Final Report

Compliance with the United States Environmental Protection Agency Effluent Limitation Guidelines – Turbidity Control and Surface Outlets

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16. Abstract
A goal of this research was to maximize turbidity reduction using passive polyacrylamide (PAM) applications and investigate the longevity of PAM's effectiveness. Results indicate PAM application may provide an effective alternative for turbidity reduction where SCDOT sites discharge to waterways with sediment-related water quality standards in place. Research findings show that granular polymer/flocculants applied directly to ditch checks can significantly reduce turbidity below a level of 280 NTU. To optimize turbidity reduction effectiveness where necessary, it is recommended that PAM be reapplied at least once every seven days to ensure continued flocculation over time. In addition, proper maintenance and regular inspections must be a priority for reducing TSS and turbidity. Infrequent or poor maintenance routinely corresponded to lower trapping efficiencies for individual practices. Another research goal was to evaluate SCDOT sediment basin design. Results showed 80% reduction in turbidity or greater than 82% reduction in TSS could be achieved with skimmers alone or through a combination of skimmer and baffle systems. With addition of a granular polymer, turbidity and TSS reduction exceeded 90%. A final element of investigation compared sediment basin performance using a single baffle with performance achieved using three baffles when PAM is used. Statistical analysis of results confirmed the 3-baffle configuration performed better than 1 baffle for reducing turbidity. For TSS reduction however, no statistical difference between the two configurations was found. Finally, a series of laboratory bioassays was conducted to evaluate acute and chronic toxicological effects resulting from exposure to commercially available PAM formulae. Toxicities reported here are well above dosage recommendations made by the manufacturers.

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Introduction

The South Carolina Department of Transportation (SCDOT) currently implements a South Carolina Department of Health and Environmental Control (SCDHEC) mandated design criteria for stormwater runoff that drains to a single outfall (drainage area for the specific single outlet at the location of exit at the SCDOT project property or rights-of way boundary) from land disturbing activities which disturb ten (10) acres or more, to meet a removal efficiency of 80% suspended solids for the 10-year, 24-hour storm event for best management practices (BMPs) as part of active construction projects. In 2009, the US Environmental Protection Agency (USEPA) proposed an additional numeric effluent standard for a turbidity limit of 280 NTU, as measured at the point of site discharge. Such a change would result in South Carolina moving from being a design standard state to being a performance standard state, which would likely have considerable financial consequences.

For SCDOT to be capable of complying with potential numeric turbidity standards, assessment of current best management practices and development of potential new BMPs would be necessary. To meet this proposed rule, research was conducted to measure and evaluate turbidity in stormwater discharges from SCDOT construction sites and in controlled experimental field testing of current SCDOT specified sediment control BMPs. The research assessed other passive treatment BMPs such as polymers and chemical flocculants. Finally, this research evaluated selected BMPs deployed in different soils from representative regions of the state (coast, midlands and upstate) to quantify BMP performance.

Research Objectives:

This research evaluated turbidity and surface water withdrawal associated with SCDOT construction site stormwater discharge. The project consisted of two parts. Part A determined effluent values for TSS and turbidity from select SCDOT BMPs, with and without the use of flocculants. Part B evaluated the effectiveness of surface water withdrawal systems and baffle configurations deployed within sediment basins.

Specific research objectives for Part A included:

1. Measurement and evaluation of TSS and turbidity levels in construction site stormwater discharges from active SCDOT construction sites prior to any treatment with ditch application BMPs.
2. Measurement and evaluation of TSS and turbidity levels in stormwater discharges from controlled research field experiment testing prior to any treatment with ditch application BMPs.
3. Measurement and evaluation of TSS and turbidity levels from selected standard ditch application BMPs measured from SCDOT active construction sites and controlled field experiments.
4. Measurement and evaluation of TSS and turbidity levels from selected standard ditch application BMPs following passive flocculent treatment from SCDOT active construction sites and controlled field experiments.

Specific research objectives for Part B include:

5. Evaluate surface withdrawal methodologies and baffle systems with respect to SCDOT construction sites so that the most viable method can be selected for field tests.
6. Measurement and evaluation of TSS and turbidity levels from SCDOT site runoff prior to any surface withdrawal BMP, i.e., inflow to sediment basins (SCDOT active construction sites).
7. Measurement and evaluation of TSS and turbidity levels after passing through a basin featuring surface withdrawal and baffle systems, i.e., outflow (controlled field experiments).
8. Provide recommendations for specifications and design aids based on research results for the various BMPs investigated (Parts A and B).

Executive Summary:

Research on SCDOT construction sites investigated reducing turbidity and TSS using wattles (sediment tubes), rock ditch checks and rock ditch checks with washed #57 stone on the upstream face with and without a passive granular PAM application at three active roadway construction sites in the upstate, midlands, and coastal regions of South Carolina. It was observed that both rock ditch checks and rock ditch checks having washed stone and a passive PAM application were most effective in reducing turbidity showing an average decrease in of 58-63%. Wattles with a passive PAM treatment reduced turbidity values on average by 36%. Without PAM, turbidity in several instances across multiple BMP checks showed a small increase in turbidity. These increases are thought to be in part caused by resuspension of deposited sediment in the channel. It was also observed that the passive addition of PAM as a flocculant, increased the TSS removal efficiency for rock ditch checks, rock ditch checks with washed stone and sediment tubes. The use of PAM on construction sites can reduce TSS and turbidity.

This research also confirms proper BMP installation, maintenance and regular inspections should be a priority in effectively reducing TSS and turbidity. It was observed in the field over many storm events that resuspension and erosion within unmaintained channels or associated with unmaintained BMPs resulted in increased TSS values. Infrequent maintenance often corresponded to higher TSS and lower trapping efficiencies. One goal of this research was to maximize turbidity reduction using passive polyacrylamide (PAM) applications. Additional research efforts were directed at examining responses in turbidity levels when PAM applications could become desiccated. Results of this research indicate that PAM application may be necessary for effective turbidity and suspended sediment reduction. This research has shown that granular PAM applied directly to sediment tubes can significantly reduce turbidity below a level of 280 NTU. The following conclusions can be summarized from the results.

1. Under both field conditions and controlled experiments, sediment tube wattles without PAM application provide no significant reduction in turbidity.
2. Granular PAM applied directly on wattles provided better reductions in turbidity and TSS than PAM delivered through a permeable bag.
3. In controlled experiments, PAM applied before each run provided a quicker decrease in turbidity than applying a single time prior to the commencement of testing.

4. Turbidity levels less than 280 NTU in effluent flows were achieved within three sediment tubes when PAM was applied before each run. PAM applied a single time prior to testing created turbidity levels lower than 280 NTU within five sediment tubes.
5. Under designed conditions, reapplication of granular PAM to sediment tubes after periods of dry weather and before storm events will consistently reduce turbidity below 280 NTU.

PAM longevity is critical in deciding when to reapply as a flocculant for turbidity and TSS reduction. Statistically, no significant differences in turbidity reduction were observed between first applications of PAM and PAM which had been reapplied to sediment tubes and endured a three-, five-, or ten-day desiccation period before any subsequent runoff event. However, results for the ten-day waiting period yielded the two highest mean turbidities for test channel effluent: 342 and 477 NTU. Based on a 280 NTU target value and deploying linear interpolation of data between five- and ten-day period yielded a 6.7-day optimized reapplication interval. Therefore, it is recommended that PAM be reapplied at least once every seven days to ensure proper turbidity reductions.

Based on this research, proper maintenance and regular inspections should be a priority in reducing TSS and turbidity. Infrequent maintenance of drainage channels and associated BMPs often corresponded to higher TSS values and lower trapping efficiencies. The use of PAM on construction sites can reduce TSS and turbidity. PAM with either sediment tubes, rock ditch checks, and rock ditch checks with washed stone consistently showed TSS reductions. PAM reduced turbidity in many of the observed storms.

Another primary goal of the research was to evaluate SCDOT sediment basin design and assess conditions with various surface skimmers and baffle configurations. Results showed that 80% reduction in turbidity could be achieved with either skimmers alone or through a combination of skimmer and baffle arrangements. With the addition of PAM, this turbidity reduction could be greater than 90%. Without PAM, effluent levels ranged between 60-400 NTUs while with PAM, levels were between 16-160 NTUs. Similarly, when assessing TSS, greater than 82% reductions were achieved with either skimmers or skimmers used in conjunction with baffles. When PAM was added to basins, TSS reductions increased to greater than 90%. Similar results could be seen when investigating peak turbidity and TSS values.

A final element of investigation compared sediment basin performance using only one baffle with performance achieved using three baffles when using PAM as a flocculant. Statistical analysis of results confirmed the 3-baffle configuration performed better than 1 baffle for reducing turbidity discharged from the sediment basin. While there was a statistical difference between 1 and 3 baffles, both resulted in turbidity reductions greater than 90%. For TSS, no statistical difference between 1 baffle and 3 baffles was found. TSS reductions for either configuration were greater than 95%.

A series of laboratory bioassays was conducted to evaluate acute and chronic toxicological effects resulting from exposure to commercially available PAM formulae. The vertebrate Fathead Minnow species *P. promelas* showed to be the least sensitive in comparison to *D. magna* in acute exposures as

described by LC_{50} values. The order of toxicity for PAM flocculants was similar for *P. promelas* and *D. magna* for acute exposures. Cationic PAM flocculants appeared to be the most toxic. Anionic PAM flocculants showed the least toxicity for all species – except for *C. dubia* under chronic exposure conditions. Toxicities reported from this research are well above dosage recommendations made by the manufacturers.

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1. Background

The U.S. Environmental Protection Agency (USEPA) originally published effluent limitations guidelines (ELGs) to control the discharge of pollutants from construction sites (40 CFR Part 450). While the numeric turbidity limits for construction site discharges may be required in future construction permits, the non-numeric requirements were included in the construction general permit approved by the United States Environmental Protection Agency (USEPA) in the summer of 2012. In addition, the uniqueness of South Carolina Department of Transportation (SCDOT) construction on linear projects led SCDHEC to develop a separate Construction General Permit (CGP) for SCDOT that became effective in 2013 to address its construction-related activities and contained the non-numeric requirements specified by USEPA. The ELGs may ultimately require numeric turbidity limits for construction site stormwater discharges. The requirements would likely subject construction site stormwater discharges to a maximum allowable turbidity numeric effluent limit commonly measured in nephelometric turbidity units (NTUs). Turbidity is a measure of the cloudiness or opacity in stormwater runoff caused by suspended solids, particles and aggregates.

The USEPA promulgated non-numeric requirements exercising best management practices (BMPs) in six categories:

1. Erosion and sediment control,
2. Soil stabilization,
3. Dewatering,
4. Pollution prevention,
5. Prohibited discharges (such as wastewater than includes cement and stucco), and
6. Surface outlets that withdraw water from the surface when discharging from basins or impoundments.

SCDOT currently implements a SCDHEC mandated total suspended solids (TSS) design removal requirement of 80% on construction projects that drain to a single outfall from land disturbing activities which disturb ten (10) acres or more for the 10-year, 24-hour storm event. SCDOT currently implements all six required categories with surface outlets, being a new requirement for basins and impoundments that include sediment basins.

For SCDOT to be capable of complying with potential new future numeric turbidity standards, evaluation of current BMPs and development of new BMPs are necessary. The 80% design standard could be coupled with numeric turbidity standards resulting in the necessity to monitor construction site stormwater discharges to measure and report turbidity values. This will require research that includes the measurement and evaluation of turbidity in stormwater discharges from SCDOT construction sites and/or in discharges from controlled field experiment research testing conditions prior to treatment and after treatment with current SCDOT BMPs. Such research will also evaluate other passive treatment BMPs such as polymers, flocculants and/or coagulants. This proposed research will be required to evaluate selected BMPs on soils from the different regions of the state (coast, midlands and upstate) to quantify BMP performance with different South Carolina (SC) soil types.

To comply with surface water withdrawal requirements, specifications for SCDOT construction plans will need to be determined. Such specifications will require research that includes the measurement and evaluation of whether surface outlets can be installed and maintained to provide water quality benefits on linear SCDOT projects in South Carolina.

This research will measure TSS and turbidity level of stormwater discharges on active SCDOT construction sites and/or in controlled field experiment testing conditions. The research will investigate how effective existing BMPs employed by SCDOT are capable of controlling turbidity in addition to the effectiveness of using surface water withdrawal and baffle systems within sediment basins. The research will also measure how selected BMPs enhanced with flocculants control turbidity for the SC regional soil types. Both the USEPA and SCDHEC anticipate the use of passive treatment to address numeric effluent limitations for turbidity. In general, passive treatment systems do not rely on electrically powered pumping of stormwater or mechanical filtration, and instead control turbidity using select best management practices either alone or in combination with polymers or other flocculants. Understanding basic physical and chemical characteristics of polymers and other flocculants associated with SCDOT-specific applications are essential to optimizing treatment specifications and standard details related to construction-derived sediments.

Results from the proposed research will provide data, information and recommendations with the intent of minimizing the risks of non-compliance concerning new future numeric turbidity-related numeric effluent limits that may be promulgated by USEPA and enforced by SCDHEC.

Research Objectives:

This research project evaluated turbidity and surface water withdrawal associated with SCDOT construction site stormwater discharge. This project consisted of two parts. Part A determined effluent values for TSS and turbidity from select SCDOT construction sites and BMP evaluations with and without the use of flocculants. Part B evaluated the effectiveness of surface water withdrawal and baffle systems on SCDOT sediment basins.

Specific research objectives for Part A included:

1. Measurement and evaluation of TSS and turbidity levels in construction site stormwater discharges from active SCDOT construction sites prior to any treatment with ditch application BMPs.
2. Measurement and evaluation of TSS and turbidity levels in stormwater discharges from controlled research field experiment testing prior to any treatment with ditch application BMPs.
3. Measurement and evaluation of TSS and turbidity levels from typical SCDOT ditch application BMPs from SCDOT active construction sites and controlled field experiments.

4. Measurement and evaluation of TSS and turbidity levels from selected SCDOT ditch application BMPs following passive flocculent treatment from SCDOT active construction sites and controlled field experiments.

Specific research objectives for Part B include:

5. Evaluate surface withdrawal methodologies and baffle systems with respect to SCDOT construction sites so that the most viable method can be selected for field tests.
6. Measurement and evaluation of TSS and turbidity levels from SCDOT site runoff prior to any surface withdrawal and baffle system BMP, i.e., inflow from SCDOT active construction sites or controlled field experiments.
7. Measurement and evaluation of TSS and turbidity levels after passing through a basin featuring surface withdrawal and baffle systems, i.e., outflow from SCDOT active construction sites or controlled field experiments.
8. Measurement and evaluation of TSS and turbidity levels from surface withdrawal and baffle systems compared to selected SCDOT BMPs following passive flocculent treatment from SCDOT active construction sites and controlled field experiments.
9. Provide recommendations for specifications and design aids based on research results for the various BMPs investigated (Parts A and B).

Anticipated Deliverables:

1. Statistically valid data set representing TSS and turbidity values from selected active SCDOT construction site stormwater runoff prior to treatment.
2. Statistically valid data set representing TSS and turbidity reduction performance of typical SCDOT ditch application BMPs.
3. Statistically valid data set representing turbidity reduction performance of selected additional BMPs.
4. Statistically valid data set representing TSS and turbidity reduction performance from commonly utilized BMPs modified using selected passive treatment system options.
5. Recommendations for turbidity monitoring requirements that recognize the special difficulties associated with highway construction sites.
6. Design guidelines on BMP selection to reduce turbidity.
7. Statistically valid data representing TSS and turbidity values from selected SCDOT construction site stormwater runoff prior to surface withdrawal treatment.
8. Statistically valid data representing TSS and turbidity reduction performance of SCDOT sediment basins including surface withdrawal and baffles.
9. Recommendations as to whether surface withdrawal and baffle systems are beneficial for SCDOT projects including sediment basins.
10. If surface withdrawal and baffle systems are deemed beneficial, deliverable to include applicable standard specifications, drawings, and design aides.

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 (USEPA, 2005). Without proper controls these erosion rates can be as high as 35 to 45 tons per acre per year (USGAO, 1998).

Temporary Erosion Control Devices

Erosion prevention and sediment control BMPs include ditch check structures and ponding structures which seek to reduce velocity of runoff minimizing erosion and encourage settling of suspended particles. The goal of sediment control is to keep eroded sediment on-site and minimize offsite impacts.

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.

Sediment tubes, wattles, tubes, and compost socks are all examples of temporary erosion prevention and sediment control devices that consist of compacted natural fibers encased in tubular netting. Sediment tubes are available in various diameters depending on application and allow water to flow through or over the fiber matrix while retaining sediment. These products are used for slope interruption, act as check dams in areas of concentrated flow, inlet protection, and construction site perimeter sediment control. For this research, the naming convention used by SC Department of Transportation (SCDOT) and SC Department of Health and Environmental Control (SCDHEC) to describe temporary sediment control devices acting as ditch checks will be sediment tubes (SCDHEC, 2005; SCDOT, 2011). Three main types of natural sediment tubes are becoming widely accepted. Excelsior sediment tubes are made of excelsior fibers, wood slivers typically cut from aspen, poplar, and spruce. Coir sediment tubes are constructed from the shredded husk fibers of coconut. Lastly, straw sediment tubes are made of basic straw materials. These devices are less expensive than standard channel BMPs, require less man-power for installation (unlike rock check dams), and are commonly deployed on linear projects, such as highway construction, where space is limited (McLaughlin et al., 2009).

Typically, 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, to let suspended sediment settle. Some states, including South Carolina, now require porous baffles and surface withdrawal from sediment basins to utilize the full basin volume and discharge less turbid water. Typical BMPs found on construction sites include silt fences, sediment basins, rock check dams, and temporary erosion control measures. These products function as sediment retention devices by reducing flow velocity and allowing gravitational settling.

Total Suspended Solids (TSS)

Total suspended solids (TSS) has been used to evaluate proper functioning of sediment control structures for many years. TSS resulting from erosion are held in the water column by turbulence and encompass both inorganic solids (such as sand, silt, clay) and organic solids (such as algae and detritus) (Thaxton and Palermo, 2000). Suspended Solids (SS) measurements are not routinely used to detect and correct short-term problems or permit violations for two reasons; sediment concentrations cannot be determined easily or quickly in the field and transportation to a laboratory for analysis is time-consuming and can be costly (Thackston and Palermo, 2000). Timely, accurate field estimation of sediment loading could be facilitated through the development of precise relationships between suspended solids and turbidity.

Turbidity

In general terms, turbidity refers to the cloudiness of water. Nephelometric turbidity is an index of light-scattering by suspended particles in water and can be used to quantify water clarity (Davies-Colley and Smith, 2001). Waters with high concentrations of fine suspended sediment are classified as turbid and described by having low visual clarity. According to Mitchell (2000), cloudiness of water is mostly controlled by fine sediment particles with diameters less than 0.05mm that creates intense light scattering. Turbidity measurements quantify the optical impact on water quality by measuring light attenuation, the reduction of light transmission through water (Davies-Colley and Smith, 2001). Figure 1.1 below shows an example of how turbidity resulting from a Piedmont subsoil changes with as a function of settling time.

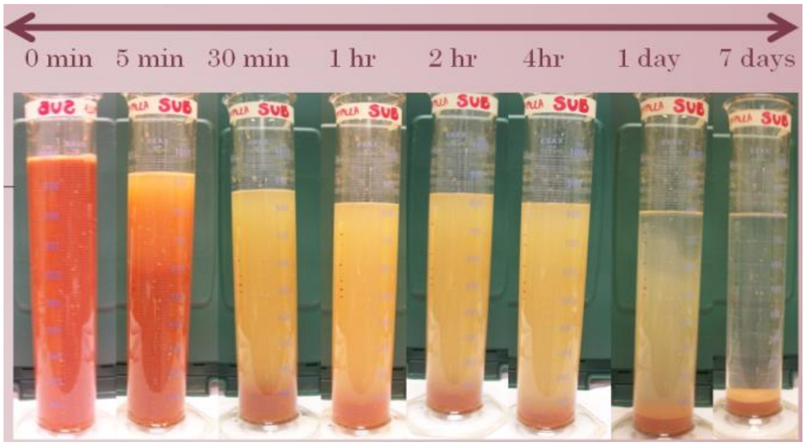


Figure 1.1. **Example of a subsoil turbidity over time.**

Turbidity measurements are gaining increased usage as an indicator of sediment pollution in surface runoff from disturbed areas such as active construction sites. In some states, turbidity has become a regulated pollutant in discharge from construction sites due to corresponding negative environmental impacts. Turbidity effluent guidelines were also selected based on the ability to easily measure and achieve instantaneous results.

In 2009, USEPA released proposed regulations stating that discharges from construction sites disturbing 20 acres or more must comply with a numerical effluent limit of 280 NTU, beginning August 2011 (USEPA, 2009). The same effluent limit would apply to areas disturbing 10 acres or more by February 2014 (USEPA, 2009). Due to industry outcry and potential lawsuits over possible errors in calculating the numeric effluent limit, USEPA revealed that it improperly interpreted data and a stay was issued by the courts rendering the numeric effluent limit moot (USEPA, 2010).

South Carolina has established an in-stream water quality standard for turbidity in which waters with more than 25 percent of samples greater than 50 NTU, collected over a five-year period, are considered impaired waterbodies and listed for turbidity on South Carolina's 303(d) list (SCDHEC, 2004). Of the 1037 impaired waterbodies on the 2016 303d list, 63 are impaired by turbidity (SCDHEC, 2016).

Polyacrylamide

Polyacrylamide (PAM) is a generic term which refers to a broad range of chemical polymers formed from acrylamide subunits. There are hundreds of synthesized PAM varieties which vary in polymer chain length and shape as well as in number and type of functional groups. PAM can be chemically manipulated to be cationic, anionic, or nonionic and is commercially available in several forms (block, powder, emulsion) that can be used in a variety of applications to induce flocculation.

Anionic PAM is commonly used in environmental applications due to low aquatic toxicity when compared to nonionic and cationic PAM. 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) when applied in a terrestrial environment. 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 interest to protect water bodies from disturbed landscapes and meet current and potential future environmental regulations.

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. Comparatively recent successes with low rate application rates in irrigation led to a renewed interest in use of PAM on construction sites for erosion prevention and sediment control (Sojka et al., 2007).

Studies on erosion prevention with PAM have shown that PAM was significantly more effective at reducing TSS and turbidity during storm events immediately following application, with efficacy diminishing during subsequent events with no re-application (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. These results suggest a potential benefit to re-application when PAM is used as an erosion prevention measure.

North Carolina is currently promoting and regulating the use of chemical flocculants, such as PAM, for erosion and sediment control on active construction sites, specifically to aid in removal of fine suspended sediment within sediment basins. Regulations specify that permittees can only use chemicals that are listed on the North Carolina Division of Water Quality Approved PAMS/Flocculants List as well as suggesting a maximum recommended concentration (NCDENR, 2011). To meet regulatory requirements, stormwater treated with chemical flocculants or polymers must be routed through sediment basins and/or settling devices to maximize removal of flocculated material prior to discharge to surface waters (NCDENR, 2011).

Construction Site BMPs and Polyacrylamide

Neither ditch checks nor sediment basins significantly reduce turbidity of stormwater runoff (Bhardwaj and McLaughlin, 2008; Berry, 2012). However, research has shown introduction of PAM to these practices can reduce turbidity. PAM use on construction sites can involve active and passive treatment systems. Active treatment involves using energy inputs, usually pumping, to inject PAM into turbid water. Passive treatment introduces PAM into turbid waters without energy inputs in such a way that runoff encounters the chemical compound as it moves naturally through the on-site sediment control practices.

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. 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 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, Canada 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 reduced 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). Blocks 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 (2014) at the Alabama site. The application and re-application of granular PAM to conventional BMPs has potential to address desiccation issues associated with PAM block applications, thus reducing the total amount of PAM necessary for significant turbidity reduction.

Current research suggests PAM application combined with BMPs in construction site runoff can be effective in achieving turbidity reduction objectives established by state and federal effluent limits. Several dosing methods have been explored to evaluate PAM effectiveness in reducing construction-derived turbidity. Research on compost filter socks showed significant turbidity reductions when compared to bare soil, and addition of PAM to compost filter socks significantly reduces turbidity when compared to compost filter socks without polymer (Faucette et al., 2009). One study compared multiple ditch checks in series, with and without PAM application, and found PAM application reduces turbidity by 61-93% when compared to untreated ditch checks (McLaughlin and McCaleb, 2010). In the same study, excelsior sediment tubes performed better than rock ditch checks and rock ditch checks wrapped with excelsior blanket in reducing turbidity when treated or untreated with PAM (McLaughlin and McCaleb, 2010). On a roadway project in the North Carolina mountains, McLaughlin et al. (2009), found an 86% reduction in mean turbidity levels when PAM was applied to sediment tubes.

Berry (2012) looked at passive treatment methods of introducing PAM to a series of five excelsior wood sediment tubes in a triangular channel under simulated runoff conditions. Sediment tubes with no PAM did not reduce 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 subsequently simulating multiple storms, significant reduction occurred, but did not take place 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 desiccation of PAM and its effect on turbidity reduction. Several days after the final runoff simulation of each test, he performed an additional runoff simulation on the same installed sediment tubes. This experiment simulated construction site activity in which an extended dry period may occur between rain events. In the treatment involving multiple storm simulations with no reapplication, the 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. Such results suggested a need for routine or scheduled PAM re-application on construction sites.

Existing Specifications for Polyacrylamide Use

PAM is included in several 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 supporting evidence that PAM has greater benefits when used for sediment control (ALDOT, 2012; NCDOT, 2013). All specifications reviewed share common language addressing requirements to follow manufacturer's application recommendations, to only use approved varieties of PAM, and to capture flocculated material prior to discharge into natural systems. Several states go into greater instructional detail. For example, Florida recommends 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 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.

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).

More examples of how states specify PAM use for sediment control can be found in Table 1.1.

Table 1.1. 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://ww.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.

2. Work Plan

For Part A of this project, data was collected at both the lab scale and field scale. Field research was conducted representing three (3) geographic areas across South Carolina, including the coast, midlands and upstate. Instrument-based and grab sampling was conducted on active SCDOT construction sites. On selected sites where instrument-based techniques were used, time/flow-based composite sampling using Parshall flumes was utilized to obtain storm-weighted averages for ease of comparison between sites and among BMPs. Storm samples were taken using ISCO automated samplers. With real-time automated weather stations, site visits were conducted each time a storm event occurred to collect the samples. Samples were returned to the lab for further analysis of TSS and turbidity. Turbidity and TSS data assessments were made for both the influent and effluent of selected BMPs on SCDOT sites. This data allowed for assessment of turbidity levels from selected BMP discharges in addition to reduction efficiencies of the various BMPs employed. The BMPs evaluated consisted of sediment tubes, rock ditch checks (with and without washed stone on the face), and sediment basins as available. An additional BMP evaluated was the use of baffle systems in sediment basins where possible. Monitoring for field sites for Part A was conducted for two (2) or more storms, each having greater than 0.5 inches of rainfall to provide storm flow turbidity data. This data allowed for assessment of turbidity levels from selected BMP discharges in addition to reduction efficiencies. Initial studies were conducted without flocculants, followed by comparison with projects having passive flocculent treatment.

For lab scale studies, a constructed channel at the Clemson University Erosion Research Facility was used to evaluate various ditch checks (Appendix A, Figure A.1). This test channel was used for both evaluation of ditch checks without the use of any flocculating agent as well as with this agent. These tests were used to evaluate the various techniques employed to passively apply PAM to the ditch checks. Tests were also conducted to evaluate the application interval of PAM.

Under Part B of this proposal, research was conducted across the state on active SCDOT construction sites containing sediment basins to determine if surface withdrawal structures can reduce downstream turbidities and TSS. Since only one site during the study contained an active basin with skimmers and baffles, measurement and evaluations were conducted in a controlled research field experiment setting at the Clemson University Erosion Research Facility. For baffle testing, lab experiments were also conducted in controlled experiments using a sediment dam/basin constructed at the Clemson University Erosion Research Facility. Various baffle placements, material type, and mesh-opening configurations (0, 5-15, 15-25, 25-35, >35%) were tested to evaluate effectiveness. Known concentrations and turbidity levels were released into the baffled basin/dam whereby influent and effluent samples were taken to evaluate removal efficiencies. Passive flocculent testing was then evaluated on these various baffle configurations to evaluate removal efficiencies of flocculent additions. These laboratory assessments along with field tests, were then used to develop construction specifications for baffle arrangements and installations.

Test Channel Design Methodologies

This research focused on optimizing sediment tube configuration with passive PAM application for turbidity reduction. Research was aimed at answering questions related to how to effectively administer PAM, as well as determining how dry weather after runoff events affect PAM and turbidity reductions. Ultimately, the goal of this phase of research was to provide recommendations on PAM application method, application frequency, and sediment tube configuration to achieve highest turbidity reductions.

Experimental Site

To replicate conditions found on a typical construction site, a 185-ft triangular channel, 12-ft wide with an average depth of 1.65-ft, at a 7% slope was constructed and lined with a 50 mil HDPE liner (Appendix A, Figure A.1). To have correct spacing between five sediment tubes (reasoning for the selected spacing will be explained later in this section), 150-ft of channel length was needed, but a steep slope at the upper portion of the channel would have resulted in a non-uniform slope between sediment tubes. The channel was lined to prevent scouring and erosion, which would add to the total sediment load during experimentation and compromise results.

