PASSIVE CHEMICAL DOSING APPARATUS FOR CONSTRUCTION SITE STORMWATER TURBIDITY REDUCTION

By

KARL M. GARBRECHT

Bachelor of Science in Biosystems Engineering

Oklahoma State University

Stillwater, Oklahoma

2010

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2011

PASSIVE CHEMICAL DOSING APPARATUS FOR CONSTRUCTION SITE STORMWATER TURBIDITY REDUCTION

Thesis Approved:

Dr. Jason Vogel

Thesis Adviser

Dr. Dan Storm

Dr. Garey Fox

Dr. Sheryl A. Tucker

Dean of the Graduate College

.

TABLE OF CONTENTS

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

Figure Page

Figure Page

Figure Page

CHAPTER I

INTRODUCTION

The Clean Water Act of 1972 recognizes the importance of mitigating the impacts of pollution in aquatic ecosystems and Section 303(d) mandates regulators set total maximum daily loads for specific contaminants in impaired waters. Sediment has been identified as a leading cause of surface water impairment in United States because it can physically impact benthic environments, reduce sunlight penetration, and chemically impact receiving waters with adsorbed contaminants such as pathogens, heavy metals, or organic compounds (USEPA 2004, Davies-Colley and Smith 2001, Bhardwaj and McLaughlin, 2008, and Droppo et al. 2008). Due to the potential detrimental effects of excess sediments in aquatic ecosystems it is of interest to quantify and monitor sediment loads in surface water. Conventional gravity settling or filtration methods for suspended sediment concentration analysis are time consuming and laborious which has led to using turbidity as a surrogate measurement (Riley 1997 and Lawler and Brown 1992). Turbidity can be thought of as the “cloudiness” of water measured in Nephelometric Turbidity Units (NTU), which is the quantification of light scattered in a solution due to suspended particulates at a reference angle (typically 90 degrees) from an incident light source (Davies-Colley and Smith 2001).

A high risk contributor to sediment pollution is disturbed land areas such as construction sites (Wolman and Schick, 1967, Daniel et al., 1978, Line et al, 2001, and Bhardwaj and McLaughlin, 2008) . In order to mitigate the potential for environmental contamination from construction sites, the EPA has attempted to establish numeric turbidity limits through Effluent Limitation Guidelines (ELGs). In November 2008 a draft ELG proposed an instantaneous maximum turbidity limit of 13 NTU for construction sites greater than 30 acres, with more than 10% clay content, and located in regions susceptible to high intensity storm events. The finalized ELG rolled out in November 2009 set the limit for an average daily value at 280 NTU for constructions sites greater than 10 acres. In January 2011 the USEPA officially stayed the 280 NTU limit. The new limit was expected to be rereleased on May 2011 and was formally withdrawn by the EPA in August 2011 Turbid surface waters resulting from sediment can remain turbid for days after suspension because of the extended settling times associated with finer particles such as silts and clays (Haan et al. 1994). Traditional techniques typically rely on gravity settling and detention times required to capture finer sediments would result in impractically large detention volumes. Accordingly, many detention basin type sediment traps are ineffective at reducing turbidity to acceptable standards with off-site discharges exceeding 30,000 NTU (McCaleb and McLaughlin 2008). Due to the silt and clay content in many soils across the Nation, many construction sites will most likely fail to meet potential turbidity limits and need to employ chemical addition to induce flocculation or coagulation to decrease runoff turbidity to the required level(Bhardwaj and McLaughlin, 2008). .

Flocculation or coagulation amendments introduced to aqueous solutions chemically bind or bridge multiple suspended particles together, thereby, increasing their effective size and ultimately their settling rate. This technique has been used extensively in municipal waste water treatment operations, the mining industry, the paper industry, and has been tested on a limited basis in environmental systems to increase suspended solids removal (Droppo et al., 2008 and

Mpofu et al., 2003). Many of the flocculation and coagulation systems used in wastewater treatment are permanent facilities which actively monitored and require energy input to meter flow and chemical amendment, mix the solution, and remove the resulting sludge. It is not financially feasible to implement a full Waste Water Treatment Plant (WWTP) on a construction operation due to their temporary nature and intermittent flow caused by rain events. Moreover, there may or may not be an energy source available to meter flows or available personnel to operate the system during a rain event. Considering the undeveloped nature of many construction sites, a passive (no energy requirement), automated system is desirable.

Current passive flocculation systems implemented on construction sites generally consist of devices known as floc logs and filter fabrics. Floc logs are blocks of solid flocculant and filter fabrics are textiles with flocculant incorporated onto the material. Both systems are installed in the path of runoff and the principle of operation is the dissolution of flocculant into the bulk flow. These systems have been shown to be effective under controlled situations ,however, there is little data on achieved dosing concentrations which is undesirable due to the influence of concentration on effectiveness and potential toxicity concerns at high doses (Bhardwaj and McLaughlin, 2008). Moreover, there is concern among industry personnel that sediment can attach to the surface or extended periods in the sun can result in surface crusting and compromise the effectiveness of floc logs and filter fabrics.

Considering the limitations of current passive flocculation systems and the potential challenges associated with a more advanced amendment dosing strategy on a construction site, a project was undertaken with the objective to develop a passive, standalone amendment dosing system which includes a mixing system to reduce stormwater turbidity through flocculation. The dosing system should be automated and able to regulate amendment dosing in such a way that dose can be predicted or determined throughout a storm event. Given the flocculant dose throughout a storm event, effluent turbidity reduction can be estimated based on sediment concentration and other parameters.

CHAPTER II

REVIEW OF LITERATURE

Erosion is governed by the relationship of sediment entrainment, transport, and deposition. During transport, particles may settle out or become re-suspended as flow and runoff change during a storm event (Haan et al., 1994). The suspended sediment in construction site runoff is comprised of various sized particles with varying settling velocities. A significant portion of the suspended sediment is often too small to settle out of in a sediment detention pond of practical size (Haan et at, 1994, Bhardwaj and McLaughlin, 2008). To enhance settling rates of the finer fraction, flocculation or coagulation amendments can added to the solution which bind or bridge multiple particles together, thereby, increasing their effective size and ultimately their settling rate. Therefore, information concerning floc formation processes is of importance and must be considered in order to optimize the design of a passive chemical dosing and mixing system. The following discussion emphasizes types of chemical amendments, their characteristics, and the conditions considered to have the greatest impact on flocculation rather than the specific physiochemical processes that govern flocculation.

There are many types of flocculation and coagulation mechanisms facilitated by various types of amendments available for particle destabilization. Coagulants typically destabilize particles through charge neutralization and differential settling where flocculants generally destabilize solutions through the formation of large flocs by bridging particles/colloids together and differential settling (Droppo et al., 2008; Jarvis et al., 2005). Amendments can also remove suspended particles through more than one mechanism making singular categorization of some amendments difficult (Droppo et al., 2008; Rasteiro et al., 2010; Mpofu et al., 2004). The physical and chemical properties of amendments vary which can influence coagulation/flocculation rates, removal efficiencies, and the characteristics of the corresponding flocs formed, such as density, floc strength, and floc size and shape. The following sections describe individual characteristics of two general amendment types (metal salts and polymers) for comparative purposes.

2.1 Metal Salts

Aluminum (Al) and ferric (Fe) salts are available as coagulant amendment in several forms; Alum (Al Sulfate), poly Al Chloride (Cl), FeCl, Fe Sulfate, and pre-polymerized metal salts. Fe and Al salts have high cationic charge densities which make them ideal coagulant amendments. Both form metal hydroxides when added to water near neutral pH, and even though Al and Fe are chemically unique, they show similar efficiencies toward phosphorus (P) removal as well as a comparable pH dependency (Szabo et al., 2008). Metal salts removal efficiencies and floc formation kinetics are concentration dependent where an increase in coagulant or primary particles leads to an increase in floc formation (Chunjuan et al., 2009; Auvray et al., 2006; Rodriguez et al., 2008; Georgantas and Grigoropoulou, 2007; Szabo et al., 2008). The toxicity of metal salts is different for various chemical species and is influenced by the concentration and solution chemistry (pH); however, they are less toxic than cationic polymer flocculants (Droppo et al., 2008; Fort and Stover, 1995). For these reasons, it is important to assess the sensitivity of potentially impacted environments on an individual basis before metal salt addition to surface waters is considered.

2.2 Polymers

Polymers include a broad category of chemical species used to destabilize solutions through flocculation and coagulation (Droppo et al., 2008; Mpofu et al., 2004). Droppo et al. (2008) reported that coagulant polymers generally have high charge densities with low molecular mass in comparison to flocculant polymers which have a lower charge densities and higher molecular mass. Polymers are available in a wide range of molecular weights, charge densities, and mixtures of polymers. Polymer destabilization is a function of flocculant added but over dosing can result in charge reversal which can stabilize particles in solution (Kang et al., 2007; McLaughlin and Bartholomew, 2007). Cationic polymers exhibit higher toxicities than anionic or neutral polymers and, therefore, may not be as suitable to natural environments (Droppo et al., 2008; McLaughlin and Bartholomew, 2007; Fort and Stover, 1995). McLaughlin and Bartholomew (2007) studied anionic and nonionic polymer flocculation efficiencies on various soils and found that flocculation was highly dependent on soil type and a mixture of polymers may be an appropriate solution. It should also be noted that polymers can have high viscosities in comparison to water which could also be a significant design consideration for injection and mixing systems as noted in experiments by Owen et al. (2008).

2.3 Metal Salts and Polymers Comparison

Droppo et al. (2008) compared the removal efficiency of chitosan (a product produced commercially by deacetylation of chitin, the structural element in the exoskeleton of crustaceans), a cationic polyacrylamide polymer, and alum at their optimum doses for sediment removal and found the cationic polymer created the largest and fastest settling flocs followed by chitosan, then alum. Additionally, Droppo et al. (2008) found flocs formed with coagulants were generally smaller and denser than those produced with flocculants; however, the large flocs produced with flocculants still settled faster. Compared to metal salts, Sekine et al. (2006), Protech (2004) and Droppo et al. (2008) found polymers to be more expensive by weight or volume but can be more effective at lower concentrations. The toxicity of metal salts is different for various chemical species and influenced by the concentration and solution chemistry (pH); however, they are less toxic than cationic polymer flocculants (Droppo et al., 2008; Protech, 2004; Fort and Stover, 1995). Protech (2004) performed toxicity tests on several common flocculants including Poly Al Cl and several cationic polymers and considered all amendments non-toxic at typical application dosages.

2.4 Mixing and Flocculation Kinetics

Another important consideration when evaluating floc formation and removal in flocculating and coagulation systems is the mixing regime. Proper mixing of the injected flocculant with the flow is needed to promote collisions between flocculant and suspended particles. Initially, elevated mixing intensities increase particle collisions due to increased turbulence, which promote rapid growth; however, increased mixing intensities also increase shear which can lead to floc breakage (Chakraborti et al., 2000; Spicer and Pratsinis, 1996; Szabo et al., 2008; Haan et al., 1994). For example, Szabo et al. (2008) observed this initial period of high floc formation to be less than a minute for high mixing intensities. The study also found this initial time period to increase as the mixing intensity decreases; therefore, high mixing intensities should be utilized as close as possible to the amendment dosing location to maximize initial floc formation (Szabo et al., 2008). In relation to steady state, floc size is an equilibrium point between floc growth and floc breakage reached after a sufficient time (Chakraborti et al., 2000; Spicer and Pratsinis, 1996; Haan et al., 1994). Furthermore, the efficiency of floc formation, i.e. the amount of collisions resulting in floc development, is impacted by floc shape and size (Chakraborti et al., 2000). Owen et al. (2008) discussed floc formation through flocculating mechanisms with respect to a growth, peak, and breakage phase. In the growth phase, flocs were still forming, the peak was when flocs were the largest, and the breakage phase was when the flocculant no longer actively bridged particles and the breakage was dominant (Owen et al., 2008). In charge neutralization floc formation, flocs continue to form or reform after breaking, which is a key difference between flocculants and coagulants (Owen et al., 2008). Therefore, chemical amendment must be considered during design of a mixing apparatus because flocculation will be irreversibly reduced at extended mixing times (Owen et al., 2008).

2.5 Flocculation and Coagulation Case Studies

The following case studies represent experiments containing key issues for flocculant and coagulant addition, which will be required for system optimization. Even though the different floc forming mechanisms must be considered, general trends between coagulation and flocculation exist which implies general design requirements will be similar for coagulants and flocculants.

A study by Spicer and Pratsinis (1996) found increasing alum concentrations increased the size of the particles developed and the rate of floc formation. Increased shear rates decreased or buffered the effect of concentration differences. Spicer and Pratsinis (1996) also found high coagulant concentration promoted larger, more open or less dense flocs at lower shear rates and at high shear rate breakage decreased floc size and increased floc density. It was concluded that at high shear rates there was no differences in floc structure for the alum injection concentrations used in the study. The study also observed increased shear rates decreased the large tail of particle size distribution and the average size. An interesting finding was all particle size distributions for a given alum injection concentration for varying shear rates will collapse to a single distribution when the size is normalized by its average length. Spicer and Pratsinis (1996) stated that once the average size of the floc is found the entire steady-state distribution for floc size can be calculated.

Gorczyca and Ganczarczyk (1996) investigated the size, shape, and settling velocities of flocs formed with alum for four clays aided by a polymerizing agent. The settling velocities and equivalent spherical diameters varied an order of magnitude between the clays, and Stokes Law did not predict a reasonable particle settling velocity. The two-dimensional fractal dimension used to characterize flocs in this study also varied, but they were within 15% of each other. The observed settling velocities for equivalent size clays reflected differences in floc shape and density (Gorczyca and Ganczarczyk, 1996).

Owen et al. (2008) conducted an investigation of flocculation within a pipe reactor at various shear rates. They found optimum reaction times between 2 and 10 seconds for shear rates between 240 and 1660 G^{-1}; larger reaction times resulted in decreased floc size. It was shown that flocculant activity after the peak phase was reduced due to increased flocculant adsorption onto solids decreasing flocculant available for additional bridging (Owen et al., 2008). The implications of these findings are that subsequent reduction in mixing intensity after the peak will not produce larger flocs; however, decreasing mixing intensities during the growth phase will produce larger flocs . Owen et al. (2008) also showed increasing solids concentration will lead to a decrease in flocculation efficiency because a large portion of the suspended particles will not come into contact with flocculant based on the rapid adsorption onto particles in close proximity to the dosing zone. Multistage flocculant adsorption significantly enhanced flocculation especially when subsequent dosing occurred after the peak reaction time (Owen et al., 2008). It is also of significance to note that Owen et al. (2008) incorporated the addition of salt solutions in his experiments, which effectively reduced the viscosity of the flocculant solution resulting in better mixing.

McLaughlin and Bartholomew, 2007 investigated turbidity reductions with numerous anionic and nonionic polyacrylamide flocculants with a number of North Carolina soils. In general, polymer addition resulted in the same turbidity reduction for most soils; however, some responded variably and had the highest turbidity reduction with a polymer solution mix (McLaughlin and Bartholomew, 2007). McLaughlin and Bartholomew (2007) identified trends in the soils which could be used to help predict flocculation efficiency and include: 1) positive correlation between extractable Fe and Ca and turbidity reduction, 2) decreased turbidity reduction in soils with increased vermiculite or smectite, and 3) decreased turbidity reduction in soils with higher sand content.

2.6 Environmental Flocculant Applications

The objective of the current project was to develop a passive, automated amendment dosing apparatus to enhance sediment flocculation/coagulation for construction site runoff collected in a detention basin. While the underlying processes of interest concerning the use of flocculation/coagulation in stormwater runoff from construction sites and the other operations are similar, there are differences that must be considered before directly applying the available technology. For instance, a WWTP is a permanent facility; therefore, the construction of permanent flocculation/coagulation infrastructure is feasible. In contrast, a construction site is a temporary operation and a permanent structure is not required or may be financially unfeasible. Additionally, WWTPs are continuous operations with actively measured flow rates and constituent loads where construction sites will experience intermittent flows with variable sediment loads. Due to the potential challenges of implementing flocculation/coagulation systems outside of their traditional industries, it is of interest to assess other innovative applications. Some examples of innovative applications are presented in the following paragraphs.

The Tahoe Key Marin is a project that utilized chitosan to increase sedimentation rates in detention ponds during a dredging project in 2002 (Macpherson et al., 2002). The treatment system included three detention ponds in series, which consisted of a large particle settling forebay, secondary treatment pond, and a tertiary treatment pond. Effluent from the forebay flowed through filter socks integrated with chitosan into the secondary treatment pond, then through chitosan filter socks again and into the tertiary settling pond. Dosing and mixing occurred passively as flow moved from one pond to the next through the filter socks. Inflow turbidity was typically over 1000 NTU and was reduced below 20 NTU with the passive dosing system to meet water quality standards.

A study by Sekine et al.(2006) used 1.5 mg/L of a 1:1 chitosan:acetic acid agent to treat turbid river water caused by bridge construction with encouraging results. The coagulant was actively pumped into the flow where mixing occurred in downstream rapids with settling occurring in downstream pools. It was found the dosage, which was below the acute toxicity for the indicator organism *Oryzias latipes* in 48 hour test to determine the lethal concentration for 50% of the population, reduced turbidity from near 900 NTU to less than 10 NTU 600 meters downstream of the construction site. Sekine et al. (2006) noted abnormal behavior was observed in fish that was similar to abnormal behavior observed in laboratory toxicity tests. However, the author could not attribute the behavior in the fish in the field to toxicity alone because of the potential influence of high turbidities on aquatic organism and increased viscosities cause by chitosan.

Wood et al.(2005) achieved near 80 % total suspended solids (TSS) removal from stormwater runoff with the addition of 4 mg/L of a cationic flocculant, which did not increase effluent toxicity based on rainbow trout toxicity tests. The study successfully used inline static mixers for flocculant mixing without clogging with dosing controlled by a peristaltic pump. The suspended sediment removed from solution had high metal concentrations, which would need to be disposed of in accordance with regulatory guidelines.

These projects demonstrate the applicability of chemical amendments to achieve enhanced sedimentation in natural and stormwater systems with passive or constant dosing mechanisms. A flocculant dosing system for the current project shares similarities with the described studies; however, there are additional considerations to optimize performance of a construction site apparatus. A fully optimized system should take into account mixing mechanisms, flow rate, dosing, and if possible sediment load in runoff.

2.7 Sediment Load in Runoff

Soil erosion during a rain event is a result of particle detachment caused by excess shear stress in concentrated flows and raindrop impact and transport which is primarily facilitated through overland and concentrated flows (Haan et al. 1994). A steady state model for sediment load is

$$\frac{dG}{dx} = D_r + D_i \qquad \text{Eq. 1}$$

where D_r, D_i, x, and G is the rill detachment or deposition rate, the inter rill loading rate, position on slope, and the sediment load of the flow, respectively (Haan et al. 1994). D_i is typically a function of slope, rainfall kinetic energy, and rainfall intensity (Haan et al. 1994). Deposition of entrained sediment is a function of the transport capacity and the sediment load. The relationship of transport capacity and sediment load is given by

$$\frac{D_r}{D_c} + \frac{G}{T_c} = 1 \qquad \text{Eq. 2}$$

where D_c and T_c is the rill detachment capacity and the sediment transport capacity of the flow, respectively (Haan et al. 1994). From these relationships it can be seen that erosion can be either source limited, where transport capacity, T_c, exceeds both D_r and D_i or transport limited where D_r and D_i exceed T_c.

2.8 Mixing Mechanisms

Amendment mixing can be carried out by two general mechanisms: (1) flow operated stirrers such as a paddle mixer or a coquette flow device, or (2) turbulent flow. Due to the energy conversion requirements, efficiency considerations, and reliability issues related to moving mechanical devices, turbulent flow is anticipated to be the most applicable mixing mechanism.

Mixing in a pipe flow reactor can be enhanced with the addition of commercially available inline static mixers, which are fixed structure design to optimize mixing and turbulence in a pipe. Static mixers are an established mixing device in processing operations and offer low capital cost, minimal to no maintenance, narrow residence times, and defined mixing behavior (Streiff and Rogers, 1994). Additionally, static mixers can provide uniform average shear with low pressure drop, ideal for flocculation system design and optimization (Chemineer, Inc.). One issue that must be addressed is the potential for clogging of the static mixers, however, there are static mixers specifically designed to avoid clogging.

2.9 Amendment Dosing

Chemical flocculation and coagulation are contingent on the interaction between chemical amendment and stabilized particles which is influenced by the concentration of amendment added for a given solution under a given mixing regime (Auvray et al., 2006; Georgantas and Grigoropoulou, 2007;, Kang et al., 2007; McLaughlin and Bartholomew, 2007; Rodriguez et al., 2008; Szabo et al., 2008; Chunjuan et al., 2009;). Therefore, it is import to consider chemical dosing concentrations in flocculation and coagulation systems. Since polymer flocculants have been shown to be more efficient for sediment removal in comparison with coagulant amendments, this discussion will focus on flocculation (Protech, 2004; Sekine et al., 2006; Droppo et al., 2008).

The intent of properly dosing a continuous, flow through flocculation system is to inject the optimum amount of flocculant for the given solution. This “optimum” amount is the flocculant concentration which satisfies the amount of flocculant needed for the given sediment concentration without overdosing. Overdosing may cause toxicity issues in the effluent, as well as, lead to charge reversal which significantly decreases flocculation efficiency (Kang et al., 2007; McLaughlin and Bartholomew, 2007). It is also hypothesized that excess unreacted flocculant can impact fluvial geomorphology of receiving water bodies by flocculating and settling sediment that would normally wash downstream. It is assumed the concentrations of flocculant used to treat construction site runoff would be insignificant in the receiving water body; however, consideration will still be given to preventing overdosing. Further dosing considerations include the floc settling rates for the flocculant and sediment types at the concentrations in the effluent. Flocculant dosing concentrations for this project were determined by laboratory jar testing discussed in Appendix 1.

Commercially available passive dosing mechanisms include flow through coated fabrics, flocculant blocks, or floc logs. Floc logs are blocks of solid flocculant and filter fabrics are textiles with flocculant incorporated onto the material. Both systems are installed in the path of runoff and the principle of operation is the dissolution of flocculant into the bulk flow. These systems have been shown to be effective; however, there is little data on achieved dosing concentrations which is undesirable due to the influence of concentration on effectiveness and potential toxicity concerns at high doses (Bhardwaj and McLaughlin, 2008).

In order to be able to predict flocculation performance and prevent flocculant under-dosing or overdosing, a regulated dosing system is preferred over dissolution-based dosing process. A passive, automated system developed in New Zealand uses rainfall to control flocculant dosing into runoff was found and was proven to be effective (Auckland Regional Council,2004). This system provided a proven system in which to compare proposed alternative designs for a passive dosing system in this study.

CHAPTER III

GENERATING CONCEPTUAL ALTERNATIVES

The information gathered during the literature review provided a basis from which to begin generating concepts for a passively regulated flocculant dosing system. Three potentially viable concepts were initially developed and evaluated compared to each other. Flocculant dosing for the systems is controlled by either rainfall volume or stormwater runoff and the following briefly discusses each system with a simplified schematic to facilitate concept description.

3.1 Rainfall Driven New Zealand Dosing System

This system was developed and tested in New Zealand (Auckland Regional Council (2004). It relies on a floating bucket placed in a larger tank containing the flocculant solution (Figure 1). The bucket is positioned to receive rainfall from a collection system, as the bucket fills and sinks it displaces the flocculant solution and causes it to flow over a release point in the larger tank; thus resulting in flocculant dosing. The system includes a detention structure in between the rain catchment structure and the floating bucket to account for lag time associated with rainfall and runoff.

