Reductions in turbidity and *Escherichia coli* density using passive polymer treatment in simulated stormwater runoff

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Abstract: Current research shows sediment basins may act as reservoirs for potentially harmful bacteria, including *Escherichia coli* (*E. coli*), preferentially attach to clay-sized particles and have been found in sediment basin outflows with high turbidity levels containing concentrations exceeding water quality standards recommended by the United States (US) Environmental Protection Agency (EPA). Since research shows *E. coli* preferentially attach to the clay fraction within sediment, it was hypothesized that a reduction in turbidity and total suspended solids (TSS) would create a corresponding reduction in bacterial density. Construction site sediment basin discharge was simulated to determine whether a sediment log configuration using anionic polymer application could reduce *E. coli* densities. Based on prior research, reductions in turbidity and suspended sediment were maximized by applying 100 g of granular polyacrylamide (PAM) directly to each of five sediment logs before simulated runoff events. PAM application successfully reduced turbidity and TSS by 96% and 92%, respectively. Discharge after the last sediment log had an average turbidity of 80 NTU and TSS of 174 mg L^{-1}. For the low *E. coli* density range (5,000-10,000 MPN/100 mL), PAM application failed to create a reduction in bacterial density, but rather an increase in *E. coli* was observed with an average discharge of 25,226 MPN/100 mL. Within the high *E. coli* density range (100,000-200,000 MPN/100 mL), a 29% reduction was recorded with an average discharge of 135,270 MPN/100 mL.

Keywords: *E. coli, sediment, stormwater, sediment basin, construction, runoff*

Citation: Privette III, C. V., C. B. Sawyer, J. W. Berry, J. C. Hayes, and W. C. Bridges Jr. 2017. Reductions in turbidity and *Escherichia coli* density using passive polymer treatment in simulated stormwater runoff. Agricultural Engineering International: CIGR Journal, 19(3): 1–8.

1 Introduction

Construction site runoff transports a variety of pollutants, including sediment, oils, heavy metals, organic matter, and bacteria, into surrounding surface waters and can cause a wide range of environmental impairment. Specifically, bacteria, in elevated concentrations, can create an environment for water-borne illness and become a hazard to public health. In response to elevated bacteria levels in recreational waters, the US EPA initiated the BEACH program in 1997 to reduce risks to human health caused by exposure, either by ingestion, inhalation, or body contact, to pathogens, primarily from sewage and stormwater runoff (US EPA, 2003). To maintain water quality standards, bacterial indicators, such as *E. coli*, are measured to determine whether fecal contamination exists in water bodies. According to the South Carolina Department of Health and Environmental Control (SCDHEC) 2010 Section 303(d) list of impaired water bodies, fecal coliform represents the highest number of listed impairments at 357 in South Carolina (SCDHEC, 2010). Elevated bacteria levels have recreational and economic impacts on communities, such as swimming

Receivede date: 2016-08-23 **Accepted date:** 2017-01-05

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advisories at beaches (SCDHEC, 2011) and shellfish bed harvest restrictions (SCDHEC, 2005).

Current research shows that increased sedimentation resulting from construction activities may contribute to microbial impairment in surrounding water bodies. A significant percentage of the bacteria population is associated with soil particles, thus runoff laden with suspended sediment serves as a secondary source of increased bacteria (*E. coli*) concentrations to receive water bodies (Sawyer, 2009; Wu et al., 2009; Jamieson et al., 2005). Specifically, construction site sediment basins reduce a large percentage of suspended sediment from entering receiving water bodies; however, current research indicates these basins may also contribute to the overall bacteria loading of lakes, rivers, and receiving waters.