Since the goal of this research involved simulating construction site runoff, it was important to acquire a flow rate that was representative of flow rates found on South Carolina construction sites. To determine a typical flow rate, 1-year, 24-hour rainfall events were averaged for Greenville, Richland, and Charleston Counties. The average 1-year, 24-hour rainfall amount was 3.4 inches. A peak flow rate of 2.5 cfs was calculated for a newly graded 1-acre site at a 2% slope comprised of 50% hydrologic soil group (HSG) A and 50% HSG B soils. To achieve a representative flow rate, a 4,800-gallon collapsible tank was chosen to simulate runoff from construction sites. The tank was filled with water from an adjacent pond using a 5-hp semi-trash pump. The tank had a 6-inch outlet controlled by a 6-inch gate valve that drained the tank in 12 minutes. The tank discharge flow rate was calculated over the 12-minute interval. The peak flow rate discharged from the tank was 1.91 cfs, and the average flow rate over 12 minutes was 0.72 cfs. The actual tank peak discharge was slightly less than the original design peak flowrate of 2.5 cfs

A homogenous sediment-water solution was needed to mimic runoff from a construction site. To achieve these conditions, kaolinite clay was chosen to be the test soil. Kaolinite 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. For this research project, Paragon®, a trade name for kaolinite clay used by

IMERYS Minerals Company, was acquired from the Langley, SC mine. Specifications for this material can be found in Appendix A, Table A.1.

An 11-hp pump with a flow rate of 335 gallons per minute was used to recirculate the mixture keeping kaolinite clay suspended in the 4,800-gallon tank. A nozzle configuration was developed to increase velocity and keep particles suspended. Each nozzle produced an average velocity of 17 ft/s, which was determined mathematically using the known flow rate of the 11-hp pump and area of the 1-in nozzles. For each run, target turbidity in the tank was between 1,600 and 2,000 NTU and measured by an Analite NEP160 display with NEP260 probe handheld turbidity meter, with a range of 0-3,000 NTU (McVan Instruments, 2012). Based on the reading, the amount of Kaolinite added to the tank varied from 50-lbs to 100-lbs to produce similar tank turbidity readings.

For this research, 20-in diameter, 10-ft American Excelsior Curlex® Sediment Logs® were selected (American Excelsior Company, 2012). Selection of sediment tubes was governed by price and recommended products on the SCDOT Qualified Product List 57. Based on the length of the channel, five sediment tubes were used in series. Following SCDOT specifications, the spacing requirement for sediment tubes acting as ditch checks on a greater than 6% slope is 25-ft (SCDOT, 2011). Following SCDOT guidelines, for this research sediment tubes were placed at 25-ft spacing (Appendix A, Figure A.2).

Due to the lined channel, SCDOT-specified installation of sediment tubes could not be performed. To anchor the tubes, tee posts were bent 90 degrees with a 10-in over hang and driven into the ground so that only approximately 14-in remained. Tubes were then compacted under the tee posts to ensure under cutting of the tube would not occur. SCDOT specifications dictate that for in-field installation sediment tubes should be trenched to a depth that is 20% of the sediment tube diameter (SCDOT, 2011). Thus, the effective ponding depth for this research versus SCDOT specifications is very similar.

Six ISCO 3700 samplers were programed to sample the entire simulated runoff event (Teledyne ISCO, 2012). Liquid detectors activated samplers and sampling continued over 4-min time intervals. Sampling stopped when liquid detectors were inhibited. Sampling probes were placed directly at the outlet of the tank and on the downstream side of each sediment tube.

Polymer Optimization

Applied Polymer Systems, Inc. 700 Series Silt Stop Polyacrylamide Erosion Control Powder was chosen to be the flocculating agent for this project (APS, 2012). The 700 series is a polyacrylamide co-polymer powder that is tailored to be soil specific. To determine the correct polymer to use with the kaolinite, a series of laboratory scale jar tests were performed. Six polymer types within the 700 series were tested, which include #705, #707, #712, #730, #740, and #745. To test each polymer, manufacture instructions for testing APS powders were followed (APS, 2012). Jars were observed for clarity of water, largest particulate formed, and the time it took for particles to settle. Jar tests showed that kaolinite responded best to APS #705 polymer.

Polymer Application Technique Evaluations

To test if PAM application techniques affected turbidity, four tests varied the application of APS #705 polymer, while keeping all other parameters constant. For this experiment, a simulated runoff event consisting of 4,800 gallons of water and complete draining of the tank is referred to as a run. A test consisted of five separate runs aimed at determining the longevity of PAM completed within 24-hrs. All tests were duplicated for statistical accuracy. In many cases, a 6th run was added to each of the tests and completed several days after the previous run. The waiting period between the last run was to allow the tubes and PAM to dry to evaluate each test, used tubes were discarded, the channel was cleaned, and excess sediment accumulation in the tank was removed. Descriptions of the three PAM applications and control experiment are described below:

1. The experimental control consisted of runs where no PAM was applied. The control was thus able to assess whether sediment tubes alone would have any effect on turbidity.
2. 100-g of granular #705 PAM applied directly on each of the five sediment tubes and reapplied each time before five simulated runoff events.
3. 100-g of #705 PAM applied directly on each of the five sediment tubes applied only once before five simulated runoff events.
4. The fourth test applied 500-g of #705 PAM in a 6” x 26” smooth weave 400-micron permeable bag. A bag was placed on the upstream side of each sediment tube. Thus, the bag for tube one was placed at the outlet of the tank and the bag for tube two was placed on the downstream side of tube one, etc. Bags remained in place throughout a test.

Longevity Testing of PAM

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 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.

Wait times of 0, 3, 5, and 10 days were given alphabetic designations of "f," A, B, and C 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 enough 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 to represent the five-day wait time. Finally, one ten-day test was conducted to assess whether longer duration intervals would have similar results.

Statistical Analysis

Tests performed to compare mean turbidity and TSS of runs, sample positions, application techniques and application intervals include, regression analysis, analysis of variance, and t-tests. The statistical significance tests used an alpha value of ≤ 0.05 unless otherwise stated. Statistical calculations were performed with JMP statistics software (SAS Institute Inc., Cary, NC, USA).

Field Testing Procedures

Procedures described above were used on active SCDOT construction sites to measure TSS and turbidity discharges to evaluate linear BMPs. Instrument stations were established at the start of each conveyance channel before the first BMP and after the last BMP to establish "Before and After" turbidity readings to evaluate the sediment removal efficiency of the BMPs. Automated sampling equipment was deployed at each station to collect runoff samples for TSS and further turbidity analysis.

Field Sites

In September of 2013, automated sampling instrumentation and 6-inch Parshall Flumes were deployed in a runoff conveyance channel associated with the widening of SC Highway 9 in Boiling Springs, SC

(Appendix B, Figure B.1). The channel ran parallel to Holden Drive, which runs perpendicular to and down-grade from Highway 9 as shown in Figure B.2 in Appendix B. The channel had a slope of 5% and then flattened out at the bottom of the hill, before discharging into a designed sediment basin. The channel was lined with turf reinforcement matting in the center and erosion control blankets 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 6.9 acres, with 2.2 acres being roadway. 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. 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 3.2 from the 30-inch culvert.

Likewise, in December 2014, automated sampling instrumentation was deployed and staked in a runoff conveyance channel associated with the widening of SC Highway 52 in Darlington, SC. The channel ran parallel to Hwy 52 (Appendix B, Figure B.3). The channel was soil based with sparse vegetation on the sides for stabilization, had a slope of 1%, and received direct runoff from the project along Hwy 52, and then discharged into a sediment basin. The drainage area contributing runoff to the channel was 20.6 acres, with 0.25 acres of that being the road. Based on the NRCS Web Soil Survey, the area of interest was 51% Foxworth sand, 25% Alpin sand, 23% Johnston sandy loam, and a small area of Autryville sand. Instrumentation was installed at the top of channel and bottom of the channel enclosing three ditch checks made of either coiler waddles or Class A rip rap faced with washed stone (Appendix B, Figure B.4).

Finally, automatic sampling equipment and 6-inch Parshall Flumes were installed in the coastal plains of South Carolina. The first linear conveyance channel monitored was off SC Highway 41 in Charleston, SC adjacent to a bridge replacement over the Wando River (Appendix B, Figure B.5 and B.6). This site was eventually relocated due to lack of flow and progression of the construction. However, data was collected for two adequately sized storms in this channel. The site consisted of three sediment tubes in a low sloped channel typical of the region. The predominant soil types were a sand and silt mix. The second site used was in Summerville SC, off exit ramp 197 on Interstate 26 east bound and had a slope of 0.05%. Flumes were placed to enclose four BMP structures. Three BMP types were monitored, these were sediment tubes, rock check dams with class A riprap, and the same rock check dams with #57 washed stone on the face. NRCS Web Soil Survey indicated that the roughly 0.81-hectare drainage was 100% Pantego Sandy Loam.

The coastal and upstate monitoring sites consisted of a 6-inch Parshall flume with a Campbell Scientific CS451 pressure transducer to measure flow depth (Appendix B, Figure B.7). From this depth, the flow rate through the flume was calculated. The flumes were installed with 45-degree plywood wing walls. Installation involved trenching 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. The mid-state monitoring site did not use a

Parshall flume, top of channel data was collected from within the channel with an ISCO Teledyne AV Probe to record depth of the runoff, and a Campbell Scientific OBS 500 turbidimeter.

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 data logger 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 were triggered based on presence of runoff through the Parshall flumes at the upstate and coastal sites. 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 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 and 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 Appendix B, Table B.1. Samples of 750 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 fifteen 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.

A “base station” was also established at the site to record rainfall and enable telecommunication (Appendix B, Figure B.8). This consisted of a Campbell CR1000 data logger connected to a tipping bucket rain gage, a RF401 radio, and cellular modem. Programming was established such that one could communicate with the system remotely using Campbell Loggernet software. Rainfall data was available by connecting to the CR1000 data logger. Flow rate and turbidity data was available by communicating through the base station to the instrument stations using radio telemetry. Figure 3.8 in the Appendix shows the instrument station at the bottom of the channel which included the base station (white box and large antenna) and rain gage.

Background data was collected for runoff events on BMPs with no PAM treatment, followed by a period of PAM application and reapplication to evaluate turbidity reduction using PAM. Each PAM application involved applying 100 grams of granular APS #705, #710, #712 PAM for the upstate site, coastal region, and mid-state respectively.

The specific PAM product used for each site was based on jar test results, 200 mL of deionized water was placed in a container with 5 mg of dried soil collected from the research sites. The jar was inverted repeatedly until a homogenous mixture was seen. Baseline turbidity analysis measurements were recorded, the turbidity analysis is described in the next section. Afterwards, a 0.05 mL dissolved PAM product was injected into the jar and turbidity readings were noted, this process was repeated several times to determine the best application rate of PAM and which PAM product was most efficient in reducing turbidity. The most effective granular PAM for the region was applied upon the top and upstream face of the BMP structures, such that runoff was likely to make contact. During this study, PAM was reapplied after periods of rain which caused runoff events. This was compared to the specification to reapply after every 0.5-inch rain event which is used in North Carolina NCDOT (NCDOT, 2013). Observations made support it being an effective rule for reapplying 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.

Scaled Basin Analysis

The sediment basin was located at the Clemson University Erosion Research Facility in Pickens County, South Carolina. The pond design was built at a 1:5 scale from the SCDOT standard drawing. The inlet channel was an 89.9’ parabolic concrete cloth lined channel, and the effluent from the pond was discharged into a native grass lined earthen parabolic channel which drained into a stilling basin to allow further settling of fugitive sediments from the detention pond via a floating surface skimmer. Effluent from the settling pond was discharged through a rock ditch check dam consisting of rip rap and faced with #57 washed stone.

Inflow was provided via a 4” Multiquip (Carson, CA) pump driven by a 10.7-hp engine. The PVC inlet hose was 50’ long and located at a depth of approximately 2 feet below the water surface of the pond and 2’ above the bottom of the pond. The hose was secured to T-posts driven near the inlet and midway along the length to minimize hose movement. The inlet was protected by a strainer to minimize large debris from entering the pump. There was roughly 7’ of head between the inlet and pump. Discharge from the pump was through 50’ of flexible PVC hose and then through a series of 8” rigid pipe until emptying into the parabolic channel. The pump provided a constant flow rate of 0.8 cfs.

Cecil soil used for the study was obtained from an adjacent field. A hydrometer test was performed to determine textural composition (ASTM D 422-62 (2002)) and was found to be 71% sand, 12% silt and 17% clay. Before use, the soil was screened through a 0.25”x 0.25” screen to remove large rocks, roots, and clods. No other soil treatment was performed prior to use. Four cubic feet of soil was added to the water stream during each run via an 18”x 6” slot cut into the top of the last pipe, the soil was added at a steady as possible rate. Soil deposited after each run was left in the pond to investigate the possibility of resuspension of the deposited soil on subsequent runs. After each third run, the pond was pressure-washed to remove residual sediment deposits and new baffle material was installed.

Baffles of various materials and percent openings were tested to determine which percent opening and/or materials were optimal in reducing TSS and turbidity. Figure 2.1 shows several of the baffles tested and the percent openings of each. The baffle listed as “Baffle 4D” in figures and tables is Baffle 4 that was doubled over to provide increased resistance to flow. Many contractors use this method in the field. Baffles #6 and #7 (not shown in Figure 2.1) consisted of curled excelsior wood material and synthetic turf reinforcement matting.

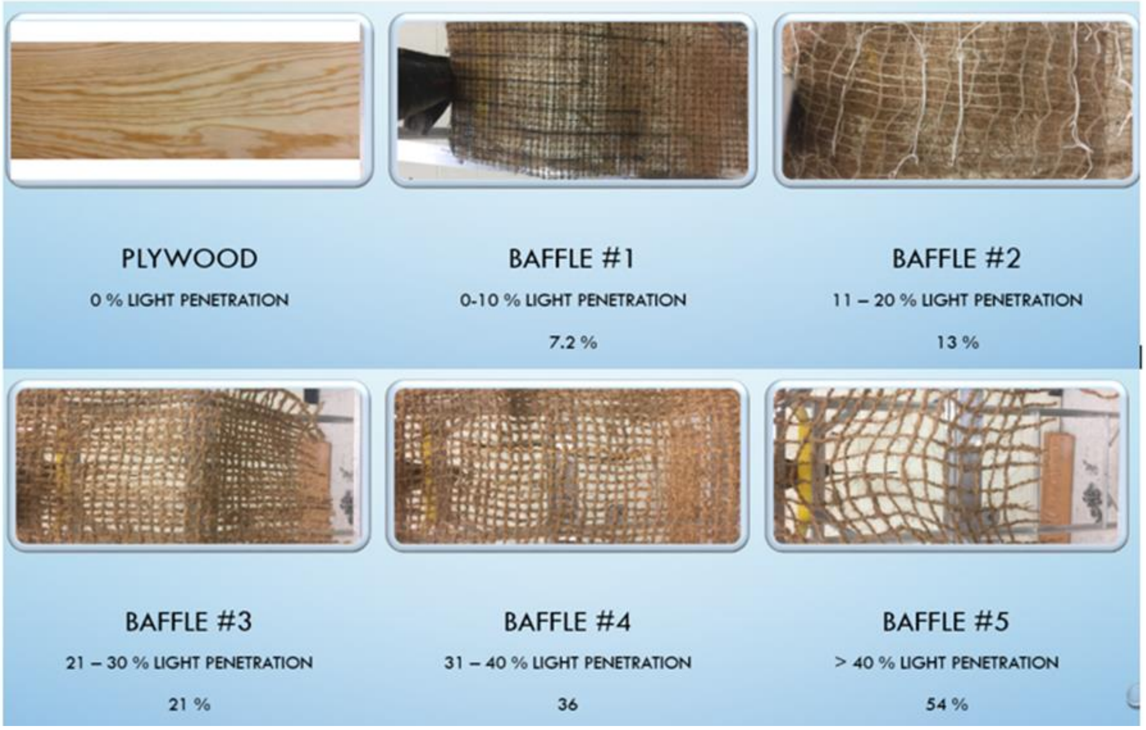


Figure 2.1. Various baffles tested with corresponding percent light penetration ratings.

Plastic encased stainless steel ¼” cable was strung between the top and bottom of the T-post to provide additional support such that the baffle material would be less prone to sagging during the multiple tests. Baffles were secured to the T-posts and cable with cable ties. Figure C.2 in Appendix C shows the sediment basin with baffles installed.

Test runs were initially performed with surface skimmers alone to determine basin efficiency without baffles. Each test consisted of three runs, and tests were performed for each baffle material and weave configuration. The basin was power-washed between each test to remove deposited sediment. The effects of PAM were then evaluated using the same test/run methodology. Prior to each baffle, a passive application of 100 g of PAM was evenly distributed along the bottom and sides lopes of the basin.

Water samples were taken using ISCO 3700 auto-samplers located at the bottom of the inlet channel prior to entering the sediment basin, at mid-basin after the first baffle, and inside the discharge pipe (Appendix C, Figure C.2). The timing sequence of the sample collection, Table C.1 in Appendix C, was formulated to capture the “first flush” of the event and then at intervals allowing the duration of the basin cycle to be captured.

After each run the collected samples were taken back for laboratory analysis. Each sample was analyzed for TSS and turbidity. TSS analysis was conducted via ASTM 2440D methodology and turbidity analysis was done using the USEPA 180.1 procedure. Additionally, after the third run, sediment samples were collected in each section of the basin to determine the size distribution of the particles deposited. The particle size analysis consisted of sieve analysis and pipette analysis. The sieve analysis determined the particles in the basin section between 2mm and .063mm. The pipette analysis determined the particles less than 0.063mm to 0.002mm, any remaining mass was considered < 0.002mm. Sieve analysis followed ASTM C136/C136M procedure with the mass of sample ran through the sieve stack being 15g. The pipette procedure (Olmstead et al., 1930) without chemical dispersion, was used to determine the fraction of silt and clay in each basin section.

Several different methods were used to determine the percent change in TSS and turbidity for a given baffle and skimmer system.

The mean of each individual run for the influent and effluent was used to determine the percent reduction for each baffle.

$$\frac{\dfrac{\sum \mathit{Individual\ Run\ Influent\ Values}}{n} - \dfrac{\sum \mathit{Individual\ Run\ Effluent\ Values}}{n}}{\dfrac{\sum \mathit{Individual\ Run\ Influent\ Values}}{n}} * 100 \qquad (1)$$

The mean of all three runs were calculated and used to determine the percent change. This methodology would simulate the performance of the sediment basin between the mandated maintenance and the accumulated sediment removal.

$$\frac{\dfrac{\sum_1^3 \mathit{Influent\ Values}_i}{\sum_1^3 n_i} - \dfrac{\sum_1^3 \mathit{Effluent\ Values}_i}{\sum_1^3 n_i}}{\dfrac{\sum_1^3 \mathit{Influent\ Values}_i}{\sum_1^3 n_i}} * 100 \qquad (2)$$

Lab 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 evenly suspended, displaying a homogenous solution. A 30mm aliquot was pulled from the sample bottle using a pipette. One sample was collected for each bottle. The sample was then transferred into a Hach turbidimeter vial. The vial was wiped clean, carefully inverted 10 times, and placed into the turbidimeter. The Hach turbidimeter measures turbidity by sending light through the vial and measuring reflectance back in NTUs. After turbidity analysis, samples were analyzed for TSS using Standard Method 2540 B (APHA, 2005).

For each region in this study a particle size analysis was conducted. Soil samples were collected from the research sites, multiple samples per site were analyzed from upstream and in channel locations. The analysis consisted of weighing 10g of 2mm or less sized soil, drying them in an oven overnight at 104 degrees Celsius and placing them in a nest of sieves that had a top to bottom size order from 2, 1, 0.5, 0.25, 0.125, 0.063 mm and a catch pan at the base. The sieves were then shaken using a motorized sieve shaker for 3 minutes. The weight of each sieve was recorded along with the sieve plus sample weight. The sieves are then placed in order over a funnel draining to the 1L graduated cylinder. Using deionized water, the sieves and catch pan were rinsed to wash the remaining sediment into the graduated cylinder, continuing to rinse until the graduated cylinder was filled to 1L. The rinsed sieves were then dried overnight at 104 degrees Celsius and weighed once pulled from the oven and placed in a desiccator for 30 minutes. The cylinders' contents were then agitated using a magnet and magnetic plate. Using a 25mL pipette, samples were extracted at different time intervals as shown in Appendix B, Table B.2 based on an initial sample temperature taken in degrees Celsius. The samples were extracted at 150mm from the top of the graduated cylinder for the first 4 steps and then raised to 100mm and 50mm respectively for the remaining two sample intervals. The collected samples were deposited into beakers that were then dried overnight at 104 degrees Celsius and weighed once pulled from the oven and placed in a desiccator for 30 minutes. The delivery volume was recorded, and the values were used to calculate sand, silt, and clay percentages, by weight of soil samples by particle size. Textural classifications were calculated based on these percentages.

Statistical Analysis

Due to the relatively small runoff sample size collected during 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. This analysis was run on both water samples collected and OBS turbidimeter readings from qualifying storms. LSD means test and analysis of variance (ANOVA) were completed to determine if there were significant statistical differences between BMPs. Samples were time weighted based on the sampling increment shown in Appendix Table 3.1 and averaged over the total storm period.

Toxicity Testing Methods

Due to inherent uncertainty associated with environmental application of flocculants, including PAM, toxicity tests were conducted on selected polymer compounds. Laboratory assays were conducted to assess toxicity impacts on both invertebrate and vertebrate species: *Daphnia magna* (*D. magna*) assay and *Pimephales promelas (P. promelas)* assay. These procedures were used to determine the nominal LC_{50} of the various flocculants tested. An LC_{50} assay is a standard aquatic toxicology measure of the toxicity of the surrounding medium that would kill half (50%) of the sample population of the test organisms within a specified period as a result of their exposure to the analyte. Acute toxicity (single dose) tests were conducted on *D. magna* and *P. promelas*, while chronic toxicity (8-day exposure; 24-hour renewal) was evaluated using *Ceriodaphnia dubia (C. dubia)*.

Five commercially available PAMs were selected for use in toxicity testing. Three were anionic and 2 were cationic. Each was mixed into solution at concentrations provided in the manufacturer's specifications. PAM was weighed in a laminar flow hood and then added to the exposure water and allowed to stir for 48-hours to allow maximum dissolution of the PAM, but to limit bacterial growth that could influence toxicity.

Daphnia magna assays

Organisms were cultured in reconstituted moderately hard water renewed daily. Daphnid neonates were exposed to selected flocculants for 48 hours under static conditions with a 24-hour renewal period. Static renewal tests were conducted with a 16:8-hour light: dark cycle. Tests were blocked around chloride levels of 3, 10, 40, and 60 mg/L. Hardness and humic acid were used in conjunction with six concentrations of each PAM flocculent in a complete factorial design totaling 48 treatments per blocked test.

Test water was mixed in 15-L polypropylene carboys and aerated for 48 hours before use. Reconstituted waters were prepared from reagent-grade salts ($CaSO_4$, KCl, and $MgSO_4$), humic acid and ultrapure water. Selected flocculants were used to prepare a stock in ultrapure water acidified to pH 2. This stock was used to fortify all dilution waters and mixed in graduated pitchers before testing. New stock solution was prepared for each bioassay. Appropriate volumes of each flocculant stock were added to 600-ml polypropylene beakers to generate the desired flocculent concentrations.

After thorough mixing, 40 ml of the control or treatment solution was poured into six replicate 50-ml polystyrene test chambers. Mortality, temperature, feeding, and light levels were measured daily. Mobility, determined using a handheld 2X magnifying lens, was monitored and recorded during the first 12 hours, then at 24 and 48 hours. The absence of any appendicular movement was used as the endpoint for mortality. After mobility was recorded at test completion, contents of the polystyrene test chambers, for each treatment level, was recombined in a beaker. Dissolved oxygen and pH were measured and recorded. Aliquots were removed for final analyses of dissolved organic carbon (DOC), alkalinity, hardness, chloride, and silver.

Pimephales promelas assays

Fathead minnow larvae (P. *promelas*) less than 24 hours old were purchased and inspected for viability upon receipt. The fish were acclimated in water with equivalent hardnesses to test conditions (soft, moderately hard, and hard) for 3 days before experiments commenced. Minnows were fed brine shrimp larvae before the start of experiments.

Acute (96-hour), single dose, nonrenewal tests were conducted at 22 ± 1°C with a 16:8-hour light: dark cycle. Fluorescent bulbs provided a light intensity between 50–100 ft-c. Mean alkalinity and pH were 93 mg $CaCO_3$/L and 8.3, respectively. Dissolved oxygen was controlled so concentrations never falls below 7.3 mg/L. Tests were blocked around chloride levels of 3, 20, 40, and 60 mg/L. Hardness and humic acid was used in conjunction with six concentrations of each flocculent concentration in a complete factorial design, totaling 54 treatments per blocked test. Each treatment had three replicates containing 10 fish.

Test water was mixed in 15-L polypropylene carboys and aerated for 48 hours before test initiation. Reconstituted waters were prepared from reagent-grade salts (humic acid and ultrapure water. Each flocculent was used to prepare a stock in ultrapure water acidified to pH 2. This stock was used to fortify all dilution waters, which were mixed in graduated polypropylene pitchers before testing. New stock solution was prepared for each bioassay. An extra-large transfer pipette was used to place 10 fry into each 600-ml polypropylene beaker not more than 30 minutes after the addition of 500 ml of test solution. Mortality was assessed daily and will be defined as lack of movement or response to tactile stimuli.

Temperature, pH, and dissolved oxygen of test solutions were measured before test initiation and then daily for the remainder of each 96-hour test. Alkalinity and hardness were measured at test initiation (0 hours) and completion (96 hours). Each test solution was analyzed for flocculent concentrations at test initiation and completion or whenever 100% mortality occurred.

3. Findings and Conclusions

The following findings were derived from the various lab studies focusing on channel ditch checks with and without flocculation, lab scale sediment basin evaluation, and field data collected on site at various SCDOT construction sites.

Application Techniques and Spacing

To evaluate how application treatments, affect turbidity and TSS, a JMP model was developed to analyze response of mean turbidity and TSS across runs, sample locations, and duplicate tests. Simple means testing within each treatment determined whether change in turbidity was caused by PAM application. For this research, the sample location for the tank outlet, sediment tube 1, sediment tube 2, sediment tube 3, sediment tube 4, and sediment tube 5 will be referred to as L0, L1, L2, L3, L4, and L5, respectively.

Treatment 1: Control

Representing the control, Treatment 1 was intended to evaluate whether sediment tubes by themselves have any effect on turbidity and TSS. To determine whether turbidity reductions occurred across sediment tube positions, turbidity values at each sample location were averaged for all runs. Simple means testing showed there was no statistical numeric difference in turbidity values across sediment tube position. F –test results revealed that mean turbidity across sample locations (F-stat = 0.0588, p = 0.9975, n = 60) was not significantly different. In Figure 3.1, turbidity remains constant across locations for all runs, in which locations connected by same letter are not significantly different. Had sediment tubes created a reduction, turbidity values would have been statically different across locations. Mean turbidity discharged from sediment tube 5 was 3104 NTU, which is well above the proposed USEPA 280 NTU effluent limit. Results suggest that sediment tubes alone are insufficient to reduce turbidity below proposed regulated limits.

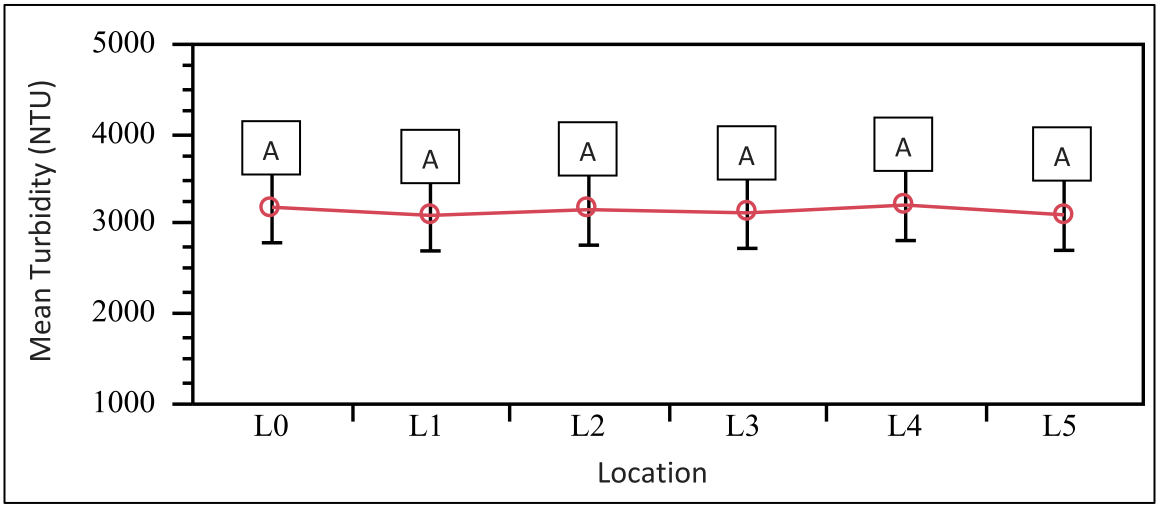


Figure 3.1 – **Mean turbidity across sample locations for Treatment 1.**

Cumulative turbidity percent reduction values may appear to suggest a slight reduction in turbidity, but statistical results demonstrate that none are significantly different (p = 0.9817). Figure 3.2 shows mean turbidity percent reductions across locations for all runs; sample locations connected by same letter are not significantly different.