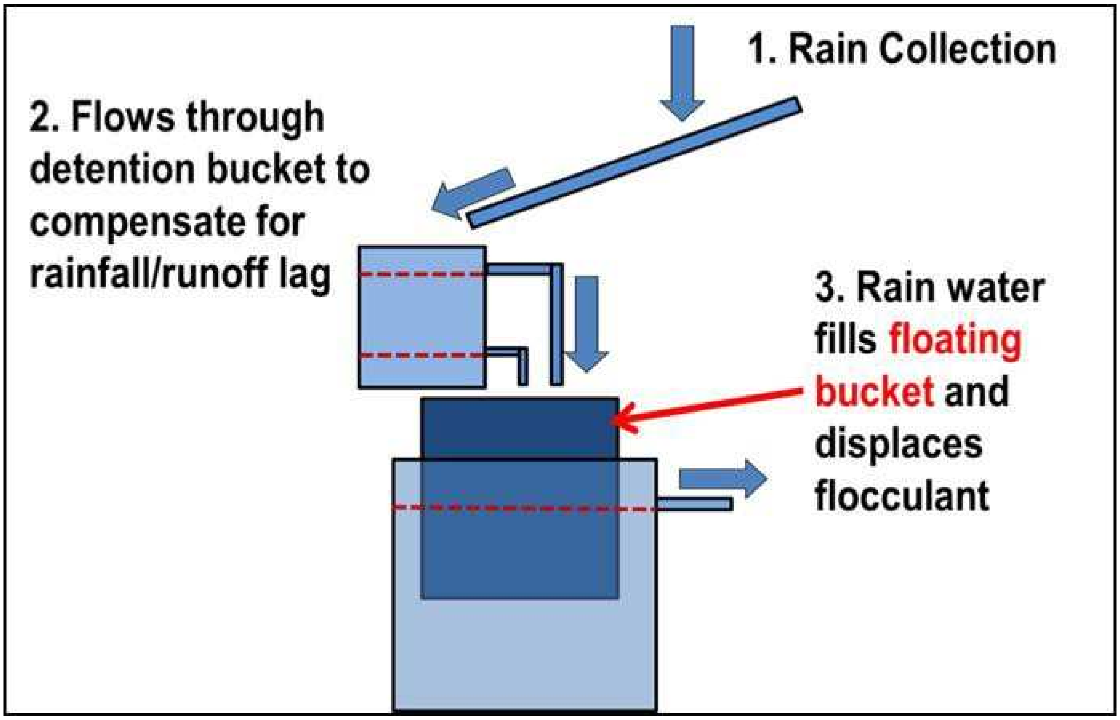


Figure 1. Schematic of operating principles for the New Zealand System. Rainfall is collected at the Rain Collection system, routed through a detention bucket, then into a floating bucket which displaces flocculant as it fills and sinks in the largest bucket that houses flocculant.

3.2 Tipping Bucket and Paddle Wheel Dosing Systems

These designs rely on rainfall or stormwater flow to actuate the flocculant dosing mechanisms. To operate, the tipping bucket uses rainfall from a collection system or a portion of stormwater runoff from a diversion structure, and the paddle wheel uses runoff as it flows in a ditch or conveyance or from runoff in a diversion. Both systems are collectively referred to as an actuation device in the following sections; however schematics are only shown for the tipping bucket. Below are three potential flocculant metering systems.

3.2.1 Gate Mechanism

An activation device will alternately open and close a gate system which controls flocculant dosing (Figure 2). When the tipping bucket fills and tips, gate 1 will open releasing flocculant while gate 2 closes restricting further flocculant injection. Simultaneously, gate 3 will close while gate 4 opens recharging the left dosing cylinder for another discharge. The process reverses when the tipping bucket tips back to the original position.

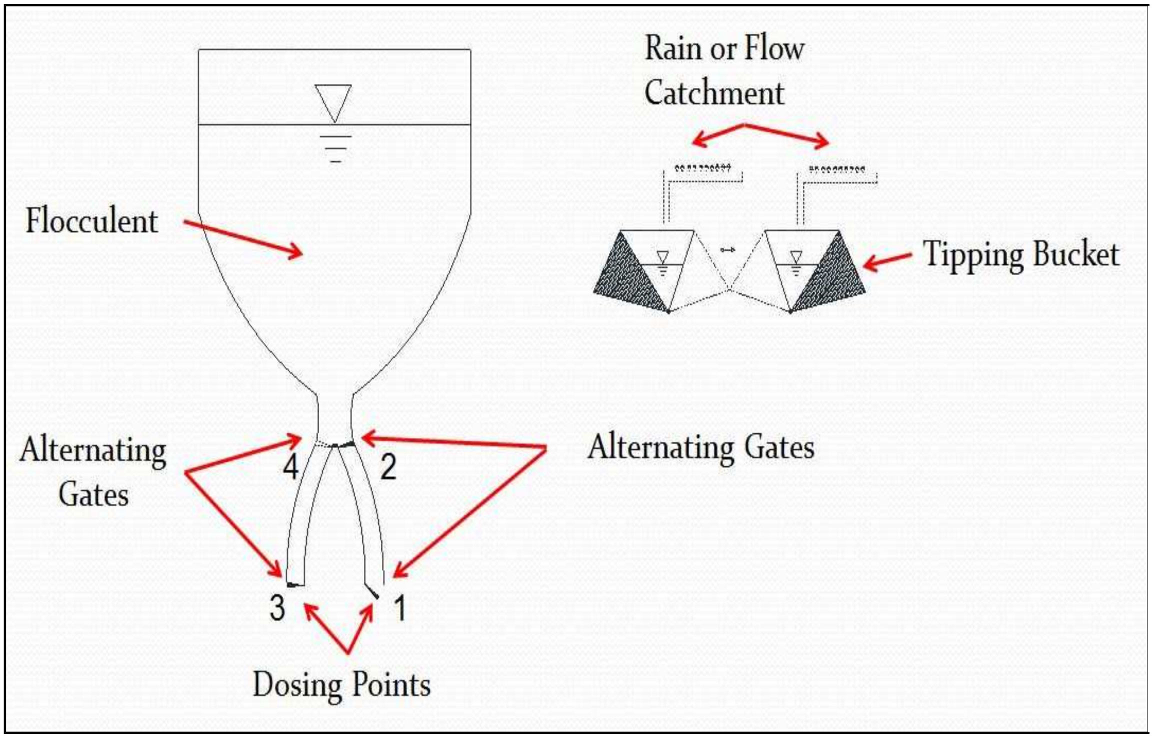


Figure 2. Schematic of operating principles for the Gate Mechanism. The tipping bucket in the top right is used to actuate gates. As the tipping bucket fills and tips, gate 1 will open releasing flocculant while gate 2 closes restricting further flocculant injection. Simultaneously, gate 3 will close while gate 4 opens recharging the left dosing cylinder for another discharge. The process reverses when the tipping bucket tips back to the original position.

3.2.2 Plunger Mechanism.

This system uses an oscillating plunger controlled by an actuating mechanism to displace liquid flocculant (Figure 3). There is one piston moving back and forth shown in two different positions (Figure 3) which forces flocculant through the dosing point. It is important to note that the dosing points are elevated to a position at the same hydraulic potential as the flocculant housing so as not to overflow through the dosing point. The hydraulic potential would be maintained with a bubble tube. The fluid surfaces in the schematic do not align; however, they should be taken to be at the same hydraulic potential as mentioned.

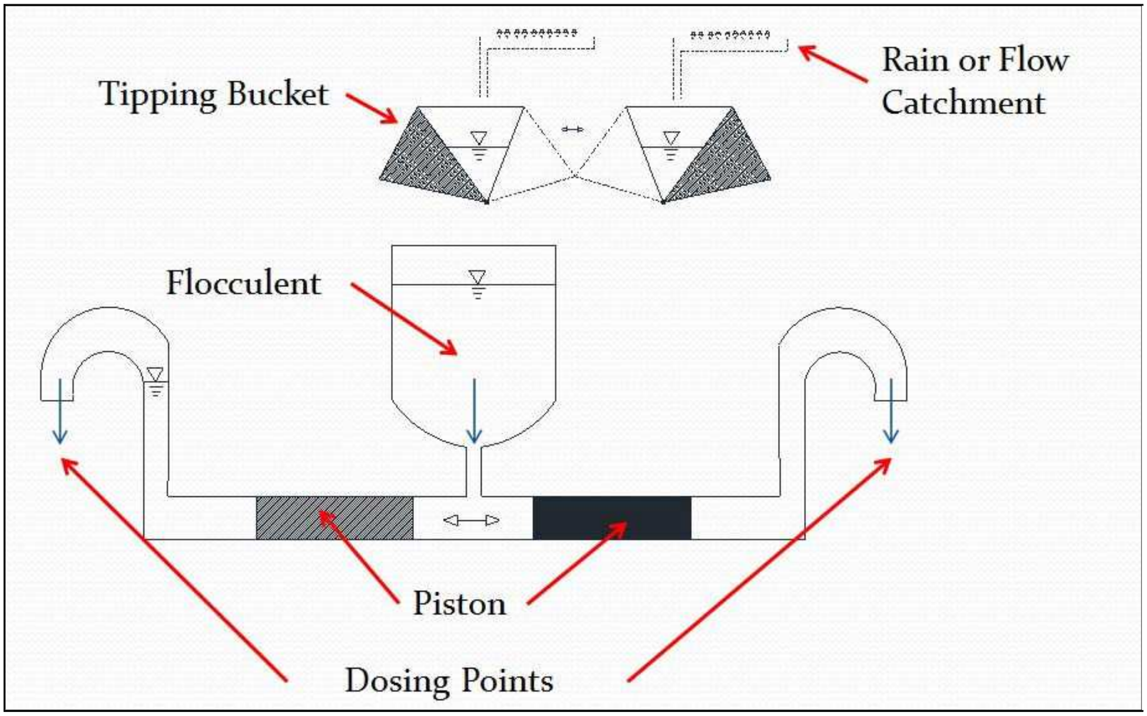


Figure 3. Schematic of operating principles for the Piston Mechanism. The tipping bucket in the top center is used to actuate a piston which move left and right. The piston allows flocculant to flow out of the housing container and into a pipe connected to the dosing points which are at the same hydraulic potential as the flocculant housing tank (not shown in figure). When the tipping bucket moves the plunger to the alternate position flocculant is displaced out the corresponding dosing point.

3.2.3 Paddle Wheel.

The paddle wheel may be used in place of the tipping bucket as the actuating mechanism and would be placed in the flow path of the stormwater runoff channel where the rotation of the wheel operates the moving components.

3.3 Pressure Differential Dosing Mechanism

This system uses an elevated tank to house the flocculant and provide flow potential for flocculant dosing. The tank could incorporate a bubble tube to maintain head if needed (Figure 4). Dosing can be carried out in a pipe, pipe constriction (venture meter), flow control structure or runoff channel. In order to initiate and terminate flocculant flow, a float valve must be incorporated into the device.

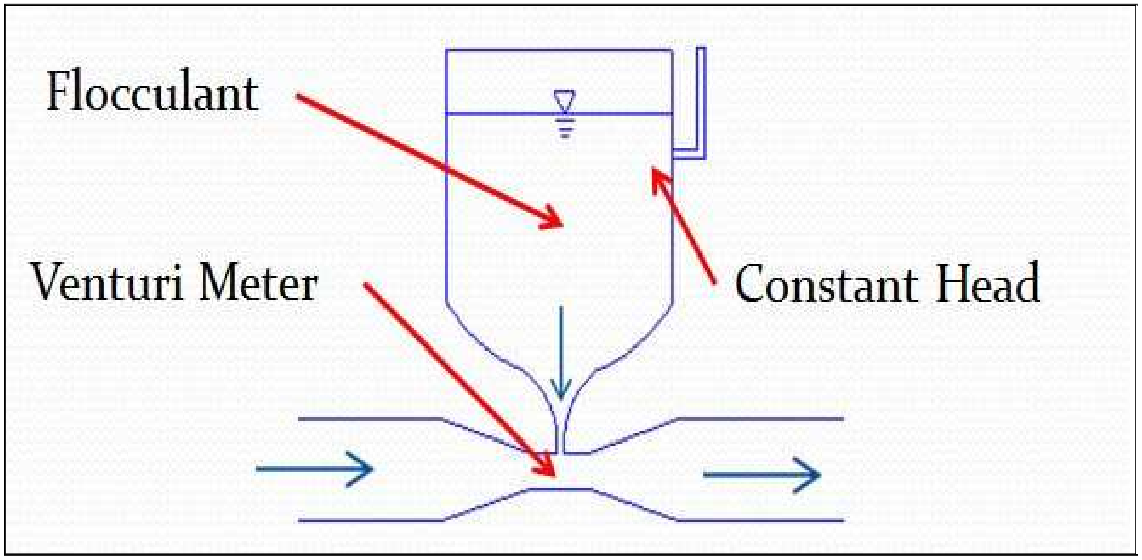


Figure 4. Pressure differential schematic for flocculant dosing.

3.4 Initial Concept Discussion

All of the above systems can be engineered to work successfully for the proposed application; however, some will take considerably more design work and maintenance than others. For instance, to connect a tipping bucket to gates or a piston would require gears and other moving parts that demand increased maintenance making those concepts undesirable for a construction site. Therefore, the pressure differential concept is identified as the best concept for refinement for an alternative design. It was suspected this concept may be ideal in a controlled environment and shows potential, but there are concerns regarding its performance on a construction site. Some of these concerns include the mechanics of a float system or how to regulate flocculant flow in a pressure driven system.

3.5 Pressure Differential Concept Refinement

The refinement process resulted in adding float actuated valves to the pressure differential dosing system to control flocculant injection (hereafter referred to as float dosing system). Two variations were considered, both of which collect stormwater runoff in a forebay that discharges through a flow control structure that flows into a settling basin (Figure 5).

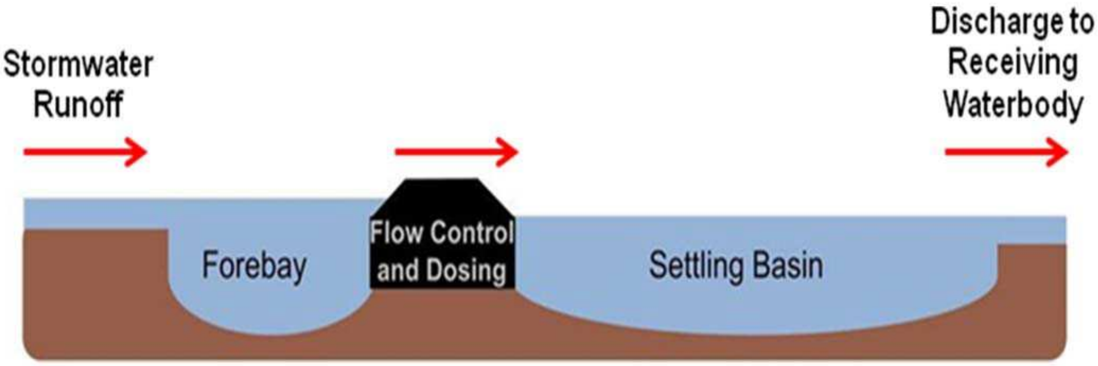


Figure 5. General schematic of dosing concept modeled during the study.

Sand and other larger particle size sediments can negatively impact flocculation efficiency (McLaughlin and Bartholomew, 2007), and thus should be removed prior to flocculant injection. A forebay not only settles out larger sized particles (sand and aggregates), but also serves as a flow dentition system and allows a location for a debris removal structure. One of the variations relied on pipe flow while the other relied on a flume. Flow through both structures can be adequately predicted based on a reference height of water. Pipe flow equations can predict discharge based on head differential of the inlet and outlet, and flume discharge is measured based on flow depth within the flume. Due to concerns of pipes clogging the flume was chosen as the preferred flow control structure and the pipe concept was no longer pursued. Hypothetical advantages and disadvantages could be found for the selected alternative when compared to the New Zealand System; however, at this point it was not apparent which concept was best suited to the project application. Therefore, a modeling study was conducted in order to make the most judicious selection.

CHAPTER IV

METHODS

4.1 Modeling Alternative Systems

The rainfall driven New Zealand System and Float Dosing System were compared based on a synthetic 2-year 24-hour design storm for Greenville County, South Carolina on different catchments due to the sponsor's intended region of application and the requirements given in the initial EPA's initial ELGs. The rainfall/runoff calculations were performed in Sedimot IV which used a Type II synthetic storm event for Greenville County, NC and rectangular catchments with no onsite flow routing. A description of the catchments and software parameters is given in Appendix 1. A target dose was used to evaluate each system's performance based on a Weighted Variance (WV) which was the flow weighted deviation from the target dose given as:

$$\square\square \; ൭\cdot൭ \; \frac{\sum^{?} ? \square\square \frown \square\square \square_{?} ?^{\square} \square_{\square}}{\sum^{?}_{\square\square\,\square} \square} \qquad \text{Eq. 3}$$

where □ is an integer corresponding to each time step, □ is the total number of time steps, $\square_{?}$ is the concentration of flocculant in the effluent , $\square_{\square}$ is the target concentration of flocculant in , and $\square_{?}$ is the volumetric flow . A constant target dose was used for the simulation which would suggest the simulation assumes a constant sediment concentration in the runoff. It is realized that sediment concentrations will vary during the storm event and runoff only indicates the maximum potential sediment a constant target dose was still used.

The governing processes for the New Zealand System were assumed to be (1) the collection of rainfall in a catchment system of given size, (2) detention time of collected rainfall (3) the displacement of flocculant from the housing as collected rainfall fills the New Zealand System, and (4) the dispensing of flocculant into the runoff. Code was created in MATLAB and assumed the following:

1. Volume of flocculant dosed equal to the volume of rainfall collected.

2. Detention structure was a reservoir that had a stage-height discharge controlled by pipe flow.

The implications of the first assumption require the flocculant mixture to have the same density or near the density of water. With these assumptions made, the flocculant concentration in the effluent could be determined.

The governing processes for the flume concept were (1) the system collects storm water runoff in a forebay which (2) discharged into a settling basin through a flume, and (3) dosing was actuated and terminated by the height of water in the forebay. Code was created in MATLAB and assumed the following:

1. Maximum flow through the float valves was constant through the rain event (potential change in head in the flocculant reservoir was not taken into account)
2. Float valves had an assumed linear change in flow with change in height of the attached float until the maximum flow rate was reached. This assumption was incorporated into the model based on observed valve performance as mentioned later on.

Discharge through the flume is controlled by a stage discharge relationship given for commercially available flume designs. The flumes were sized to handle the peak flow rate of the watershed for the synthetic storm previously described. The New Zealand System and Float Dosing System relied on the same numerical routing procedure given in Haan et al.(1994) as follows:

$$\Delta S_i = \frac{I_i + I_{i+1}}{2}\Delta t - \frac{O_i + O_{i+1}}{2}\Delta t \qquad \text{Eq. 4}$$

$$S_{i+1} = S_i + \Delta S_i \qquad \text{Eq. 5}$$

$$h = \frac{S_i}{A} \qquad \text{Eq. 6}$$

where ΔS_i is change in storage of a reservoir at the current iteration at the current time step, Δt is the length of each time step, I_i, I_{i+1}, O_i, and O_{i+1} are inflow and outflow rates, respectively, at the current and next iteration. h and A are the height in the forebay and area of the forebay which assumed a rectangular forebay, respectively. If it is assumed

$$O_{i+1} = O_i \qquad \text{Eq. 7}$$

for the first iteration for the current time step, then ΔS_i Can be solved for and the resulting S_i can be used to calculate a new O_{i+1}. This procedure was repeated until O_{i+1} converges to a value less than 1% different than the previous iteration. The reservoirs for the New Zealand System/ Float System were a detention bucket/forebay, the inflow was rain /runoff and outflow pipe flow equations/flume stage discharge equations respectively. The volumetric flow out of the reservoir was assumed to be the amount of flocculant solution dosed into the runoff for that time step. Dosing in the Float System was assumed to actuate and terminate based on the stage in the flume and binary float operation. The initial float was assumed to have non binary operation based on observed operation of float valves used. Operation of this float was assumed to be modeled with a linear function based on float height until a maximum constant value is reached. The simulation was run in MATLAB and the code used to the generate results are provided in Appendix III.

Subsequent work resulted in replacement of the float valves with ball valves after prototype testing. Theoretical operation of these valves based on available flow coefficient data and assumed constant pressure drop across the valve is included in the modeling results section.

4.2 Jar Testing

The optimum range or target flocculant concentration was determined through a series batch experiments performed in the laboratory using automated stirrers where a known mass of flocculant is added to a solution with a known suspended particle concentration. The suspended particle concentration used was 40 g/l which was based on predicted peak sediment loads from Sedimot IV, described in Appendix I, from a three acre site and flocculant concentrations were varied. Based on information presented in section 2.7 and output results from Sedimot IV, it is noted sediment concentrations will vary throughout out the storm event. However, the peak sediment concentration was used in order to determine flocculant concentrations needed during more extreme events. The sediment was allowed to settle in a large beaker for a given period of time to simulate the effect of a forebay to remove larger particles. The suspended sediment remaining in the supernatant was removed from solution and used in jar tests. Jar testing procedures and results are presented in further detail in Appendix II.

4.3 Prototype Field Testing

The prototype turbidity reduction system described previously was tested in an experimental channel at the USDA ARS Hydraulics laboratory near Stillwater, Oklahoma (http://www.ars.usda.gov/spa/stillwater/heru). The water source for the tests was Lake Carl Blackwell near the test site (http://lcb.okstate.edu/). Six test runs were completed using three different flow rates (0.75, 1.5, 2.25 cfs or 0.021, 0.042, 0.063 cms), with a target flocculant concentration of 0 and 0.08 g/L of HydroFloc 445L. The maximum discharge capable through the experimental set up was just above 2.25 cfs (0.063 cms) and the two lower flow rates were incrementally less by 0.75 cfs (0.021 cms). The target flocculant concentration is 0.005 g/l higher than the lower bound, 0.075 g/l, of the optimum range found in the jar tests.

A local soil (clayey sand; 57% sand, 18% silt, 25% clay, D50=0.1 mm) was used as the sediment source for testing the prototype. For these tests, sediment was delivered by hand to the flow, mixed with a 3-blade rotary mixer, which passed through a flow straightener directly upstream of the forebay, and then the sediment laden flow was directed through a cutthroat flume and into the dosing and mixing system (Figure 6). The forebay was sized to capture larger sized particles were from the input test water based on the settling rate of a 0.05 mm sand particle. Sediment from the low flow control run filled the forebay and was left in that condition for the remainder of the tests. Sediment was introduced by hand into the channel at constant rate for each run. Turbidity samples were collected before the cutthroat flume and at 25 (7.62), 50 (15.24), 75 (22.86), and 100 (30.48) feet (m) downstream from the flume (Figure 7).

