STORMWATER RECHARGED: INNOVATING WITH ELECTRICAL FLOCCULATION

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PRESENTER BIO

Megan Armstrong is a Ph.D. student in Auburn University's Department of Civil and Environmental Engineering under the advisement of Dr. Michael A. Perez. She also works as an engineering intern for Fagan Consulting, LLC, under the advisement of Barry Fagan. Further, she serves as the technical connection between Auburn University and Fagan Consulting as they work on an SBIR project that entails developing a small-scale, portable electrical flocculation device to help meet stormwater quality goals.

Barry Fagan is an owner and vice president of Fagan Consulting LLC located in Prattville, Alabama. Fagan Consulting is an engineering consulting firm with a primary focus on stormwater management and water quality protection. Barry has over 30 years of stormwater management-related experience at project and programmatic levels, serving in roles of inspector, practitioner, project manager, trainer, manager, leader, and consulting expert. Barry has trained thousands of construction stormwater management professionals in practical application, inspection, contract administration, and environmental leadership. Barry and Fagan Consulting support infrastructure delivery at the intersection of built and natural environments.

Dr. Michael Perez is the Brasfield and Gorrie Associate Professor in the Department of Civil and Environmental Engineering at Auburn University. He oversees research at the Auburn University – Stormwater Research Facility, specializing in full-scale evaluation of construction and post-construction stormwater management practices. He currently serves as the chair of the standards and practices committee for the International Erosion and Sediment Control and as chair of the Transportation Research Board's AKD50 standing committee on Hydrology, Hydraulics and Stormwater. He is a licensed Professional Engineer in the State of Alabama and is a Certified Professional in Erosion and Sediment Control.

Dr. Shiqiang (Nick) Zou is an assistant professor in the Department of Civil and Environmental Engineering at Auburn University. His research focuses on developing reliable electrochemical systems to transform resource-intensive water/wastewater management into a resource-supplying hub. His research synergistically integrates electrochemistry with membrane separation and bioprocess to develop energy-efficient engineering processes. He is an active member of the American Chemical Society, the

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Dr. Wesley Donald is a Research Fellow in the Department of Civil Engineering at Auburn University. His research focus is on ditch check practices; assisting in the testing of sediment barriers in sheet flow applications; evaluating catch basin inserts for urban runoff applications; evaluating rainfall-induced erosion and practices and products to minimize its effect; providing training in erosion and sediment control technologies to industry practitioners; and instructing undergraduate and graduate students. Dr. Donald serves as the chair of the International Erosion and Sediment Control Editorial Committee.

KEYWORDS: Electrical Flocculation, Turbidity Removal, Erosion and Sediment Controls, Stormwater, Runoff

ABSTRACT

The construction, operation, and maintenance of public infrastructure systems generate pollutants such as sediment, heavy metals, and nutrients, which are contaminants the U.S. Environmental Protection Agency identifies as the most widespread in affecting the beneficial uses of the Nation's rivers and streams. To mitigate these impacts, construction sites located near waters of the United States, impaired waterbodies, or areas served by municipal separate storm sewer systems are required to develop and implement a stormwater pollution prevention plan. These plans must incorporate control measures to reduce contaminant impacts on downstream waterbodies.

In response to these challenges, Fagan Consulting LLC, in partnership with Auburn University, is developing a self-contained, portable stormwater treatment device through a Small Business Innovation Research contract with the United States Department of Transportation. The device employs electrical flocculation technology to meet desired water quality goals. This innovative device, similar to electrocoagulation systems in water and wastewater treatment, harnesses electrical current to induce the formation of flocs with suspended contaminants, thereby enhancing settling and removal efficiencies. This process achieves the effectiveness of chemical flocculation without the use of chemical compounds, pumps, or filters. Further, the "electrical floc generator" operates effectively using 12 volts of power. Its design allows for versatile applications – it can be a standalone, battery-powered unit for mobility or be integrated into a fixed location with an external power source. Additionally, the scalability of the device enables it to handle larger flows and pollutant loads effectively, making it a valuable tool for stormwater management practices. This flexibility makes it an ideal solution for a variety of settings, from construction sites to post-construction environments.

Preliminary testing of the device demonstrated its ability to reduce total suspended solids, iron, copper, lead, cadmium, and phosphate by up to 90% for flows through a 5.1 cm (2-in.) pipe. Additionally, the device maintained an efficient balance between energy consumption and pollutant removal, achieving reductions of up to 90% for turbidity with a specific energy consumption (SEC) range of 0.031–0.100 kWh/m^3. Further, spectrophotometer testing was conducted to assess the amount of dissolved aluminum (Al^{3+} ions) that would be released using the floc generator. Results from the spectrophotometer testing indicated that 0.22 mg/L of dissolved aluminum was present in the effluent of the samples. Since there is no specific guidance for stream protection from aluminum, these values were compared to the National Secondary Drinking Water Regulations, which recommend a maximum of 0.20 mg/L in drinking water. Research and development will continue to fully refine and optimize the floc generator. Future research will focus on addressing the electrode surface area to flow rate ratio, aluminum conversion rates and potential toxicity, electrode longevity, and non-sediment contaminant removal.

1.1 INTRODUCTION

Stormwater management is fundamental to the design and operation of roadways to mitigate the impacts transportation infrastructure has on water quality and to assure compliance with state and federal regulations. State department of transportations (DOTs) are challenged with the responsibility to maintain and protect local environments while maintaining a safe, reliable, and cost-effective transportation system. Sediment, along with heavy metals, nutrients, and pathogens, remains one of the most widespread pollutants contaminating the Waters of the United States (WOTUS), according to the U.S. Environmental Protection Agency (USEPA) (*1*, *2*). Sediment can bind to heavy metals through cationic exchange, adsorb to nutrients, and attach to pathogens, not only facilitating their transport but increasing the total pollutant load in waterways. Additionally, sediment brings harmful physical effects to waterbodies when mobilized. Suspended sediments degrade water quality by blocking sunlight, reducing aquatic plant growth, impairing visibility, and destroying aquatic habitats. Waterbodies near roadway construction sites are particularly vulnerable to the accumulation of these pollutants, making land protection essential to prevent their spread. Despite decades of regulatory action, over half of the United States' assessed waterways are listed as impaired or threatened from urban non-point source runoff. Increased urban runoff pollution coupled with aging systems earned stormwater infrastructure a letter grade of "D" on the 2021 American Society of Civil Engineers Infrastructure Report Card.