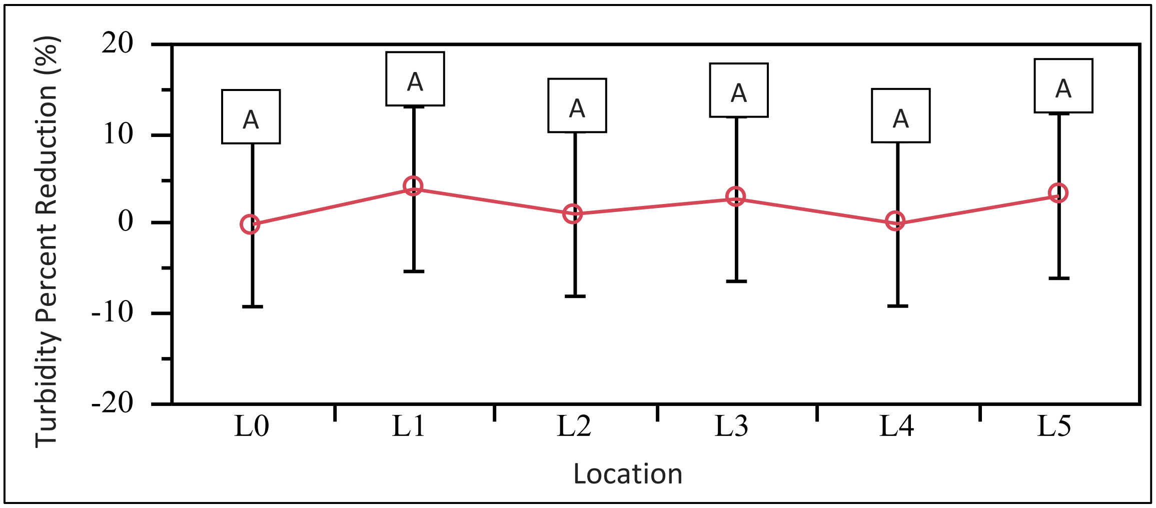


Figure 3.2 – **Cumulative percent reduction of turbidity for Treatment 1.**

Statistical analysis failed to find a relationship between mean TSS and sample location (F-stat = 1.2802, p = 0.3112, n = 30). Graphical results show a significant decrease at location L2 in TSS; however, due to a TSS increase at location L3, L4, and L5 it is possible to conclude that a decrease in TSS failed to occur. Figure 3.3 shows mean TSS across sample locations for all runs; runs connected by same letter are not significantly different.

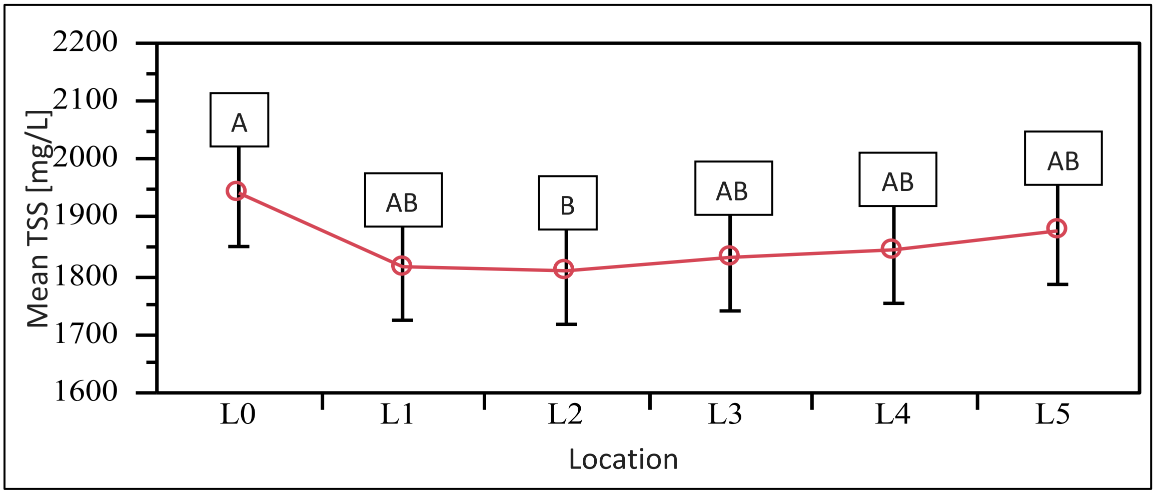


Figure 3.3 – **Mean TSS concentration across all sample locations for Treatment 1.**

Graphical results suggest cumulative TSS percent reduction occurs across sample locations, but statistical results show that no values are significantly different (p = 0.38). Figure 3.4 shows average TSS percent reductions across locations for all runs, sample locations connected by same letter are not significantly different.

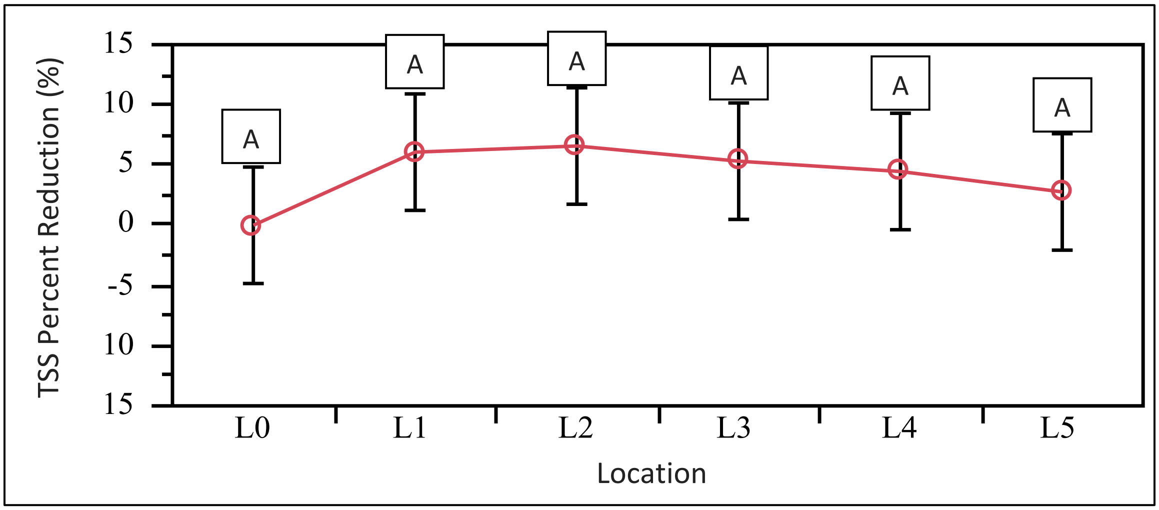


Figure 3.4 – **Cumulative percent reduction TSS across sample locations for Treatment 1.**

A summary graph found in Appendix A, Figure A.3, displays turbidity across sample locations for each run. Mean turbidity increases with runs and turbidity remains constant across locations for each run. With lack of consistent reductions in turbidity it is possible to conclude that sediment tubes alone are ineffective at reducing turbidity. From Figure A.4, TSS data is highly variable and displays no evidence of consistent TSS reduction.

Treatment 1 results strongly suggest sediment tubes as installed provided no significant reduction in turbidity levels for simulated sediment-laden flows. Further, results did not achieve a mean turbidity value that would meet the proposed USEPA numeric turbidity effluent limit of 280 NTU. In addition, sediment tubes provided no significant reduction in finely suspended sediment that cause high turbidity levels. Lack of consistent reductions in turbidity and TSS may be attributed to the open-weave construction of the sediment tubes, which allows fine sediment to pass through and provides minimal resistance to decrease flow rate. Based on results from Treatment 1, it is possible to conclude that sediment tubes are not effective in reducing turbidity under simulated flow conditions for the experiment, which are likely to be found on linear construction projects.

Treatment 2: Multiple PAM Applications

To test various PAM application methods, Treatment 2 applied 100-g granular APS #705 PAM sprinkled to each of the five sediment tubes before each subsequent run. F-test results show a constant mean turbidity (Figure 3.5) over 5 runs (F-stat = 0.3720, p= 0.8266, n = 60). Based on this result, mean turbidity did not fluctuate greatly between runs and any change in turbidity for Treatment 2 due to PAM interaction would be evident across sample locations.

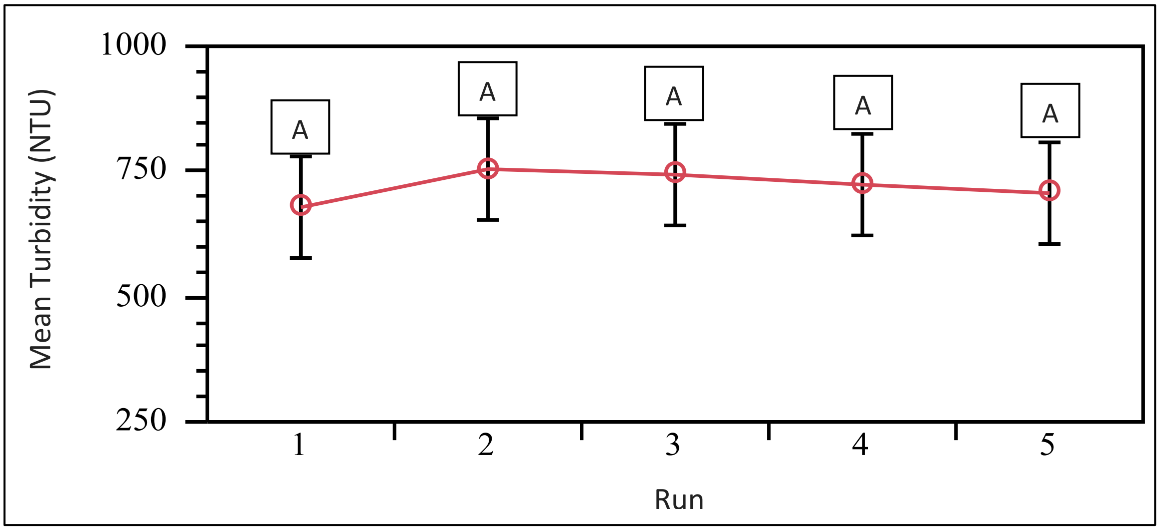


Figure 3.5 – Mean turbidity across runs for Treatment 2.

F–test results revealed that mean turbidity across sampled locations (F-stat =246.95, p = <.0001, n = 60) was significantly different. Additionally, follow-up t-test results show a significant difference in mean turbidity (Table 3.1) numbers across locations L0, L1, and L2 and failed to find a significant difference between locations L3, L4, and L5. Mean turbidity discharged from L5 is 82 NTU, well below the proposed 280 NTU limit. Based on statistical results, a significant decrease in mean turbidity is achieved with two sediment tubes in series. However, turbidity levels achieve the proposed 280 NTU limit between location L2 and L3 (Figure 3.6). Therefore, three sediment tubes would be needed to meet the proposed turbidity numeric effluent limits based on the tested flow conditions.

Table 3.1 – Mean turbidity for all locations within Treatment 2.

Location					
L0	L1	L2	L3	L4	L5
2192 (n=39)	1311 (n=57)	412 (n=65)	202 (n=67)	126 (n=67)	82 (n=69)

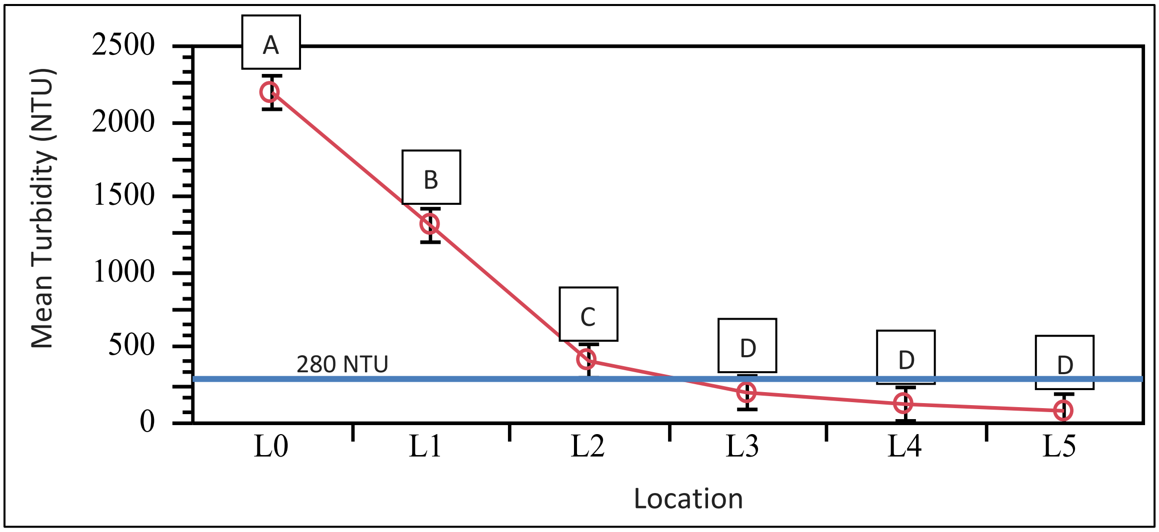


Figure 3.6 - Mean turbidity across sample locations for Treatment 2.

Percent reduction allows for quantification of how the system performs and calculation of turbidity removal at each sample location. With five sediment tubes in place, mean cumulative percent reduction of turbidity is 96% (Figure 3.7). T-test results indicate a significant difference in mean turbidity percent reduction values across locations L1, L2, L3, and L5. These results will be important to correctly determine the number of sediment tubes needed in a treatment series for turbidity.

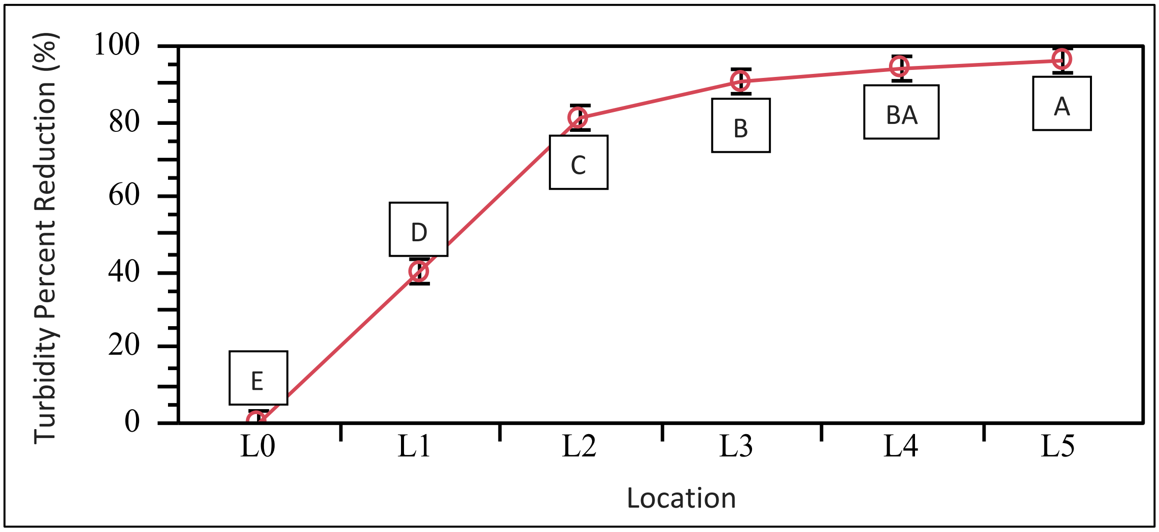


Figure 3.7 – Cumulative percent reduction of turbidity for Treatment 2.

Figure A.5 in Appendix A illustrates how well Treatment 2 performed as evidenced by the tight grouping of turbidity values. T-tests reveal no significant difference between location and run turbidity values (p = 0.96), which suggests Treatment 2 reduces turbidity to the same level in every run.

Figures 3.8 displays a continuous decrease in mean TSS across sample locations. F-test results show a decrease in mean TSS over sample locations (F-stat = 54.6003, p<0.0001, n = 60). Figure A.6 in Appendix A shows the average TSS across each run across each log location.

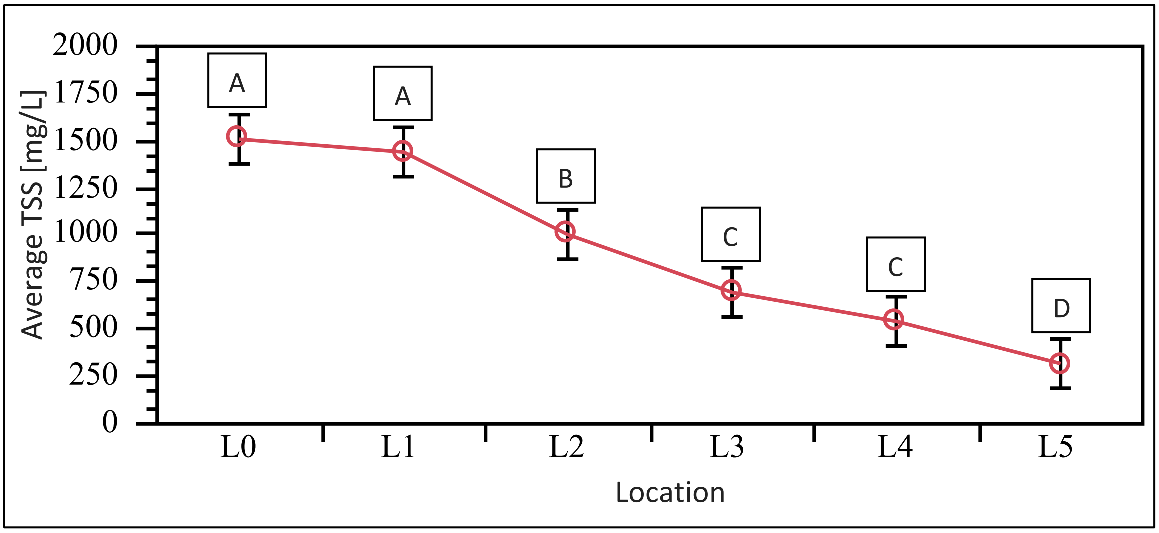


Figure 3.8 – Mean TSS concentration for all sample locations for Treatment 2.

Cumulative TSS percent reductions increased with sample location (Figure 3.9) as PAM interactions with clay particles created large flocs that gradually settled out of suspension. Percent reduction data does reveal minimal TSS reduction between locations L0 and L1, which is likely due to the lack of PAM interaction and settling time between the tank outlet and the first sediment tube.

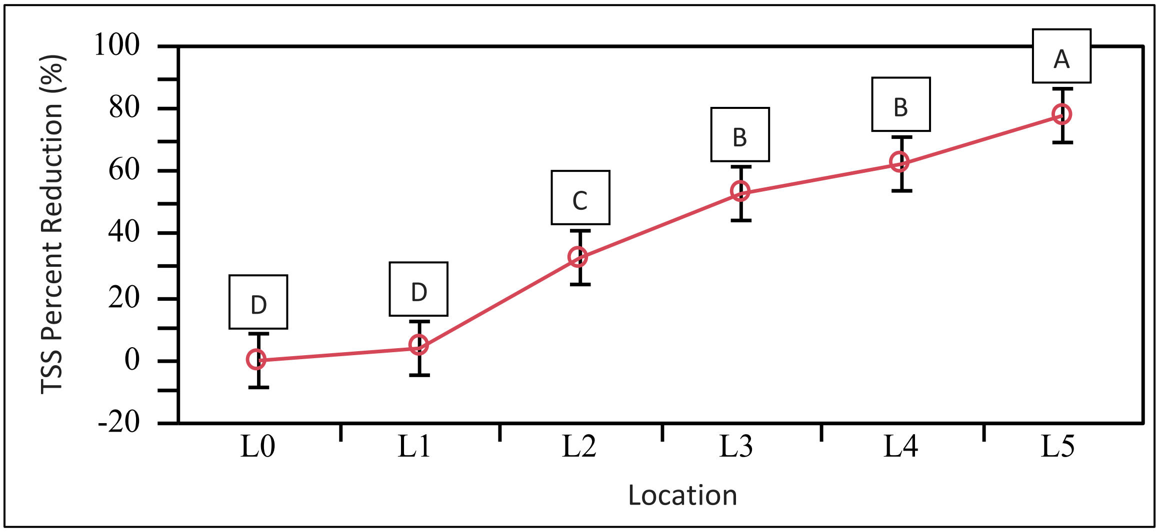


Figure 3.9 – Cumulative TSS percent reduction for Treatment 2.

In summary, results from Treatment 2 demonstrate the effectiveness of PAM application for turbidity reduction under designed conditions. Mean discharge from location L5 of turbidity and TSS is 82 NTU and 319 mg/L, respectively. Additionally, mean cumulative reduction for turbidity and TSS is 96% and 78%, respectively. Due to the removal efficiency of Treatment 2, no significant difference in turbidity values was observed after sediment tube 2, but three sediment tubes are needed to achieve the proposed USEPA 280 NTU effluent limit. Depending on turbidity regulations, sediment tubes configuration with sprinkled PAM can be modified to effectively reduce turbidity.

Treatment 3: Single PAM Application

For Treatment 3, 100-g granular APS #705 PAM was sprinkled on each of five sediment tubes before the initial run and not applied again. F-test results revealed that mean turbidity differed across sampled locations (F-stat = 114.60, p <.0001, n = 54). T-test comparisons (Figure 3.10) show a strong significant difference between sample locations L0, L1, L2, and L3 (p<0.0001). Despite a large difference in mean turbidity at sample position L4 and L5, only a weak significant difference (p = 0.053) exists. A weak significant difference between the two sample positions may most likely be attributed to an overlap in turbidity measurements caused by an increase in turbidity from resuspension. Table 3.2 shows mean turbidity discharged at location L5 is 61 NTU, well below the USEPA 280 NTU turbidity effluent limit. Results indicate that three sediment tubes are likely necessary to achieve turbidity levels that are significantly different; subsequent sediment tubes may not provide statistically different turbidity results.

Table 3.2 – Mean turbidity for all sample locations in Treatment 3.

Location					
L0	L1	L2	L3	L4	L5
2388 (n=30)	1796 (n=33)	1010 (n=54)	581 (n=57)	289 (n=60)	61 (n=63)

Figure A.7 in Appendix A shows that PAM application in Treatment 3 does not decrease in effectiveness with consecutive runs. Results indicate that no statistically significant difference exists between mean turbidity values at each sample location for each run (p=0.7382). Mean cumulative percent reduction of turbidity at location L5 is 97% (Figure 3.11). Based on t-test results, percent reduction values at all locations were significantly different (p<0.0001).

Figures 3.12 displays a continuous decrease in mean TSS across locations. F-test results (F-stat =7.5888, p = 0.0001, n = 51) show a decrease in mean TSS over five runs for Treatment 3. Similar results for TSS can be seen for each run in Appendix A, Figure A.8.

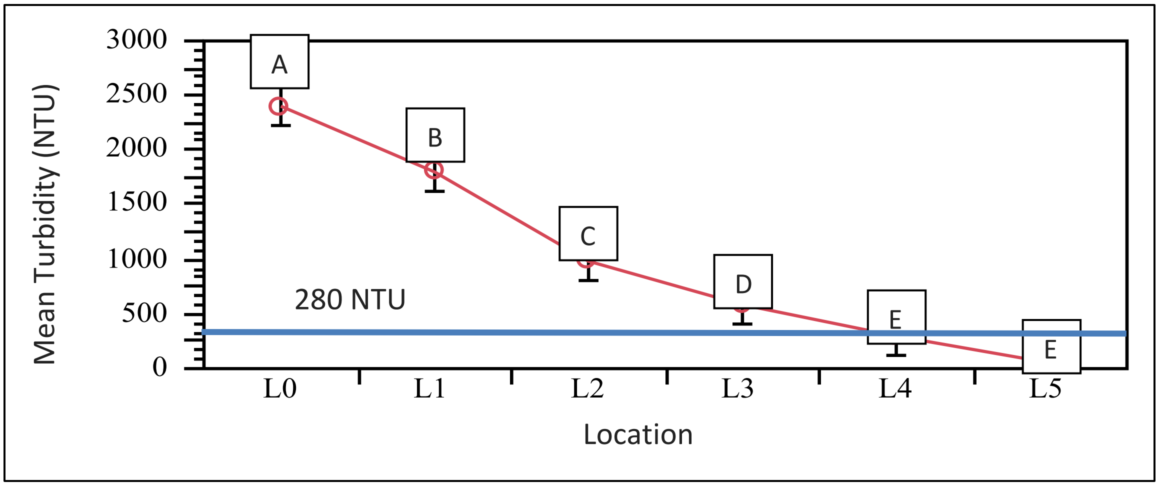


Figure 3.10 – **Mean turbidity across sample locations for Treatment 3.**

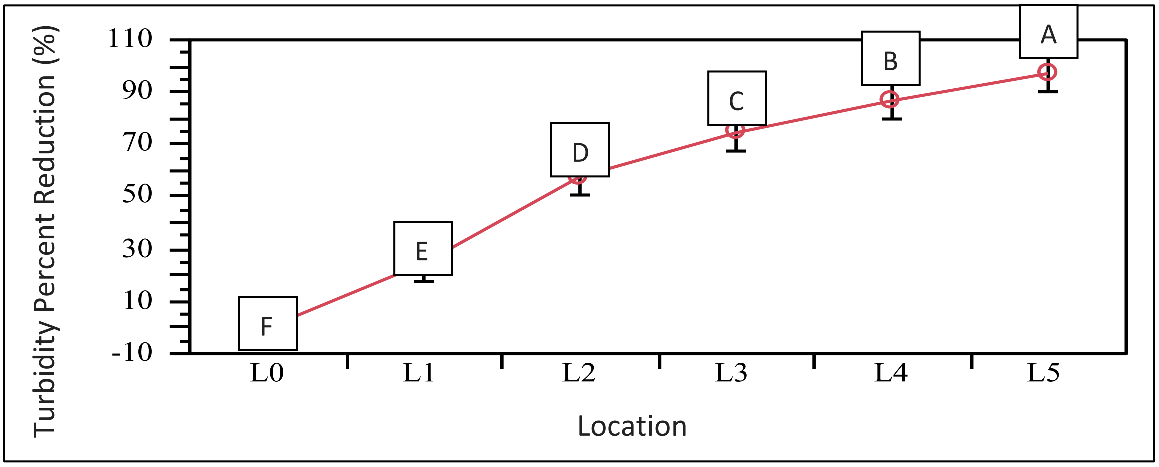


Figure 3.11 – **Cumulative percent reduction of turbidity for Treatment 3.**

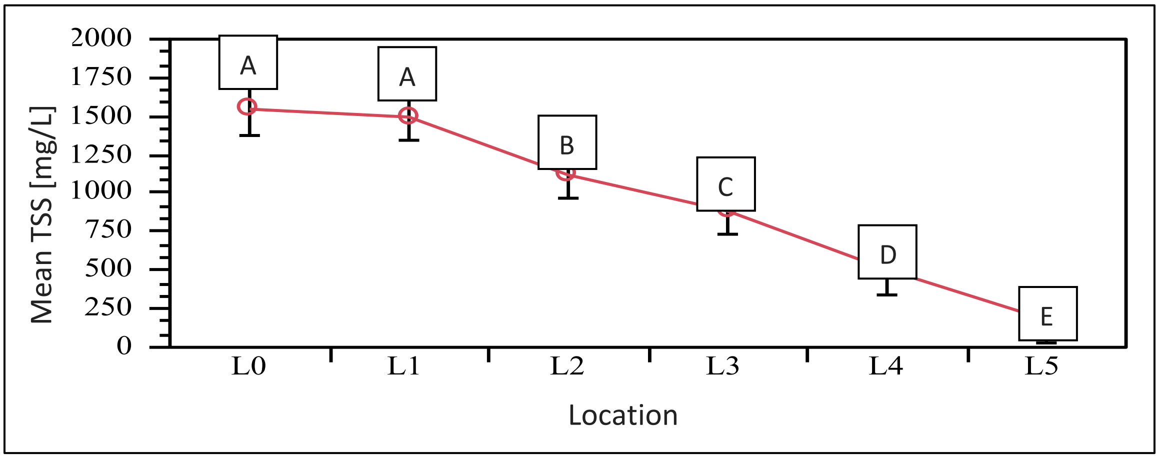


Figure 3.12 – **Mean TSS concentration across sample locations for Treatment 3.**

Cumulative TSS percent reductions increased with sample locations (Figure 3.13) as PAM interactions with clay particles created large flocs that gradually settled out of suspension. Percent reduction data does reveal minimal TSS reduction between locations L0 and L1, which is likely due to the lack of PAM interaction and settling time between the tank outlet and the first sediment tube.

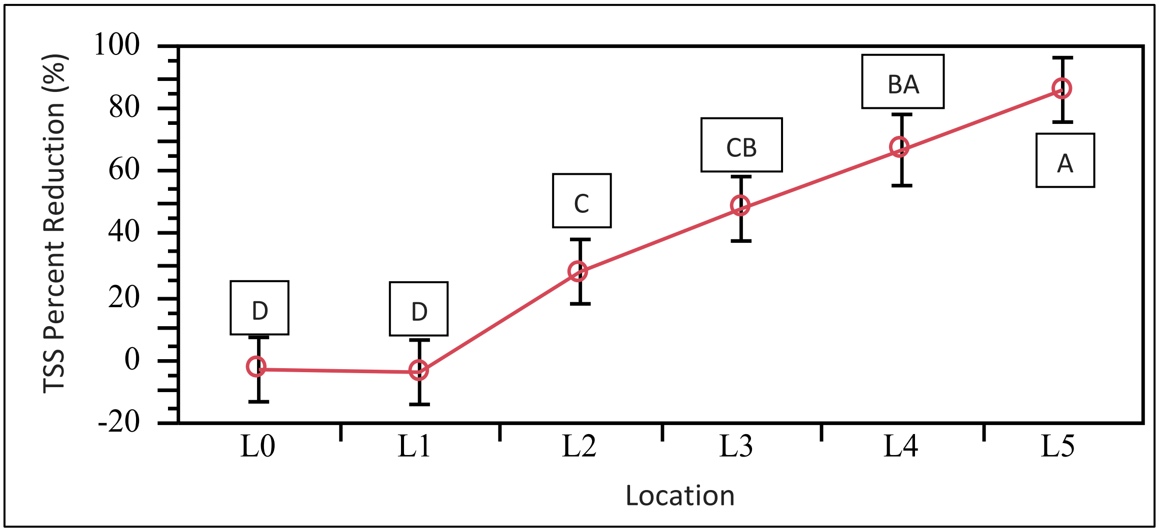


Figure 3.13 – Cumulative percent Reduction TSS across sample locations for Treatment 3.

