Improvements in Stormwater Detention Technologies through Large-Scale Testing Techniques

by

Jaime Catherine Schussler

A dissertation submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy in Civil Engineering

Auburn, Alabama
May 7th, 2022

Keywords: Sediment Basin, Stormwater Detention, Erosion and Sediment Control, Construction Stormwater, Smart Stormwater

Approved by

Michael A. Perez, P.E., Chair, Assistant Professor of Civil Engineering

Wesley C. Donald, Research Fellow IV, Civil Engineering

Xing Fang, P.E., Professor of Civil Engineering

Eve Brantley, Professor of Crop, Soil, and Environmental Sciences

Thorsten J. Knappenberger, Associate Professor of Crop, Soil, and Environmental Science

ABSTRACT

Due to urbanization and a changing climate, stormwater management has become increasingly discussed, regulated, and researched. In many areas of the United States, one effect of climate change has taken form in more intense or frequent storms, yielding increased stormwater runoff events. There are unique challenges faced in each land development stage to preserve and protect water resources. If mismanaged, stormwater runoff can expedite overland and streambank erosion processes, resulting in profound environmental and economic implications. Stormwater detention systems are commonly implemented in construction and post-construction stormwater management to capture sediment and additional pollutants and attenuate discharge flow rates. This dissertation presents results from techniques used to evaluate the performance of stormwater detention technologies to provide science-based design guidance and solutions.

This research includes existing erosion and sediment control technologies used in the construction industry, existing research, performance, and cost assessments. Specifically, this dissertation investigates sediment basins, which are considered a temporary sediment control practice typically employed onsite perimeters to detain sediment from stormwater runoff before discharge. Sediment basins are heralded for effective sediment capture; however, design and installation techniques vary nationwide. Researchers at the Auburn University - Stormwater Research Facility (AU-SRF) examined the performance of an in-channel sediment basin design, which uses existing roadside conveyance features to minimize the required footprint for installation. The traditional design detailed an earthen berm installed to the full channel height with an armored overflow spillway and a perforated riser pipe for primary dewatering.

The large-scale testing described in this dissertation follows a 2018-2019 field-monitoring study of the in-channel sediment basin design on the construction of U.S. 30 in Tama County, IA. Field data indicated negligible turbidity and total suspended solids reduction when comparing

inflow and discharge samples. In an effort to improve performance, several structural treatments and one chemical treatment were evaluated through large-scale, controlled flow and sediment introduction testing. Treatments included: (1) geotextile lining, (2) a floating surface skimmer, (3) porous flow baffles, (4) an upstream forebay, and (5) application of flocculant. Performance was categorized through water quality, quantity, and soil retention data. Sediment retention was reported as high as 96% by weight when an upstream forebay, geotextile lining, surface skimmer, and surface were used as a system, and 98% when flocculant was added to the skimmer. The sediment retention can be compared to 76% when only a geotextile liner was used. When flocculant was applied, turbidity reduction increased by 42%, and discharge turbidities were consistently below 100 NTU during dewatering periods. Flocculant reduced the captured D_{50} particle size by 400%, on average, indicating that flocculant aids in capturing the finest particles, which may decrease required storage volume and detention times in basins. In addition to experimental testing, a spreadsheet-based tool was developed to aid in the implementation of in-channel sediment basins and the structural and chemical components that enhanced sediment capture and turbidity reduction.

In some cases, sediment basins become permanent installations to control post-development flows. As post-construction stormwater designs and performance face enhanced regulations and site footprints remain limited, technologies are being developed to design basins with a smaller footprint while still achieving hydrologic and water quantity goals. However, it is important to understand and achieve water quality and quantity goals to meet design standards and regulations. The final portion of this dissertation describes the development of a standardized test procedure to evaluate permanent outlet systems in post-construction basins in Alabama. A 2,790 ft^3 (79.0m^3), large-scale sediment basin was retrofitted with an impervious plastic liner to prevent infiltration during testing, emulating a post-construction dry-detention basin. Sediment was introduced at a rate ranging between 100 to 300 mg/L to simulate a 1.5 in. (3.8 cm) rainfall depth across a 0.6 ac (2.43 ha) contributing area made up of 90% impervious surfaces. The testing apparatus was calibrated using an Alabama native, Sandy Loam soil. After several calibration tests, an orifice size of 0.70 in. (1.78 cm) was selected for the dewatering cap. The target inflow sediment concentration was eventually achieved by introducing 35 lb (16 kg) of sieved soil throughout the 60-minute testing window. To ensure a consistent introduction rate, one volumetric pound of sediment was passed through the adjustable density over a 1.5 minute period until all 35 lb (16 kg) were introduced. According to mass balance equations, the control testing was providing at least 75% sediment capture during settling periods.

In summary, the findings presented in this dissertation are expected to inform the performance, design, and implementation of stormwater detention practices, particularly on sites with limited footprints, to minimize detrimental downstream effects.

ACKNOWLEDGEMENTS

My doctoral degree would not have been possible without the many people who have supported me on my graduate journey. I would like first share my most sincere appreciation for advisor, Dr. Michael Perez, whose devotion and contribution to my professional and personal development has remained evident and unending. Dr. Perez's drive and enthusiasm to continually better himself, his students, and the built-world around him has inspired me in many ways, but especially to become a patient and intentional mentor. I would also like to thank Drs. Wesley Donald and Blake Whitman for their continual mentorship and belief in my abilities. I am grateful for the guidance from my doctoral committee members, Dr. Xing Fang, Dr. Eve Brantley, and Dr. Thorsten Knappenberger throughout this research effort.

This dissertation would not have been possible without the support of the Iowa Department of Transportation, Auburn University Highway Research Center, and the Auburn University Department of Civil and Environmental Engineering. I would like to thank Mr. Guy Savage, Mr. Kris Ansley, and the undergraduate research assistants, namely Blake Daiber, Andrew Garcia, John Wright, Jacob Hudson, and Ryan Anthony for their coordination, support, and shared efforts to make this research possible. I would like to thank my research group for our shared hours, both laboring and laughing. Most importantly, I would like to thank my friend and colleague, Dr. Billur Kazaz for her unwavering support and joy in the office, during fieldwork, and in our home. She has been a constant reminder that life's successes are much sweeter when shared.

I have been blessed with friends and family, who have sacrificed and supported me as I pursued my doctoral degree. I would like to first thank the strong women who have shared my journey, and continue to pave the way for women in STEM, most especially, Sydney Brooks, Kristyn Johnson, Brittany McWatters, Emily Brezler, Jessica Taylor, Jessica Talbot, Veronica Ramirez, Catherine Bower, Sylwia Stawska, and Patricia Carcamo. Additionally, I would like to thank Parker Dulin for his friendship and allyship. Finally, I would like to thank my best friend, Maxx, who has more than earned his “dogtorate,dogree” with hours spent by my side.

I am the most grateful for the love, support, and sacrifice of my parents, Sue and Greg Schussler, siblings Christine and Bryant Brueckner, Michelle and Jason Nellis, and my partner, Aaron Fewell. Your examples of tenacity, resiliency, and reliability have inspired and grounded me throughout this pursuit. You were the first to encourage me, believe in me, and celebrate me. I owe this all to you.

I would finally like to dedicate this dissertation to my niece, Mae Nellis, who has provided immense joy and inspiration to improve myself, the environment, and the educational institutions of tomorrow. I look forward to watching you lead, inspire, and invite others on your life’s journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AASHTO	American Association of Highway and Transportation Officials
ALDOT	Alabama Department of Transportation
AL-SWCC	Alabama Soil and Water Conservation Committee
ANOVA	Analysis of Variance
AU-SRF	Auburn University Stormwater Research Facility
BMP	Best Management Practice
CGP	Construction General Permit
CN	Curve Number
DOT	Department of Transportation
DNR	Department of Natural Resources
E&SC	Erosion and Sediment Control
HSG	Hydrologic Soil Groups
Iowa DOT	Iowa Department of Transportation
LiDAR	Laser Imaging Detection and Ranging
MUSLE	Modified Universal Soil Loss Equation
NCAT	National Center for Asphalt Technology
NPDES	National Pollutant Discharge Elimination System
NTU	Nephelometric Turbidity Unit
RUSLE	Revised Universal Soil Loss Equation
SWPPP	Stormwater Pollution Prevention Plan
TARP	Technology Acceptance Reciprocity Partnership
TRM	Turf Reinforcement Mat
TS	Total Solids
TSS	Total Suspended Solids
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency

1. CHAPTER ONE: INTRODUCTION

1.1. BACKGROUND

As a result of urbanization, infrastructure is continually developed or updated to meet the needs and desires of increasing populations. As a result, natural water and soil resources are disrupted. In many areas of the United States, there has been an increase in storm intensity and frequency, increasing stormwater runoff and downstream implications *(Wuebbles et al., 2017)*. More frequent and intense storm events present unique challenges in preserving and protecting water bodies during and after land development. In 2020, more than 50% of assessed U.S. Waters were designated as impaired, indicating limitations for recreational use, human consumption, and aquatic life support (*United States Environmental Protection Agency [USEPA] 2020*). In addition to heavy metals and nutrients, sediment is one of the most detrimental pollutants affecting receiving waterbodies *(USEPA 2005)*. Sediment loading may be attributed to several sources, such as expedited erosion due to inadequate erosion and sediment control (E&SC) during construction or streambank erosion due to increased flow rates and stage levels *(Kerkez et al., 2016).*

During construction, natural cover and vegetation is removed, leaving bare soil susceptible to erosion from overland flows and drifts. The sediment then suspends in stormwater runoff and may be discharged offsite if not properly managed. An estimated 3.9 billion tons (3.5 billion metric tons) of sediment is discharged from construction sites into U.S. waterbodies annually *(Mitchell et al., 1991)*. This is enough to fill Lake Guntersville, the largest lake in Alabama, with 26 ft (8 m) of sediment. Downstream consequences associated with sediment-laden discharge include but are not limited to: (a) increased siltation and turbidity, which hinders aquatic habitats, feeding, and reproduction; (b) reduced conveyance capacities leading to flooding; and (c) poor public perception and economic pressure from decreased recreation and increased treatment costs *(Bugg et al.,* 2017).

Increased siltation alters the substrate of a stream bed, which may inhibit certain plant growth and decrease the littoral zone. Additionally, increased turbidity reduces sunlight penetration and inhibits photosynthesis, required for vegetation and phytoplankton survival *(Boyd, C.E., and Lichtkoppler, F. 1979)*. Higher trophic level organisms rely on phytoplankton for food, such as zooplankton and larval fish, impacting the food chain *(Boyd, C.E., and Lichtkoppler, F. 1979)*. Vegetation provides aquatic habitat and also stabilizes the stream. If vegetation is disturbed, further erosion may occur. Similarly, siltation may coat plants, rocks, or other stream features that serve as hosts for food, also impacting the food chain. Siltation decreases conveyance capacities and patterns, which may eventually affect spawning migrations, but may also clog the gills and block feeding appendages of macroinvertebrates and filter feeders, such as mussels *(Western Australia Waterwatch 2001)*. Suspended sediment absorbs heat from sunlight and increases water temperature, which decreases available dissolved oxygen (DO). Decreased DO stresses aquatic life, induces disease, and results in fishkills *(Boyd, C.E., and Lichtkoppler, F. 1979)*.

Environmental consequences carry remediation costs (*USEPA 2019, Bugg et al., 2017*). Erosion control and on-site sediment control are typically more cost-effective and easier to implement than managing soil after being deposited elsewhere (*United States Department of Agriculture [USDA] 2006).* The last cost assessment associated with soil erosion in the U.S. was conducted in 1995, which was estimated as high as $44 billion per year (*Pimentel et al., 1995*), or $78.4 billion in 2021 with inflation *(Federal Reserve Bank of Minneapolis 2022)*. While some of the remediation efforts, such as the cost of dredging and disposing of accumulated sediment, are easier to quantify, the loss of aquatic habitats, diminished water quality, and loss of nutrient-rich soil is difficult to assess. Furthermore, loss of nutrient-rich soils may require topsoil replacement to achieve vegetative growth, and reformation of these soils is a long, slow, natural process (*Goldman et al., 1986*).

1.1.1. Erosion and Sediment Control

By 1992, the National Pollutant Discharge Elimination System (NPDES) outlined the Construction General Permit (CGP), which requires stormwater pollution prevention plans (SWPPPs) to be implemented on construction projects exceeding one acre (0.4 hectares) in disturbance (*USEPA 2019*). The SWPPP includes a comprehensive plan for the design, installation, and maintenance of E&SC practices. An effective SWPPP is essential to managing on-site soils and preventing sediment-laden discharge. Erosion controls are intended to prevent or reduce the displacement of soils by reducing the erosive forces of raindrops, runoff, and wind. Erosion controls include cover practices such as blankets, mulches, and matting and flow interrupters to decrease flow velocities or relocate flow paths such as ditch checks, slope interrupters, and slope drains. Sediment controls are installed to prevent or reduce dislodged, suspended sediment discharged from a construction site. Sediment controls include sediment barriers, basins, inlet protection, and flocculants. Many E&SCs had been historically implemented without performance data.

Traditionally, rules of thumb are used in E&SC design and accepted as "best" management practices. State Departments of Transportation (DOTs) are major facilitators of linear construction. Due to the nature of linear construction, projects are predisposed to many locations of site discharge. DOTs are constrained to balance a cost-conscious budget and adequate stormwater management program. Decreasing water quality, increased regulations, and the risk of hefty fines and stop-work orders for poor stormwater and pollution management induced from enforcement agencies has ignited testing, research, training, and education within the E&SC field.

In the past decade, research efforts have been conducted to answer the call for scientifically backed data on the design, implementation, and maintenance of E&SC practices *(Kaufman et al., 2000, Chapman et al., 2014, Fang et al., 2015, McLaughlin et al., 2001, Zech et al., 2009, Donald et al., 2013, Perez et al., 2016, Whitman et al., 2021)*. Evaluations of E&SC practices have improved performance through enhanced design and installation techniques.

1.1.2. Cost Assessment of Erosion and Sediment Control Industry

In addition to environmental implications caused by soil erosion, there are substantial economic burdens. While some remediation efforts, such as the cost of dredging and disposing of accumulated sediment, are easier to quantify, the loss of aquatic habitats, diminished water quality, and loss of nutrient-rich soil is difficult to assess. Loss of nutrient-rich soils may require topsoil replacement to achieve vegetative growth, and reformation of these soils is a long, slow, natural process *(Goldman et al.,1986)*. Effective E&SC practices are essential to managing on-site soils and preventing sediment-laden discharge. Evaluations of E&SC practices, including silt fence and wattle ditch checks, have improved performance through enhanced design and installation techniques *(Donald et al., 2014a, 2014b, 2015)*. Modified design and installation techniques often include additional materials and increased labor, and may yield an increased cost. State agencies, such as DOTs, are constrained to balance a cost-conscious budget and adequate stormwater management program. The USDA's Erosion Control Treatment Selection Guide has a six-step process regarding "proper treatment selection" for erosion control. Of the six steps, four include "cost-effective" solutions; however, limited peer-reviewed literature exists on E&SC cost-benefits *(USDA 2006)*. Existing literature is primarily from the early 2000s and is not adjusted for inflation of materials, labor, or mobilization.

A 1973 report by the USEPA titled "Erosion and Sediment Control, Construction Activities *(USEPA 1973)*" was published in response to the 1972 publication "Guidelines for Erosion and Sediment Control Planning and Implementation *(USEPA 1972)*" which summarized structural and vegetative E&SC practices. The report provided cost-related information for E&SC practices collected from contract estimates, furnished job costs, and equipment and supply catalogs, among other sources. Costs were sourced for watersheds in California and Virginia, representing the arid western U.S. and humid eastern U.S., respectively. Theoretical soil loss and sediment removal costs were also included in the report. "Control effectiveness" and duration were used for comparable annual estimated costs. The report concluded that soil loss potential and E&SC costs varied based on location; however, erosion control costs were lower than removing sediment downstream *(USEPA 1973)*.

A 2003 Stormwater Magazine article cataloged annual highway project E&SC expenditures from 1998-2001 from participating agencies (38 DOTs and two federal land highway divisions) *(Mitchell et al., 2003)*. The average spending on E&SC on DOT projects was $9.01 million/year and $60.12/lane-mile *(Mitchell et al., 2003)*. Temporary E&SC accounted for up to 8% of total project cost; however, an average of 3% of a highway construction's budget was attributed to E&SC spending. Additionally, 63% of the participating states reported annual E&SC cost increases. Individual practice costs such as riprap, seeding, silt fence, and sodding were recorded, but ditch checks were not a subset reported.

SEDSPEC, an E&SC planning and design tool, was developed to predict peak runoff and design hydrologic and E&SC measures used on site. SEDSPEC calculates dimensions, cost, and maintenance of E&SC practices based on a series of user inputs. Cost estimation relied on RS Means Heavy Construction cost data from 1997. In the included case study noted in the original publication, only runoff diversion ditches were included in the cost estimate and provided per linear meter *(Tang et al., 2004)*.

The Water Resources Research Institute of The University of North Carolina delivered a 2005 report regarding the cost-effectiveness of standard sediment control systems on construction sites in North Carolina. Several structural and vegetative E&SC practices were cataloged with installation and maintenance cost and effectiveness in reducing sediment from literature. Ditch checks, or check dams, were estimated at $40- $100/ ton ($36-$91/ metric tonne) and 77% effective; however, rock check dams were the only reported ditch check type *(Wossink et al., 2005)*.

A cost table of selected E&SC practices is provided in the New York State Standards and Specifications for Erosion and Sediment Control and includes a disclaimer stating that the E&SC cost is highly variable. Cost may vary depending on the availability and proximity of material, time of year, and regional costs trends *(Lake, D.W., 2016)*. These factors, among others, make it challenging to estimate E&SC costs considering all locations and times of the year. Similarly, other state agencies may have state-specific language regarding E&SC spending. Due to the complexity of estimating the cost of soil erosion and subsequent mitigation, there are gaps in the literature regarding E&SC cost.

1.1.3. Post-Construction Stormwater

Development replaces pervious areas with impervious surfaces, such as roads, hardscapes, or building roofs. Traditionally, stormwater has been conveyed away from developed areas to avoid flooding. This results in the hydromodification of natural waterways, including flow rates and paths, which produce additional downstream consequences *(Fletcher et al., 2015)*. In response, many local and state entities require post-construction stormwater management practices to achieve stormwater quantity and quality goals. These requirements are mandated through the NPDES Municipal Separate Storm Sewer (MS4) Permit *(USEPA 2021)*. MS4 permits often follow Low Impact Development design principles to control peak flow discharge rates to mimic pre-development conditions *(Fletcher et al., 2015)*. Detention basins are common in post-construction stormwater management plans (PCSWMP) due to their ability to store large runoff volumes, capture particulate, and mitigate post-development hydrology *(Emerson et al., 2005)*. However, limited site footprints do not always allow a basin with adequate detention volume. Smart stormwater systems, such as FloodCon LLC's Automated Outlet Structures, are being developed to achieve hydrologic benchmarks while adjusting to site constraints. Water quality effects remain unknown. It is important to understand water quality behavior in response to the smart systems to ensure treatment is not compromised and the systems are properly implemented.

1.2. RESEARCH OBJECTIVES

This dissertation is divided into six components associated with the evaluation of stormwater detention practices.

The specific objectives of this research are as follows:

(1) Catalog E&SC practices and published performance,

(2) Determine cost metrics associated with E&SC implementation,

(3) Develop large-scale testing techniques for in-channel sediment basins to evaluate water quality and sediment retention performance in response to structural sediment basin treatments,

(4) Determine particle settling behavior and downstream concentrations in response to flocculant application upstream of sediment basins,

(5) Provide design guidance for the implementation of in-channel sediment basins,

and,

(6) Develop standardized test procedures to evaluate permanent outlet systems in post-construction basins.

To meet these research objectives, nine tasks were identified:

(1) Identify, describe, evaluate, and apply literature related to E&SC design, implementation tools, and cost assessments,

(2) Identify, describe, evaluate, and apply literature and SWPPPs related to sediment basin design and implementation,

(3) Design and construct an appropriately scaled test to repeatedly and reliably evaluate an in-channel sediment basin for field- performance comparison,

(4) Develop an applicable methodology and testing apparatus for large-scale performance-based testing of in-channel sediment basins using Iowa rainfall and soil loss estimations,

(5) Analyze collected water quality and sediment retention data for evaluating the effectiveness of an in-channel sediment basin in response to structural treatments and flocculant application,

(6) Develop a spreadsheet-based tool to aid in-channel sediment basin design,

(7) Develop large-scale testing methodology, protocols, testing apparatus, and perform replicable tests on an impervious, post-construction basin to evaluate the water quality and sediment retention performance when an automated outlet structure is used for discharge,

(8) Calibrate testing apparatus to match estimated sediment concentrations in post-construction runoff, as described in literature, and

(9) Collect and analyze water quality samples using mass balance to determine water quality improvements and sediment capture.

1.3. Expected Outcomes

This research intends to enhance stormwater management techniques through informed and validated design and implementation tools. Scientific results from large-scale sediment basin testing are expected to drive an alternative basin design to capture, detain, and treat stormwater in a channel environment for sites with limited footprints and promote flocculant application in construction stormwater management. The spreadsheet-based tool was developed to aid in the implementation of in-channel basins, and tested technologies, into their stormwater management program and estimate sediment capture on-site. Additionally, this research presents standardized testing methods to evaluate and validate smart stormwater outlet structures to achieve water quality and quantity standards set in current post-construction stormwater regulations. Enhanced basins will protect water quality downstream of developed and developing areas, reduce regulatory compliance issues, and improve public perception. Future research efforts are expected to continue advancing the knowledge and resources in stormwater management.

1.4. Organization of Dissertation

This dissertation is sectioned into eight chapters that organize, illustrate, and describe the steps to meet the defined research objectives. Following this chapter, Chapter Two: *Evaluations of Erosion and Sediment Control Technologies*, provides an overview of existing erosion and sediment control technology, research, and implementation. Chapter Three: *Sediment Basin Design and Performance* reviews current sediment basin design standards introduces an in-channel sediment basin design, cost, and field-performance data. Chapter Four: *In-Channel Sediment Basin Performance Improvements through Large-Scale Testing* describes the design, testing apparatus, and procedures developed to evaluate sediment basin performance in response to various structural treatments. Water quality and sediment retention results from large-scale testing are presented and discussed in this chapter. Chapter Five: *Upstream Flocculant Application and Downstream Impacts*, builds from Chapter 4 by describing the introduction of flocculant into large-scale testing and reports on residual concentrations collected from the sediment basin discharge samples. Chapter Six: *In-Channel Sediment Basin Design Tool* describes the development and implementation of an Excel-based tool aid in the design and implementation of in-channel basins. Chapter Seven: *Smart Stormwater Structures for Permanent Installation* presents post-construction stormwater design and regulations and standardized testing techniques to evaluate automated outlet structures intended for permanent installation. Chapter Eight: *Conclusions and Impact* summarize the major findings and impact of this research effort and highlights topics for future studies in advancing stormwater management techniques and technologies.

2. CHAPTER TWO: PERFORMANCE AND COST ASSESSMENTS OF EROSION AND SEDIMENT CONTROL TECHNOLOGIES AND IMPLEMENTATION

2.1. Performance Evaluation through Multi-Scale Testing

The shortage of performance-backed design guidance often leads to inadequate design, improper placement, ineffective installation, and meager maintenance, ultimately resulting in complete failure. Initial E&SC practice testing and research efforts emerged through field monitoring, including ditch check practices, silt fence sediment barriers, and sediment basins *(McLaughlin et al., 2001, Zech et al., 2009, Fang et al., 2015).* However, uncontrolled site conditions make objective, successful research problematic. After the wide acknowledgment of the difficulties faced during field monitoring, there was a shift to controlled testing (*Fang et al., 2015, McLaughlin et al., 2001, Zech et al., 2009, Donald et al., 2013).* Controlled testing has been completed at the bench, intermediate, and large scales for proof of practice before field testing or validation.

2.1.1. Field Testing

McLaughlin et al., *(2009)* conducted a field study that compared natural fiber wattles (e.g., coconut coir and straw) to riprap ditch checks on two roadway projects over nine months, capturing 36 monitored storm events. The study revealed that fiber wattles are a less expensive alternative to rock check dams while still providing sediment retention. In addition, the study concluded that wattle ditch check performance is optimized when impoundment pools reach upslope to the downstream face of the preceding ditch check *(McLaughlin et al., 2009)*. These findings indicate that the spacing between consecutive ditch checks in a channel is a function of the installed height and channel slope.

After a small-scale proof-of-practice study validated silt fence tieback potential to retain sediment, the tiebacks were evaluated on a 600 ft. (183 m) section of a 3H:1V fill slope on an

Alabama DOT (ALDOT) construction site in Auburn, AL *(Zech et al., 2009)*. A 300 ft. (91 m) linear silt fence segment and 300 ft. (91 m) silt fence segment with tie backs were installed next to each other and observed for field performance during four storm events ranging in rainfall depths of 0.4 to 2.5 in. (1.0 to 6.4 cm). The tieback system distributed the total sediment load between the six tieback sections and prevented erosion at the toe of the slope; however, the linear silt fence segment had concentrated flow at the toe of the fence, resulting in erosion and downstream scour *(Zech et al., 2009)*. While tiebacks proved to enhance sediment capture, researchers cautioned that the increased storage would increase hydrostatic pressure on the silt fence and could result in catastrophic failure (*Zech et al., 2007, 2008*). Subsequent large-scale testing of sediment barriers quantified this impact and provided structural and dewatering improvements. Failure was expected for the linear silt fence segment if not maintained *(Zech et al., 2009)*.

