit, granular PAM applied to RDC or RDC-WS may or may not be adequate to meet such a limit. Downstream sediment traps or ponds could potentially help achieve this goal by giving the runoff additional settling time after PAM is introduced.

The observations made during this study with respect to reapplication of PAM were considered together in order to make the following suggested specification. When granular PAM is being applied to sediment control structures, it is to be reapplied after every rain event of 0.5 inches or greater. If no such event occurs for 5 calendar days, PAM should be reapplied. All tests in this study involved 100 grams of granular APS #705 PAM, sprinkled on the top and upstream face of each sediment tube or rock check relevant to the research. Based on this study, such a specification should ensure effective PAM is constantly present in order to reduce turbidity of runoff during a storm event.

APPENDICES

Appendix A

Turbidity data collected and environmental parameters recorded for Chapter 4: Longevity of PAM for Turbidity Reduction of Simulated Stormwater

Appendix A contains data relevant to the longevity of PAM for turbidity reduction. Table A.1 contains the raw data with average and percent reduction calculations. Blank spaces within the dataset indicate samples were not taken during that time period. More samples were gathered on some tests due to increased drainage time because of sediment tubes limiting flow. Some samples were missed due to sampling equipment malfunction. Table A.2 summarizes rain and temperature data relevant to the tests.

Table A.1: Turbidity data for PAM longevity analysis.

Wait Time (W.T.)	Test	Run	Treatment	Location	Average Turbidity (NTU)	Percent Red.	Time = 0 min	Time = 4 min	Time = 8 min	Time = 12 min	Time = 16 min	Time = 20 min
A (3 Day)	1	1	f	L0	1897.0	0.0%		2024	1770			
A	1		f	L1	1413.5	25.5%		1450	1377			
A	1		f	L2	942.0	50.3%		929	987	910		
A	1		f	L3	447.8	76.4%	106	308	544	833		
A	1		f	L4	274.3	85.5%		169	296	358		
A	1	2	A2	L0	2832.3	0.0%	3281	3006	2210			
A	1		A2	L1	1702.4	39.9%	1974	2329	1637	1340	1232	
A	1		A2	L2	944.2	66.7%	321	1550	1355	675	820	
A	1		A2	L3	510.4	82.0%	105	735	760	425	527	
A	1		A2	L4	148.6	94.8%	81	212	294	72	84	
A	1	3	A3	L0	2074.3	0.0%	2310	2266	1985	1736		
A	1		A3	L1	1644.0	20.7%		1823	1465			
A	1		A3	L2	802.5	61.3%	735	1237	954	284		
A	1		A3	L3	311.8	85.0%	366		533	172	176	
A	1		A3	L4	72.2	96.5%	223	54	28	29	27	
A	2	1	f	L0	2027.5	0.0%	2102	2193	2126	1689		
A	2		f	L1	1407.0	30.6%	1434	1075	1712			
A	2		f	L2	668.0	67.1%	668					
A	2		f	L3	470.3	76.8%	221	729	389	542		
A	2		f	L4	271.3	86.6%	291	343	215	236		
A	2	2	A2	L0	2485.5	0.0%	2879	2297	2833	1933		
A	2		A2	L1	1047.3	57.9%	687	1052	1890	560		
A	2		A2	L2	170.0	93.2%			329	80	101	
A	2		A2	L3	159.4	93.6%	168	209	250	105	65	
A	2		A2	L4	69.0	97.2%	129	103	58	26	29	
A	2	3	A3	L0	2088.0	0.0%	2394	2034	2189	1735		
A	2		A3	L1	1552.8	25.6%	1117	1671	1822	1601		
A	2		A3	L2	387.0	81.5%	239	605	800	167	124	
A	2		A3	L3	205.5	90.2%	401	253	304	200	40	35
A	2		A3	L4	91.8	95.6%	166	129	133	58	43	22
B (5 Day)	3	1	f	L0	1901.3	0.0%	1889	1816	1999			
B	3		f	L1	1462.3	23.1%	1288	1343	1921	1297		
B	3		f	L2	682.3	64.1%	949	614	574	592		

Wait Time (W.T.)	Test	Run	Treatment	Location	Average Turbidity (NTU)	Percent Red.	Time = 0 min	Time = 4 min	Time = 8 min	Time = 12 min	Time = 16 min	Time = 20 min
B	3		f	L3	383.4	79.8%	550	521	407	244	195	
B	3		f	L4	177.4	90.7%	343	198	138	125	83	
B	3	2	B2	L0	1852.7	0.0%	2080	1680	1798			
B	3		B2	L1	1207.8	34.8%	945	1232	1334	1320		
B	3		B2	L2	531.5	71.3%	412	546	612	556		
B	3		B2	L3	611.0	67.0%	161	1840	420	263	371	
B	3		B2	L4	168.4	90.9%	91	293	208	149	101	
B	3	3	B3	L0	1992.5	0.0%	1973	1832	2224	1941		
B	3		B3	L1	1152.8	42.1%	814	1204	1427	1166		
B	3		B3	L2	366.6	81.6%	446	639	347	219	182	
B	3		B3	L3	158.5	92.0%	302	169	218	92	85	85
B	3		B3	L4	161.8	91.9%	285	210	94	85	72	225
B	4	1	f	L0	2254.7	0.0%	2275	2188	2301			
B	4		f	L1	1962.3	13.0%	1992	1894	2001			
B	4		f	L2	1382.0	38.7%	1147	1135	1636	1610		
B	4		f	L3	815.0	63.9%	637	897	878	848		
B	4		f	L4	368.0	83.7%	421	430	488	331	170	
B	4	2	B2	L0	2116.0	0.0%	1980	1991	2377			
B	4		B2	L1	1142.3	46.0%	795	1208	1424			
B	4		B2	L2	505.0	76.1%	467	479	694	540	345	
B	4		B2	L3	270.0	87.2%	412	374	421	220	103	90
B	4		B2	L4	126.7	94.0%	176	179	174	79	72	80
B	4	3	B3	L0	2415.0	0.0%	2482	2256	2621	2301		
B	4		B3	L1	1844.3	23.6%	1842	1733	2036	1766		
B	4		B3	L2	1078.6	55.3%	990	826	1184	1257	1136	
B	4		B3	L3	754.6	68.8%	739	795	943	692	604	
B	4		B3	L4	422.6	82.5%	473	525	495	336	284	
B	6	1	f	L0	2104.7	0.0%	2338	2057	1919			
B	6		f	L1	1315.0	37.5%	1006	1436	1394	1424		
B	6		f	L2	456.4	78.3%	451	775	818	165	73	
B	6		f	L3	180.2	91.4%	160	353	436	76	33	23
B	6		f	L4	71.8	96.6%	90	123	178	16	10	14
B	6	2	B2	L0	2071.5	0.0%	2452	2216	2045	1573		
B	6		B2	L1	981.4	52.6%	845	1115	1360	1327	260	
B	6		B2	L2	461.0	77.7%	413	689	845	305	53	

Wait Time (W.T.)	Test	Run	Treatment	Location	Average Turbidity (NTU)	Percent Red.	Time = 0 min	Time = 4 min	Time = 8 min	Time = 12 min	Time = 16 min	Time = 20 min
B	6		B2	L3	298.8	85.6%	584	543	473	117	40	36
B	6		B2	L4	164.5	92.1%	381	291	230	40	23	22
B	6	3	B3	L0	2287.7	0.0%	2294	2210	2359			
B	6		B3	L1	1906.3	16.7%	2561	1616	1880	1568		
B	6		B3	L2	785.8	65.7%	992	1122	1220	403	192	
B	6		B3	L3	462.3	79.8%	810	882	804	138	77	63
B	6		B3	L4	268.7	88.3%	440	586	422	89	46	29
C (10 day)	5	1	f	L0	2730.3	0.0%	2555	2598	2950	2818		
C	5		f	L1	2050.0	24.9%	1108	2274	2625	2193		
C	5		f	L2	844.0	69.1%	433	893	1227	1114	553	
C	5		f	L3	414.8	84.8%	245	497	946	459	205	137
C	5		f	L4	121.7	95.5%	85	187	279	79	61	39
C	5	2	C2	L0	2838.8	0.0%	2959	2681	2718	2997		
C	5		C2	L1	2224.2	21.6%	1564	2098	2182	2615	2662	
C	5		C2	L2	812.0	71.4%	528	778	903	946	905	
C	5		C2	L3	607.7	78.6%	326	811	748	865	568	328
C	5		C2	L4	323.5	88.6%	300	377	437	394	223	210
C	5	3	C3	L0	2193.5	0.0%	2469	2181	2188	1936		
C	5		C3	L1	1662.3	24.2%	1353	1665	1780	1851		
C	5		C3	L2	993.4	54.7%	970	1087	1290	763	857	
C	5		C3	L3	733.0	66.6%	875	858	1023	608	301	
C	5		C3	L4	477.4	78.2%	594	712	653	292	136	

Table A.2: Rainfall and temperature data for each test.

Wait Time (W.T.)	Test	Run	Treatment	Location	Average Turbidity (NTU)	Percent Red.	Date of Run	Temp [˚F]	Rain During W.T. [in]	Date of Rain
A (3 Day)	1	1	f	L0	1897.0	0.0%	11/13/2013	50	N/A	
A	1		f	L1	1413.5	25.5%				
A	1		f	L2	942.0	50.3%				
A	1		f	L3	447.8	76.4%				
A	1		f	L4	274.3	85.5%				
A	1	2	A2	L0	2832.3	0.0%	11/16/2013	60	0.16	11/15/2013
A	1		A2	L1	1702.4	39.9%			0.01	11/16/2013
A	1		A2	L2	944.2	66.7%				
A	1		A2	L3	510.4	82.0%				
A	1		A2	L4	148.6	94.8%				
A	1	3	A3	L0	2074.3	0.0%	11/19/2013	52	0.58	11/17/2013
A	1		A3	L1	1644.0	20.7%			0.01	11/18/2013
A	1		A3	L2	802.5	61.3%				
A	1		A3	L3	311.8	85.0%				
A	1		A3	L4	72.2	96.5%				
A	2	1	f	L0	2027.5	0.0%	12/3/2013	55	N/A	
A	2		f	L1	1407.0	30.6%				
A	2		f	L2	668.0	67.1%				
A	2		f	L3	470.3	76.8%				
A	2		f	L4	271.3	86.6%				
A	2	2	A2	L0	2485.5	0.0%	12/6/2013	71	0.29	12/3/2013
A	2		A2	L1	1047.3	57.9%			0.22	12/4/2013
A	2		A2	L2	170.0	93.2%			0.25	12/5/2013
A	2		A2	L3	159.4	93.6%			0.09	12/6/2013
A	2		A2	L4	69.0	97.2%				
A	2	3	A3	L0	2088.0	0.0%	12/9/2013	42	0.21	12/6/2013
A	2		A3	L1	1552.8	25.6%			0.11	12/7/2013
A	2		A3	L2	387.0	81.5%			0.22	12/8/2013
A	2		A3	L3	205.5	90.2%			0.54	12/9/2013
A	2		A3	L4	91.8	95.6%				
B (5 Day)	3	1	f	L0	1901.3	0.0%	1/26/2014	51	N/A	
B	3		f	L1	1462.3	23.1%				
B	3		f	L2	682.3	64.1%				