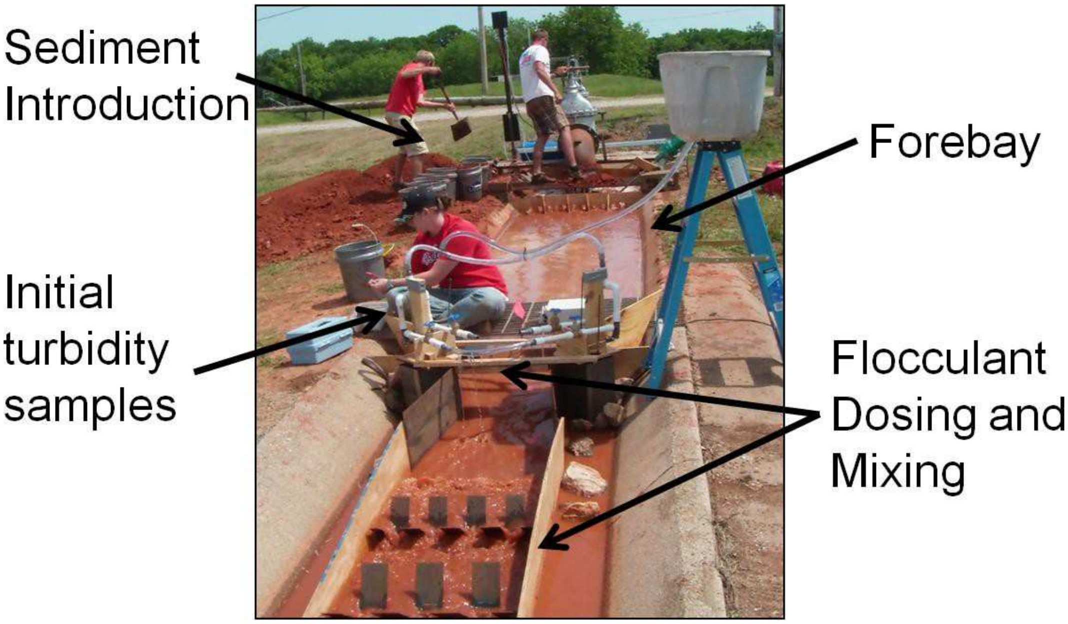


Figure 6. Testing setup at the upstream end of the turbidity reduction system. Sediment introduction took place at the beginning of the channel into a mixing chamber, passed through a flow straightener into a forebay, then through the dosing and mixing system, and into the setting channel.

Figure 7. Testing setup at the downstream end of the turbidity reduction system. The left image was the view looking down the settling channel from above the flume., the middle image is a Hach Hydrolab MiniSonde that was used in the channel, and the right image was the view facing upstream from the discharge point of the settling channel. Turbidity samples were collected before the cutthroat flume and at 25 (7.62), 50 (15.24), 75 (22.86), and 100 (30.48) feet (m) downstream from the flume in the settling channel.

The samples before the flume were collected in bottles during the tests, and analyzed with a Hach 2100N turbidimeter after the test was completed. Samples from the sampling point 25 feet (7.62 m) downstream from the flume were analyzed in the field using a Hach 2100N turbidimeter. The turbidity at the 50 (15.24), 75 (22.86), and 100 (30.48) feet (m) sampling locations was measured at 30-second intervals with a Hach Hydrolab MiniSonde. Different types of turbidity measuring instruments were used based on equipment available. Turbidity measurements from each piece of equipment were taken from a standard solution for benchmarking. It was found each piece of equipment produced agreeable measurements as long as they were calibrated.

Minitab 15 Statistical Software was used perform statistical analysis on the collected turbidity data. A General Linear Model (GLM) was used to investigate influence of experimental factors on turbidity reduction. Experimental factors included of flocculant concentration, time of turbidity reading, and flow rate. A One-Way ANOVA and a Tukey Comparison with a family error rate were used to investigate differences between mean percent turbidity reduction at each sampling time between the control and flocculant tests with an alpha of 0.05

CHAPTER V

RESULTS AND DISCUSSION

5.1 Modeling Results

The flume concept was determined to be the most appropriate design for the project objectives. The New Zealand System concept could maintain flocculant concentrations near the target dose for a catchment to which it was calibrated; however changes in the catchments resulted in changes in dosing.

5.1.1 Rainfall Driven New Zealand System

A schematic of the New Zealand System is shown in Figure 1 and described in Auckland Regional Council (2004), which provides further details on the system and field testing results. The performance of the New Zealand System (Figure 8) on a 1 acre (4047 m^2) watershed with a Curve Number (CN) of 90 is shown in Figure 9.

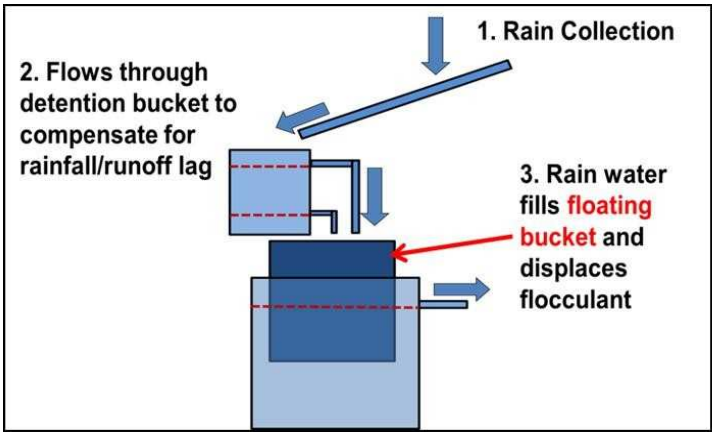


Figure 8. New Zealand Dosing System Schematic

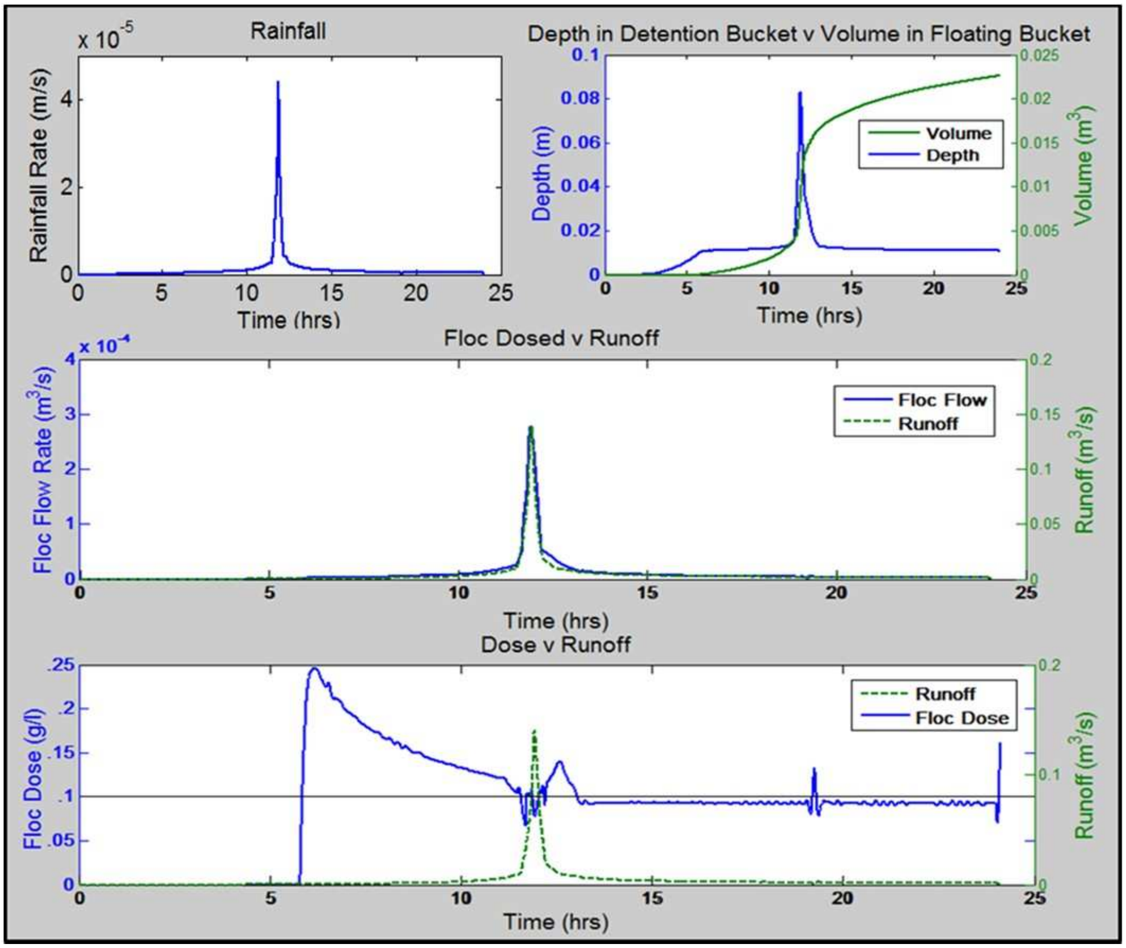


Figure 9. . Calculations used to determine New Zealand System performance. Rainfall is rainfall rate with time; depth in Detention Bucket v Volume in Floating Bucket shows the depth of water collected in the detention bucket with time and the volume of the floating bucket with time; Floc Dosed v Runoff shows the floc flow, flow rate of flocculant, with time and runoff , runoff from

the site, with time; Dose v Runoff shows the floc dose, concentration of flocculant in the effluent, with time and the Runoff, runoff from the site, with time. [hrs: hours; m^3/s; cubic meters per second; g/l: grams per liter; m/s: meters per second; m^3:cubic meters ; Floc: Flocculant]

These data were generated using a synthetic design storm event with the corresponding runoff predicted based on an idealized rectangular construction site with no flow routing. The simulation results showed in Figure 9 plots characteristics of the system throughout the duration of the storm event. The top left plot has depth in the detention bucket. The detention bucket has pipes with riser heights at various stages which convey water to the floating bucket. These pipes diameter and a riser heights were manual calibrated so that discharge to the floating bucket (i.e. floc flow fate) would match runoff as close as possible as shown in the center figure. Three different riser stages and pipe diameters were used. Adding intermediated stages at various diameters would create better agreement between discharge and runoff, however, this was considered impractical for actual implementation. Finally, the resulting dosing profile is a function of floc flow rate over runoff rate and is shown in the bottom figure. The target floc dose for the simulations was 0.1 g/l and is shown with the horizontal line. Dosing concentrations were found to be sensitive to variations in the floc flow relative to runoff especially at low runoff rates. Some of the smaller abrupt increase or decreases in dose are suspected to be a result of numerical methods used in rainfall/runoff generation from Sedimot IV and the numerical methods used in the simulation. For this reason, a smoothing function utilizing a moving average was applied to the data shown in Figure 8.

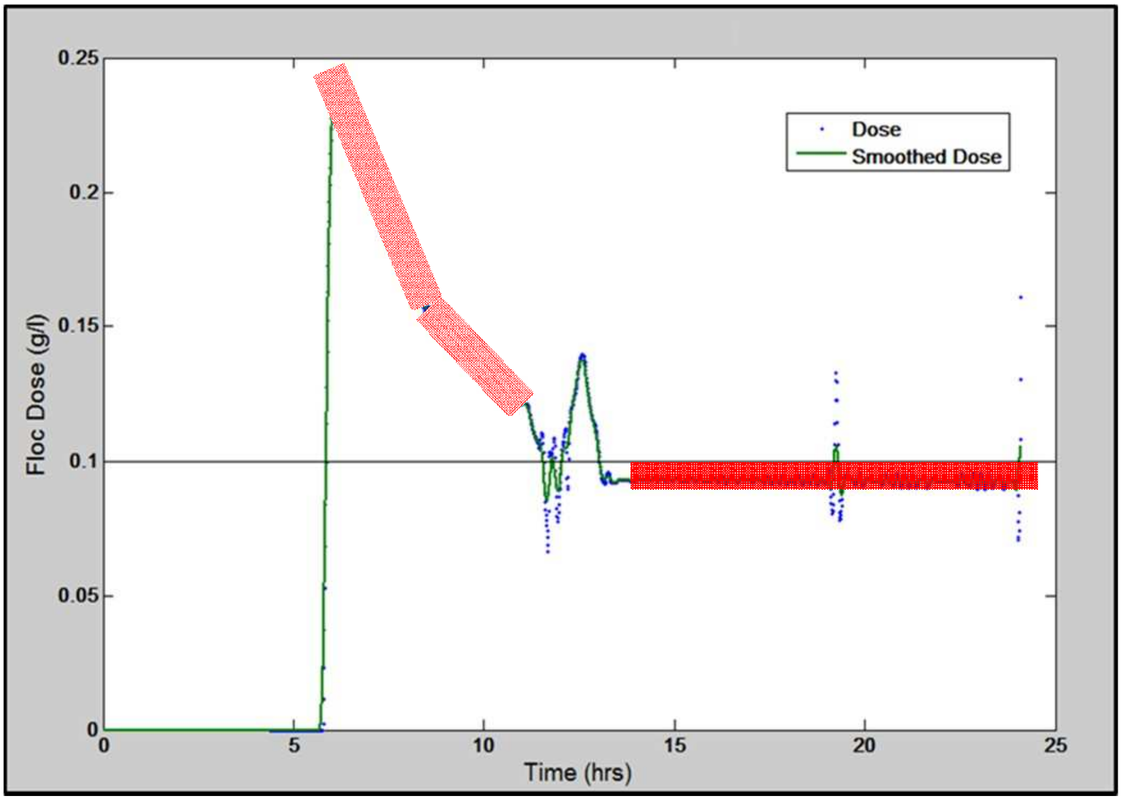


Figure 10. Dose, the computed dosing concentration, throughout the storm event with the Smoothed Dose, a moving average of Dose. Oscillations in dose suspected to be a result of rainfall/runoff values are highlighted. [hrs: hours; g/l: grams per liter; Floc: Flocculant]

The period of the moving average was such that large oscillations relative to preceding and succeeding values are dampened. The smaller oscillations that are suspected to be a result of numerical calculations used to generate rainfall/runoff data are highlighted in red. A smoothed line will be used in all subsequent figures mitigate some of these oscillations. Subsequent figures also have rainfall or runoff overlaid with data by after being multiplied by a scaling factor for reference.

Since this system is designed based on an anticipated rainfall runoff relationship, any changes in the watershed or discrepancies in the modeling will result in changes in the dosing concentrations. For instance, if the system is calibrated using a rainfall runoff relationship that relies on the CN Method changes in CN due to construction activities or errors in estimating CN will cause deviations from the targeted dose. Figure 11 shows a system designed for the same scenario as for Figure 9 and 10, but also includes the expected dose if the CN increased from 90 to 95 and decreased from 90 to 85. The flow weighted averages for all three CN are shown in the horizontal lines with same color as its corresponding series.

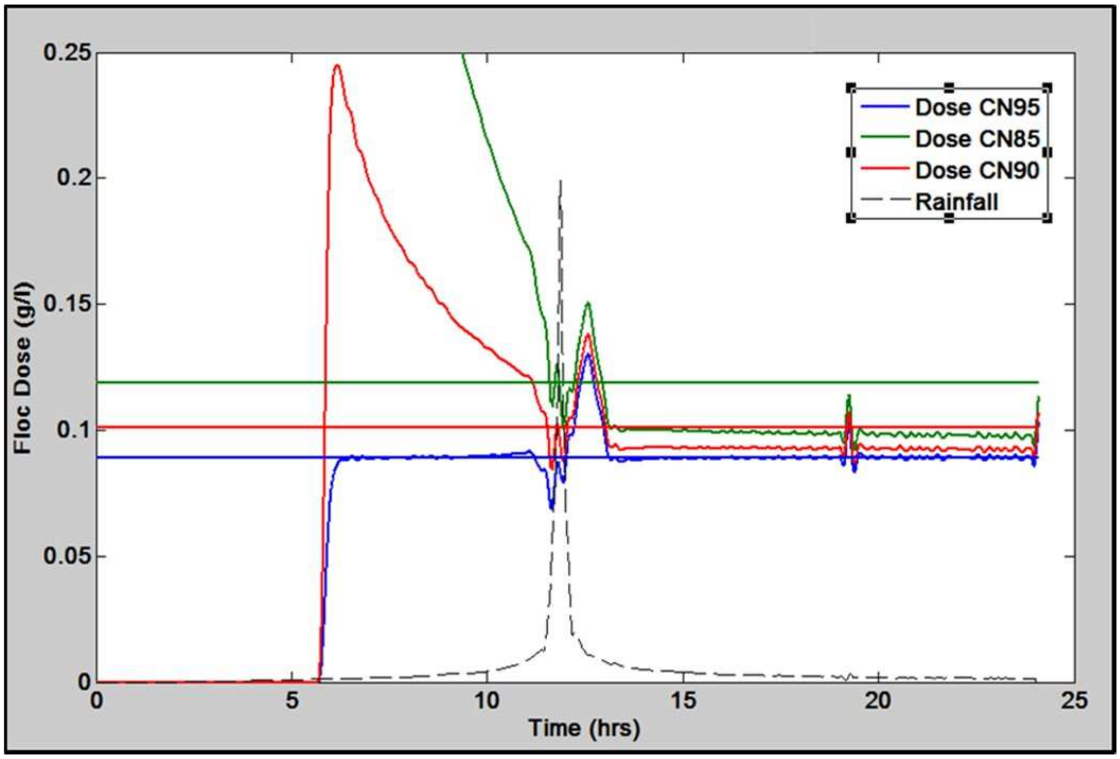


Figure 11. Effect of changing CN on simulated dosing concentrations calculated for the New Zealand System which was calibrated to a site with CN of 90.Dose CN95 is the resulting dosing concentration for a site with a curve number of 95, dose CN85 is the resulting dosing concentration for a site with a curve number of 85, dose CN90 is the resulting dosing concentration for a site with a curve number of 90 to which the system was calibrated, and rainfall is the rainfall on the site throughout the storm event. [hrs: hours; g/l: grams per liter; CN: Curve Number: Floc: Flocculant]

For a targeted dose of 0.1 (g/l), the flow weighted dose decreased to 0.089 (g/l) when the CN increased to 95 and increased to 0.119 (g/l) when the CN decreased to 85. These dosing correspond to an 11% decrease and a 19% increase from the targeted dose. Suppose, that the target dose rate was for 0.089 (g/l) for a site anticipated to have a CN of 95 and a change in the watershed resulted in a CN of 85 the flow weighted dose would increase from 0.089 (g/l) to 0.119 (g/l) which corresponds to an increase of 34% in the concentration for a change of 10 units in CN. A change of 5 to 10 units in CN estimation can result from errors in estimation of the quality of ground cover or soil group based on published CN for expected land use in Haan et al. (1994) and can also be impacted by antecedent moisture content.

Another parameter of interest in rainfall runoff modeling is the Time of Concentration (TC) for the watershed. A method that was used to investigate the potential impact of changing TC was to vary timing of runoff. The timing of runoff and TC can sometimes be difficult to accurately estimate and can changes on a watershed with hydrologic changes such as a construction site. The initial scenario with runoff times delayed by 2 and 5 minutes is plotted in Figure 12 and the impact to the dosing profile if runoff is shifted sooner by 2 and 5 minutes is plotted in Figure 13.

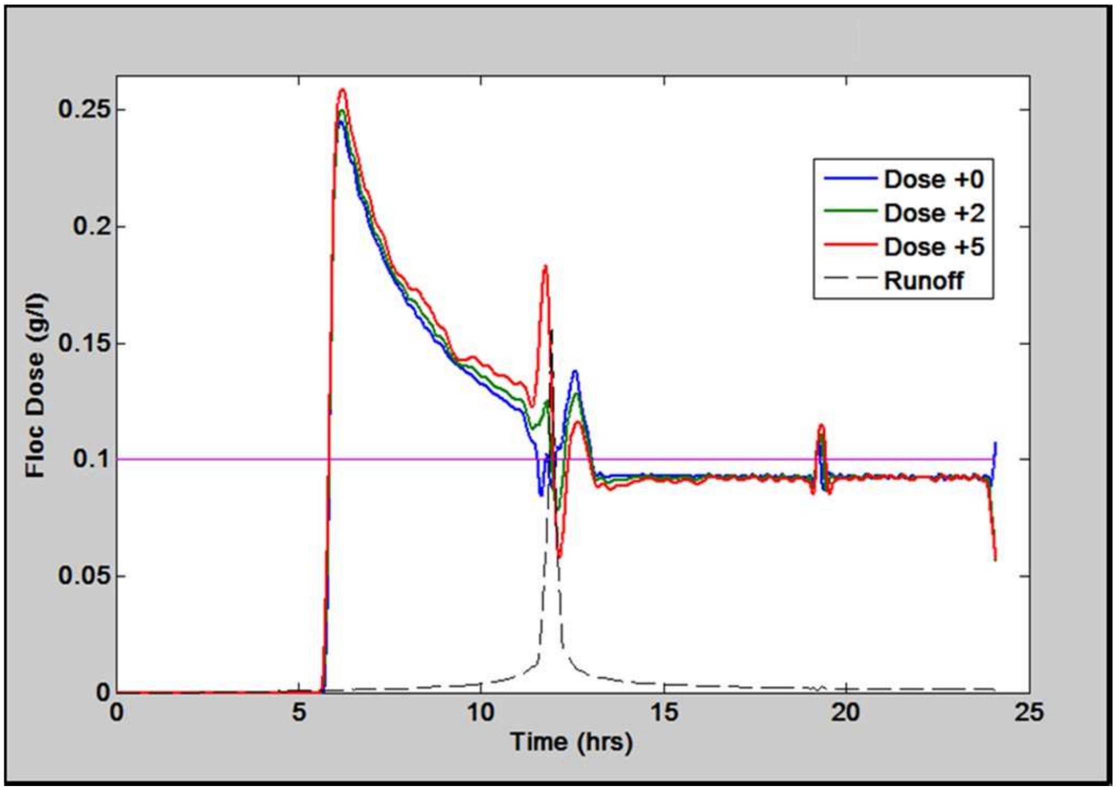


Figure 12. Impact of time of concentration changes by delaying runoff by 2 and 5 minutes to dosing concentrations. dose +0 is the resulting concentration if the timing of runoff is not changed, dose +2 is the resulting concentration if the timing of runoff is delayed 2 minutes, dose +5 is the resulting concentration if the timing of runoff is delayed 5 minutes, and runoff is the site runoff throughout the storm event. The pink horizontal line is the target concentration of 0.1(g/l). [hrs: hours; g/l: grams per liter; Floc: Flocculant]

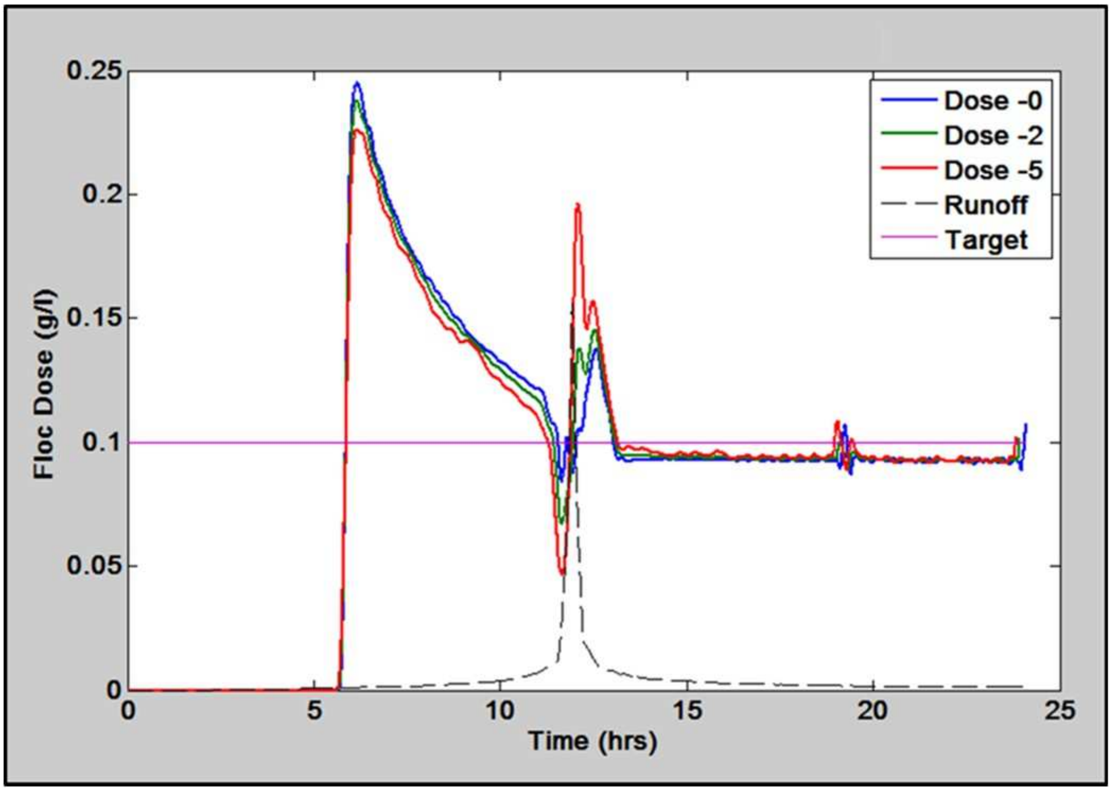


Figure 13. Impact time of concentration changes by shifting runoff sooner by 2 and 5 minutes to dosing concentrations. Dose -0 is the resulting concentration if the timing of runoff is not changed, dose -2 is the resulting concentration if the timing of runoff is 2 minutes sooner, dose +5 is the resulting concentration if the timing of runoff is 5 minutes sooner, and runoff is the site runoff throughout the storm event. [hrs: hours; g/l: grams per liter; Floc: Flocculant]

It should be noted that TC were not actually varied, however, inferences are being drawn as if TC were actually being varied. Shifting the timing of runoff instead of varying TC neglects the spreading of the hydrograph and reduction of peak flow which can be characteristic of increasing TC and vice versa for decreasing TC. It is expected that these neglected processes would decrease or increase the magnitude of variations seen in Figure 12 and 13, respectively. Since dose is essentially rainfall divided by runoff, when runoff is delayed for a period of time the dose will increases as rainfall rate (i.e. mass flow rate of floc) increases until runoff begins to increase. When peak rainfall is reached and rainfall rate decreases, the runoff rate still increases for a short period and the dose rapidly decreases until the change in runoff decreases. This process will be reversed if runoff rates were shifted sooner. The impact of this process is evident in the simulation and it can be concluded that deviation from the targeted dose has the potential to increase with increased error in timing of runoff and potentially TC.