Fang et al., monitored a sediment basin during highway construction for three months in Franklin County, AL. The basin was designed to ALDOT standards, incorporating a surface skimmer for dewatering, three coir baffles for flow dissipation, and flocculant introduction in the inflow channel for increased capture and followed USEPA sizing criteria of 3,600 ft^3 of volume per drainage ac (252 m^3/ha). Automated water sampling was employed at inflow, within, and discharge locations of the basin for turbidity and TSS analysis, but programming the samplers to characterize the inflows and performance of the basin accurately was challenging. Changing site conditions caused runoff rates, volumes, and durations to vary *(Fang et al., 2015)*. Limitations to the monitoring effort included unpredictable site conditions, representative sampling, and reliance on contractors for construction, instrumentation, and treatment within the sediment basin, highlighting the need for controlled, large-scale testing of sediment basins to depict performance accurately.

Although not an exhaustive list of all field monitoring efforts, McLaughlin et al., Zech et al., and Fang et al., *(2001, 2015, 2009)* acknowledged the challenges incurred during field testing. Unpredictable weather events, inconsistent soil types, weather patterns and contractor activities on monitoring sites inhibited the collection of repeatable, reliable, and attributable scientific-based results.

2.1.2. Controlled Testing

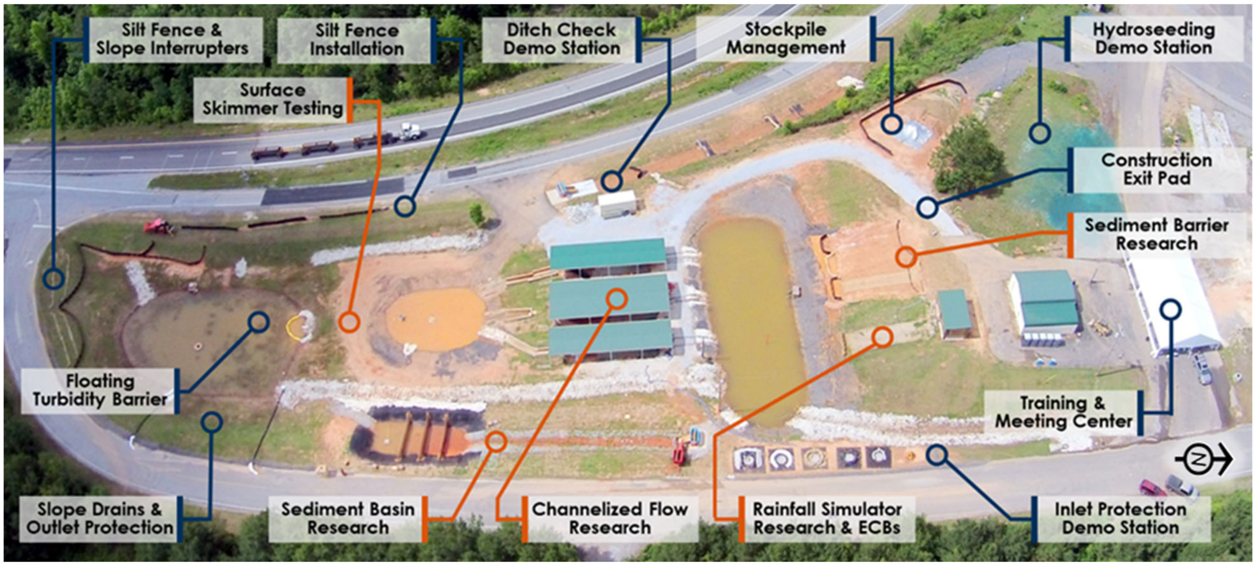
While field studies provided a starting point for E&SC practice testing, Kaufman and Chapman et al., *(2000 and 2014)* also called for credible, scientific results when designing and implementing E&SC plans. A handful of laboratories, including those at TRI Environmental, Penn State University, North Carolina State University, Texas A&M Transportation Institute, the University of Illinois Urbana-Champaign, and The Auburn University – Stormwater Research Facility (AU-SRF) (previously the AU-Erosion and Sediment Control Testing Facility) have created controlled environments for large-scale testing of E&SC practices. These testing facilities aim to mimic field conditions for repeatable, scientific-based design, installation, and maintenance of stormwater management practices while controlling variables for performance attribution. Tests conducted at these facilities are primarily driven by or adapted from test methods set by American Society for Testing and Methods (ASTM) or the American Association of State Highway and Transportation Officials (AASHTO) *(ASTM, 2006, 2007, 2018)*. The following section details the controlled, publicly-funded studies conducted at the AU-SRF.

2.2. AUBURN UNIVERSITY STORMWATER RESEARCH FACILITY

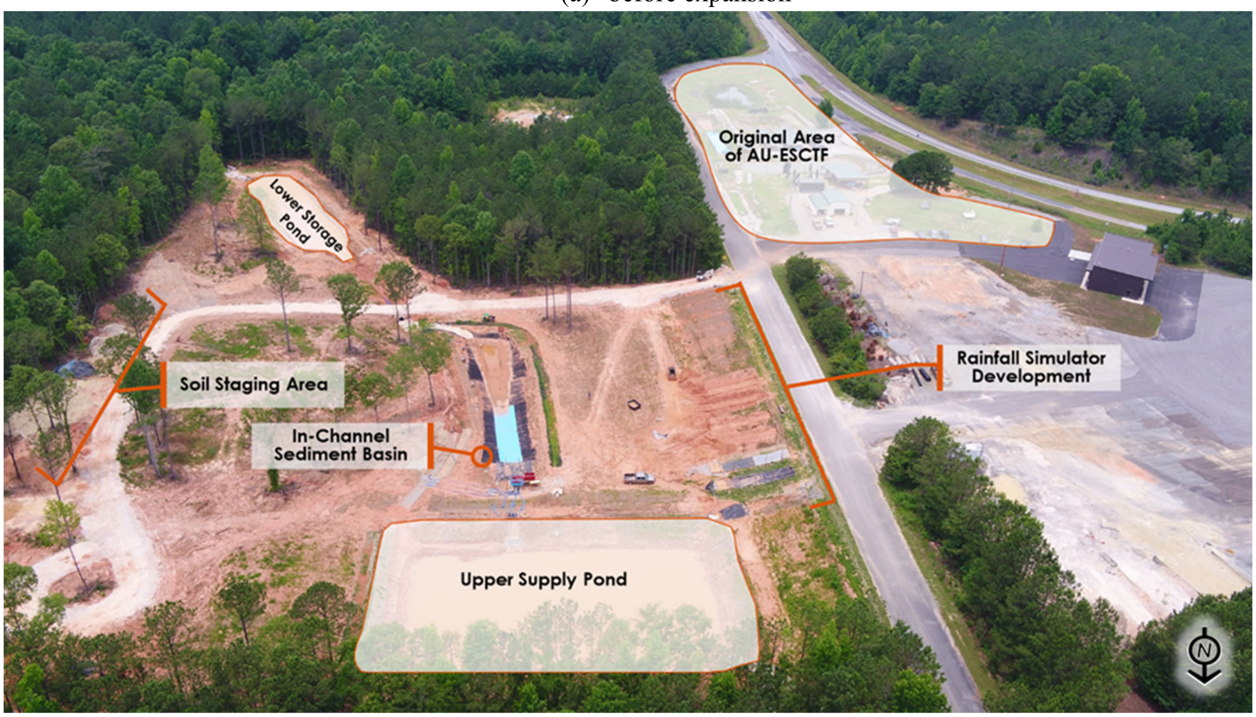
The AU-SRF is an outdoor research center aimed to improve and develop stormwater technologies and strategies, situated at the National Center for Asphalt Technology (NCAT) Test Track Facility in Opelika, AL. It was designed and constructed in 2009 to evaluate E&SC practices implemented by ALDOT during roadway construction but hosts research projects for additional state highway agencies and product manufacturers. Researchers at the AU-SRF have designed sediment, flow, and rainfall simulation apparatuses to evaluate the design, installation, and maintenance of ditch checks, inlet protection practices, sediment basins, sediment barriers, and erosion control practices. The findings from these projects have been presented in academic journals, technical reports, and conference proceedings, reflected in DOT standards, and communicated within the industry at annual in-person training events.

Since its inception, the AU-SRF has aimed its mission to create "environmental stewards within the construction industry by developing improved E&SC stormwater technologies and practices; advancing the body of knowledge through research and development, product evaluation, and training *(Samuel Ginn College of Engineering, 2021)*." This mission encompasses three primary focus areas: (1) research and development, which occurs through large-scale, performance-based testing (2) product evaluation, conducted through third-party, standardized testing methods and (3) training at hands-on field days and workshops for knowledge and technology transfer. Researchers at the AU-SRF are constantly engaged with the industry and identify industry needs through field and training events, professional organizations and meetings, mentorship, and connections with graduate students who entered the workforce.

The AU-SRF recently entered its second decade, and the area and capabilities of the outdoor laboratory were expanded. The once 2.25 ac (1.00 ha) facility recently gained an additional 7.5 ac (3.04 ha) through expansion activities. The expansion included two new storage ponds to increase the original water storage volume from 73,000 to 253,993 ft^3 (2,067 to 7,192 m^3). The AU-SRF before and after the expansion is pictured in Figure 2.1 (a) and (b), respectively.



(a) before expansion



(b) post-expansion 2021

Figure 2.1. Auburn University Stormwater Research Facility.

2.2.1. Erosion and Sediment Control Research from AU-SRF

This review incorporates the existing, formative literature generated from, and associated with, the AU-SRF and presents ongoing projects and capabilities. The projects reviewed are listed in Table 2.1.

Table 2.1. Summary of reviewed literature

Practice	Author/ Year	Test Type	Topic
Sediment Barriers	Zech et al., 2008	Small-Scale	Evaluation of Silt Fence Tie Backs
	Zech et al., 2007	Method	Silt Fence Tie Back Design Method
	Zech et al., 2009	Field	Field Evaluation of Silt Fence Tie Backs
	Bugg et al., 2017a	Large-Scale	Development of Large-Scale Sediment Barrier Testing Apparatus and Methodology
	Bugg et al., 2017b	Large-Scale	Evaluation of Silt Fence Installations
	Whitman et al., 2018	Large-Scale	Evaluation of Wire-Backed and Nonwoven Silt Fence Installations
	Whitman et al., 2019	Large-Scale	Evaluation of Innovative and Manufactured Sediment Barrier Products
	Whitman et al., 2020	Large-Scale	Evaluation of Silt Fence Dewatering Board
	Whitman et al., 2019	Small-Scale	Development of Geotextile Testing for Silt Fence Applications
	Liu et al., 2021	Model	Silt Fence Design Excel Tool
Ditch Checks	Donald et al., 2013	Large-Scale	Development of Large-Scale Ditch Check Testing Apparatus and Methodology
	Donald et al., 2014	Large-Scale	Evaluation of Wattle Ditch Checks
	Donald et al., 2015	Large-Scale	Evaluation of Silt Fence Ditch Checks
	Donald et al., 2016	Method	Hydraulic Method for Ditch Check Evaluation
	Whitman et al., 2021	Small-Scale	Hydraulic Performance Evaluation of Wattles
	Schussler et al., 2020	Field	Field Evaluation of Wattle and Silt Fence Ditch Check Installations
Inlet Protection/ Catch Basin	Perez et al., 2015	Large-Scale	Development of Large-Scale Inlet Protection Practices Testing Apparatus and Methodology
	Perez et al., 2015	Large-Scale	Evaluation of Inlet Protection Practices
	Basham et al., 2019	Large-Scale	Development of Large-Scale Catch Basin Insert Testing Apparatus and Methodology
Sediment Basin	Fang et al., 2015	Field	Field Evaluation of ALDOT Sediment Basin
	Perez et al., 2016	Large-Scale	Development of Large-Scale Sediment Basin Testing Apparatus and Methodology
	Perez et al., 2019	Large-Scale	Evaluation of Sediment Basin with Lamella Settler
	Liu et al., 2020	Bench- Scale	Optimization of Bench-Scale Lamella Settlers
	Perez et al., 2016	Model	Sediment Basin Design Excel Tool
	Schussler et al.,	Field	Field Evaluation of Iowa DOT Sediment Basins
Erosion Control	Shoemaker et al., 2012	Small-Scale	Evaluation of Anionic PAM as Erosion Control
	Ricks et al., 2020	Small-Scale	Evaluation of Mulches and Hydromulches as Erosion Control
	Ricks et al., 2019	Large-Scale	Development of Large-Scale Rainfall Simulator
UAV	Perez et al., 2015	Case Study	UAV E&SC Site Inspections
	Kazaz et al., 2021	Case Study	Object Detection of Stormwater Practices using UAS
Other	Perez et al., 2015	Method	Selection of E&SC based on Regional Hydrology

2.2.2. Sediment Barriers

Sediment barriers, commonly referred to as perimeter controls, are designed to intercept sheet flow and promote settling through impoundment. They often serve as a last-line defense before offsite discharge. Sediment barrier projects at the AU-SRF have ranged from small- to large-scale testing *(Mitchell et al., 1991; Zech et al., 2008, 2009, 2011; ASTM et al., 2007; Whitman et al., 2018, 2019a, 2019b, 2020; Perez et al., 2016; Bugg et al., 2017, Donald et al., 2016).*

In the year leading to the development of the AU-SRF, researchers began investigating silt fences as a sediment barrier. Design guidance suggested that silt fences should include tiebacks, or J-hooks, to avoid flow bypass and minimize erosion at the toe of installed fences; however, there was no quantitative evidence of its effectiveness. An intermediate-scale (1:6) testing apparatus was developed to compare a standard installed silt fence and silt fence with tiebacks. The model was 8 by 8 ft. (2.4 by 2.4 m) and situated at a 3H:1V slope. A rainfall intensity of 3 in. /hr (7.6 cm/ hr) was uniformly applied to a fully saturated silty sand soil to compare erosion and sediment capture exhibited by the standard silt fence and silt fence with J-hook. The average sediment discharge from the standard silt fence and silt fence with J-hook installations were 13,912 g and 1,455 g, respectively. The silt fence with J-hook acted as a temporary detention basin and provided 3.6 times the storage volume provided by the standard installation. As previously hypothesized, temporary detention allowed sedimentation to occur, which provided more treatment than filtration *(Zech et al., 2008)*. Zech et al., *(2009)* then conducted field evaluations, as described in the Field Testing section.

Zech et al., (*2011*) developed a method to design and place silt fence tiebacks along the perimeter of a construction site. The method implemented the Soil Conservation Service (SCS) curve number method to estimate construction site runoff volume from a storm. The storage capacity of silt fence tiebacks could be compared to the runoff from the given drainage area. This method provided information to designers on the adequacy of silt fences included in E&SC plans *(Zech et al., 2015).* Perez et al., (*2016)* expanded Zech et al., (2015) methods for efficient sizing methods of E&SC practices based on Technical Release–55. Geographic Information System Mapping (GIS) was used to collect information on regional hydrology, such as rainfall and soil curve number. Multiple linear regressions were used to predict storm volumes, peak flow rates, and 30-, 60-, and 90- minute peak volumes. Such models minimize extensive hydrologic analysis but allow E&SCs to be selected and sized according to site characteristics.

While silt fence tiebacks proved to enhance sediment capture, researchers cautioned that the increased storage would increase hydrostatic pressure on the silt fence and could result in catastrophic failure (*Zech et al., 2008 and 2011*). To quantify this impact, among others, a large-scale testing apparatus was developed at the AU-SRF, including a simulated flow and sediment introduction system. Trash pumps deliver water from a supply pond to an equalizing tank with a weir, where valves are used to achieve the desired flow depth and associate rate. Sediment is introduced using a hydraulic-driven conveyor belt. The calibrated flow and sediment are mixed in a trough, and the sediment-laden flow is applied to a 20 ft. (6.1 m) wide test slope. The 3H:1V impervious test slope was constructed of sheet metal with several diversion vanes to ensure well-mixed water and sediment delivery. A 12 ft by 20 ft (3.7 m by 6.1 m) earthen section was exposed upstream of the installed practice to represent field-like conditions. The test setup provided space to simulate design criteria for 0.25 to 0.50 ac (0.10 to .20 ha) per 100 ft (30.5m) of installed sediment barriers. The sediment barrier testing apparatus is shown in Figure 2.2 below.

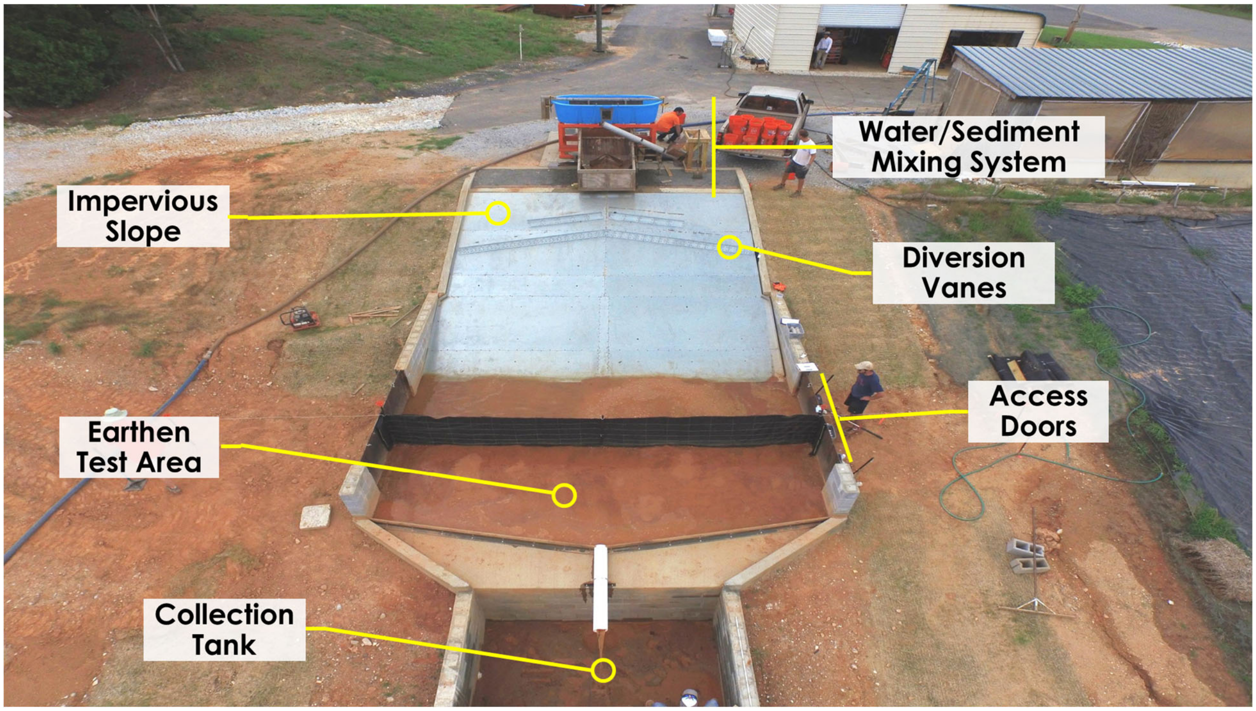


Figure 2.2. Sediment barrier testing apparatus.

Flow and sediment introduction were modeled using historical rainfall data from a 2-yr, 24-hr storm applied to a determined drainage area with an associated curve number. With this information, the peak 30-minute discharge was determined and used with the Modified Universal Soil Loss Equation (MUSLE) with the other required parameters, including volume of runoff, peak flow, erodibility, length-slope, cover management, and erosion practice factors.

Analyzed parameters included structural integrity monitored through photographs, erosion and sediment deposition tracked in topographical surveys, ponding depth, pool length, discharge flow rates, turbidity, and total suspended solids (TSS) of water quality samples from four locations. Water sampling locations were: (1) on test slope; (2) immediately upstream of sediment barrier; (3) immediately downstream of sediment barrier; and (4) at discharge pipe (*2*).

After developing the apparatus, Bugg et al., *(2017)* conducted testing on ALDOT silt fence installations: (a) manual trenched and (b) sliced installation of a wire-reinforced geotextile. The ALDOT standard included a 32 in. (81.3 cm) tall geotextile trenched or sliced into the ground and connected to steel woven wire reinforcement with galvanized C-rings. The wire backing was attached to studded 0.95 lb/ft (1.41 kg/m) T-posts, which is much less dense than AASHTO standard (1.25 lb/ft [1.9kg/m]), with aluminum wire ties. Posts were spaced the maximum allowable 10 ft (3 m) on-center. The Alabama Soil and Water Conservation Committee (AL-SWCC) silt fence was also tested. This installation implemented a woven, polypropylene-reinforced silt fence and a 2 by 2 in. (5.1 by 5.1 cm) hardwood stake configuration, spaced 4 ft (1.22 m) on-center, installed to a height of 24 in. (61 cm) *(Bugg et al., 2017).*

Sediment retention for each of the three installations was 82.7, 66.9, and 90.5%, respectively. The two ALDOT installations experienced structural failure during simulated rain events. In each failure episode, the center post deflected, causing overtopping of the impounded stormwater. The deflection in the steel post hindered the impoundment capability, thus limiting sedimentation. When compared to the AL-SWCC trenched silt fence, the hardwood posts did not deflect. In addition to post material, the AL-SWCC installation had post-placement at 4 ft (1.2 m) on-center, compared to ALDOT's 10 ft (3 m), which may have also aided in maintaining the structural integrity. The maintained structural integrity provided adequate time for sedimentation. Additionally, the woven geotextile used in the AL-SWCC installation had a lower flow-through value, which aided impoundment; however, the lower flow-through rate increased hydrostatic forces acting on the silt fence *(Bugg et al., 2017)*.

Continued large-scale testing was conducted in the sediment barrier apparatus at AU-SRF, evaluating eight modifications of wired-backed, nonwoven silt fence installations *(Whitman et al., 2018)*. The performance of the ALDOT standard evaluated by Bugg et al., (*2017*) was used as the performance baseline. Variations to the standard included decreasing geotextile height, increasing T-post weight, decrease post spacing, and adding a trench offset. Each installation was tested in three 30-minutes tests. Of the modifications, an installation with a fence height of 24 in. (61.0 cm), anchored with T-posts spaced 5 ft (1.5 m) on-center, and offset 6 in. (15.2 cm) downstream of the trench performed best. 93% of sediment was retained with 0.18 ft (0.004 m) post deflection. Whitman et al., *(2018)* named this installation the "heavy-duty silt fence (HDSF)," which is referenced again in a subsequent comparison study of sediment barrier in 2019. Whitman et al., *(2018)* concluded that increasing T-post weight and decreasing spacing increased silt fence performance.

Whitman et al.,'s *(2019)* study evaluated manufactured sediment barrier practices, including two manufactured silt fence systems, three sediment retention barrier (SRB) installations, and three manufactured SRBs in the sediment barrier apparatus at the AU-SRF. The HDSF (*Whitman et al., 2018*) was used as the study baseline. The two manufactured silt fence systems included a Georgia DOT Type C and multi-belted silt fence (MBSF). Compared to the HDSF, impoundment depths decreased by 25% and 55%, and flow increased by 27% and 45%, respectively, for the GDOT Type C and MBSF. GDOT Type C and MBSF sediment retention was 90% and 85%, respectively. Whitman et al., *(2019)* considered all tested systems and concluded that impoundment depths of 1 ft (0.30 m) or greater consistently retained 90% of sediment; however, impoundment depths of greater than 1.5 ft (0.46 m) had no increase in sediment retention capability. SRBs were the only products in the study to improve water quality *(Whitman et al., 2019)*.

Whitman et al.,'s 2020 study aimed to design and evaluate a silt fence that maintained its sediment retention and water quality standard but dewatered at a controlled rate to relieve increased hydrostatic pressure. This study also examined commonly used support posts for structural integrity and developed guidance for adequate post spacing. The large-scale testing apparatus at the AU-SRF was used to evaluate and compare performance between the HDSF and an alternative installation. The alternative installation implemented the same technique but had an additional component: a 24 by 24 in. (31 by 61 cm), 0.75 in (1.9 cm) thick, plywood dewatering board. Four 1 in. (2.54 cm) dewatering orifices were drilled along the centerline of the plywood board at 3, 6, 9, and 12 in. (7.6, 15.2, 22.9, and 30.5 cm) above the ground surface. A v-notch weir was cut along the top of the board, with its invert at 18 in. (45.7 cm) above the ground. A geotextile underlay with riprap was installed at the back toe of the dewatering board to minimize downstream scour. Silt fence installations were compared for sediment retention, water quality, and effluent flow rate *(Whitman et al., 2020).*

The silt fence installation, including the dewatering board, had 96% sediment retention by volume. Although the dewatering board decreased dewatering time from 24+ hour to 4 hours, the sediment retention by volume was not adversely affected. The sediment retention of the dewatering board installation proved to be consistent with the average sediment retention (91%) of silt fence systems evaluated by Whitman et al., *(2018)* and Donald et al., *(2016).* The average turbidity was 944 Nephelometric Turbidity Units (NTU) with the dewatering board installed, compared to ~1,000 NTU without a dewatering board. However, there were differences exhibited during dewatering. The standard installation was blinded with sediment after repeated loading and thus had water retention exceeding 24 hrs, whereas the dewatering board allowed the alternative installation to dewater in 4 hrs. In addition to the dewatering board, five post types were evaluated in an automatic load testing machine to determine maximum post spacing. Three metal T-post with unit weights of 0.95, 1.25, and 1.33 lb/ft (01.4, 1.9, and 2.0 kg/m) and two hardwood posts with cross-section dimensions of 1.3 by 1.6 in (3.3 by 4.1 cm) and 1.8 by 1.8 in (4.6 by 4.6 cm) were each tested three times, for a total of 15 tests. Structural analyses indicated that maximum spacing for these posts should be 3.94, 5.91, 7.87, 4.92, and 4.92 ft (1.2, 1.8, 2.4, 1.5, and 1.5 m), respectively *(Whitman et al., 2020)*.