Results from Treatment 3 again indicate how effective PAM application is for turbidity reduction in runoff. Average discharge from location L5 of turbidity and TSS is 61 NTU and 169 mg/L, respectively. Additionally, average reduction for turbidity and TSS is 97% and 76%, respectively. Turbidity does increase slightly with increasing runs, but analyses indicates these increases are not statistically different and make it difficult to conclude that turbidity increases are due to loss of PAM effectiveness. To achieve the proposed 280 NTU limit, five sediment tubes are needed for Treatment 3.

Treatment 4: PAM Bag

PAM dosing for Treatment 4 consisted of 500-g granular #705 PAM in a 6” x 26” smooth weave 400-micron permeable bag placed at the tank outlet and on the downstream side of sediment tubes one thru four. Analysis of variance testing showed there is a difference in turbidity values (Table 3.3) across sampled locations. F –test results revealed that mean turbidity across locations (F-stat = 48.4705, $p<0.0001$, n = 58) is significantly different. Mean turbidity discharged from sediment tube 5 was 915 NTUs; well above the proposed USEPA 280 NTU effluent limit. Figure 3.14 shows mean turbidity across sampled locations for all runs; locations connected by same letter are not significantly different. Figure A.9 in Appendix A shows mean turbidity across sampled locations for each run.

Table 3.3 –Mean turbidity for all sample location in Treatment 4.

Location					
L0	L1	L2	L3	L4	L5
3198 (n=34)	1738 (n=34)	1560 (n=36)	1167 (n=40)	1236 (n=36)	915 (n=48)

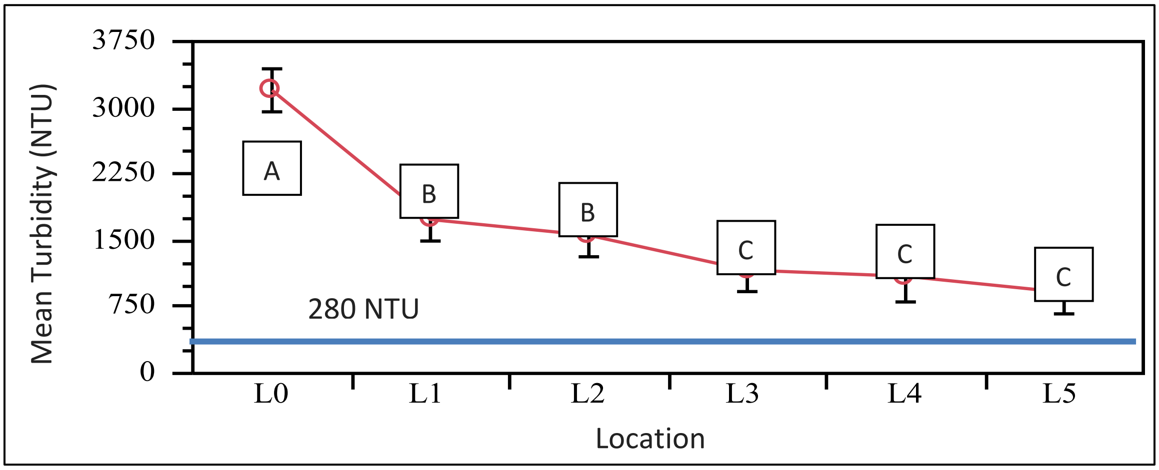


Figure 3.14 – Mean turbidity across sample locations for Treatment 4.

From Figure 3.15 below, it is evident that run 1 displays a significant decrease in turbidity, but turbidity also increases with subsequent runs. Turbidity discharged from run 1, location L5 is 152 NTU, whereas turbidity at run 5, location L5 is 1127 NTU. Such an increase in turbidity by run may point to the overall ineffectiveness of a passive PAM bag application over multiple runoff events. During the start of run 1 PAM inside the bag remained in granular form; however, after run 1 it was observed that the PAM swelled from interaction with water and became a solid, gelatinous log. Results show that run 1 mean turbidity is well below 280 NTU, which may show that, under the described test conditions, granular PAM is most effective at reducing turbidity.

Figure A.10 (Appendix A) depicts a decrease in turbidity percent reduction over runs, which reaffirms conclusions that PAM bags become ineffective at reducing turbidity below USEPA regulated limits. Mean cumulative turbidity percent reduction achieved for Treatment 4 was 71

TSS concentrations within Treatment 4 fail to consistently decrease across sample locations. F-test results show a significant difference in mean TSS across sample positions exists (F-stat = 5.7209, p = 0.0004, n = 55). Statistically sample location L0 is different than sample location L1-L5 (p=0.0033). After location L0, TSS concentration levels are not significantly different and appear to remain stable across locations L1 thru L5 as shown in Figure 3.15. Figure A.11 (Appendix A) illustrates how TSS concentration increases with runs. This graph further supports the theory that PAM deployed in bags creates substantial reduction in TSS during the first run, but loses reducing effectiveness with subsequent runs.

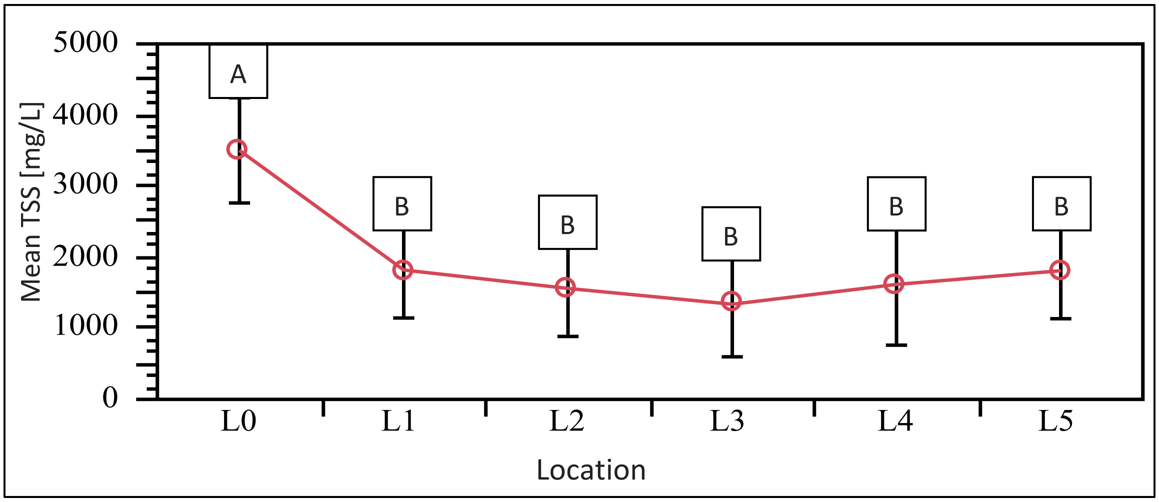


Figure 3.15 – Mean TSS concentration for sample locations for Treatment 4.

Based on results, Treatment 4 declines in effectiveness to reduce turbidity with each run. Mean turbidity and TSS discharged at location L5 were 915 NTU and 1810 mg/L, respectively. The decrease in turbidity reduction is likely attributed to change in PAM composition from granular to gelatinous decreasing surface to volume ratio, and opportunity for chemical reactions between PAM and suspended sediment.

Comparison of Treatments

A side by side comparison was used to determine which treatment achieved the lowest turbidity and created a significant turbidity reduction in the fewest sediment tubes. To effectively compare treatments, it is essential to determine whether turbidity values from each treatment are significantly different. A graph comparing all treatments for mean turbidity across sampled locations is displayed in Figure 3.16. Similarly, Figure 3.17 compares percent reduction for each treatment.

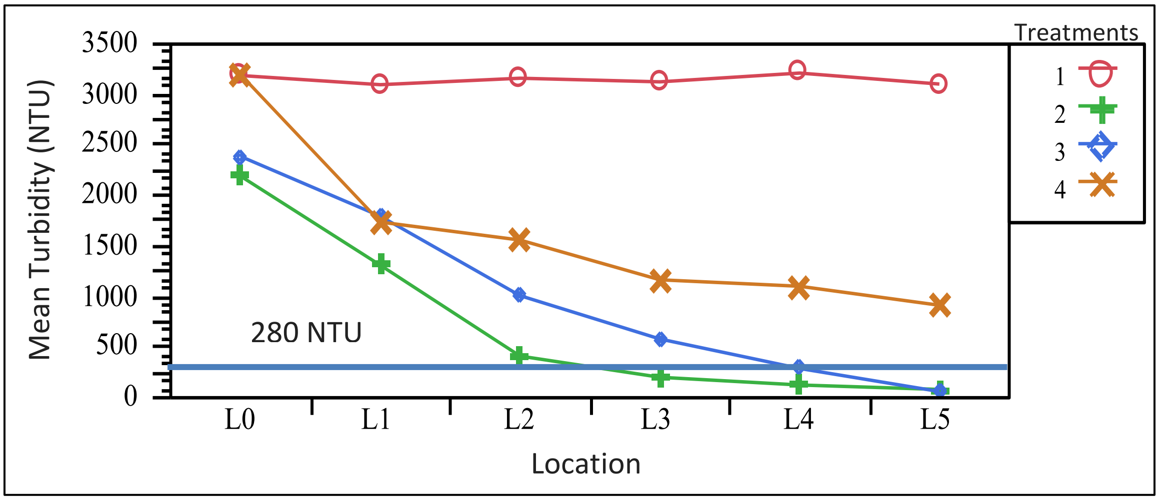


Figure 3.16 – Comparing mean turbidity across sampled locations for each treatment.

F-test results reveal a significant difference in mean turbidity across sample positions within treatments exists (F-stat = 37.7199, p<0.0001, n=232). Results did indicate a significant difference (p <.0001) in mean turbidity at location L5 between Treatment 1, 3104 NTU, and Treatment 4, 915 NTU. Statistically, Treatment 2 & 3 are different (p = 0.0002) than Treatment 4. T-test results failed to show a significant difference (p = 0.9253) between mean turbidity values at location L5 for Treatment 2, 82 NTU, and Treatment 3, 61 NTU. When comparing mean turbidity between Treatment 2 and 3, a statistical difference (p = 0.0197) exists across locations L1, L2, and L3. Graphical results (Figure 3.17) show that Treatment 2 reaches a lower turbidity more quickly than Treatment 3.

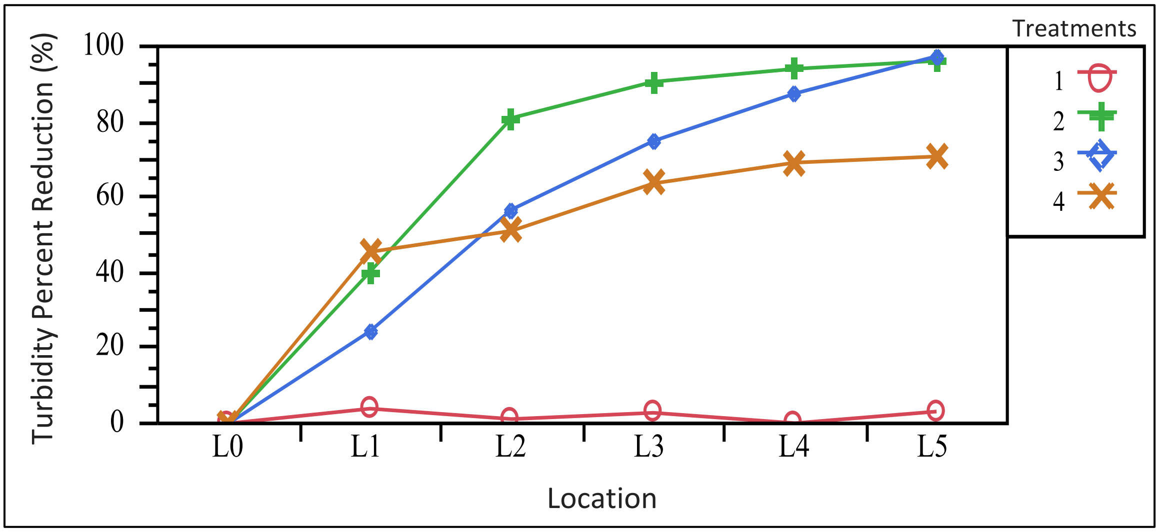


Figure 3.17 - **Comparing turbidity percent reduction for each treatment.**

T-test results comparing percent reduction found no significant difference (p = 0.8156) between Treatment 2 and Treatment 3 at location L5. Results did show a significant difference (p<.0001) in percent reduction across locations L2 and L3 for Treatment 2 compared to Treatment 3. Based on these results, it is evident that Treatment 2 creates a more rapid reduction in turbidity than the other test treatments.

PAM Desiccation Effects

To better understand turbidity reduction effects related to PAM applications becoming desiccated, a 6th run was completed several days after run 5 for Treatments 2, 3, and 4. A 6th run allowed PAM applications to dry and acted as days or weeks that normally occur between rain events. Comparison of the 6th run with runs 1 – 5 within the same treatment are displayed in Appendix A Figures A.12-A.14.

For Treatment 2 (PAM sprinkled on sediment tube before each run), mean turbidity discharged from location L5 on the 6th run is 100 NTU, which statistical results prove not to be significantly different than mean turbidity discharges of runs 1- 5 (p = 0.925). Additionally, percent reduction throughout run 6 is 97% which is not significantly different than runs 1 – 5 (p = 0.799). Treatment 3 mean turbidity discharged from location L5 on the 6th run is 1283 NTU, which statistical results prove to be significantly different than mean turbidity discharges of runs 1- 5 (p <.0001). Percent reduction within run 6 at location L5 is 41%, which is significantly different compared to runs 1 – 5 (p <.0001).

Figure A.14 in Appendix A depicts that Treatment 4 shows a decrease in turbidity across sample locations, but shows an increase in mean turbidity with each run. Mean turbidity discharged from location L5 on the 6th run is 1863 NTU, which statistical results prove to be different than mean turbidity discharges of runs 1&2 (p = 0.0007 and p = 0.0076, respectively) but not significantly different than mean turbidity discharges of runs 3, 4, and 5 (p = 0.1298). Reduction in mean turbidity before discharge at location L5 within run #6 is 47%.

In order to effectively determine which PAM application is least effected by desiccation effects, a side by side comparison for all treatments with a run 6 is shown in Figure A.15. Statistical analysis shows a weak significant difference in average turbidity at location L5 between Treatment 2 and Treatment 3 (p = 0.073). Due to events while sampling, only one test within Treatment 2 experimented with PAM dry out effects, whereas Treatment 3 and 4 had duplicate dry out tests run. This explains why Treatments 3 and 4 have two turbidity values computed for an average turbidity and Treatment 2 only has one set of turbidity values (Figure A.15). This weak significant difference between Treatment 2 (n=38) and 3 (n=78) is primarily due to a small sample size that may be creating error in the data.

Treatment 2 shows that if PAM is reapplied to sediment tubes after subsequent PAM applications have dried, similar turbidity reductions are still achieved. Treatment 3 and 4 lack substantial reductions in turbidity and fail to meet the USEPA proposed 280 NTU numeric effluent limit. Observations reveal that once PAM becomes wet and dries out, the outer layers of PAM form a hard crust over the surface on which PAM is applied. Based on results presented above, as PAM dries out between rain events it may become less effective at flocculating sediment particles.

Application Intervals Testing

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.

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. Tables 3.4 and 3.5 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 3.4. **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 3.5. **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 3.4 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 3.18 shows these overall means. All of them share the letter "A," indicating no significant differences.

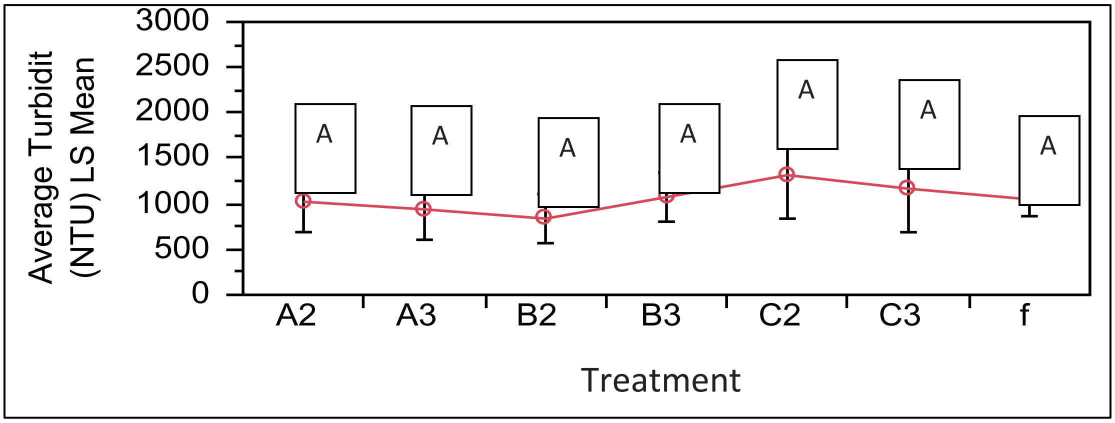


Figure 3.18. **Overall LS mean turbidity for each treatment.**

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 3.19 illustrates this.

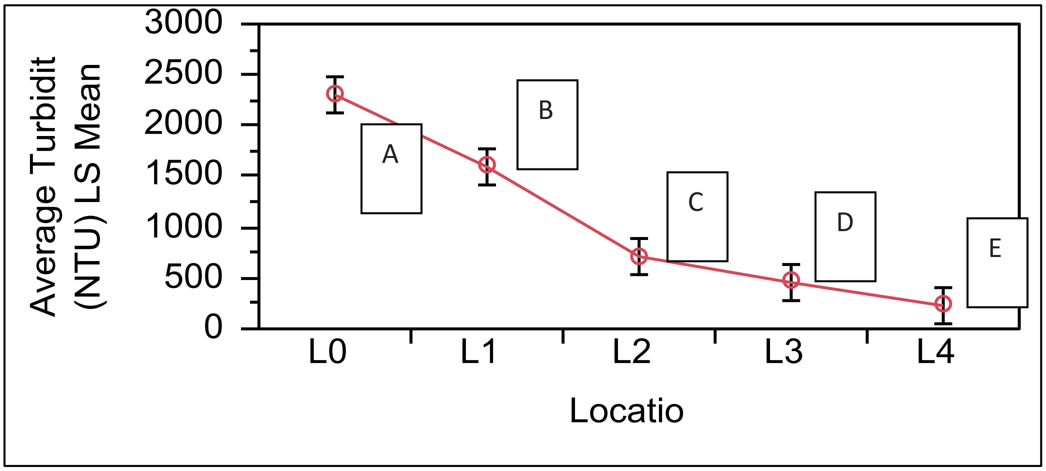


Figure 3.19. **LS mean turbidity at each sample location, all treatments combined.**

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. To better understand this statement, consider Figure 3.20, 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.

It was then desired to combine runs into treatments based only on wait time 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 3.21. The means for each treatment were then plotted together in Figure 3.22. Letters representing similarity from Fisher's LSD test for the combined treatments are shown in Figure 3.22.

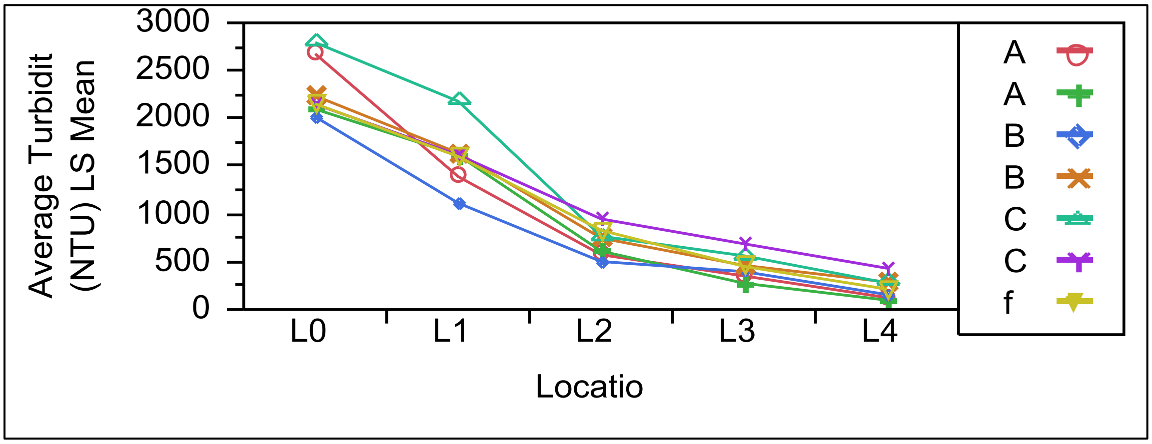


Figure 3.20. **LS mean turbidity for each treatment at each location.**

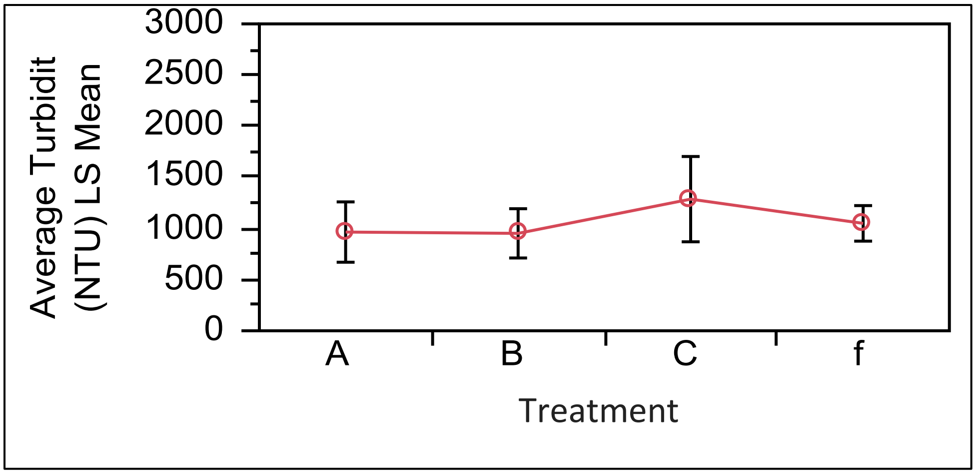


Figure 3.21. **Overall LS means for combined treatments A, B, C, and f.**

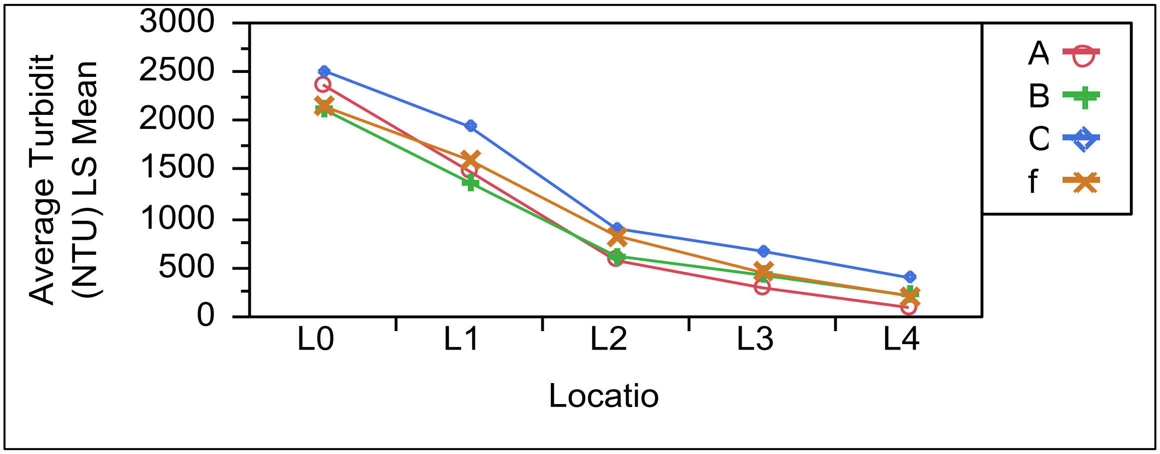


Figure 3.22. **LS mean turbidity for each treatment at each location, combined treatments.**

Field Tests

Appendix A contains the data sets that are relevant to this field study. 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 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 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 Parshall flumes 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.

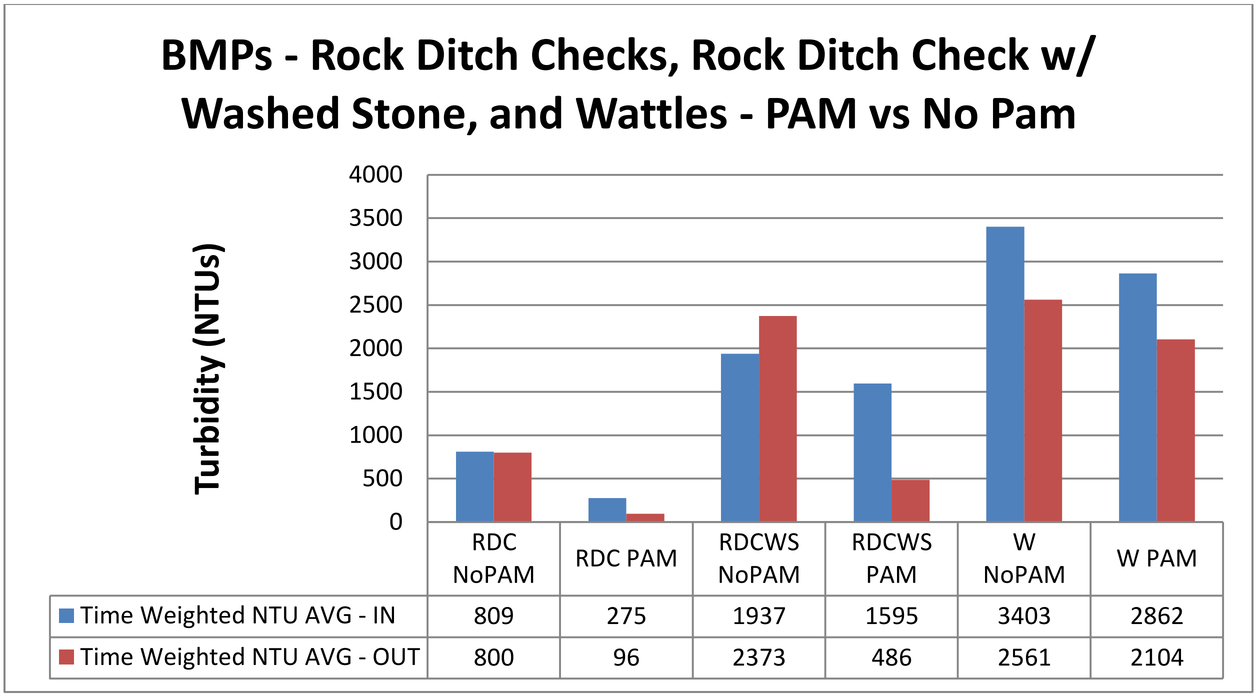
Samples were collected from both top of channel and bottom of channel stations. The samples turbidities were analyzed individually, the turbidity values were then summed and divided by the number of samples; a mean turbidity value was established for both top of channel (inflow) and bottom of channel (outflow). The determined means and corresponding percent changes were compared by location in channel, BMP, presence of PAM application, and by region.

Table 3.6 provides a breakdown of the inflow and outflow turbidities that were measured within all three regions, coastal (C), midlands (MID), and upstate (US), over all linear BMPs installed both with and without PAM. The linear BMPs that were investigated were rock dick checks (RDC), rock ditch checks with washed stone on face (RDCWS), and sediment tubes or wattles (W). As shown in Table 3.6, discharge turbidities varied greatly across BMPs, regions, and whether PAM was used. For rock ditch checks when no PAM was used, turbidity increased 57%. When PAM was used on this type BMP, turbidity was reduced by 64%. A similar trend was seen for rock ditch checks with washed stone. Without PAM data showed a 6% increase in turbidity while with PAM, showed a 58% decrease. Log wattles showed a 26% decrease without PAM and a 36% decrease when PAM was used to reduce turbidity.

With respect to turbidity and rock ditch checks (RDC) that did not contain PAM, results were mixed ranging from 89% removal to an increase of 254%. With PAM, RDC all had positive removals as related to turbidity ranging from 52 to 77%. A similar trend was seen with respect to rock ditch checks faced with washed stone (RDC-WS). For no PAM applications, turbidity reductions ranged from -128% to 54%. With the application of PAM, turbidity removals were on the order of 33-84%. Surprisingly, log wattles both with and without PAM showed positive removals for turbidity. Without PAM, reductions ranged from 2-49%. With PAM, these ranges were 21-51%. These results can be seen in Figure 3.23 below.

Table 3.6. **Table of laboratory analysis observations; turbidity reductions.**

Treatment	**Time Weighted NTU AVG**	**Time Weighted NTU AVG**	**NTU**
	IN	OUT	Diff
C-RDC-NoPAM	40	43	-8%
C-RDC-NoPAM	119	421	-254%
US-RDC-NoPAM	1640	183	89%
US-RDC-NoPAM	1035	2609	-152%
US-RDC-NoPAM	1210	742	39%
			-57%
C-RDC-PAM	117	44	62%
C-RDC-PAM	318	153	52%
US-RDC-PAM	391	90	77%
			64%
MID-RDC-WS-NoPAM	3796	5126	-35%
MID-RDC-WS-NoPAM	3309	7546	-128%
MID-RDC-WS-NoPAM	2019	1419	30%
US-RDC-WS-NoPAM	1367	866	37%
US-RDC-WS-NoPAM	2609	1190	54%
C-RDC-WS-NoPAM	161	149	8%
C-RDC-WS-NoPAM	299	317	-6%
			-6%
US-RCD-WS-PAM	1165	785	33%
C-RDC-WS-PAM	1199	188	84%
			58%
C-W-NoPAM	3534	3458	2%
C-W-NoPAM	3273	1663	49%
			26%
C-W-PAM	1070	528	51%
C-W-PAM	306	178	42%
MID-W-PAM	2000	1367	32%
MID-W-PAM	8074	6341	21%
			36%
Averages without PAM	Averages with PAM		



	RDC NoPAM	RDC PAM	RDCWS NoPAM	RDCWS PAM	W NoPAM	W PAM
🟦 Time Weighted NTU AVG - IN	809	275	1937	1595	3403	2862
🟥 Time Weighted NTU AVG - OUT	800	96	2373	486	2561	2104

Figure 3.23. Turbidity values for both influent and effluent flow through various linear BMPs with and without PAM.