Four different simulations were ran that varied both CN and TC for a 1 acre (4047 m^2) watershed designed and calibrated for a CN of 90 (Figure 14).

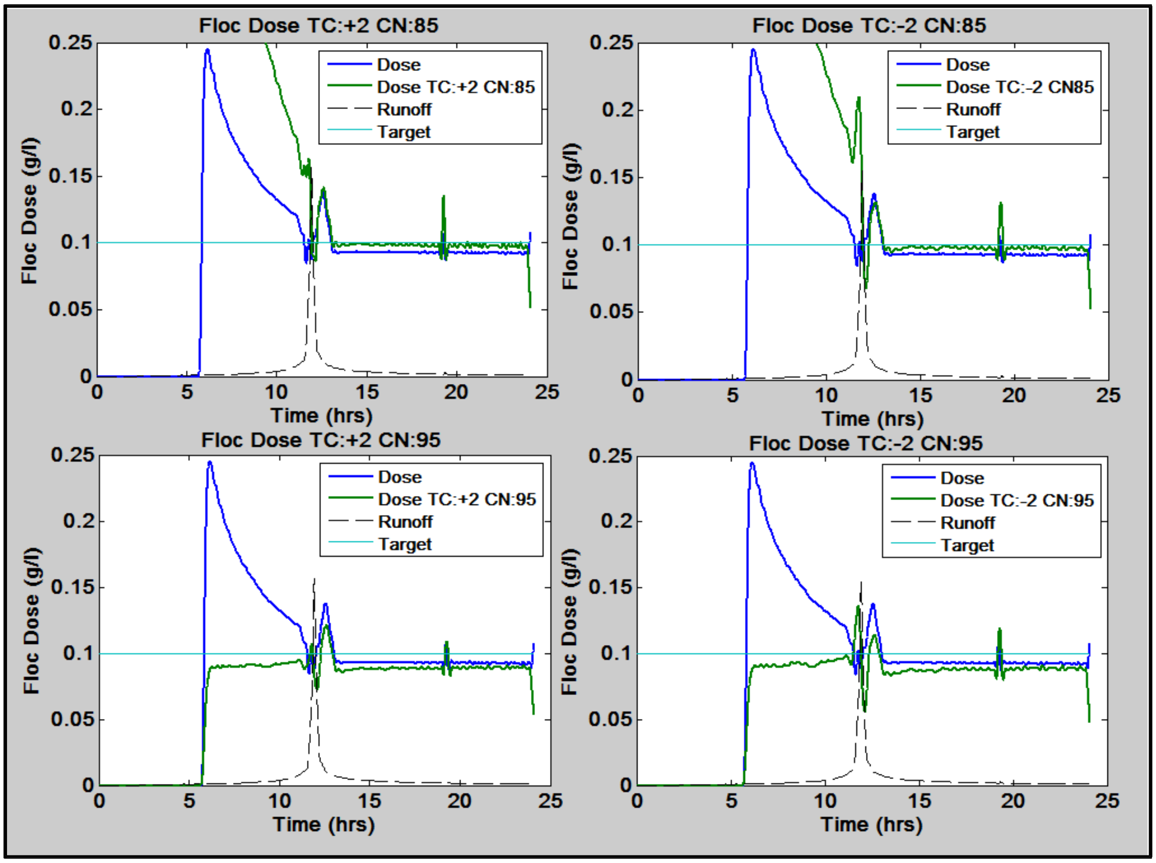


Figure 14. Four different scenarios varying CN and TC for a 1 acre (4047 m^2) watershed. Dose is the calculated dose for a site with original conditions (where the change in TC is 0 minutes and the CN is 90), dose TC:+2 CN:85, dose TC:-2 CN:85, dose TC:+2 CN:95, dose TC:-2 CN:95 is the calculated dose when the site runoff is shifted 2 minutes later and CN is 85, shifted 2 minutes sooner and CN is 85, shifted 2 minutes later and CN is 95, shifted 2 minutes sooner and CN is 95 respectively. Runoff is runoff throughout the storm event scaled so it can be viewed with other data for reference, and target is the target concentration of 0.1 (g/l). [hrs: hours; g/l: grams per liter; CN: Curve Number; TC: Time of Concentration; Floc: Flocculant]

A deviation from the predicted timing of runoff of +/- 2 minutes was used based on data presented and methods given in Haan et al.(1994) for a short grass to bare/untiled land use, respectively.The simulations indicate that multiple disprepencies in modeling can lead to compounding deviations from the targeted dose. Also, it seems that a decrease in CN is more sensitive to variations in timing of runoff than an increased CN. The same analysis was performed on a watershed of 3 acres (4047 m^2) (Figure 15). A deviation from the predicted timing of runoff of +/- 4 minutes was used based on data presented and methods given in Haan et al.(1994) for a short grass to bare/untilled land use, respectively.

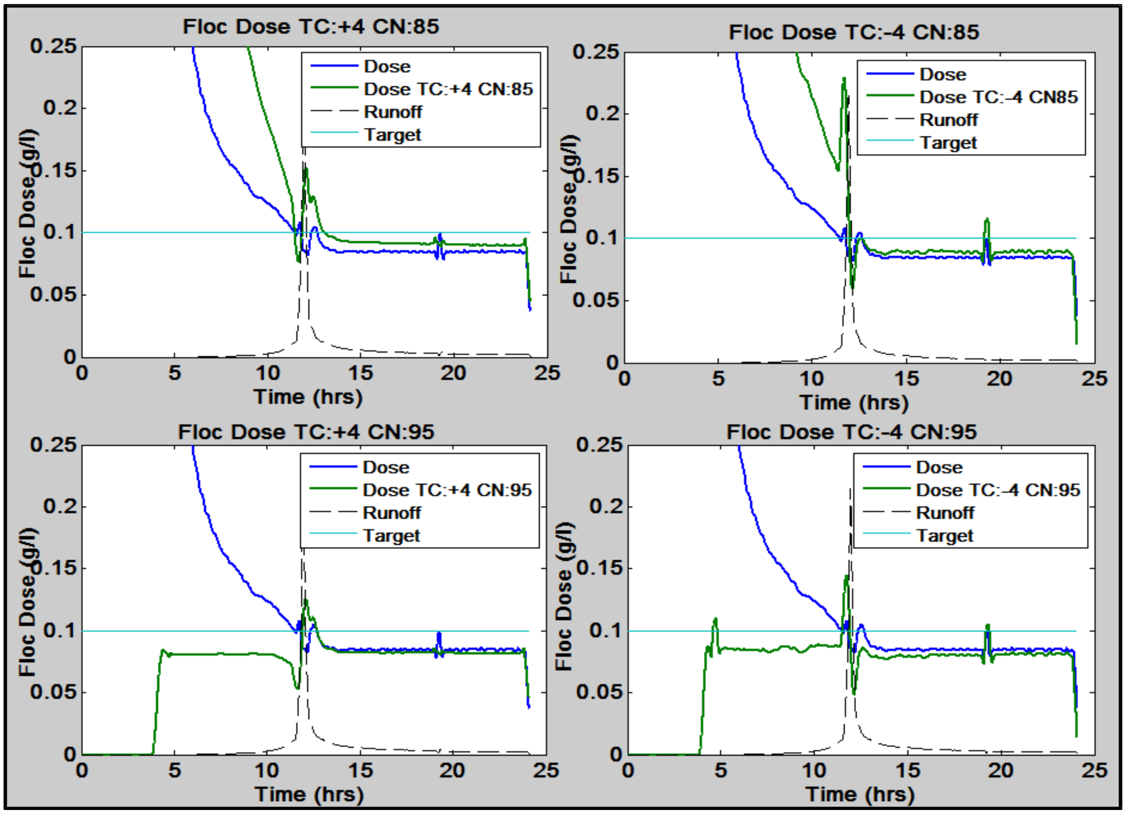


Figure 15. Four different scenarios varying CN and TC for a 3 acre (12141 m^2) watershed. Dose is the calculated dose for a site with original conditions (where the change in TC is 0 minutes and the CN is 90), dose TC:+4 CN:85, dose TC:-4 CN:85, dose TC:+4 CN:95, dose TC:-4 CN:95 is the calculated dose when the site runoff is shifted 2 minutes later and CN is 85, shifted 2 minutes sooner and CN is 85, shifted 2 minutes later and CN is 95, shifted 2 minutes sooner and CN is 95 respectively. Runoff is runoff throughout the storm event scaled so it can be viewed with other data for reference, and target is the target concentration of 0.1 (g/l). [hrs: hours; g/l: grams per liter; CN: Curve Number; TC: Time of Concentration; Floc: Flocculant]

It was demonstrated that sizing and calibration of the system relies on runoff modeling and is a critical step in the design process. Any modeling discrepancies or hydrologic changes to the site during construction activities may result in altered dosing profiles. It would be possible to account for some long term hydrologic changes on the site such as paved or cleared areas but this would require modifications to the dosing system. However, these changes are still subject to errors and other onsite changes such as antecedent moisture content would be difficult to adjust for. Moreover, the dosing concentrations were most variable while runoff rates are rapidly changing during the most intense part of the hydrograph which typically has the highest sediment concentration. This is a result of the dosing system not being able to reproduce the exact shape of the runoff hydrograph when being routed through the detention bucket. It should be noted the shape of discharge through the detention bucket is a result of the pipe flow models as height in the detention bucket changes; however, other detention structures will also alter the discharge shape. It should be noted that the system could achieve fairly consistent dosing rates on the watershed to which it was designed and for a site with an increasing CN. Therefore, if the New Zealand System method were used it is suggested it be designed for the minimum CN expected during the duration of the project. Furthermore, the simulation used a synthetic storm event for North Carolina, as is common practice for storm water system analysis that has a rapid rising and falling limb which may be more intense than storms for other areas. It is speculated this system would be better suited to areas with mild or steadier storm events because the simulations showed the system maintained consistent dosing at the end of the storm events where rainfall and runoff were relatively constant.

5.1.2 Float Dosing Using a Flume

The simulated dosing of the float dosing system on a 1 acre (4047 m^2) watershed with runoff corresponding to a CN of 95 is variable during the storm event but can maintain a fixed range of concentrations (Figure 16).

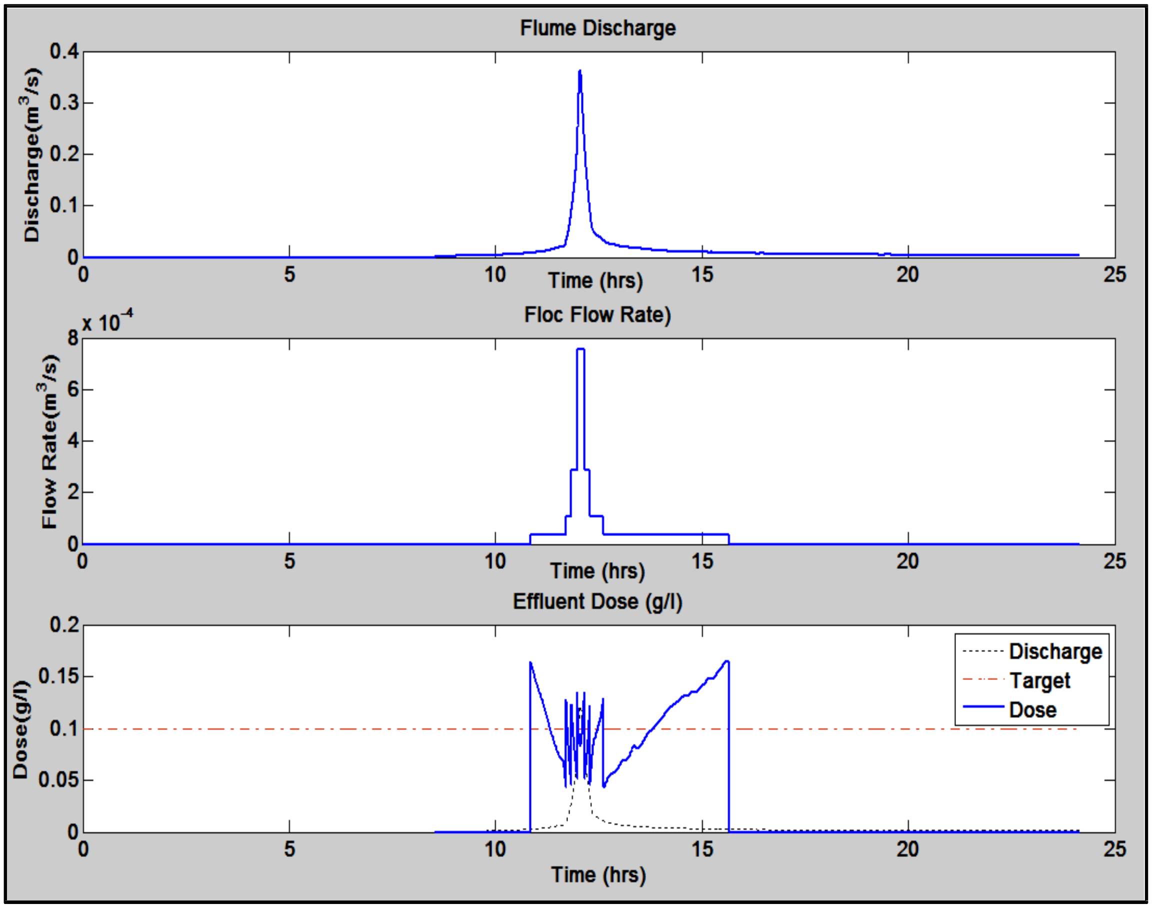


Figure 16. Calculations used to determine float dosing system performance. The top chart shows discharge through the flume; the middle chart shows flocculant flow rate; and the bottom chart shows the dose (flocculant concentration in the effluent), darget (Target flocculant dose in the effluent), and discharge (scaled discharge through the flume). [hrs: hours; m^3/s; cubic meters per second; g/l: grams per liter; Floc: Flocculant]

As runoff begins the forebay begins to fill and discharge through the flume into the settling basin.

The first float is actuated at a designed height which corresponds to the first step in the central figure and the first jump in the dosing concentration in the bottom figure of Figure 16. This process is more clearly show in Figure 17 where the vertical black lines connect increases in floc flow rate to increases in dosing concentration as float valves are actuated and terminated.

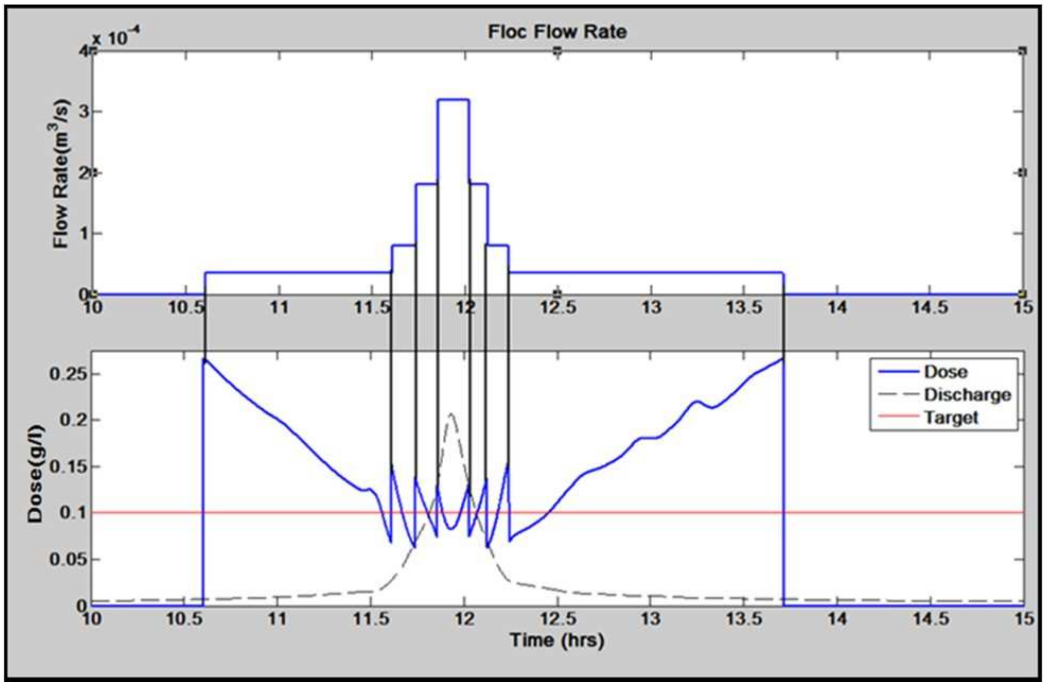


Figure 17. The top chart shows flocculant flow rate vs. time and the bottom chart shows the dose, flocculant concentration in the effluent, target, target flocculant dose in the effluent, and discharge, scaled discharge through the flume. [hrs: hours; m^3/s; cubic meters per second; g/l: grams per liter; Floc: Flocculant]

The dosing profile is flocculant flow divided by runoff. The first float valve is actuated when a specific stage is reached in the forebay and it is assumed to instantaneously dose the maximum amount of flocculant capable for that valve system. Then as runoff increases, the dosing concentration is reduced until another float valve is actuated corresponding to another instantaneous jump in dosing concentration. The same process occurs in reverse during the falling limb of the hydrograph. In reality, the float vales do not achieve true binary operation. It took roughly 3 inches (7.62 cm) of change in forebay stage to achieve maximum flow through each float system in the prototype system. To incorporate this valve characteristic into the system a smoothing curve based on a moving average was used which acts to dampen the extreme high and lows which will be used in subsequent figures (Figure 18).

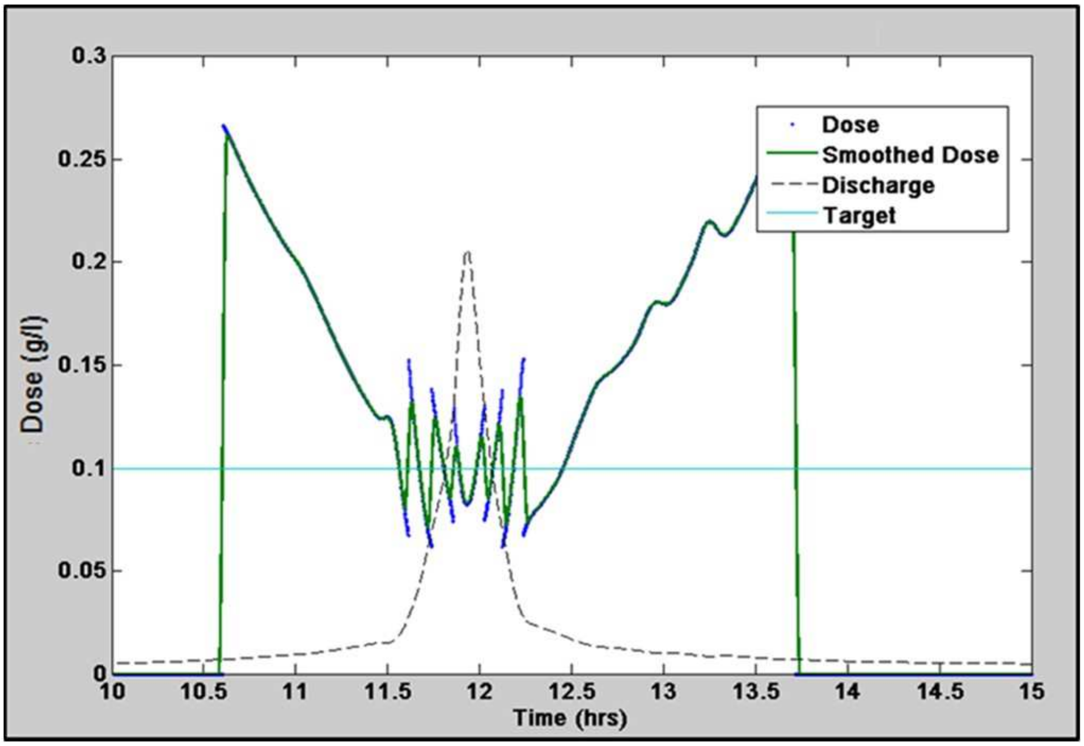


Figure 18. The chart shows the dose, flocculant concentration in the effluent, target, the target flocculant concentration in the effluent, discharge, scaled discharge through the flume, and the smoothed dose, dose with a smoothing function applied. [hrs: hours; g/l: grams per liter; Floc: Flocculant]

The span of the moving average was chosen so that the effect of the smoothing curve in relation to calculated dose corresponded to a change in height of roughly 3 inches (7.62 cm) or less in the forebay to be conservative. It should be noted that the smoothing function had little impact on the dosing concentration for the initial float which would have the greatest benefit from non-binary operation in an actual system. The non-binary process observed allows the initial float to be set at a lower level than indicated by the model and treat a much larger portion of the rising and falling limb without over dosing. This was simulated by assuming flow through the valve would increase as a linear function of height for the first float (Figure 17).