Today, 80% of the U.S. population lives in areas regulated by municipal separate storm sewer system (MS4) permits. These areas are required to develop and implement stormwater pollution prevention plans (SWPPPs). SWPPPs outline best management practices (BMPs) to prevent contaminants, primarily sediment, from being transported from the site into nearby waterways. Various BMPs, including erosion and sediment control (ESC) measures and products, are available to mitigate sediment transport. Sediment control techniques such as sediment basins, rock check dams, mulch berms, silt fences, and vegetated buffer strips are implemented to capture larger sediment particles and discharge less turbid runoff. Settling of these larger particles is important but can be achieved by using techniques that slow and trap runoff. However, runoff polishing, or turbidity removal, presents a greater challenge due to the difficulty of settling smaller particles gravitationally. Therefore, a need exists to develop enhanced stormwater management practices that are easy to employ and maintain while minimizing the potential for other pollutant concerns associated with treatment measures.

Numerous department of transportation offices and state environmental agencies have permitted chemical flocculants and coagulants to provide final polishing of stormwater runoff to remove the suspended fine particles. However, these measures are often passively dosed with minimal monitoring that often includes the determination of soil-specific characteristics. This can further complicate the process, and the effectiveness of chemical flocculants and coagulants can be inconsistent. Furthermore, many agencies view these products as chemical treatments and are reluctant to employ them on their projects for fear of creating further pollutant potential (*4*). A need exists to develop enhanced, easy stormwater management practices to employ and maintain while minimizing the potential for other pollutant concerns associated with treatment measures.

One treatment mechanism that has been proven in the treatment of drinking water, wastewater, and industrial water sectors is electrical flocculation, which is a process that uses electrical energy to remove contaminants from water by applying current to sacrificial metal electrodes (*5*). Electrical flocculation operates by applying an electric current through metal plates as water passes between them. The current generates charged ions, which then bind to pollutant particles of opposite charges, forming larger aggregates. As these electrically neutralized particles, or flocs, agglomerate and their settling velocity and removal rates are accelerated. This enables non-settleable contaminants to be removed through gravitational settling within a liquid matrix.

2.1 LITERATURE REVIEW

Electrical flocculation removes pollutants from water by dissolving metal ions, such as aluminum or iron, from the anode, which then binds to and neutralizes negatively charged contaminants. This process combines the advantages of electrochemistry and traditional chemical techniques (*6*). Notably, electrical flocculation distinguishes itself as an environmentally friendly technology by bypassing the need for chemical additives. Furthermore, the electrical flocculation process can be initiated by activating a switch, requiring only a brief startup duration (*7*–*9*). It also distinguishes itself from traditional water treatment methods through its modular design, which enables deployment even within confined spaces. The technology's ability to accommodate elevated water velocity contributes to its versatility, rendering it ideal for various applications. Unlike conventional approaches like membrane filtration and ion exchange, electrical flocculation provides an advantage by minimizing sludge production and eliminating the generation of brine streams, which often require extra disposal or treatment.

Electrical flocculation has a wide range of uses, as it can effectively remove many types of unwanted contaminants, such as suspended solids, colloidal substances, nutrients, metals, dissolved solids, pesticides, and pathogens. Electrical flocculation has been widely employed in the treatment of diverse forms of industrial wastewater, including textile wastewater, pharmaceutical wastewater, pulp and paper industry wastewater, and dairy wastewater. Researchers have found that the electrical flocculation process is efficient in reducing water pollutants such as arsenic, fluoride, microalgae, and other contaminants (*10*).

2.1.1 Stormwater Contaminants

An understanding of the pollutants typically present in construction and post-construction stormwater runoff is essential to address the treatment of such runoff effectively. As per the National Cooperative Highway Research Program (NCHRP) findings, the common contaminants encountered in construction stormwater runoff include heavy metals, debris, sediment, and nutrients. Complex traffic patterns and dynamics on highways play a significant role in the downstream transportation of these contaminants. Table 1 shows the runoff pollutants transported by highways (combined average annual daily traffic) with the corresponding concentrations (*11*).

Table 1 Contaminants Found in Highway Runoff

Contaminant	Concentration (mg/L)
Total Suspended Solids (TSS)	67.5
Total Nitrogen (TN)	1.36
Total Phosphorous (TP)	0.18
Dissolved Phosphorus (DP)	0.05
Aluminum (Al)	4.81
Iron (Fe)	1.90
Biological Oxygen Demand (BOD)	6.83
Chemical Oxygen Demand (COD)	8.80
Total Dissolved Solids (TDS)	58.0

2.1.2 Electrical Flocculation Variables

Electrical flocculation is a method for reducing contaminant levels by creating cationic and anionic ions that bind to form a coagulant that attracts anionic pollutants within water. The choice of electrode material impacts the removal of contaminants, with aluminum (Al), iron (Fe), and stainless steel (SS) being the most commonly used. Aluminum electrodes are favored for their cost-effectiveness and their ability to generate ions that promote coagulation, making them highly effective in treating turbidity, color, and heavy metals. The higher resistance of iron leads to increased electrical energy consumption (EEC) compared to Al electrodes. While iron is less expensive than aluminum, it experiences a greater mass loss rate than aluminum, resulting in double the operating costs (*12*, *13*). Along with material choice, reaction time is important for determining the overall efficiency of the process. Longer reaction times improve contaminant removal but increase energy consumption and electrode wear. Optimal times range from 10 to 30 minutes in batch systems, though flow-through systems rely more on the flow rate to determine efficiency.