One parameter that stands out with respect to both BMP effectiveness and PAM application is regions. For BMPs installed in the midlands, it was noticed that elevated turbidities on inflow existed as compared to the two other regions. This can be seen in Figure 3.24 below. Analysis of variance and standard deviations between the three regional data sets showed this difference. Particle size analysis indicated soils for the research sites are as follows; in the upstate project site soil was comprised of 39.9% sand, 18.1% silt, and 42% clay. Soils in the midlands project site were comprised of 91.25% sand, 3% silt, and 5.75% clay. Particle size analysis indicated soils in the coastal project area were comprised of 78% sand, 19% silt, and 3% clay. Observations of this midlands site showed much higher sediment loads and depositions within the channels whereby sands comprised much of the transported sediment. At times this sediment yield resembled a bed load transport that is often found in natural sand bed channels. Extensive internal erosion and scour was occurring within these channel bottoms and side walls. As a point of interest with respect to the midlands site, while with no PAM an increase in turbidity was observed reflecting the internal erosion that occurred, when PAM was applied, even under these conditions, turbidity was reduced as shown in Figure 3.25 below.

It was observed that the passive addition of PAM as a flocculant, increased the TSS removal efficiency for rock ditch checks, rock ditch checks with washed stone and sediment tubes. The use of PAM on construction sites can reduce TSS and turbidity.

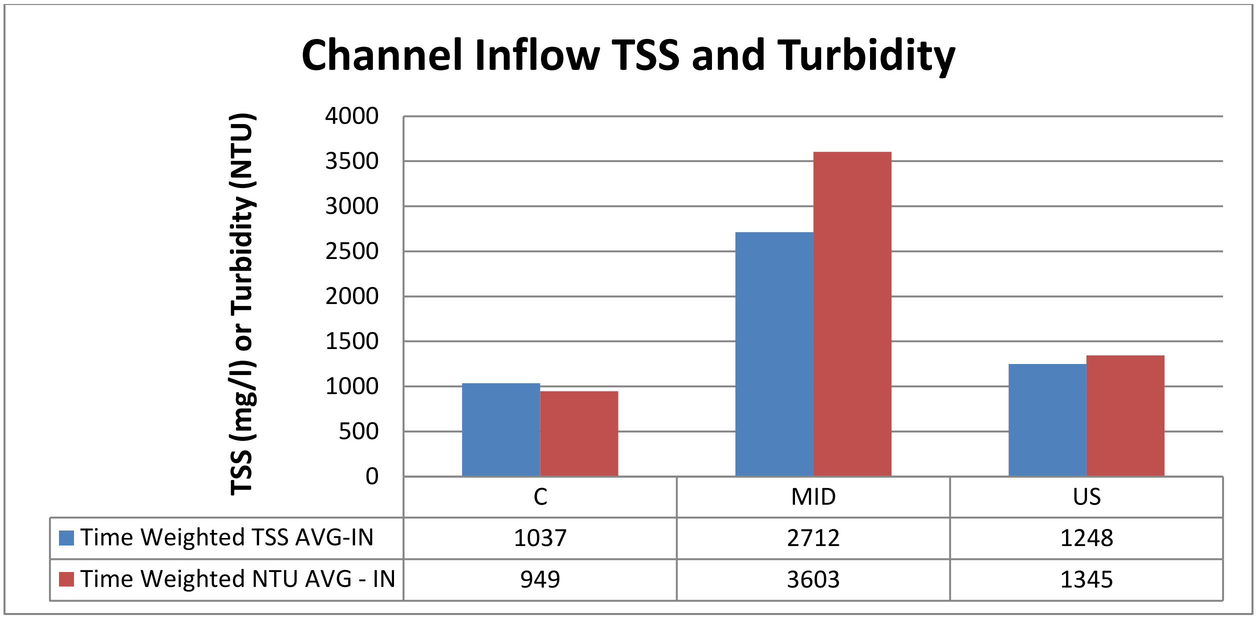


Figure 3.24. Turbidity and TSS values for influent across the three regions.

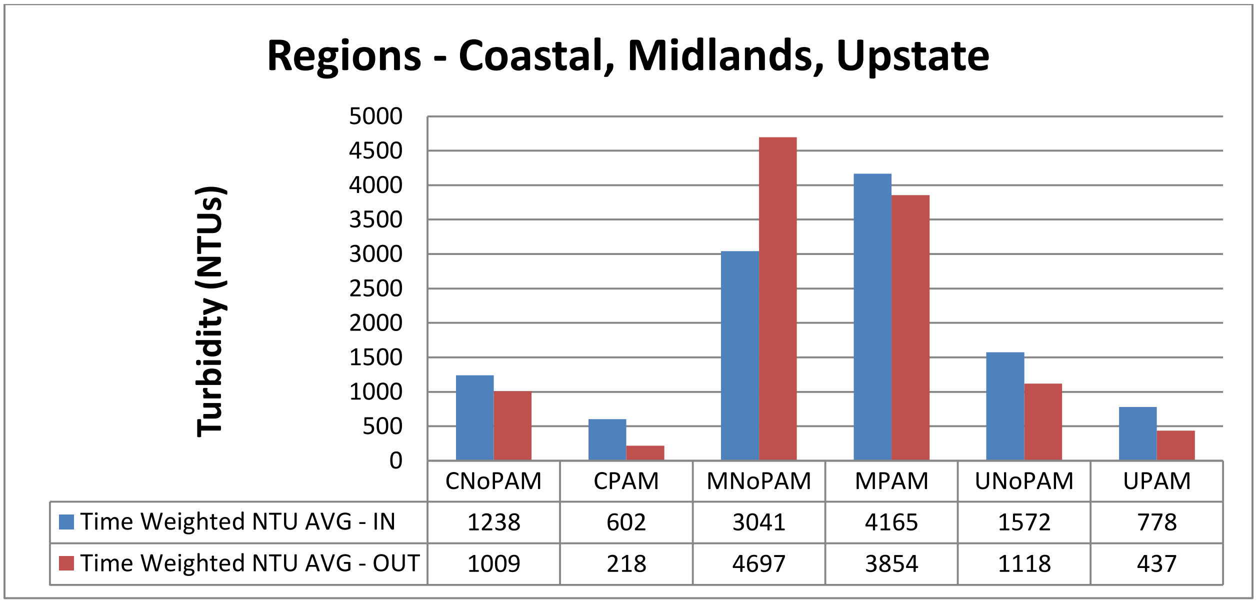
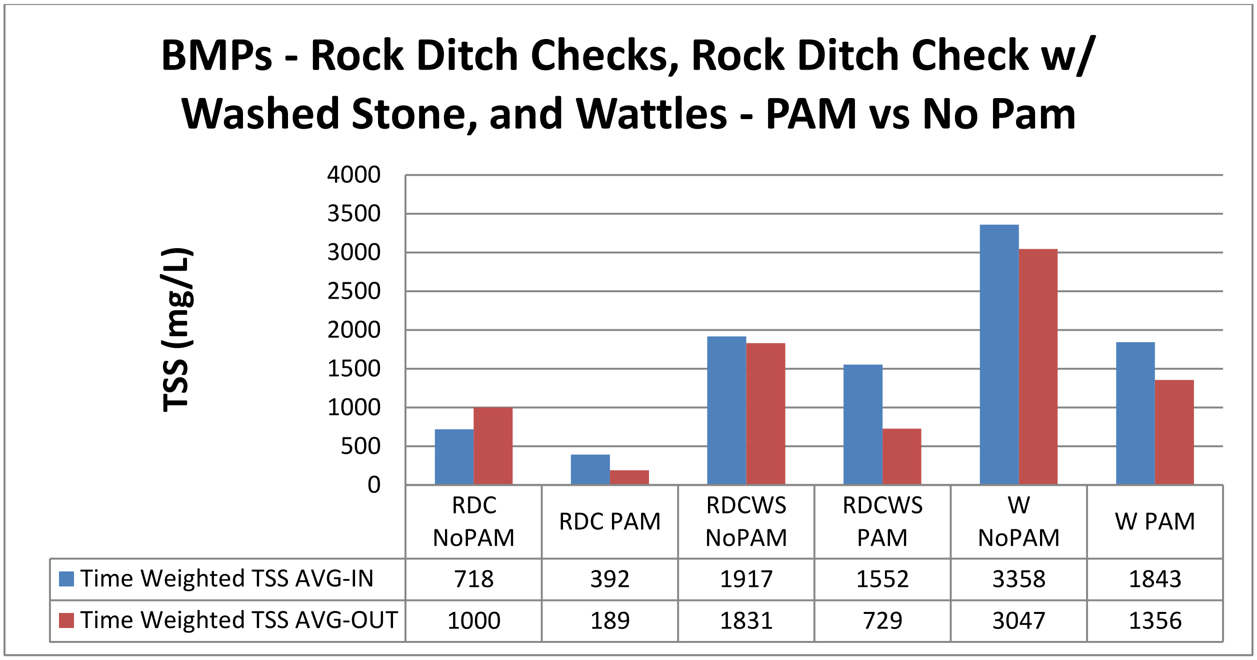


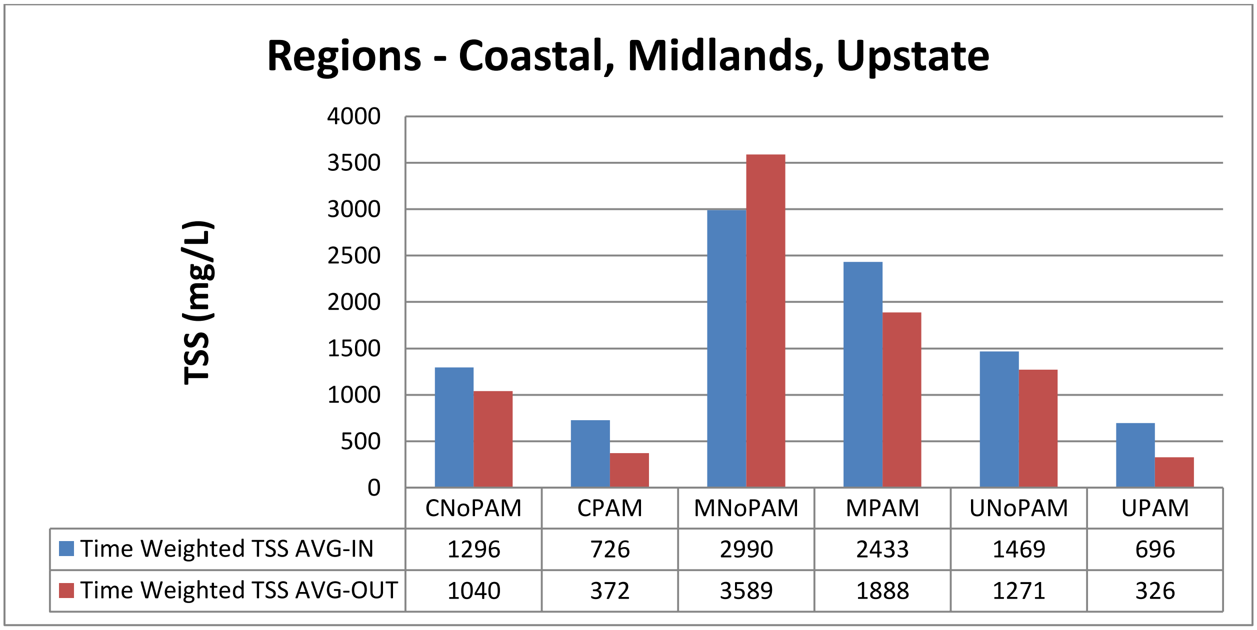
Figure 3.25. Turbidity values for both influent and effluent flow through channel sections located across the three regions with and without PAM.



	RDC NoPAM	RDC PAM	RDCWS NoPAM	RDCWS PAM	W NoPAM	W PAM
🟦 Time Weighted TSS AVG-IN	718	392	1917	1552	3358	1843
🟥 Time Weighted TSS AVG-OUT	1000	189	1831	729	3047	1356

Figure 3.26. **TSS values for both influent and effluent flow through various linear BMPs with and without PAM.**

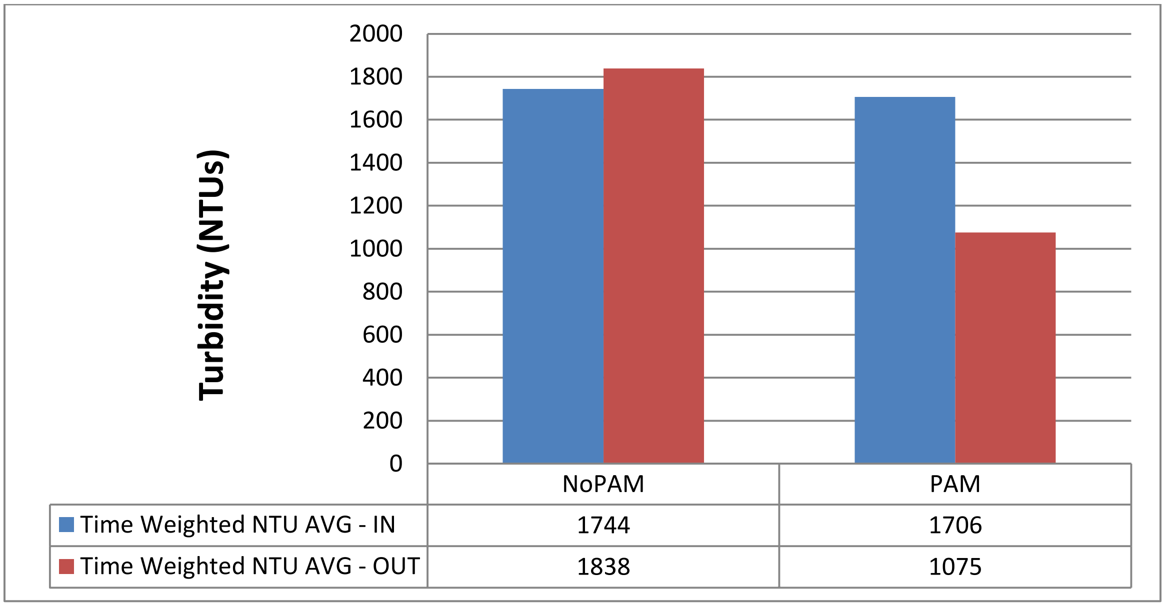
As mentioned above with respect to turbidity, similar regions effect trends were seen with TSS values. The midlands site had elevated TSS levels as compared to the other two sites. With the addition of PAM, the overall TSS values dropped across this channel. Figure 3.27 below reflects this effect.



	CNoPAM	CPAM	MNoPAM	MPAM	UNoPAM	UPAM
🟦 Time Weighted TSS AVG-IN	1296	726	2990	2433	1469	696
🟥 Time Weighted TSS AVG-OUT	1040	372	3589	1888	1271	326

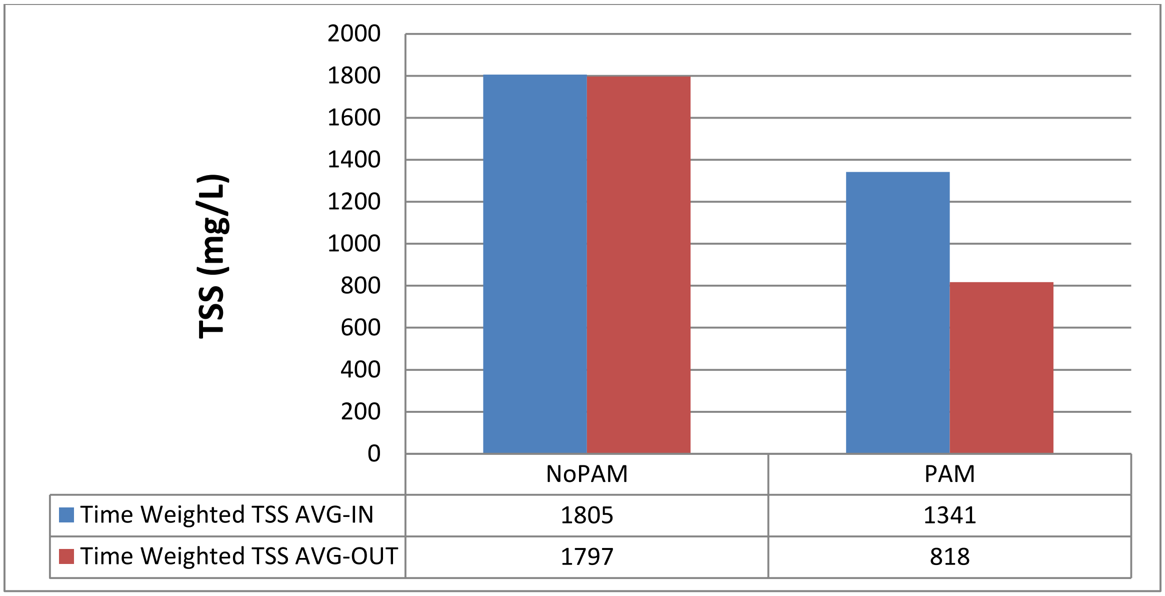
Figure 3.27. **TSS values for both influent and effluent flow through channel sections located across the three regions with and without PAM.**

Addition of PAM flocculants resulted in statistically significant reductions in both turbidity and TSS across all BMPs and state regions evaluated. Results of inflow compared to effluent water quality can be seen in Figures 3.28 and 3.29 below.



	NoPAM	PAM
🟦 Time Weighted NTU AVG - IN	1744	1706
🟥 Time Weighted NTU AVG - OUT	1838	1075

Figure 3.28. **Average turbidity values for all BMP configurations and regions.**



	NoPAM	PAM
🟦 Time Weighted TSS AVG-IN	1805	1341
🟥 Time Weighted TSS AVG-OUT	1797	818

Figure 3.29. **Average TSS values for all BMP configurations and regions.**

Scaled Basin Test

The following figures and tables represent the data collected from the lab sediment basin baffle and skimmer tests. Figures 3.30 through 3.44 detail the results of where sediment laden inflow entered the sediment basin which contained either a surface withdrawal skimmer or three installed baffles in conjunction with a surface withdrawal skimmer. Data collected was analyzed for both turbidity and TSS. Figure 3.30 (3.30a) below shows the results of all three trial runs for both skimmers and baffles as related to turbidity reductions (effluent values) when no flocculant was used. Figure 3.31 (3.31a) shows the average percent reduction (effluent value) of each configuration over all three tests runs. As can be seen in the figures below, all runs and configurations except runs 2 and 3 for Skimmer 2 and runs 2 for Baffle 1 and Baffle 2 had a greater than 80% reduction in turbidity. Once all three runs were averaged, all configurations had between 80 to 94% reductions.

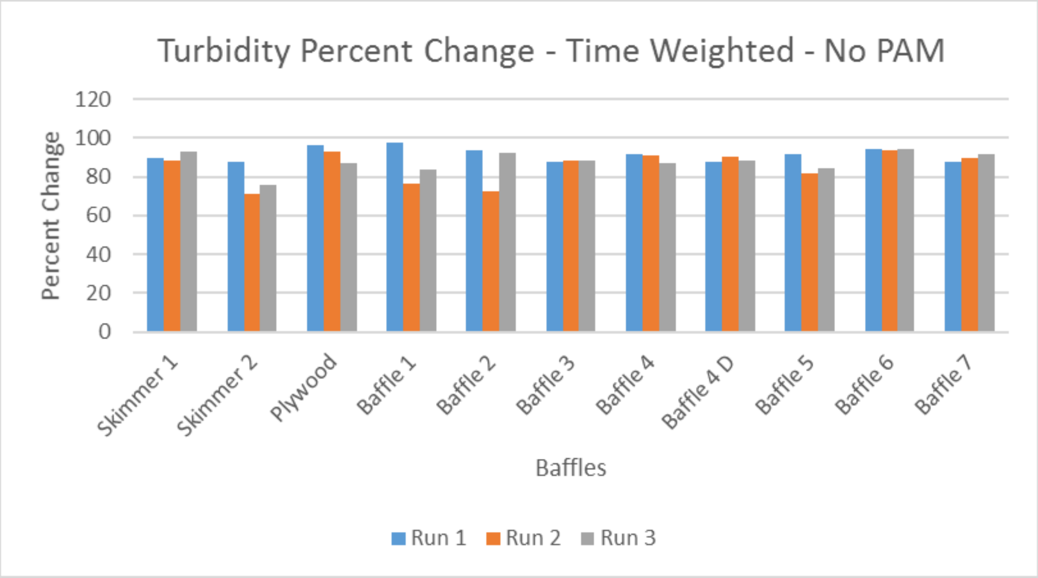


Figure 3.30. Individual turbidity percent change without PAM across three consecutive runs.

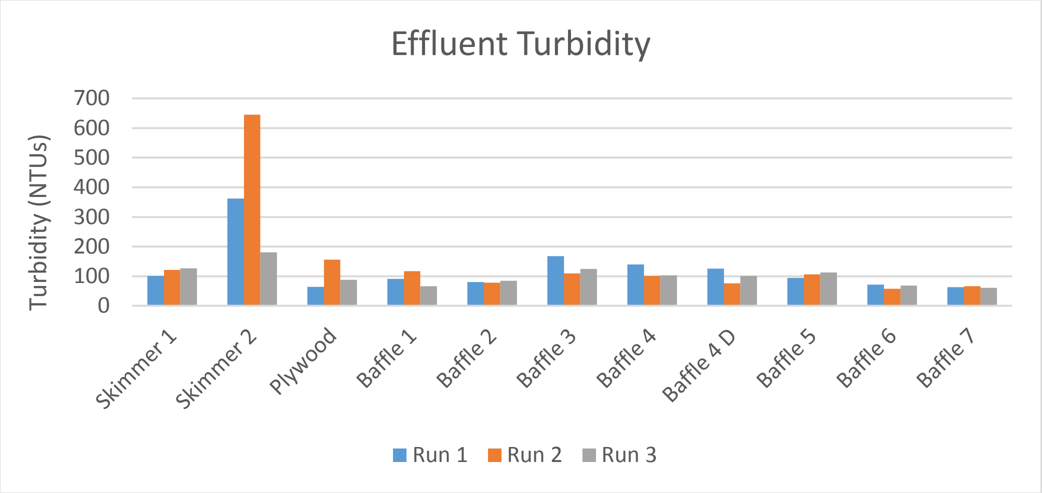


Figure 3.30a. **Individual turbidity effluent values without PAM across three consecutive runs.**

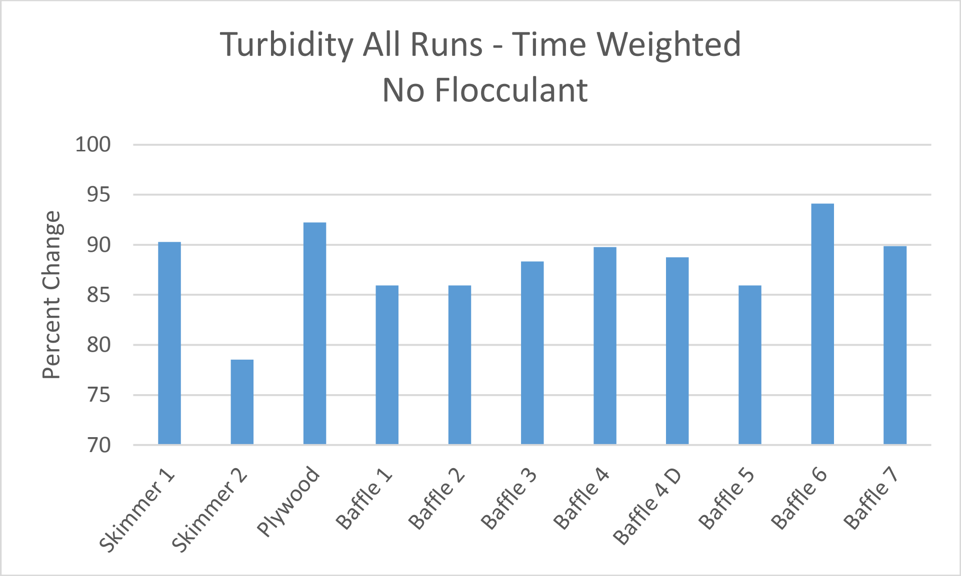


Figure 3.31. **Average turbidity reductions with various basin configurations without PAM.**

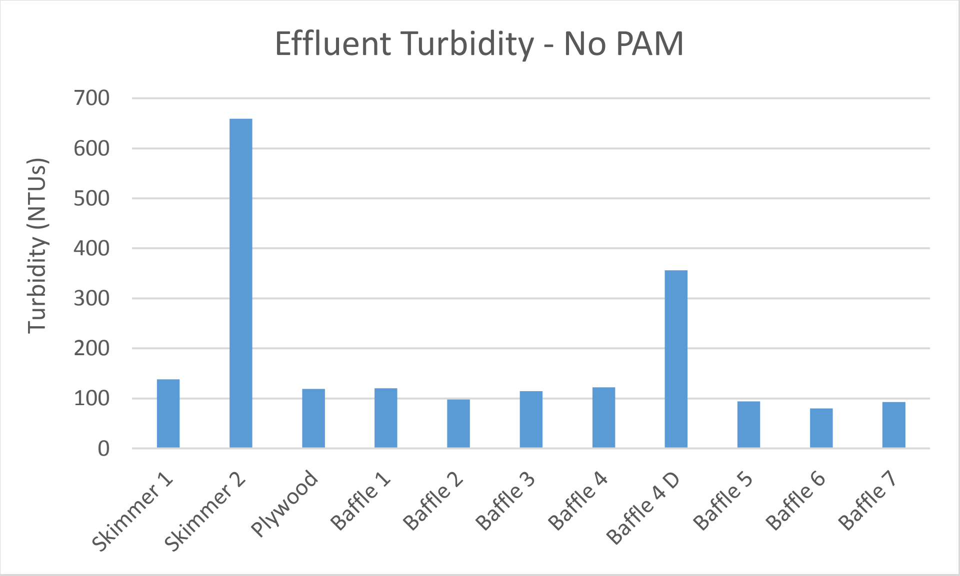


Figure 3.31a. Average turbidity effluent values with various basin configurations without PAM.

Tables 3.8 and 3.9 below show the average influent and effluent turbidities (NTUs) for all test runs for the various configurations. As can be seen in these tables, influent turbidities for non-PAM/flocculent test runs ranged between 600 to 2100 NTUs. The discharge turbidities for these same runs ranged from 60-400 NTUs. For the PAM/flocculant added runs, as shown in Table 3.9 below, influent turbidities ranged between 1100 to 2600 NTUs. These tests run had a higher influent turbidity than that of the non-PAM/flocculant runs. Even with these higher influent values, the effluent turbidity values still only ranged between 16-160 NTUs.

Figure 3.32 (3.32a) below shows the results of all three trial runs for both skimmers and baffles as related to turbidity reductions (effluent values) when a PAM/flocculant was used. Figure 3.33 (3.33a) shows the average percent reduction (effluent value) of each configuration over all three tests runs. As can be seen in the figures below, all runs and configurations had a greater than 80% reduction in turbidity except Skimmer 1. This discrepancy was the result of the poor performance of run 1, otherwise the average removal would have been on the order of 98%.

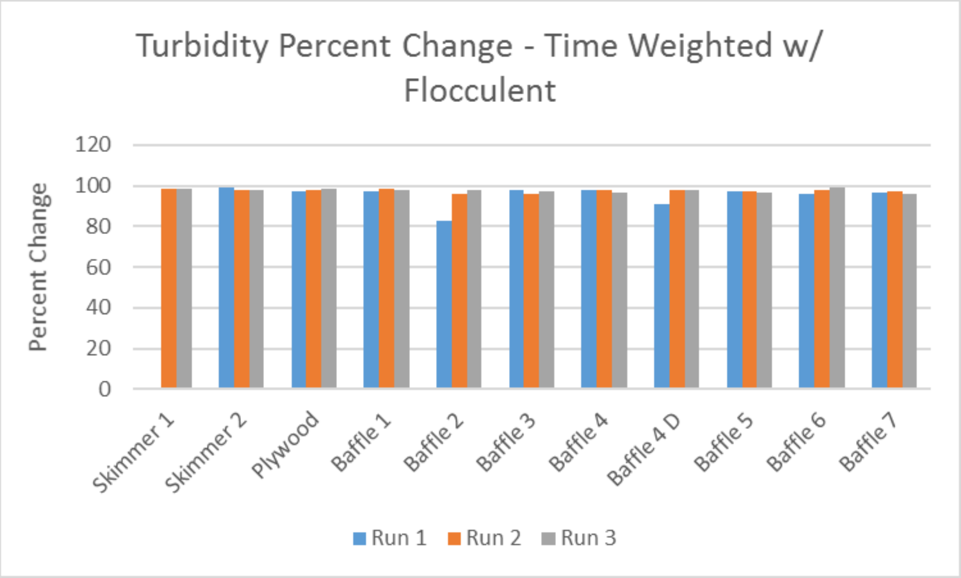


Figure 3.32. Individual turbidity percent change with PAM across three consecutive runs.