Wait Time (W.T.)	Test	Run	Treatment	Location	Average Turbidity (NTU)	Percent Red.	Date of Run	Temp [˚F]	Rain During W.T. [in]	Date of Rain
B	3		f	L3	383.4	79.8%				
B	3		f	L4	177.4	90.7%				
B	3	2	B2	L0	1852.7	0.0%	1/31/2014	50	0.04	1/30/2014
B	3		B2	L1	1207.8	34.8%				
B	3		B2	L2	531.5	71.3%				
B	3		B2	L3	611.0	67.0%				
B	3		B2	L4	168.4	90.9%				
B	3	3	B3	L0	1992.5	0.0%	2/5/2014	60	0.01	2/3/2014
B	3		B3	L1	1152.8	42.1%			0.18	2/4/2014
B	3		B3	L2	366.6	81.6%			0.03	2/5/2014
B	3		B3	L3	158.5	92.0%				
B	3		B3	L4	161.8	91.9%				
B	4	1	f	L0	2254.7	0.0%	2/9/2014	60	N/A	
B	4		f	L1	1962.3	13.0%				
B	4		f	L2	1382.0	38.7%				
B	4		f	L3	815.0	63.9%				
B	4		f	L4	368.0	83.7%				
B	4	2	B2	L0	2116.0	0.0%	2/14/2014	48	0.26	2/12/2014
B	4		B2	L1	1142.3	46.0%			0.57	2/14/2014
B	4		B2	L2	505.0	76.1%				
B	4		B2	L3	270.0	87.2%				
B	4		B2	L4	126.7	94.0%				
B	4	3	B3	L0	2415.0	0.0%	2/19/2014	71	0.03	2/16/2014
B	4		B3	L1	1844.3	23.6%				
B	4		B3	L2	1078.6	55.3%				
B	4		B3	L3	754.6	68.8%				
B	4		B3	L4	422.6	82.5%				
B	6	1	f	L0	2104.7	0.0%	3/15/2014	70	N/A	
B	6		f	L1	1315.0	37.5%				
B	6		f	L2	456.4	78.3%				
B	6		f	L3	180.2	91.4%				
B	6		f	L4	71.8	96.6%				
B	6	2	B2	L0	2071.5	0.0%	3/20/2014	70	1.15	3/16/2014
B	6		B2	L1	981.4	52.6%			0.27	3/17/2014
B	6		B2	L2	461.0	77.7%				

Wait Time (W.T.)	Test	Run	Treatment	Location	Average Turbidity (NTU)	Percent Red.	Date of Run	Temp [˚F]	Rain During W.T. [in]	Date of Rain
B	6		B2	L3	298.8	85.6%				
B	6		B2	L4	164.5	92.1%				
B	6	3	B3	L0	2287.7	0.0%	3/25/2014	53	0.15	3/25/2014
B	6		B3	L1	1906.3	16.7%				
B	6		B3	L2	785.8	65.7%				
B	6		B3	L3	462.3	79.8%				
B	6		B3	L4	268.7	88.3%				
C (10 day)	5	1	f	L0	2730.3	0.0%	2/21/2014	51	N/A	
C	5		f	L1	2050.0	24.9%				
C	5		f	L2	844.0	69.1%				
C	5		f	L3	414.8	84.8%				
C	5		f	L4	121.7	95.5%				
C	5	2	C2	L0	2838.8	0.0%	3/3/2014	57	0.66	2/22/2014
C	5		C2	L1	2224.2	21.6%				
C	5		C2	L2	812.0	71.4%				
C	5		C2	L3	607.7	78.6%				
C	5		C2	L4	323.5	88.6%				
C	5	3	C3	L0	2193.5	0.0%	3/13/2014	50	0.08	3/4/2014
C	5		C3	L1	1662.3	24.2%			0.63	3/7/2014
C	5		C3	L2	993.4	54.7%			0.53	3/8/2014
C	5		C3	L3	733.0	66.6%			0.13	3/13/2014
C	5		C3	L4	477.4	78.2%				

Appendix B

Programming for Campbell Scientific instrumentation used in Chapter 5: Enhancement of Linear Sediment Control BMPs with PAM in Upstate SC

Appendix B contains the text from the program run by the CR206x dataloggers during the study. It was written using the "CRBasic Editor" function of Campbell Scientific Loggernet software, with the assistance of Campbell Scientific engineers. When level of water in the flume exceeded 0.1 feet, as indicated by the CS451 pressure transducer, the program began collection of turbidity data using the OBS500 turbidimeter. The logger also sent a signal opening a steady state relay which caused the ISCO sampler to begin a time based sampling protocol. This sampler trigger worked by keeping the trigger pin of the sampler grounded (relay closed) until it was time for sampling, at which point the ground was removed (relay open).

Initially the program was created to include regular movement of the shutter to wipe the lenses clean. However, this mechanism consistently became jammed by sediment particles which made data collection impossible. In the normally dry environment of a runoff conveyance channel, the wiping mechanism was not necessary so that part of the program was "commented out," meaning an apostrophe was put in front of the text to make it a comment and not an active part of the program. This text was left in the program and this appendix because in other applications the wiping mechanism might be useful, for example in a pond where algae growth could be an issue.

```
'CR200/CR200X Series
'Program Karl Lambert

'Modified by Boyd Bringhurst 7/26/2013.  Open and close counts are meaningless since
if it
' repots how far the shutter moves, not its' position.  I commented that logic out and
' put in an open shutter before the program starts to run so that it will start in a known
state.

'This version of the program is set to apply 5 volts to pin F
'of the sampler to enable the sampler program.  The green wire
'is connected to pin F.   Connect the green wire to VX1.  The control
'will enable the sampler when the level rises above 0.1ft and the
'manual control for the sampler (Sampler_Enabled) is >= 1.

'Declare Variables and Units
Public BattV
Public OBS500(9)
Public CS450(2)
Public Enc_RH
Public Sampler_Enabled
Public TimeCounter
```

```
Public obsDatOpen(4),obsDatClose(4)

Public Trigger,Open,Close


Dim i


Units BattV=Volts

Units Enc_RH=%,


Alias CS450(1) = Lvl_ft

Alias CS450(2) = TempC_CS450


Units Lvl_ft = ft

Units TempC_CS450 = deg C



Alias OBS500(1) = turb_bs

Alias OBS500(2) = turb_ss

Alias OBS500(3) = ratio

Alias OBS500(4) = tempC_obs500

Alias OBS500(5) = raw_obs

Alias OBS500(6) = raw_ss

Alias OBS500(7) = open_current
```

```
Alias OBS500(8) = close_current

Alias OBS500(9) = wet_dry


Units turb_bs = fbu

Units turb_ss = fnu

Units ratio = fnru

Units tempC_obs500 = degC

Units raw_obs = volts

Units raw_ss = volts

Units open_current = mA

Units close_current = mA

Units wet_dry = YesNo


'Define Data Tables

DataTable(DataTable,Lvl_ft > Trigger,-1)

  DataInterval(0,1,Min)

  Minimum(1,BattV,False,False)

  Sample (2,CS450())

  Sample (9,OBS500())

  Sample (1,Sampler_Enabled)

  Sample (1,Enc_RH)

EndTable
```

```
'Main Program
BeginProg

  Trigger = 0.1
  ExciteV (Ex1,mV5000)
  SWBatt (1 )
  SDI12Recorder (obsDatOpen(),"0M3!",1.0,0)
  Close = 0
  Open = 1
  obsDatOpen(1) = 20800
  For i = 1 To 9
        OBS500(i) = -99
      Next i

  Scan(1,min)
    'Default Datalogger Battery Voltage measurement 'BattV'
    Battery(BattV)

    'CS450/CS455 Pressure Transducer measurements
    'Lvl_ft' and 'Temp_C_2'
    SDI12Recorder(Lvl_ft,"1M2!",1,0)
```

```
Lvl_ft=Lvl_ft*2.30666

If Lvl_ft > Trigger Then TimeCounter = TimeCounter + 1

If Lvl_ft < (0.9*Trigger) Then TimeCounter = 0


'OBS500 Wiper Control

'If Lvl_ft > Trigger Then

 ' If TimeCounter MOD 60 = 0 Then

  '  SDI12Recorder (obsDatClose(),"0M7!",1.0,0)

   ' SDI12Recorder (obsDatOpen(),"0M3!",1.0,0)

  'EndIf

'EndIf


'OBS500 Smart Turbidity Meter (SDI-12)

'will only sample if the water level is above 0.1 ft.

'Close OBS500 if water level is below needed measurement height

'If Lvl_ft < (0.9*Trigger) AND Close < 0.5Then

 ' SDI12Recorder (obsDatClose(),"0M7!",1.0,0)

 ' If obsDatClose(1) > 20000 Then

  '  Close = 1

   ' Open = 0

'  EndIf

 ' For i = 1 To 9
```

```
  '  OBS500(i) = -99
  'Next i
'EndIf

' If Lvl_ft > Trigger AND Open < 0.5 Then
'  SDI12Recorder (obsDatOpen(),"0M3!",1.0,0)
'  If obsDatOpen(1) > 20000 Then
 '   Close = 0
  '  Open = 1
'  EndIf
'EndIf

If TimeCounter >= 1 Then
  SDI12Recorder(OBS500(),"0M6!",1,0)
EndIf

'CS210 measurement 'Enc_RH'
PortSet(2,1)
VoltSe(Enc_RH,1,1,0.1,0)

'Sampler Control Section
'if the water level rises to 0.1 ft the sampler will be enabled and
```

```
    'and stay enabled.
    If Lvl_ft > Trigger Then  'units of ft
      ExciteV (Ex1,mV0)
    EndIf

    'Call Data Tables and Store Data
    CallTable(DataTable)

  NextScan
EndProg
```

Appendix C

Summary table of runoff events for Chapter 5: Enhancement of Linear Sediment Control Practices with PAM in Upstate SC

Appendix C shows the turbidity parameters for all runoff events of interest as well as relevant changes to the instruments and best management practices in the research channel. The raw data from the instruments would have taken up hundreds of pages, as readings were collected every minute at two instrument stations during runoff events. A description of the calculation of these parameters can be found in the Results and Discussion section of Chapter 5.

Table C.1: Summary table of relevant activities and turbidity parameters for runoff events.