Following Whitman et al.,'s studies on design and installation improvements, researchers constructed a small-scale flume test to evaluate effluent flow rates, sediment retention, and water quality impacts of varying silt fence geotextiles (*Whitman et al., 2019 and 2020*). While ASTM D5141 exists to evaluate the filtering performance of geotextiles, flow and sediment introduction rates are limited *(ASTM 2018).* Whitman et al.,'s modified method applied regionally specific hydraulic and sediment loading expected for the peak 30 minutes of the 2-yr, 24-hr storm to test realistic parameters. Previous AU-SRF studies found that filtering is a secondary function of silt fence s, and the majority of sediment is removed through sedimentation (*Zech et al 2008*). Thus, filtering performance tests like ASTM D5141 were not indicative of the entire treatment provided by a given geotextile. Two nonwoven and three woven silt fence geotextiles were individually installed in a 4 by 16 by 3 ft (1.2 by 4.8 by 0.9 m) polypropylene-lined wooden flume lined. Water and sediment introduction occurred on a 3H:1V slope that transitioned to 1%, where the silt fence installation was located. Flow introduction followed the methodology from Bugg et al., (*2017*); however, sediment was introduced by hand at a rate of 7.5 lb/min (3.3 kg/min). All geotextiles tested had reported effluent flow rates ranging from 93 to 324 gpm/ft^2 (3,784 to 13,183 lpm/m^2) during ASTM clean water tests.

During Whitman et al.,'s *(2019)* sediment-laden tests, flow rates were reduced to a range of 0.86 to 10.45 GPM/ft^2 (35.2 to 425.7 lpm/m^2) during testing and 0.18 to 0.96 GPM/ft^2 (7.4 to 39.2 lpm/m^2) during dewatering. Data collection indicated that flow rates were 43% lower for nonwoven than woven geotextiles and had average sediment retention of 97% and 91%, respectively. Water quality analyses indicated that during flow, 46% of turbidity reduction occurs due to sedimentation, whereas turbidity reduction during dewatering occurs through filtration (19%) (*Whitman et al., 2019*).

Sediment barrier research at the AU-SRF has developed testing methods to evaluate silt fence design and installation and performance-based metrics to evaluate support posts and geotextiles used in silt fence applications. AU-SRF sediment barrier research revealed that sediment barriers provide primary treatment through sedimentation, which guided design improvements, including the heavy duty silt fence (HDSF), dewatering board, and selection of support posts and silt fence material. These design improvements are now reflected in the ALDOT standard drawings. For ease of implementation, Liu et al., developed spreadsheet-based design tool for silt fence sediment barriers. Regional hydrologic and volumetric parameters are considered, and yield size and estimate maintenance requirements for silt fence sediment barrier segments in linear, J-hook, and C-configurations (*Liu et al., 23)*.

2.2.3. Ditch Checks

Ditch checks, or check dams, are installed within conveyance channels to intercept flow, decrease flow velocity and create impoundments of subcritical flow. Such impoundments reduce erosive forces, shear stress along the channel surface and promote sedimentation. Ditch checks are commonly assembled from various materials, including silt fence, wattles, riprap, sandbags, hay bales, and other proprietary products (*Schussler et al., 2021*). The AU-SRF designed and installed a testing apparatus to evaluate channelized flow E&SC practices. The research includes methods for hydraulic performance characteristics and installation methods for wattle and silt fence ditch checks (*ASTM 2018 and Donald et al., 2016*).

The large-scale channelized flow apparatus at the AU-SRF, shown in Figure 2.3, was designed considering ASTM D7208-06 (*ASTM 2006*). The trapezoidal test channel had a longitudinal slope of 5% with a depth of 1.5 ft (0.5 m) and top and bottom widths of 13 ft (4 m) and 4.0 ft (1.2 m), respectively. In total, the channel is 40 ft (12 m) long with a 25 ft (7.5 m) sheet metal lined section and 15 ft (4.6 m) earthen section for practice installation. Flow introduction followed the methods as described in Bugg et al., (*2017*). Eight cross-sections spaced 3 ft (91.4 cm) apart lengthwise, and eight cross-sections spaced 1 ft (30.5 cm) apart were used to mark points for erosion and sedimentation, water depth, and velocity measurements (*Donald et al., 2013*).

Figure 2.3. Photo of ditch check test apparatus.

In total, seven wheat-straw wattle installations were tested, with varied staking configurations, the geotextile underlays, trenching, and ground anchoring. The control installation was the previous ALDOT standard: concave upstream wattle, secured through the media with wooden stakes every 2 ft (0.6 m), and driven at least 1.5 ft (0.5 m) into the ground. After testing, results indicated that the subcritical impoundment length was improved by 99%, including teepee staking, geotextile underlay, and sod stapling. Results from this testing influenced ALDOT to modify their detail for enhanced impoundment, decreased channel erosion, and increased sediment capture *(Donald et al., 2013).*

In continued testing, Donald et al., *(2016)* evaluated the hydraulic performance exhibited by five wheat straw, two excelsior fiber, and one synthetic fiber-filled wattles. The installation determined as most effective and feasible (MFE) was repeated for each wattle type (*Donald et al., 2013*). Water depth and velocity measurements were taken once steady-state flow was achieved. Researchers determined that reducing the velocity head and increasing depth defined a ditch check's ability to impound flow. Results indicated that fill density, rather than material, was the most significant mitigating factor for creating and sustaining impoundments at medium and high flow conditions (*Donald et al., 2014*).

The methodology described in Donald et al., (*2014*) was replicated to evaluate various silt fence ditch check installations. The baseline installation used ALDOT's standard detail requiring a 45-degree V-shaped installation, pointed downstream, concave to the flow path. T-posts were to be installed at the center of the V and on either side. Posts were spaced 10 ft (3 m), with a 6 by 6 in. (15.2 by 15.2 cm) trench, wire backing reinforcement, and 32 in. (81.3 cm) above ground height. The ALDOT standard was compared to four other modified installations with varied energy dissipaters, underlays, and dewatering weir at the vertex. The best performing installation included: a weir, geotextile splash pad and stone energy dissipater, and geotextile underlay pinned to the channel bottom. The ALDOT pinned installation was then subjected to a longevity test with sediment-laden runoff introduced, following the methodology from Bugg et al., (*2017*). After 6 tests in two months, pre-and post-test surveys indicated that 91.2% of sediment introduced was retained; however, some erosion occurred downstream of the practice, potentially due to flows from quickly dewatering returning to supercritical flow state (*Donald et al., 2015*).

The increased height of silt fence ditch checks, compared to alternative ditch checks, allows longer spans of a channel to be protected due to impoundment depth, which minimizes the cost of ditch checks needed in a single channel. This research determined that a weir on silt fence ditch checks allows the practice to control its discharge to enhance the structural integrity and sediment capture. The weir, splash pad, and appropriate ground anchoring improved structural integrity and were adopted by ALDOT (*Donald et al., 2015*).

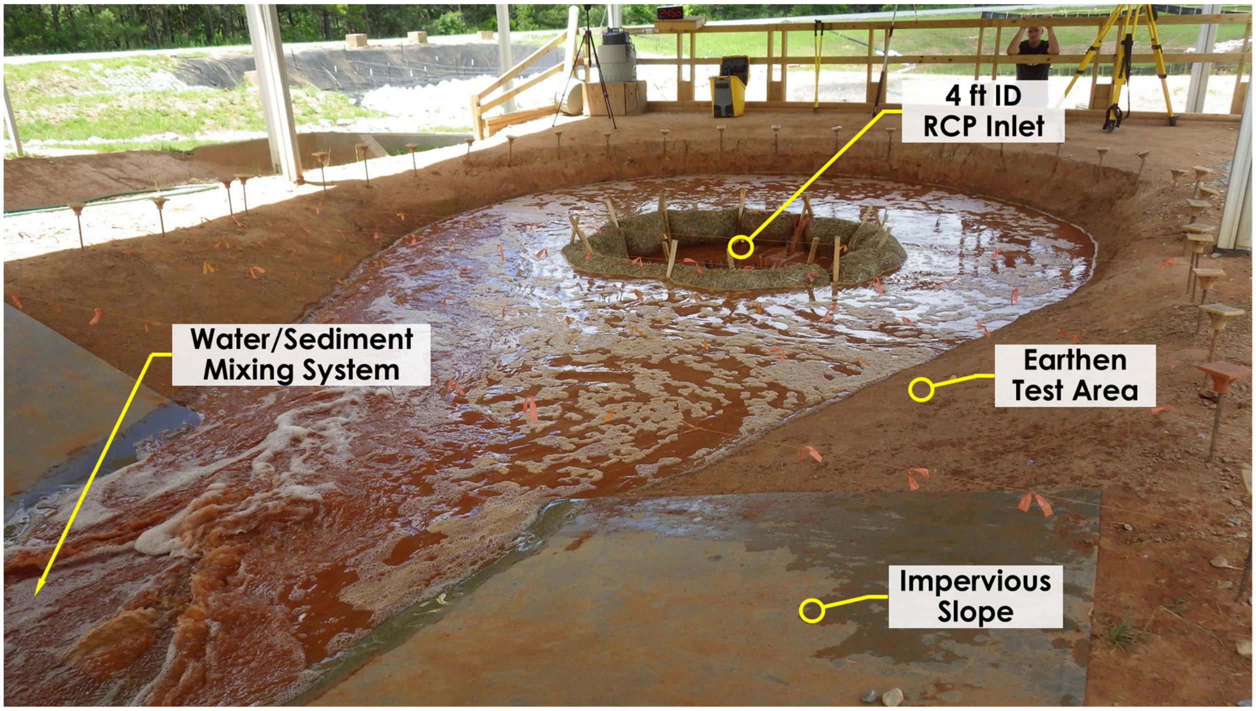
Donald et al., developed a hydraulic performance criterion to compare wattle ditch checks in varying channel and flow conditions (*Donald et al., 2016*). The performance considered sub- and supercritical flows to characterize ditch check performance. Donald et al., plotted the Froude number (F), considering flow velocity, gravity, and hydraulic depth, versus water depth (y) to specific energy (E) ratios (i.e., y/E) for open-channel flow. A third-order polynomial relationship was generated after plotting the data. An inflection point was identified on the curve at $y/E = 0.75$ and F of approximately 0.8. This indicated a change in flow behavior that would improve impoundment and increase sedimentation potential with a decreasing F. This research allowed large-scale test data to be normalized and compared, despite varying flow conditions (*Donald et al., 2016*).

Building on Donald et al.,'s 2016 performance criterion, Whitman et al., *(2021)* evaluated the effects of wattle fill material and encasement on hydraulic performance through clean water tests. Eight wattles were tested in a hydraulic flume at Iowa State University and classified into one of the four following classes (C1-C4). C1 was the least effective at sustaining subcritical flows and had depth and length ratio percent differences less than 20% and 30%, respectively. C2 and C3 indicated depth percent differences ranging from 10% to 20% and length percent differences ranging from 20% to 30% for C2 and 10% to 20% for C3. C4 was the most effective at maximizing subcritical flows. Only miscanthus grass filled wattles were classified C4, with a depth and length percent difference less than 10%. Results suggest that excelsior wattles fall into C1; wheat straw wattles in C2; coconut coir, wood chips, synthetic wattles in C3; and miscanthus wattles in C4 (*Whitman et al., 2021*).

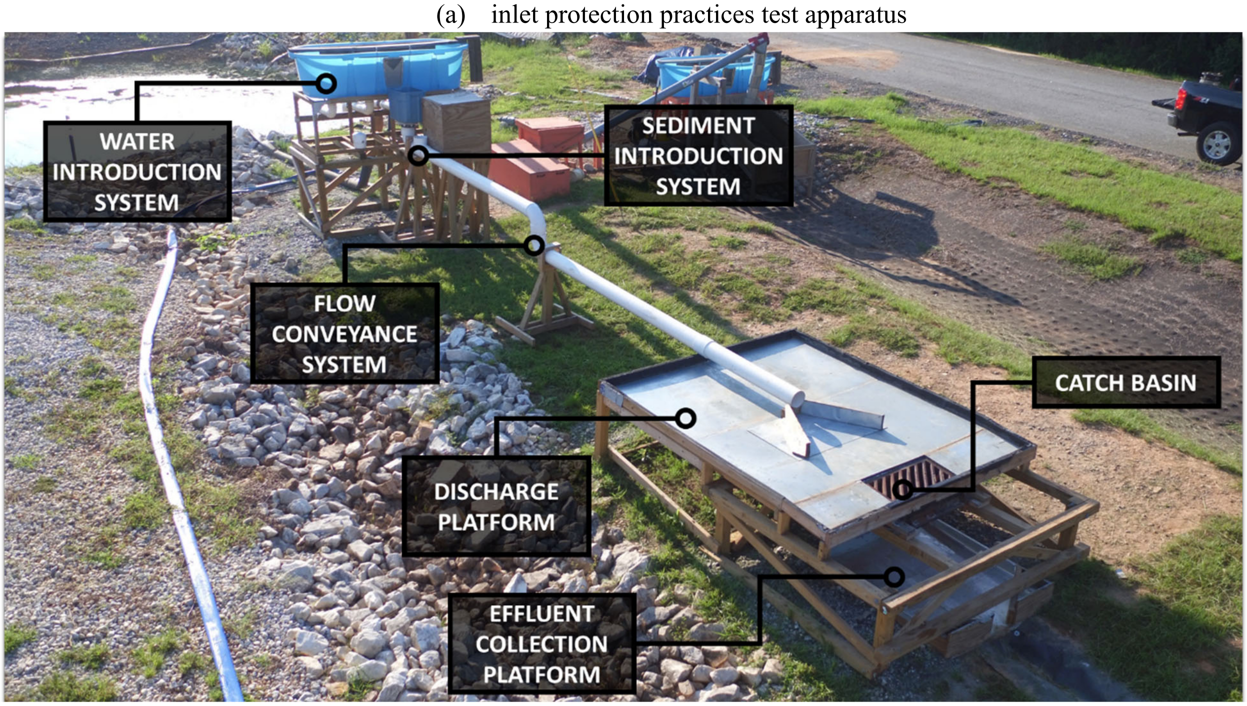
The AU-SRF developed methods to evaluate ditch check practices, which has led to improvements in installation in ALDOT and beyond. Ditch check test apparatuses at the AU-SRF are continually maintained for future ditch check evaluations.

2.2.4. Inlet Protection Practices and Catch Basin Inserts

Storm drains collect and convey stormwater runoff to a subsurface system. This subsurface drainage system is installed and connected early in construction phases and leaves inlets susceptible to erosion and collection of sediment. Inlet Protection Practices are required during construction to impound stormwater, prevent erosion, and promote sedimentation to minimize the offsite transport of sediment. In post-construction applications, catch basin inserts are manufactured systems installed into existing storm drain inlets or catch basins to treat runoff before entering the subsurface system to minimize clogging or transport of pollutants. Large-scale testing apparatuses for both inlet protection practices and catch basin inserts have been constructed at the AU-SRF considering ASTM D7351-07 (*2007*) and are shown in Figure 2.4(a) and 4(b), respectively.



(a) inlet protection practices test apparatus



(b) catch basin insert test apparatus

Figure 2.4. Test apparatus.

An inlet protection practice test channel was designed and installed at the AU-SRF according to the ALDOT median stormwater conveyance channels. The channel measured 44 ft (13.4 m) in length, 19 ft (5.8 m) in width, with a 4 ft (1.2 m) channel bottom, and is situated at a

5% slope where 20 ft. (6.1 m) of the channel is sheet metal, and 24 ft (7.3 m) is earthen with a 4 ft. (1.2 m) storm drain inlet structure.

A water introduction system was designed to achieve and monitor flow rate, as described in previous sections. Sediment was introduced through a 6.0 in. (15.2 cm) grain auger, calibrated to meet the desired introduction rate. Data collection included pre-and post-test channel surveys, ponding length and depth, flow velocity, and water quality (turbidity and TSS). In tests conducted for ALDOT, an inlet protection practice was subjected to a flow rate of 1.25 ft^3/s (0.035 m^3/s) and sediment loading rate of 46.7 lb/min (21.2 kg/min) for a 30-minute test to mimic the peak flow of a 2-yr, 24-hr storm in Alabama (*Perez et al., 2015a and 2015b*). ALDOT inlet protection practices including, aggregate, sandbag, silt fence, and wattle barriers, were evaluated in the test channel at AU-SRF. Installation techniques varied to improve structural integrity and thus sediment retention (*Perez et al., 2015*).

The standard ALDOT aggregate inlet protection practice detailed a 1.5 by 5.5 in. (3.8 by 14 cm) raised lumber board installed 2 ft (61 cm) outside the inlet. A rock berm with 1 ft (30.5 cm) top and 1H:1V slopes installed on top of a geotextile underlay served as the inlet protection practice. Clean water tests resulted in a dewatering time of 2 minutes. The most feasible and effective (MFE) installation replaced the lumber with concrete blocks and wrapped the blocks and rock in geotextile. These improvements increased the impoundment length by 110% and increased the dewatering time to 13 minutes (*Perez et al., 2015*).

The ALDOT sandbag inlet protection practice called for an 8 ft (2.4 m) diameter stacked sandbags, ensuring no gaps. In total, sandbags were required to be stack three high, two sandbags wide on the first two rows, and a single sandbag on the top. To minimize dislodging of sandbags and short-circuiting, an underlay was added under the installation. In addition, the diameter was decreased to 6 ft (1.8 m), and the middle row of sandbags was rotated 90 degrees. This installation increased the impoundment length by 171% and dewatered in 120 minutes (*Perez et al., 2015*).

The industry-typical silt fence inlet protection practice created a 7 by 7 ft (2.1 by 2.1 m) square around the inlet and used T-posts and wire back to support the geotextile. During testing, the installation failed due to the hydrostatic pressuring, causing cave-in. The silt fence inlet protection practice installation included lumber bracing along the top perimeter of the silt fence square with diagonal bracing. The silt fence was blinded with sediment, so a dewatering board was added to aid dewatering and decreased time from more than 24 hours to 90 minutes (*Perez et al., 2015*).

The last tested inlet protection practice was a wattle barrier. The ALDOT standard wattle inlet protection practice called for a 20 in. (50.8 cm) diameter wattle installed in a 5 ft (1.5 m) diameter circle around the inlet and secured by wooden stakes spaced 3 ft (1 m) apart. During testing, the wattle became buoyant and allowed the flow to pass underneath. A geotextile underlay was added, and the wattle was secured to the channel bottom with sod staples and stakes to combat the buoyancy. Impoundment length was increased by ten times, with a dewatering time of 9 minutes (*Perez et al., 2015*). This study aided ALDOT and DOTs with similar inlet protection practices to improve standard designs and selection of inlet protection practice type.

In later testing, the Ohio Department of Transportation (ODOT) was interested in evaluating catch basin inserts for post-construction applications. The Ohio EPA specified that TSS must be reduced by 80% from post-construction practices but lacked scientific data for approved designs and products *(Ohio Environmental Protection Agency 2013)*. Researchers at the AU-SRF designed an apparatus where a manufactured ODOT Type 3A catch basin frame was installed *(Ohio Department of Transportation [ODOT], 2016)*. Flow was introduced following the procedure in Bugg et al., 2017 but implemented a v-notch weir. A 0.75 in. (1.91 cm) feeder controlled sediment introduction. Flow and sediment mixed when introduced into a 20 ft (6.1m) long, 6 in. (15.2 cm) polyvinyl chloride (PVC) pipe at a 2% slope. The pipe surfaced on the 8 by 8 ft (2.4 by 2.4 m) drainage platform, even with the top of the catch basin. Raised plywood was installed to mimic a curb (*Basham et al., 2019*).

Flow and sediment introduction rates were adopted from the ODOT Location & Design Manual, Volume Two *(ODOT, 2018)*, which used the rational method with a curve number of 0.9 and rainfall intensity of 0.65 in./hr (16.5 mm/hr), but can be adapted for other geographical locations. Researchers selected a small, medium, and large (0.1, 0.2, and 3 ac [0.04, 0.08, and 1.2 ha], respectively) drainage area for testing. The corresponding flow and sediment introduction rates for each 70-minute test were 0.06, 0.12, and 0.18 ft^3/s (1.7, 3.4, and 5.1 L/s) and 7.1, 14.2, and 21.3 lb (3.22, 6.44, and 9.66 kg), respectively (*Basham et al., 2019*). Catch Basin Inserts were evaluated for sediment retention and TSS reduction. A nonproprietary catch basin insert was developed from nonwoven geotextile with an apparent opening size of 300 microns for preliminary testing. The bag also had an overflow cutout. TSS removal was 57, 53, and 49% at the low, medium, and high flow conditions. Overflow conditions were reached in the medium and high flow conditions, reducing efficiency due to the discharge of untreated water. This research developed an apparatus and testing methods to analyze proprietary and nonproprietary catch basin inserts quantitatively (*Basham et al., 2019*).

Research on inlet protection practices and catch basin inserts has informed designers nationwide on practice efficiency and improved design. Enhanced performance of such practices minimizes sediment and pollutants reaching our nation's subsurface drainage system and minimizes intensive maintenance and water treatment (*Basham et al., 2019*).

2.2.5. Sediment Basin

Sediment basins are a temporary sediment control practice typically employed on construction sites to detain sediment from stormwater runoff before discharge. Sediment basins are heralded in the construction industry for effective sediment capture; however, design and installation techniques vary nationwide. In the past decade, researchers at the AU-SRF have conducted field-, large-, and small-scale projects to evaluate the performance of sediment basins.

Before developing a sediment basin testing apparatus at the AU-SRF, Fang et al. *(2015)*, monitored a sediment basin during highway construction for three months in Franklin County, AL, as described in Field Testing section. To eliminate influence from unpredictable field variables, a large-scale sediment basin was designed and installed at the AU-SRF to evaluate performance with reproducible results. The installed basin had a total volume of 2,790 ft^3 (79.0 m^3), and is shown in Figure 2.5. The 3,600 ft^3/ac (252 m^3/ha) design criterion was applied, and flow and sediment rates were calculated to mimic the local 2-yr, 24-hr rain event. The SCS Type III local 2-yr, 24-hr storm event over a 0.242 ac (0.0.98 ha) area resulted in a flow introduction rate of 1.50 ft^3/s (0.042 m^3/s) for a 30-minute experimental test. The peak discharge from this storm was plugged into the MUSLE to estimate sediment yields based on individual storm events. The estimated soil loss resulted in 1,348 lb. (611 kg), or 44.9 lb/ min (20.4 kg/min) for 30 minutes (*Perez et al., 2016*).

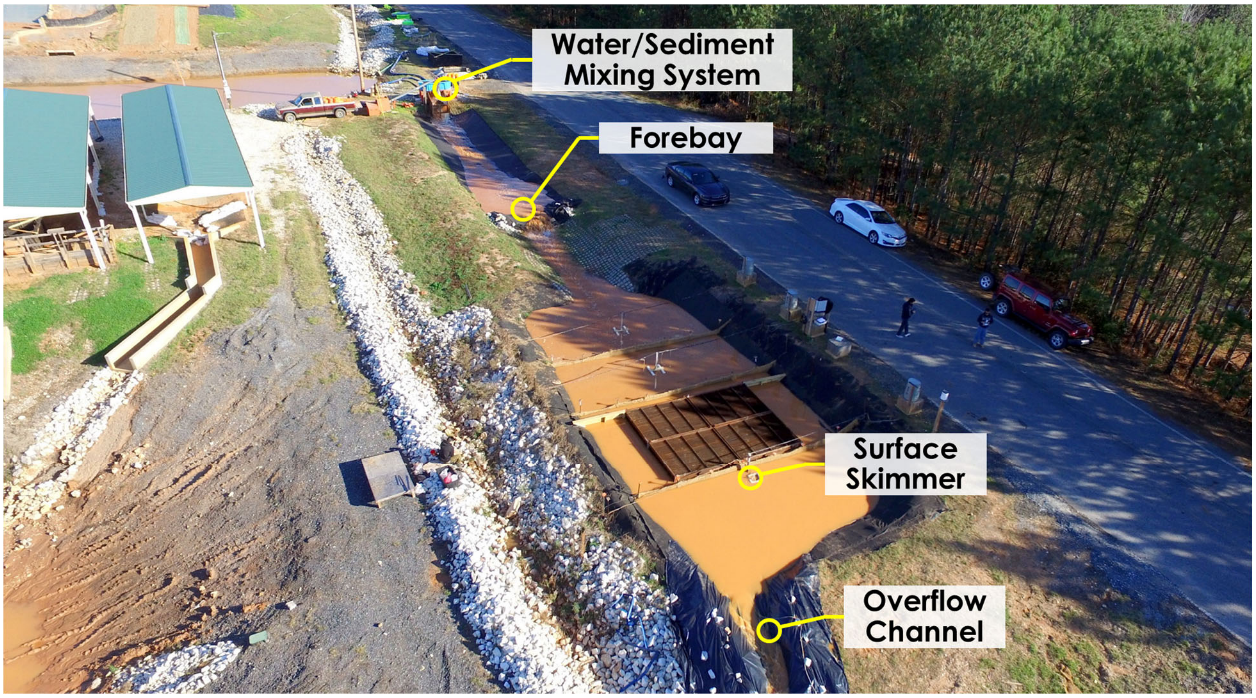


Figure 2.5. Sediment basin at the AU-SRF.

During large-scale testing, the sediment basin performance was evaluated when incorporating baffles, an excavated sump, and lamella settling technology using a triplicate testing regime. Each component was installed in a clean and empty basin and tested three times (filling and dewatering completely). Data collection during testing included analysis of water quality, flow rate, basin storage, sediment deposition, and sediment sampling for particle characterization to evaluate the performance of the basin in response to each installation. After the MFE design was selected, the basin was tested in filling and overflow conditions. Preliminary results indicated that the excavated sump upstream of the basin had no significant effect on the performance of the capture efficiency of the basin. However, the area allowed for capture and storage of sediment within the channel where dredging and maintenance activities would be easier to perform. The second treatment, modified coir baffle system with reduced percent open areas (POA) (10.9% vs. 21.7% POA), was less effective in treating turbidity within the basin than the standard baffle.

Testing high-rate lamella settlers within the third bay, in both an (a) upward flow and (b) parallel flow, provided turbidity reduction of 18.2% and 29.0%, respectively *(Perez et al., 2019)*.