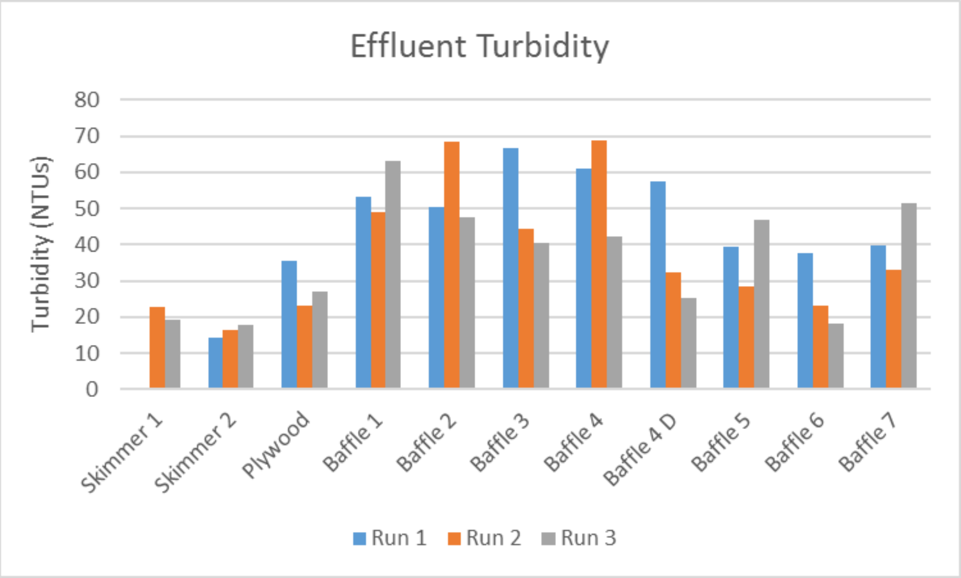


Figure 3.32a. Individual turbidity effluent values with PAM across three consecutive runs.

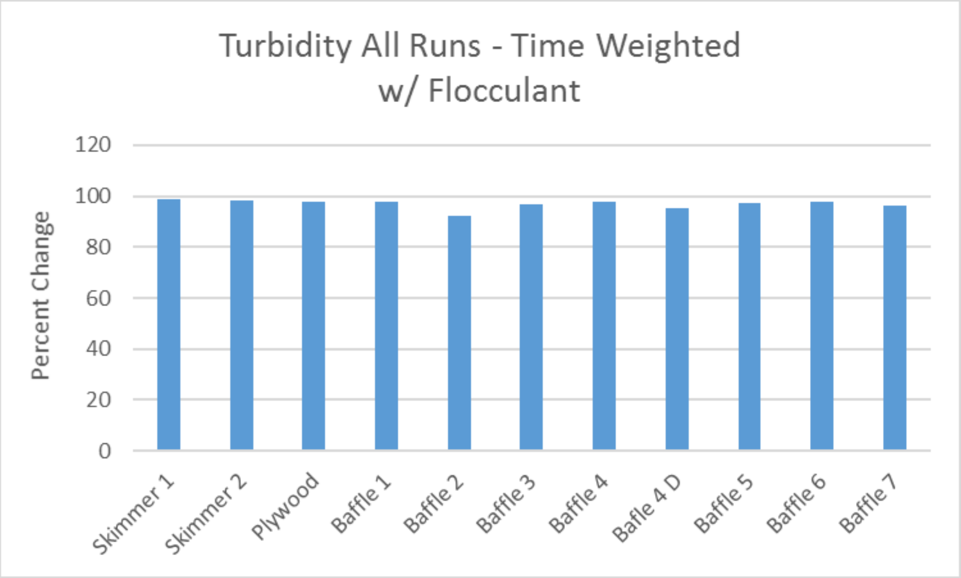


Figure 3.33. **Average turbidity reductions with various basin configurations with PAM.**

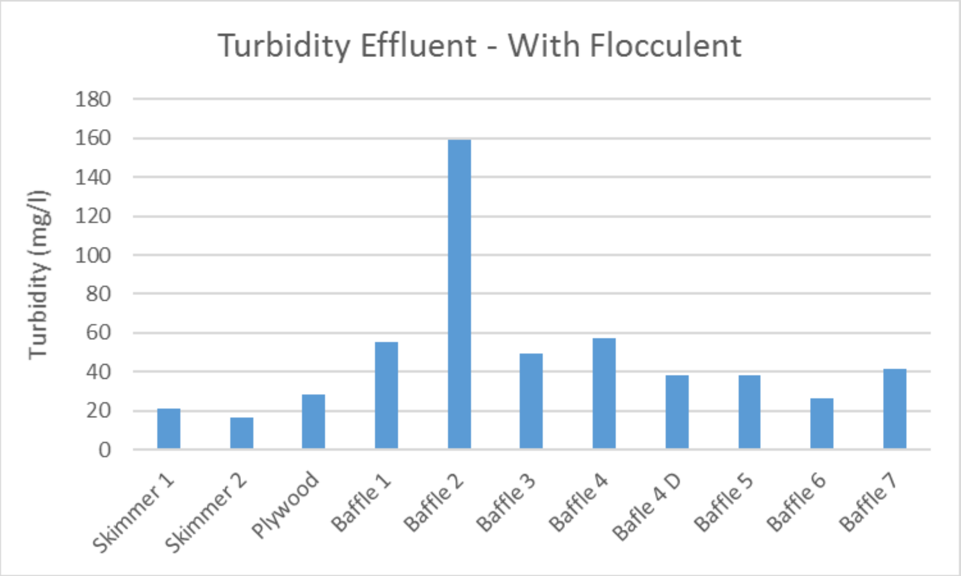


Figure 3.33a. **Average turbidity effluent levels with various basin configurations with PAM.**

Table 3.7 Turbidity time weighted average influent / effluent without PAM.

Basin Configuration	Influent	Effluent
Skimmer 1	1275.368	116.223
Skimmer 2	2012.019	395.7826
Plywood	1599.924	103.0841
Baffle 1	1589.834	91.71925
Baffle 2	862.734	81.08824
Baffle 3	1140.758	134.0156
Baffle 4	1182.966	114.9847
Baffle 4 D	889.2422	100.9838
Baffle 5	822.0657	104.5967
Baffle 6	1132.163	65.95463
Baffle 7	646.154	63.60833

Table 3.8. Turbidity time weighted average influent / effluent with PAM.

Basin Configuration	Influent	Effluent
Skimmer 1	1122.73	26.73886
Skimmer 2	1188.259	16.31324
Plywood	1456.565	28.5268
Baffle 1	2460.628	55.11597
Baffle 2	2102.529	158.9036
Baffle 3	1768.138	49.20574
Baffle 4	2555.521	57.30421
Baffle 4 D	1117.952	38.43988
Baffle 5	1288.474	38.16427
Baffle 6	1217.717	26.3638
Baffle 7	1182.932	41.38688

Figure 3.34 (3.34a) below shows the results of all three trial runs for both skimmers and baffles as related to TSS reductions (effluent value) when no PAM/flocculent is used. Figure 3.35 (3.35a) shows the average percent reduction (effluent value) of each configuration over all three tests runs. As shown in the figures below, all runs and configurations except run 1 for Baffle 4 D, run 2 for Baffle 2 and all runs with Skimmer 2 had a greater than 80% reduction in TSS. Once all three runs were averaged, all configurations had between 82 to 95% reductions except for Skimmer 2.

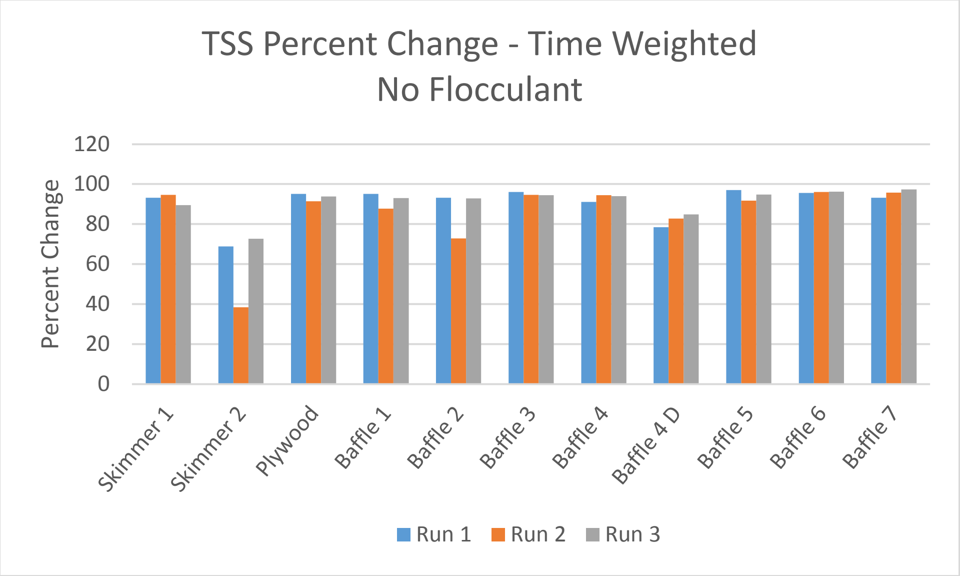


Figure 3.34. **Individual TSS percent change without PAM across three consecutive runs.**

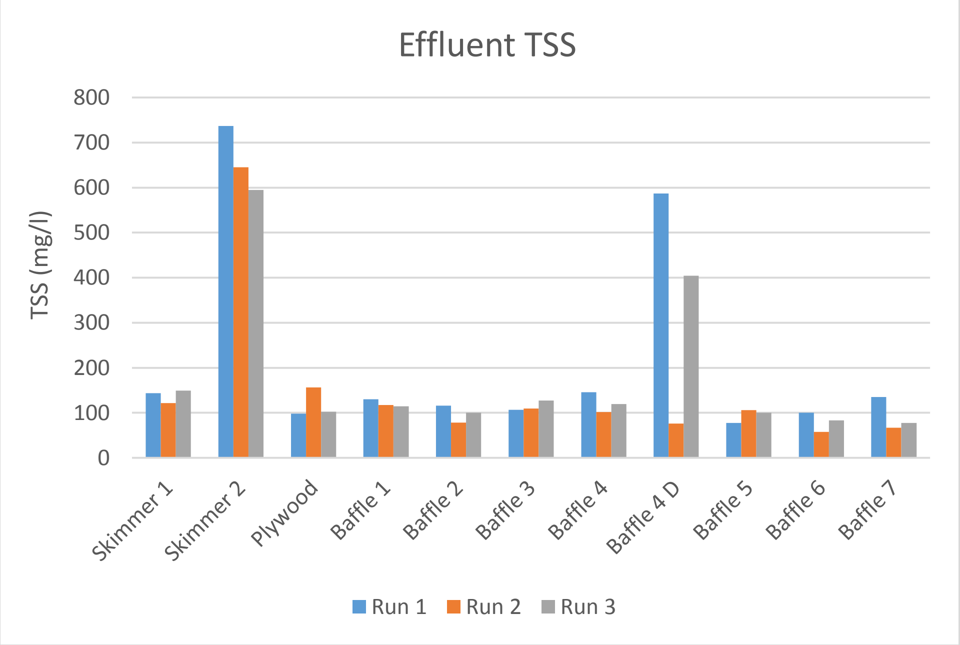


Figure 3.34a. **Individual TSS effluent values without PAM across three consecutive runs.**

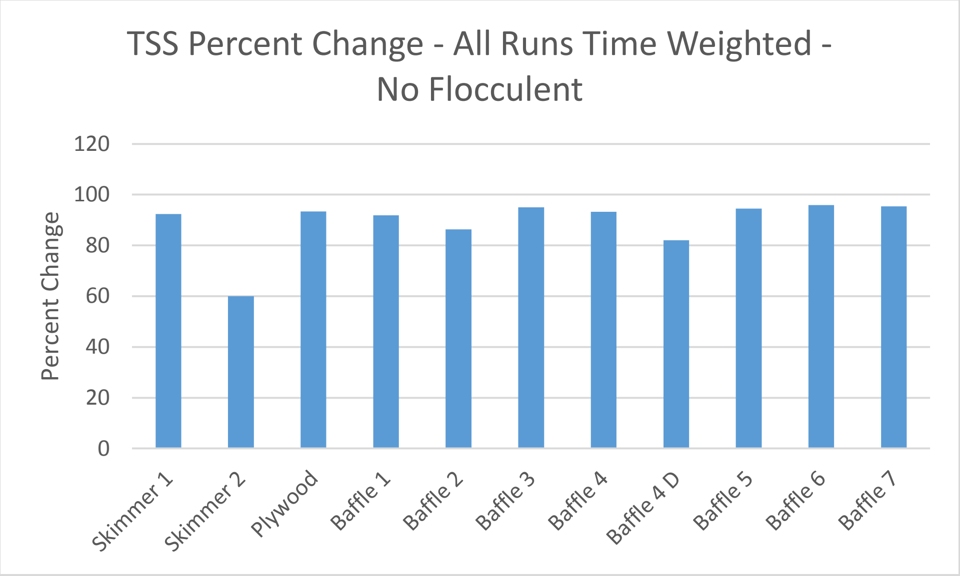


Figure 3.35. Average TSS reductions with various basin configurations without PAM.

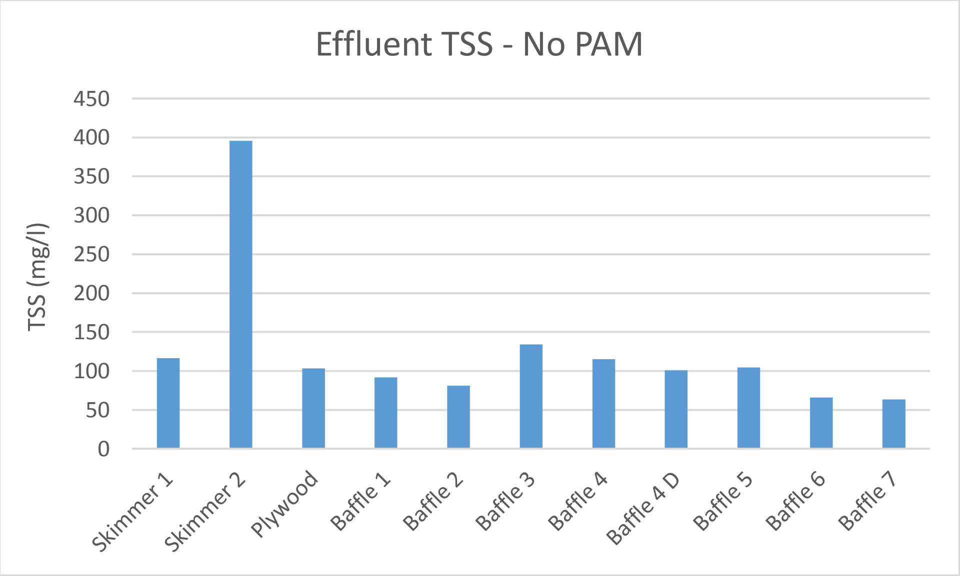


Figure 3.35a. Average TSS effluent values with various basin configurations without PAM.

Tables 3.9 and 3.10 below show the average influent and effluent TSS (mg/L) for all tests runs for the various configurations. As can be seen in these tables, influent TSS for no PAM/flocculant tests runs ranged between 1200 to 2600 mg/L. The discharge TSS values for these same runs ranged from 88-1000 mg/L. For the PAM/flocculant added runs, as shown in Table 3.11 below, influent turbidities ranged between 1400 to 3200 NTUs. These tests runs had a slightly higher influent TSS than that of the non-flocculant runs. Even with these slightly higher influent values, the effluent TSS values only ranged between 39-260 mg/L. With PAM, effluent TSS values were almost half of what they were with no PAM being used.

Figure 3.36 (3.36a) below shows the results of all three trial runs for both skimmers and baffles as related to TSS reductions (effluent values) when a flocculant was used. Figure 3.37 (3.37a) shows the average percent reduction (effluent value) of each configuration over all three tests runs. As can be seen in the figures below, all runs and configurations had a greater than 80% reduction in TSS except for runs 1 of Skimmer 1. Once all three runs were averaged, all configurations had between 92 to 98% reductions if run 1 of Skimmer 1 was removed.

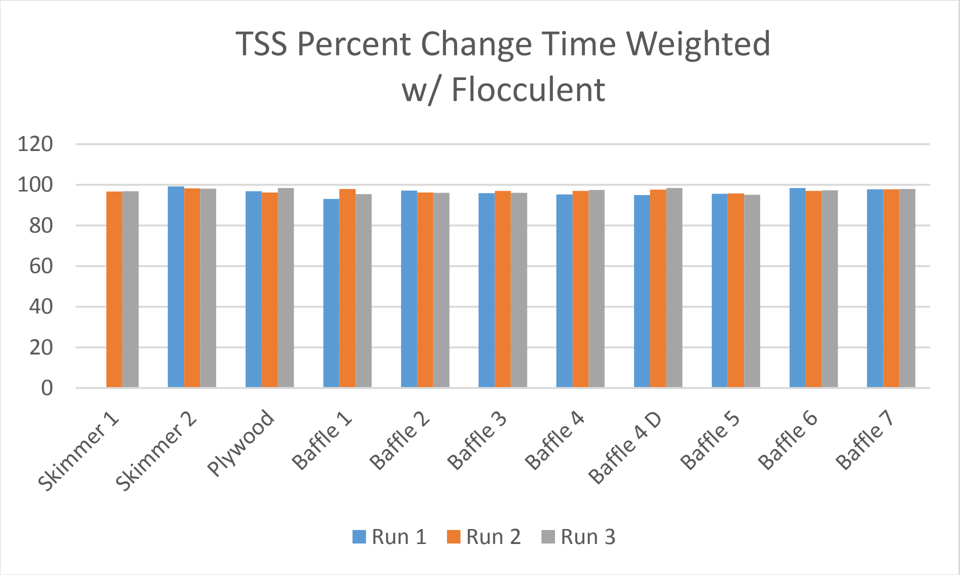


Figure 3.36. **Individual TSS percent change with PAM across three consecutive runs.**

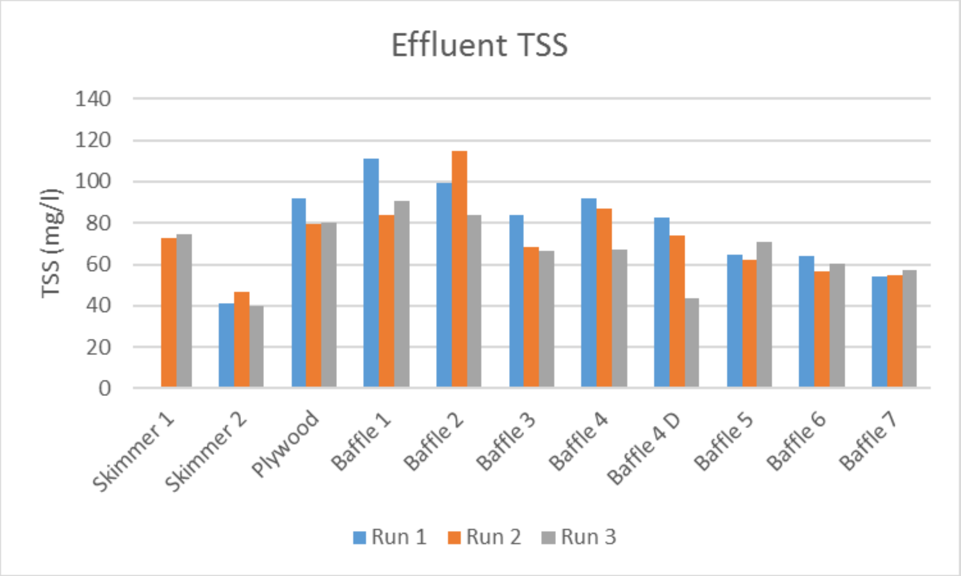


Figure 3.36a. **Individual TSS effluent values with PAM across three consecutive runs.**

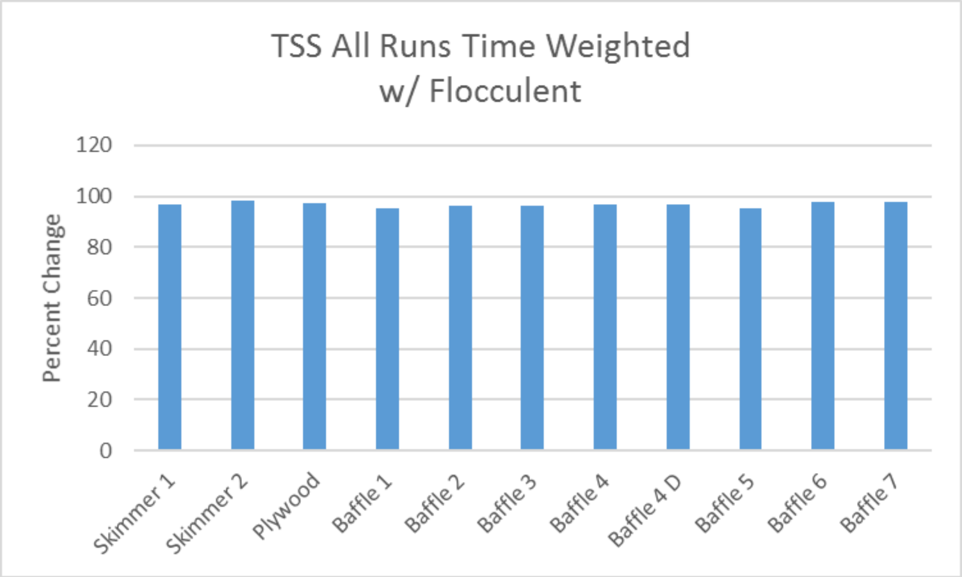


Figure 3.37. **Average TSS reductions with various basin configurations with PAM.**

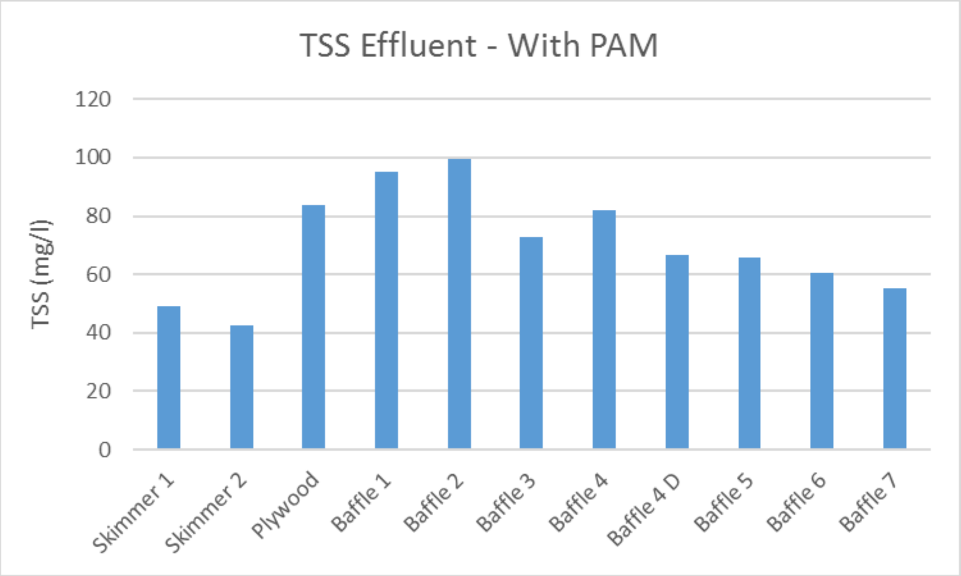


Figure 3.37a. **Average TSS effluent values with various basin configurations with PAM.**

Table 3.9. **TSS time weighted average influent / effluent without PAM.**

Basin Configuration	**Influent**	**Effluent**
Skimmer 1	2192.828	153.4367
Skimmer 2	2422.167	1003.03
Plywood	1924.381	128.835
Baffle 1	2134.762	169.9495
Baffle 2	1184.095	114.5367
Baffle 3	2438	119.1361
Baffle 4	1991.548	131.3222
Baffle 4 D	2443.187	441.4944
Baffle 5	1976.524	98.45899
Baffle 6	2170	88.40556
Baffle 7	2590.333	110.8333

Table 3.10. **TSS time weighted average influent / effluent with PAM.**

Basin Configuration	**Influent**	**Effluent**
Skimmer 1	1517.101	76.71078
Skimmer 2	3193.344	42.5537
Plywood	3229.638	83.775
Baffle 1	2473.644	95.25324
Baffle 2	2816.711	99.3787
Baffle 3	1949.454	72.8787
Baffle 4	2479.355	82.01605
Baffle 4 D	2417.422	66.66759
Baffle 5	1426.844	65.76399
Baffle 6	2722.956	60.35833
Baffle 7	2463.613	55.40048

Addition of PAM flocculants to evaluated sediment basins resulted in statistically significant reductions in both turbidity and TSS across all baffle and skimmer configurations. Results of inflow compared to effluent water quality can be seen in Figures 3.38 and 3.39 below.

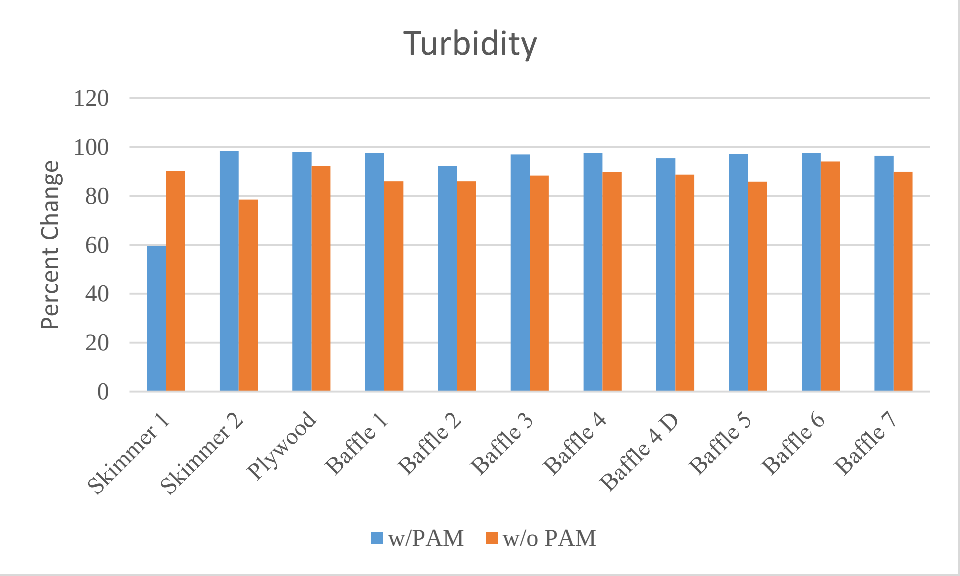


Figure 3.38. Percent change in average turbidity with and without PAM.

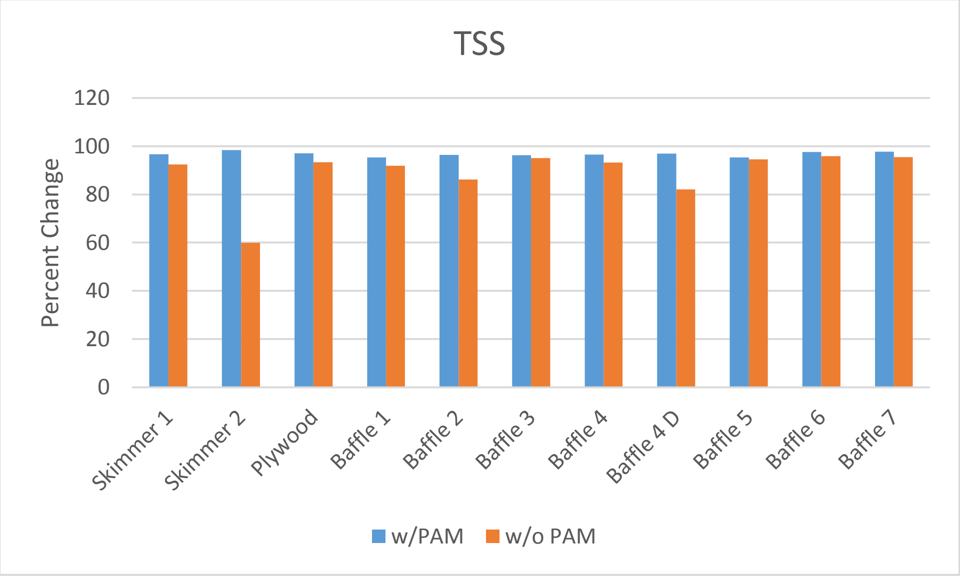


Figure 3.39. Percent change in average TSS with and without PAM.

A final component of the investigation compared single-baffle to three-baffle configurations while using PAM as a flocculant applied to the basin (Figures 3.40 – 3.43). For these comparisons, Baffle 4 was used. Using LSD tests with an alpha of 0.05, the three-baffle configuration resulted in a statistically significant greater reduction in turbidity than the single-baffle installation. For TSS, no statistical difference between single-baffle and three-baffles was found.