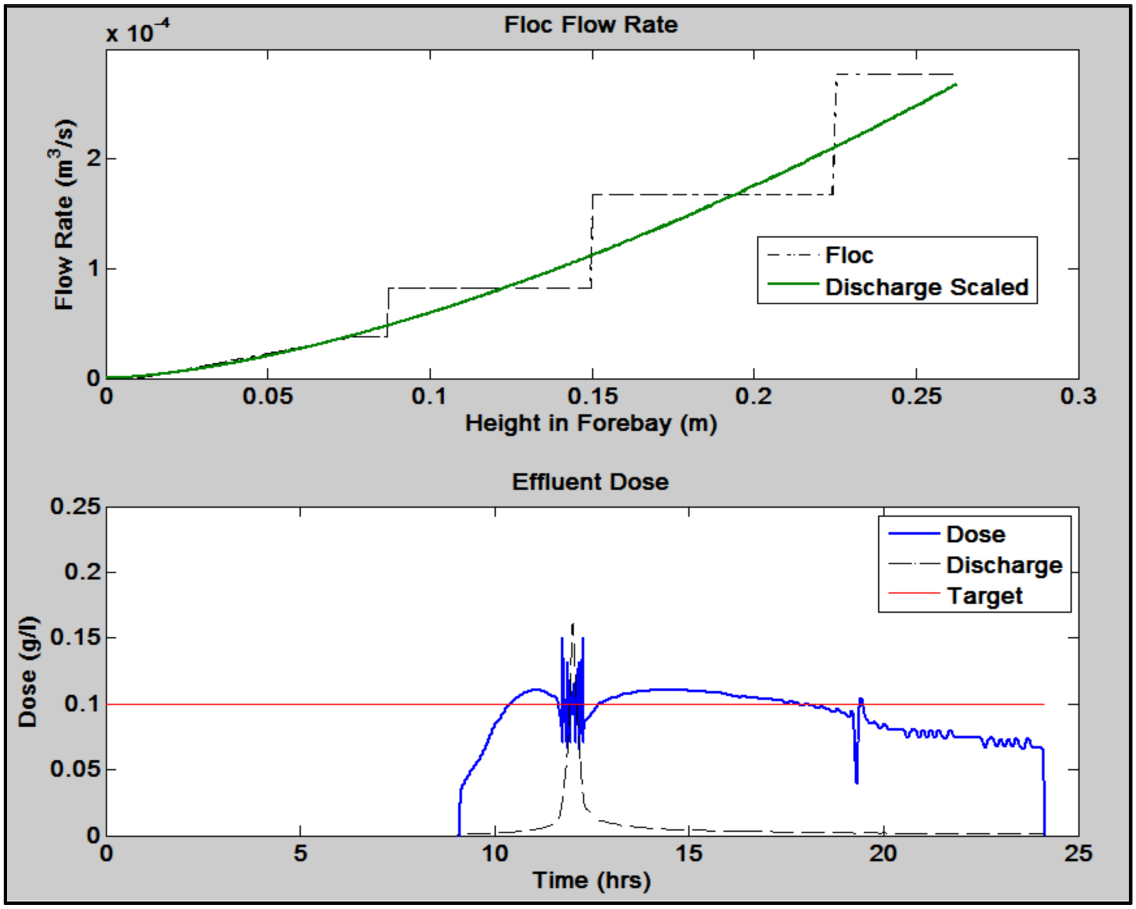


Figure 19. Effect of non-binary operation for initial float vale on dosing concentration. The top chart has floc, the flocculant flow rate discharged into the runoff, and discharge scaled, the discharge through the flume scaled so it can be viewed with floc, vs. stage height in the forebay. The bottom graph has dose, flocculant concentration in the effluent, target, target flocculant dose in the effluent, and discharge, scaled discharge through the flume plotted against time. [hrs: hours; m3/s; cubic meters per second; g/l: grams per liter: m: meters; Floc: Flocculant]

The operation of the float valve in reality is nonlinear but since the relationship of change in height of the forebay versus change in angle of the valve can be easily controlled, a linear function has been applied for simplicity.

The Float based system it is not directly impacted by changes in the watershed since it is runoff actuated (Figure 20 and Figure 21).

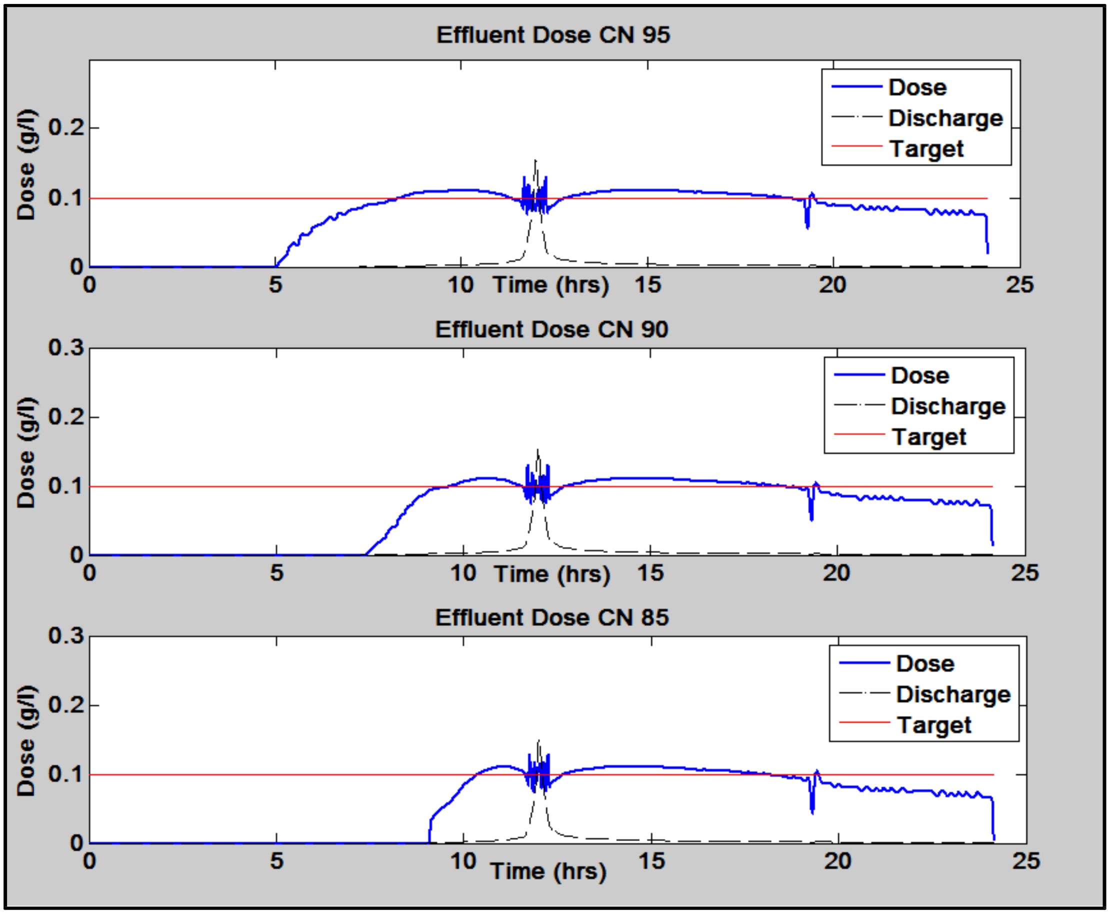


Figure 20. Effect of CN on dosing concentrations on 1 acre (4047 m^2) watershed. The top, middle, and bottom chart plots the simulated performance of the flume system on a site with a CN of 95, 90, and 85, respectively. The dose, flocculant concentration in the effluent, target, target flocculant dose in the effluent, and discharge, scaled discharge through the flume are plotted against time. [hrs: hours; g/l: grams per liter; CN: Curve Number]

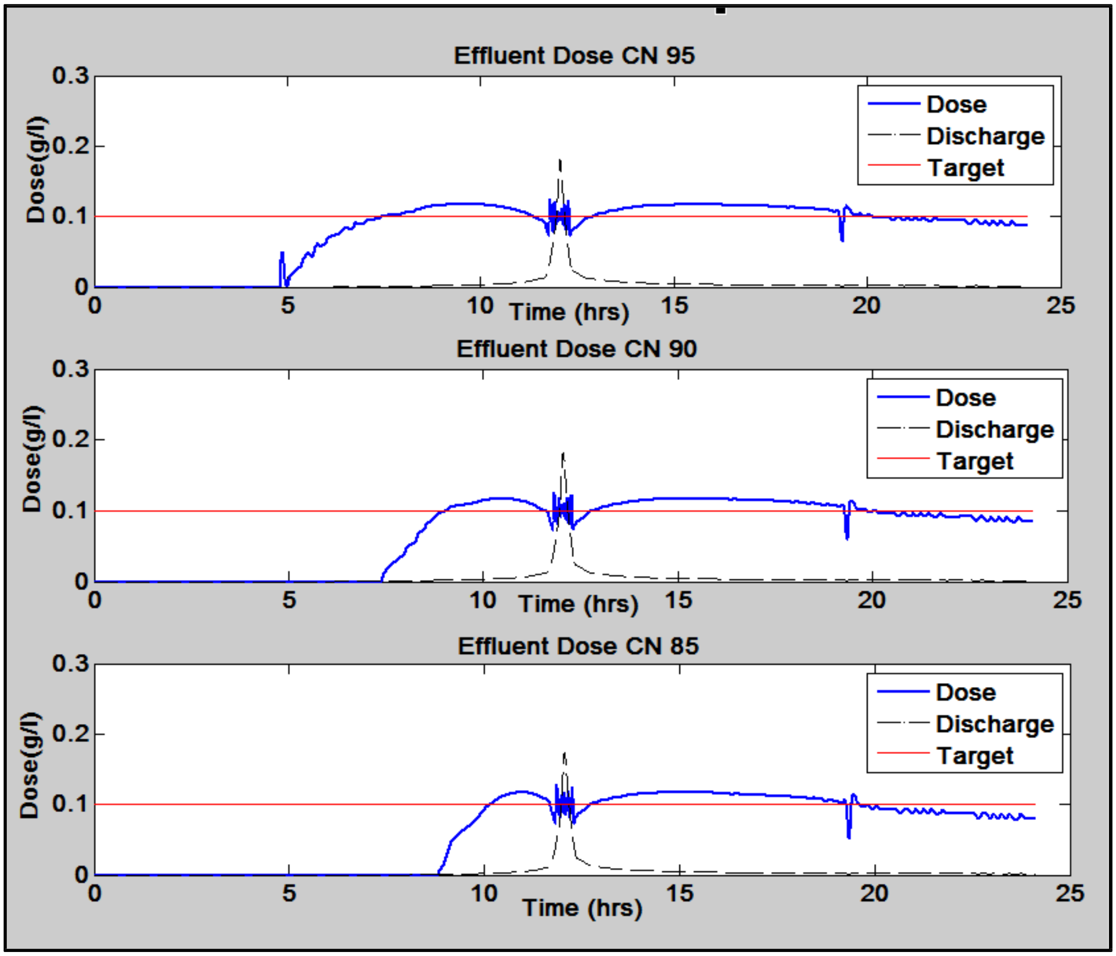


Figure 21. Effect of CN on dosing concentrations on 3 acre (12141 m^2) watershed. The top, middle, and bottom chart plots the simulated performance of the flume system on a site with a CN of 95, 90, and 85, respectively. The dose, flocculant concentration in the effluent, target, target flocculant dose in the effluent, and discharge, scaled discharge through the flume are plotted against time. [hrs: hours; g/l: grams per liter; CN: Curve Number]

The dosing concentration for every flow rate through the system is unique because a certain stage only actuates a certain number of float systems as seen in top figure of Figure 19. The only change in dosing profiles throughout the storm is associated with the magnitude of discharge with respect to time. Accordingly, a change in the timing of runoff or the TC does not impact dosing concentration and would only act to shift the dosing profile with respect to the x-axis.

The WV with respect to the target dose were calculated for the two systems on each watershed (Table 1 and Table 2).

Table 1. Weighted Variance of the predicted concentration for each simulation for the New Zealand System from the target dose. [CN: Curve Number; TC: Time of Concentration]

Watershed	CN:90 TC:+0	CN:85 TC:+2/4	CN:85 TC:-2/4	CN:95 TC:+2/4	CN:95 TC:-2/4
1 Acre	0.3	2.2	3.4	0.3	0.5
3 Acre	0.3	2.2	5.7	0.4	0.8

Table 2. Weighted Variance of the predicted concentration for each simulation for the New Float System from the target dose. [CN: Curve Number]

Watershed	CN 95	CN 90	CN 85
1 Acre	0.3	0.3	0.3
3 Acre	0.4	0.3	0.3

It is considered that both systems can be adequately designed to passively maintain chemical dosing concentrations in runoff, however, the WV for the New Zealand System when CN is less than the designed CN is and order of magnitude higher than the rest of the simulations.

Although this computer simulation demonstrated only one potential realization of a storm event, it was concluded that the Float Dosing System is more applicable to a construction site environment. The resulting dose in the effluent is known for the Float System since it has a unique dose for each stage in the flume. However, since the Float System is not capable of monitoring sediment concentrations in the runoff, it must rely on flow as an indicator of maximum potential sediment concentration. The target flocculant concentration for the simulation was assumed to be constant throughout the runoff event. If a lower concentration was desired at lower flow rates, the Float System could adjust for this by changing the maximum flocculant flow rate through each of the four float operated valve systems to a desired rate. The New Zealand System must use rainfall as an indication of runoff so dose in the effluent is unknown, however, an expected dose may be found by modeling runoff. The New Zealand System must also use modeled runoff rates as an indication of maximum potential sediment load in the flow.

Additionally, the need for accurate hydrologic modeling on a site specific basis adds complexity to the use of the New Zealand System and requires separate systems for each site.

In summary, the simulated performance of the New Zealand System (and information in Auckland Regional Council, 2004) has demonstrated its applicability, but due to the dynamic nature of construction site environments a runoff based system is more desirable. To demonstrate proof of concept for project sponsors of the flume system a laboratory-scale apparatus was developed using a v-notch weir (Figure 22).


Demonstration Apparatus

Water begins to collect behind flow control structure

Flocculant injection occurs at designed height

Figure 22. Laboratory prototype of the float dosing apparatus using a v-notch weir and a two float system.

Subsequent work after full-scale prototype construction and the field testing discussed later in the document resulted in replacing the lever and float valves with discs and ball valves. Ball valves are not intended for flow throttling, however, empirical data is available from manufacturers to estimate flow based on angle of the valve. By specifying the radius of a disc which rotates the valve, flow through the valve can be simulated with respect to height in the flume (Figure 23).

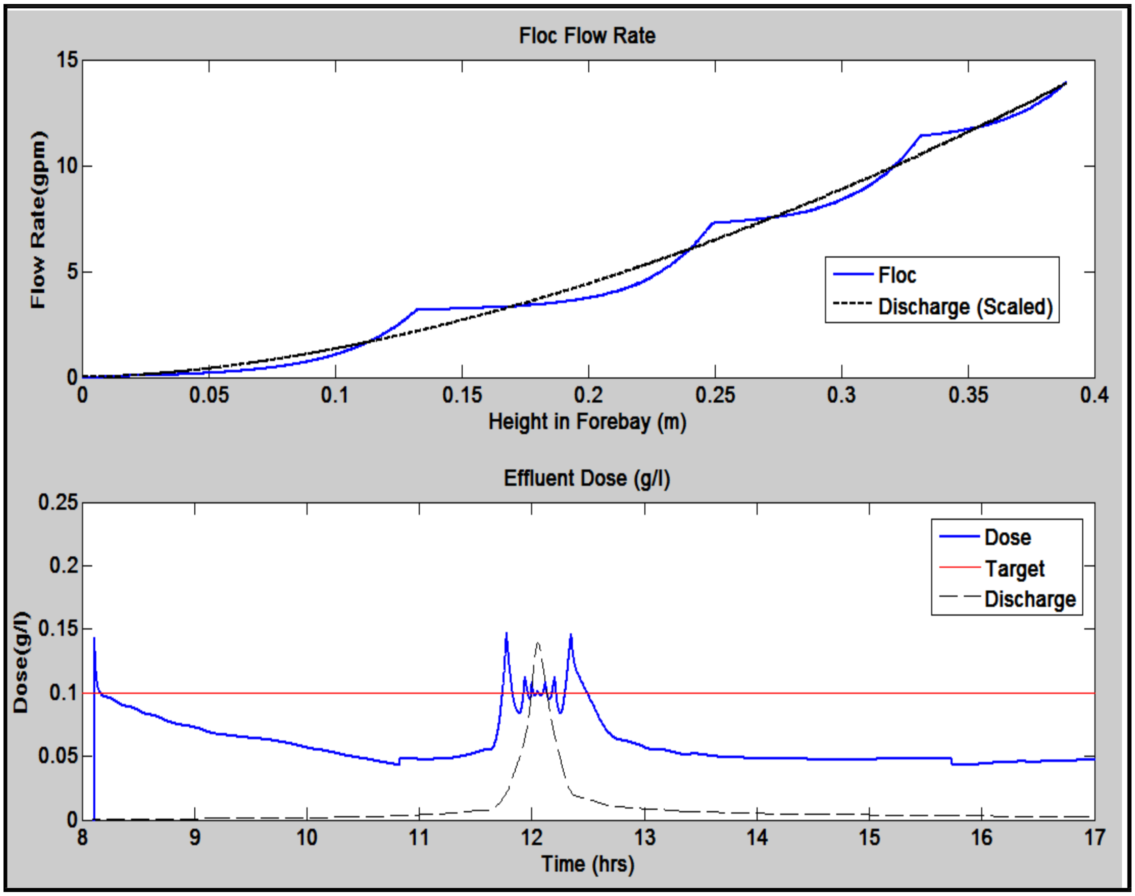


Figure 23. Stage discharge for ball valves. The top chart has floc, the flocculant flow rate discharged into the runoff, and discharge scaled, the discharge through the flume scaled so it can be viewed with floc, vs. stage height in the forebay. The bottom graph has dose, flocculant concentration in the effluent, target, target flocculant dose in the effluent, and discharge, scaled discharge through the flume plotted against time. [m: meters; hrs: hours; gpm: gallons per minute; g/l: grams per liter; Floc: Flocculant]

5.2 Initial Prototype Design

The overall system design included a settling forebay with trash removal, a flow actuated dosing mechanism, a turbulent flow mixing system, and a settling basin. The flocculant injection apparatus utilized a flume and float system to dynamically dose optimum flocculant concentrations based on flow rates. The mixing system was comprised of in-stream static mixers similar to static mixers non –clogging static mixers designed for wastewater treatment.

The principle of operation is a relationship between forebay stage and discharge through a flow control structure (flume) which permits the activation of a series of float valves (Label 1 in Figure 24) positioned at predetermined stages to maintain flocculant concentrations in a desired range. Flocculant flows under gravity from the housing (Label 5 in Figure 24) through the float valve dosing system. The apparatus may use pipes, weirs, flumes, etc. as flow control structures and a variety of valves as the dose actuating mechanism. The developed prototype uses a metal cutthroat flume (Label 2 in Figure 24) as the flow control structure due to its ability to discharge a wide range of flows and its tolerate to high backwater conditions without impacting the stage-discharge relationship. The purpose of the mixing structure (Label 3 in Figure 24 and 25) is to generate turbulent flow conditions following flocculant injection in order to enhance interaction between flocculant molecules and suspended particles. Proper mixing is critical to facilitate efficient flocculation and, therefore, is an integral part of the system.

Fixed structures have been designed and employed in the wastewater industry to induce highly efficient mixing conditions in pipe systems. These structures provided the basis for the open channel mixing system that was designed and constructed in the prototype. One challenge was to producing sufficient turbulence under a wide range of flow conditions which is one reason the developed structures are similar in shape with varying sized blades. The idea of placing the smallest structure first is to change of the direction of local flow in more locations across the channel to dissipate heterogeneity in flocculant concentrations resulting from discrete dosing points. Additionally, a flow control structure in the sedimentation basin downstream of the injection and mixing apparatus provided stage control within the mixing system and the development of a hydraulic jump (Label 4 in Figure 25) at the entrance to the mixing system. A hydraulic jump is a highly turbulent flow phenomenon which also contributes to mixing within the designed system.

The flume used in the prototype apparatus included two stilling wells, one on each side, which houses the floats that actuate the float valves. The holes on either side of the mouth of the flume allowed water to flow in and out of the stilling wells (Label 1 in Figure 25). As water levels in the mouth of the flume and stilling wells increased, the floats rose and opened the float valves (Label 2 in Figure 26). By positioning the floats at staggered heights with reference to the flume bottom, an automated, passive dosing mechanism actuated by flow was achieved.

The prototype plumbing system was designed to convey liquid flocculant to the float valves and then to the diffuser (Label 3 in Figure 26), which distributed flocculant across the width of the channel. The gate valves (Label 4 in Figure 26) incorporated into the plumbing provided a simple and easy means of calibration for flocculant flow rates which allow for variable dosing rates.

The described prototype was therefore able to satisfy the previously stated objectives and is unique to the author's knowledge in the following ways:

1. Flow control structure uses a stage-discharge relationship with prepositioned float valves that allow passive, standalone flocculant dosing to actuate and terminate at designed discharges.
2. Employs gate valves in a passive flocculant dosing apparatus to control maximum flocculant flow rates during operation.
3. Uses open channel mixing structures developed based on existing inline static mixers for pipes.
4. Uses a backwater control structure to induce a hydraulic jump at a desired location to facilitate flocculant mixing.

Figure 24. Prototype turbidity reduction system. (1) float valves for flocculant dosing, (2) metal cutthroat flume for flow measurement, (3) mixing structure, (4) hydraulic jump upstream of the mixing structure, and (5) flocculant tank.

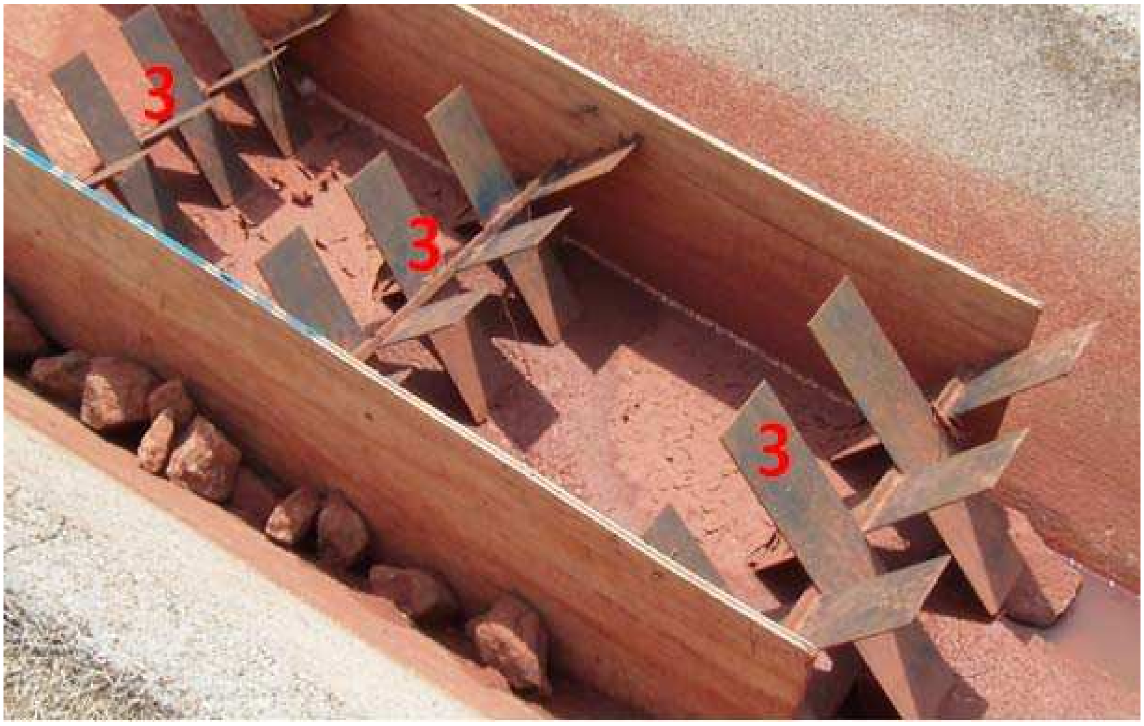


Figure 25. Mixing structures (3) for the Float Dosing system.