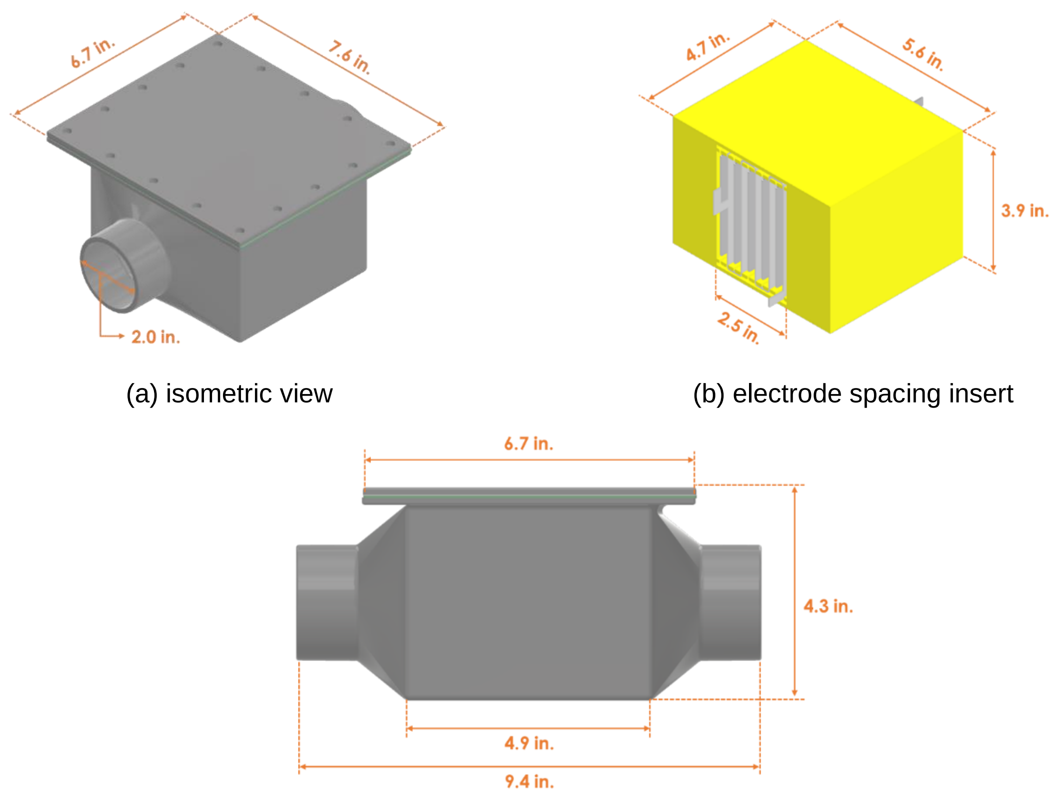
Electrical current density and interelectrode distance are also essential for achieving optimal electrical flocculation performance. Current density, which measures the amount of electric current applied per unit of electrode surface area, directly affects the pace of electrochemical reactions and the release of coagulant. Higher current densities generally lead to faster contaminant removal but can accelerate electrode wear and increase energy costs. Studies suggest that the optimal electrical current density for electrical flocculation processes typically falls between 20 and 120 A/m^2 (*14*, *15*). Similarly, interelectrode distance influences the effectiveness of the process by affecting the electric field distribution and the coagulant formation rate. Research has shown that spacing electrodes between 5 to 20 mm (0.39 to 0.79 in.) is ideal for maximizing removal efficiency, with larger distances reducing effectiveness. Balancing these parameters, material choice, reaction time, electrical current density, and interelectrode distance, ensures the electrical flocculation process is optimized for various water treatment applications.

3.1 PROTOTYPE DEVELOPMENT

Two sets of prototypes were developed and tested. These devices, prototype A and B, were identical except for the wiring configurations of the aluminum electrodes. Initially, these prototypes were designed to evaluate design properties such as, electrode wiring configurations (series and parallel), turbidity reduction of sediment, and mixing. Prototype C, a larger version of prototypes A and B, was evaluated for turbidity reduction, heavy metal and nutrient reduction, and field-scale performance. Further, all prototypes discussed, A, B, and C, were designed using Autodesk Inventor® and subsequently 3D printed. Also, the electrodes used for each prototype comprised 1 mm (0.04 in.) thick grade 6061 aluminum electrodes, maintaining an interelectrode distance of 1.3 cm (0.5 in.).

3.1.1 Prototypes A and B

Two floc generator prototypes evaluated included prototype A, where the electrodes were wired in series and prototype B, where the electrodes were wired in parallel. Both prototypes were comprised of the same electrode housing unit. Electrode housing for the prototypes was designed and printed in three separate components: a top, an electrode spacing insert, and an electrode insert housing, depicted in Figure 1. The prototypes measured 17.0 by 19.3 cm (6.7 by 7.6 in.) on the top component. The length from outlet to outlet measured 23.9 cm (9.4 in.) with each outlet having a diameter of 5.1 cm (2 in.). Further, ten aluminum electrodes were placed into the insert slots before sealing the prototype. Each of the ten electrodes comprising the prototypes had an individual surface area of 101.9 cm^2 (15.8 $in.^2$), with an anodic area of 509.0 cm^2 (78.9 $in.^2$).



(a) isometric view

(b) electrode spacing insert

(c) side view

Figure 1 Prototypes A and B Components and Dimensions.

After evaluating prototype A, prototype B was designed and constructed with parallel circuitry, attempting to decrease electrode resistance and increase overall electrical current. Enhanced electrical flocculation performance was the goal. This is because the total resistance of a series circuit is the sum of the resistance value across each component in the system. In contrast, the parallel circuit is the sum of one over the resistance value across each element in the system. This theory is explained by Eq. 1 and Eq. 2.