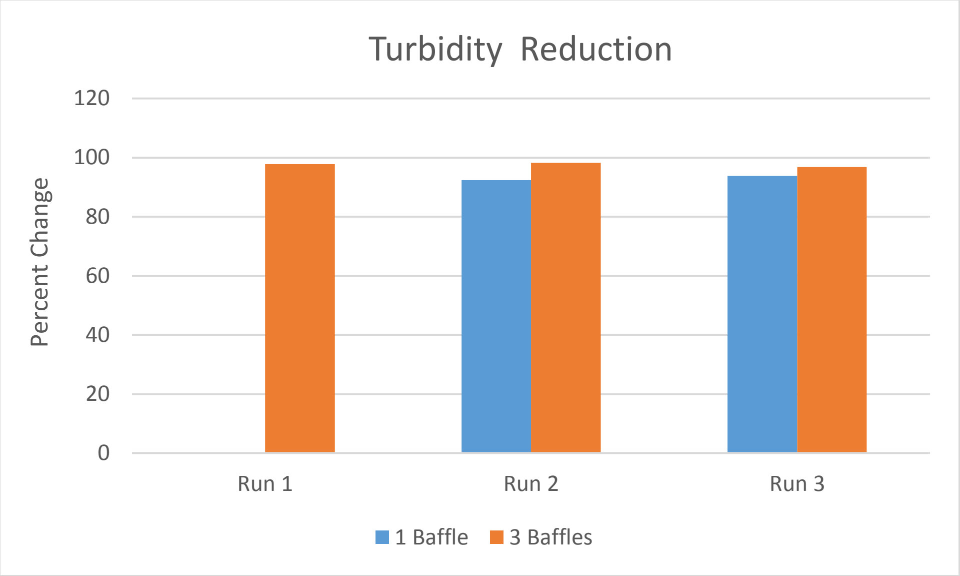


Figure 3.40. **Turbidity reductions using single- and three-baffle configurations with the addition of PAM.**

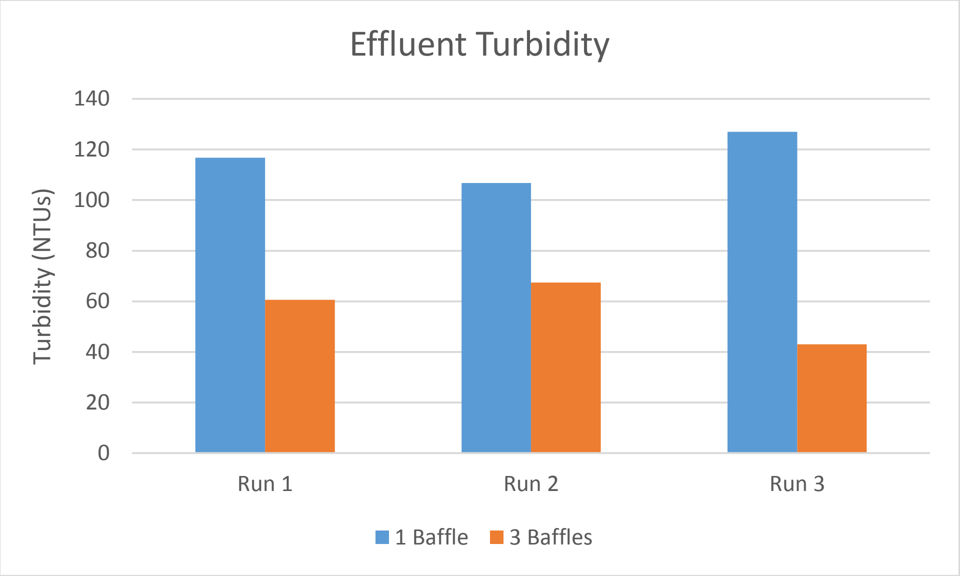


Figure 3.41. **Effluent turbidity using single- and three-baffle configurations with the addition of PAM.**

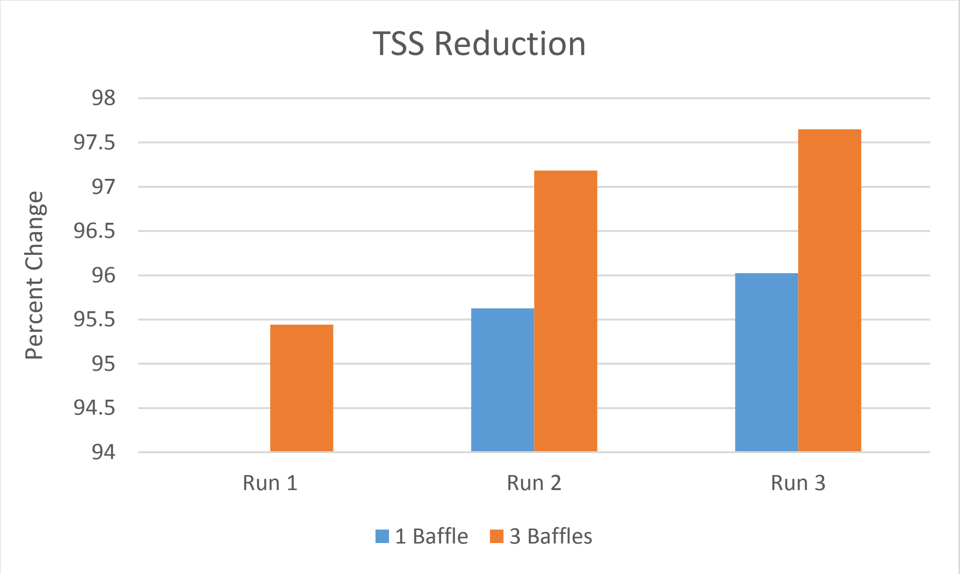


Figure 3.42. **TSS reductions using single- and three-baffle configurations with the addition of PAM.**

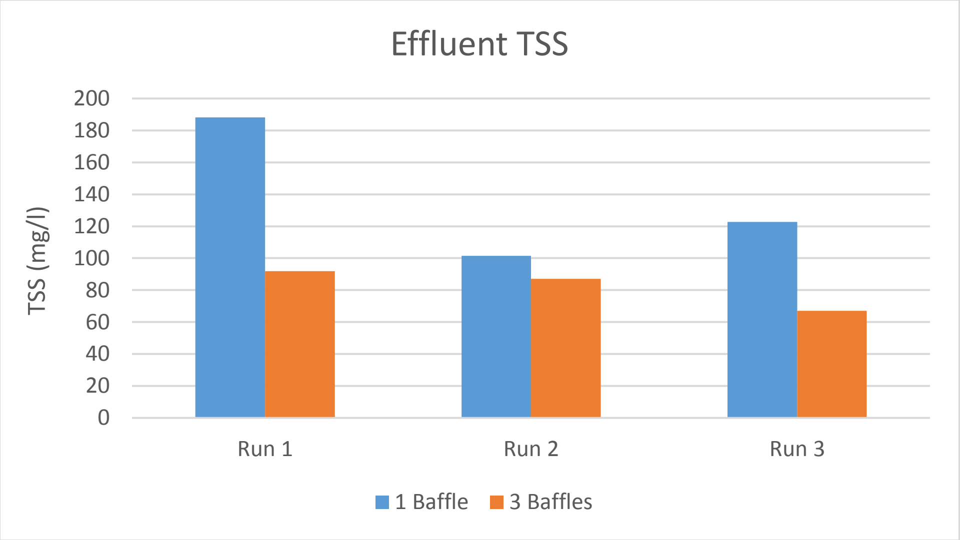


Figure 3.43. **Effluent TSS using single- and three-baffle configurations with the addition of PAM.**

Toxicity Tests

Acute toxicity bioassays are conducted until mortality is observed in all the test organisms and is used to assess concentrations of potential contaminants that will result in lethal doses. Chronic toxicity bioassays evaluate the adverse effects of long-term exposure and typically occur at much lower concentrations than those that might cause acute toxicity. The sublethal evaluation provides results that assess effects on organism growth, reproduction and behavior.

Fat head minnow (vertebrate) mortality is shown in Table 3.12. Each PAM is listed in the left-hand column, with corresponding LC_{50} values shown in the middle column. The column on the right lists LC_{50} values from material safety data sheets provided by the manufacturer. Note that no values were LC_{50} were provided by the manufacturer of PAM 1. Additionally, PAM 3 lists an LC_{50} > 100 mg/L, which could have infinite values. Results indicate PAM 1 is the least toxic to *P. promelas*. PAMs 3 and 5 are similar in toxicities, and PAM 4 is the most toxic. PAM 2 (anionic) is not represented in Table 3.11.

Table 3.11. ***P. promelas* mortality.**

PAM Flocculant	LC_{50} (mg/L)	MSDS LC_{50} (mg/L)
PAM 1 - Anionic	3,250.00	
PAM 3 - Anionic	1,239.00	> 100
PAM 4 - Cationic	48.12	22.8
PAM 5 - Cationic	825.50	1110

D. magna (invertebrate) mortality is summarized in Table 3.12. For *D. magna*, PAM 3 and 1 were not significantly different in their toxicities. Again, PAM 4 was the most toxic of the 4 represented in this table. The MSDS for PAM 4 shows a much higher LC50 than what experimental results indicate. Oftentimes, this may be attributed to the health of the culture organisms. Standard reference toxicity tests (using sodium chloride) were conducted with *D. magna* once monthly to confirm the health of organisms utilized in these experiments was normal.

Table 3.12. ***D. magna* mortality**

PAM Flocculant	LC_{50} (mg/L)	MSDS LC_{50} (mg/L)
PAM 1	868.90	> 420
PAM 3	1,337.00	> 100
PAM 4	7.50	135.0
PAM 5	360.70	

Results for chronic toxicity bioassays using *C. dubia* are shown in Table 3.13. Note that in place of LC_{50} values provided in the right-hand column for each MSDS, chronic toxicity assays may use EC (effective concentration) at which chronic effects are observed. Such values are typically much lower than those associated with lethal effects provided by LC_{50} values. PAM 3 showed a much higher chronic toxicity for

C. dubia reproduction than for *D. magna* or *P. promelas* mortality. PAM 4 was again one of the more toxic compounds.

Table 3.13. *C. dubia* chronic toxicity

PAM Flocculant	EC_{50} (mg/L)	MSDS EC_X (mg/L)
PAM 1	102.06	27.7 (EC_{25})
PAM 3	8.77	
PAM 4	12.24	
PAM 5	72.01	352.0

Note that PAM 2 is not listed in any of the 3 tables above. PAM 2 contained a proportion that did not fully dissolve, and therefore interfered with testing procedures and protocol. For PAM 2, resulting toxicity was more likely due to effects associated with conductivity rather than the PAM itself.

4. Recommendations

PAM Application Techniques

One goal of this research was to maximize turbidity reduction with a passive PAM application in simulated construction site runoff. Additional research efforts were directed at examining responses in turbidity levels when PAM applications could become desiccated. The following conclusions can be summarized from the results.

1. Under both field conditions and controlled experiments, sediment tubes without PAM application provide no significant reduction in turbidity or TSS.
2. Granular PAM applied directly on sediment tubes provided better reductions in turbidity and TSS than PAM delivered through a permeable bag.
3. In controlled experiments, PAM applied before each run provided a quicker decrease in turbidity than applying a single time prior to the commencement of testing.
4. Turbidity levels less than 280 NTU in effluent flows were achieved within 3 sediment tubes when PAM was applied before each run. PAM applied a single time prior to the commencement of testing created turbidity levels lower than 280 NTU within five sediment tubes.
5. Once applied PAM (either in sprinkle or tube form) becomes wet from storm events and dries out during periods of dry weather, it loses effectiveness in reducing turbidity.
6. In controlled experiments, reapplication of granular PAM to sediment tubes after periods of dry weather and before storm events will consistently reduce turbidity below 280 NTU.

Results indicate that PAM application may be necessary for significant turbidity and suspended sediment reduction. This research suggests that granular PAM applied directly to sediment tubes can significantly reduce turbidity below USEPA's proposed 280 NTU turbidity numeric effluent limit under the derived test conditions.

Scheduling Application

PAM longevity is critical in deciding when to reapply as a flocculant for turbidity and TSS reduction. Statistically, no significant differences in turbidity reduction were observed between first applications of PAM and PAM reapplied to sediment tubes and endured a three-, five-, or ten-day desiccation period before any subsequent runoff event. However, results for the ten-day waiting period yielded the two highest mean turbidities for test channel effluent: 342 and 477 NTU. Based on a 280 NTU target value and deploying linear interpolation of data between 5- and 10-day period yielded a 6.7-day optimized reapplication interval. Therefore, it is recommended that PAM be reapplied at least once every seven days to ensure proper turbidity reductions.

Field Data

Research on SCDOT linear best management practices analyzed reducing turbidity and TSS using sediment tubes, rock ditch checks (RDC) and rock ditch checks with washed #57 stone (RDC-WS) on the upstream face at three active roadway construction sites in the upstate, midlands, and coastal regions of South Carolina. In addition, data were collected from these BMP installations with and without a granular PAM application. It was observed that both RDC and RDC-WS with a PAM treatment were most effective in reducing turbidity showing an average decrease in turbidity of 58-63%. Sediment tube wattles with a PAM treatment reduced turbidity values on average by 36%. Without PAM, turbidity in several instances across multiple BMP checks showed small increases. These increases are thought to be in part caused by resuspension of sediment from within the channel. It was also observed that the passive addition of PAM as a flocculant, increased the TSS removal efficiency for rock ditch checks, rock ditch checks with washed stone and sediment tubes. The use of PAM on construction sites can reduce TSS and turbidity.

This research also confirms proper BMP installation, maintenance and regular inspections should be a priority in effectively reducing TSS and turbidity. It was observed in the field that over many storm events that resuspension and erosion within unmaintained channels or associated with unmaintained BMPs resulted in increased TSS values. Infrequent maintenance often corresponded to higher TSS and lower observed trapping efficiencies.

Basin Configuration

Baffles placed in detention basins dissipate the energy of flowing water and spread it over the width of the sediment basin thereby increasing the hydraulic retention time and allowing suspended sediment time to settle out of the water column. Skimmers also aid in improvement of effluent water quality by only withdrawing from the basin surface. Results from this study suggest that with either skimmers or skimmers and baffle combination, greater than an 80% reduction in turbidity could be achieved. With the addition of PAM, reductions could exceed 90%. Without PAM, effluent levels ranged between 60-400 NTUs, while with PAM, discharged effluent was between 16-160 NTUs. Only Run 1 of Skimmer 1 did not have similar results. Likewise, when assessing TSS, greater than 82% reductions were achieved with either skimmers or skimmers used in conjunction with baffles. When PAM was added, these values increased to greater than 90%. Similar results could be seen when investigating peak turbidity and TSS values.

A final investigation that was conducted compared single baffle and three-baffle configurations. For these tests, PAM was used as a flocculant. LSD tests (alpha = 0.05) confirm the three-baffle configuration performed better than single baffle configuration for reducing turbidity from basin effluent. While there was a statistical difference between single and three baffles, both resulted in reductions greater than 90%. With single baffle, turbidity effluent average values were around 120

NTUs, while with three baffles, they were around 60 NTUs. For TSS, no statistical difference between single baffle and three baffles was found. TSS reductions for both configurations were greater than 95%.

Therefore, if a sediment basin is to be used for turbidity reduction, then a three-baffle configuration should be employed. If a basin is required solely for TSS reduction however, then the current SCDOT lower state baffle standard should be sufficient.

Toxicity

The vertebrate Fathead Minnow species *P. promelas* showed to be the least sensitive in comparison to *D. magna* in acute exposures as described by LC_{50} values. The order of toxicity for PAM flocculants was similar for *P. promelas* and *D. magna* for acute exposures. Cationic PAM Flocculants appeared to be the most toxic. Previous research has also suggested that cationic forms of contaminants, specifically cationic surfactants, are more toxic than the anionic form. Conductivity may describe the toxicity of PAM 2 for *P. promelas* and *D. magna*. Several states have banned the use of cationic PAM due to the toxic nature of these compounds. Anionic PAM flocculants showed the least toxicity for all species – except for *C. dubia*. This could be a result of the flocculation of food particles. Toxicities reported here are well above the dosage recommendations. It is important to recognize the tests were conducted at high concentrations. Toxicity could be because organisms simply struggled to move through highly viscous solutions and used more energy to swim. More energy exertion for swimming, decreases energy for other important biological functions. Many Material Safety Data Sheets (MSDS) were found to be inconsistent with reporting methods.

Footnotes and References

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Appendix

Appendix A. Lab Channel Experimental Design

Figure A.1. **Channel Design. On left, upstream view of channel from bottom. On right, downstream view of channel from tank outlet during experimentation.**

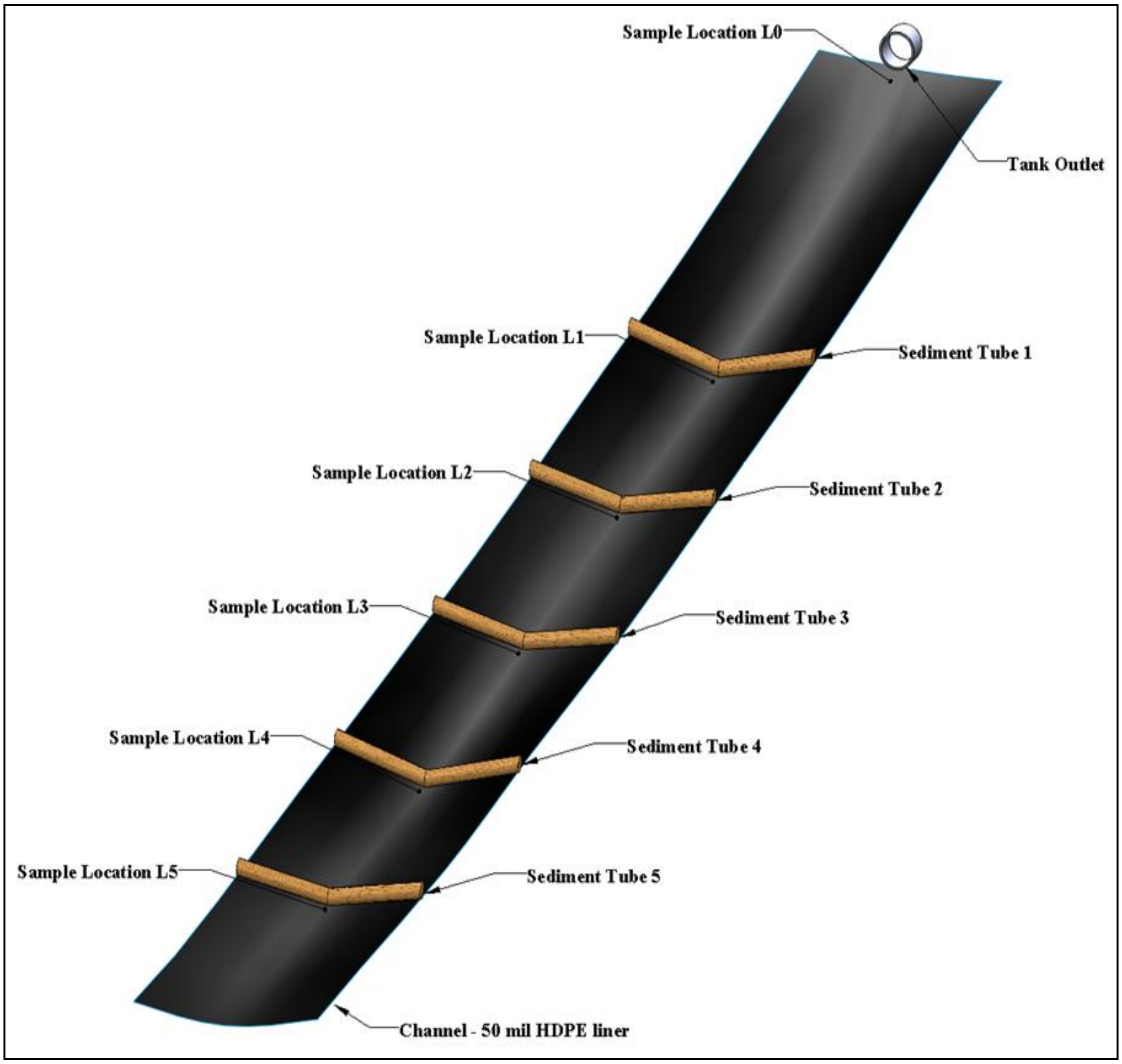

Figure A.2. Channel design schematic.

Table A.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

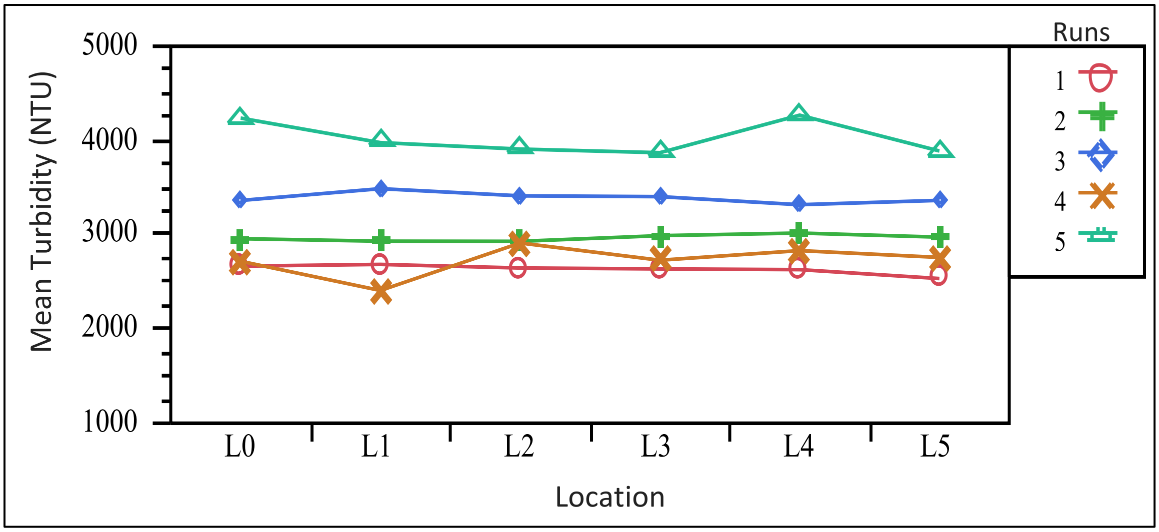

Figure A.3. **Mean turbidity across sample locations for each run within Treatment 1.**

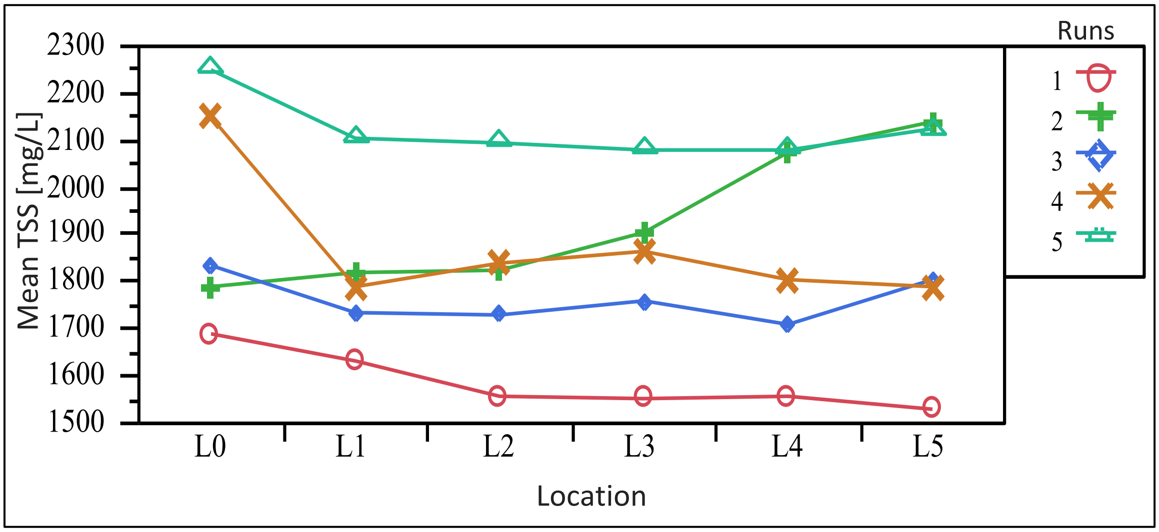

Figure A.4. **TSS concentration across sample locations for all runs within Treatment 1.**

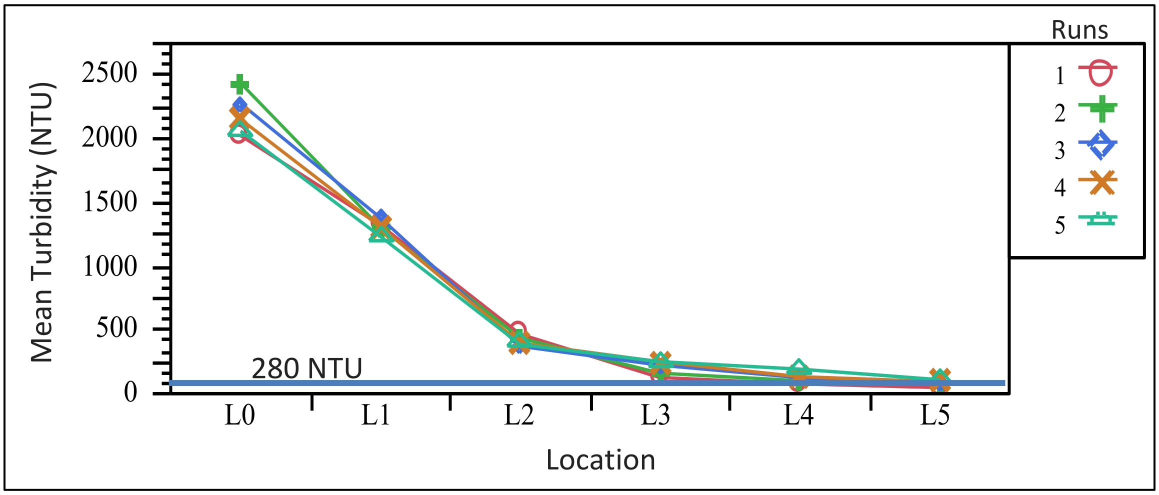

Figure A.5. **Mean turbidity across sample locations for each run within Treatment 2.**

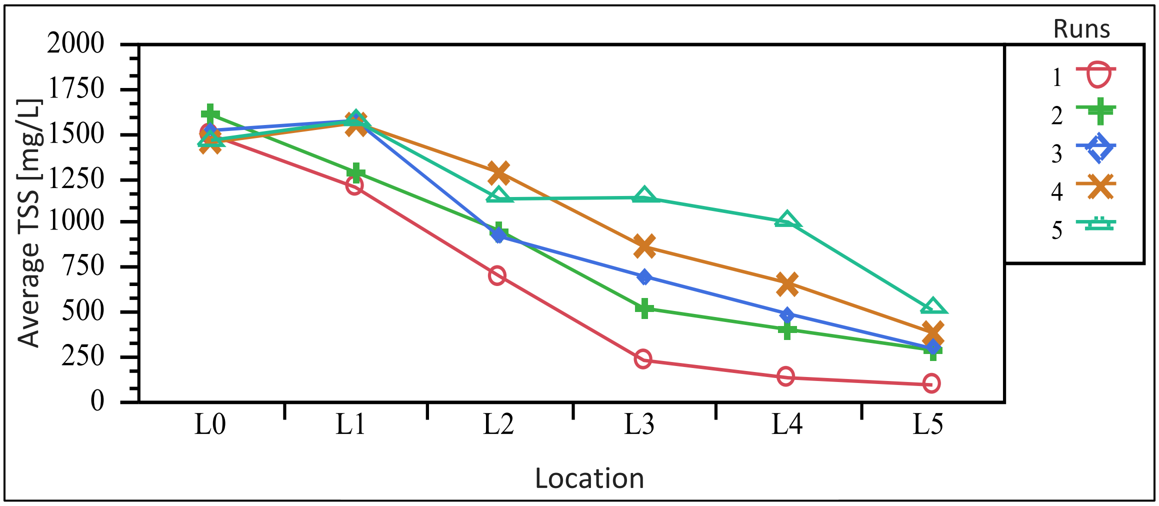

Figure A.6. **TSS concentration across sample locations for all runs within Treatment 2.**

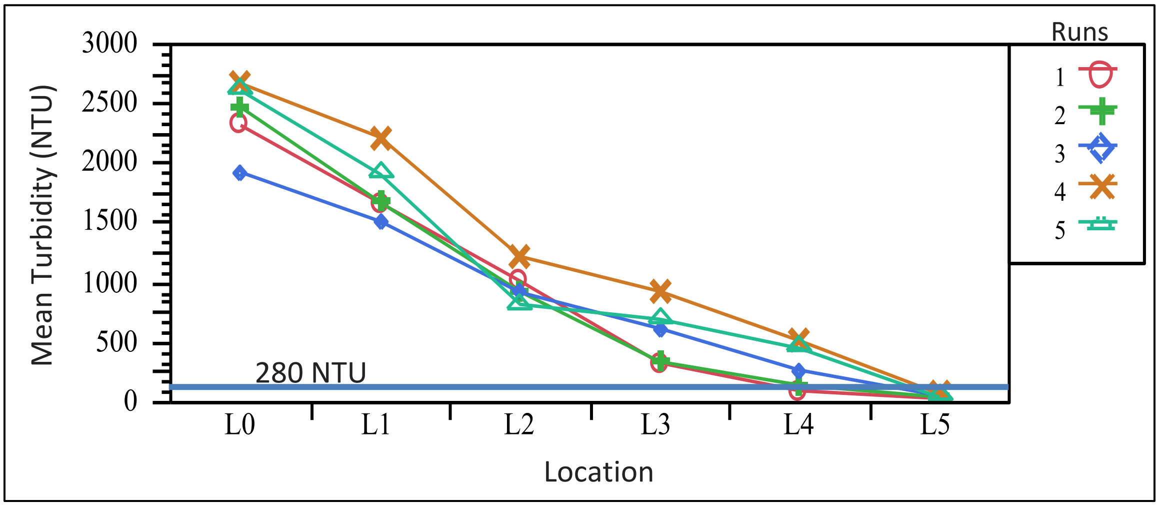

Figure A.7. **Mean turbidity across sample locations for each run within Treatment 3.**