Following the increased turbidity reduction exhibited in the basin by the lamella settlers, three small-scale reactors (22.0 by 12.5 by 13.5 in. [56 by 32 by 34 cm]) were designed to study optimized settling with lamella plates. The three reactors included (a) control with no plates, (b) reactor with nine plates at 1.0 in. (2.5 cm) spacing, and (c) reactor with 18 plates spaced 0.5 in. (1.3 cm). Lamella plates were 9.8 by 10 in. (25 by 25.4 cm) and installed at a 55-degree angle. Five synthetic soils were individually mixed with water and introduced into the tanks to achieve one of three study residence times (0.5, 1.0, and 1.5 hours) at three different concentrations (500 mg/L, 1,000 mg/L, and 5,000 mg/L). Turbidity reduction and particle size distribution were recorded to optimize the design of the small-scale settlers. The highest turbidity removal rates were exhibited using a 1.5 hr residence time with 18 plates spaced 0.5 in. (1.3 cm) apart. Turbidity reduction ranged from 62.8% to 90.0%. A full-factorial method model was developed to predict turbidity reduction from inflow concentration, plate spacing, and residence time using the measured data. This study is expected to guide designers in implementing full-scale lamella settlers in sediment basins and provide turbidity reduction predictions (*Liu et al., 2020*).

As a product of the large-scale sediment basin testing at the AU-SRF, Perez et al., *(2016)* developed an open-source, hydrologic-based design tool SEDspread. This tool allows designers to select site-specific parameters, including sizing factor (i.e., 2-yr, 24-hr storm, or 3,600 ft^3/ac [252 m^3/ha]). Additionally, soil and storm data were derived from geospatial data for an entered U.S. mailing zip code. The tool then produces the basin capacity, configuration, and dewatering rate to achieve regulation. If desired, SEDspread contains a section for baffle design, where the user can indicate the number of bays and post spacing. The tool uses this user data, with the basin geometry, to determine the length of each bay, the number of required posts, the height of the baffle, and the total length of the required material. A case study was performed on two local construction site sediment basins in Auburn, AL, which compared site basin design and implementation to SEDSpread outputs. The two studied basins were sized for 3,600 ft^3/ac (252 m^3/ha) criteria and volumetrically undersized for the 2-yr, 24-hr storm, according to SEDSpread, by a factor of three, a similar conclusion reached during fieldwork by Fang et al., *(2015)* (*Perez et al., 2016*).

Sediment basin research from the AU-SRF has been incorporated into the ALDOT standard drawings and the AL Handbook for E&SC and serves as an example for basin design throughout the country. Outside of the state, SEDspread's unique capability to be customized with geospatial data allows designers nationwide to create and verify sediment basin designs. Following research at the AU-SRF, Schussler et al., (*2020*) field monitored a single in-series, in-channel sediment basin design for the Iowa DOT, which indicated negligible turbidity and TSS reductions. Researchers aimed to incorporate and test design improvements on an in-channel basin during construction; however, timeline, contractor, and area constraints did not allow for installation and evaluation, which is described in Performance during Field-Monitoring (*Schussler et al., 2020*). Instead, researchers continued work at the AU-SRF in in-channel sediment basin design, which is described in detail in Chapter Four: In-Channel Sediment Basin Performance Improvements through Large-Scale Testing.

2.2.6. Erosion Control

In addition to the many sediment control practices researched at the AU-SRF, hydromulches and rolled erosion control products have been investigated at small-, medium- and large scales. Erosion control practices aim to prevent the dislodgment of soil by covering or stabilizing bare soil.

To begin research on erosion control products at the AU-SRF, a small-scale rainfall simulator apparatus was constructed to simulate the 2-yr, 24-hr storm in central Alabama (4.0-4.5 in. [10.2-11.4 cm]). Rainfall was simultaneously applied to two 4 by 2 by 0.25 ft (1.2 by 0.6 by 0.08 m) plots, which mimicked a 3H:1V fill slope. The plots were packed to 95% density with native Alabama soils. The plots were treated with various doses of anionic polyacrylamide (PAM) (15, 25, and 35 lb/ac [16.8, 28, and 39.2 kg/ha]) through two treatments: dry and semi-dissolved solutions and subjected to four 15-minute rainfall events, totaling 4.4 in. (11.2 cm), and compared to a bare soil test for sediment retention and turbidity reduction. Dry PAM, applied at a rate of 35 lb/ac (39.2 kg/ha), reduced soil loss by 50% and reduced turbidity up to 97%. The semi-dissolved PAM, applied at the same rate with a 48-hr drying period, reduced soil loss by 76% and turbidity by 69%. While both applications provided increased treatment compared to the bare soil test, researchers suggested the dried PAM performed better as a sediment control and semi-dissolved PAM performed better as EC, as indicated by soil loss and turbidity reduction (*Shoemaker et al., 2012*).

Using the same rainfall simulator apparatus and analysis methods, researchers continued testing on two mulches and four hydromulches. All hydromulches were applied according to manufacturer recommendations. The treatments to the baseline, bare soil test included (1) conventional straw, crimped, (2) conventional straw, tackified, (3) wood fiber hydromulch (2,000-2,500 lb/ac [2,241-2,802 kg/ha]), (4) straw and cotton hydromulch (2,000 lb/ac [2,241 kg/ha]), (4) cotton fiber-reinforced matrix hydromulch (3,500 lb/ac [3,923 kg/ha]), and (6) bonded wheat fiber matrix hydromulch (3,000 lb/ac [3,362 kg/ha]). When compared to the bare-soil test, the mulches reduced turbidity by 80%, 98%, 85%, 92%, 95%, and 99%, and soil loss by 96%, 98%, 94%, 97%, 99%, and 100%, respectively *(Ricks et al., 2020).* Turbidity and sediment loss reduction values indicated that mulches were an effective EC; however, researchers advised that future erosion control studies be conducted through full-scale testing. As the AU-SRF grew, a 40 by 8 ft (12 by 2.4 m), 3H:1V slope was constructed with ten sprinklers to supply uniform rainfall, as shown in Figure 2.6 (*Ricks et al., 2019*).

When designing the first plot at the AU-SRF, researchers considered ASTM D6459-15, the standard for determining the performance of rolled erosion control products under rainfall simulation (*ASTM 2015*). The standard applies the Revised Universal Soil Loss Equation (RUSLE) to determine the soil erodibility (*K*) of the soil used and cover management factor (*C*), provided by a rolled product. The rainfall simulator at the AU-SRF targeted to meet the rainfall intensities of 2.0, 4.0, 6.0 in/hr (50.8, 101.6, and 152.4 mm/hr) for 20 minutes each, consecutively, for a total test time of 60 minutes (*Schussler et al., 2020*). Four 14 ft (4.27 m) sprinklers were installed on each length side and one sprinkler on each width side to achieve this. Windscreens were installed to prevent the influence of outside environmental elements. During calibration testing, the sprinklers provided rainfall intensities with relative errors ranging between 1.17 and 4.00% and uniform rainfall distributions of 85.7 to 87.5% (*Ricks et al., 2019*).

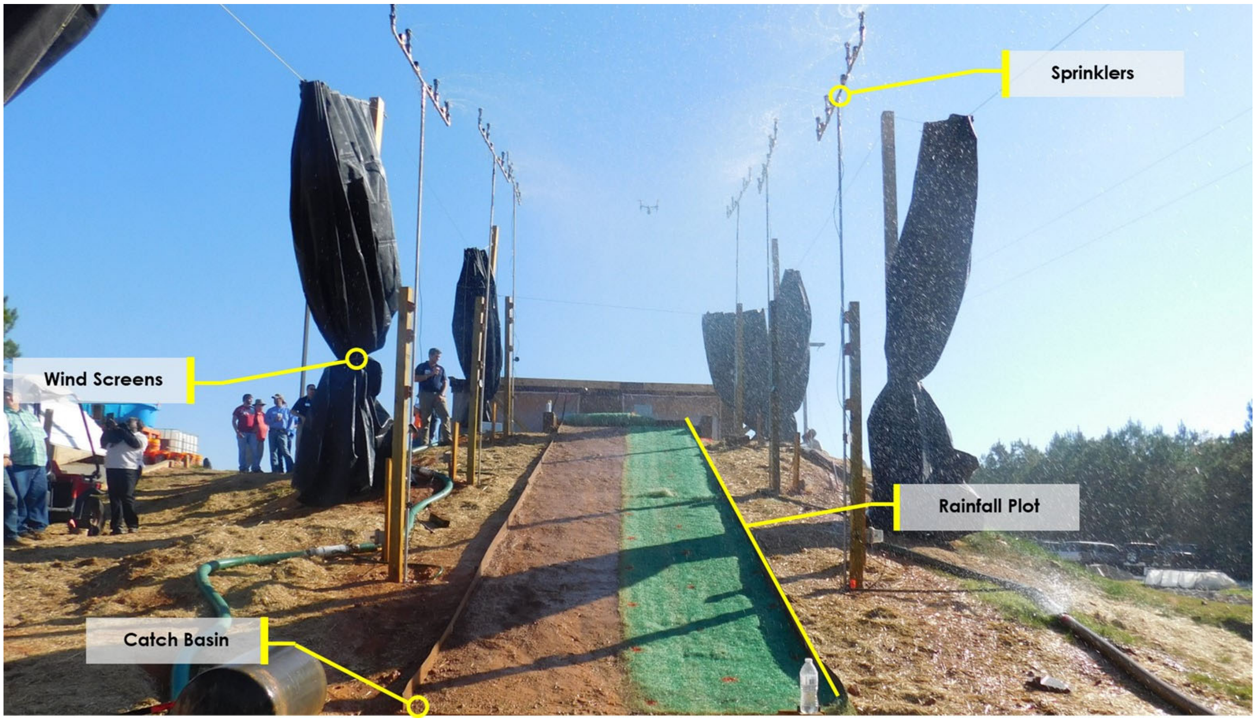


Figure 2.6. Rainfall simulator plot.

In addition to the existing rainfall slope, six 3H:1V plots and six 4H:1V plots are being constructed at the AU-SRF, with an expected completion of 2022. The plots will be filled with three different soil types to analyze erosion control products for their application on various topographies and soils.

2.2.7. Technology Transfer and Training

In addition to scholarly contributions, the AU-SRF disseminates stormwater knowledge gained from research through various channels, including social media platforms, such as LinkedIn™, Twitter™, YouTube™, Facebook™ and in-person conference and training events. Since 2014, the AU-SRF has opened annually to practitioners to teach design, installation, and maintenance methods in a combination of classroom and hands-on activities. The training event includes a 1.5- day hands-on installer training event that includes a half day of classroom instruction and a full day of field instruction, and a 1-day field day where runoff events are simulated in the large-scale apparatuses. This allows practitioners to observe the impoundment and sediment retention efficiencies of varying E&SC installations and products. Demonstration areas include hydroseeding; construction exit pad and housekeeping; stockpile management; sediment barriers; erosion control blankets; ditch check practices; channelized flow; surface skimmers; floating turbidity barrier; silt fence installation; perimeter control techniques and slope interrupters; slope drains, outlet control, and level spreader; sediment basin; inlet protection practices; and pipe inlet protection *(Perez et al., 2019)*.

More than 750 participants have attended training events at AU-SRF and included regulators, inspectors, supervisors, installers within DOTs, county and city agencies, private builders and engineers, and the environmental community and citizens. As a result of pre- and post-training event surveys distributed to participants, Perez et al., (*2019*) found that technical knowledge level was increased by an average of 82% and 36% for the hands-on and field day training, respectively. Classroom activities and demonstration areas are continually developed and advanced with ongoing research at the AU-SRF to fulfill the training portion of the mission statement.

2.2.8. Impact

Since its inception, the AU-SRF promoted a desire to improve how construction stormwater is managed in Alabama. An initial desire to challenge or confirm, through scientific testing, traditionally accepted as "best" management practices, created opportunities to learn how commonly used practices could be made more effective. Over the past decade, an intentional effort to communicate research findings and advance the state of practice in Alabama and beyond has produced practical and implementable outcomes. While there are still many states with antiquated construction stormwater management approaches, rules of thumb E&SC designs are largely being phased out with the availability of scientifically-backed design guidance. Scientifically-based design has been adopted in Alabama and has influenced the design and research decisions and programs across the U.S.

2.3. Integration of Large-Scale Testing Into Field Validation

Several modified silt fence and wattle ditch check design and installation methods were adapted from Donald et al.,'s *(2014 and 2015)* large-scale testing and evaluated for field performance on an active Iowa DOT construction site. Field installation and performance monitoring to evaluate ditch check practices occurred during active construction on U.S. Highway 30 in Tama County, Iowa, throughout the 2018 and 2019 construction seasons. In total, the expansion spanned 12 mi (19.3 km) and involved 4.5 million yd^3 (3.44 million m^3) of grading, and included the use of approximately 3,500 ditch check practices. The project included the construction of a divided four-lane arterial highway, including the addition of two shoulders, a median, and the demolition of two existing lanes. The expansion required abandoning two operational lanes and constructing four lanes with accompanying shoulders and median to accommodate increased traffic flow throughout the U.S. 30 corridor between Ames and Cedar Rapids, Iowa.

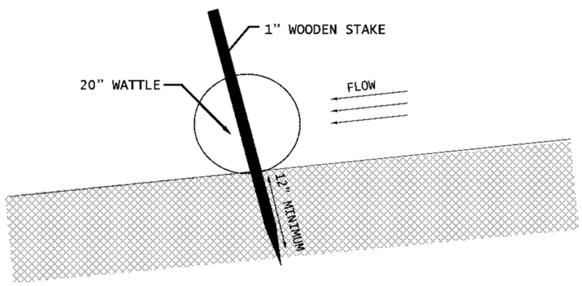
Initial site visits were used to identify the type, frequency, and locations of ditch checks already implemented on-site. In addition, installation techniques, failure modes, and potential improvements for each ditch check type were cataloged. These visits were used to collect soil samples for classification and identify experimental sections. A comprehensive literature review was completed to develop alternative ditch check designs and installation techniques. Standard and modified practices were installed in July 2019 and monitored through December 2019. Field data collection included daily rainfall depths, topographic channel surveys, and pre- and post-rain event visual inspection. This data was used to record rainfall patterns, sediment deposition, channel erosion, and catalog modes of failure and field longevity. Alternative designs were analyzed for significant differences in sediment retention.

2.3.1. Evaluated Ditch Check Practices

One wattle and three silt fence ditch check designs were developed for field evaluation. These designs considered the standard Iowa DOT details, field performance, and improvements to ditch check practices observed in large-scale testing. Potential improvements applicable to the Iowa DOT standard designs were cataloged from the literature.

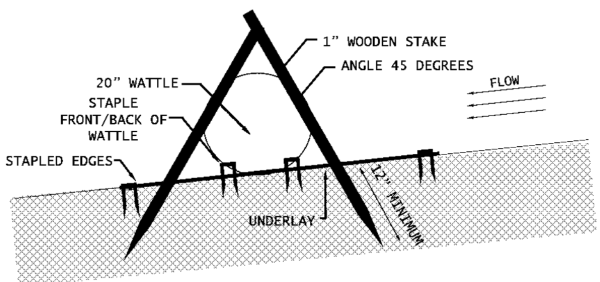
The Iowa DOT standard wattle ditch check installation specified that the excelsior wattles were to be installed perpendicular to flow direction in channels and extend up the fore- and back-slope. Wattles were staked through the netting and fill material every 2.0 ft (0.6 m) on-center. Stakes were driven into the ground a minimum of 12 in. (30 cm) *(Iowa DOT 2017)*. Field observations during preliminary site visits showed wattles commonly exhibited undercutting due to inadequate ground attachment or wattle buoyancy during flows. Several observed wattles were dislodged from their original position and washed downstream.

A modified wattle installation design was developed to address deficiencies commonly observed on-site. The modified design included a natural fiber underlay and an alternative staking pattern. In this design, a 20 in. (51 cm) wattle was installed perpendicular to flow on top of a natural fiber underlay in an attempt to stabilize the soil proximal to the installation from eroding, while promoting intimate ground contact and minimize undercutting. The underlay was pinned using 6 in. (15 cm) sod staples on the face of inflow on the back side at 5 in. (12.7 cm) spacing on-center. The center and sides of the underlay perpendicular to the wattle were pinned at 12 in. (30.5 cm) on-center. Both, wattle and underlay, extended past the high-water mark on the fore- and back-slope. Eleven-gauge steel, 6.0 in by 1.0 in. (15 cm by 2.5 cm), U-shaped sod staples were used to secure the 20 in. (51 cm) wattle to the ground to further aid in ground contact. A non-destructive teepee staking configuration was implemented to combat the buoyancy of less dense wattle fill materials. Stakes were spaced every 2 ft (0.61 m), angled at 45 degrees, and driven at least 12 in. (30 cm) into the ground. Figure 2.7 illustrates the standard (W-S) and modified wattle (W-M) design and installation.



(a) W-S staking detail

(b) W-S field installation



(c) W-M staking detail

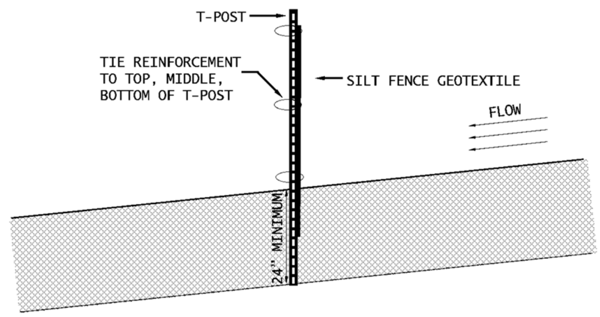
(d) W-M field installation

Figure 2.7. Wattle ditch check design and installations.

The standard Iowa DOT silt fence ditch check (SF-S.) specifies 4 ft (1.2 m), 1.25 lb/ ft (1.86 kg/m) steel T-posts to be driven at least 28 in. (71 cm) into the ground perpendicularly across the flow channel. Posts are spaced at a maximum of 4 ft (1.2 m) apart. The silt fence geotextile extends a minimum of 19 in. (48 cm) above the ground line and is wire- or cable- tied to the post through the top, middle, and bottom of the material. Ties are angled, with the highest point on the back of the post. The specifications call for the geotextile to be either trenched 4 in. by 12 in. (10 cm by 30 cm) or sliced 12 in. (30 cm) into the ground *(Iowa DOT 2017)*.

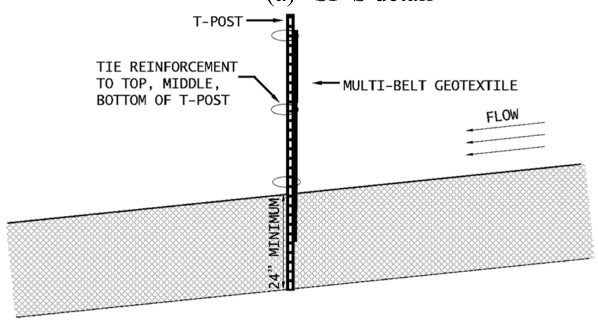
During initial site visits, standard silt fence ditch checks were observed with T-post deflection and signs of overtopping. In some cases, T-posts were dislodged and the silt fence was undercut. In addition, geotextile tears were observed. Three modified silt fence ditch check designs were developed to facilitate improved performance. Modifications to the standard design included the incorporation of a multi-belted geotextile, wire reinforcement, weir, v-shaped installation placement within the channel, and ground attachment.

Modified Design 1 (SF-M1) followed SF-S, but substituted a proprietary multi-belted geotextile. The multiple belt geotextile system has manufacturer claims of providing reinforcement without the need for additional wire backing. Added material strength decreases the potential for tears, and distributes hydrostatic pressure, decreasing potential for T-post deflection and eventual overtopping. Modified Design 2 (SF-M2) and Modified Design 3 (SF-M3) altered the T-post installation spacing, added 14-gauge, 6.0 in. by 6.0 in. (15 by 15 cm) steel mesh reinforcement, and incorporated an overflow weir. SF-M2 and SF-M3 designs implemented steel T-posts installed in a V-shape, with the tip of the V pointing downstream in the direction of the flow. Posts were designed to be spaced at a maximum of 3 ft (0.9 m) apart and driven a minimum of 2 ft (0.6 m) in the ground. Wire mesh was tied to the T-posts at the top, middle, and bottom and terminated at the ground line. The standard geotextile is tied to the top of the reinforcement every 2 in. (5 cm) O.C. using C-ring type fasteners. A dedicated overflow weir should be cut into the geotextile material at the vertex of the installation. The developed design calls for the lowest point on the weir at the vertex to be below the bottom of the silt fence at the outermost edges. SF- M2 implements a 6 in. offset and trenching for ground attachment. The trench was specified to be 6 in. by 6 in. (15.2 cm by 15.2 cm) into the ground, whereas SF-M3 was offset 6 in. (15.2 cm) and sliced into the ground 12 in. (30 cm). Figure 2.8 depicts the silt fence designs through illustrations and installation pictures.



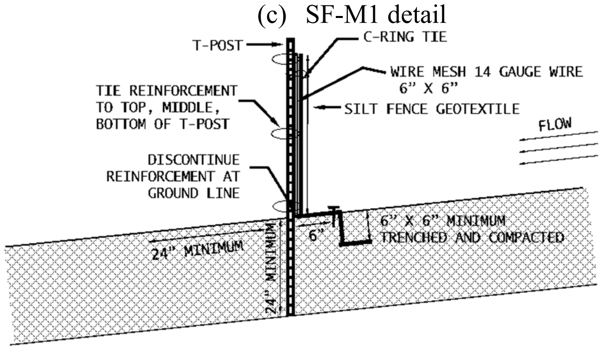
(a) SF-S detail

(b) SF-S field installation



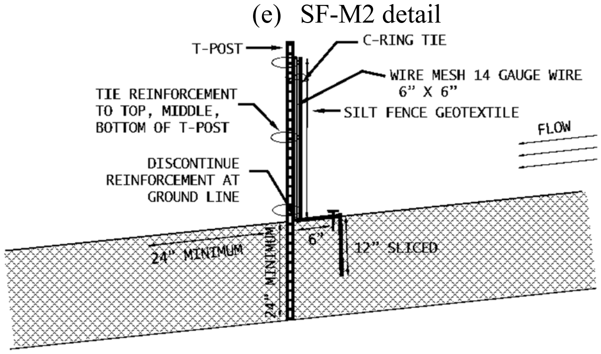
(c) SF-M1 detail

(d) SF-M1 field installation



(e) SF-M2 detail

(f) SF-M2 field installation



(g) SF-M3 detail

(h) SF-M3 field installation

Figure 2.8. Silt fence ditch check designs and installations.

2.3.2. In-Field Installation

To minimize variations in contributing areas, channel characteristics, soil type, and vegetation during monitoring, standard and modified ditch checks were installed in a consecutive median channels within a one mile (1.6 km) stretch of the project. The ditch check spacing was dependent on median grade and height of ditch check practices. The equation for ditch check spacing is shown in Eq. 2.1. Considering a 3% channel grade, silt fence ditch checks (19 in. [0.5 m] height) were spaced at 52.8 ft (16.1 m), whereas a 12 in. (0.3 m) wattles were spaced at 33.3 ft (10.2 m).

$$Ditch\ Check\ Spacing = \frac{Height\ of\ Practice}{Longitudinal\ Slope\ (\%)} \qquad \textbf{Eq. 2.1}$$

Standard and modified ditch check designs were installed for field monitoring. The channel sequence implemented two standard installations to one modified installation (i.e. standard, standard, modified) and repeated three times. This sequence was used to fit three replicates of the alternate design in a single channel. Two standards were installed upstream of each modified design to maintain the integrity of the E&SC plan, while intercepting the first flows to provide consistent results of the current design. In total, nine wattle ditch checks were installed in a single median channel. Three wattle fill types were installed in the field study: excelsior, straw, and woodchip. There were 26 total wattle installations: nine excelsior, nine straw, and eight woodchip. Each wattle type was installed in a different median channel. Due to differences between channels (e.g., drainage areas, slopes, soil types, ground cover, and precipitation patterns), wattle fill types could not be directly compared; however, installation configurations were compared for performance.

Similar to wattle installations, four silt fence ditch check designs were installed in a single channel. One standard and three modified designs were installed in an alternating pattern and repeated three times, resulting in 12 total silt fence ditch checks installations. Practices were installed in an alternating pattern to ensure all silt fence ditch checks could be evaluated in a single median to minimize biased results from different slopes. All evaluated designs are summarized in Table 2.2.