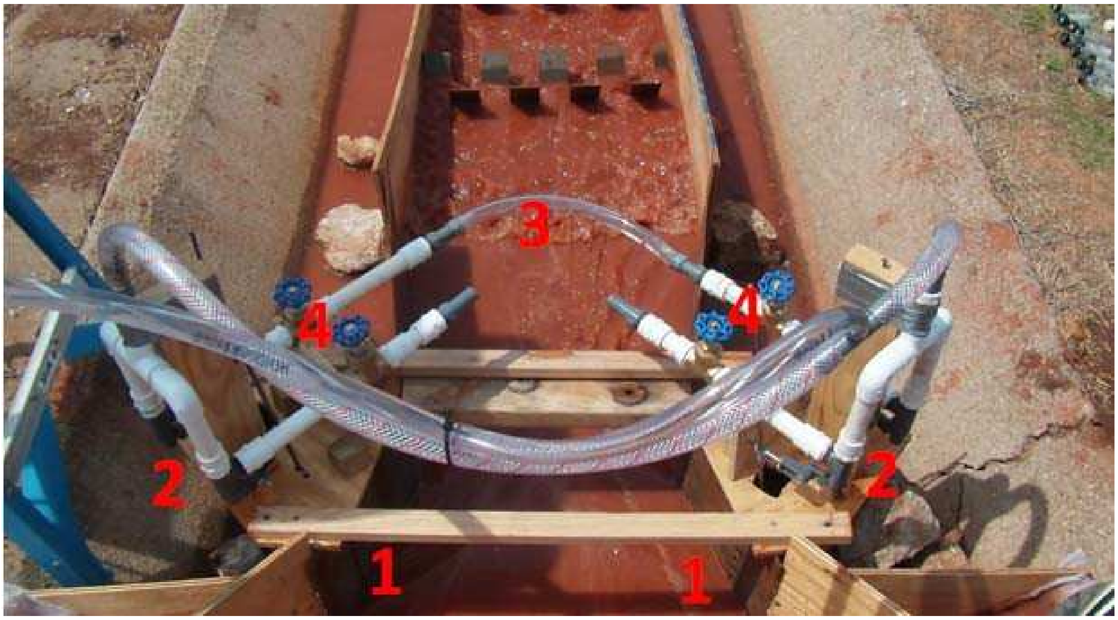


Figure 26. Plumbing system for the Float Dosing turbidity reduction system. (1) stilling wells on either side of the cutthroat flume, (2) float valves, diffuser system for even flocculant injection, and gate valves for calibration of flocculant dosing rates.

The described prototype as built had several drawbacks concerning its practical implementation. Most notably, the plastic float valves leaked a considerable amount in relation to flow through the valve while they were open. The valves used were lower quality (<$10) but based on the design of this type of valve; most are prone to some leaking. Additionally, these valves use a lever attached to a pivot point so the connection between the float and the end of the lever moves in an arc where the floats tend to move vertically. This incongruity makes it difficult to place guides for the float rods and requires a jointed connection between the floats and levers. An alternative valve actuating system was developed to circumvent these issues.

The alternative system uses a quarter turn ball valve to actuate and terminate flow. Movement of the valve is controlled by a disc with a counterweight system and float. As the stilling well fills the float rises (releasing tension on one side of the disc) and the counterweight rotates the disc which opens the valve. The drawback of this alternative is force the needed to overcome friction associated with ball valves. The benefits include a use of a widely available, inexpensive, completely sealed, valve and more congruent movement of components.

Additionally, this alternative could use a butterfly valve to control flocculant flow rate and a cam instead of circular disc. By combining the movement of a float with a cam connected to a butterfly valve the discharge of flocculant can be matched to the stage discharge relationship of the flume which eliminates the need for multiple floats. An implicit procedure has been developed to numerically dimension a cam that include the effect of a loss coefficient and flow coefficient as a function of valve angle.

An appeal to four separate valves is the maximum flow rate through each system is limited based on a gate valve at the terminal end of each plumbing component. If a different flocculant with a different viscosity is used the maximum flow rate can easily be calibrated by opening or closing the gate valve after each ball valve. If viscosity impacts the flow rate vs. angle of valve, the maximum flow rate will still be achieved at the same point for each valve. Deviations from pressure drop based on viscosity will have greater impacts as the valve opens but not when the valve is completely open. If a single cam is used a different shaped cam may or may not be needed for changes in viscosity.

Maintenance for the proposed overall system design described in the previous section includes assessing sediment accumulation, ensuring piping and flow paths are free of debris, and maintaining appropriate levels of flocculant in the flocculant housing. As sediment and flocs accumulate in the forebay and settling basin, storage volume will decrease which will reduce system performance. Given a detailed site description, a minimum storage volume can be established which will dictate when sediment in the forebay and settling basin must be removed if necessary. Accumulated sediment in the forebay and settling basin will be mostly sand and flocculated particles, respectively, and may have the potential to be safely returned to the landscape at the construction site or buried in place. The system's piping and flow paths will require periodic inspection and the potential for the flocculant to freeze is yet to be determined. A runoff ditch can be visually inspected along with piping inspection if pipe materials are transparent (acrylic or clear hose, for example). Maintaining flocculant levels will consist of a routine assessment and subsequent inspection after rain events. Flocculant that has remained in the flocculant tank longer than its expected effective shelf life may be spread on the sediment at the construction site for erosion control depending on the type of flocculant.

5.3 Jar Testing Results

Jar test results show turbidity reductions up to 97 percent for the soils used in the study. It was concluded that the optimum range of concentration of flocculant for the soils tested was 0.75 to 0.1 (g/l). More detailed results are presented in Appendix II.

5.4 Prototype Field Testing Results

Average turbidity data for the tests by station are given in Table 4 and Figure 27 and 28 plot collected turbidity for each test by station. The addition of flocculant decreased the turbidity significantly, with an average turbidity of 400 NTU at the end of the channel for the experimental conditions. In addition, flow rate did not appear to affect the turbidity levels.

For all tests, the average turbidity reduction with flocculant addition had a 95 % confidence interval of 83% to 85% at the end of the channel while turbidity reduction for the controls had a 95% confidence interval of 16% to 25% for the experimental conditions (Figures 27, 28 and 29). There was a malfunction at Station 3 during the flocculant addition tests, so no data were collected from that station.

Table 4. Average turbidity by station number for all field tests. [NTU: Nephelometric Turbidity Unit; g/l: grams per liter; cfs: cubic feet per second]

Flocculant Concentration(g/l)	Experimental Flow Rate (cfs)	Average Turbidity (NTU)					Standard Deviation (NTU)
		Station Number					Station Number
		1	2	3	4	5	1
0	0.75	1960	1910	1850	1820	1780	262
	1.5	1720	1460	1400	1410	1330	383
	2.25	2420	2070	1910	1950	1990	342
0.08	0.75	2780	649		520	410	500
	1.5	2730	624		498	391	333
	2.25	2770	1440		524	399	576

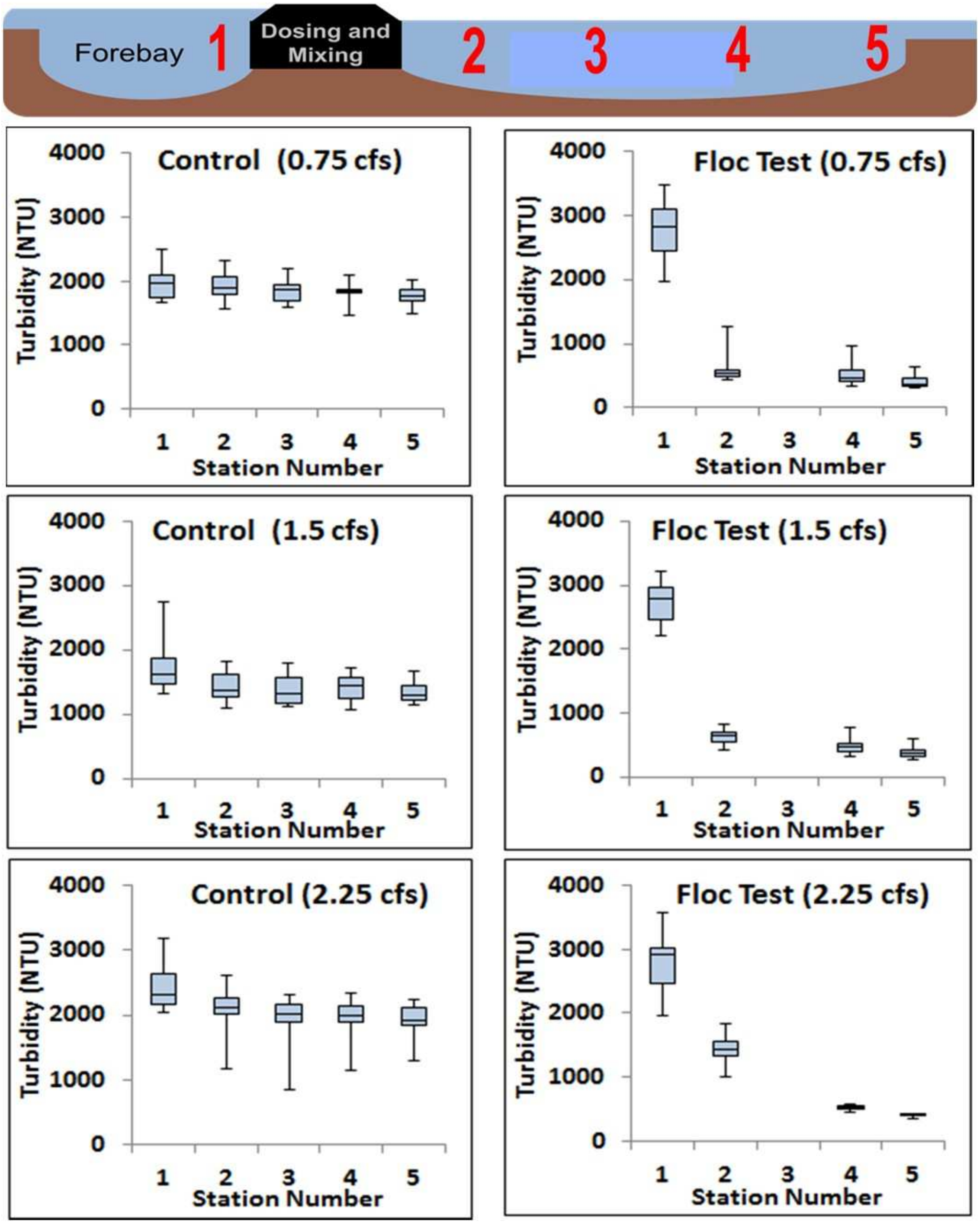


Figure 27. Box plots of turbidity by station for each test. The lowest bar for each box represents the 0th percentile or lowest value and the highest bar for each box represents the 100th percentile or highest value. The lower portion of each box represents the 25th to 50th percentile of the data and the upper portion of each box represents the 50th to 75th percentile of the data. The middle bar through each box is the median or 50th percentile. [NTU: Nephelometric Turbidity Unit; cfs: cubic feet per second; Floc: Flocculant]

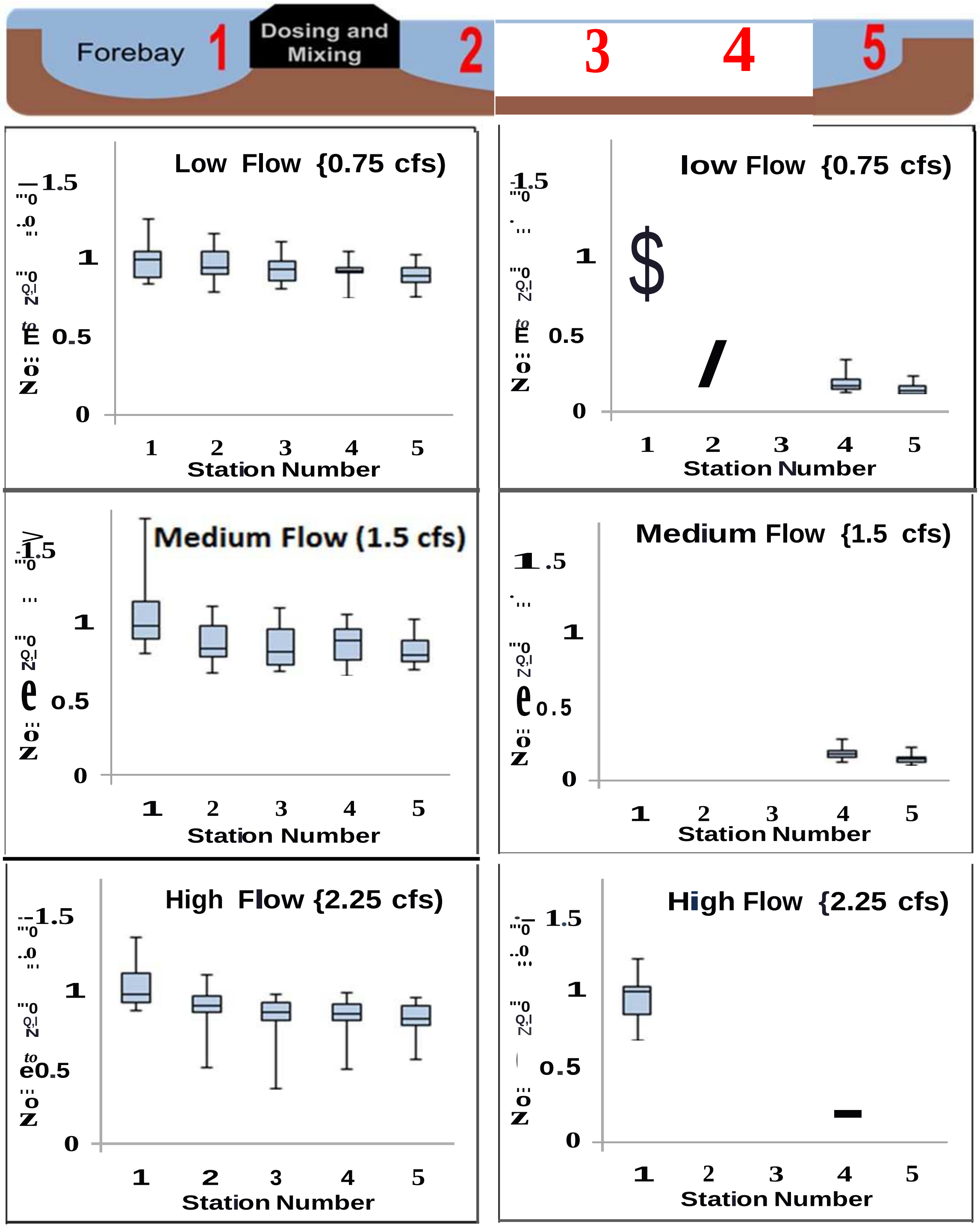


Figure 28. Box plots of normalized turbidity by station for each test. The lowest bar for each box represents the oth percentile or lowest value and the highest bar for each box represents the lOOth percentile or highest value. The lower portion of each box represents the 25th to 50thpercentile of the data and the upper portion of each box represents the 50th to 75th percentile of the data. The middle bar through each box is the median or 50th percentile. [cfs: cubic feet per second]

Different flow rates caused different sampling times after flocculant dosing for each station. Therefore, the influence of time on turbidity reduction may provide further insight to the effect of experimental factors. Mean turbidity reduction with and without flocculant dosing seemed to fall onto one line with the exception of the low flow control experiment (Figure 29).

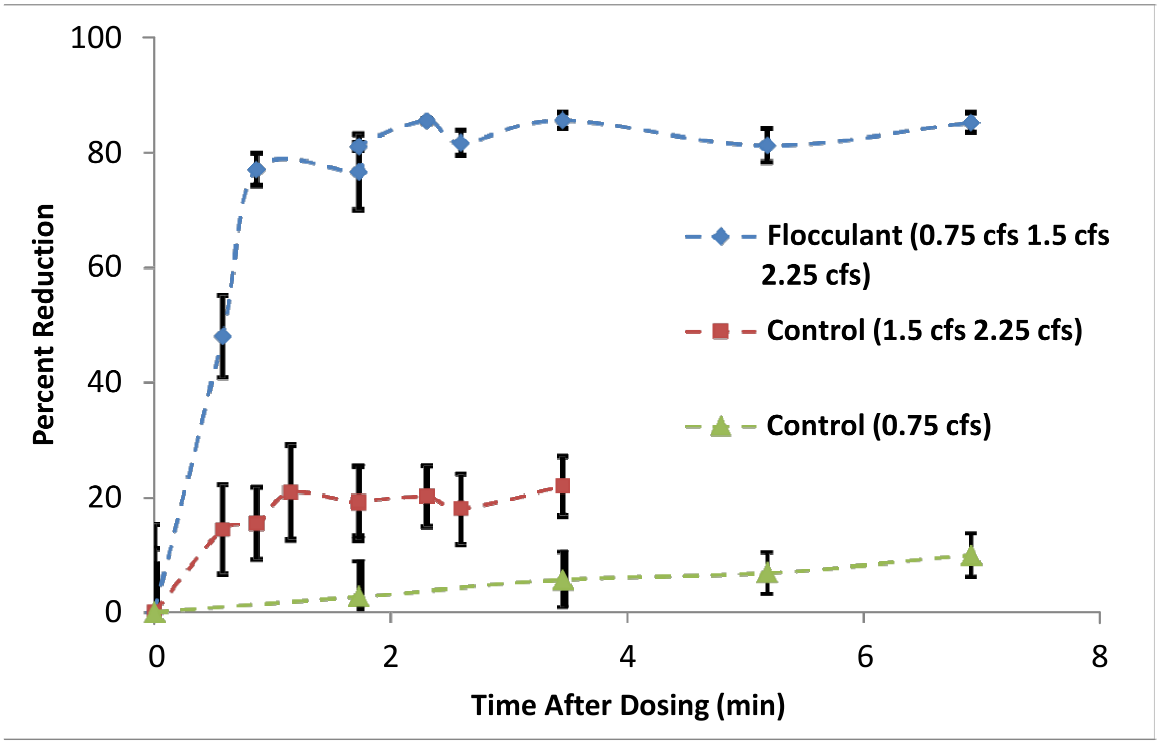


Figure 29. Mean turbidity reduction with 95% confidence intervals versus time after flocculant dosing for field testing data. Flow rates in parenthesis on legend indicated which experimental data was included in which series. [cfs: cubic feet per second]

This is suspected to be a result of the unfilled forebay during the low flow control run which trapped coarser particles before the initial turbidity sample leaving only finer particles in suspension. In the experiment, average turbidity reduction with flocculant addition had a 95 % confidence interval of 83% to 85% at the end of the channel and reduction did not significantly increase in sampling times after 1.7 minutes for an alpha of 0.05. Turbidity reduction for the control runs in the experiment had a 95% confidence interval of 16% to 25% and reduction did not significantly increase in sample times after 0.5 minutes.

A General Linear Model (GLM) was used to investigate the effect of experimental factors on the response variable. The response variable in the system was either the measured turbidity (NTU) or the measured turbidity normalized by the average inflow turbidity at Station 1 for each run and the experimental factors are described in Table 5.

Table 5. Experimental factors for GLM. [cfs: cubic feet per second; min: minute; NTU: Nephelometric Turbidity Unit]

Factor	Type	Description
Factor	Factor	Control or Flocculant Dosed
Q	Factor Level	Flow Rate (cfs)
Time	Covariate	Time of sample after passing through the Flume (min)
Average1	Covariate	Average inflow turbidity for that experiment (NTU)

Initial test results from the GLM performed in Minitab 15 with all variables and interactions considered on turbidity (NTU) and normalized turbidity are in Appendix IV. Tests found the effect of flow rate, Q, on the system insignificant. The GLM found average inflow turbidity at Station 1 significant when the response variable is turbidity (NTU) only. This indicates the percent decrease in turbidity was not affected by inflow turbidity in our experiments. If inflow turbidity had been significant it may have indicated higher flocculant dosages are required to flocculate the higher suspended sediment load. All insignificant factors and their interaction terms were removed from the model which left the significant effects of Factor, Time, and the first order interaction of Factor and Time which were able to account for 82% of the variance observed in the data. The significant interaction term indicates effect of time on normalized turbidity values are influenced by the Factor.

A One-Way ANOVA and a Tukey Comparison with a family error rate found significant differences with up to 75% increased reduction when flocculant is added for all pairs except the initial sample (Figure 30). The three left most points that correspond to a jump in difference in mean reduction resulting from the extend times of the low flow runs where the control low flow was ran without sediment accumulation in the forebay.

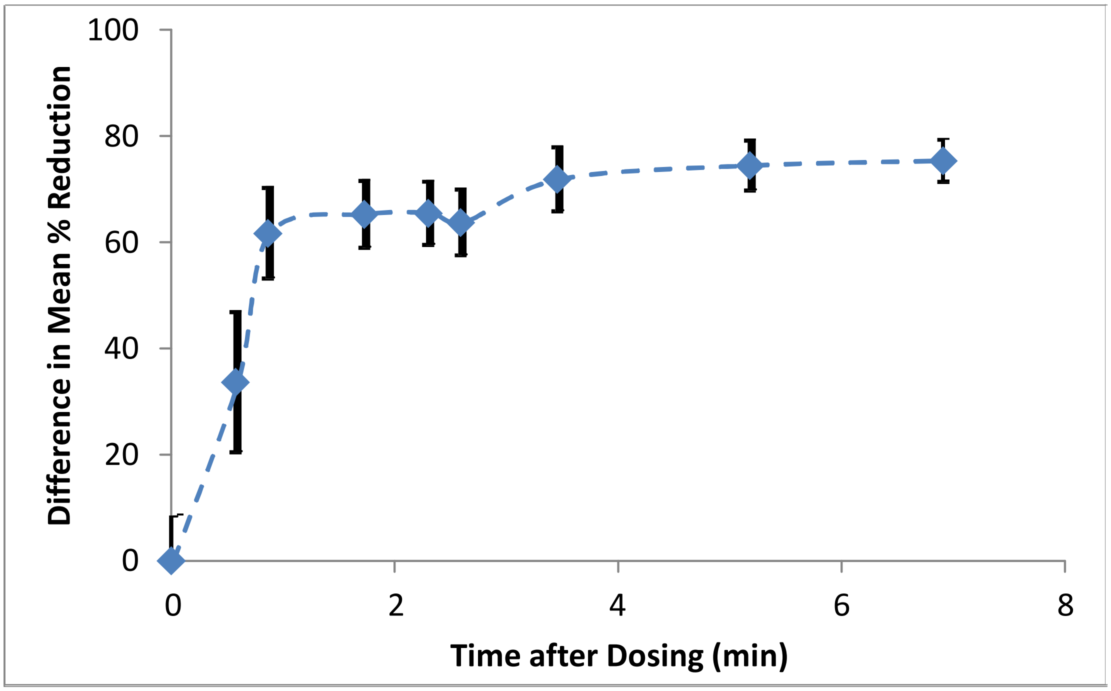


Figure 30. Differences between mean percent turbidity reduction at each sampling time between the control and flocculant tests.[min: minutes; %: percent; Flocc.: Flocculant]

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

A novel runoff actuated float dosing system was designed, its performance during a synthetic storm event on idealized catchments was simulated, and a prototype was demonstrated to operate as intended during field scale tests. The design of the system includes a forebay, a passive, flow-based dosing system, a turbulent mixing system to facilitate floc development, and a settling basin. Modeling simulations showed it was capable of maintaining flocculant dosing concentrations in predetermined ranges and had a unique relationship between stage in a flow control structure and flocculant dosing concentration. Field scale tests demonstrated the prototype dosing system operated as intended and the flocculant dosed by the system was able to reduce inflow turbidity from an overall average of 2760 NTU to 400 NTU (85% reduction) for all tests in the channel.