TOP	Turbidity Parameter	FNRUs		BOTTOM	Turbidity Parameter	FNRUs	BMP
9/21/2013	Power failure at TOP			9/21/2013	Average (Time) =	2122	RDC
				3.1"	Std Deviation =	744	
					Average (Flow) =	2411	
					Max =	3210	
					10% Max =	3029	
					n =	211	
9/21/2013	Power failure at TOP			9/25/2013	Average (Time) =	1355	RDC
Switched to dual small battery set up.				0.88"	Std Deviation =	263	
					Average (Flow) =	1402	
					Max =	1877	
					10% Max =	1815	
					n =	96	
10/7/2013	Average (Time) =	1047		10/7/2013	Average (Time) =	2258	RDC
2.1"	Std Deviation =	820		2.1"	Std Deviation =	622	
	Average (Flow) =	1040			Average (Flow) =	2547	
	Max =	2364			Max =	3242	
	10% Max =	2352			10% Max =	3186	
	n =	22			n =	186	
10/24/2013	OBS500 moved to downstream part of flume at TOP to prevent burying by sediment.						
11/26/2013	Average (Time) =	310		11/26/2013	Average (Time) =	1185	RDC
3.53"	Std Deviation =	299		3.53"	Std Deviation =	443	
	Average (Flow) =	443			Average (Flow) =	1317	
	Max =	1845			Max =	2421	
	10% Max =	1019			10% Max =	1954	
	n =	1049			n =	1168	
12/4/2013	PAM was applied to RDC for first time.						

TOP	Turbidity Parameter	FNRUs		BOTTOM	Turbidity Parameter	FNRUs	BMP
12/7/2013				12/7/2013	Average (Time) =	37	RDC
Logical absence of data, small storm.				0.15"	Std Deviation =	20	w/ PAM
					Average (Flow) =	38	
					Max =	57	
					10% Max =	57	
					n =	4	
12/8/2013				12/8/2013	Average (Time) =	190	RDC
Logical absence of data, small storm.				0.28"	Std Deviation =	70	w/ PAM
					Average (Flow) =	188	
					Max =	320	
					10% Max =	299	
					n =	28	
12/9/2013	Average (Time) =	457		12/9/2013	Average (Time) =	162	RDC
0.49"	Std Deviation =	298		0.49"	Std Deviation =	149	w/PAM
	Average (Flow) =	395			Average (Flow) =	142	
	Max =	1039			Max =	420	
	10% Max =	970			10% Max =	404	
	n =	30			n =	89	
12/10/2013	Average (Time) =	213		12/10/2013	Average (Time) =	391	RDC
0.31"	Std Deviation =	174		0.31"	Std Deviation =	179	w/ PAM
	Average (Flow) =	245			Average (Flow) =	451	
	Max =	707			Max =	645	
	10% Max =	525			10% Max =	624	
	n =	63			n =	61	
12/12/2013	PAM reapplied.						
12/14/2103	Average (Time) =	962*		12/14/2013	Average (Time) =	616	RDC
	Std Deviation =	602		1.07"	Std Deviation =	471	w/ PAM
	Average (Flow) =	N/A*			Average (Flow) =	957	
	Max =	3004			Max =	1635	
	10% Max =	N/A*			10% Max =	1473	
	n =	136			n =	248	
*Only partial dataset recorded. See discussion and turbidigraph.							

TOP	Turbidity Parameter	FNRUs		**BOTTOM**	Turbidity Parameter	FNRUs	**BMP**
1/1/2014	PAM reapplied. Replaced dead batteries at BOTTOM.						
1/10/2104	Average (Time) =	158		1/10/2013	Average (Time) =	113	RDC
0.68"	Std Deviation =	230		0.68"	Std Deviation =	34	w/ PAM
	Average (Flow) =	126			Average (Flow) =	111	
	Max =	848			Max =	161	
	10% Max =	744			10% Max =	159	
	n =	27			n =	49	
1/11/2014	Average (Time) =	810		1/11/2014	Average (Time) =	286	RDC
1.34"	Std Deviation =	708		1.34"	Std Deviation =	160	w/ PAM
	Average (Flow) =	1048			Average (Flow) =	346	
	Max =	4000			Max =	730	
	10% Max =	2184			10% Max =	610	
	n =	506			n =	536	
1/13/2014	PAM reapplied.						
1/30/2014	PAM reapplied after snow and winter weather.						
2/20/2014	Power failure at BOTTOM addressed by switching to large battery system.						
	Today started RDC-WS background data collection.						
2/21/2014	Average (Time) =	1124		2/21/2014	Average (Time) =	1231	RDC-WS
0.8"	Std Deviation =	797		0.8"	Std Deviation =	625	
	Average (Flow) =	1621			Average (Flow) =	1671	
	Max =	2286			Max =	2473	
	10% Max =	2178			10% Max =	2435	
	n =	137			n =	144	
3/7/2014	Average (Time) =	438		3/7/2014	Average (Time) =	627	RDC-WS
1.91"	Std Deviation =	496		1.91"	Std Deviation =	224	
	Average (Flow) =	535			Average (Flow) =	688	
	Max =	2653			Max =	1164	
	10% Max =	1551			10% Max =	1065	
	n =	692			n =	711	

TOP	Turbidity Parameter	FNRUs		**BOTTOM**	Turbidity Parameter	FNRUs	**BMP**
3/11/2014	PAM applied to RDC-WS for the first time.						
3/16/2014	Average (Time) =	390		3/16/2014	Average (Time) =	146	RDC-WS
1.14"	Std Deviation =	272		1.14"	Std Deviation =	42	w/ PAM
	Average (Flow) =	346			Average (Flow) =	150	
	Max =	1140			Max =	283	
	10% Max =	899			10% Max =	219	
	n =	260			n =	305	
3/21/2014	PAM reapplied.						
4/3/2014	PAM reapplied.						
4/7/2014	Average (Time) =	1058		4/7/2014	Average (Time) =	517	RDC-WS
2.06"	Std Deviation =	516		2.06"	Std Deviation =	223	w/ PAM
	Average (Flow) =	1216			Average (Flow) =	598	
	Max =	2104			Max =	1086	
	10% Max =	1822			10% Max =	926	
	n =	401			n =	394	

Appendix D

Rainfall data collected for Chapter 5: Enhancement of Linear Sediment Control BMPs with PAM in Upstate SC

Appendix D contains all rainfall data collected at the Boiling Springs, SC SCDOT construction site for the duration of this study. Storms which caused a depth of at least 0.1 feet of runoff were highlighted for emphasis. A cumulative rainfall calculation was also included for these storms. All “zero” readings which were not part of these runoff events were removed. There were three periods of time where power at the rain collection station was lost. One was very brief and no runoff events were missed. Unfortunately, two periods of power failure caused missing data for runoff events. This was determined by the presence of data at the top of the channel but absence of data at the bottom of the channel and rain data. This problem was ultimately solved by using a large marine deep cycle battery instead of a network of smaller batteries. This is highly recommended for future studies. An approximation of the storm size for missed runoff events was included in Table D.1 at the chronological location where they occurred. Theses approximations came from daily rainfall data recorded by SCDOT personnel at the site.

Table D.1: Rainfall data for the duration of the study.

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]	Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
9/20/2013 14:40	START DATA COLLECTION		9/21/2013 19:00	0.07	1.9
			9/21/2013 19:10	0.1	2
9/20/2013 15:10	0.03		9/21/2013 19:20	0.09	2.09
9/20/2013 15:20	0.01		9/21/2013 19:30	0.13	2.22
			9/21/2013 19:40	0.13	2.35
9/21/2013 13:50	0.01	0.01	9/21/2013 19:50	0.14	2.49
9/21/2013 14:00	0	0.01	9/21/2013 20:00	0.17	2.66
9/21/2013 14:10	0	0.01	9/21/2013 20:10	0.09	2.75
9/21/2013 14:20	0	0.01	9/21/2013 20:20	0.14	2.89
9/21/2013 14:30	0	0.01	9/21/2013 20:30	0.08	2.97
9/21/2013 14:40	0	0.01	9/21/2013 20:40	0.06	3.03
9/21/2013 14:50	0	0.01	9/21/2013 20:50	0.03	3.06
9/21/2013 15:00	0	0.01	9/21/2013 21:00	0.04	3.1
9/21/2013 15:10	0.01	0.02			
9/21/2013 15:20	0.01	0.03	9/22/2013 3:10	0.01	
9/21/2013 15:30	0	0.03			
9/21/2013 15:40	0	0.03	9/25/2013 2:50	0.01	0.01
9/21/2013 15:50	0.01	0.04	9/25/2013 3:00	0.01	0.02
9/21/2013 16:00	0.01	0.05	9/25/2013 3:10	0	0.02
9/21/2013 16:10	0.03	0.08	9/25/2013 3:20	0	0.02
9/21/2013 16:20	0.02	0.1	9/25/2013 3:30	0	0.02
9/21/2013 16:30	0.03	0.13	9/25/2013 3:40	0	0.02
9/21/2013 16:40	0.03	0.16	9/25/2013 3:50	0	0.02
9/21/2013 16:50	0.03	0.19	9/25/2013 4:00	0	0.02
9/21/2013 17:00	0.02	0.21	9/25/2013 4:10	0	0.02
9/21/2013 17:10	0.03	0.24	9/25/2013 4:20	0	0.02
9/21/2013 17:20	0.03	0.27	9/25/2013 4:30	0	0.02
9/21/2013 17:30	0.05	0.32	9/25/2013 4:40	0	0.02
9/21/2013 17:40	0.15	0.47	9/25/2013 4:50	0	0.02
9/21/2013 17:50	0.17	0.64	9/25/2013 5:00	0	0.02
9/21/2013 18:00	0.28	0.92	9/25/2013 5:10	0	0.02
9/21/2013 18:10	0.16	1.08	9/25/2013 5:20	0	0.02
9/21/2013 18:20	0.35	1.43	9/25/2013 5:30	0	0.02
9/21/2013 18:30	0.18	1.61	9/25/2013 5:40	0	0.02
9/21/2013 18:40	0.14	1.75	9/25/2013 5:50	0	0.02
9/21/2013 18:50	0.08	1.83	9/25/2013 6:00	0	0.02