Table 2.2. Summary of evaluated ditch check designs

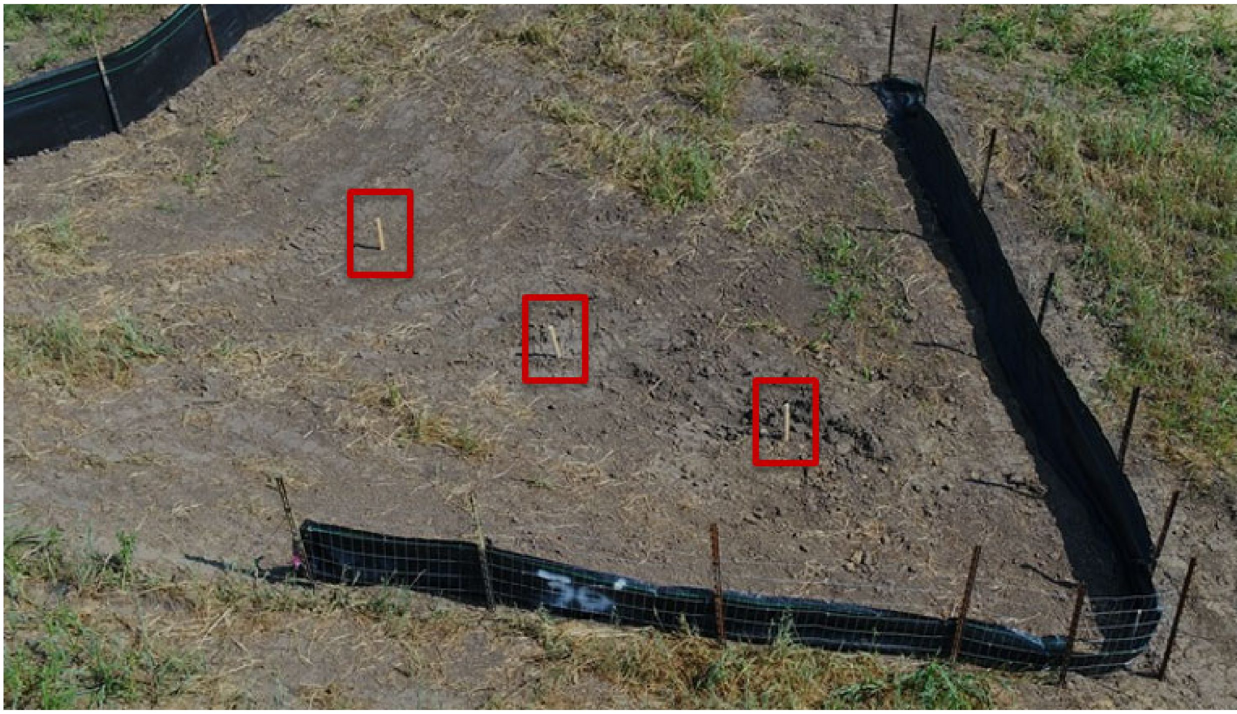
Type	Installation	Name	Description
Silt Fence	Iowa DOT standard	SF- S	Standard
	Modified 1	SF-M1	Standard with belted multi-belted material
	Modified 2	SF-M2	V-shaped with weir, offset trench, and wire reinforcement
	Modified 3	SF-M3	V-shaped with weir, offset slice, and wire reinforcement
Wattle	Iowa DOT Standard	W-S	Staked through wattle to channel
	Modified 1	W-M	Natural fiber underlay, nondestructive teepee staking, sod stapled to channel bottom

2.3.3. Field Monitoring & Data Collection

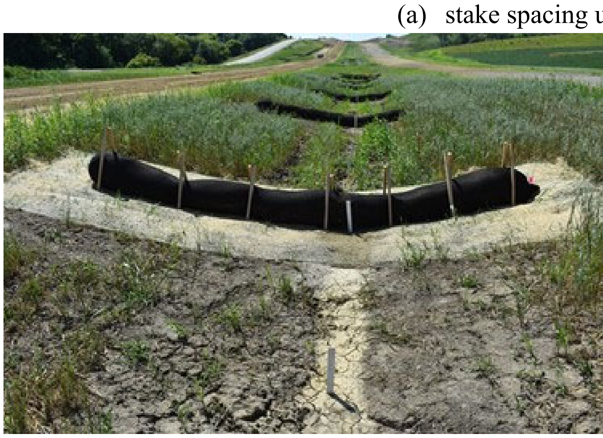
Field monitoring and data collection included: rainfall depths, topographic channel surveys, and images pre- and post-rain events. Daily rainfall was recorded using an ISCO 674 rain gauge located near the center of the experimental median area. A Trimble R8 GNSS was used for topographic surveying at the start of sampling. Ten visual inspections were conducted approximately weekly within the first twelve weeks of monitoring. Two more inspections, spaced monthly, were completed prior to field monitoring concluded in December 2019. Visual inspections documented field observations such as practice deficiencies, modes of failure, sedimentation patterns, and general sight notes. Eight perspective photographs were taken of each practice during visual inspections and compiled into a thorough report.

Practice deficiencies recorded included: flow bypass, T-post deflection, undercutting, scour, and overtopping. Flow bypass was recorded when the observed high water-line was above the highest point on the edge of a practice, or the flow line routed beyond the extent of a practice. T-post deflection was considered when T-posts observably migrated from the original perpendicular position in respect to the ground line. Undercutting was the predominant failure mode and was recorded when the flow line ran underneath a practice, rather than through or over, and began eroding. In some cases, undercutting caused silt fence geotextiles to dislodge from the ground or created a gap of several inches between a wattle and the channel. Scour was observed when dewatering caused erosion on the backside of a practice, mostly observed at the vertex of modified silt fence ditch checks.

Stakes were spaced every 10 ft (3.05 m) in the flow lines of the experimental channels upstream of monitored ditch check practices and surveyed at installation. Stakes were installed to expose 12 in. (31 cm) above the ground line. At the end of the monitoring season, measurements were taken from the top of the exposed stake to the ground line to determine sediment accumulation or erosion within the centerline of the channel during the monitoring period. Figure 2.9 shows several examples of the stakes in the experimental channels.



(a) stake spacing upstream of silt fence ditch check



(b) stakes in wattle channel

(c) stake shown on wattle after undercutting

Figure 2.9. Channel stakes.

Using the collected topographic data, original and post-monitoring channel profiles were compared to determine net sediment accumulation. Channel profiles were used to calculate sediment accumulation area and estimate a sediment volume. Channel widths were found by importing aerial images into GIS and using the measure tool. The average channel widths for the channels with excelsior, straw, and woodchip wattles were 21.9 ft (6.7 m), 20.6 ft (6.3 m), and

14.7 ft (4.5 m), respectively. Original data collection included LiDAR scans, but post-processing surfaces were inaccurate due to channel and site vegetation noise.

2.3.4. Field Performance

Field performance evaluations were conducted on silt fence and wattle ditch checks during active construction throughout the construction season of 2019. Soil samples indicated a lean clay with sand (CL-SC), according to the Unified Soil Classification System (USCS), was the primary soil on site.

2.3.5. Performance Assessment

Due to vegetative establishment in the straw and excelsior installation medians, the channels were stabilized and did not experience observable erosion. The wood chip wattle median was used to compare installation techniques. The modified installation, which included an excelsior underlay sod stapled to the channel bottom and nondestructive teepee staking, captured 1158% more sediment than the standard installation, 1.51 ft^3 (0.043 m^3) and 0.12 ft^3 (0.0034 m^3), respectively.

Weekly inspections indicated that all five standard woodchip installations exhibited undercutting after 2.99 in. (7.59 cm) of rain, whereas one of the three modified installations exhibited flow bypass after 11.21 in. (28.47 cm) of rain. Sedimentation patterns and lack of wattle extension beyond channel side slopes eventually caused flow to bypass the wattle. An example of undercutting is shown in Figure 2.10.

(a) undercutting upstream

(b) undercutting in two points on downstream side

Figure 2.10. Observed wattle ditch check deficiencies.

Silt fence ditch check performance was assessed in the same manner as wattle ditch checks. The average channel width was determined to be 20.3 ft (6.2 m) for the silt fence ditch checks. Yielding 0.51 ft^3 (0.014 m^3) average sediment retention for SF-S. SF-M1 had an 18% increase of sediment retention at 0.6 ft^3 (0.017 m^3) of sediment accumulation. SF-M2 and SF- M3 exhibited 304% and 153% more sediment accumulation with 2.06 ft^3 (0.058 m^3) and 1.29 ft^3 (0.037 m^3), respectively. Figure 2.11 compares the average sediment retention of each type of ditch check practice monitored.

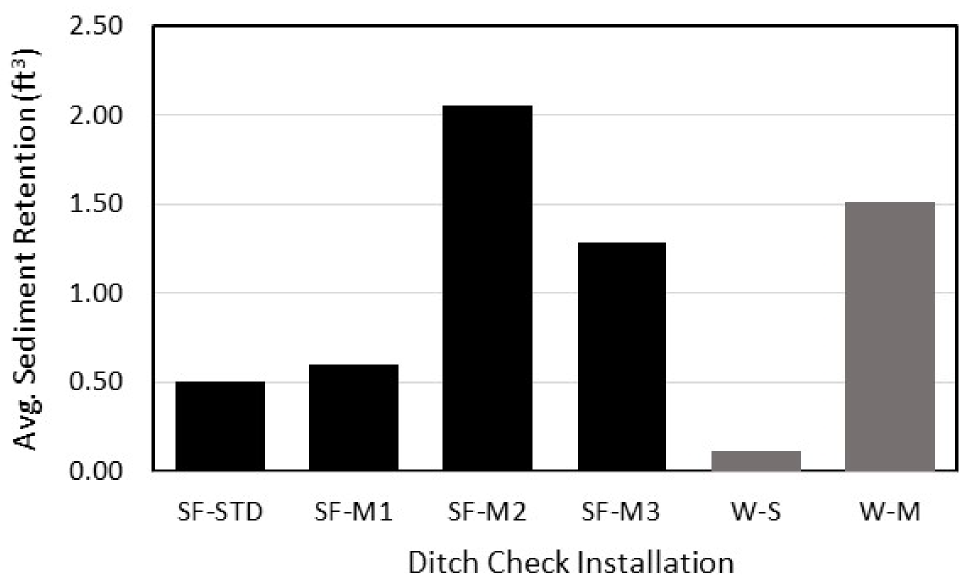


Figure 2.11. Average sediment retention upstream of monitored ditch check installations.

Weekly visual inspections were conducted to observe the sediment retention and erosion patterns, and failure modes. All SF- S and SF-M1 experienced T-post deflection, with eventual undercutting within two of the three monitored installations. Based on these observations, it is recommended to extend the geotextile on the ground and staple to the channel to avoid ground disturbance. M2 and M3 exhibited signs of scour at the weir, due to overtopping. There were no signs of deterioration to the structural integrity of the practices. To minimize the scour due to overtopping, it would be recommended to include an energy dissipater at the vertex in future installations. Silt fence deficiencies are depicted in Figure 2.12.

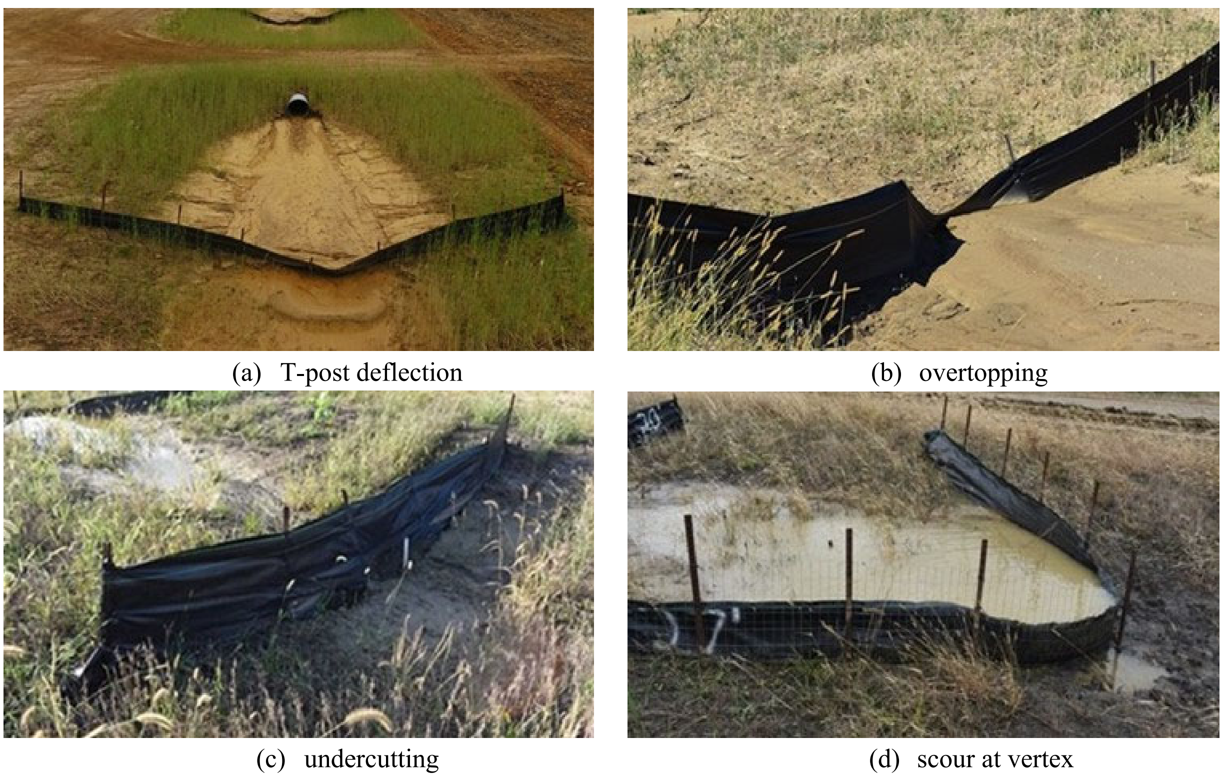


Figure 2.12. Observed silt fence ditch check deficiencies.

2.3.6. Data Analysis

To compare sediment retention, ANOVA and subsequent t-tests were conducted to determine the significance of installation method. T-tests were selected due to the limited sample size of installations. In total, one t-test was conducted comparing the sediment retention of the standard and modified wattle, and six t-tests were conducted comparing the sediment retention of each silt fence ditch check installation to the others.

The first t-test compared the standard and modified wattle ditch check. A p-value of less than 0.05 was considered to be significant. The t-test resulted in a p-value of 0.0017, indicating significance. ANOVA analyses were conducted on the average sediment retention of the silt fence installations and indicated statistically significant differences at the 90% confidence level. Subsequently, a series of six paired t-tests were completed to determine which pairs of silt fence installations were significantly different at the 85% confidence level. A p-value of less than 0.15 was considered to be significant. There were significant differences in the measured sediment accumulation upstream of the SF-S and SF-M2, SF-M1 and SF-M2, SF-S and SF-M3, and SF-M1 and SF-M3 installations. Table 2.3 summarizes all statistical comparisons.

Table 2.3. Statistical significance comparisons

Type	Comparison	P-Value
Silt Fence[a]	SF-S, SF-M1	0.8554
	SF- S and SF-M2	0.1012*
	SF- S and SF-M3	0.1174*
	SF-M1 and SF-M2	0.1114*
	SF-M1 and SF-M3	0.1273*
	SF-M2 and SF-M3	0.2695
Wattle[b]	W-S and W-M	0.0017*

Note: [a] silt fence at 85% confidence interval and p <0.15; [b] wattle at 95% confidence interval and p<0.05; * indicates statistical significance

2.3.7. Cost Analysis

A cost analysis was conducted to quantify the price differences between the standard and modified designs if installed in a depressed Iowa DOT highway median. The standard median design includes a 10 ft (3.05 m) channel bottom, 4 ft (1.22 m) depth, and 6:1 side slopes, as shown in the Iowa DOT Design Manual (*Iowa DOT 2019)*. Quantity take-offs for cost estimates were determined using the standard, depressed Iowa DOT highway median. Ditch check types were cataloged according to the Iowa DOT Standard Road Plan for Erosion Control and included silt fence, wattles, and riprap.

The Iowa DOT provided costs of the standard designed ditch checks from ongoing projects. All costs included materials and labor for installation. Quotes for material were requested from four E&SC product suppliers nationwide to determine the cost of the modified designs. Materials requested for quotes are shown in Table 2.4.

Table 2.4. Materials for modified installations

	Component	Specifications
Silt Fence	Geotextile	woven, 36 in. (1.0 m) wide, 150 lb (68 kg) grab strength
	Studded T-Post	4 ft (1.22 m), 1.33 lb/ ft (1.98 kg/m), painted
	Cable Ties	50 lb (23 kg)
	Sod Staples	6 in. (15.2 cm), 11 gauge
	Welded Wire Fence	14 gauge steel wire
	C-Ring Ties	1 in. (2.54 cm), 16 gauge, galvanized steel
	Multi-belted Silt Fence	n/a
	Class D Erosion Stone	limestone, dolomite, quartzite, or granite
Wattle	Natural Fiber Underlay	Excelsior
	Wooden Stakes	1 × 1 in (2.54 × 2.54 cm), 36 in. (1.0 m) long
	Excelsior`	12 in. (0.33 m) and 20 in. (0.51 m)
	Straw w/ net	
	Straw w/ sock	
	Wood Chip	
	Standard Coir	
	Premium Coir	
	Miscanthus	
	Synthetic	

Individual material costs from the suppliers were averaged per unit and corrected for outliers. The quantity of each material necessary for individual installations was tallied, and the cost was totaled. The total cost was divided by practice width (ft. [m]) for final material estimates. For example, a modified wattle installation would consist of:

$$Material\ Cost\ (MC) = \sum \frac{Avg.(Wattle + \ stakes + \ underlay + pins}{ft\ (m)}$$ **Eq. 2.2**

Estimated material costs (MC) were subtracted from the provided Iowa DOT costs to determine the cost added for installation.

$$DOT\ cost - \ \ MC = Installation\ Cost\ (IC), \frac{\$}{ft\ (m)}$$ **Eq. 2.3**

Productivity rates (ft/min [m/min]) for the standard silt fence and wattle ditch checks were determined using recorded times from field installations. The productivity rate was multiplied by installation cost to result in labor cost (LC).

$$PR \times IC = Labor\ Cost\ (LC), \frac{\$}{min}$$ **Eq. 2.4**

The resulting labor cost was divided by the productivity rate for the modified installations to result in a labor correction cost.

$$\frac{LC}{PR_2} = Labor\ Correction\ Cost\ (LCC), \frac{\$}{ft\ (m)}$$ **Eq. 2.5**

Finally, the labor correction cost was added to the raw material cost to develop a total cost for the modified designs, inclusive of materials and labor.

$$LCC + MC = Total\ Cost\ (TC), \$$$ **Eq. 2.6**

The estimated costs for the modified designs could then be compared to the standard design but did not consider performance. Researchers developed a single metric to include the cost estimate and field performance. To do so, the total cost of each design was divided by the average sediment retention volume to present a cost per retained sediment volume ($\$/ft^3$ [$\$/m^3$]). The cost/ accumulation ($/volume) metric was calculated to simplify the two analyses, similar to a cost/benefit analysis. This metric considered the average sediment volume retained behind a practice from all replicates and estimated cost from the typical channel geometry and specified practice detail.

2.3.8. Cost-Retention Comparison

It was determined that SF-M2 and SF-M3 retained significantly more sediment than SF-S at the 85% confidence interval. Similarly, W-M retained significantly more sediment than the W-S at the 95% confidence interval; however, the modified installations required more materials and additional labor time. Using the described Iowa DOT channel with a 10 ft (3.05 m) channel bottom, 4 ft (1.22 m) depth, and 6:1 side slopes, SF-M2 and SF-M3 increased material cost by 18% and total cost by 15% and 14%, respectively. While SF-M2 and SF-M3 included additional components (wire reinforcement, c-rings, and sod staples), the length of material and the number of t-posts were reduced due to the difference in the design of the silt fence ditch check. SF-M2 and SF-M3 utilized a v-shape configuration with a weir cut at the channel centerline. The weir is field installed at an elevation lower than the upstream, v-shape wings. The weir ensures that the ditch check dewaters at the center point on the installation, preventing flow bypass around the wing and decreasing the required amount of material. The calculations for length of practice are shown in Equations 8-11.

From the developed equations, SF-M2 and SF-M3 material lengths were determined to be 14 ft. (4.3 m), compared to the 29 ft. (8.8 m) required for SF-S and SF-M1. As determined by the equations, the reduced length reduces quantities of silt fence components needed and thus reduces cost. This demonstrated that the standard Iowa DOT ditch check detail enhanced performance and optimized material costs.

The sediment volume retained was divided by the cost. SF-S, SF-M2, and SF-M3 had costs of \$71.08, \$20.28, and \$32.08 per ft^3 (\$2,510, \$716, and \$1,144 per m^3), respectively. Thus, the cost per volume was reduced by up to 70% with the modified silt fence installations. Material, labor, total cost, and cost per volume are shown in Table 2.5. Results from the field study indicated that SF-S and SF-M1 exhibited t-post deflection and eventual undercutting. Although these practices were not maintained during field monitoring, associated repair or replacement costs would be expected in real-world conditions. SF-M2 and SF-M3 indicated signs of scour at the vertex but did not cause failure. Researchers suggested adding an energy dissipater, such as a geotextile splash pad, which would slightly increase the material cost.

The standard and modified wattle designs were compared using the same methodology. Observations from the field monitoring study noted that the wood chip wattles were used for performance comparisons, as the channel remained in "construction conditions" (i.e., minimal vegetation and active contributing area). When comparing the standard and modified installations of the wood chip wattles, the modified installation's volume accumulation was 12 times that of the standard. Labor cost for the modified wattle installation increased by 300%; however, the total cost increased by 134%. Meanwhile the cost per volume accumulation of the modified (\$183.83/ft^3 [\$6,456/m^3]) was 11% that of the standard (\$1,718/ft^3 [\$68,710/m^3]). Like the silt fence ditch checks, the modified installation had increased field longevity and minimized undercutting compared to the standard installation, requiring less maintenance. Wattle material, labor, total cost, and cost per volume are shown in Table 2.5.

Table 2.5. Ditch check cost and sediment retention

Name	Material cost ($)	Labor $/ft ($/m)	Total Labor ($)	Total Cost ($)	Volume ft^3 (m^3)	Cost / vol $/ft^3 ($/m^3)
SF-S	$33.43	0.10 (0.32)	$2.82	$36.25	0.51 (0.014)	71.08 (2,510)
SF-M1	$51.31	0.10 (0.32)	$2.82	$54.14	0.60 (0.017)	90.23 (3,186)
SF-M2	$39.32	0.17 (0.57)	$2.45	$41.77	2.06 (0.058)	20.28 (716)
SF-M3	$39.32	0.15 (0.49)	$2.10	$41.42	1.29 (0.037)	32.08 (1,144)
WC-S	$189.33	0.56 (1.84)	$16.80	$206.13	0.12 (0.003)	1,717.75 (60,662)
WC-M	$227.79	1.66 (5.45)	$49.80	$277.59	1.51 (0.043)	183.83 (6,492)

While there are higher initial costs for the modified designs, savings are expected in cost per volume of retained sediment, maintenance, and replacement. As contractors become more comfortable installing the modified ditch check designs, labor costs are expected to decrease.

2.3.9. Development of CheckSpread

To aid in the design and E&SC selection for channels, researchers developed an Excel tool, CheckSpread, that provides design and cost information for various Iowa DOT ditch checks. CheckSpread asks for user input for channel geometry parameters, including length, slope, width, depth, and side slopes (H: V). Users can then toggle from a selection of ditch check types (e.g., rip rap, silt fence, wattle) and installation methods from this study (e.g., standard or modified). Although field monitoring of rip rap ditch checks was not completed on-site, CheckSpread includes the option. CheckSpread has an option for the standard Iowa DOT design and a modified design developed by Donald et al., *(2014)*, which implemented a geotextile over- and underlay.

The tool relies on Eq. 2.7 to determine the spacing of ditch checks and then divides the channel's total length by the spacing to determine the number of wattles needed within the provided channel.

$$\frac{Length\ of\ ditch, m\ (ft.)}{Ditch\ check\ space, m\ (ft.)} = Number\ of\ ditch\ checks \qquad \textbf{Eq. 2.7}$$

An additional menu is enabled if a wattle is selected. The menu contains eight wattle fill media and encasement combinations. Most wattles have 12 in. (30.5 cm) and 20 in. (50.8 cm) options. The tool references media impoundment ratios developed for wattles in the clean-water, flume-study conducted by Whitman et al., *(2021)*. The spacing is adjusted for the media type by multiplying spacing by the impoundment factor; subsequently, the number of ditch checks is also adjusted. Riprap and silt fence ditch checks assume an impoundment ratio of 1.00 since impoundment ratios have yet to be tested in the apparatus. Table 2.6 displays wattle fill media and their impoundment ratios.

Table 2.6. Wattle fill media impoundment ratios

Fill Media	Encasement	Ratio
Miscanthus	Sock	0.96
Straw	Net	0.72
Straw	Sock	0.75
Excelsior	Net	0.61
Wood Chip	Sock	0.83
Synthetic	Net	0.82
Premium Coir	Net	0.81
Standard Coir	Net	0.80

After a ditch check type is selected, the tool calculates the required width of the ditch check types based on the channel geometries shown below.

$$Std.SF\ Length = BW + (L_1 \times Ht) + (L_2 \times Ht) \quad \textbf{Eq. 2.8}$$

$$Mod.SF\ Length = \left(\frac{BW}{2} \times \sqrt{2}\right) \times 2 \quad \textbf{Eq. 2.9}$$

$$Wattle\ Length = BW + (L_1 \times Ht) + (L_2 \times Ht) \quad \textbf{Eq. 2.10}$$

$$Rip\ Rap\ Length = BW + \sqrt{{L_1}^2 + D^2} + \sqrt{{L_2}^2 + D^2} \quad \textbf{Eq. 2.11}$$

where,

BW = bottom width (ft [m])
$L1$ = bottom width (ft [m])
$L1$ = foreslope (H:V)
$L2$ = backslope (H:V)
Ht = height of ditch check (ft [m])
D = channel depth (ft [m])

To provide a cost estimate, the calculated width of the ditch check is then multiplied by the material cost per length. The cost of each ditch check and the total cost to arm the channel is then output to users. Cost information relies on a second, locked sheet within the Excel tool. This sheet contains all referenced costs and length calculations. The development of CheckSpread was completed for the Iowa DOT using average material costs from suppliers in the first quarter of

2020; however, this tool can be updated with new costs and modified with additional ditch check designs.

In addition to cost information, the spacing, quantity, and schematics of the channel cross-section and ditch check spacing are output. The channel cross-section schematic displays the channel in orange and overlays the practice width and height in blue. To the right of the cross-section, the complete channel length is displayed in blue. Vertical lines indicate ditch check practices. As an example, the standard Iowa DOT channel geometry was input for a 300 ft (100 m) channel (as displayed in Figure 2.13).