6.2 Future Work

The alternative system with circular discs that actuate ball valves is currently being fabricated for a 3 acre site and will be implemented on a construction site for field testing and monitoring. Additionally, a cam has been designed through a numerical procedure to actuate a butterfly valve for use with the 1 acre prototype system. This cam will allow the four floats to be replaced by one float.

Before final field testing it is recommended information on floc stability, including the effect of solution concentration, be conducted. Accordingly, it is also recommended to investigate flocculant viscosity as function of concentration, temperature, and time after dilution as it affects flow through the system (ball valve and butterfly valves), and its ability to homogenously mix into the effluent. The mixing system used during prototype testing proved effective; however, it is not expected the mixing system could convey more than 2.5 cfs (0.071 cms) which is less than the flume is designed to convey. There is also the possibility to optimize this component of the system. Variables that affect turbidity reduction or removal efficiency are mixing intensity as controlled by flow through the system, static mixer design, slope of rectangular channel that houses static mixers, and length of mixing controlled by spacing and number of static mixers.

Further work on the mixing system should include characterization of shear rates and turbulence for the different sizes at different flow rates. It is anticipated that the larger diameter structures produce more turbulence and higher shear rate since Reynolds Number and shear rate for tank stirrers are proportional to a characteristic length (width of static mixer blades) (Spicer and Pratsinis 1996). Shear rate equations form tank stirrers do not directly apply to static mixers and the shear rate for static mixers is proportional to the pressure drop (which will be a function of slop and flow rate) across the element which can be used to compare differences in blade shape and size, at least qualitatively (Komax Systems, Inc.).

REFERENCES

Auckland Regional Council. 2004. The Use of Flocculants and Coagulants to Aid the Settlement of Suspended Sediment in Earthworks Runoff: Trials, Methodology and Design [draft], June 2004 Technical Publication 227, Auckland Regional Council, ISSN 1175-205X ISBN 1-877353-31-0.

Auvray, Franck, Eric D. Van Hullebusch, Veronique Deluchat, Veronique, Michel Baudu. 2006. Laboratory investigation of the phosphorus removal (SRP and TP) from eutrophic lake water treated with aluminum. *Water Research* 40(14):2713-2719.

Bhardwaj, A. K., R. A. Mclaughin. 2008. Simple Polyacrylamide Dosing Systems for Turbidity Reduction in Stilling Basins. Transactions of the ASABE. 51(5):1653-1662.

Chakraborti, Rajat K., Joseph F. Atkinson, John E. Van Benschoten. 2000. Characterization of Alum Floc by Image Analysis. *Environ. Sci. Technol*. 34(18): 3969–3976.

Chemineer Inc. Kenics KM Static Mixers. North Andover, Ma: Chemineer Inc.. Available at: www.chemineer.com/kenics_km_static_mixers.php. Accessed on 27 October 2010 .

Chunjuan, Dong, Liu Xiao, Lv Bingnan, Chen Suyun. 2009. Chemical Enhanced Phosphorus Removal from the Effluent of Micro-Aerobic EGSB System. Bioinformatics and Biomedical Engineering. In *Proc. ICBBE 2009 3rd International Conference*.

Daniel, T. C., P. E. Mc Guire, D Stoffel, and B. Miller. 1978. Sediment and Nutrient Yield from Residential Construction. *Journal of Environmental Quality* 8(3):304-308.

Davies-Colley, R. j. and D. G. Smith. 2001. Turbidity, Suspended, Sediment, and Water Clarity: A review. 2001. *JAWRA* 37(5): 1085-101.

Droppo, I.G., K. Exall, K. Stafford. 2008. Effect of chemical amendments on aquatic floc structure, settling and strength. *Water Research* 42:169-179.

Fort, Douglas J., Enos L. Stover. 1995. Impact of Toxicities and Potential Interactions of Flocculants and Coagulant Aids on Whole Effluent Toxicity Testing. *Water Environment Research* 67(6):921-925.

Georgantas, D. A., H.P. Grigoropoulou. 2007. Orthophosphate and metaphosphate ion removal from aqueous solution using alum and aluminum hydroxide. *Journal of Colloid and Interface Science* 315(1):70–79.

Gorczyca, B., J. Ganczarczyk. 1996. Image Analysis of Alum Coagulated Mineral Suspensions. *Environmental Technology* 17(12):1361–1369.

Haan, C. T., B. J. Barfield, J. C. Hayes. 1994. *Design Hydrology and Sedimentology for Small Catchments*. Oxford, UK: Academic Press of Elsevier Science.

Jarvis, P. B. Jeffeson, J. Gregory, S.A. Parsons. 2005. A review of floc strength and breakage. *Water Research* 39: 3121-3137.

Kang, Joo-Hyon, Yingxia Li, Sim-Lin Lau, Masoud Kayhanian, Michael K. Stenstrom. 2007. Particle Destabilization in Highway Runoff to Optimize Pollutant Removal. *Journal of Environmental Engineering* 133(4) 426-434.

Komax Systems Inc. Reynolds Number. Huntington Beach, Ca.. Available at http://www.komax.com/det-reynolds.html . Accessed on 5 November 2011.

Lawler, Damian M., and Robert M. Brown. 1992. A simple and inexpensive turbidity meter for the estimation of suspended sediment concentrations. Hydrological Processes 6(2): 159-168.

Line, D. E., and N. M. White. 2001. Efficiencies of Sediment Traps on Two North Carolina Construction Sites. *Transactions of the ASABE* 44 (5): 1207-1215.

McCaleb, M. M. and Richard A. McLaughlin. 2008. Sediment Trapping Efficiency by Five Different Sedimentation Devices on Construction Sites. *Transactions of the ASABE* 51 (5): 1613-1621.

McLaughlin, Richard A., Andrew Bartholomew. 2007. Soil Factors Influencing Suspended Sediment Flocculation by Polyacrylamide. *Soil Science Society of America Journal* 71 (2): 537-544.

Mpofu, P., J. Addai-Mensah, J. Ralston. 2004. Flocculation and dewatering behavior of smectite dispersions: effect of polymer structure type. *Minerals Engineering* 17: 411-423.

Owen, A.T., P.D. Fawell, J.D. Swift, D.M. Labbett, F.A. Benn, J.B. Farrow. 2008. Using turbulent pipe flow to study the factors affecting polymer-bridging flocculation of mineral systems. *International Journal of Mineral Processing* 87: 90-99.

Protech General Contracting Services Inc. 2004. Polymer Coagulants and Flocculants for Stormwater Applications. Technical Report no. 01.1. Dixon, Ca. Available at: www.protechgcs.com/Library/TR01.1-electronic.pdf. Oct 2010.

Rasteiro M.G., F. A. P. Garcia, P. J. Ferreira, E. Antunes, D. Hunkeler, C. Wandrey. 2010. Flocculation by Cationic Polyelectrolytes: Relating Efficiency with Polyelectrolyte Characteristics. *Journal of Applied Polymer Science* 116:3603–3612.

Riley, S. J.. 1997. The sediment concentration–turbidity relation: its value in monitoring at Ranger Uranium Mine, Northern Territory, Australia. *Catena* 32(1):1-14.

Rodriguez, I.R., C. Amrhein, M.A. Anderson. 2008. Reducing dissolved phosphorous loading to the Salton Sea with aluminum sulfate. *Hydrobiologia* 604: 37-44.

Sekine, M., A. Takeshita, N. Oda, M. Ukita, T. Imai, T. Higuchi. 2006. On-site treatment of turbid river water using chitosan, a natural organic polymer coagulant. *Water Science and Technology* 53(2): 155-181.

Spicer, Patrick T., Sotiris E. Pratsinis. 1996. Shear-Induced Flocculation: The Evolution of Floc Structure and the Shape of the Size Distribution at Steady State. *Water Research* 30(5): 1049-1056.

Streiff, F.A., J. A. Rogers. 1994. Don't overlook static-mixer reactors. *Chemical Engineering* 101: 74-82.

Szabo, A., I Takacs, S. Murthy, G.T. Daigger, I. Licsko, S. Smith. 2008. Significance of Design and Operational Variables in Chemical Phosphorous Removal. *Water Environment Research* 80(5): 407-416.

U.S. Environmental Protection Agency. 1993. Guidance specifying management measures for sources of nonpoint pollution in coastal waters. USEPA 840=B-92-002. U.S. Gov. Print. Office, Washington, D.C.

U.S. Environmental Protection Agency. 2004. National Water Quality Inventory: Report to Congress. USEPA 841-R-08-011. U.S. Gov. Print. Office, Washington, D.C.

Wolman, Gordon, Asher Schick. 1967. Effects of construction on fluvial sediment, urban and suburban areas of Maryland. *Water Resources Research* 3(2):451-464.

Wood, J., C. He, Q. Rochfort, J. Marsalek, P. Seto, M. Yang, P. Chessie, S. Kok. 2005. High-rate stormwater clarification with polymeric flocculant addition. *Water Science and Technology* 51(2):79-88.

APPPENDICES

APENDIX I

All data computed from Sedimot IV used the following parameters.

Table 1. Input site data used to generate rainfall/runoff values for the different catchments used in the modeling simulation.

Parameter	**Value**
Peak Rate Factor	350
NRCS Parameter	20.3
Tendency To Rill	2
Rills Per Unit Area	3
Practice Factor	0.95
Erodibility	0.1
Percent Clay	12.5
Percent Silt	21.5
Percent Sand	12.6
Rainfall	4.2 inches / 24 hour
Season	Growing
AMC	Average
Slope	1%
1 Acre Slope Length	250 ft
3 Acre Slope length	450 ft

Curve Numbers values for runs were 85, 90, and 95 and computed on a one and three acre rectangular site.

APPPENDIX II

Jar Testing Description and Summarized Data

Author: Aaron Mittelstet

There are many flocculants commercially available, yet they all produce different results based on the type of soil utilized. To test several flocculants at a field scale would be very time consuming and expensive. Jar tests permit the testing of multiple flocculants, a variety of soils, and other factors, such as mixing speeds and sediment concentrations, in a rapid, controlled environment. The objectives of this research was to identify the best flocculant to utilize for construction sites in Greenville County, South Carolina and to test that flocculant on three different soil types (Cecil, Hiwassee, and Pacolet) at various mixing speeds and sediment concentrations.

All tests were performed using Phipps & Bird square two-liter jars (B-KER[2]) with mixing speed capabilities ranging from 5 to 300 revolutions per minute (rpm) and stirring times ranging from 1 second to 60 minutes. The initial jar tests were performed with a Cecil soil from Greenville County, South Carolina to test various flocculants and efficiency in sediment removal. Five flocculants (SuperFloc 705[1], Hydrofloc 445L[2], FloPam[3] SH and VLM, and aluminum sulfate) were tested singly or in combination to determine the best to utilize in larger scale flume and field

---

[1] http://www.acfenvironmental.com/
[2] http://www.aquaben.com/
[3] http://www.snfinc.com

experiments. All of the flocculants were anionic polymers except for aluminum sulfate, a coagulant. Each flocculant was tested at concentrations recommended by the manufacturer.

Most jar test procedures recommend a flash mixing speed at approximately 120 rpm for one minute followed by slower mixing (40 rpm) for 20 minutes (ASTM International, 2008). The flash mixing produces the turbulence necessary to bring the particles in contact with other particles while the slower mixing increases the size of floc. In the larger scale flume experiments, a turbulence level and duration corresponding to a velocity of 90 to 150 rpm for approximately five seconds was expected, and thus the tests were performed at a mixing speed of 90 rpm for five seconds. One of the largest sources of error with jar tests was determining the appropriate settling time. A settling time of four minutes was initially expected in the flume experiments and was therefore utilized in the jar tests.

Each of the initial tests were completed with air dried Cecil soil at 40 g/L. This 40 g/L concentration was based on predicted peak sediment loads from Sedimont IV computer simulations described in Appendix I from a three-acre, two-year, 24-hour storm event for Greenville County, South Carolina. The simulations predicted roughly 30 g/l and 40 g/l was chosen to be conservative. The soil was prepared by using a 10 mesh sieve to remove the larger particles. To represent the settling forebay which removes sand and larger particles, the jars were first mixed for 30 seconds at 120 rpm and allowed to settle for 66 seconds. The settling time calculated corresponded to the time a 0.05 mm diameter sand particle needed to settle the depth of the beakers used based on Stokes Equation.. After 66 seconds of settling, the supernatant liquid was poured into another jar and the remaining soil particles and aggregates were carefully washed into an aluminum container and oven dried at 104 degrees Celsius for at least 12 hours. The dried soil was weighed and used to calculate the concentration of the supernatant. The jar containing the supernatant liquid was then brought back up to 2 L in volume with dechlorinated water. Due to the large sand and aggregate content, on average, 93% of the soil settled out within the 66 seconds leaving only approximately 7% remaining in the supernatant. Therefore, although a 40 g/L concentration was initially utilized, only approximately 2.8 g/L was used in the jar tests.

Once the volume in the jar was increased to two liters, the flocculant was added and mixed for 5 seconds at 90 rpm. After a four-minute settling time, 75 ml was collected using the B-KER^2 sample port located 10 cm from the bottom, 50 ml of which was filtered to determine total suspended solids (TSS) and 25 ml was used to test for total dissolved solids (TDS). Using a standard vacuum filtering apparatus, the 50 ml was filtered and oven dried for one hour at 104 degrees Celsius. Turbidity was measured using a 2100Q Hach turbidity meter. Various concentrations of Hydrofloc 445L were tested to determine the optimal quantity to inject in the large-scale flume experiments. Eight concentrations ranging from 0.0 to 0.15 g/L were tested using a local clayey sand soil from Stillwater, Oklahoma. Comprehensive testing of the Hydrofloc 445L was also conducted on each of the three Greenville County, South Carolina soils (Cecil, Hiwassee, and Pacolet) used in the flume experiment. Jar tests were completed for each soil to test the decrease in TSS and turbidity at various sediment concentrations and mixing speeds. Three concentrations of sediment (2.0, 20, and 40 g/L) were used for each soil at three different mixing speeds (90, 120, 150 rpm). For these experiments, the sand and larger aggregates were removed by wet sieving the soils using 35, 60, and 230 mesh sieves. All tests were completed by injecting 0.05 g/L of Hydrofloc 445L, mixing it for five seconds, and letting it settle for four minutes.

Results and Discussion

Based on the percent removal of silt and clay from suspension, the top flocculant choices were SuperFloc 705, HydroFloc 445L, and FloPam SH (Table 1). Each reduced the quantity of silts and clays in suspension by at least 93%. Other flocculant characteristics, such as viscosity, stability in solution, and ease of mixing, were also considered when assessing the best flocculant to utilize in the flume experiments (Table 2). Since each of the three flocculants was effective in removing the silt and clay, length of stability was the determining factor. Since the HydroFloc 445L was stable the longest in liquid form, it was selected as the flocculant that was to be used in the additional jar tests and flume experiments.

The turbidity reduction results for the eight Hydrofloc concentrations ranging from 0.0 to 0.15 g/L are shown in Figures 1 and 2. It was concluded that the optimum range of concentration of flocculant for the soils tested was 0.75 to 0.1 g/l. Turbidity samples were taken each minute for five minutes. Based on these results, there was little difference in reduction between 0.05 g/L and greater suspended sediment concentrations. After two minutes the reduction at 0.05 g/L was 93% (2020 to 152 NTUs) compared to a 94% reduction (1850 to 111 NTUs) at 0.15 g/L. Based on these results, a concentration of 0.05 g/L was used for the remaining tests. These tests also show that most of the reduction occurs in the first minute of settling and that the four minute settling time expected in the flume settling basin is sufficient. At 0.05 g/L, the turbidity decreased by 91% (190 NTUs) after one minute and 94% after five minutes (131 NTUs).

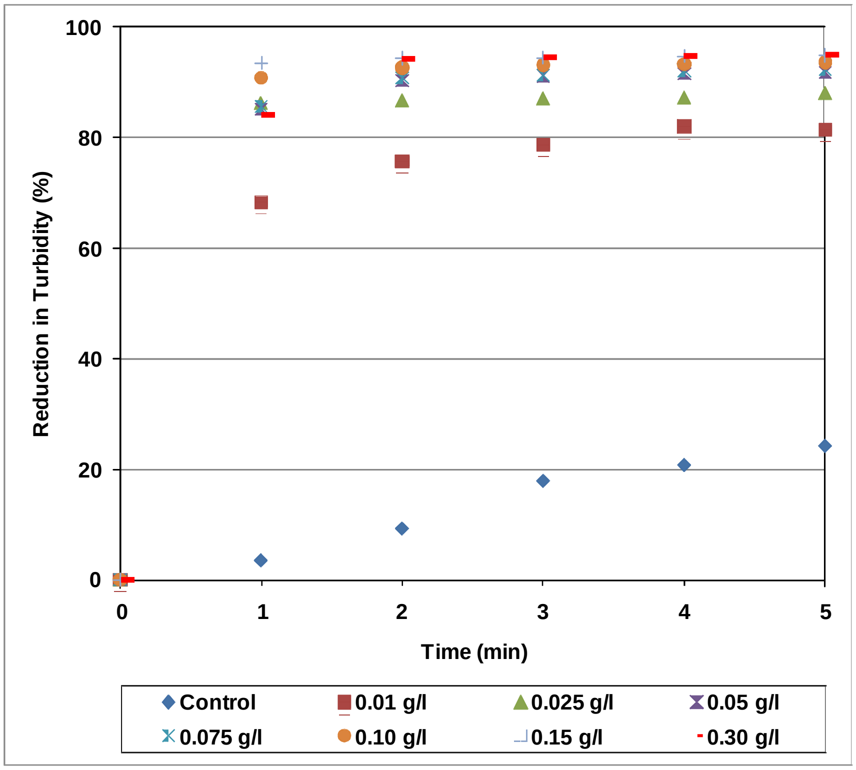
Table 1. Seven flocculants and flocculant combinations used in the jar tests, their dose, percent removal of silt and clay, and the number of days they are stable. [N/A: not applicable]

Flocculant	Dose (mg/L)	Percent Removal Silt and Clay	Percent Removal Sand, Silt, Clay	Stability (days)
Control	0	38	93	N/A
SuperFloc 705	4	92	99 99	1
Hydrofloc	50	93	>99	90
FloPam SH (solution)	12	86	98	10
	4	93	>99	10

FlowPam SH (powder)	12	58	95	365
FlowPam VLM (solution)	40	90	99	1
Aluminum sulfate	30	71	98	stable
FloPam SH & Alum	30-Dec	84	98	10

Table 2. The final four flocculants considered, with pros and cons that were analyzed in determining the flocculant to use in the flume experiments.

Flocculant	Pros	Cons
HydroFloc 445L	Highest removal efficiency Extended stability in concentrated form	Very high viscosity
Superfloc 705	High removal efficiency Moderate viscosity	Difficult to mix Very short stability
FloPam SH (solution)	Easy to mix Low viscosity High removal efficiency	Short stability
FloPam VLM (solution)	High removal efficiency Moderate Viscosity	Very short stability


100
80
60
40
20
0
Reduction in Turbidity (%)
0
1
2
3
4
5
Time (min)
Control
0.01 g/l
0.025 g/l
0.05 g/l
0.075 g/l
0.10 g/l
0.15 g/l
0.30 g/l

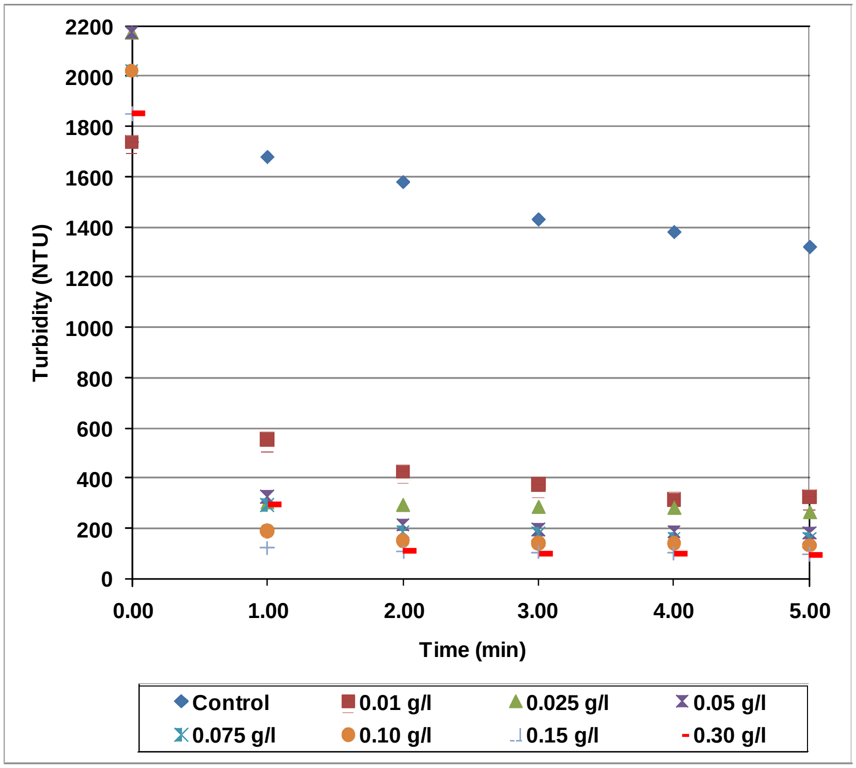

2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Turbidity (NTU)
0.00
1.00
2.00
3.00
4.00
5.00
Time (min)
Control
0.01 g/l
0.025 g/l
0.05 g/l
0.075 g/l
0.10 g/l
0.15 g/l
0.30 g/l

Figure 1. Turbidity and percent reduction in turbidity for various concentrations of Hydrofloc 445L from 0 to 5 minutes including the control for the clayey sand from near Stillwater, Oklahoma.

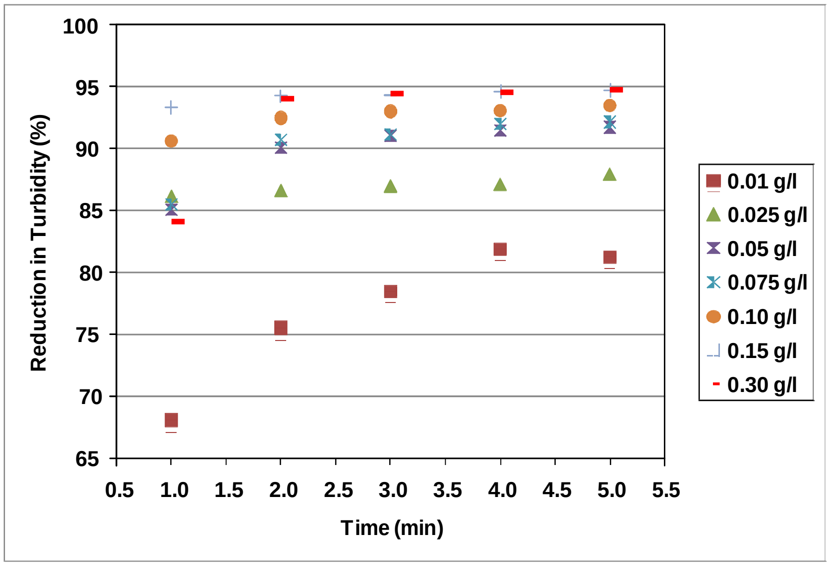


Figure 2. Percent reduction in turbidity for various concentrations of Hydrofloc 445L from 0 to 5 minutes excluding the control for the clayey sand from near Stillwater, Oklahoma.

The Hiwassee soil had a 97% reduction (4280 to 139 NTUs) at 120 rpm at a sediment concentration of 40 g/L. The smallest decrease in turbidity occurred with the Cecil soil at 90 rpm at 2 g/L with a reduction of 32% (132 to 126 NTUs). The percent of silt and clay removed through the flocculation process ranged from 49% removal for the Cecil at 120 rpm at 2.0 g/L to 98% for the Hiwassee soil at 120 rpm at 20 g/L (Figure 4).