Two studies investigated several sediment basins in upstate South Carolina and found these systems could act as reservoirs for bacterial indicators. Sawyer (2009) found mean water column bacteria concentrations were significantly higher than EPA's recommended contact recreational water quality standards at all sediment basins monitored as part of the study. Similarly, Kunkel et al. (2013a) observed outflow *E. coli* densities were higher than inflow densities in sediment basins. Additionally, *E. coli* levels in the water column decreased faster than that in sediment (Kunkel et al., 2013a). Some other results confirmed the existing research that *E. coli* was more closely associated with smaller sediment particles, and deposited sediment within basins which provided protection for *E. coli* (Burton et al., 1987). Kunkel et al. (2013b) reported that the highest levels of *E. coli* was associated with soil particles less than 0.004 mm, and the greatest density of *E. coli* occurred in the top 2.54 cm of deposited sediment. These findings further support that *E. coli* adhere to the silt and clay fraction of soil.

Turbidity and bacteria concentration are interconnected when compared to sediment basin discharge. Silt and clay fractions influence turbidity greatly and are easily resuspended during a rainfall event. Consequently, high turbidity in the outflow caused by resuspension results in high bacteria concentrations at the outlet (Kunkel et al., 2013a). Resulting discharge may exceed the recommended EPA limit of 126 MPN/100 mL for a 5 sample geometric mean, as well as the single 235 MPN/100 mL grab sample.

Current research suggests a limited number of structural stormwater best management practices (BMPs) may successfully reduce fecal coliform levels in stormwater discharge. The comparison between retention ponds, detention basins, bioswales, and media filter in various states across the US indicated that bioswales and detention ponds had few effect on reducing bacteria levels, whereas retention basins and media filters showed signs of bacterial removal (Clary et al., 2008). However, Clary et al. (2008) observed the BMPs that nothing could reliably reduce the bacteria levels in discharge. Similarly, a study in Charlotte, NC monitored nine stormwater BMPs, including one wet retention pond, two stormwater wetlands, two dry detention basins, and one bioretention area, to evaluate the reductions in bacterial densities. They found that wetlands and bioretention cells could reduce *E. coli* concentrations in discharge by greater than 50% and had effluent concentrations lower than the EPA standard for *E. coli* (Hathaway et al., 2009). Davies and Bavor (2000) also found bacterial removal in constructed wetlands outperform wet retention ponds. A study in San Francisco, CA, diverted 0.44 million L of stormwater into a natural riparian buffer before entering an adjacent lake, and found that the lake levels of *E. coli* was significantly lower than that in the discharged stormwater (Casteel et al., 2005). Findings above support the conclusions that BMPs, which could effectively reduce bacteria numbers, have extensive ambient sunlight to exposure and treat stormwater through the physical process of infiltration.

Construction sites may pose a larger problem for bacteria removal, due to potentially high loading rates of sediment. Because of plant life that thrive in bioretention areas and stormwater wetlands, these BMPs are not designed to handle large quantities of sediment and are usually constructed to treat post-construction stormwater. Current research has focused on the use of rolled erosion control products to filter and promote settling of sediment-associated bacteria particles. In a recent study, compost filter socks were found to reduce total coliforms and *E. coli* by 74% and 75%, respectively (Faucette et al., 2009).

To reduce bacteria levels, several studies have explored the use of flocculants in simulated runoff. Recently, reductions in bacteria numbers from irrigation pond water were reported by using three flow rates (7.5, 15.5, 22.5 L min^{-1}) in irrigation furrows where PAM was applied directly to the soil in the first 1.0 m (Sojka and Entry, 2000). In addition, a 90% reduction in microorganisms has been observed when PAM is applied to soil where cattle, fish, and swine wastewater runoff occurs (Entry and Sojka, 2000). A study simulating stormwater pollutant removal found filter socks combined with polymer treatment (BactoLoxx®) increased the removal efficiencies of *E. coli* by 89%-99% (Faucette et al., 2009). Additional research is required to determine whether bacterial reductions in construction site runoff under higher flow conditions are achievable with polymer application.

The objectives of this study are to determine whether passive PAM treatment for lowering turbidity may result in a corresponding reduction in bacterial density.

2 Materials and methods

2.1 Experimental site

To simulate stormwater runoff conditions found on a typical construction site, a high-density polyethylene HDPE-lined triangular channel was constructed with the following dimensions: 56.4 m length, 3.66 m width, 0.50 m average depth, and 7% slope. Figure 1 shows a labeled schematic and corresponding site photograph, indicating sample locations. The channel was lined to prevent scouring and erosion, which could affect total sediment load during experimentation and potentially compromise results.