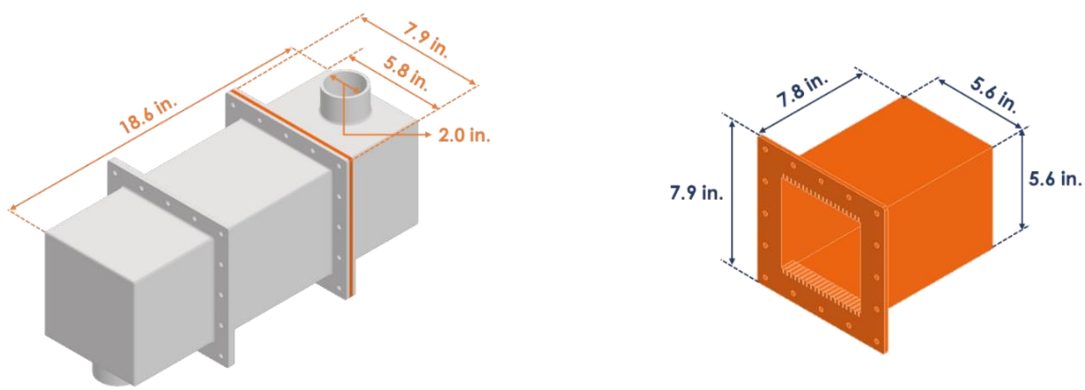
$$R_t(series) = R_1 + R_2 + R_3 + \dots R_n \quad \textbf{Eq. 1}$$

$$R_t(parallel) = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \frac{1}{R_n} \quad \textbf{Eq. 2}$$

Prototype B maintained identical electrode material, electrode surface area, interelectrode distance, housing unit, and insert to prototype A. During prototype B testing, it was observed that the electrical current did not increase compared to measurements observed with prototype A. Therefore, there were no significant differences in turbidity reduction between the two prototypes. Expected outcomes were that the parallel circuitry would yield a higher electrical current density over the electrode due to decreased plate resistance. This discrepancy was attributed to the high overall resistance of the system, primarily caused by the elevated electrical resistance of the water. Following comprehensive lab-scale testing of both prototypes, it was concluded that their performances were notably similar.

3.1.2 Prototype C

For prototype C, a larger electrode housing unit was 3D printed to accommodate 20 large electrodes. Its design consists of four separate components: two end caps, a middle coupling, and an electrode spacing insert. The floc generator measures 47.2 cm (18.6 in.) in length, with a width and height of 14.7 cm (5.8 in.), Figure 2. The flanges that connect these components extend outwards by approximately 2.54 cm (1 in.) in all directions. The electrode spacing insert, designed to fit within the middle coupling and hold 20 plates, has a length of 19.8 cm (7.8 in.) and a width and height of 14.22 cm (5.6 in). The circular attachment outlets are both 5.1 cm (2 in.) in diameter to connect to a 5.1 cm (2 in.) PVC pipe.



(a) isometric view (b) electrode spacing insert

Figure 2 Prototype C Components and Dimensions.

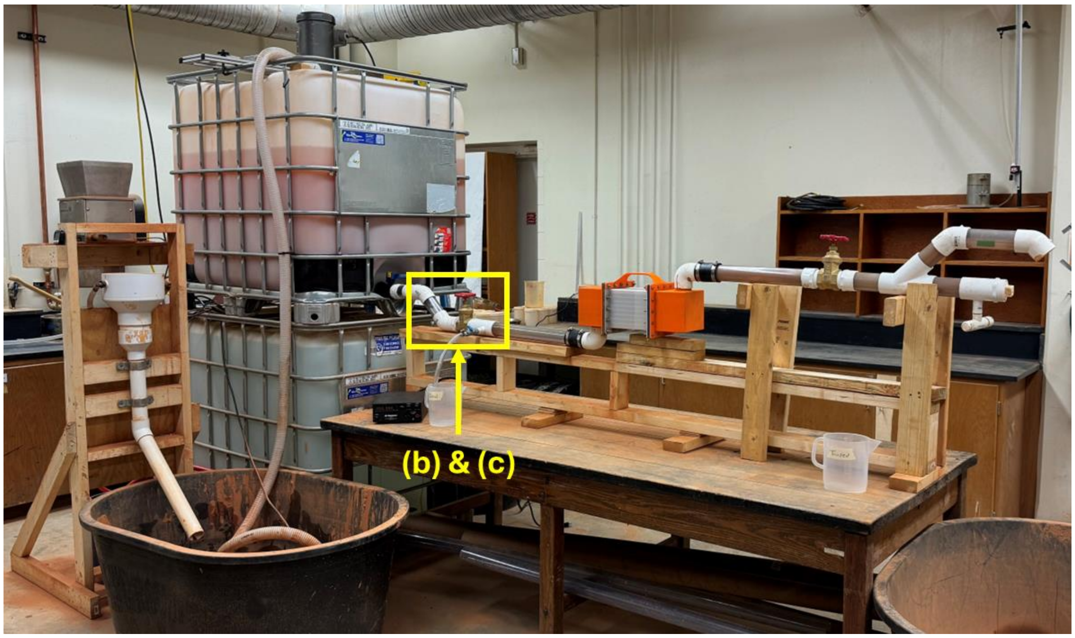
The decision to increase electrode size aimed to reduce plate resistance, anticipating increased electrical flocculation performance. Each electrode in prototype C had a surface area of 261.9 cm^2 (40.6 $in.^2$) and an anodic area of 1,310.3 cm^2 (203.1 $in.^2$), which is 2.5 times larger than the electrodes used for prototypes A and B. To establish a waterproof seal upon closure, rubber gaskets were positioned on either side of the middle insert. Since it was determined that the circuitry would not change the effectiveness of the floc generator prototype, series circuitry was chosen for simplicity. On the upstream side, a 3D-printed baffle was employed to prevent the entrapment of large debris between the electrodes.