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
9/25/2013 6:10	0	0.02
9/25/2013 6:20	0	0.02
9/25/2013 6:30	0	0.02
9/25/2013 6:40	0	0.02
9/25/2013 6:50	0	0.02
9/25/2013 7:00	0	0.02
9/25/2013 7:10	0	0.02
9/25/2013 7:20	0	0.02
9/25/2013 7:30	0	0.02
9/25/2013 7:40	0.01	0.03
9/25/2013 7:50	0	0.03
9/25/2013 8:00	0.01	0.04
9/25/2013 8:10	0.02	0.06
9/25/2013 8:20	0.01	0.07
9/25/2013 8:30	0	0.07
9/25/2013 8:40	0.01	0.08
9/25/2013 8:50	0.03	0.11
9/25/2013 9:00	0.05	0.16
9/25/2013 9:10	0.09	0.25
9/25/2013 9:20	0.06	0.31
9/25/2013 9:30	0.05	0.36
9/25/2013 9:40	0.06	0.42
9/25/2013 9:50	0.06	0.48
9/25/2013 10:00	0.08	0.56
9/25/2013 10:10	0.06	0.62
9/25/2013 10:20	0.05	0.67
9/25/2013 10:30	0.02	0.69
9/25/2013 10:40	0.01	0.7
9/25/2013 10:50	0.01	0.71
9/25/2013 11:00	0.05	0.76
9/25/2013 11:10	0.03	0.79
9/25/2013 11:20	0.02	0.81
9/25/2013 17:20	0.01	
9/25/2013 17:30	0.01	
9/25/2013 17:40	0.01	
9/25/2013 17:50	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
9/25/2013 19:30	0.01	
9/25/2013 20:10	0.01	
9/25/2013 22:00	0.01	
10/7/2013 2:20	0.34	0.34
10/7/2013 2:30	0.06	0.4
10/7/2013 2:40	0.03	0.43
10/7/2013 2:50	0.1	0.53
10/7/2013 3:00	0.07	0.6
10/7/2013 3:10	0.13	0.73
10/7/2013 3:20	0.04	0.77
10/7/2013 3:30	0.13	0.9
10/7/2013 3:40	0.16	1.06
10/7/2013 3:50	0.12	1.18
10/7/2013 4:00	0.21	1.39
10/7/2013 4:10	0.16	1.55
10/7/2013 4:20	0.03	1.58
10/7/2013 4:30	0	1.58
10/7/2013 4:40	0.04	1.62
10/7/2013 4:50	0.05	1.67
10/7/2013 5:00	0.09	1.76
10/7/2013 5:10	0.1	1.86
10/7/2013 5:20	0.11	1.97
10/7/2013 5:30	0.07	2.04
10/7/2013 5:40	0.01	2.05
10/7/2013 5:50	0.02	2.07
10/7/2013 6:00	0	2.07
10/7/2013 6:10	0.01	2.08
10/7/2013 6:20	0	2.08
10/7/2013 6:30	0	2.08
10/7/2013 6:40	0	2.08
10/7/2013 6:50	0	2.08
10/7/2013 7:00	0	2.08
10/7/2013 7:10	0	2.08

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
10/7/2013 7:20	0.01	2.09
10/7/2013 7:30	0	2.09
10/7/2013 7:40	0	2.09
10/7/2013 7:50	0	2.09
10/7/2013 8:00	0	2.09
10/7/2013 8:10	0	2.09
10/7/2013 8:20	0.01	2.1
10/17/2013 13:50	0.02	
10/17/2013 14:10	0.01	
10/17/2013 14:30	0.02	
10/17/2013 14:40	0.03	
10/17/2013 14:50	0.04	
10/17/2013 17:20	0.01	
10/18/2013 7:10	0.01	
10/19/2013 6:30	0.01	
10/28/2013 9:10	0.01	
11/1/2013 8:50	0.01	
11/1/2013 9:20	0.01	
11/1/2013 9:40	0.01	
11/1/2013 10:00	0.01	
11/1/2013 10:10	0.01	
11/1/2013 10:20	0.01	
11/1/2013 10:30	0.02	
11/1/2013 10:40	0.01	
11/1/2013 11:10	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
11/1/2013 11:20	0.01	
11/1/2013 11:30	0.01	
11/2/2013 4:40	0.01	
11/2/2013 15:50	0.01	
11/2/2013 16:00	0.01	
11/2/2013 16:30	0.01	
11/7/2013 9:50	0.01	
11/15/2013 19:20	0.01	
11/15/2013 19:30	0.01	
11/15/2013 19:40	0.01	
11/15/2013 20:30	0.01	
11/15/2013 20:40	0.03	
11/15/2013 20:50	0.03	
11/15/2013 21:00	0.01	
11/15/2013 21:10	0.01	
11/15/2013 21:20	0.01	
11/15/2013 21:30	0.01	
11/15/2013 21:40	0.01	
11/16/2013 3:20	0.01	
11/17/2013 15:20	0.01	
11/17/2013 16:00	0.01	
11/17/2013 16:20	0.06	
11/17/2013 16:30	0.07	
11/17/2013 16:40	0.03	
11/17/2013 17:00	0.01	
11/17/2013 17:10	0.02	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
11/17/2013 17:30	0.01	
11/17/2013 17:40	0.01	
11/17/2013 18:00	0.01	
11/17/2013 18:10	0.02	
11/17/2013 18:20	0.02	
11/17/2013 18:30	0.02	
11/17/2013 18:40	0.01	
11/17/2013 18:50	0.01	
11/17/2013 19:20	0.01	
11/17/2013 19:30	0.01	
11/17/2013 19:40	0.01	
11/17/2013 19:50	0.01	
11/17/2013 20:00	0.04	
11/17/2013 20:10	0.01	
11/17/2013 20:20	0.01	
11/17/2013 21:30	0.01	
11/17/2013 22:10	0.01	
11/17/2013 22:40	0.01	
11/17/2013 23:00	0.03	
11/17/2013 23:20	0.01	
11/17/2013 23:30	0.01	
11/18/2013 0:10	0.01	
11/18/2013 4:20	0.01	
11/21/2013 18:10	0.01	
11/21/2013 20:30	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
11/21/2013 21:00	0.01	
11/21/2013 21:30	0.01	
11/21/2013 22:50	0.01	
11/22/2013 1:40	0.01	
11/26/2013 1:40	0.01	0.01
11/26/2013 1:50	0	0.01
11/26/2013 2:00	0	0.01
11/26/2013 2:10	0	0.01
11/26/2013 2:20	0.01	0.02
11/26/2013 2:30	0	0.02
11/26/2013 2:40	0.01	0.03
11/26/2013 2:50	0.01	0.04
11/26/2013 3:00	0.02	0.06
11/26/2013 3:10	0.02	0.08
11/26/2013 3:20	0.03	0.11
11/26/2013 3:30	0.03	0.14
11/26/2013 3:40	0.02	0.16
11/26/2013 3:50	0.04	0.2
11/26/2013 4:00	0.03	0.23
11/26/2013 4:10	0.04	0.27
11/26/2013 4:20	0.03	0.3
11/26/2013 4:30	0.02	0.32
11/26/2013 4:40	0.02	0.34
11/26/2013 4:50	0.03	0.37
11/26/2013 5:00	0.02	0.39
11/26/2013 5:10	0.03	0.42
11/26/2013 5:20	0.02	0.44
11/26/2013 5:30	0.04	0.48
11/26/2013 5:40	0.02	0.5
11/26/2013 5:50	0.04	0.54
11/26/2013 6:00	0.04	0.58
11/26/2013 6:10	0.04	0.62

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
11/26/2013 6:20	0.05	0.67
11/26/2013 6:30	0.04	0.71
11/26/2013 6:40	0.03	0.74
11/26/2013 6:50	0.04	0.78
11/26/2013 7:00	0.04	0.82
11/26/2013 7:10	0.03	0.85
11/26/2013 7:20	0.04	0.89
11/26/2013 7:30	0.05	0.94
11/26/2013 7:40	0.03	0.97
11/26/2013 7:50	0.03	1
11/26/2013 8:00	0.03	1.03
11/26/2013 8:10	0.01	1.04
11/26/2013 8:20	0.03	1.07
11/26/2013 8:30	0.03	1.1
11/26/2013 8:40	0.03	1.13
11/26/2013 8:50	0.02	1.15
11/26/2013 9:00	0.04	1.19
11/26/2013 9:10	0.03	1.22
11/26/2013 9:20	0.04	1.26
11/26/2013 9:30	0.04	1.3
11/26/2013 9:40	0.03	1.33
11/26/2013 9:50	0.04	1.37
11/26/2013 10:00	0.04	1.41
11/26/2013 10:10	0.04	1.45
11/26/2013 10:20	0.03	1.48
11/26/2013 10:30	0.03	1.51
11/26/2013 10:40	0.03	1.54
11/26/2013 10:50	0.03	1.57
11/26/2013 11:00	0.05	1.62
11/26/2013 11:10	0.05	1.67
11/26/2013 11:20	0.05	1.72
11/26/2013 11:30	0.02	1.74
11/26/2013 11:40	0.02	1.76
11/26/2013 11:50	0.04	1.8
11/26/2013 12:00	0.04	1.84
11/26/2013 12:10	0.05	1.89
11/26/2013 12:20	0.04	1.93

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
11/26/2013 12:30	0.04	1.97
11/26/2013 12:40	0.02	1.99
11/26/2013 12:50	0.02	2.01
11/26/2013 13:00	0.03	2.04
11/26/2013 13:10	0.01	2.05
11/26/2013 13:20	0.04	2.09
11/26/2013 13:30	0.05	2.14
11/26/2013 13:40	0.02	2.16
11/26/2013 13:50	0.04	2.2
11/26/2013 14:00	0.02	2.22
11/26/2013 14:10	0.03	2.25
11/26/2013 14:20	0.09	2.34
11/26/2013 14:30	0.06	2.4
11/26/2013 14:40	0.03	2.43
11/26/2013 14:50	0.01	2.44
11/26/2013 15:00	0.01	2.45
11/26/2013 15:10	0.03	2.48
11/26/2013 15:20	0.06	2.54
11/26/2013 15:30	0.03	2.57
11/26/2013 15:40	0.02	2.59
11/26/2013 15:50	0.02	2.61
11/26/2013 16:00	0.02	2.63
11/26/2013 16:10	0.02	2.65
11/26/2013 16:20	0.03	2.68
11/26/2013 16:30	0.08	2.76
11/26/2013 16:40	0.03	2.79
11/26/2013 16:50	0.03	2.82
11/26/2013 17:00	0.02	2.84
11/26/2013 17:10	0.02	2.86
11/26/2013 17:20	0.02	2.88
11/26/2013 17:30	0	2.88
11/26/2013 17:40	0.01	2.89
11/26/2013 17:50	0.01	2.9
11/26/2013 18:00	0.01	2.91
11/26/2013 18:10	0	2.91
11/26/2013 18:20	0.01	2.92
11/26/2013 18:30	0.02	2.94

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
11/26/2013 18:40	0	2.94
11/26/2013 18:50	0	2.94
11/26/2013 19:00	0.01	2.95
11/26/2013 19:10	0.01	2.96
11/26/2013 19:20	0	2.96
11/26/2013 19:30	0.01	2.97
11/26/2013 19:40	0	2.97
11/26/2013 19:50	0.01	2.98
11/26/2013 20:00	0.03	3.01
11/26/2013 20:10	0.02	3.03
11/26/2013 20:20	0.01	3.04
11/26/2013 20:30	0.1	3.14
11/26/2013 20:40	0.06	3.2
11/26/2013 20:50	0.05	3.25
11/26/2013 21:00	0.05	3.3
11/26/2013 21:10	0.04	3.34
11/26/2013 21:20	0.06	3.4
11/26/2013 21:30	0.03	3.43
11/26/2013 21:40	0.01	3.44
11/26/2013 21:50	0	3.44
11/26/2013 22:00	0	3.44
11/26/2013 22:10	0.04	3.48
11/26/2013 22:20	0.01	3.49
11/26/2013 22:30	0.01	3.5
11/26/2013 22:40	0	3.5
11/26/2013 22:50	0	3.5
11/26/2013 23:00	0.02	3.52
11/26/2013 23:10	0	3.52
11/26/2013 23:20	0	3.52
11/26/2013 23:30	0	3.52
11/26/2013 23:40	0	3.52
11/26/2013 23:50	0.01	3.53
POWER OUT		
12/1/2013 15:30 TO 12/4/2013 12:20		
NO RUNOFF EVENTS MISSED		