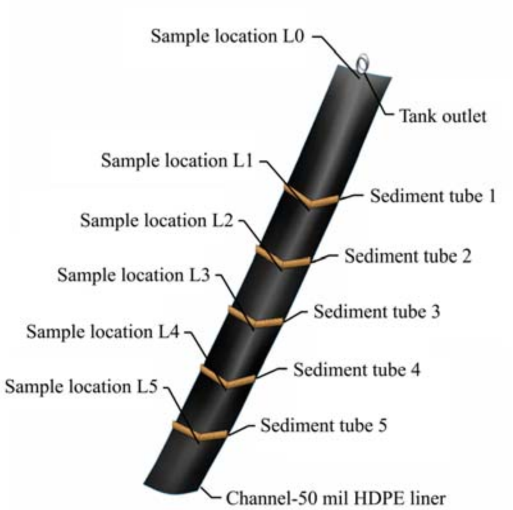

Figure 1 Channel design schematic and test channel photograph showing ditch check sediment logs

To determine a realistic experimental flow rate, one year, 24 hour rainfall events were averaged for Greenville, Richland, and Charleston counties in South Carolina. The resulting average rainfall depth was 86.6 mm. A peak flow rate of 0.07 m^3 s^{-1} was calculated for a newly graded 0.404 hectare site with a 2% watershed slope and comprised equally of hydrologic soil groups A and B. To simulate the experimental flow rate, an 18.2 m^3 collapsible tank was chosen to simulate runoff from construction sites. The tank outlet was controlled by a 152 mm gate valve which drained the tank in 12 minutes. The peak flow rate discharged from the tank was 0.05 m^3 s^{-1} with an average flow rate of 0.02 m^3 s^{-1} over the 12 mins period.

A simulated sediment-laden stormwater solution was needed to mimic runoff from a construction site. To achieve these conditions, kaolinite clay was selected. Kaolinite is a naturally occurring clay easily suspended in water and represents the silt/clay fraction that would be found in a Piedmont soil. An 8200 watt pump with a flow rate of 20 L s^{-1} was used to recirculate the solution utilizing a nozzle configuration to increase dispersal velocity and enhance particle suspension. Targeted turbidity within the tank was 1,600-2,000 NTU and measured by an Analite NEP160 display with NEP260 probe handheld turbidity meter (McVan Instrument).

Log wattle ditch checks are commonly deployed within channels as sediment control structures for construction site runoff. For this research, 508 mm diameter and 3.05 m American Excelsior Curlex® sediment logs (American Excelsior Company) were selected. Sediment logs were placed within the channel at 7.62 m intervals. Based on channel length, five sediment logs were used in series (Figure 1). To anchor logs, steel tee posts were bent 90 degrees with a 254 mm over hang and driven into the ground. Sand bags were used to anchor log ends.

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

2.2 Polymer optimization

The 700 series silt stop polyacrylamide erosion control powder (Applied Polymer Systems, Inc.), was chosen as flocculating agent. The 700 series is a soil-specific polyacrylamide co-polymer powder. 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 included #705, #707, #712, #730, #740, and #745. Jars were observed for clarity of water, largest particulate formed, and flocculation time and the kaolinite responded best to #705 polymer.

2.3 *E. coli* experimentation

Bacteria experimentation included two trials to determine if PAM application to treat turbidity would also reduce *E. coli* within the channel and at the point of discharge. Previous research (Berry, 2012) indicated PAM sprinkled in 100 g doses directly on sediment logs consistently had highest turbidity reductions, and thus it was selected for this study. A control test referred to as Treatment 1, which had no PAM application, only bacteria-sediment mixture and five sediment logs, included a series of five tank discharges of simulated construction site runoff completed within 24 hours. Tests were then duplicated for statistical accuracy. Treatment 2 tests were then conducted where 100 g of PAM was sprinkled on each sediment log and then reapplied using the same dose after each tank discharge. The PAM application test included five runs completed within 24 hours. The entire test was duplicated for statistical accuracy. All sediment logs were removed and replaced with new logs at the completion of each test.