4.1 EVALUATION OF PROTOTYPE

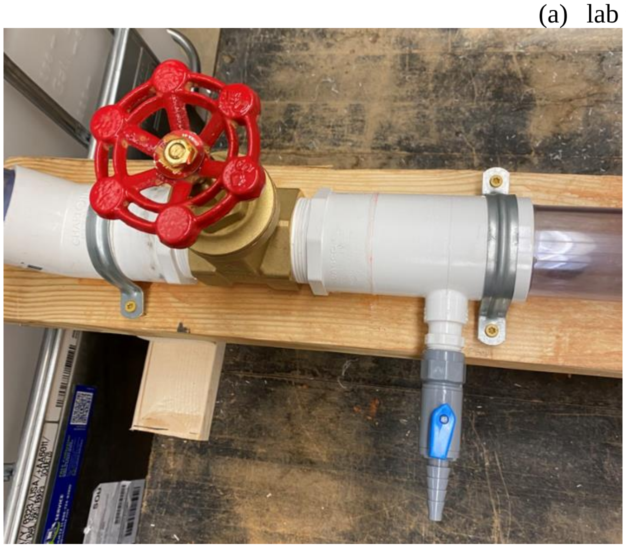
A total of 70 test series were conducted with the prototypes. Among the 70 tests, 58 were dedicated to assessing the prototypes' performance through the manipulation of specified parameters, while the remaining 12 focused on the evaluation of mixer performance. Among the 58 tests, 29 used prototype A, 21 employed prototype B, and 14 tests were conducted with prototype C. Evaluations covered a flow rate range of 1.9 to 71.9 L/min (0.5 to 19 gpm), voltage range of 6-24V, and a current range of 1-12A.

4.1.1 Testing Apparatus

A testing apparatus was designed and constructed to facilitate the testing of the prototypes. The testing system consisted of a simulated stormwater prepping area, two 1,041 L (275 gal) IBC tote to store the stormwater, a PVC channel containing the sampling port, a floc generator insert location, and an upstream and downstream valve. The simulated stormwater runoff prepping station consists of a flow and sediment introduction mechanism, a 416 L (110 gal) storage tank, a pump, and two 1,041 L (275 gal) IBC totes. The PVC piping system featured an upstream gate valve, a sampling port, connections for the insertion of the device, static mixers, a downstream gate valve, inclined piping, and a sediment deposit valve, as depicted in Figure 3. The sampling port was positioned upstream of the floc generator to facilitate the collection of control samples for comparative analysis with treated samples. The installation of the inclined piping section was constructed to ensure continuous saturation of the floc generator. This consideration is important, as the electrolytic process of the electrical flocculation is only active when water is in direct contact with the electrodes.



(a) lab testing setup



(b) upstream valve & sampling port

(c) elbow in sampling port

Figure 3 Electrical Flocculation Testing Setup.

4.1.2 Methodology

All experimental tests conducted in this study used soil sourced from the Auburn University Stormwater Research Facility. Given that the prototypes under investigation are designed for the polishing phase of sedimentation, only fine sediment was employed to replicate sediment-laden runoff discharging emanating from a BMP. Specifically, larger sediment particles would have already settled during the rapid settling phase of the sedimentation process. An equal amount of soil sieved through the 50, 100, and 200 sieves were consistently mixed in at 92.4 g/min. The sieve opening sizes are listed in Table 2.

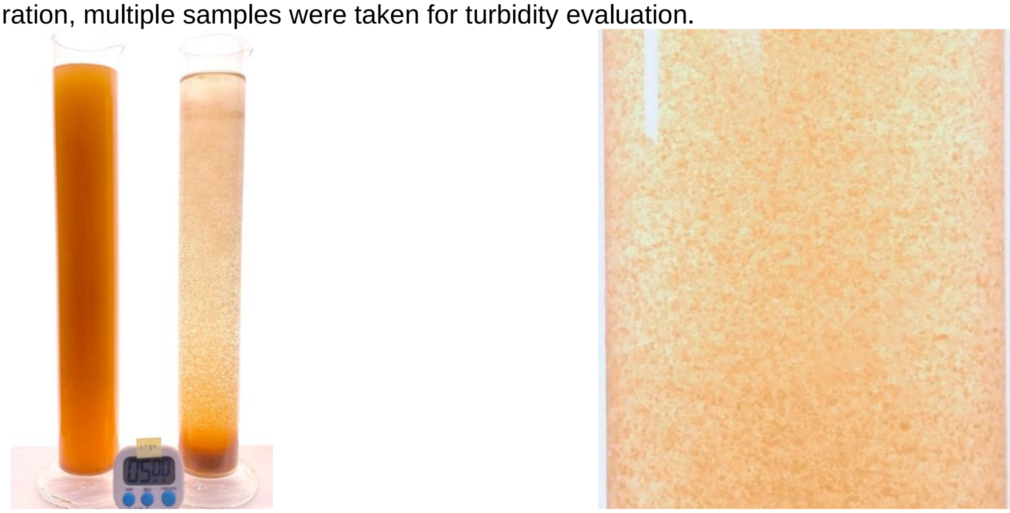
Table 2 Sieve Size with Particle Diameter

Sieve No.	**50**	**100**	**200**
Particle Diameter (mm)	0.30-0.15	0.15-0.07	0.07-0.05

After initializing the sediment introduction, the experimental setup began with the simultaneous flow and sediment introduction. Flow introduction allowed the 416 L (110 gal) trough to gradually fill, a step that eventually triggered the pump's flotation device, resulting in the pump's automatic activation. This pump was used to fill the IBC from the 416 L (110 gal) trough. Furthermore, before the testing phase began, the IBC tote was filled to its designated capacity of 1,041 L (275 gal). The gravitational discharge of the IBC tote facilitated flow introduction into the floc generator. Before each test, the flow rate was determined by filling a 2,000 mL (67.6 oz.) and timing it for three iterations. The final flow rate was found by averaging three times and converting the measurement from mL/sec to gpm.

4.1.3 Sampling Process

During testing, a series of 2,000 mL (67.6 oz.) samples were systematically collected upstream and downstream of the floc generator. The sample taken upstream of the prototype was labeled as “control,” while the sample taken downstream of the prototype was labeled as “treated.” The total number of samples taken per test was six samples: three control and three treated. When each sample was taken, current and flow rates were recorded. The samples were then transferred into graduated cylinders for sedimentation evaluation. Both the control and treated samples, obtained simultaneously during the test, were poured into grouped graduated cylinders, Figure 4. This allowed for a visual comparison of the settling rates between the two samples. The photographs in Figure 4 show the progression of floc formation and settling. During the settling duration, multiple samples were taken for turbidity evaluation.