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/5/2013 1:40	0.01	
12/5/2013 1:50	0.01	
12/5/2013 2:00	0.01	
12/5/2013 2:10	0.02	
12/5/2013 2:20	0.02	
12/5/2013 2:30	0.01	
12/5/2013 2:40	0.01	
12/5/2013 2:50	0.01	
12/5/2013 3:40	0.01	
12/5/2013 7:50	0.01	
12/5/2013 19:40	0.02	
12/5/2013 19:50	0.01	
12/5/2013 20:00	0.02	
12/5/2013 21:40	0.01	
12/5/2013 23:40	0.02	
12/5/2013 23:50	0.01	
12/6/2013 1:30	0.01	
12/6/2013 11:50	0.01	
12/6/2013 23:10	0.01	0.01
12/6/2013 23:20	0	0.01
12/6/2013 23:30	0.02	0.03
12/6/2013 23:40	0.02	0.05
12/6/2013 23:50	0.02	0.07
12/7/2013 0:00	0.04	0.11
12/7/2013 0:10	0.02	0.13
12/7/2013 0:20	0	0.13
12/7/2013 0:30	0	0.13
12/7/2013 0:40	0.01	0.14
12/7/2013 0:50	0	0.14

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/7/2013 1:00	0	0.14
12/7/2013 1:10	0	0.14
12/7/2013 1:20	0	0.14
12/7/2013 1:30	0	0.14
12/7/2013 1:40	0	0.14
12/7/2013 1:50	0	0.14
12/7/2013 2:00	0	0.14
12/7/2013 2:10	0	0.14
12/7/2013 2:20	0	0.14
12/7/2013 2:30	0	0.14
12/7/2013 2:40	0	0.14
12/7/2013 2:50	0	0.14
12/7/2013 3:00	0	0.14
12/7/2013 3:10	0	0.14
12/7/2013 3:20	0	0.14
12/7/2013 3:30	0	0.14
12/7/2013 3:40	0.01	0.15
12/8/2013 5:50	0.01	0.01
12/8/2013 6:00	0	0.01
12/8/2013 6:10	0	0.01
12/8/2013 6:20	0	0.01
12/8/2013 6:30	0	0.01
12/8/2013 6:40	0	0.01
12/8/2013 6:50	0.01	0.02
12/8/2013 7:00	0	0.02
12/8/2013 7:10	0	0.02
12/8/2013 7:20	0	0.02
12/8/2013 7:30	0.01	0.03
12/8/2013 7:40	0	0.03
12/8/2013 7:50	0.07	0.1
12/8/2013 8:00	0.06	0.16
12/8/2013 8:10	0.04	0.2
12/8/2013 8:20	0	0.2
12/8/2013 8:30	0	0.2
12/8/2013 8:40	0.01	0.21
12/8/2013 8:50	0	0.21

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/8/2013 9:00	0	0.21
12/8/2013 9:10	0	0.21
12/8/2013 9:20	0	0.21
12/8/2013 9:30	0	0.21
12/8/2013 9:40	0	0.21
12/8/2013 9:50	0	0.21
12/8/2013 10:00	0	0.21
12/8/2013 10:10	0	0.21
12/8/2013 10:20	0	0.21
12/8/2013 10:30	0	0.21
12/8/2013 10:40	0.01	0.22
12/8/2013 10:50	0	0.22
12/8/2013 11:00	0	0.22
12/8/2013 11:10	0	0.22
12/8/2013 11:20	0	0.22
12/8/2013 11:30	0	0.22
12/8/2013 11:40	0	0.22
12/8/2013 11:50	0	0.22
12/8/2013 12:00	0	0.22
12/8/2013 12:10	0	0.22
12/8/2013 12:20	0	0.22
12/8/2013 12:30	0	0.22
12/8/2013 12:40	0	0.22
12/8/2013 12:50	0	0.22
12/8/2013 13:00	0	0.22
12/8/2013 13:10	0	0.22
12/8/2013 13:20	0	0.22
12/8/2013 13:30	0.01	0.23
12/8/2013 13:40	0.01	0.24
12/8/2013 13:50	0	0.24
12/8/2013 14:00	0.01	0.25
12/8/2013 14:10	0	0.25
12/8/2013 14:20	0.01	0.26
12/8/2013 14:30	0	0.26
12/8/2013 14:40	0	0.26
12/8/2013 14:50	0.01	0.27
12/8/2013 15:00	0	0.27

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/8/2013 15:10	0	0.27
12/8/2013 15:20	0	0.27
12/8/2013 15:30	0	0.27
12/8/2013 15:40	0	0.27
12/8/2013 15:50	0	0.27
12/8/2013 16:00	0	0.27
12/8/2013 16:10	0	0.27
12/8/2013 16:20	0	0.27
12/8/2013 16:30	0	0.27
12/8/2013 16:40	0	0.27
12/8/2013 16:50	0	0.27
12/8/2013 17:00	0	0.27
12/8/2013 17:10	0	0.27
12/8/2013 17:20	0	0.27
12/8/2013 17:30	0	0.27
12/8/2013 17:40	0	0.27
12/8/2013 17:50	0	0.27
12/8/2013 18:00	0	0.27
12/8/2013 18:10	0	0.27
12/8/2013 18:20	0	0.27
12/8/2013 18:30	0	0.27
12/8/2013 18:40	0	0.27
12/8/2013 18:50	0	0.27
12/8/2013 19:00	0	0.27
12/8/2013 19:10	0	0.27
12/8/2013 19:20	0	0.27
12/8/2013 19:30	0.01	0.28
12/9/2013 1:10	0.01	0.01
12/9/2013 1:20	0	0.01
12/9/2013 1:30	0	0.01
12/9/2013 1:40	0	0.01
12/9/2013 1:50	0	0.01
12/9/2013 2:00	0	0.01
12/9/2013 2:10	0	0.01
12/9/2013 2:20	0.02	0.03
12/9/2013 2:30	0.05	0.08

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/9/2013 2:40	0.02	0.1
12/9/2013 2:50	0	0.1
12/9/2013 3:00	0	0.1
12/9/2013 3:10	0.03	0.13
12/9/2013 3:20	0.01	0.14
12/9/2013 3:30	0	0.14
12/9/2013 3:40	0	0.14
12/9/2013 3:50	0	0.14
12/9/2013 4:00	0	0.14
12/9/2013 4:10	0	0.14
12/9/2013 4:20	0	0.14
12/9/2013 4:30	0	0.14
12/9/2013 4:40	0	0.14
12/9/2013 4:50	0.01	0.15
12/9/2013 5:00	0.01	0.16
12/9/2013 5:10	0	0.16
12/9/2013 5:20	0	0.16
12/9/2013 5:30	0.01	0.17
12/9/2013 5:40	0.01	0.18
12/9/2013 5:50	0.01	0.19
12/9/2013 6:00	0.03	0.22
12/9/2013 6:10	0.02	0.24
12/9/2013 6:20	0.01	0.25
12/9/2013 6:30	0.02	0.27
12/9/2013 6:40	0	0.27
12/9/2013 6:50	0	0.27
12/9/2013 7:00	0	0.27
12/9/2013 7:10	0.01	0.28
12/9/2013 7:20	0	0.28
12/9/2013 7:30	0.01	0.29
12/9/2013 7:40	0.02	0.31
12/9/2013 7:50	0	0.31
12/9/2013 8:00	0	0.31
12/9/2013 8:10	0.02	0.33
12/9/2013 8:20	0.02	0.35
12/9/2013 8:30	0.04	0.39
12/9/2013 8:40	0	0.39

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/9/2013 8:50	0	0.39
12/9/2013 9:00	0.02	0.41
12/9/2013 9:10	0	0.41
12/9/2013 9:20	0	0.41
12/9/2013 9:30	0.01	0.42
12/9/2013 9:40	0	0.42
12/9/2013 9:50	0	0.42
12/9/2013 10:00	0	0.42
12/9/2013 10:10	0	0.42
12/9/2013 10:20	0	0.42
12/9/2013 10:30	0	0.42
12/9/2013 10:40	0	0.42
12/9/2013 10:50	0.01	0.43
12/9/2013 11:00	0	0.43
12/9/2013 11:10	0	0.43
12/9/2013 11:20	0	0.43
12/9/2013 11:30	0	0.43
12/9/2013 11:40	0.01	0.44
12/9/2013 11:50	0	0.44
12/9/2013 12:00	0	0.44
12/9/2013 12:10	0	0.44
12/9/2013 12:20	0	0.44
12/9/2013 12:30	0	0.44
12/9/2013 12:40	0	0.44
12/9/2013 12:50	0	0.44
12/9/2013 13:00	0	0.44
12/9/2013 13:10	0	0.44
12/9/2013 13:20	0	0.44
12/9/2013 13:30	0.01	0.45
12/9/2013 13:40	0.01	0.46
12/9/2013 13:50	0	0.46
12/9/2013 14:00	0	0.46
12/9/2013 14:10	0	0.46
12/9/2013 14:20	0.01	0.47
12/9/2013 14:30	0	0.47
12/9/2013 14:40	0.01	0.48
12/9/2013 14:50	0.01	0.49

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/10/2013 1:20	0.01	0.01
12/10/2013 1:30	0	0.01
12/10/2013 1:40	0	0.01
12/10/2013 1:50	0	0.01
12/10/2013 2:00	0	0.01
12/10/2013 2:10	0	0.01
12/10/2013 2:20	0	0.01
12/10/2013 2:30	0	0.01
12/10/2013 2:40	0	0.01
12/10/2013 2:50	0	0.01
12/10/2013 3:00	0	0.01
12/10/2013 3:10	0	0.01
12/10/2013 3:20	0	0.01
12/10/2013 3:30	0	0.01
12/10/2013 3:40	0	0.01
12/10/2013 3:50	0	0.01
12/10/2013 4:00	0	0.01
12/10/2013 4:10	0	0.01
12/10/2013 4:20	0	0.01
12/10/2013 4:30	0.01	0.02
12/10/2013 4:40	0	0.02
12/10/2013 4:50	0	0.02
12/10/2013 5:00	0	0.02
12/10/2013 5:10	0	0.02
12/10/2013 5:20	0	0.02
12/10/2013 5:30	0	0.02
12/10/2013 5:40	0	0.02
12/10/2013 5:50	0	0.02
12/10/2013 6:00	0	0.02
12/10/2013 6:10	0	0.02
12/10/2013 6:20	0	0.02
12/10/2013 6:30	0.03	0.05
12/10/2013 6:40	0.01	0.06
12/10/2013 6:50	0.11	0.17
12/10/2013 7:00	0.09	0.26
12/10/2013 7:10	0.02	0.28