To simulate low bacteria levels found in construction site effluent, wastewater from a nearby dairy lagoon was collected and introduced into the collapsible tank. Samples showed that 0.25 m^3 of lagoon sludge resulted in *E. coli* concentrations of 5,000-10,000 MPN/100 mL within the 18.2 m^3 tank. A 187 watt sump pump was used to transfer sludge from the lagoon to the transfer tank. Wastewater was fed into the 18.2 m^3 tank by gravity as it was simultaneously filled up with pond water. To achieve higher bacteria concentrations, a second method involved creating a slurry of 0.02 m^3 of fresh bovine manure collected from a free-stall dairy barn, introduced into the collapsible tank, and agitated. The resulting mixture produced bacteria concentrations between 100,000-200,000 MPN/100 mL when added to the collapsible tank. Turbidity within the tank was monitored to ensure it remained within the target range of 1,600-2,000 NTU. The bacteria-sediment mixture was agitated for 20 minutes and then allowed to settle for 1 h. This time interval provided an opportunity for viable bacteria to attach to sediment particles. After settling, the recirculation pump was turned on five minutes to resuspend sediment before the tank valve was opened and sampling commenced.

Samples were analyzed for *E. coli* most probable number (MPN), turbidity, and TSS. To reduce the risk of cross contamination between runs, sampler tubing was triple rinsed with tap water and then triple rinsed with deionized water.

2.4 Samples analysis

Bacteria enumeration was completed within six hours of sample collection using the Colilert® enzyme substrate procedure, and method 9223 B from standard methods for the examination of water and waste water (AHPA, 2005). Dilutions of collected samples were necessary to keep detectable bacteria numbers within the range provided by the Colilert® QuantiTray 2000 system. A Hach 2100AN benchtop turbidimeter (Hach Company) was used to measure turbidity from samples following standard method 2130 B (AHPA, 2005).

In addition to bacterial enumeration and turbidity, selected samples were analyzed for TSS using standard method 2540 D (AHPA, 2005). Typically, the first and last samples collected for a given location were analyzed for TSS. If the first or last sample lacked adequate volume, the next or previous sample, respectively, was selected.

2.5 Statistical analysis

Statistical calculations were performed with JMP software, a product of SAS Institute Inc. in Cary, NC, USA. Regression analysis, analysis of variance, and t-tests were used to evaluate and compare mean *E. coli* density, turbidity, and TSS among runs and sample positions. The statistical significance tests used an alpha value of ≤0.05.

3 Results and discussion

3.1 Turbidity results

A JMP model was created to compare turbidity, TSS, and *E. coli* density with differing PAM applications. Treatment 1 acted as a control, consisting of sediment logs with no PAM application, whereas Treatment 2 involved dosing each sediment log with 100 g of granular PAM. Samples obtained at the tank outlet, sediment log 1, sediment log 3, and sediment log 5 will be referred to as locations L0, L1, L3, and L5, respectively. Results indicated a strong difference in mean turbidity between Treatment 1 and Treatment 2. Side by side data comparison for both treatments was displayed in Figure 2 which represented the mean turbidity levels at each sample location over 5 experimental test runs.

From F-test analysis, there was no significant difference (F-stat = 0.4795, p = 0.7002, n = 40) between turbidity values in each sample location existed in Treatment 1. No turbidity reduction in Treatment 1 most likely showed that sediment logs alone provided no ability to reduce turbidity. Treatment 2 displayed a significant decrease in average turbidity across sample locations (F-stat = 59.4258, p<0.0001, n = 44). Turbidity at location L5 for all runs within Treatment 2 was not significantly different and combined for a mean discharged turbidity of 80 NTU. In a side by side comparison (Figure 2), a substantial reduction was observed in Treatment 2 versus Treatment 1; in which Treatment 2 reduced turbidity by 96%. While logs alone appeared to provide no statistical change in effluent turbidity, treated wattles might afford the construction industry a viable alternative should proposed regulations require additional turbidity reductions.