(a) sample comparision between control (left) and treated (right) sample after 5 min. of settling

(b) closeup photo of floc formation

Figure 4 Sample Comparison.

5.1 RESULTS

This section provides an analysis of each evaluation conducted in the lab testing apparatus from all three prototypes. The primary focus of these evaluations was on assessing and comparing the efficiency of these devices in reducing turbidity. Key parameters such as electrolysis time, electrical current density, and voltage were evaluated to understand their influence on the performance of the prototypes.

5.1.1 Parameters Measured and Evaluated

To evaluate the device's efficacy, a comparison was made between turbidity values obtained from control and treated samples, a metric commonly referred to as turbidity reduction. The calculation of turbidity reduction values in each test involved contrasting the average inflow turbidity with that of the treated samples. The applied turbidity reduction formula is expressed in Eq. 3. NTU values from the treated samples at corresponding sampling times were employed to determine turbidity reduction across various time points.

$$Turbidity\ Reduction(\%) = \frac{Inflow_{avg.}(NTU) - treated\ (NTU)}{Inflow_{avg.}(NTU)} \quad \textbf{Eq. 3}$$

Turbidity reduction values were calculated at specific sample intervals, including 0, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, and 90 minutes. These values were assessed by comparing turbidity from control to treated samples within each interval, ensuring that comparisons were only made across identical time points. The turbidity reduction values are then termed (TR5) for turbidity comparisons after each sample has been settling for 5 minutes. After obtaining the turbidity reduction data, it was plotted to view trends and relationship identifications.

5.1.2 Voltage

The evaluations included testing three voltage values: 6, 12, and 24 volts. Initially, a constant voltage of 12 volts was set to mimic the power output of an average car battery. Power sources such as photovoltaic-powered generators, car batteries, or gas-powered generators would be used in field conditions. The 6-volt setting represented a lower power system for the electrodes, while 24 volts simulated using two batteries. The primary objective was to determine whether 12 volts could generate sufficient coagulant from the floc generator. Figure 5 provides a correlation between flow rate and turbidity reduction after 20 minutes of settling has occurred (TR20) with all three voltages plotted.

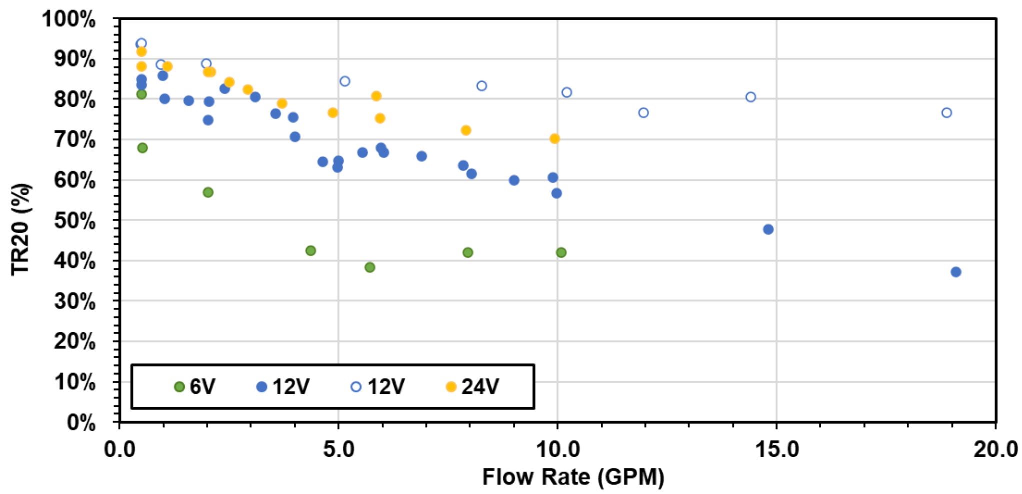


Figure 5 Comparison of Flow Rate to TR20 at Various Amperages.

In the plot, green represents 6 volts, blue represents 12 volts, and yellow represents 24 volts. Solid-filled markers indicate evaluations using prototypes A and B, while white-filled markers represent evaluations conducted with prototype C. The findings revealed that the green range corresponded to lower turbidity reduction values, while the blue and yellow ranges aligned with higher turbidity reduction values. Since the TR20 values for the 12-volt (blue) and 24-volt (yellow) ranges were similar, 12 volts was selected as the optimum voltage.

5.1.3 Electrolysis Time and Aluminum Conversion

In continuous-flow electrical flocculation systems, the electrolysis duration is tied to the flow rate of the fluid moving through the system. Electrolysis is a process that uses an electric current to drive a chemical reaction by splitting water molecules into hydrogen and oxygen or dissolving metal ions from electrodes in a solution. Higher flow rates result in a shorter electrolysis time, potentially reducing treatment efficiency due to insufficient exposure to the electric field. On the other hand, a lower flow rate extends the electrolysis duration, increasing the amount of released ions per unit volume while decreasing the volume treated per amount of time.

Aluminum hydroxide ($Al(OH)_3$) is a solid precipitate that is relatively stable and insoluble in neutral or slightly alkaline conditions. It does not easily dissolve in water, reducing its bioavailability and potential harm. However, there are concerns related to the potential for excess aluminum ions (Al^{3+}) remaining in the treated water. To evaluate this potential concern, preliminary spectrophotometry analysis was conducted to determine the conversion rate of dissolved aluminum (Al^{3+}) to aluminum hydroxide ($Al(OH)_3$). These preliminary evaluations tested at a flow rate of 37.9 L/min. (10 gpm), 750 NTU initial turbidity, and an amperage of 9.5A. Results showed that the clean sample had a measurable dissolved aluminum concentration of 0.52 mg/L, while the sediment-laden sample contained 0.22 mg/L, yielding a conversion rate of 57%.