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/10/2013 7:20	0.01	0.29
12/10/2013 7:30	0	0.29
12/10/2013 7:40	0	0.29
12/10/2013 7:50	0.01	0.3
12/10/2013 8:00	0	0.3
12/10/2013 8:10	0	0.3
12/10/2013 8:20	0	0.3
12/10/2013 8:30	0	0.3
12/10/2013 8:40	0.01	0.31
12/14/2013 9:30	0.01	0.01
12/14/2013 9:40	0	0.01
12/14/2013 9:50	0	0.01
12/14/2013 10:00	0	0.01
12/14/2013 10:10	0	0.01
12/14/2013 10:20	0	0.01
12/14/2013 10:30	0.02	0.03
12/14/2013 10:40	0.02	0.05
12/14/2013 10:50	0.04	0.09
12/14/2013 11:00	0.04	0.13
12/14/2013 11:10	0.05	0.18
12/14/2013 11:20	0.05	0.23
12/14/2013 11:30	0.04	0.27
12/14/2013 11:40	0.05	0.32
12/14/2013 11:50	0.03	0.35
12/14/2013 12:00	0.03	0.38
12/14/2013 12:10	0.02	0.4
12/14/2013 12:20	0.04	0.44
12/14/2013 12:30	0.06	0.5
12/14/2013 12:40	0.08	0.58
12/14/2013 12:50	0.09	0.67
12/14/2013 13:00	0.07	0.74
12/14/2013 13:10	0.07	0.81
12/14/2013 13:20	0.07	0.88
12/14/2013 13:30	0.06	0.94
12/14/2013 13:40	0.07	1.01
12/14/2013 13:50	0.04	1.05

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
12/14/2013 14:00	0.01	1.06
12/14/2013 14:10	0	1.06
12/14/2013 14:20	0	1.06
12/14/2013 14:30	0	1.06
12/14/2013 14:40	0	1.06
12/14/2013 14:50	0	1.06
12/14/2013 15:00	0	1.06
12/14/2013 15:10	0.01	1.07
POWER OUT		
12/16/2013 0:30 TO 1/1/2014 16:30		
RUNOFF EVENTS MISSED:		
12/22/2013 TO 12/23/2013		4
12/29/2013		2.41
1/2/2014 11:20	0.01	
1/2/2014 11:30	0.01	
1/2/2014 11:40	0.01	
1/2/2014 11:50	0.01	
1/2/2014 12:10	0.01	
1/2/2014 12:20	0.02	
1/2/2014 12:30	0.01	
1/2/2014 12:50	0.01	
1/2/2014 13:10	0.01	
1/2/2014 13:40	0.01	
1/2/2014 13:50	0.01	
1/2/2014 14:10	0.01	
1/2/2014 15:10	0.01	
1/2/2014 15:40	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
1/2/2014 16:50	0.01	
1/5/2014 7:20	0.02	
1/5/2014 7:30	0.01	
1/5/2014 11:00	0.01	
1/5/2014 21:50	0.01	
1/5/2014 23:10	0.03	
1/6/2014 2:00	0.01	
1/6/2014 2:10	0.01	
1/6/2014 2:20	0.01	
1/6/2014 2:30	0.01	
1/6/2014 3:00	0.01	
1/10/2014 0:30	0.01	0.01
1/10/2014 0:40	0	0.01
1/10/2014 0:50	0	0.01
1/10/2014 1:00	0	0.01
1/10/2014 1:10	0	0.01
1/10/2014 1:20	0	0.01
1/10/2014 1:30	0	0.01
1/10/2014 1:40	0	0.01
1/10/2014 1:50	0	0.01
1/10/2014 2:00	0	0.01
1/10/2014 2:10	0.02	0.03
1/10/2014 2:20	0.01	0.04
1/10/2014 2:30	0	0.04
1/10/2014 2:40	0	0.04
1/10/2014 2:50	0	0.04
1/10/2014 3:00	0	0.04
1/10/2014 3:10	0.01	0.05
1/10/2014 3:20	0	0.05
1/10/2014 3:30	0	0.05

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
1/10/2014 3:40	0	0.05
1/10/2014 3:50	0	0.05
1/10/2014 4:00	0	0.05
1/10/2014 4:10	0	0.05
1/10/2014 4:20	0	0.05
1/10/2014 4:30	0	0.05
1/10/2014 4:40	0	0.05
1/10/2014 4:50	0	0.05
1/10/2014 5:00	0.01	0.06
1/10/2014 5:10	0	0.06
1/10/2014 5:20	0	0.06
1/10/2014 5:30	0	0.06
1/10/2014 5:40	0.03	0.09
1/10/2014 5:50	0.03	0.12
1/10/2014 6:00	0.07	0.19
1/10/2014 6:10	0.02	0.21
1/10/2014 6:20	0.02	0.23
1/10/2014 6:30	0.01	0.24
1/10/2014 6:40	0.01	0.25
1/10/2014 6:50	0	0.25
1/10/2014 7:00	0	0.25
1/10/2014 7:10	0.01	0.26
1/10/2014 7:20	0	0.26
1/10/2014 7:30	0	0.26
1/10/2014 7:40	0.01	0.27
1/10/2014 7:50	0	0.27
1/10/2014 8:00	0	0.27
1/10/2014 8:10	0	0.27
1/10/2014 8:20	0	0.27
1/10/2014 8:30	0	0.27
1/10/2014 8:40	0	0.27
1/10/2014 8:50	0	0.27
1/10/2014 9:00	0	0.27
1/10/2014 9:10	0.03	0.3
1/10/2014 9:20	0.01	0.31
1/10/2014 9:30	0.02	0.33
1/10/2014 9:40	0	0.33

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
1/10/2014 9:50	0.01	0.34
1/10/2014 10:00	0	0.34
1/10/2014 10:10	0	0.34
1/10/2014 10:20	0	0.34
1/10/2014 10:30	0.07	0.41
1/10/2014 10:40	0.03	0.44
1/10/2014 10:50	0.02	0.46
1/10/2014 11:00	0	0.46
1/10/2014 11:10	0	0.46
1/10/2014 11:20	0	0.46
1/10/2014 11:30	0	0.46
1/10/2014 11:40	0	0.46
1/10/2014 11:50	0.01	0.47
1/10/2014 12:00	0.01	0.48
1/10/2014 12:10	0	0.48
1/10/2014 12:20	0	0.48
1/10/2014 12:30	0	0.48
1/10/2014 12:40	0.01	0.49
1/10/2014 12:50	0	0.49
1/10/2014 13:00	0	0.49
1/10/2014 13:10	0	0.49
1/10/2014 13:20	0.01	0.5
1/10/2014 13:30	0	0.5
1/10/2014 13:40	0	0.5
1/10/2014 13:50	0	0.5
1/10/2014 14:00	0	0.5
1/10/2014 14:10	0.01	0.51
1/10/2014 14:20	0	0.51
1/10/2014 14:30	0	0.51
1/10/2014 14:40	0	0.51
1/10/2014 14:50	0	0.51
1/10/2014 15:00	0	0.51
1/10/2014 15:10	0	0.51
1/10/2014 15:20	0	0.51
1/10/2014 15:30	0.01	0.52
1/10/2014 15:40	0	0.52
1/10/2014 15:50	0	0.52

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
1/10/2014 16:00	0	0.52
1/10/2014 16:10	0	0.52
1/10/2014 16:20	0	0.52
1/10/2014 16:30	0.02	0.54
1/10/2014 16:40	0	0.54
1/10/2014 16:50	0	0.54
1/10/2014 17:00	0	0.54
1/10/2014 17:10	0	0.54
1/10/2014 17:20	0.01	0.55
1/10/2014 17:30	0	0.55
1/10/2014 17:40	0	0.55
1/10/2014 17:50	0	0.55
1/10/2014 18:00	0	0.55
1/10/2014 18:10	0	0.55
1/10/2014 18:20	0	0.55
1/10/2014 18:30	0	0.55
1/10/2014 18:40	0	0.55
1/10/2014 18:50	0	0.55
1/10/2014 19:00	0.01	0.56
1/10/2014 19:10	0	0.56
1/10/2014 19:20	0	0.56
1/10/2014 19:30	0	0.56
1/10/2014 19:40	0	0.56
1/10/2014 19:50	0	0.56
1/10/2014 20:00	0	0.56
1/10/2014 20:10	0	0.56
1/10/2014 20:20	0	0.56
1/10/2014 20:30	0	0.56
1/10/2014 20:40	0	0.56
1/10/2014 20:50	0.01	0.57
1/10/2014 21:00	0	0.57
1/10/2014 21:10	0	0.57
1/10/2014 21:20	0.01	0.58
1/10/2014 21:30	0.01	0.59
1/10/2014 21:40	0.01	0.6
1/10/2014 21:50	0	0.6
1/10/2014 22:00	0	0.6

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
1/10/2014 22:10	0	0.6
1/10/2014 22:20	0.01	0.61
1/10/2014 22:30	0.01	0.62
1/10/2014 22:40	0	0.62
1/10/2014 22:50	0	0.62
1/10/2014 23:00	0	0.62
1/10/2014 23:10	0	0.62
1/10/2014 23:20	0.01	0.63
1/10/2014 23:30	0	0.63
1/10/2014 23:40	0.01	0.64
1/11/2014 0:30	0.01	0.01
1/11/2014 0:40	0	0.01
1/11/2014 0:50	0	0.01
1/11/2014 1:00	0	0.01
1/11/2014 1:10	0	0.01
1/11/2014 1:20	0	0.01
1/11/2014 1:30	0	0.01
1/11/2014 1:40	0.01	0.02
1/11/2014 1:50	0	0.02
1/11/2014 2:00	0.02	0.04
1/11/2014 2:10	0.02	0.06
1/11/2014 2:20	0.02	0.08
1/11/2014 2:30	0	0.08
1/11/2014 2:40	0	0.08
1/11/2014 2:50	0.01	0.09
1/11/2014 3:00	0	0.09
1/11/2014 3:10	0	0.09
1/11/2014 3:20	0.01	0.1
1/11/2014 3:30	0	0.1
1/11/2014 3:40	0.01	0.11
1/11/2014 3:50	0	0.11
1/11/2014 4:00	0.01	0.12
1/11/2014 4:10	0	0.12
1/11/2014 4:20	0.01	0.13
1/11/2014 4:30	0	0.13
1/11/2014 4:40	0	0.13