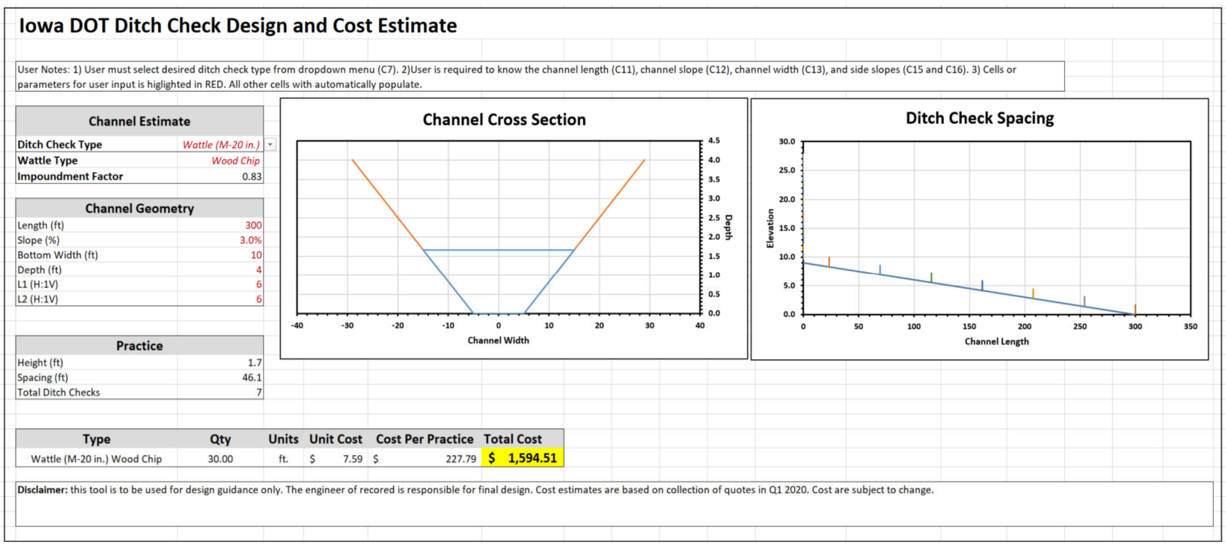


Figure 2.13. CheckSpread user input example.

The spacing, quantity, length of practice, cost, and total cost per channel for each wattle type are compared in Table 2.7.

Table 2.7. Example output of CheckSpread

Group	Type	Spacing (ft)	Spacing (m)	Qty	Length (ft)	Length (m)	Unit Cost ($/ft)	Unit Cost ($/m)	Channel Cost ($)
	SF-S	52.8	15.9	6	29.0	8.8	1.20	3.94	209.23
	SF-M2	50.0	15.1	6	14.1	4.3	2.83	9.28	240.09
	Rip Rap- S	66.7	20.1	5	24.42	7.4	17.63	57.83	2,152.89
	Rip Rap- M	66.7	20.1	5	24.42	7.4	18.06	59.24	2,204.95
12 in. (30 cm) Wattle-S	Miscanthus	27.7	8.4	11	22.0	6.7	2.06	6.76	453.42
	Straw Net	24.0	7.2	13	22.0	6.7	1.15	3.77	329.53
	Straw Sock	25.0	7.5	12	22.0	6.7	2.31	7.58	610.10
	Excelsior	20.3	6.1	15	22.0	6.7	1.28	4.20	422.47
	Wood Chip	27.7	8.4	11	22.0	6.7	2.51	8.23	606.32
	Synthetic	27.3	8.2	11	22.0	6.7	4.34	14.24	1,050.52
	Premium Coir	27.0	8.1	12	22.0	6.7	7.35	24.11	1,940.66
	Standard Coir	26.7	8.0	12	22.0	6.7	6.58	21.58	1,737.38
20 in. (51 cm) Wattle-S	Miscanthus	53.3	16.1	6	30.0	9.1	5.10	16.73	917.25
	Straw Net	40.0	12.1	8	30.0	9.1	2.61	8.56	626.64
	Straw Sock	41.7	12.6	8	30.0	9.1	5.78	18.96	1,387.05
	Excelsior	33.9	10.2	9	30.0	9.1	2.96	9.71	799.47
	Wood Chip	46.1	13.9	7	30.0	9.1	6.31	20.70	1,325.31
	Synthetic	45.6	13.7	7	30.0	9.1	11.33	37.16	2,379.24
	Premium Coir	45.0	13.6	7	30.0	9.1	19.56	64.16	4,107.52
	Standard Coir	44.4	13.4	7	30.0	9.1	17.45	57.24	3,665.40
12 in. (30 cm) Wattle-M	Miscanthus	32.0	9.6	10	22.0	6.7	3.34	10.96	735.44
	Straw Net	24.0	7.2	13	22.0	6.7	2.43	7.97	696.16
	Straw Sock	25.0	7.5	12	22.0	6.7	3.59	11.78	948.53
	Excelsior	20.3	6.1	15	22.0	6.7	2.56	8.40	845.50
	Wood Chip	27.7	8.4	11	22.0	6.7	3.79	12.43	916.54
	Synthetic	27.3	8.2	11	22.0	6.7	5.62	18.43	1,360.74
	Premium Coir	27.0	8.1	12	22.0	6.7	8.63	28.31	2,279.09
	Standard Coir	26.7	8.0	12	22.0	6.7	7.86	25.78	2,075.81
20 in. (51 cm) Wattle-M	Miscanthus	53.3	16.1	6	30.0	9.1	6.38	20.93	1,147.99
	Straw Net	40.0	12.1	8	30.0	9.1	3.89	12.76	934.30
	Straw Sock	41.7	12.6	8	30.0	9.1	7.06	23.16	1,694.70
	Excelsior	33.9	10.2	9	30.0	9.1	4.24	13.91	1,145.59
	Wood Chip	46.1	13.9	7	30.0	9.1	7.59	24.90	1,597.51
	Synthetic	45.6	13.7	7	30.0	9.1	12.61	41.36	2,648.45
	Premium Coir	45.0	13.6	7	30.0	9.1	20.84	68.36	4,376.72
	Standard Coir	44.4	13.4	7	30.0	9.1	18.74	61.47	3,934.60

Designers may opt to use this tool when selecting appropriate and cost-conscious ditch protection designs. From the given example, silt fence ditch checks are the most affordable material and require six total installations in the given channel. When reported with field-monitoring results, the designer may elect to spend $30 extra per channel to arm the channel with the modified silt fence ditch check for increased sediment capture. Field longevity and maintenance costs should be estimated and considered when selecting channel design.

The tool relies on a reference page of raw material cost components and calculated labor factors, as described in Equations 2.1-2.5, and may be customized and updated for other DOTs or users. While the tool provides design guidance, it is the engineer of record's responsibility to review and approve the final design.

2.3.10. Conclusions

Although there is a desire for performance-backed erosion and sediment control design guidance, there are intricacies in field and scaled testing that make objective, reliable, and transferrable results difficult to obtain. Uncontrollable weather, soil, and grading patterns on an active construction site proved to be difficult in early erosion and sediment control research. The field largely switched to scaled research, at facilities like the AU-SRF. Scaled research minimizes external site variables and allows a practice's performance to be attributed to controlled installation parameters, which is essential to developing scientific-based design.

The practices tested in scaled testing are often installed with attention to detail and may be considered "best case scenario." Despite using native soils and site-specific modeled rainfalls or flows, scaled research eliminates the variability experienced on site, leaving gaps in realistic site installation and feasibility. To combat this, researchers at the AU-SRF have been working with research sponsors at departments of transportation to develop the Most Feasible and Effective – Installation (MFE-I) during testing. The MFE-I, which typically incorporates one or more modifications from the standard installation proven to enhance effectiveness, as determined by preceding research results. Feasibility considers the design, installation, and maintenance constraints of real-world sites. Feasibility is determined through the collaboration of research team and project sponsors. In addition, to the MFE-I design and testing, AU-SRF provides installer training and field days to extend research findings to the parties responsible for real-world installation.

This chapter reviewed a case study, applying the findings from an Alabama DOT project conducted at the AU-SRF to and active project in Tama County, Iowa *(Donald et al., 2014 and 2015)*. This case study highlighted the importance in large-scale testing and transferability of findings. Despite soil, topographic, and weather differences between Alabama and Iowa, the enhanced ditch check practices improved sediment capture during active construction, when compared to the standard designs. While field-results also indicated positive results, the cost of implementation was unknown. Cost estimates and field evaluations were conducted independently but combined into a single metric to present cost savings or expenditures associated with each design.

3. CHAPTER THREE: SEDIMENT BASIN DESIGN AND PERFORMANCE

3.1. Introduction

Sediment basins are a sediment-control practice, typically employed on the edge of disturbed watersheds to capture suspended solids by providing residence time for captured runoff, promoting sedimentation *(Thaxton et al., 2004)*. Sediment basins are used to provide volumetric storage, promoting gravitational settling, and have been shown to trap 75% - 90% of suspended solids, heavy metals, and other organic compounds *(Fennessy and Jarrett 1997, Bidelspach et al., 2004, Perez et al., 2016)*. Performance is dependent on basin parameters such as size, geometry, energy dissipation, dewatering mechanism, and use of flocculants, but the design and inclusion of these components vary nationwide.

Sediment basins capture, detain, and treat stormwater by providing residence time to promote gravitational settling of suspended particles prior to off-site discharge. The stormwater residence time within a basin is dependent on their design and construction. Sediment basin design includes volumetric sizing and geometries, inflow channel, dewatering mechanism, and emergency overflow or spillway; however, the "one size fits all" approach is not applicable for sediment basin design due to varying hydrologic and soil conditions across construction sites *(Fifield 2015, Perez et al., 2017)*. Additional components such as baffles and dewatering skimmers have been investigated through large-scale testing and proved to enhance the performance of sediment basins.

3.1.1. Sizing and Geometry

Sizing and geometry are arguably the most influential components to the efficiency of a sediment basin due to their influence on the residence time and resulting sediment capture. In a pioneering study by Hazen in 1904, sediment capture was determined to be proportional to sediment basin surface area; however, it was independent of the basin depth *(Hazen 1904)*. Sufficient volume is required to ensure stormwater will not overtop the basin, allowing untreated, sediment-laden water to exit the site. Basins should be designed long and narrow to optimize settling across the flow length. Typically, a minimum length to width ratio of 2:1 is recommended *(Chen 1975)*; however, recent studies have indicated sediment basin ratios of 1:2 may be just as effective as velocity is spread across a wider area *(Kang et al., 2015)*.

Early sediment basin design guidance required a storage volume of 1,800 ft^3 (125 m^3) of storage per drainage acre (hectare); however, in 1992, the USEPA identified a new design standard requiring storage volume of 3,600 ft^3 (252 m^3) of storage per drainage acre (hectare). This sizing guideline was based on the assumption that a 2-yr, 24-hour rainfall event of 3 in. (7.62cm), would produce 1.0 in (2.54 cm) of runoff, or approximately 3,600 ft^3 (252 m^3) of storage per drainage acre (hectare) *(USEPA 1992)*. This method was criticized for not providing sufficient storage to fully capture runoff from the 2-yr, 24-hr rainfall event, which is probable to occur on a highway construction project *(Fifield 2015)*. Currently, the USEPA CGP allows for sizing sediment basins using one of two methods: (a) the calculated volume of runoff from a 2-yr, 24-hr design storm, or (b) 3,600 ft^3 (252 m^3) of storage per acre (hectare) drained into the basin *(USEPA 2022)*. The two design methods may result in different volumes required depending on local hydrology. Sediment basin details include a primary and auxiliary spillway. Auxiliary spillways are utilized in overflow conditions and must be designed to safely pass larger storm events, such as the 10- or 25-yr storm event. To prevent washout, the auxiliary spillways are armored with a TRM, geotextile, or erosion stone *(IECA 2020, ALDOT 2020, NCDOT 2015)*.

Perez et al., *(2016)* developed a hydrologic-based design tool SEDspread, that allows designers to select site-specific parameters, including sizing factor (i.e., 2-yr, 24-hr design storm, or 3,600 ft^3/ac (252 m^3/ha) to provide basin capacity and configuration. In addition, designers can input a U.S. zip code from which soil and storm data is derived. A case study was performed on two local construction site sediment basins in Auburn, AL. The case studies compared basin design and implementation to SEDSpread outputs. The two basins in the case study were designed to the 3,600 ft^3/ac (252 m^3/ha) but were undersized for the 2-yr, 24-hr design storm by a factor of three *(Perez et al., 2016)*.

Fang et al., conducted a three-month field study that monitored a sediment basin during highway construction in Franklin County, AL *(2015)*. The monitored basin was excavated to accommodate 20,288 ft^3 (574.5 m^3) of stormwater runoff, which followed the 3,600 ft^3/ac (252 m^3/ha) USEPA sizing criteria. Five of sixteen storms during the monitoring period resulted in overflow over the auxiliary basin spillway. Larger storms generated highly turbid inflow and re-suspended previously settled material. The researchers suggest this could be due to the under-sizing of the basin by a factor of 4.8 when compared to the 2-yr, 24-hr design storm (97,115 ft^3 [2,750 m^3] determined from modeling) *(Fang et al., 2015)*.

3.1.2. Forebay

Several sediment basin designs include a forebay created by a ditch check and/ or excavated area upstream of the basin. The forebay is designed to capture rapidly settable solids in an easily accessible location. The forebay provides an area for concentrated deposition that is more easily maintained and reduces the sediment load introduced into the basin. Sediment capture in the forebay decreases dredging efforts in the basin and increases field longevity. Minimal research has been conducted on forebays, but they may be compared to a silt basin or sediment traps without a dewatering mechanism. McCaleb and McLaughlin *(2008)* determined that sediment traps with rock outlets and 3 ft. (1 m) standing pool trapped up to 73% of introduced sediment. Perez et al., *(2016)* tested two basin configurations with varying forebay components. The first implemented a rock check dam with geotextile overlay and the second implemented the same rock check dam with overlay with an excavated area just upstream of the check dam, which captured 76% and 80% of sediment, respectively.

3.1.3. Lining and Stabilization

One of the most effective erosion control practices is minimizing disturbed areas on a site. This approach also applies to the implementation of sediment basins to prevent the basin from contributing to sediment discharge. Disturbed areas within and around sediment basins should be stabilized by (1) establishing vegetative cover or (2) lining with non-woven geotextile to prevent erosion (IECA 2021). Stabilization prevents erosion of the inflow channel and basin. Minimal research exists examining the difference between lined and unlined basins, but a 2000 study by Madaras and Jarrett found 36% higher sediment yield in unlined basins.

3.1.4. Flow Dissipation

Sediment basins are typically assumed to have laminar flow; however, turbulence may occur during intense rainfall events causing resuspension of previously deposited sediment (*Perez et al., 2016*). Baffles dissipate flow across the width of the basin and decrease turbulence. Turbulent flow conditions within a sediment basin are undesirable in that they cause resuspension and prolonged suspension of sediment *(Goldman et al., 1986)*. Baffles are installed perpendicular to the inflow, intercepting the flow, and should exceed the full depth of the sediment basin *(Perez et al., 2016)*. Baffles aid in minimizing the resuspension of finer particles. Goldman et al., *(1986)* states that any retention pond with a ratio smaller than 10:1 should employ baffles within the pond. Several DOTs have adopted porous baffles or energy dissipaters for sediment basins *(TDOT 2020, ALDOT 2020, NCDOT 2015)*.

Thaxton et al., conducted a sediment basin study at North Carolina State University, which compared the average particle size captured in a basin with and without baffles. The smallest grain size captured in a basin without baffles was between 2.7 x 10^{-3} to 3.4 x 10^{-3} in. (68-86 microns); however, the addition of baffles allowed capture for grains just 1.2 x 10-3 to 1.7 x 10-3 in. (30-42 microns). In the study, three materials were tested across three different flow velocities. Overall, an evenly installed jute/ coir baffle performed the best by most effectively absorbing inflow momentum, diffusing energy, and damping the turbulent density. The jute/coir baffles were a combination of distributed jute germination biotextile backed with coir fiber and reduced mean flow velocity by 75% compared to the control, open flow basin *(Thaxton et al., 2004)*.

3.1.5. Dewatering

A dewatering mechanism is necessary for treated stormwater to exit the basin without permanent ponding *(Thaxton et al., 2004)*. The USEPA CGP requires dewatering sediment basins from the surface, presumably the least turbid portion of the water column, due to gravitational settling *(USEPA 2022)*. Traditionally, effluent has been discharged through perforated riser pipes, which pull water across a larger portion of the water column. There is contention within the E&SC field if a riser pipe is still considered a surface dewatering mechanism. Instead, floating surface skimmers have become more commonly implemented, sized, and selected based on the desired dewatering rate. Sediment basins are typically designed to detain stormwater for periods ranging between 24 to 72 hours but can be up to seven days *(Fang et al., 2015)*.

An adequate settling time can be determined, and the skimmer can be selected for solid removal prior to discharge *(Perez et al., 2016)*. Various sediment retention rates using a skimmer as the primary dewatering mechanism have been determined in controlled research studies. Examples include (1) Millen et al., found that a skimmer discharged 45% less sediment than a riser pipe *(1997)* and (2) Jarrett et al., concluded sediment loss from a basin equipped with a perforated riser principal spillway was 1.8 times greater than when a floating surface skimmer was used *(2001)*.

3.2. Design

Basin design and construction vary across the U.S.; however, several DOTs implement all the sediment basin components described. As an example, the Alabama Department of Transportation (ALDOT) sediment basin detail is shown in Figure 3.1. The sediment basin is excavated with a length-to-width ratio of at least 2:1 and lined to prevent erosion within the basin. Channel armoring at the inlet protects the transition from channelized flow to the settling pond. The defined inflow channel is also lined and includes an excavated forebay, consisting of an excavated sump and riprap ditch check. This provides an easily accessible area to capture rapidly settling solids and maintain, decreasing the frequency of dredging requirements of the basin and providing additional stormwater storage. A dedicated flocculant introduction zone is shown downstream of the forebay to promote flocculation of the smaller, suspended particles. Three baffles split the basin into four sections, and a skimmer is installed in the fourth bay for dewatering (ALDOT 2020).

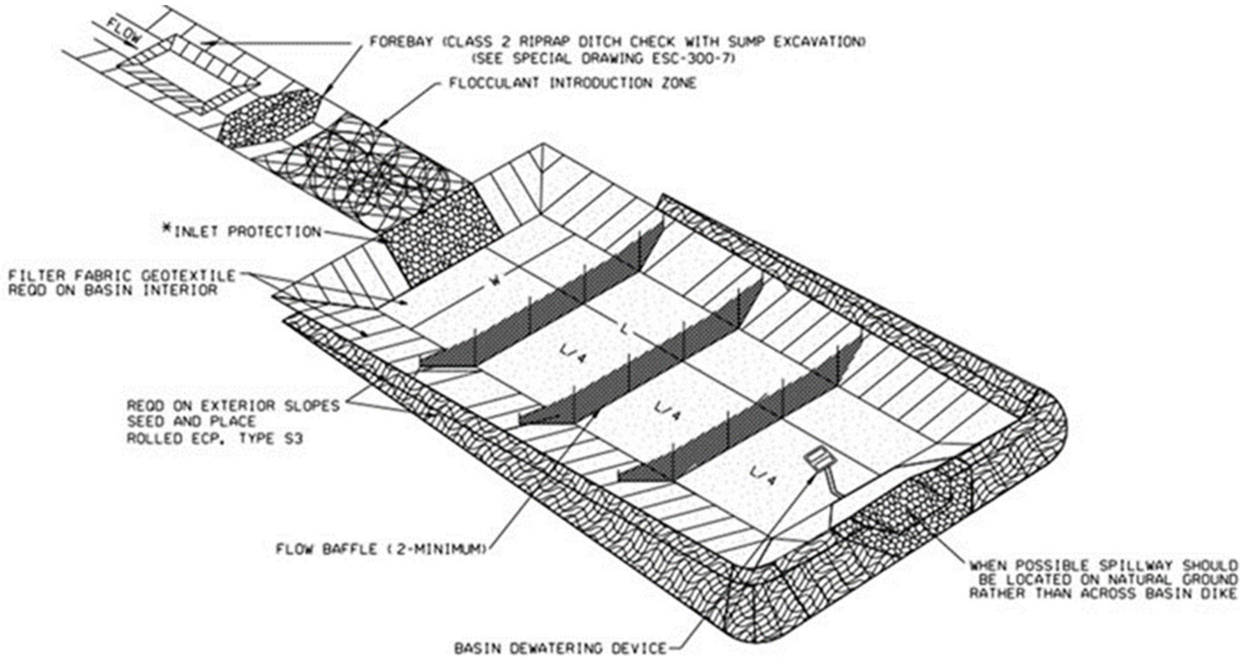
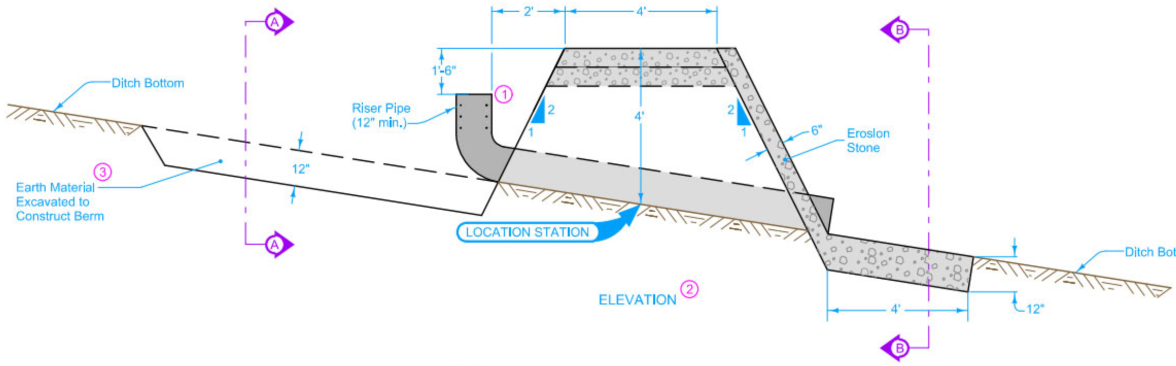
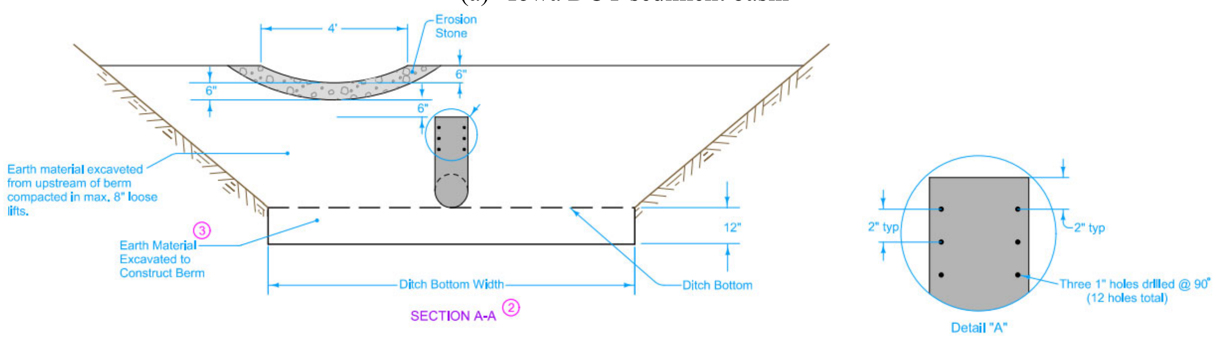


Figure 3.1. ALDOT sediment basin detail (ALDOT 2020).

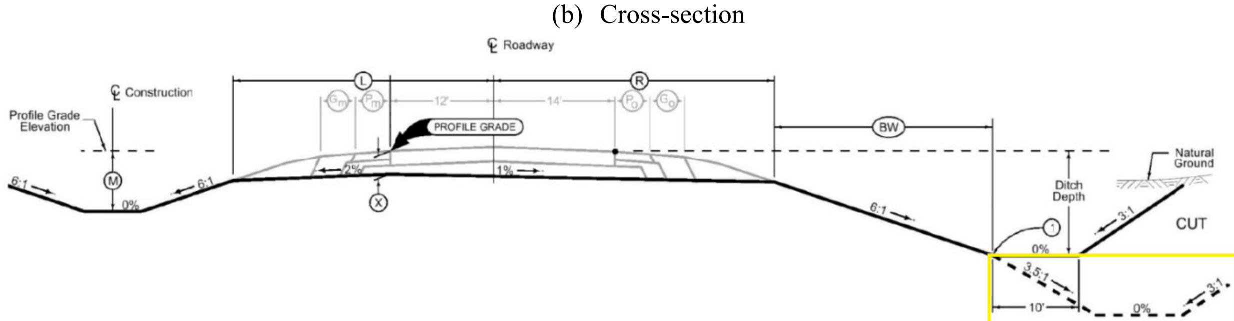
Many DOTs require a dedicated excavated pond and implement one or more of the sediment components described. However, additional sediment basin designs exist. The Iowa DOT's standard sediment basin detail is designed to create temporary detention within the typical channel environment. Iowa DOT design standards specify a trapezoidal channel with a 3.5H: 1V foreslope, 3H:1V backslope, 10 ft (3.0 m) channel bottom, and 3% grade. The basin portion was constructed by excavating an additional 12 in. (30 cm) and using the material to create an earthen berm. The berm has a 4 ft (1.2 m) top width and is 4 ft (1.2 m) high at the midpoint of the berm. Side slopes are 1H: 2V. Situated along the berm, a 4 ft (1.2 m) wide by 6 in. (15 cm) deep spillway allows runoff to bypass the sediment basin when the volume capacity is exceeded. The spillway is armored with erosion stone to prevent scour during overtopping events. A 4 ft (1.2 m) erosion stone apron extends beyond the toe of the berm along the downstream face of the sediment basin. A 12 in. (30 cm) diameter corrugated riser pipe was installed through the berm. The upstream face of the dewatering pipe is turned upward at a 90-degree bend to create a riser structure at the end of the sediment basin. The top of the riser pipe was drilled with three 1.0 in. (2.5 cm) holes spaced 2.0 in. (5 cm) along the top of the pipe at every quarter-turn for a total of 12 perforations.