Moreover, determining an optimal flow rate to amperage ratio ensures adequate coagulant dosage while maintaining high contaminant removal efficiencies and releasing environmentally safe effluent. Figure 6 presents a graphical comparison of settling duration to turbidity reduction at three different flow rates: 3.8 L/min. (1 gpm), 37.8 L/min. (10 gpm), and 71.9 L/min. (19 gpm). Since coagulant release is influenced by electrolysis time rather than flow rate, we anticipated greater turbidity reduction at lower flow rates due to a higher concentration of coagulant per unit volume. After 20 minutes of settling, turbidity reduction was 89% at 3.8 L/min. (1 gpm), compared to 81% and 77% at 37.8 L/min. (10 gpm) and 71.9 L/min. (19 gpm), respectively, illustrating a non-linear relationship.

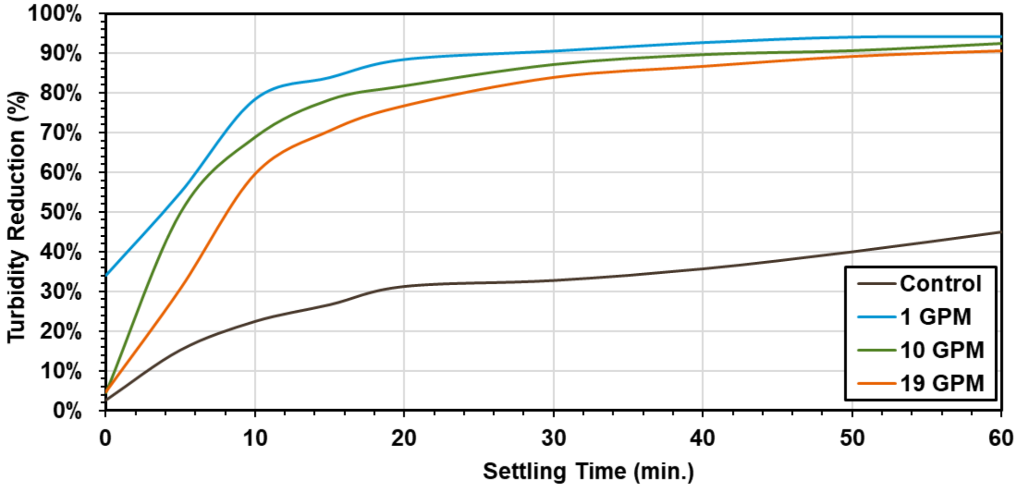


Figure 6 Series vs. Parallel Circuitry Comparison.

5.1.4 Nutrients, Heavy Metals, and Emerging Contaminants

These tests involved adding predetermined amounts of heavy metals and nutrients to simulate stormwater runoff, effectively inoculating it with specific contaminants. Contaminants inoculated into the system include cadmium (Cd), copper (Cu), iron (Fe), lead (Pb), nickel (Ni), nitrate (NO_3^-), phosphorous (P), and zinc (Zn) (Lantin et al. 2019). Table 3 provides a detailed outline of the contaminants used to impregnate the solution, along with their respective concentrations.

Table 3 Contaminants for Pollutant Loading Testing

Contaminant	Concentration (mg/L)
Cadmium (Cd)	0.072
Copper (Cu)	0.029
Iron (Fe)	12.74
Lead (Pb)	0.162
Nickel (Ni)	0.012
Nitrate (NO_3^-)	1.843
Phosphorous (PO_4^{3-})	0.183
Zinc (Zn)	0.889

This evaluation, conducted at a flow rate of 37.9 L/min (10 gpm), allowed water to pass through the floc generator, mixers, and the settling system. A 1,041 L (275 gal.) IBC tote and a 416 L (110 gal) trough were filled with simulated stormwater at approximately 75 NTU, which was then spiked with specific substances to achieve the desired concentrations. Six samples, comprising three control and three treated samples, were sent to the University of Georgia's Agricultural & Environmental Services Laboratories for water quality analysis. Table 4 details the pollutant concentrations in both the control and treated samples.

Table 4 Contaminant Concentrations Measured in Pollutant Loading Testing

Contaminant	Control (mg/L)	Treated (mg/L)	% Reduction
Cadmium (Cd)	0.064	0.025	60%
Copper (Cu)	0.070	<0.050	>70%
Iron (Fe)	13.01	3.520	73%
Lead (Pb)	0.150	0.028	82%
Nickel (Ni)	0.010	0.030	-200%
Phosphate (PO_4^{3-})	0.340	0.110	68%
Zinc (Zn)	1.320	0.880	33%

Analysis of the data revealed that the electrical flocculation process was effective in precipitating heavy metals such as Cd, Cu, Fe, Pb, and Zn. Despite using 6061 grade aluminum, which contains up to 5% trace levels of elements including Mg, Si, Fe, Cu, Cr, Zn, Ti, and Mn, there was a notable reduction in the discharge of these pollutants from upstream to downstream of the device. Regarding nutrients, a 68% decrease in phosphate$^-$ was observed. These results are preliminary, and additional testing is needed before conclusive claims can be made to the capability of the floc generator in treating heavy metals and nutrients.

5.1.5 Electrode Longevity

To assess the lifespan of the electrodes, longevity evaluations were performed. Prototype C was tested in the lab setup, operating at a constant 12 volts for 100 hours. Amperage readings were recorded every five minutes throughout the evaluation, as shown in Figure 7. At the start of testing, the device drew 11.8 amps at 12 volts. A significant drop in amperage occurred within the first 25 minutes, decreasing from 11.8 amps to 5 amps. Between 26 and 62 minutes, the amperage stabilized at an average of 5.5 amps. A second drop was observed between 63 and 65 minutes, where amperage fell from 5.2 to 3.2 amps. For the remainder of the test, the amperage leveled off at an average of 2.6 amps.