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
1/11/2014 4:50	0.02	0.15
1/11/2014 5:00	0.04	0.19
1/11/2014 5:10	0.13	0.32
1/11/2014 5:20	0.02	0.34
1/11/2014 5:30	0.01	0.35
1/11/2014 5:40	0.05	0.4
1/11/2014 5:50	0.04	0.44
1/11/2014 6:00	0.03	0.47
1/11/2014 6:10	0.04	0.51
1/11/2014 6:20	0.03	0.54
1/11/2014 6:30	0.03	0.57
1/11/2014 6:40	0.05	0.62
1/11/2014 6:50	0.02	0.64
1/11/2014 7:00	0.03	0.67
1/11/2014 7:10	0	0.67
1/11/2014 7:20	0	0.67
1/11/2014 7:30	0	0.67
1/11/2014 7:40	0	0.67
1/11/2014 7:50	0	0.67
1/11/2014 8:00	0.01	0.68
1/11/2014 8:10	0	0.68
1/11/2014 8:20	0	0.68
1/11/2014 8:30	0	0.68
1/11/2014 8:40	0	0.68
1/11/2014 8:50	0	0.68
1/11/2014 9:00	0	0.68
1/11/2014 9:10	0	0.68
1/11/2014 9:20	0	0.68
1/11/2014 9:30	0	0.68
1/11/2014 9:40	0	0.68
1/11/2014 9:50	0	0.68
1/11/2014 10:00	0	0.68
1/11/2014 10:10	0.08	0.76
1/11/2014 10:20	0.06	0.82
1/11/2014 10:30	0.01	0.83
1/11/2014 10:40	0	0.83
1/11/2014 10:50	0.01	0.84

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
1/11/2014 11:00	0.01	0.85
1/11/2014 11:10	0.02	0.87
1/11/2014 11:20	0.01	0.88
1/11/2014 11:30	0.02	0.9
1/11/2014 11:40	0.02	0.92
1/11/2014 11:50	0.03	0.95
1/11/2014 12:00	0.03	0.98
1/11/2014 12:10	0.04	1.02
1/11/2014 12:20	0.03	1.05
1/11/2014 12:30	0.05	1.1
1/11/2014 12:40	0.02	1.12
1/11/2014 12:50	0.02	1.14
1/11/2014 13:00	0.04	1.18
1/11/2014 13:10	0.04	1.22
1/11/2014 13:20	0.03	1.25
1/11/2014 13:30	0.03	1.28
1/11/2014 13:40	0.02	1.3
1/11/2014 13:50	0.02	1.32
1/11/2014 14:00	0.02	1.34
1/13/2014 20:30	0.01	
1/13/2014 20:50	0.01	
1/13/2014 21:00	0.01	
1/13/2014 21:20	0.01	
1/13/2014 21:30	0.01	
1/13/2014 22:10	0.01	
1/13/2014 22:20	0.01	
1/13/2014 23:40	0.01	
1/14/2014 0:30	0.01	
1/14/2014 1:30	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
1/14/2014 2:00	0.01	
1/14/2014 2:10	0.01	
1/14/2014 2:20	0.01	
1/14/2014 3:30	0.01	
1/14/2014 4:40	0.01	
1/14/2014 5:20	0.01	
1/14/2014 5:50	0.01	
1/14/2014 7:20	0.01	
1/14/2014 8:40	0.02	
1/14/2014 9:20	0.01	
2/3/2014 1:30	0.01	
2/3/2014 6:20	0.01	
2/3/2014 6:30	0.01	
2/3/2014 6:40	0.01	
2/3/2014 7:10	0.03	
2/3/2014 7:50	0.02	
2/3/2014 8:00	0.01	
2/3/2014 8:30	0.01	
2/3/2014 8:40	0.01	
2/3/2014 8:50	0.01	
2/4/2014 17:00	0.01	
2/4/2014 17:20	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
2/4/2014 20:20	0.01	
2/4/2014 21:50	0.01	
2/4/2014 23:40	0.01	
2/5/2014 0:10	0.01	
2/5/2014 1:30	0.01	
2/5/2014 4:20	0.01	
2/5/2014 4:30	0.01	
2/5/2014 4:40	0.02	
2/5/2014 4:50	0.01	
2/5/2014 5:00	0.02	
2/5/2014 5:10	0.01	
2/5/2014 5:20	0.03	
2/5/2014 5:30	0.01	
2/5/2014 5:50	0.02	
2/5/2014 6:00	0.04	
2/5/2014 6:10	0.03	
2/5/2014 6:20	0.01	
2/5/2014 6:30	0.02	
2/5/2014 6:40	0.03	
2/5/2014 6:50	0.01	
2/10/2014 13:40	0.01	
2/10/2014 14:50	0.01	
2/10/2014 15:20	0.01	
2/10/2014 15:40	0.01	
2/10/2014 16:20	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
POWER OUT		
2/11/2014 0:20 TO 2/20/2014 11:50		
RUNOFF EVENTS MISSED:		
2/14/2014		0.57
2/19/2014		2.10
2/21/2014 4:50	0.01	0.01
2/21/2014 5:00	0.01	0.02
2/21/2014 5:10	0.02	0.04
2/21/2014 5:20	0	0.04
2/21/2014 5:30	0	0.04
2/21/2014 5:40	0.01	0.05
2/21/2014 5:50	0	0.05
2/21/2014 6:00	0.01	0.06
2/21/2014 6:10	0	0.06
2/21/2014 6:20	0	0.06
2/21/2014 6:30	0.02	0.08
2/21/2014 6:40	0.15	0.23
2/21/2014 6:50	0.19	0.42
2/21/2014 7:00	0.09	0.51
2/21/2014 7:10	0.06	0.57
2/21/2014 7:20	0.03	0.6
2/21/2014 7:30	0.05	0.65
2/21/2014 7:40	0.04	0.69
2/21/2014 7:50	0.03	0.72
2/21/2014 8:00	0.02	0.74
2/21/2014 8:10	0.02	0.76
2/21/2014 8:20	0	0.76
2/21/2014 8:30	0	0.76
2/21/2014 8:40	0.01	0.77
2/21/2014 8:50	0	0.77
2/21/2014 9:00	0	0.77
2/21/2014 9:10	0	0.77
2/21/2014 9:20	0	0.77
2/21/2014 9:30	0.02	0.79
2/21/2014 9:40	0	0.79
2/21/2014 9:50	0	0.79

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
2/21/2014 10:00	0	0.79
2/21/2014 10:10	0	0.79
2/21/2014 10:20	0	0.79
2/21/2014 10:30	0	0.79
2/21/2014 10:40	0	0.79
2/21/2014 10:50	0	0.79
2/21/2014 11:00	0.01	0.8
3/3/2014 7:20	0.01	
3/3/2014 8:10	0.01	
3/3/2014 8:30	0.01	
3/3/2014 8:40	0.01	
3/3/2014 13:30	0.01	
3/3/2014 13:50	0.02	
3/3/2014 14:00	0.02	
3/3/2014 14:10	0.01	
3/3/2014 14:20	0.01	
3/3/2014 14:30	0.01	
3/3/2014 14:50	0.01	
3/3/2014 15:10	0.01	
3/3/2014 15:30	0.01	
3/3/2014 16:00	0.01	
3/3/2014 16:10	0.01	
3/6/2014 16:50	0.01	0.01
3/6/2014 17:00	0.01	0.02
3/6/2014 17:10	0.01	0.03
3/6/2014 17:20	0.01	0.04
3/6/2014 17:30	0	0.04

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/6/2014 17:40	0.01	0.05
3/6/2014 17:50	0	0.05
3/6/2014 18:00	0.01	0.06
3/6/2014 18:10	0.01	0.07
3/6/2014 18:20	0.01	0.08
3/6/2014 18:30	0.02	0.1
3/6/2014 18:40	0.01	0.11
3/6/2014 18:50	0.01	0.12
3/6/2014 19:00	0.01	0.13
3/6/2014 19:10	0.01	0.14
3/6/2014 19:20	0.02	0.16
3/6/2014 19:30	0.01	0.17
3/6/2014 19:40	0.01	0.18
3/6/2014 19:50	0.01	0.19
3/6/2014 20:00	0.01	0.2
3/6/2014 20:10	0.01	0.21
3/6/2014 20:20	0	0.21
3/6/2014 20:30	0.01	0.22
3/6/2014 20:40	0	0.22
3/6/2014 20:50	0.01	0.23
3/6/2014 21:00	0.01	0.24
3/6/2014 21:10	0.01	0.25
3/6/2014 21:20	0.01	0.26
3/6/2014 21:30	0.02	0.28
3/6/2014 21:40	0.01	0.29
3/6/2014 21:50	0.02	0.31
3/6/2014 22:00	0.02	0.33
3/6/2014 22:10	0.02	0.35
3/6/2014 22:20	0.02	0.37
3/6/2014 22:30	0.02	0.39
3/6/2014 22:40	0.02	0.41
3/6/2014 22:50	0.02	0.43
3/6/2014 23:00	0.01	0.44
3/6/2014 23:10	0.01	0.45
3/6/2014 23:20	0.01	0.46
3/6/2014 23:30	0.02	0.48
3/6/2014 23:40	0.01	0.49

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/6/2014 23:50	0.02	0.51
3/7/2014 0:00	0.02	0.53
3/7/2014 0:10	0.02	0.55
3/7/2014 0:20	0.03	0.58
3/7/2014 0:30	0.03	0.61
3/7/2014 0:40	0.04	0.65
3/7/2014 0:50	0.04	0.69
3/7/2014 1:00	0.04	0.73
3/7/2014 1:10	0.03	0.76
3/7/2014 1:20	0.04	0.8
3/7/2014 1:30	0.04	0.84
3/7/2014 1:40	0.03	0.87
3/7/2014 1:50	0.03	0.9
3/7/2014 2:00	0.02	0.92
3/7/2014 2:10	0.01	0.93
3/7/2014 2:20	0.01	0.94
3/7/2014 2:30	0.02	0.96
3/7/2014 2:40	0.02	0.98
3/7/2014 2:50	0.02	1
3/7/2014 3:00	0.01	1.01
3/7/2014 3:10	0.03	1.04
3/7/2014 3:20	0.03	1.07
3/7/2014 3:30	0.03	1.1
3/7/2014 3:40	0.02	1.12
3/7/2014 3:50	0.02	1.14
3/7/2014 4:00	0.03	1.17
3/7/2014 4:10	0.03	1.2
3/7/2014 4:20	0.04	1.24
3/7/2014 4:30	0.03	1.27
3/7/2014 4:40	0.03	1.3
3/7/2014 4:50	0.03	1.33
3/7/2014 5:00	0.03	1.36
3/7/2014 5:10	0.02	1.38
3/7/2014 5:20	0.03	1.41
3/7/2014 5:30	0.04	1.45
3/7/2014 5:40	0.03	1.48
3/7/2014 5:50	0.02	1.5

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/7/2014 6:00	0.03	1.53
3/7/2014 6:10	0.02	1.55
3/7/2014 6:20	0.03	1.58
3/7/2014 6:30	0.03	1.61
3/7/2014 6:40	0.02	1.63
3/7/2014 6:50	0.03	1.66
3/7/2014 7:00	0.01	1.67
3/7/2014 7:10	0.01	1.68
3/7/2014 7:20	0.02	1.7
3/7/2014 7:30	0.01	1.71
3/7/2014 7:40	0.01	1.72
3/7/2014 7:50	0.01	1.73
3/7/2014 8:00	0.01	1.74
3/7/2014 8:10	0.01	1.75
3/7/2014 8:20	0.01	1.76
3/7/2014 8:30	0	1.76
3/7/2014 8:40	0.01	1.77
3/7/2014 8:50	0.01	1.78
3/7/2014 9:00	0.01	1.79
3/7/2014 9:10	0	1.79
3/7/2014 9:20	0.01	1.8
3/7/2014 9:30	0.01	1.81
3/7/2014 9:40	0.01	1.82
3/7/2014 9:50	0.01	1.83
3/7/2014 10:00	0.01	1.84
3/7/2014 10:10	0.01	1.85
3/7/2014 10:20	0.01	1.86
3/7/2014 10:30	0.01	1.87
3/7/2014 10:40	0	1.87
3/7/2014 10:50	0.01	1.88
3/7/2014 11:00	0	1.88
3/7/2014 11:10	0.01	1.89
3/7/2014 11:20	0	1.89
3/7/2014 11:30	0.01	1.9
3/7/2014 11:40	0	1.9
3/7/2014 11:50	0	1.9
3/7/2014 12:00	0	1.9