(a) Iowa DOT sediment basin



(b) Cross-section



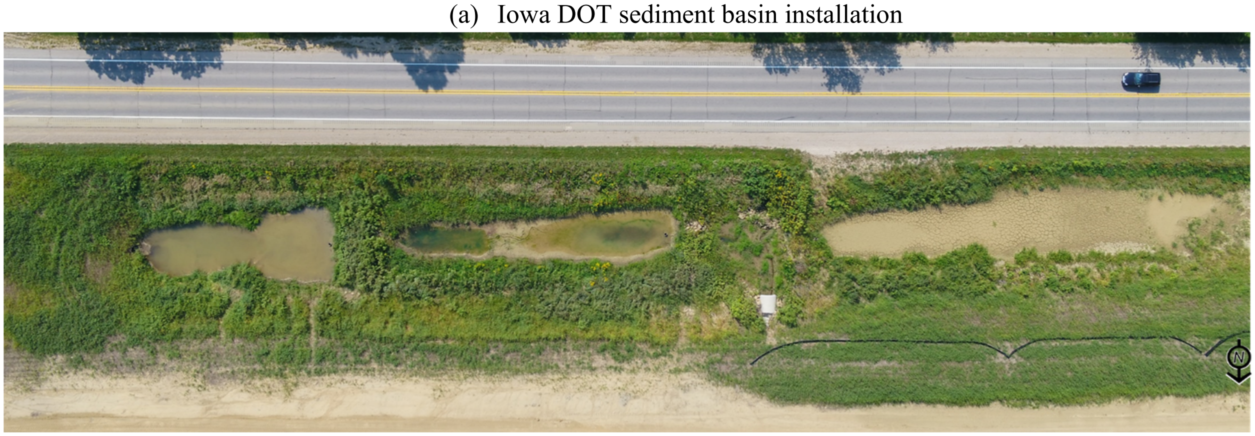
(c) Channel details

Figure 3.2. Iowa DOT standard design details (2017-2018).

3.3. Performance during Field-Monitoring

In 2018, the Iowa DOT led a field-monitoring project of erosion and sediment control practices. If functioning correctly, the sediment from sediment-laden runoff would be retained within the basin, and reflected in turbidity and total solids reduction prior to discharge. Several in-channel sediment basins were instrumented and monitored on the U.S. Highway 30 project. Teledyne™ ISCO 6712 automated water samplers were deployed to collect samples at the inflow and discharge of the evaluated sediment basins. A Teledyne™ ISCO 674 rain gauge was connected to one of the samplers, measuring rainfall depth occurring on-site. Samplers were programmed to take 25 oz (0.75 L) samples from the basin at regular 12-hr intervals. Each sample was collected in an individual 33.8 oz (1.0 L) pie-shaped bottle. Water samples from the basins were evaluated in a laboratory setting for turbidity and total solids; upstream and downstream measurements were plotted over time. The monitored sediment basins are shown in Figure 3.3.

(a) Iowa DOT sediment basin installation



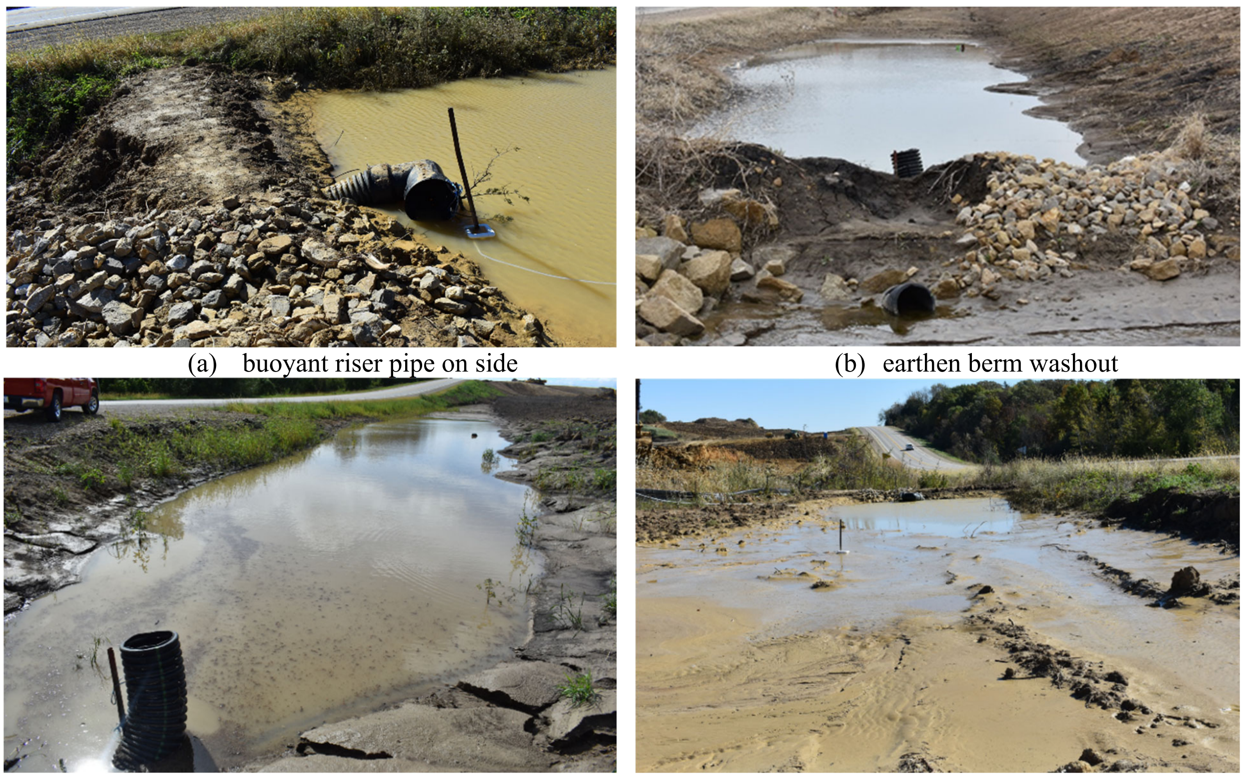
(b) aerial photo of monitored basins

Figure 3.3. Sediment basins from field monitoring.

3.3.1. In-Channel Sediment Basin Monitoring

Initial monitoring occurred on a temporary sediment basin from September 21, 2018 through October 16, 2018. During this time period, 7.40 in. (18.8 cm) of rain were observed over seven qualifying rain events. A qualifying event was defined as more than 0.25 in. (0.64 cm) of rain within a 24-hr period. Across all collected data, average turbidity at the inflow and outflow sampling locations was 853 and 975 NTU with a standard deviation of 1,563 and 2,016 NTU, respectively. Turbidity in the basin ranged from 43 to 6,781 NTU at inflow and 45 to 9,236 NTU at discharge. Total solids concentrations ranged from 2.0 to 4,007 mg/L at inflow and 32 to 3,794 mg/L at discharge. The average total solids concentrations at the inflow and outflow sampling locations were 469 and 490 mg/L with a standard deviation of 894 and 892 mg/L, respectively. Concentrations peaked on October 9, 2018 after receiving nearly 2.30 in. (5.84 cm) of rain across a three-day period. During this measurement, turbidity values at discharge were measured at 9,236 NTU, which was more than 1.5 times greater than turbidity measured at the inflow. On average, the basin increased turbidity by 92 NTU prior to discharge, with a standard deviation of 760 NTU. The basin decreased total solids concentrations by an average of 15.5 mg/L with a standard deviation of 345 mg/L. The high standard deviations are indicative of the wide range of measured turbidity and total solids experienced during monitoring.

Consecutive storm events likely caused the site to reach field saturation, increasing runoff and erosive forces with each event. Increased sediment load and lacking maintenance likely caused sediment deposition to exceed the dead storage, or available volume beneath the discharge pipe, within the basin. In addition, increased flow velocities may have caused turbulence at the inflow of the basin, re-suspending and discharging previously settled material. Dewatering deficiencies were observed during monitoring. The dewatering riser pipe was inadequately anchored to the basin floor and became buoyant. This caused the basin to retain excessive stormwater causing subsequent events to flow through the auxiliary spillway. Erosion stone used to armor the spillway had washed out, resulting in erosion of the earthen berm. Discharge downstream of the earthen berm was not captured, as discharge samples were taken proximal to the discharge pipe. However, it is likely discharged turbidity and total solids concentrations were significantly higher than captured by the sampler due to suspending and transporting washed-out material. Several of the sediment basin deficiencies are included in Figure 3.4



(a) buoyant riser pipe on side (b) earthen berm washout (c) no defined inflow path (d) channel and basin erosion

Figure 3.4. Sediment basin deficiencies.

3.3.2. Basins in Series

In the subsequent construction season, two basins in series were instrumented and analyzed from May 17, 2019 through September 1, 2019. The first and second basins in the series had flow paths of approximately 75 ft (22.9 m) and 100 ft (30.5 m), respectively, with the first basin acting as a forebay to capture rapidly settable solids. The sediment basin system collected a drainage area of 6.56 ac (2.65 ha). The riser pipe from Basin 1 dewatered to Basin 2. In total, there were

15 qualifying events during monitoring. Four automated samplers were deployed between the two basins. Samplers A and B were used to sample the first basin at inflow and discharge, respectively. Samplers C and D were used to sample the second basin at inflow and discharge, respectively. Sampler B collected at the discharge of the first basin, which then discharged to the inflow at Sampler C. All samples were collected from the surface of the water column using floating sampling devices.

Over the course of sampling, 802 viable water samples were collected (190 A-inflow, 192 B-discharge, 214 C-inflow, and 206 D-discharge). Some sample bottles were empty due to dry basin conditions after dewatering. Samplers A and B sampled the first basin in the series, which presumably provided pretreatment for the second basin allowing the rapidly settable solids to drop from suspension. Due to the accumulation of sediment at the inflow of the upstream basin, Sampler A's intake became beached, resulting in several periods without sample collection. Increased algae growth, plant materials, and gastropods were observed in water samples, attributed to the warmer sampling season. Due to this contamination affecting total solids measurements, turbidity was used as the primary measurement for evaluating performance of the basins in series.

The first basin provided an average sediment reduction of 215 NTU with a standard deviation of 511 NTU (comparing Samplers B to A). The second basin decreased turbidity by an average of 870 NTU with a standard deviation of 1,282 NTU (Comparing Samplers D to C). Basin 1 dewatered through a riser pipe to Basin 2. Thus, data collected from Sampler B and Sampler C should have reflected similar turbidity values, however, due to the floating intakes, Sampler B represented a skimmer-like dewatering system. When evaluated as a system, an average turbidity reduction of only 9 NTU with a standard deviation of 88 NTU was achieved. A large increase in turbidity was observed between sample location C and sample location B. This suggests a large amount of sediment-laden stormwater was introduced to sampling point C through the riser structure that hydraulically connected the two basins.

3.3.3. Field Study Conclusions

Water quality results (i.e., turbidity and total solids) indicated that sediment basins were providing negligible water quality improvements. In several cases water quality had increased levels of turbidity and total solids prior to discharge. In the single basin, turbidity increased by an average 92 NTU after residence in the basin, whereas the basins in series provided a turbidity decrease of 9 NTU, negligible treatment when considering turbidity values reaching a magnitude of 10^3 NTU. Average treatment of the basin system provided 0.5% reduction. The lack of water quality improvements was attributed to: (1) sediment contribution from destabilized sediment basin and channel, (2) resuspension of sediment deposited on the basin floor, (3) lack of energy dissipation upstream and within the basin, and (4) inadequate detention time and dewatering.

3.3.4. Limitations

Monitoring was conducted on existing in-channel basins, and conditions including live and dead storage capacities were unknown. Installation of the basins was not monitored and could have varied from DOT specification; therefore, results cannot be directly extrapolated to other basins. The monitored sediment basins were subject to unpredictable site conditions, including rainfall, soils, drainage areas, and changing topography due to ongoing grading. While results may be indicative of the basins on the Tama US 30 site, the repeatability of results on other construction sites is uncertain. Samplers were programmed on 12-hr time-based intervals and were collected every 12 days. In several samples, there was algae growth or other organic matter that may have interfered with water quality testing. The presence of organic matter often only allowed for measurements of turbidity rather than total solids. Total solids tests would have provided a better measure of the rapidly settable solids that are not characterized in turbidity readings.

3.3.5. Impact and Continued Research

The SWPPP for the Tama U.S. 30 expansion included more than 70 sediment basins and 450 silt basins, indicating that detention practices were heavily relied on for sediment capture prior to offsite discharge *(Johnson et al., 2017)*. The installation cost was $3,200 per temporary sediment control basin, according to contract documents, totaling more $200,000 for only sediment basins on the Tama U.S. 30 project *(Skogerboe, 2020)*. Considering this significant investment and the potential to enhance sediment capture, research was continued to assess methods to enhance the treatment efficiency of the Iowa DOT sediment control basin design. Following a literature and SWPPP review, potential modifications to the standard design were proposed and included an upstream forebay, stabilization of the channel and sediment basin through geotextile lining, energy dissipation within the basin from porous baffles, and surface dewatering. To minimize the unknowns related to field-testing, modifications to the basin design have been tested using large-scale testing techniques at the AU-SRF. This research effort is detailed in Chapter Four: In-Channel Sediment Basin Performance Improvements through Large-Scale Testing.

4. CHAPTER FOUR: IN-CHANNEL SEDIMENT BASIN PERFORMANCE IMPROVEMENTS THROUGH LARGE-SCALE TESTING

4.1. Introduction

Sediment basins capture, detain, and treat stormwater by providing residence time to promote gravitational settling of suspended particles prior to off-site discharge. In-channel basins utilize existing channels on-site to treat stormwater and provide an opportunity to maximize length-to-width flow ratios. As a result of the use of existing infrastructure, installation time and costs are reduced; however, minimal performance data exists. The field monitoring during Iowa DOT active construction, presented in Section 3.3 Performance during Field-Monitoring, concluded that the basins provide negligible treatment. Although turbidity reduction was inconsistent in the systems, the single monitored basin increased turbidity by an average of 92 NTU, and the basins in series provided an average turbidity reduction of 9 NTU. Sampled inflow turbidities reached up to 10,000 NTU, thus the turbidity reduction in the two monitored systems were considered negligible. This research, conducted at the AU-SRF, implemented large-scale testing techniques to evaluate in-channel basin performance in response to various structural treatments. Research findings are expected to guide the design and implementation of effective, sediment control basins for enhanced environmental stewardship during construction.

4.2. Construction

After evaluating the available area for construction at the AU-SRF, a 200 ft (61 m) channel was designed using AutoCAD™ following the Iowa DOT channel and basin design specification. The channel cross-section and profile, as designed, are shown in Figure 4.1.

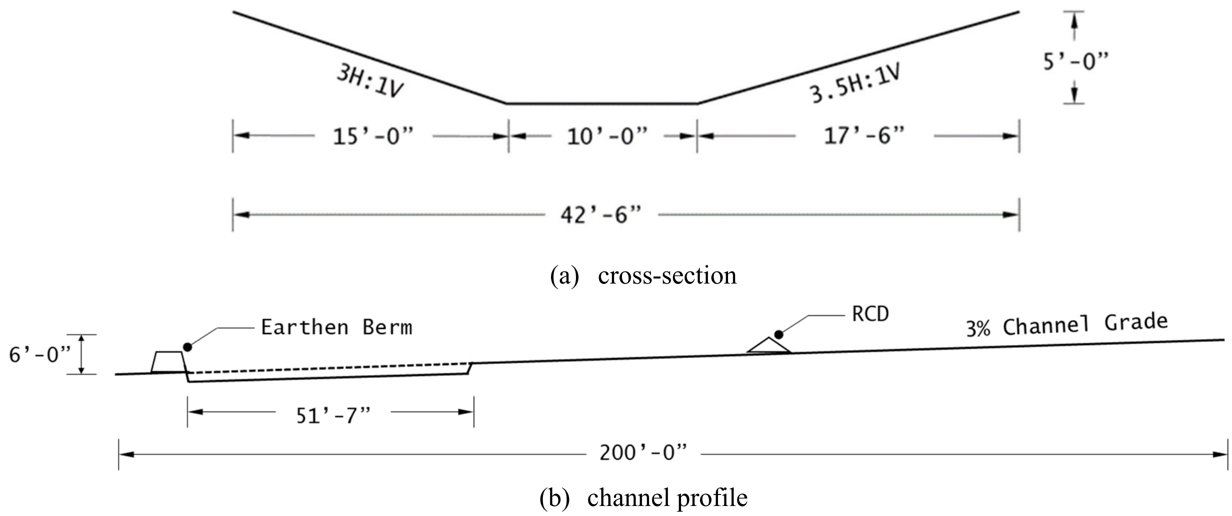


Figure 4.1. Channel design from AutoCAD™ Civil 3D.

A storage volume of 3,031 ft^3 (85 m^3) was determined based on the AutoCAD™ design. The channel was staked out using a Trimble robotic total station using this design. The channel was excavated with a excavator (CAT 320D), graded with a bulldozer (CAT D5), and compacted with a vibratory soil compactor (CAT CP44B). Approximately 20 yd^3 (15 m^3) of excavated material was used to construct the earthen berm, and the excess material was stockpiled. Construction was completed within two days using four total operators. Following construction, a Bobcat E32 Compact Excavator was used to dig out a portion of the earthen berm to install a 12 in. (0.3 m) PVC pipe, which tied the dewatering riser pipe into an adjacent conveyance channel. The earthen berm was backfilled and compacted. A 4 ft (1.3 m) wide section above the installed pipe was shaped into a 1 ft. (0.3 m) deep channel to serve as the auxiliary spillway. Twelve perforations were drilled into a 12 in (0.3 m) 90° PVC elbow following the Iowa DOT standard dewatering riser and attached to the 12 in. (0.3 m) PVC pipe running through the earthen berm on the sediment basin side. An 8 oz (227 g) geotextile fabric was anchored to the basin and over the auxiliary spillway area to protect the grade and maintain the structural integrity of the basin until testing started. Images from channel and sediment basin construction are shown in Figure 4.2.

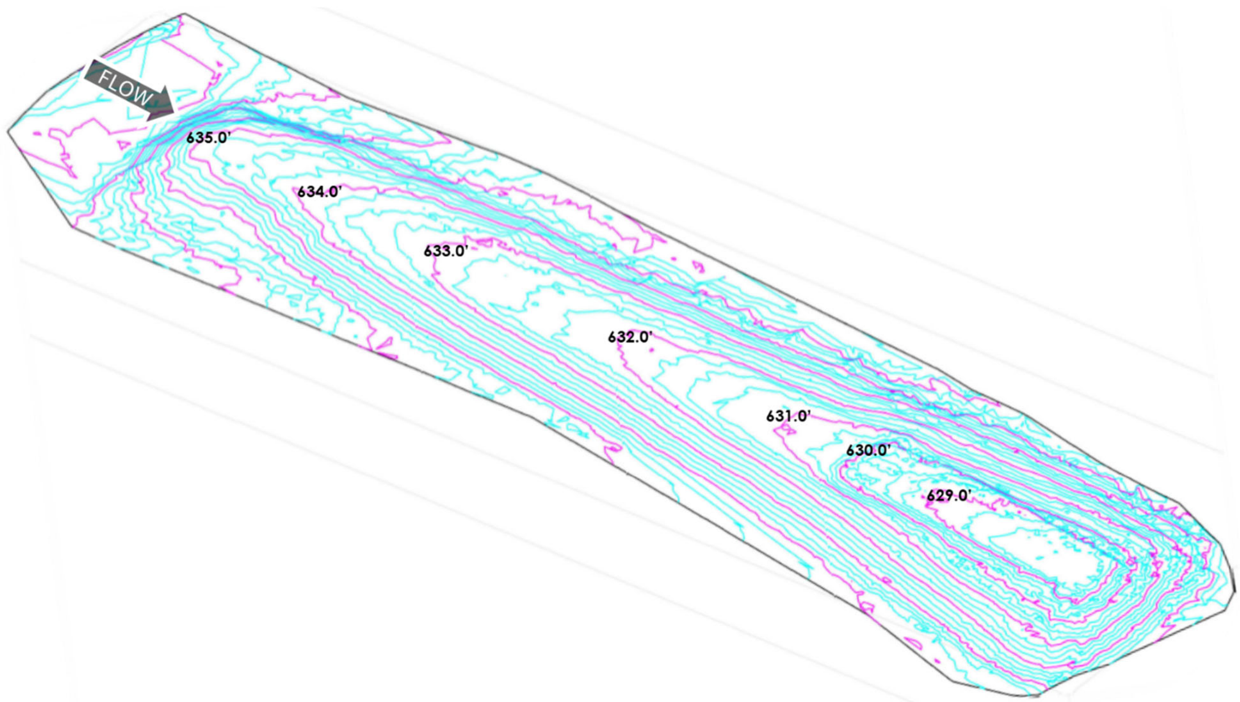
(a) channel grading

(b) excavating basin and surveying grade

(c) auxiliary spillway construction

Figure 4.2. Channel construction.

Before testing, the geotextile was removed, and a Trimble™ SX 10 Scanning Total Station and Trimble™ R2 GNSS RTK were used to survey the basin as-built on February 25, 2021. The scan of the as-built basin resulted in a volume of approximately 3,031 ft^3 (86 m^3). A contoured diagram of the basin is shown in Figure 4.3.



Note: contour interval 0.25 ft (0.8 m)

Figure 4.3. Contour diagram of as-built sediment basin.

The base scan was placed and analyzed in AutoCAD 3D™. Stage-Storage was determined using the surface contour method, the graph of the relationship is shown in Figure 4.4 below.

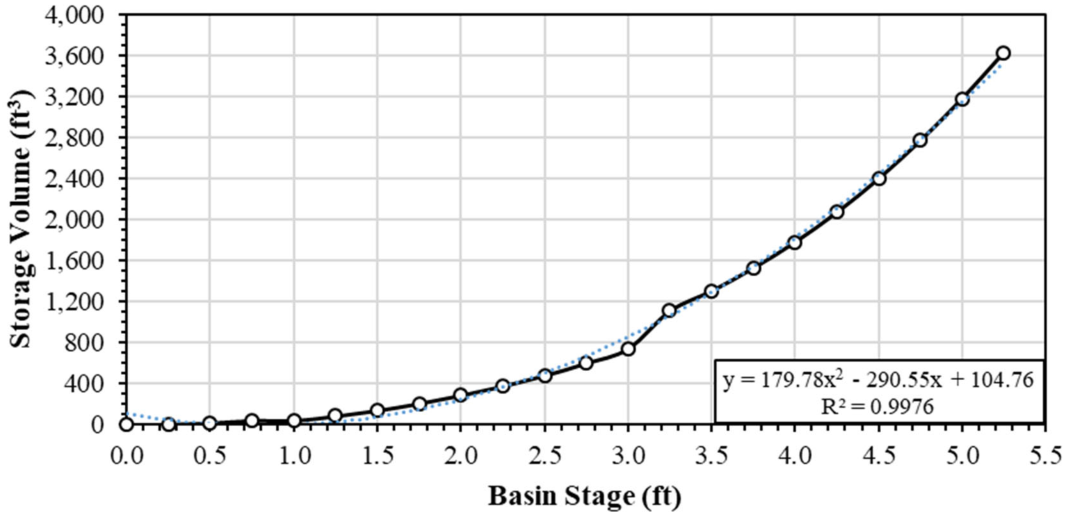


Figure 4.4. Stage-storage relationship.

After scanning, new 8 oz (227 g) geotextile fabric was anchored to the basin to protect the grade and maintain the structural integrity of the basin until testing commenced. A 10 × 10 ft (3.1 × 3.1 m) concrete pad was poured at upstream side of the basin to host the flow and sediment introduction apparatuses. A rigid plastic liner was placed and anchored directly downstream of the concrete pad to prevent erosion from occurring where flow is highly concentrated. A turf reinforcement mat (TRM) was installed where the 12 in. (0.3 m) PVC pipe daylighted in the conveyance channel to prevent erosion at discharge. Class D erosion stone was installed on top of the TRM and over the depression in the earthen berm to satisfy the auxiliary spillway requirements.

Following several natural fill and dewatering cycles from rainfall on-site, it was observed that flow and sediment were discharging into the basin at many locations longitudinally down the channel, and water was flowing underneath the dewatering pipe through the earthen berm. A small earthen berm was constructed spanning the length of the channel to divert flow away from the basin. This channel was covered in a TRM and seeded to provide permanent stabilization. The second issue was rectified by peeling back the geotextile near the discharge, excavating approximately 1 ft (0.3 m) material around the dewatering pipe, and backfilling with bentonite

HolePlug®, which swelled when wet to prevent flow under the dewatering pipe. A 3 in. (7.6 cm) depth of native soil was packed on top of the HolePlug® and re-covered with geotextile. An aerial of the basin prior to testing is shown in Figure 4.5.

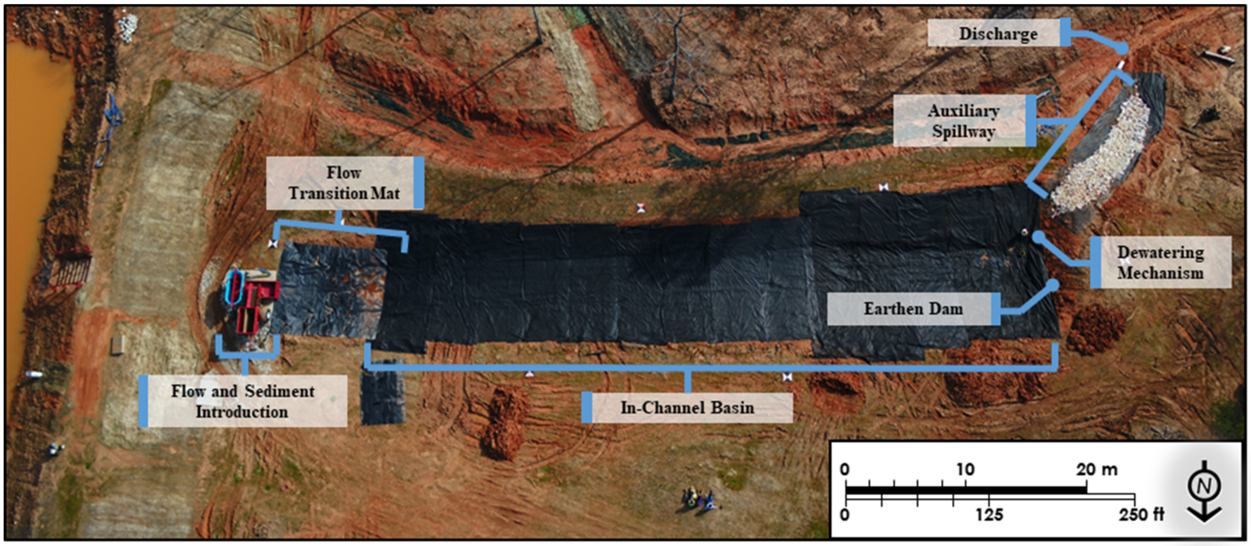


Figure 4.5. Aerial image of in-channel sediment basin at AU-SRF.