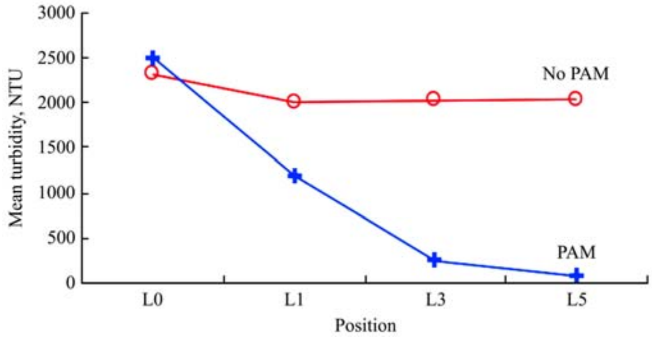

Figure 2 Mean turbidity comparison of Treatment 1 (no PAM) and Treatment 2 (100 g PAM application)

As expected, TSS concentrations followed similar trends as turbidity and statistically significant reductions only occurred when PAM was presented. TSS comparisons for each treatment were shown in Figure 3. The statistical analysis in Treatment 1 showed no significant difference in TSS concentration between sample locations (F-stat = 1.9442, p = 0.1550, n = 40). Results confirmed that sediment logs alone provided no decrease in TSS concentration within Treatment 1. Statistical results validated a large decrease in TSS across sample locations (F-stat = 33.2155, p<0.0001, n = 44) within Treatment 2 (Figure 3). TSS discharged at location L5 was 174 mg L^{-1} which equated to a 92% reduction. In a side by side comparison (Figure 3), a substantial reduction was observed in Treatment 2 versus Treatment 1. Existing construction regulations varied significantly among states and countries, ranging from non-existent to stringent. Log wattles treated with PAM would provide low-cost sediment control alternatives that are effective, simple to deploy, and easily maintained.

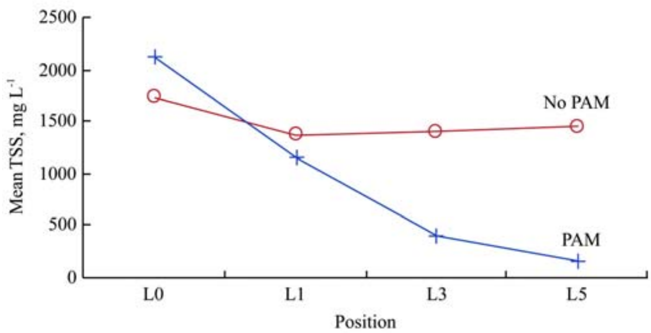

Figure 3 Mean TSS comparison of Treatment 1 (no PAM) and Treatment 2 (100 g PAM application)

3.2 Bacteria results

E. coli were analyzed by density within each treatment and were reported as MPN per 100 mL. For this experiment, solutions with low and high *E. coli* densities were used to evaluate whether percent bacterial reduction was affected differently by initial concentrations. The two *E. coli* densities were comprised of a low range (5,000-10,000 MPN/100 mL) and a high range (100,000-200,000 MPN/100 mL). Inherent natural variability of *E. coli* resulted in high standard errors within bacterial results. Figure 4 and Figure 5 showed the trend of *E. coli* density in each treatment.