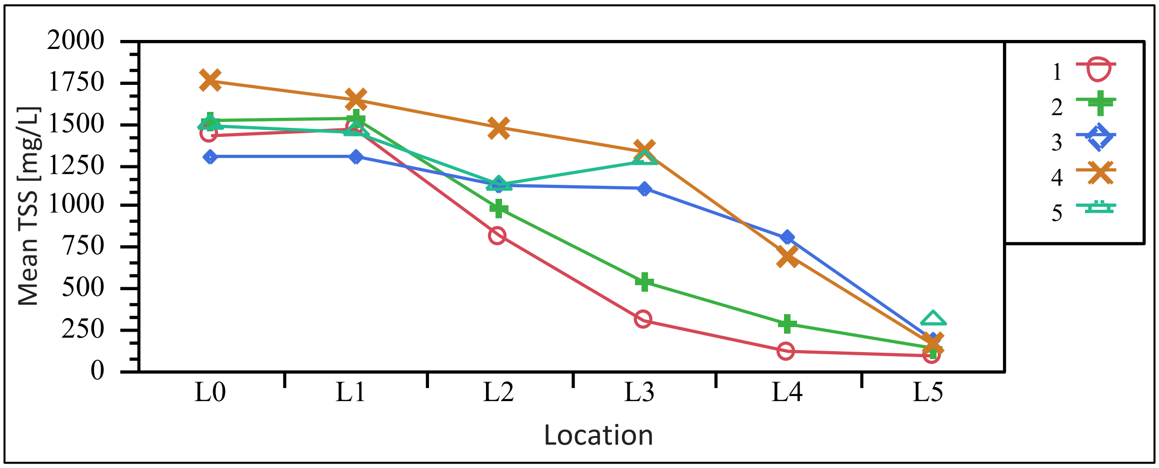

Figure A.8. **TSS concentration across sample locations for all runs in Treatment 3.**

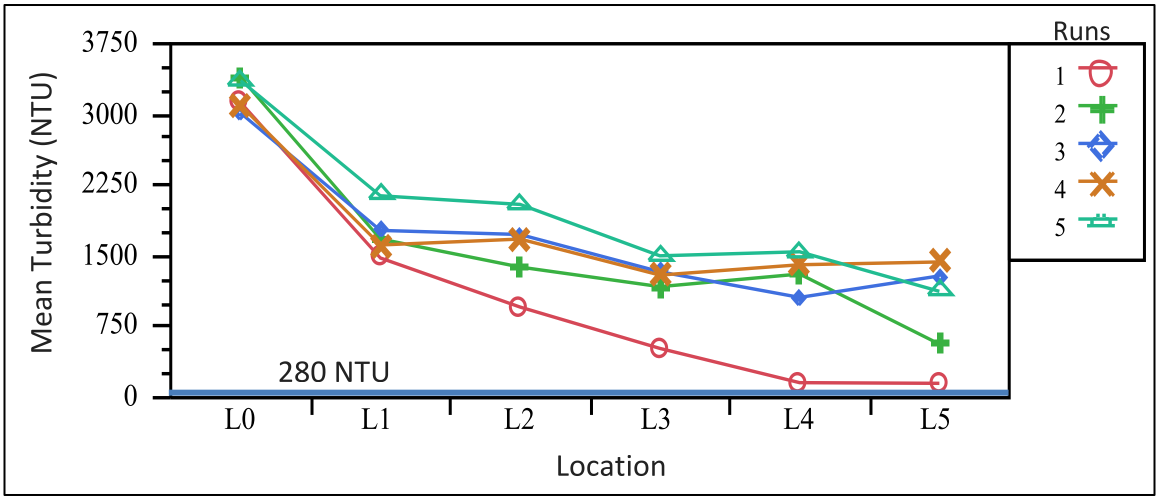

Figure A.9. **Mean turbidity across sample locations for each run in Treatment 4.**

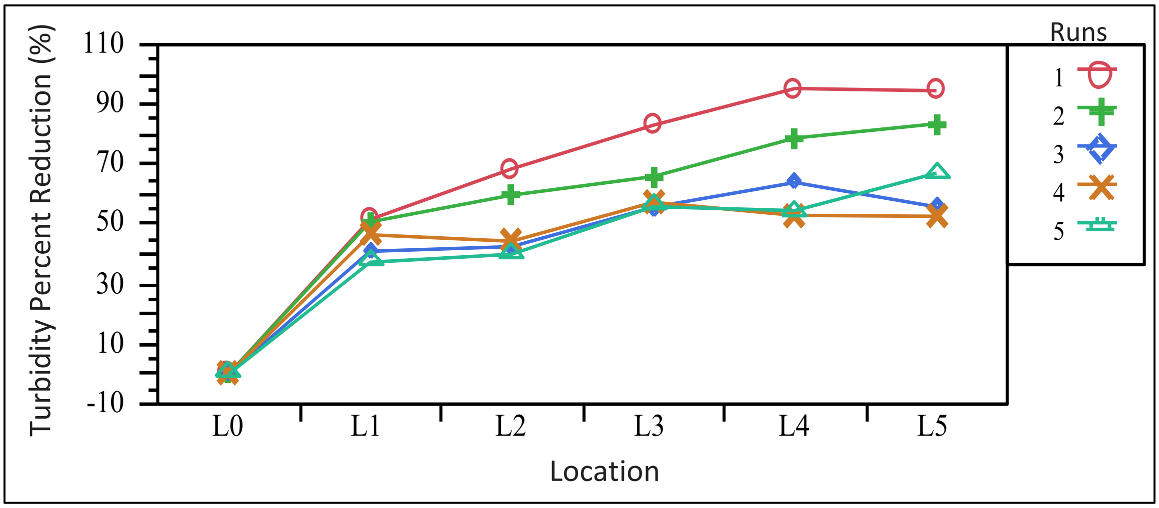

Figure A.10. **Cumulative percent reduction of for each run turbidity Treatment 4.**

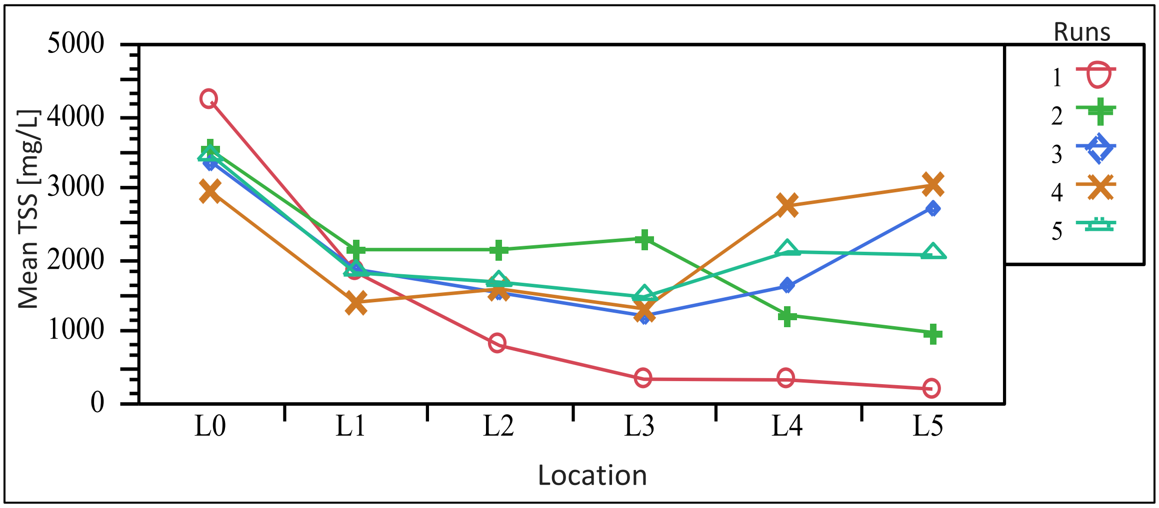

Figure A.11. **Mean TSS concentration for all runs within Treatment 4.**

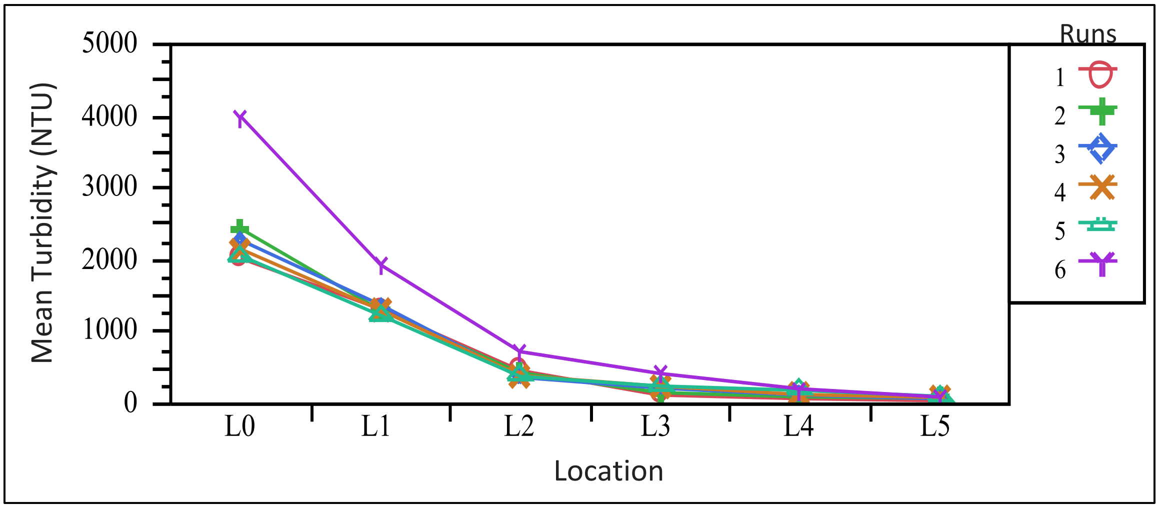

Figure A.12. **Turbidity 6th run comparison to previous runs for Treatment 2.**

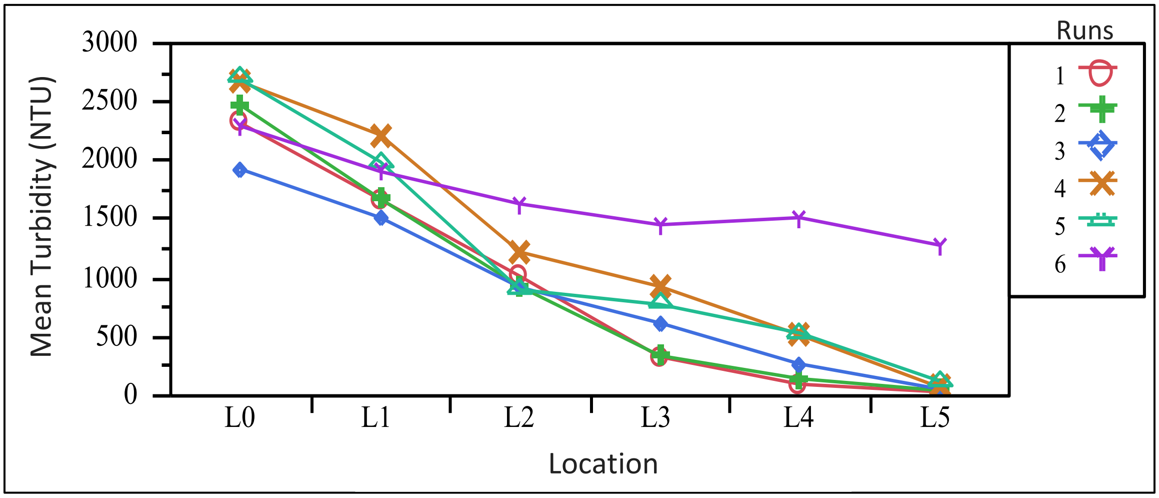

Figure A.13. **Turbidity 6th run comparison to previous runs for Treatment 3.**

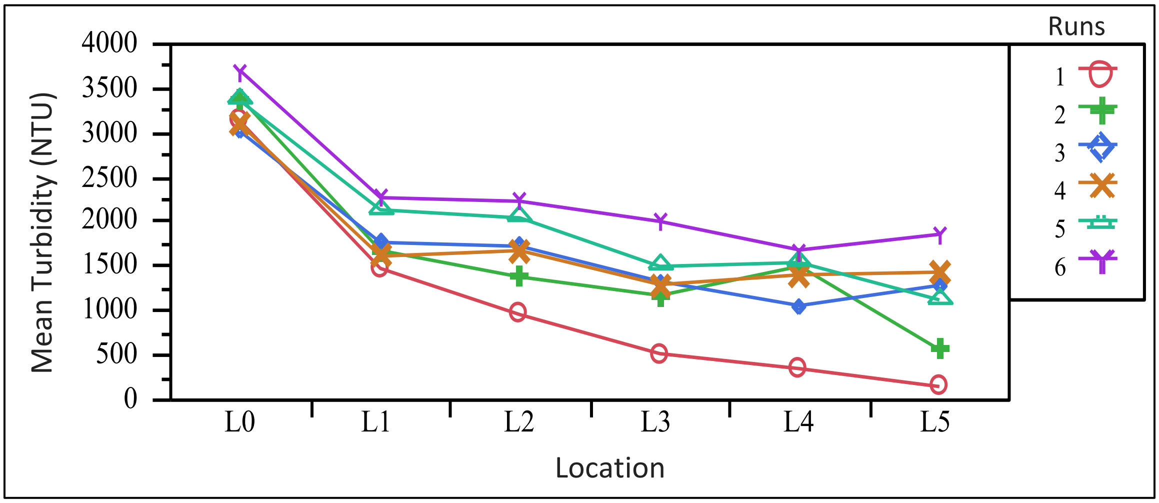

Figure A.14. **Turbidity 6th run comparison to previous runs for Treatment 4.**

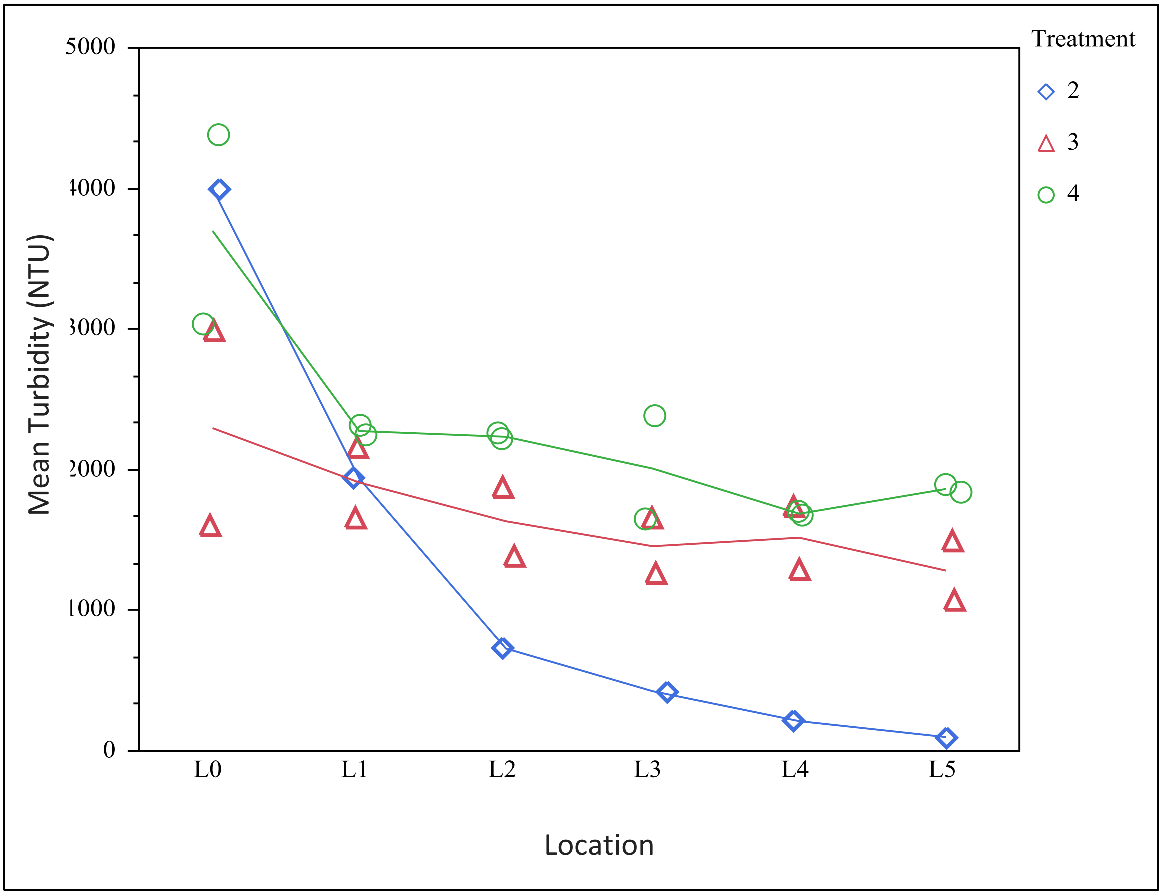

Figure A.15. Mean turbidity across sample locations for run 6 of treatment 2, 3, and 4.

Appendix B. Field Site Characteristics

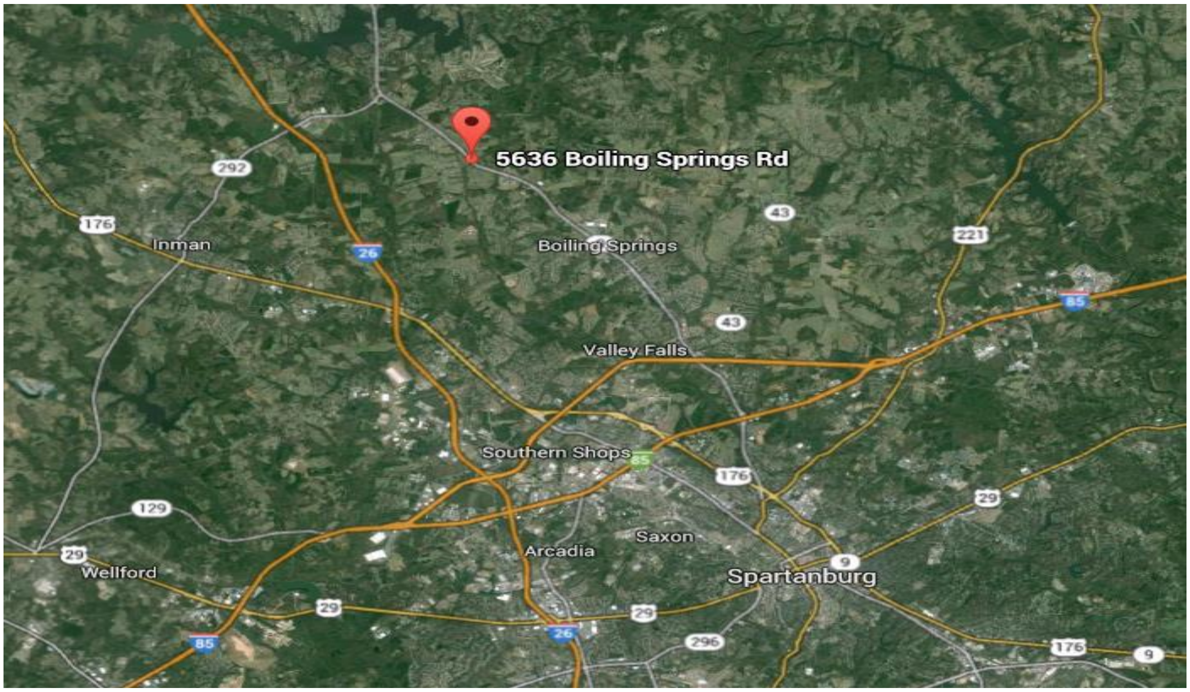

Figure B.1. **Location map showing the location of the upstate Project Site.**

Figure B.2. **Upstate research station showing instrumentation.**

Figure B.3. Location map showing the location of the midlands research site.

Figure B.4. Midlands research channel showing instrumentation.

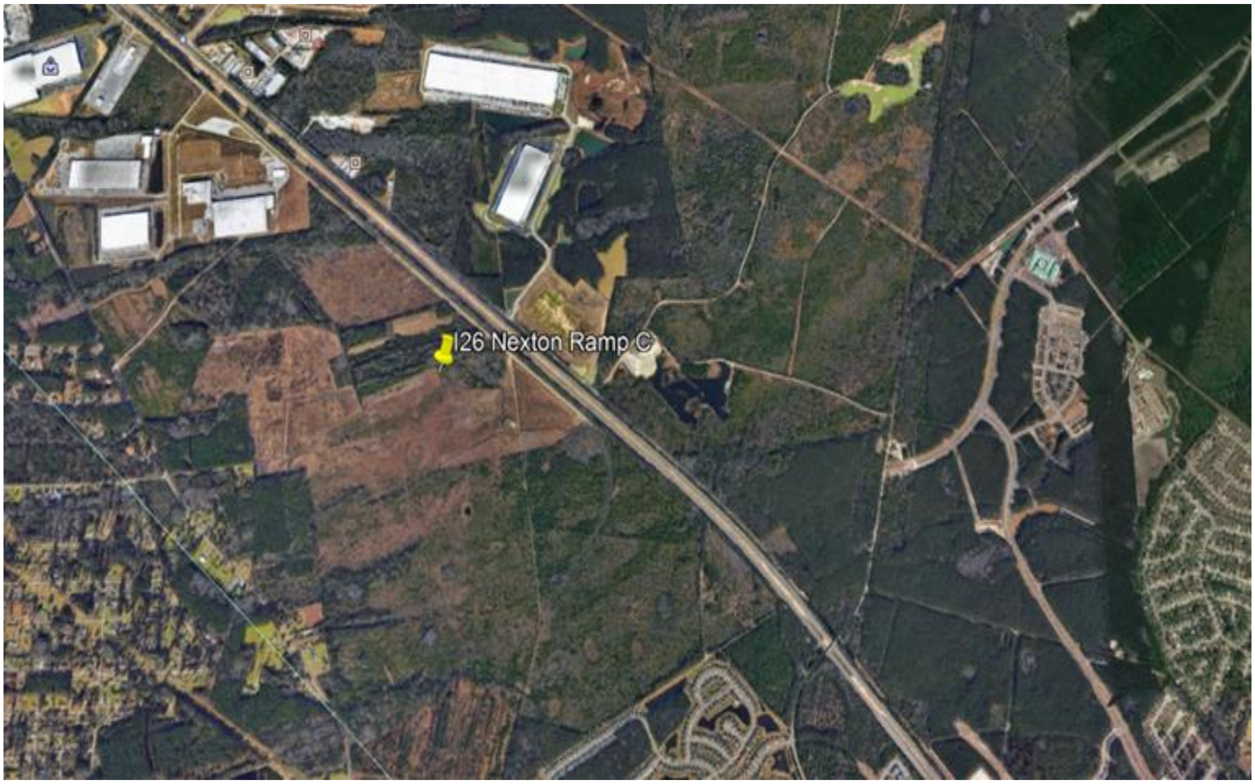

Figure B.5. Location map showing the location of the coastal research site.

Figure B.6. Coastal research station showing instrumentation and Parshall flume.

Figure B.7. Probes mounted in the 6" Parshall Flume.

Table B.1. ISCO-Teledyne sampling schedule, activated by runoff reaching the 0.1 ft. trigger point.

Bottle #	Time Since Enable [min]	Bottle #	Time Since Enable [min]
1	0	13	120
2	5	14	135
3	10	15	150
4	15	16	165
5	20	17	180
6	25	18	195
7	30	19	210
8	45	20	225
9	60	21	240
10	75	22	255
11	90	23	270
12	105	24	285

Figure B.8. **Image of a “base station” installed at the upstate location, equipped with a rain gauge and cellular modem.**

Table B.2. Table of timed intervals for extracting samples for particle size analysis, based on particle size and water temperature in degrees Celsius.

Particle Size (cm)	Time to Fall 150 mm @21	Time to Fall 150 mm @22	Time to Fall 150 mm @23	Time to Fall 150 mm @24	Time to Fall 150 mm @25	Time to Fall 150 mm @26	Time to Fall 150 mm @27	Time to Fall 150 mm @28	Time to Fall 150 mm @29	Time to Fall 150 mm @30
0.0063	0.00.41	0.00.40	0.00.39	0.00.38	0.00.38	0.00.37	0.00.36	0.00.35	0.00.34	0.00.34
0.0031	0.02.50	0.02.46	0.02.42	0.02.39	0.02.35	0.02.32	0.02.28	0.02.25	0.02.22	0.02.19
0.0016	0.10.39	0.10.24	0.10.10	0.09.56	0.09.42	0.09.29	0.09.17	0.09.05	0.08.54	0.08.43
0.0008	0.42.37	0.41.37	0.40.39	0.39.45	0.38.50	0.37.58	0.37.08	0.36.21	0.35.34	0.34.50

	Time to Fall 100 mm @21	Time to Fall 100 mm @22	Time to Fall 100 mm @23	Time to Fall 100 mm @24	Time to Fall 100 mm @25	Time to Fall 100 mm @26	Time to Fall 100 mm @27	Time to Fall 100 mm @28	Time to Fall 100 mm @29	Time to Fall 100 mm @30
0.0004		1.53.38	1.50.58	1.48.25	1.45.59	1.43.33	1.41.14	1.39.02	1.36.56	1.34.51

	Time to Fall 50 mm @21	Time to Fall 50 mm @22	Time to Fall 50 mm @23	Time to Fall 50 mm @24	Time to Fall 50 mm @25	Time to Fall 50 mm @26	Time to Fall 50 mm @27	Time to Fall 50 mm @28	Time to Fall 50 mm @29	Time to Fall 50 mm @30
0.0002		3.47.16	3.41.56	3.36.50	3.31.58	3.27.06	3.22.28	3.18.03	3.13.53	3.05.46

Appendix C. Scaled Sediment Basin Evaluation

Figure C.1. **Scaled sediment basin with baffles installed.**

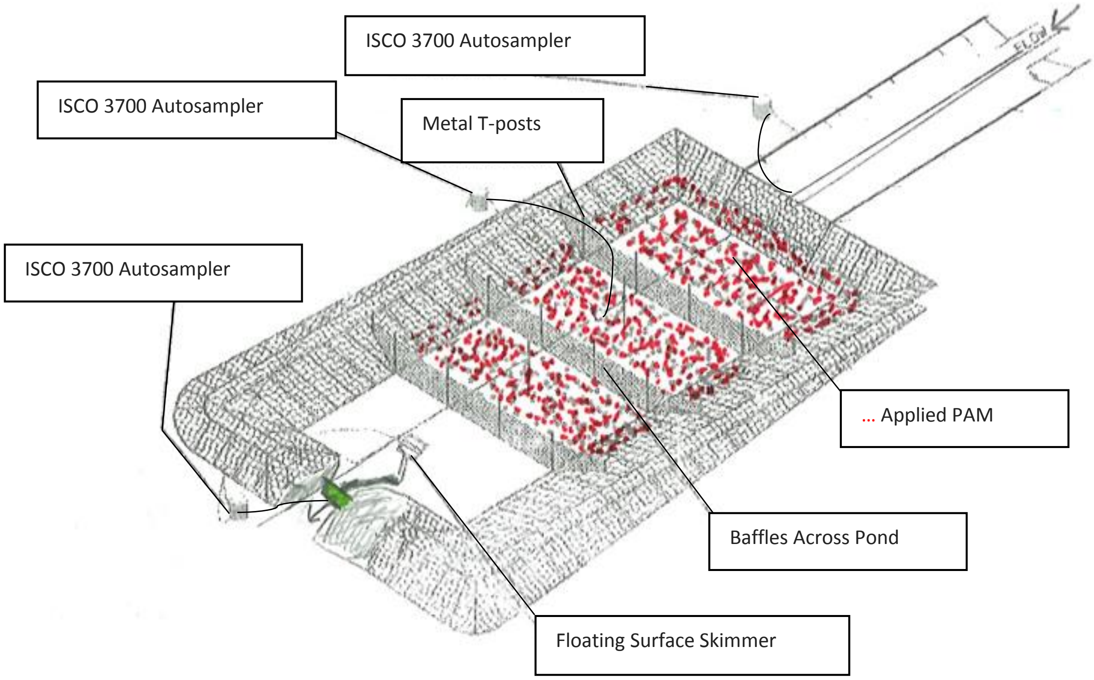

Figure C.2. **Schematic representation of pond layout with sampling locations.**

Table C.1. Influent, mid-pond, and effluent sample timing sequence.

Influent Timing		Mid/Effluent Timing	
Bottle	Time (min)	Bottle	Time (min)
1	0	1	0
2	1	2	3
3	2	3	6
4	3	4	9
5	4	5	12
6	5	6	15
7	6	7	20
8	7	8	30
9	8	9	40
10	9	10	50
11	10	11	60
12	11	12	90
13	12	13	120
14	13	14	240
15	14	15	360
		16	480
		17	600
		18	720
		19	840
		20	960
		21	1080
		22	1200
		23	1320
		24	1440

Appendix D. Toxicity

Table D.1. Pimephales promelas *(P. promelas*) vertebrate acute toxicity.

Endpoint:	Mortality (LC_{50})
Exposure Type:	Static, Non-Renewal
Exposure Duration:	96-Hours
Age of Organism:	< 24-Hours
Number of Treatments:	5 (+ 1 Control)
Replicates/Treatment:	3
Organisms/Replicate:	10

Table D.2. Daphnia magna (*D. magna*) invertebrate acute toxicity.

Endpoint:	Mortality (LC_{50})
Exposure Type:	Static, Non-Renewal
Exposure Duration:	48-Hours
Age of Organism:	< 24-Hours
Number of Treatments:	5 (+ 1 Control)
Replicates/Treatment:	3
Organisms/Replicate:	5

Table D.2. Ceriodaphnia dubia (*C. dubia*) invertebrate chronic toxicity.

Endpoint:	Effect on Reproduction
Exposure Type:	Static, Renewal
Exposure Duration:	8-Days
Age of Organism:	< 24-Hours
Number of Treatments:	5 (+ 1 Control)
Replicates/Treatment:	10
Organisms/Replicate:	1