It should be noted that these results cannot be compared to other research because other tests have much larger mixing times and settling times. For example, Kang et al. (2007) had a rapid mixing time of one minute at 100 rpm followed by slow mixing for 10 min to 8 hrs at 5 to 10 rpm. This was then followed with a settling time of 40 min to 20 hr.

For the Cecil soil, an average of 89% of the soil mass was removed through sieving; therefore only 0.20, 2.6, and 4.3 g/L were used in the jars for the three sediment concentrations (2.0, 20, and 40 g/L). This compared to 83% and 85% sediment removal through sieving for the Pacolet and Hiwassee soils, respectively (Table 3). Compared to the controls, the turbidity was much lower for the flocculated samples (Figure 3). For example, the average initial turbidity for the Cecil soil was 155, 1295, and 2923 NTUs at 2.0, 20, and 40 g/L sediment concentrations, respectfully. For the controls, the average turbidity decreased to 136, 1008, and 1993 NTUs, for the 2.0, 20, and 40 g/L sediment concentrations, respectively. With the flocculant injection, the turbidity levels further decreased to an average of 68, 163, and 399 NTUs, for the 2.0, 20, and 40 g/L sediment concentrations, respectfully. This research identified the optimal flocculant and its concentration for three Greenville County, South Carolina soils. The tests then attempted to mimic the mixing time, speed and settling time of the larger scale flume experiments and to test these parameters on three Greenville County, South Carolina soils. All tests showed a significant reduction in both the TSS and turbidity for all three soils at three mixing speeds and sediment concentrations.

Table 3. Results of jar tests performed on the three Greenville County, South Carolina soils using Hydrofloc 445L flocculant (floc.) at a concentration (conc.) of 0.05 g/L and a mixing time of five seconds at three mixing speeds and sediment concentrations.

Soil	Mixing Speed (rpm)	Sediment Conc. (g/L)	Silt & Clay Conc. (g/L)	Final Conc. of Control (g/L)	Final Conc. with Floc.	Initial Turb. (NTU)	Turb. of Control (NTU)	Turb. with Floc. (NTU)
Cecil	90	2	0.22	0.12	0.08	132	126	90
		20	0.23	0.14	0.12	153	148	58
		40	0.19	0.14	0.02	180	134	55
	120	2	2.8	1.5	0.17	1290	960	233

		20	2.4	1.3	0.08	1380	1030	136
		40	2.3	1.3	0.12	1220	1040	119
	150	2	4.5	2.6	0.52	2770	2180	610
		20	4.8	2.5	0.39	3100	1850	500
		40	4.2	2.5	0.12	2900	1950	88
Pacolet	90	2	0.32	0.17	0.04	243	199	85
		20	0.33	0.2	0.02	227	207	36
		40	0.28	0.19	0.06	230	200	77
	120	2	3.7	2.1	0.5	3360	2430	765
		20	3.6	2	0.43	3190	2210	595
		40	3.6	2	0.41	3180	2220	589
	150	2	6.4	4.1	0.55	6000	3120	615
		20	6.1	3.4	0.32	7400	2770	324
		40	7.7	6.3	0.64	9290	2730	760
Hiwassee	90	2	0.4	0.21	0.05	300	290	61
		20	0.49	0.18	0.06	320	207	39
		40	0.22	0.09	0.05	190	177	45
	120	2	3.1	1.2	0.09	2400	1490	159
		20	2.8	1.3	0.05	2230	1330	69
		40	2.5	1.2	0.12	1860	1125	103
	150	2	5	2.3	0.2	4310	2400	202
		20	4.7	2.7	0.25	4260	2960	196
		40	4.9	2.7	0.29	4280	2920	139

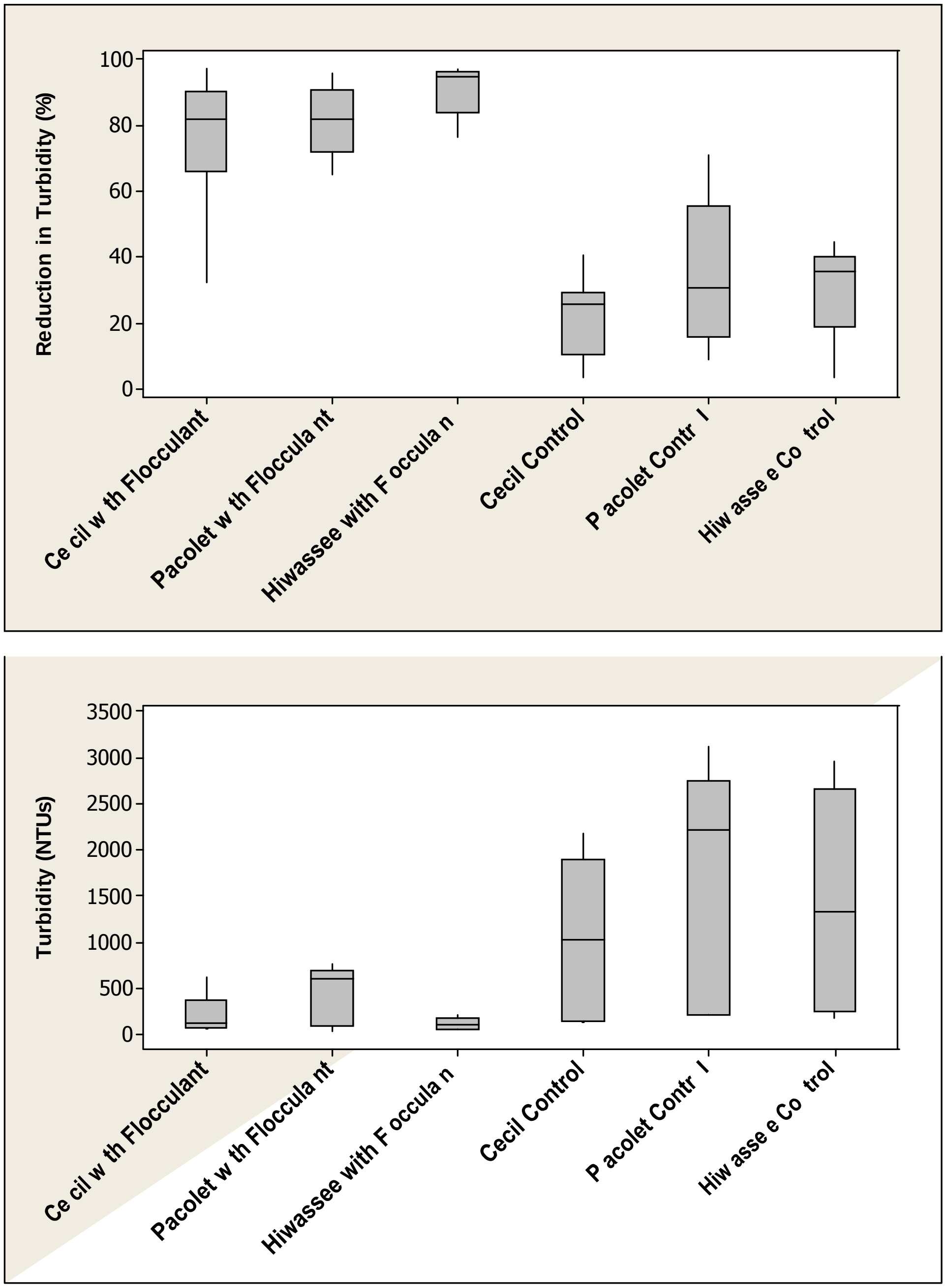


Figure 3. Box and whisker plots for the jar tests demonstrating the turbidity and reduction in turbidity for the Cecil, Pacolet, and Hiwassee soils with and without (control) flocculant.

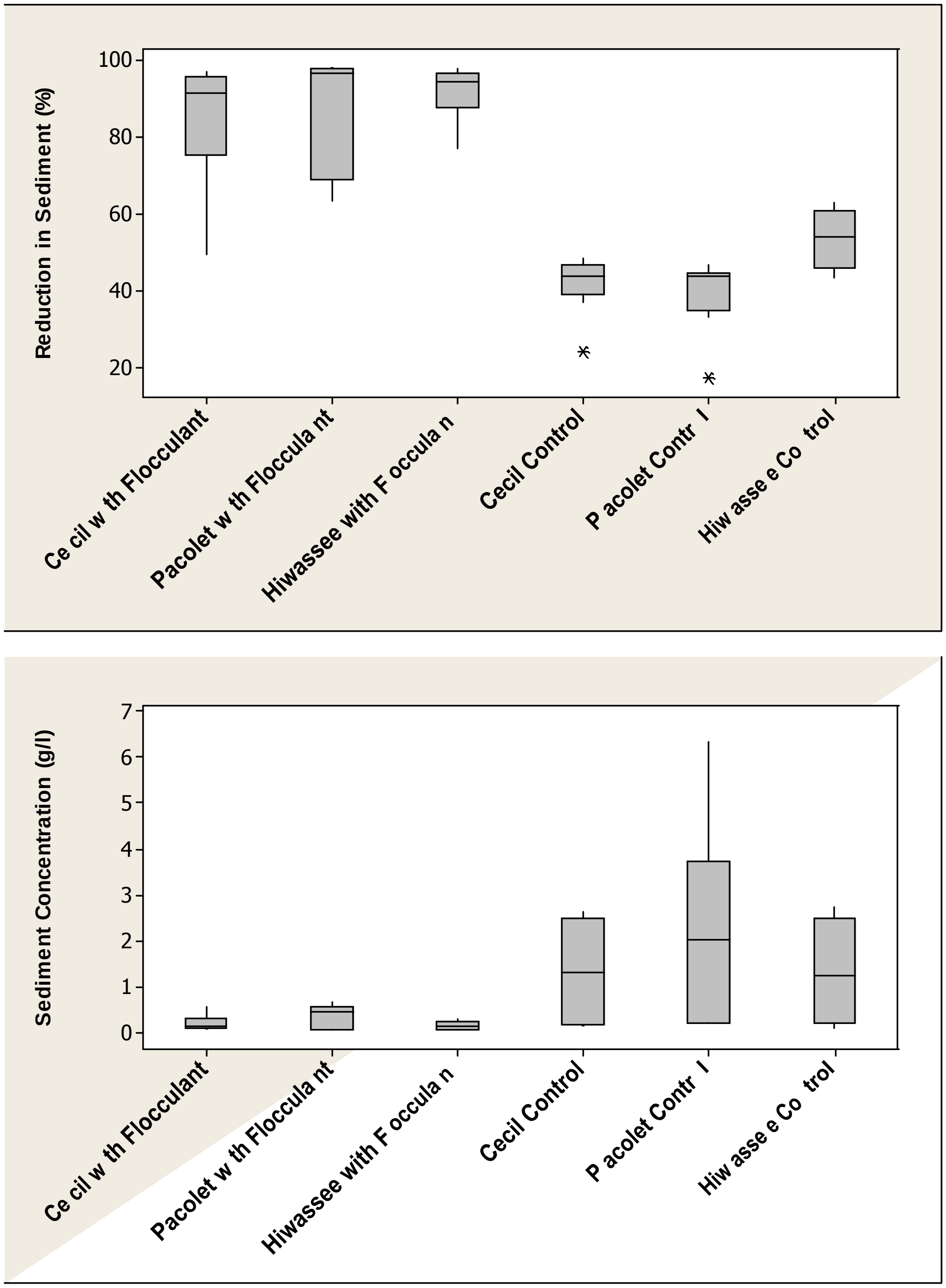


Figure 4. Box and whisker plots demonstrating the suspended sediment concentration and the reduction in suspended sediment concentration for the Cecil, Pacolet, and Hiwassee soils with and without (control) flocculant.

APPPENDIX III

MATLAB Code

Code for Float System

```
% Forebay Module
% Begin inflow outflow determination


Fricf=0.02; g=9.81; Cfeed=1000;
O2s=0; m=19320; O1=0; S1=0; S2=0; Yi=.355;Y2=0; rf=1;
Yi1=0.02;Yi2=.119;Yi3=.19;Yi4=.3;Q1=.000071;Q2=.000089;Q3=.00022;Q4=.00
0438;

width=3; length =5;

O2ssb=0;S1sb=0;S2sb=0;



for j=1:m
  I2=hydrot(j+1,3)*0.02831*rf; O1=O2s; dt=4.5; S1=S2;
O2=0;I1=hydrot(j,3)*0.02832*rf;
O2ssb=0;S1sb=0;S2sb=0;
% Begin iteration within each Hydrophraph Inflow to determine storage
and outflow
k=1;
conv=100;
while conv>1;
    dS= ((I1+I2)/2)*dt-((O1+O2)/2)*dt;
    S2=S1+dS;

    Y2 = S2/(width*length); % assum rectangular forbay

% If the hight in forebay is at least Yi m then, outflow will ocurr.
        if Y2>Yi;
        O2=1.7716*(Y2-Yi)^1.721;
        else O2=0;
        end
        k=k+1;
     Conv(k,j)=O2;
     conv=((Conv(k,j)/Conv(k-1,j)-1)*100)^2;
end
Convergence(1,j)=conv;


hydro2(1,j)=I1;
```

```
O2s=O2;
Yforebay(1,j)=Y2;
Out(1,j)=O2s;

%Dosing module

if Yforebay(1,j)>Yi+Yi1;
    if Yforebay(1,j)<Yi+Yi2
        cv=1.3*((Yforebay(1,j)-(Yi+Yi1))/(.1));
    else
        cv=1;
    end
    if cv>1
        cv=1;
    end

Qfloc1(1,j)=Q1*cv;% Flowrate of floc
else Qfloc1(1,j)=0;
end




if Yforebay(1,j)>Yi+Yi2;
Qfloc2(1,j)=Q2;% Flowrate of floc
else Qfloc2(1,j)=0;
end
if Yforebay(1,j)>Yi+Yi3;

Qfloc3(1,j)=Q3;% Flowrate of floc
else Qfloc3(1,j)=0;
end
if Yforebay(1,j)>Yi+Yi4;

Qfloc4(1,j)=Q4;% Flowrate of floc
else Qfloc4(1,j)=0;
end

Qfloc(1,j)=(Qfloc1(1,j)+Qfloc2(1,j)+Qfloc3(1,j)+Qfloc4(1,j));

Cdose(1,j)=((Qfloc(1,j)*40)/(Out(1,j)));



Y(1,j)=j;
Target(1,j)=.1;
high(1,j)=.125;
low(1,j)=.075;
X(1,j)=j*4.5/3600;
qFLOC(1,j)=Qfloc(1,j)*1850.3;


if Cdose(1,j)>0;
Crange(1,j)=(Cdose(1,j)-Target(1,j))^2*Out(1,j);
Outcr(1,j)=Out(1,j);
else
```

```
 Crange(1,j)=0;
 Outcr(1,j)=0;
end end

crange=1000*sum(Crange)/sum(Outcr)
```

Code for New Zealand System

```
Fricf=0.02; g=9.81;
O2s=0; m=2400; O1=0; S1=0; S2=0; Yi=.02; Yj=.04;Yk=.14;
f2=.04;zh=1;Area=2; rf=26;Cw=3;Co=.06;
Target=.1; conc=40;


%for z=1:500

D=.088;A=pi()*(D/2)^2;D2=.05;A2=pi()*(D2/2)^2;D3=.065;A3=pi()*(D3/2)^2;

for j=1:m

I2=hydro1(j+1,1)*rf; O1=O2s; dt=36; n=20; S1=S2;
O2=0;I1=hydro1(j,1)*rf;
O2ssb=0;S1sb=0;S2sb=0;
% Begin iteration within each Hydrophraph Inflow to determine storage
and outflow
k=1;
conv=10;
while conv>1;
    dS= ((I1+I2)/2)*dt-((O1+O2)/2)*dt;
    S2=S1+dS;
    Y2=(S2/Area);
    I22(1,j)=I2;

% If the hight in forebay is at least Yi m then, outflow will ocurr.

if Y2>Yi;
        Ow1=(Cw*(pi()*(D/2)*3.28084)*((Y2-Yi)*3.28084)^(3/2))*0.02831;
% Wier Flow
        Oo1=(Co*(pi()*(D/2)^2*10.764)*(2*32.2*(Y2-
Yi)*3.28084)^0.5)*0.02831;    %Orifice Flow

Op1=(((A*10.764)*(2*32.2*(Y2)*3.28084)^0.5)/(1+zh*3.28084)^0.5)*0.02831
;  %Pipe Flow
        Ab=[Ow1 Oo1 Op1];
        O21=min(Ab);  % Select Minimum of 3 flow regimes as Outflow
        else O21=0;
end
```

```
if Y2>Yj;
        Ow11=(Cw*(pi()*(D2/2)*3.28084)*((Y2-
Yj)*3.28084)^(3/2))*0.02831;  % Wier Flow
        Oo11=(Co*(pi()*(D2/2)^2*10.764)*(2*32.2*(Y2-
Yj)*3.28084)^0.5)*0.02831;    %Orifice Flow

Op11=(((A2*10.764)*(2*32.2*(Y2)*3.28084)^0.5)/(1+zh*3.28084)^0.5)*0.028
31;  %Pipe Flow
        Ab1=[Ow11 Oo11 Op11];
        O22=min(Ab1);  % Select Minimum of 3 flow regimes as Outflow
        else O22=0;

end

if Y2>Yk;
        Ow111=(Cw*(pi()*(D3/2)*3.28084)*((Y2-
Yk)*3.28084)^(3/2))*0.02831;  % Wier Flow
        Oo111=(Co*(pi()*(D3/2)^2*10.764)*(2*32.2*(Y2-
Yk)*3.28084)^0.5)*0.02831;    %Orifice Flow

Op111=(((A3*10.764)*(2*32.2*(Y2)*3.28084)^0.5)/(1+zh*3.28084)^0.5)*0.02
831;  %Pipe Flow
        Ab2=[Ow111 Oo111 Op111];
        O23=min(Ab2);  % Select Minimum of 3 flow regimes as Outflow
        else O23=0;

end

 O2=2*O23+2*O22+O21;
   k=k+1;
  Conv(k,j)=O2;
  conv=((Conv(k,j)/Conv(k-1,j)-1)*100)^2;
end
Convergence(1,j)=conv;
% various data stored for system analysis and visualization
hydro2(1,j)=I2*500;
O2s=O2;
Yforebay(1,j)=Y2;
Out2(1,j)=O22;
Out1(1,j)=O21;
Out(1,j)=O2s;

%Dosing calculations
Vbucket(1,j)=sum(Out(1,1:j));
Cdose85(1,j)=Out(1,j)*conc/runoff(j,1);
Cdose90(1,j)=Out(1,j)*conc/runoff(j,2);
Cdose95(1,j)=Out(1,j)*conc/runoff(j,3);

if j>9 &j<2402;
      Cdose95s2(1,j)=Out(1,j)*conc/runoff(j-8,1);
      Cdose85s2(1,j)=Out(1,j)*conc/runoff(j-8,3);
      Cdose95d2(1,j)=Out(1,j)*conc/runoff(j+8,1);
      Cdose85d2(1,j)=Out(1,j)*conc/runoff(j+8,3);
else
      Cdose85s2(1,j)=0;
      Cdose95s2(1,j)=0;
```

```
      Cdose85d2(1,j)=0;
      Cdose95d2(1,j)=0;
end

% various data stored for system analysis and visualization

X(1,j)=j*36/(3600);
XX(1,j)=runoff(j,1)/500;
out(1,j)=Out(1,j)*75;

if j >1000 & j<1401;
      WSE85(1,j)=(Cdose85(1,j)-Target)^2*runoff(j,1);
      WSE90(1,j)=(Cdose90(1,j)-Target)^2*runoff(j,2);
      WSE95(1,j)=(Cdose95(1,j)-Target)^2*runoff(j,3);

else
      WSE85(1,j)=0;
      WSE90(1,j)=0;
      WSE95(1,j)=0;

end
end
```

APENDIX IV

Minitab GLM Test Outputs

Table 1. GLM results with Turbidity (NTU) as the response variable

Source	DF	Seq SS	Adj SS	MS	F	P
Factor	1	66567060	1228381	1228381	11.72	0.001
Time	1	31508664	25678616	25678616	245.04	0
Q	2	21323969	23243	11621	0.11	0.895
Average1	1	2376424	6436782	6436782	61.42	0
Factor*Time	1	22081399	28689430	28689430	273.77	0
Factor*Time*Time	1	11118151	15534085	15534085	148.23	0
Time*Time	1	22178794	7689667	7689667	73.38	0
Q*Time	2	1626124	5018245	2509122	23.94	0
Q*Time*Time	2	5244719	5244719	2622359	25.02	0
Error	359	37621382	37621382	104795		
Total	371	221646685				

Table 2. GLM results with normalized turbidity as the response variable

Source	DF	Seq SS	Adj SS	MS	F	P
Factor	1	26.8709	0.1954	0.1954	10.86	0.001
Time	1	3.5591	3.7325	3.7325	207.39	0
Q	2	3.0067	0.0006	0.0003	0.02	0.983
Average1	1	0.0703	0.0142	0.0142	0.79	0.374
Factor*Time	1	2.6743	3.2778	3.2778	182.13	0
Factor*Time*Time	1	1.174	1.7201	1.7201	95.57	0
Time*Time	1	3.1342	1.144	1.144	63.57	0
Q*Time	2	0.168	0.8486	0.4243	23.58	0
Q*Time*Time	2	0.8658	0.8658	0.4329	24.05	0
Error	359	6.4611	6.4611	0.018		
Total	371	47.9845				

Table 3. Final GLM results with normalized turbidity as the response variable

Source	DF	Seq SS	Adj SS	MS	F	P
Factor	1	26.8709	2.9503	26.8709	974.01	0

Time	1	3.5591	6.8374	3.5591	129.01	0
Factor*Time	1	2.9665	3.6658	2.9665	107.53	0
Time*Time	1	4.4632	4.4632	4.4632	161.78	0
Error	367	10.1247	10.1247	0.0276		
Total	371	47.9845				

VITA

Karl M. Garbrecht

Candidate for the Degree of

Master of Science

Thesis: PASSIVE CHEMICAL DOSING APPARATUS FOR CONSTRUCTION SITE IMPLEMENTATION

Major Field: Biosystems Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2011.

Completed the requirements for the Bachelor of Science in Biosystems Engineering at Oklahoma State University, Stillwater, Oklahoma in December, 2011.

Name: Karl M. Garbrecht Date of Degree: December, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: PASSIVE CHEMICAL DOSING APPARATUS FOR CONSTRUCTION SITE STORMWATER TURBIDITY REDUCTION

Pages in Study: 82 Candidate for the Degree of Master of Science

Major Field: Biosystems Engineering

Scope and Method of Study:

A project with objective to design, construct, and test an automated, passive chemical dosing system for implementation on a construction site to reduce turbidity in stormwater runoff was completed. Simulated performance of alternative systems was compared through a modeling study to select and design a prototype. A prototype sized for a one acre construction site was tested in a cement channel with a solution of water and suspended sediment. The initial and resulting turbidities were measured at five locations in the flume with and without flocculant dosing for three different flow rates.

Findings and Conclusions:

The designed system included a forebay, a passive, flow-based dosing system, a turbulent mixing system to facilitate floc development, and a settling basin. Modeling simulations showed it was capable of maintaining flocculant dosing concentrations in predetermined ranges and had a unique relationship between stage in a flow control structure and flocculant dosing concentration. Field scale tests demonstrated the prototype dosing system operated as intended and the flocculant dosed by the system was able to reduce inflow turbidity from a cumulative average of 2760 NTU to 400 NTU (85% reduction) for all tests in the channel.

ADVISER'S APPROVAL: Dr. Jason Vogel