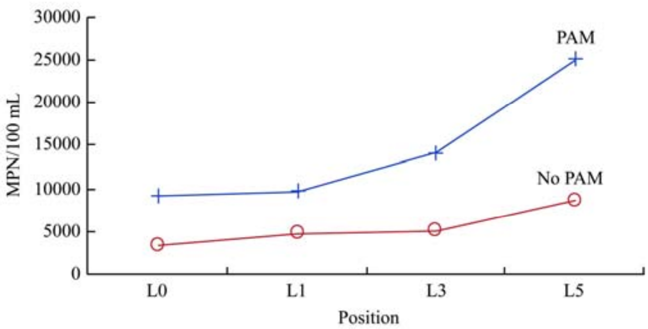

Figure 4 Mean MPN/100 mL (low *E. coli* concentration range) for each treatment

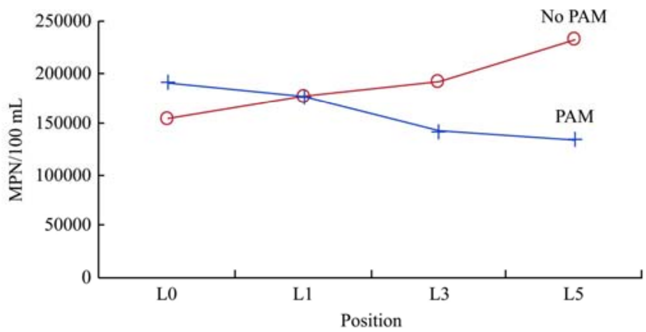

Figure 5 Mean MPN/100 mL (high *E. coli* concentration range) for each treatment

Results from sediment logs without PAM provided no significant bacterial reduction across sample locations for both the low (Figure 4) and high (Figure 5) *E. coli* density ranges. In fact, logs treated with PAM for the low *E. coli* density range (Figure 4) resulted in an increase in bacterial concentration. T-test results showed a statistically significant increase ($p = 0.0123$) between *E. coli* densities at location L0 and L5. Increasing *E. coli* density across sample locations suggested that PAM treatment was ineffective at reduction for the low *E. coli* density range. PAM treatment for the high *E. coli* density range (Figure 5) produced a 29% reduction. However, densities across sample locations were determined not to be statistically different (F-stat = 1.5956, $p = 0.2097$, $n = 40$). Apparent increases might be explained by the presence of PAM potentially affecting normal laboratory enumeration techniques.

To determine whether inconsistent *E. coli* reductions might be the result of insufficient physical and biological association between bacteria cells and clay particles, a 6th run was added to Treatment 2 for a low density range. For the 6th run, after the mix of bacteria and clay solution, the mixture was then allowed to settle for a period of 24 hours to ensure adequate time for *E. coli* cells to associate with soil particles. The mixture was then agitated to achieve a uniform solution before testing. Turbidity results (Figure 6) showed similar reductions to that of Figure 2 with a mean turbidity of 100 NTU at sample location L5 and a cumulative percent reduction of 94%. Even allowing a 24 hour association period, as shown in Figure 7, similar bacterial trends were achieved as those shown previously in Figure 4.

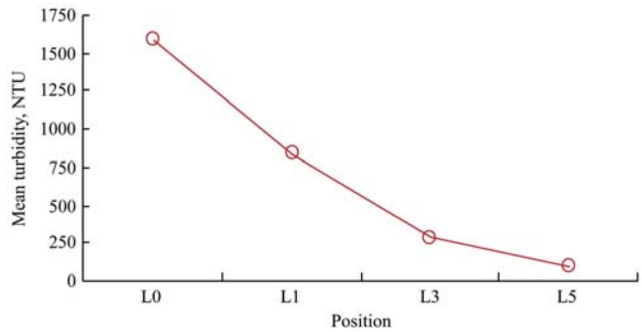

Figure 6 Mean turbidity for the 6th run after settling for 24 hours

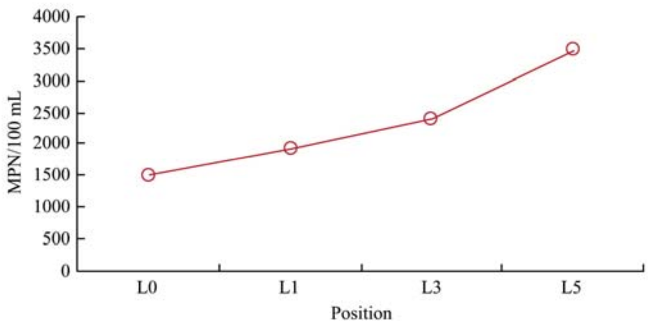

Figure 7 Mean MPN/100 mL (low *E. coli* density range) after settling for 24 hours

Grab samples collected at the end of 24 hours showed low bacteria levels and low turbidity at the surface, whereas high bacteria level and high turbidity were found near the bottom of the tank. On the basis of this data, it can be assumed that *E. coli* cells have attached to clay particles and are migrating towards the bottom due to gravitational settling. Despite additional settling time to allow for association, PAM treatment failed to show a positive reduction and *E. coli* density actually increased 127% as shown in Figure 7.