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/7/2014 12:10	0	1.9
3/7/2014 12:20	0.01	1.91
3/12/2014 6:00	0.01	
3/12/2014 6:50	0.01	
3/12/2014 7:20	0.01	
3/12/2014 8:10	0.01	
3/12/2014 8:50	0.01	
3/16/2014 7:00	0.01	0.01
3/16/2014 7:10	0	0.01
3/16/2014 7:20	0	0.01
3/16/2014 7:30	0.01	0.02
3/16/2014 7:40	0.01	0.03
3/16/2014 7:50	0.01	0.04
3/16/2014 8:00	0.01	0.05
3/16/2014 8:10	0.01	0.06
3/16/2014 8:20	0	0.06
3/16/2014 8:30	0.01	0.07
3/16/2014 8:40	0.01	0.08
3/16/2014 8:50	0	0.08
3/16/2014 9:00	0.01	0.09
3/16/2014 9:10	0.01	0.1
3/16/2014 9:20	0.01	0.11
3/16/2014 9:30	0.01	0.12
3/16/2014 9:40	0.02	0.14
3/16/2014 9:50	0.02	0.16
3/16/2014 10:00	0.02	0.18
3/16/2014 10:10	0.02	0.2
3/16/2014 10:20	0.03	0.23
3/16/2014 10:30	0.03	0.26
3/16/2014 10:40	0.03	0.29
3/16/2014 10:50	0.03	0.32

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/16/2014 11:00	0.02	0.34
3/16/2014 11:10	0.03	0.37
3/16/2014 11:20	0.01	0.38
3/16/2014 11:30	0.02	0.4
3/16/2014 11:40	0.02	0.42
3/16/2014 11:50	0.02	0.44
3/16/2014 12:00	0.04	0.48
3/16/2014 12:10	0.01	0.49
3/16/2014 12:20	0.02	0.51
3/16/2014 12:30	0	0.51
3/16/2014 12:40	0.02	0.53
3/16/2014 12:50	0.01	0.54
3/16/2014 13:00	0	0.54
3/16/2014 13:10	0.01	0.55
3/16/2014 13:20	0.01	0.56
3/16/2014 13:30	0.02	0.58
3/16/2014 13:40	0.01	0.59
3/16/2014 13:50	0.02	0.61
3/16/2014 14:00	0.02	0.63
3/16/2014 14:10	0.02	0.65
3/16/2014 14:20	0.02	0.67
3/16/2014 14:30	0.03	0.7
3/16/2014 14:40	0.01	0.71
3/16/2014 14:50	0.01	0.72
3/16/2014 15:00	0.02	0.74
3/16/2014 15:10	0.03	0.77
3/16/2014 15:20	0.02	0.79
3/16/2014 15:30	0.04	0.83
3/16/2014 15:40	0.01	0.84
3/16/2014 15:50	0.01	0.85
3/16/2014 16:00	0.02	0.87
3/16/2014 16:10	0.01	0.88
3/16/2014 16:20	0.01	0.89
3/16/2014 16:30	0	0.89
3/16/2014 16:40	0.01	0.9
3/16/2014 16:50	0.01	0.91
3/16/2014 17:00	0.01	0.92

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/16/2014 17:10	0.02	0.94
3/16/2014 17:20	0.01	0.95
3/16/2014 17:30	0.01	0.96
3/16/2014 17:40	0.01	0.97
3/16/2014 17:50	0.02	0.99
3/16/2014 18:00	0.02	1.01
3/16/2014 18:10	0.01	1.02
3/16/2014 18:20	0.01	1.03
3/16/2014 18:30	0	1.03
3/16/2014 18:40	0	1.03
3/16/2014 18:50	0	1.03
3/16/2014 19:00	0.01	1.04
3/16/2014 19:10	0	1.04
3/16/2014 19:20	0.02	1.06
3/16/2014 19:30	0.01	1.07
3/16/2014 19:40	0.02	1.09
3/16/2014 19:50	0	1.09
3/16/2014 20:00	0	1.09
3/16/2014 20:10	0.01	1.1
3/16/2014 20:20	0	1.1
3/16/2014 20:30	0	1.1
3/16/2014 20:40	0	1.1
3/16/2014 20:50	0	1.1
3/16/2014 21:00	0	1.1
3/16/2014 21:10	0.01	1.11
3/16/2014 21:20	0	1.11
3/16/2014 21:30	0	1.11
3/16/2014 21:40	0.01	1.12
3/16/2014 21:50	0	1.12
3/16/2014 22:00	0	1.12
3/16/2014 22:10	0.01	1.13
3/16/2014 22:20	0	1.13
3/16/2014 22:30	0	1.13
3/16/2014 22:40	0	1.13
3/16/2014 22:50	0	1.13
3/16/2014 23:00	0	1.13
3/16/2014 23:10	0	1.13

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/16/2014 23:20	0	1.13
3/16/2014 23:30	0	1.13
3/16/2014 23:40	0	1.13
3/16/2014 23:50	0.01	1.14
3/17/2014 0:10	0.01	
3/17/2014 1:40	0.01	
3/17/2014 3:20	0.01	
3/17/2014 3:30	0.01	
3/17/2014 3:50	0.01	
3/17/2014 4:10	0.01	
3/17/2014 8:50	0.01	
3/17/2014 10:20	0.02	
3/17/2014 10:30	0.01	
3/17/2014 10:40	0.01	
3/17/2014 14:10	0.01	
3/17/2014 14:30	0.01	
3/17/2014 15:30	0.01	
3/17/2014 16:00	0.01	
3/17/2014 16:40	0.01	
3/17/2014 17:00	0.01	
3/17/2014 17:10	0.01	
3/17/2014 17:30	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/17/2014 17:50	0.01	
3/17/2014 19:00	0.02	
3/17/2014 19:10	0.01	
3/17/2014 19:30	0.01	
3/17/2014 20:20	0.01	
3/19/2014 4:40	0.01	
3/23/2014 9:30	0.01	
3/23/2014 9:40	0.01	
3/23/2014 10:00	0.02	
3/23/2014 10:10	0.01	
3/23/2014 10:20	0.02	
3/23/2014 10:30	0.02	
3/23/2014 10:40	0.02	
3/23/2014 10:50	0.01	
3/23/2014 11:00	0.01	
3/23/2014 11:10	0.01	
3/23/2014 11:20	0.02	
3/25/2014 5:30	0.01	
3/25/2014 5:40	0.01	
3/25/2014 5:50	0.01	
3/25/2014 6:00	0.01	
3/25/2014 6:10	0.02	
3/25/2014 6:20	0.01	
3/25/2014 6:40	0.01	
3/25/2014 6:50	0.04	
3/25/2014 7:00	0.04	
3/25/2014 7:10	0.02	
3/25/2014 12:00	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/25/2014 12:10	0.01	
3/25/2014 13:10	0.01	
3/28/2014 23:40	0.01	
3/29/2014 2:20	0.01	
3/29/2014 2:30	0.01	
3/29/2014 2:40	0.01	
3/29/2014 2:50	0.01	
3/29/2014 3:30	0.01	
3/29/2014 4:10	0.01	
3/29/2014 5:30	0.01	
3/29/2014 5:50	0.01	
3/29/2014 6:40	0.01	
3/29/2014 6:50	0.03	
3/29/2014 7:00	0.02	
3/29/2014 7:10	0.01	
3/29/2014 7:20	0.01	
3/29/2014 8:00	0.01	
3/29/2014 8:40	0.01	
3/29/2014 8:50	0.02	
3/29/2014 9:00	0.01	
3/29/2014 9:20	0.01	
3/29/2014 12:50	0.03	
3/29/2014 13:00	0.01	
3/29/2014 14:40	0.01	

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
3/29/2014 14:50	0.03	
3/29/2014 15:10	0.01	
3/29/2014 15:20	0.03	
3/29/2014 15:30	0.01	
3/29/2014 18:10	0.01	
3/29/2014 21:10	0.01	
4/6/2014 23:50	0.01	
4/7/2014 1:50	0.01	0.01
4/7/2014 2:00	0.01	0.02
4/7/2014 2:10	0.04	0.06
4/7/2014 2:20	0.03	0.09
4/7/2014 2:30	0.03	0.12
4/7/2014 2:40	0.02	0.14
4/7/2014 2:50	0.02	0.16
4/7/2014 3:00	0.02	0.18
4/7/2014 3:10	0	0.18
4/7/2014 3:20	0.05	0.23
4/7/2014 3:30	0.03	0.26
4/7/2014 3:40	0.03	0.29
4/7/2014 3:50	0.05	0.34
4/7/2014 4:00	0.05	0.39
4/7/2014 4:10	0.05	0.44
4/7/2014 4:20	0.06	0.5
4/7/2014 4:30	0.04	0.54
4/7/2014 4:40	0.07	0.61
4/7/2014 4:50	0.07	0.68

Time Stamp	Rain per 10 min [in]	Cumulative Rainfall [in]
4/7/2014 5:00	0.07	0.75
4/7/2014 5:10	0.04	0.79
4/7/2014 5:20	0.05	0.84
4/7/2014 5:30	0.06	0.9
4/7/2014 5:40	0.06	0.96
4/7/2014 5:50	0.06	1.02
4/7/2014 6:00	0.06	1.08
4/7/2014 6:10	0.06	1.14
4/7/2014 6:20	0.06	1.2
4/7/2014 6:30	0.05	1.25
4/7/2014 6:40	0.05	1.3
4/7/2014 6:50	0.08	1.38
4/7/2014 7:00	0.08	1.46
4/7/2014 7:10	0.05	1.51
4/7/2014 7:20	0.04	1.55
4/7/2014 7:30	0.08	1.63
4/7/2014 7:40	0.07	1.7
4/7/2014 7:50	0.04	1.74
4/7/2014 8:00	0.03	1.77
4/7/2014 8:10	0.03	1.8
4/7/2014 8:20	0.04	1.84
4/7/2014 8:30	0.06	1.9
4/7/2014 8:40	0.05	1.95
4/7/2014 8:50	0.05	2
4/7/2014 9:00	0.03	2.03
4/7/2014 9:10	0.01	2.04
4/7/2014 9:20	0.01	2.05
4/7/2014 9:30	0	2.05
4/7/2014 9:40	0.01	2.06

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