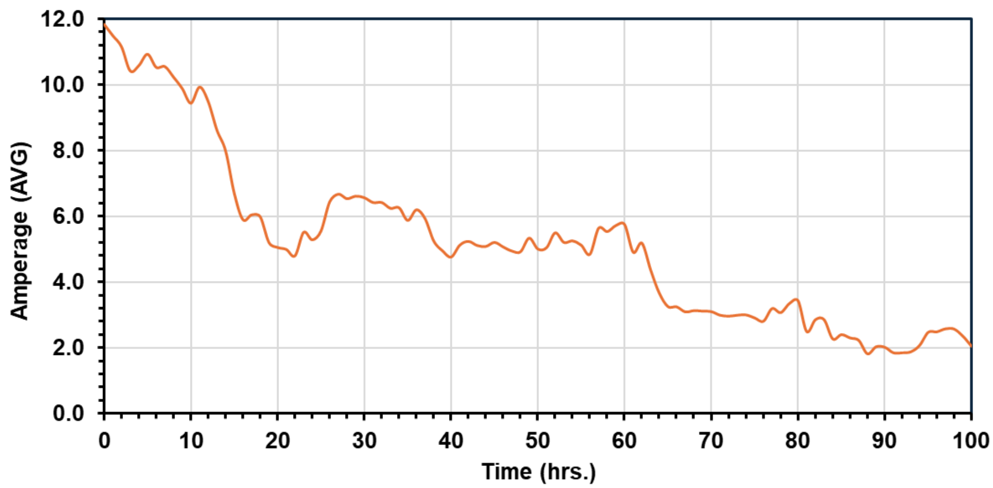


Figure 7 Experiment Time versus Average Amperage.

During the 100-hour testing period, turbidity reduction was also recorded. Every hour, two sets of samples, two treated and two control, were taken and observed, with turbidity measurements recorded for comparison. Figure 8 shows the treated and control samples after 30 minutes of settling during the 100-hour experiment. The treated samples exhibited a negative trend due to the loss of amperage over time. However, the decrease in amperage had a steeper negative slope compared to the turbidity reduction. This indicates that the device continued to treat the simulated stormwater effectively, even with amperage values more than four times lower than the starting values. The treated samples averaged 77% turbidity reduction, with 82% in the first 50 hours and 72% in the last 50 hours. The control samples showed an average turbidity reduction of 35%, with no significant change between the first and last 50 hours.

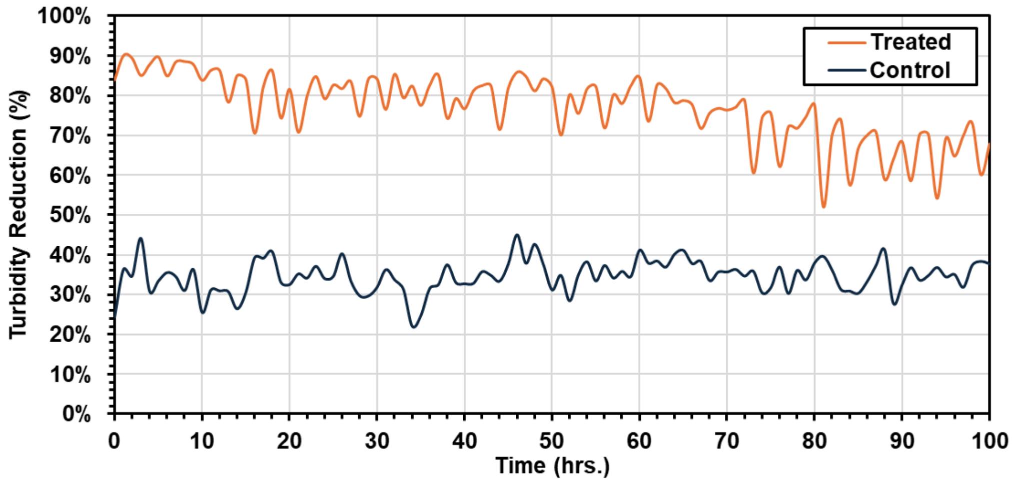


Figure 8 Experiment Time versus Turbidity Reduction.

6.1 CONCLUSIONS

In summary, managing stormwater runoff from road construction is important for minimizing environmental impacts on water quality. The pollutants generated, including sediment, heavy metals, and nutrients, present significant challenges that require effective solutions for removal. The development of innovative treatment technologies, like the electrical floc generator, offers a promising alternative to traditional methods. By leveraging electrical flocculation, this portable device provides a versatile and chemical-free option for reducing a broad range of contaminants, including TSS, metals, and nutrients, with demonstrated efficiency.

Below are the observations and performance metrics gathered during the first year of prototype development and evaluation:

- Testing showed similar turbidity reduction results when applying 12 volts and 24 volts to the device, leading to the selection of 12 volts as the optimal operating voltage.
- Spectrophotometric analysis of sediment-laden samples revealed dissolved aluminum concentrations of 0.22 mg/L, which was compared to the NSDWRs recommend maximum concentration of 0.20 mg/L in drinking water.
- Turbidity reduction after 20 minutes of sample settling was most effective at 89% with the lowest flow rate of 3.8 L/min (1.0 gpm), compared to 81% at 37.8 L/min (10.0 gpm) and 77% at 71.9 L/min (19.0 gpm).
- An SEC range of 0.031–0.100 kWh/m³ was identified as the most energy-efficient, offering a balanced tradeoff between energy consumption and treatment efficiency.
- Prototypes A and B treated flows from 5.7 to 15.1 L/min (1.5 to 4.0 gpm), while prototype C handled flows up to 71.9 L/min (19.0 gpm) without requiring additional power.
- Prototype C treated flows of 71.9 L/min (19.0 gpm) achieved up to 90% turbidity reduction after 60 minutes of settling.
- Heavy metals such as copper, lead and iron were reduced by up to 82%, with phosphate levels seeing a 68% reduction.
- Over 100 hours of testing at 12 volts, the device reduced turbidity by an average of 77% after 20 minutes of settling, even as amperage dropped from 11.8 amps to 2.6 amps.

As stormwater management continues to evolve, this technology has the potential to address gaps in current practices, offering state DOTs and other agencies an effective, modular tool to meet regulatory requirements and protect waterbodies from the harmful effects of runoff. Research and development will continue to refine and optimize the floc generator. Future research will focus on addressing the electrode surface area to flow rate ratio, aluminum conversion rates and potential toxicity, electrode longevity, and non-sediment contaminant removal. Proper evaluation of aluminum ion concentrations, conversion efficiency, and the potential for adverse effects on aquatic life is critical in developing safe and effective electrical flocculation technologies.

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