4 Conclusions

The overall goal of this research was to simulate runoff discharged from sediment basins containing high turbidity and bacterial density to determine whether PAM treatment could reduce turbidity levels, which then could result in a subsequent reduction in bacterial density. The overall goals of this research were met and several conclusions can be summarized from the results.

Based on the theory, *E. coli* cells attached to clay particles should have settled out from PAM interaction and created a decrease in total *E. coli* density sampled throughout the treatment process. PAM application produced an average turbidity discharge of 80 NTU with a total reduction of 96%. Similarly, TSS was reduced by 92% with an average discharge of 174 mg L^{-1}. Despite PAM application, no reduction in bacterial density was observed for the low *E. coli* density range, while *E. coli* displayed a positive increase across locations to 25,226 MPN/100 mL at discharge. A 29% reduction was recorded for the high *E. coli* density range with an average discharge of 135,270 MPN/100 mL; however, reductions within the high *E. coli* density range were determined to be not statistically different (F-stat = 1.5956, $p = 0.2097$, $n = 40$). Results of this research show that while PAM application results in turbidity and TSS reductions, under research conditions, granular PAM fails to reduce *E. coli* levels to the US EPA limit of 126 MPN/100 mL for a 5-sample geometric mean as well as the single 235 MPN/100 mL grab samples.

As discussion before in this paper, previous research demonstrated bacterial reductions using PAM, anionic flocculent (BactoLoxx®), and compost filter socks. Faucette et al. (2009) reported final *E. coli* reductions to 0.57×10^{10} MPN/100 mL (75%) using only filter socks and 0.02×10^{10} MPN/100 mL (99%) using BactoLoxx. The experiment above produced 73.7 mm h^{-1} of simulated rainfall-runoff for 30 minutes' durations on bare soil conditions to create 0.28 L min^{-1} of runoff (Faucette et al., 2009). PAM application reduced fecal coliforms by 90% in cattle (1.81×10^4 MPN/100 mL), fish (2.80×10^4 MPN/100 mL), and swine (1.35×10^6 MPN/100 mL) wastewater in furrow 8.6 L min^{-1} surface flow (Entry and Sojka, 2000). Although these studies recorded substantial reductions, discharged bacterial densities remained extremely elevated when compared to the US EPA limit. These studies also conducted as scale models, which could point to why high reductions occurred and may not be a valid representation of field conditions.

A possible explanation of lack of consistent reduction in *E. coli* densities is that a percentage of bacterial cells remained suspended in the water column rather than associating with clay particles. PAM treatment for bacteria would only remove those cells associated with clay particles, through flocculation. Research shows that *E. coli* cells do not reproduce within sediment basins (Kunkel et al., 2013a). Since the described testing conditions were designed to mimic sediment basin runoff, the increase in *E. coli* density was assumed not to be caused from reproduction. Increases in *E. coli* density across sample positions may result from PAM spread across sediment logs acting as a sort of biofilm, allowing *E. coli* cells to attach and creating a source of *E. coli* cells within each sediment log. Increases in *E. coli* density across sample locations may be attributed to disassociation of *E. coli* cells in accumulated flocculated clay particles during resuspension occurring at the beginning of each run. Disassociation, resulting from the impact of water, may also occur at the sediment log.

In the future, regulatory agencies may develop bacterial density effluent limits as part of the construction general permit to better regulate sediment discharge. Regulatory strengthening will hinge on whether bacterial loading from construction activity is found to significantly degrade water quality downstream. Further research evaluating alternative treatment processes will be needed to adequately reduce *E. coli*.

Disclaimer

Mention of a trade name and/or products does not imply endorsement of the product by Clemson University or the exclusion of others that might be available.

Acknowledgements

Funding provided by the Certified Erosion Prevention & Sediment Control Inspector Program at Clemson University.

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