4.3. Materials and Methods

This section describes the methods, procedures, and experimental testing regimen to evaluate the performance of the in-channel basin constructed at AU-SRF. Before testing, a flow and sediment introduction rate representative of Iowa DOT construction sites was determined. Flow and sediment introduction apparatuses were constructed and calibrated based on this determination. Data collection included water quality, quantity, and sediment quantity measures. Each of these steps is discussed in detail in the following sections.

4.4. Runoff Analysis and Flow Rate

Under section 2.2.12 of the USEPA's NPDES Construction General Permit (CGP) provides two methods for sediment basin storage: (a) 2-yr, 24-hr design storm runoff volume, or (b) 3,600 ft^3 (252 m^3) of storage per acre (hectare) drained *(2022)*. Iowa DOT follows the state-specific sizing guidance provided by Iowa Department of Natural Resources (DNR) NPDES General Permit No. 2, which requires sediment basins serving areas with more than 10 ac (4.05 ha) of disturbance to be sized to provide 3,600 ft3 (252 m3) of storage per acre (hectare) drained. The sizing parameter was increased from 1,800 ft3, to detain approximately the first flush, or the first 1.0 in. (2.5 cm) of runoff from a 3.0 in (7.6 cm) storm event. The 3.0 in. (7.6 cm) storm event was selected by the USEPA to be representative of the 2-year, 24-hour storm in selected locations as published in the 1992 Federal Register (USEPA 1992). The USEPA further assumed the 3.0 in (7.6 cm) storm event would produce 1.0 in. (2.5 cm) of runoff. The first flush is presumably the most polluted, or most sediment-laden runoff. The "one-size fits all" sizing parameter was documented in the Federal Register in 1992. The rationale is as shown in Eq. 4.1:

$$1\ in. \times \frac{1\ ft}{12\ in.} \times 1\ ac \times \frac{43{,}560\ ft^2}{1\ ac} = 3{,}637.5\ ft^3 \qquad \textbf{Eq. 4.1}$$

The TR-55 Urban Hydrology for Small Watersheds design approach calculated 1.0 in. (2.54 cm) of runoff from 24-hour distributed storms for a single drainage acre in Iowa (USDA 1986). Runoff was calculated using Eq. 4.2:

$$Q = \frac{\left(P - \frac{200}{CN} + 2\right)^2}{P + \frac{800}{CN} - 8} \qquad \textbf{Eq. 4.2}$$

where,

Q = runoff depth (in.)
P = rainfall depth (in.)
CN = curve number

For Eq. 4.2, Q was set to 1.0 in. (2.54 cm), and P was solved using CNs representative of soil types in Iowa. A GIS analysis was conducted to identify representative hydrologic soil groups and associated CNs for newly graded and developing areas, shown in Figure 4.6.

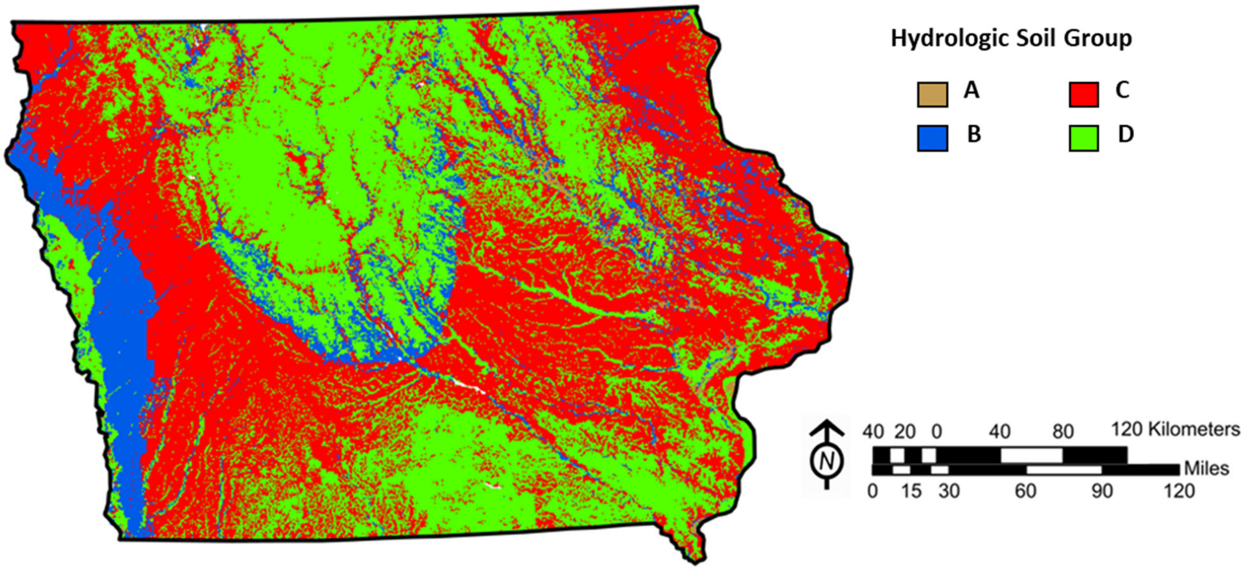


Figure 4.6. Curve number distribution for newly graded or developing areas in Iowa.

These *CNs* and respective rainfall depths were used to develop hydrographs within AutoCAD Civil 3D. Volumes were slightly above the expected 3,600 ft^3 (252 m^3) for a contributing area of 1.0 ac (0.4 ha), so rainfall was calibrated through an iterative process to most closely align with the 3,600 ft^3/ac (252 m^3/ha) sizing parameter.

Using the Iowa DOT 3,600 ft^3/ac (252 m^3/ha) sizing guidance, the designed AU-SRF sediment basin [3,031 ft^3 (86 m^3)] was determined to be representative of a 0.84 ac (0.34 ha) treatment area. The curve numbers and rainfall depths were applied to a 0.84 ac (0.34 ha) treatment area. Hydrologic soil groups (HSG), curve numbers (CN), calibrated rainfall depths (P), runoff volumes, and respective peak discharges (Q) are summarized in Table 4.1.

Table 4.1. Peak discharge and runoff values from modeled storm calibration

HSG	CN	P in. (cm)	1.0 ac. (0.40 ha) Contributing Area		0.84 ac (0.34 ha) Contributing Area	
			Vol. *ft³ (m³)*	**Q** *ft³/s (m³/s)*	**Vol.** *ft³ (m³)*	**Q** *ft³/s (m³/s)*
A	77	2.85 (7.24)	3,625 (103)	1.80 (0.05)	3,045 (86)	1.51 (0.04)
B	86	2.16 (5.49)	3,638 (103)	1.81 (0.05)	3,056 (87)	1.52 (0.04)
C	91	1.78 (4.52)	3,645 (103)	1.79 (0.05)	3,061 (87)	1.50 (0.04)
D	94	1.54 (3.91)	3,641 (103)	1.76 (0.05)	3,059 (87)	1.48 (0.04)
Avg.[a]	91.6	1.73 (4.39)	3,635 (103)	1.78 (0.05)	3,053 (86)	1.50 (0.04)

Note: average determined using weighted values from GIS analysis.

Using the state average curve number (91.6) and 1.73 in. (4.39 cm) of rainfall depth in a 24-hour distribution, the simulated storm produced 3,053 ft^3 (86 m^3) of runoff for a 0.84-acre (0.34- ha) drainage area. A flow rate of 1.70 ft^3/s (0.05 m^3/s) was used to fill the basin storage volume within a 30-minute test duration, as calculated in Eq. 4.3:

$$3{,}053\ \frac{ft^3}{test} \times \frac{1\ test}{30\ min} \times \frac{1\ min}{60\ sec} = 1.70\ \frac{ft^3}{sec} \qquad \textbf{Eq. 4.3}$$

4.4.1. Sediment Loss and Introduction Rate

Soil loss was calculated using the Modified Universal Soil Loss Equation (MUSLE) *(NRCS 2006)*, which uses runoff variables to estimate soil loss with respect to runoff rather than rainfall, and is shown in Eq. 4.4:

$$S = 95(QP_p)^{0.56}KLSCP \qquad \textbf{Eq. 4.4}$$

where,

S = sediment yield (tons)
Q = runoff volume (ac-ft)
P_p = event peak discharge (ft^3/s)
K = soil erodibility factor
LS = slope length and steepness factor
C = cover discharge (ft^3/s)
P = practice factor

Runoff volume and peak discharge from Table 4.1 were used to determine S. The K factor was estimated to be 0.26 from soil testing conducted during the Erosion and Sediment Control

Field Monitoring project *(Schussler et al., 2020)*. The LS factor was determined to be 0.83, representative of 16% slopes at 20 ft (6.1 m) lengths for conditions of high rill to interrill erosion ratios that would be considered consistent with newly graded construction conditions *(Pitt et al., 2007)*. C and P factors were estimated to be 0.5, assuming erosion and sediment control practices (i.e., mulching, seeding, ditch checks, etc.) would be implemented upstream of the basin in a treatment train. Sediment loss (tons), sediment introduction (lbs/min), and estimated soil per test (yd^3) are shown in Table 4.2.

Table 4.2. Sediment introduction modeled for AU-SRF in-channel sediment basin

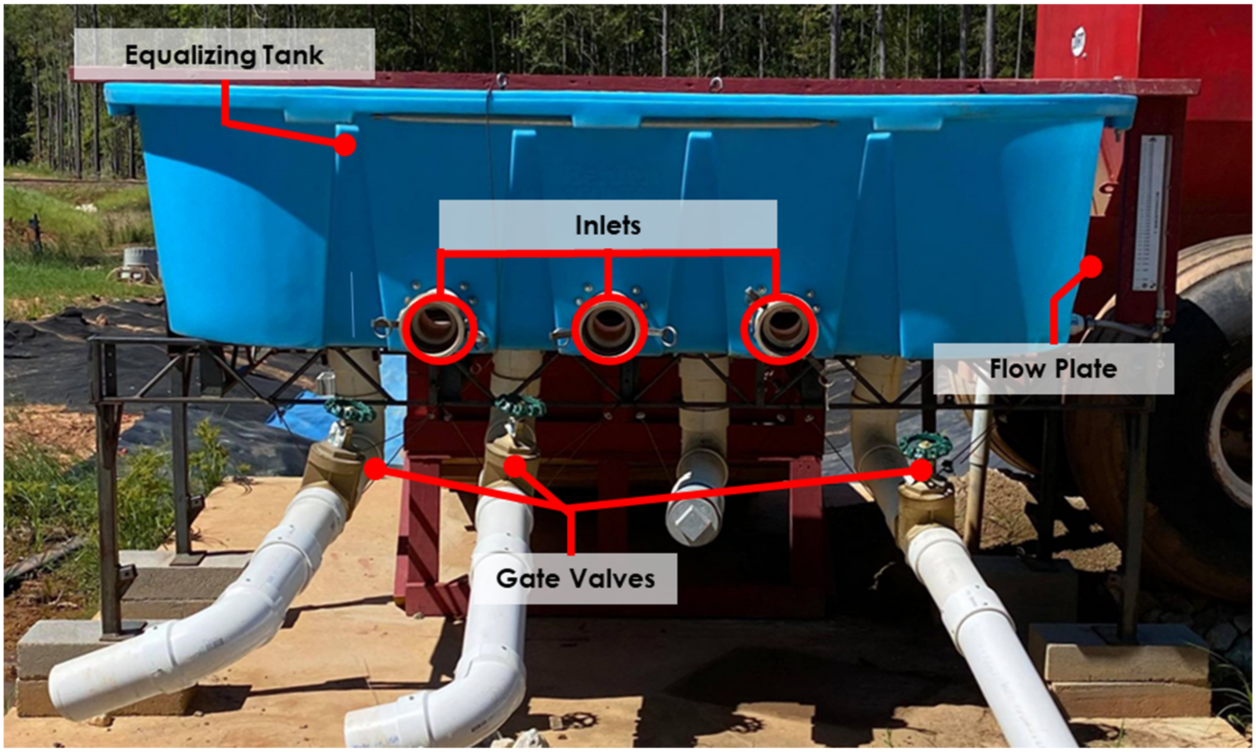
HSG	**Q** *ft^3 (m^3)*	**P_p** *ft^3/s (m^3/s)*	**S** *lbs (kg)*	**Sediment Introduction**[a] *lbs/min (kg/min)*	**Soil per Test** [b] *yd^3(m^3)*
A	1,257 (36)	1.70 (0.05)	1,889 (857)	63.0 (28.6)	0.70 (0.54)
B	1,372 (39)	1.70 (0.05)	1,944 (882)	64.8 (29.4)	0.72 (0.55)
C	1,343 (38)	1.70 (0.05)	1,966 (892)	65.5 (29.7)	0.73 (0.56)
D	1,346 (38)	1.70 (0.05)	1,968 (893)	65.6 (29.8)	0.73 (0.56)
Avg.	1,341 (38)	1.70 (0.05)	1,961 (889)	65.4 (29.7)	0.73 (0.56)

Notes:
[a] sediment introduction rate and volume calculated for 30 minutes of flow introduction
[b] soil volume estimated $S \times 0.74 \frac{tons}{yd^3}$

4.4.2. Flow and Sediment Introduction Apparatus

Attaining and maintaining accurate flow and sediment introduction rates were crucial for the performance evaluation of the sediment basin. A four-stage introduction process was developed to introduce and mix flow and sediment. The developed process included a pump system, equalizing tank with a weir, sediment introduction hopper, and mixing trough.

To introduce flow, three DuroMax 4 in. (10 cm) semi- trash water pumps (Model No. XP904WP) were used to convey water from the upper supply pond to a 300 gal (1,136 L) tank. The equalizing tank was outfitted with three 4 in. (10 cm) inlets for the pumps to tie in with flexible hosing, a rectangular weir on the basin side, and three 4 in. (10 cm) adjustable gate valves on the backside. The gate valves were adjusted to allow water to leave the tank to prevent overflows, allow pumps to be primed and pressurized before testing, and regulate the flow rate to meet testing requirements. A wooden baffle was installed perpendicular to the incoming flow through the middle of the trough to reduce turbulence. Flow passed through the rectangular weir and entered the wooden mixing trough. The water level above the weir corresponded to a flow rate shown on an accompanying gauge that was calibrated and printed on a plate. A 0.5 in. (1.3 cm) clear rubber pressure tube was run from the inside of the equalizing tub and up the side of the flow plate, which was placed and secured during flow calibration. The plate was placed when the water level reached the bottom of the weir but was not yet entering the channel; this level corresponded to the plate reading "0.00 ft3/s." The calibration was verified by tracking the time required to reach several volumetric measurement markers, in a series of 5-gal (19-L) buckets. The flow introduction system is shown in Figure 4.7. Flow introduction system.



(a) back of system

(b) weir

(c) flow plate

Figure 4.7. Flow introduction system.

Sediment was introduced using a steel hopper equipped with a hydraulically-driven conveyor belt. Sediment introduction was regulated by the height of a gate installed on the hopper and the speed determined by the hydraulic machine. A Bobcat E32 Compact Excavator was used to attach and control the hydraulics for all sediment basin testing. The end of the conveyor belt was positioned hallway over the mixing trough to allow for ample mixing of introduced flow and sediment. Diversion drains were mounted within the trough to amplify mixing before entering the test channel. The Bobcat E32 Compact Excavator was set on its second hydraulic speed option, and the gate was adjusted. To calibrate the system, the time was tracked to introduce 32.7 and 65.4 lbs (14.8 and 29.7 kg) of sediment, which needed to reach 30 and 60 seconds, respectively. The system is shown in Figure 4.8.

Figure 4.8. Flow and sediment introduction system.

4.4.3. Experimental Design and Testing Regimen

A staged-experimental testing regimen was developed to evaluate the treatments independently and as a system. Eight basin configurations, or series, were developed (S1-S8).

Each series was comprised of three test days (L1-L3), and each test included two filling periods (A/B) for 48 total tests. L1-A started with an empty, sediment-free basin. Flow and sediment were introduced for 30 minutes, or the first filling period. The basin was then left to dewater for 4.5 hours before flow and sediment were introduced for another 30 minutes, or the second filling period (L1-B). The second filling period, simulated a second runoff event, which may be experienced as back-to-back storm events in the field, when the basin is partially full. The second event evaluated the resuspension potential and performance if the auxiliary spillway was activated. The basin then dewatered for at least 48 hours before the remaining impoundment was pumped from the basin.

Subsequent tests (L2 and L3) were conducted once the basin was completely dewatered; however, deposited material from the preceding tests was not removed. This testing regimen represented a newly constructed basin subjected to several storm events before maintenance (i.e., dredging deposited material).

Since the in-channel basin was based on the Iowa DOT standard design, it was important to understand the behavior of the basin with Iowa-native soil. Despite basin evaluations conducted in Auburn, Alabama, Iowa-native soil was delivered in five mobilizations. The testing regimen utilized Alabama-native soils for calibration and base condition testing since it was abundant on-site. Figure 4.9 below represents the testing regimen and testing sequence.

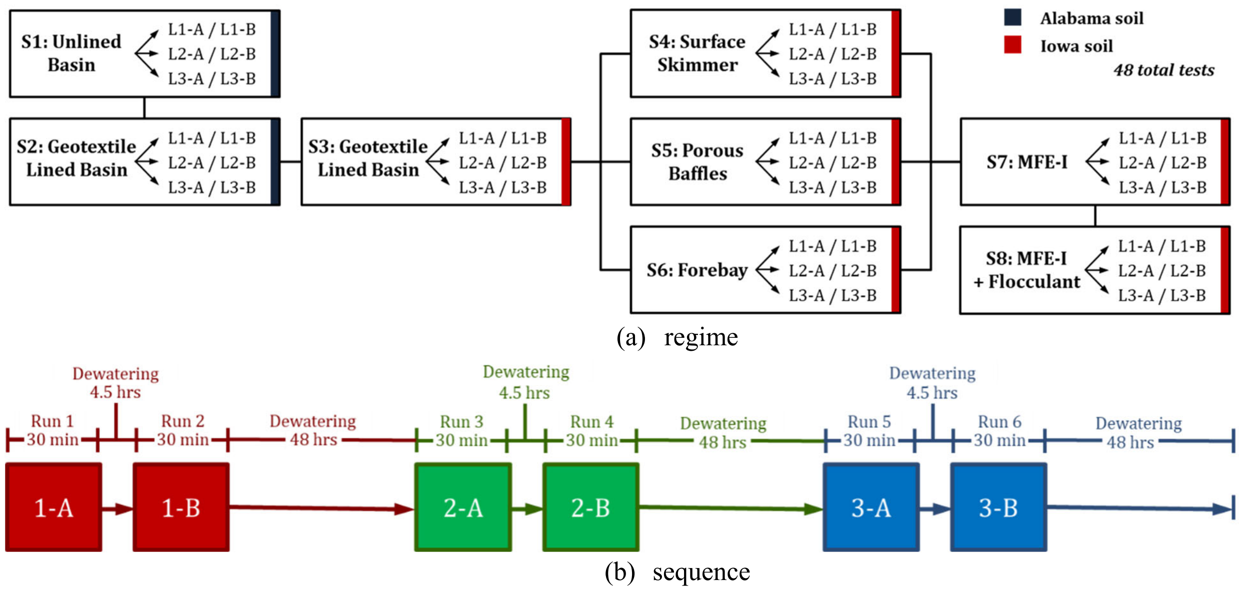


Figure 4.9. Sediment basin testing regimen.

4.4.4. Iowa Native Soil Delivery

Iowa native soil was mobilized from Tama U.S. 30 and delivered to the AU-SRF via five tractor trailer loads. When the soils arrived, there were observed color and particle size differences, indicating the soil was likely excavated from various locations and soil horizons on the size. The first delivery and soil from subsequent deliveries are shown in Figure 4.10.

(a) first delivery from Tama U.S. 30

(b) soil loads after delivery

Figure 4.10. Iowa soil delivery.

To ensure homogeneity during testing, the soils were well-mixed, using the Bobcat mini-excavator, compacted, and covered for storage. When testing began, soil was pulled from various locations in the stockpile, mixed again, and crushed to pass through the one-quarter inch shaker. Photos of the soil delivery and storage are shown in Figure 4.11.

(a) soil mixing

(b) compacted and covered stockpile

Figure 4.11. Iowa soil stockpile.

4.4.5. Soil Parameters

Before testing, soils were dried, crushed, and sieved through a 0.5 in. (1.3 cm) screen to remove large aggregate and debris. Both soil types used were classified according to AASHTO and USCS soil classifications. To classify these soils, dry and wet sieve analyses, Atterberg limits test, and hydrometer analyses were conducted according to ASTMs C136/C136M-19, D4318-00, and D7928-17, respectively. Following the required tests, the Alabama-native soil was classified as USCS Clayey Sand and AASHTO Fair to Poor Clayey soil. The Iowa- native soil was classified as USCS Sandy Lean Clay and AASHTO Clayey Soil. The soil gradations are shown in Figure 4.12.

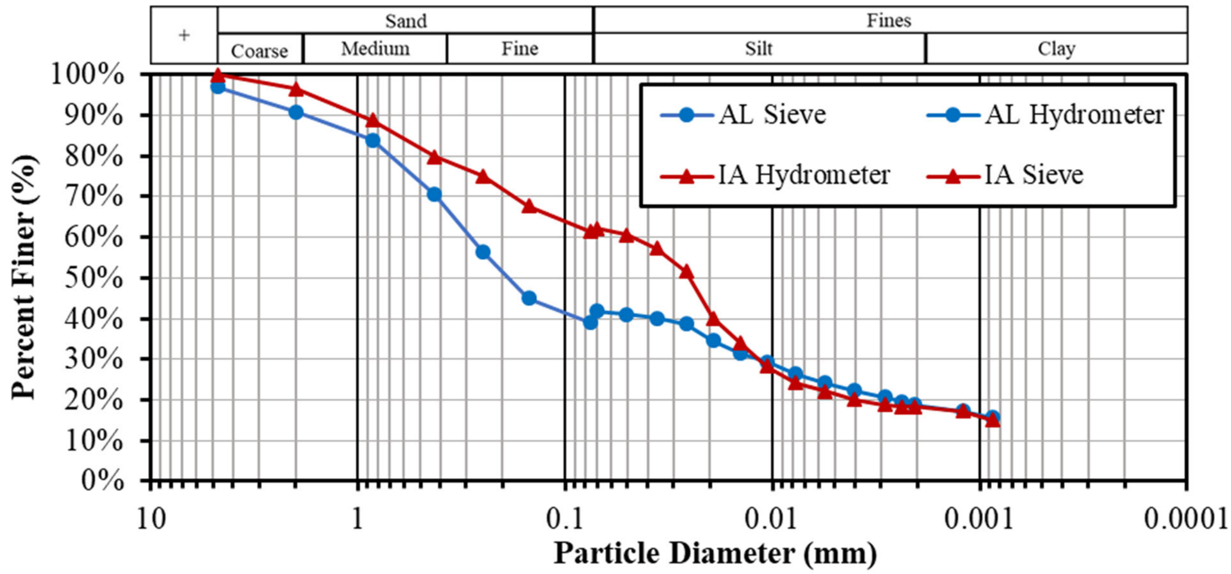


Figure 4.12. Soil gradation.

4.4.6. Data Collection

Various soil and water parameters were measured during testing to evaluate and compare the effects of the structural treatments on basin performance. Data collection included water samples for water quality analysis, stage levels within the basin, and sediment deposition after each test.

Three Campbell Scientific OBS3+ turbidity probes were placed in the basin. One sensor was located at the top of Bay 2 and the other two probes were located at the top and bottom of Bay 4. The CR850 Campbell Scientific data logger was mounted near the sensors and was powered by a 12V deep cycle marine battery. A set of Solonist M5 Levelogger and a M 1.5 Barologger were used to monitor the stage of the basin. The Levelogger was installed 6 in. (15.2 cm) off the basin floor in the fourth bay near discharge in a perforated PVC tube to protect it from direct sunlight. The logger recorded a measurement every 60 seconds. A Barologger was installed on-site and recorded atmospheric pressure every 15 minutes. Data were collected from the loggers in the Levelogger 4.5.1 Software. Levelogger data was corrected with the Barologger data, which resulted in the basin stage. The basin stage was plugged into the stage-storage relationships, shown in Figure 4.4, to monitor volume over time. This provided insight on dewatering times for the various installations.

Five Teledyne ISCO 6712 Portable automated samplers were used to collect water samples in the (1) inflow channel, (2) second bay, (3 and 4) top and bottom of the fourth bay, and (5) discharge. For samplers 2, 3, and 5, the suction tubing was mounted to floating skimmers in the center of the bays. Sample collection began when the water level reached the height of the floating skimmers. The suction tube for samplers 1 and 4 was mounted to cinder blocks and anchored in the inflow channel and Bay 4, respectively. The samplers each housed a set of 24 bottles of 34 oz (1.0 L) volume. Sampler 1 was programmed to take a 34 oz. (1.0 L) sample every two minutes during the 30-minute inflow periods for 15 samples. The second, third, fourth, and fifth samplers were programmed to take a composite sample comprised of a 17 oz. (0.5 L) sample every two minutes. Thus, one bottle was filled every four minutes during the first fill and subsequent dewatering period. The samples were started as the flow reached the intake of the sampling location. The bottles provided volume to capture samples for the 96 minutes following start. The start times for each sampling location under a certain basin configuration is shown in Table 4.3.

Table 4.3. Sampling start times

Sampling Location	S1, S2, S3, S5	S4	S6	S7, S8
Inflow	2 min	2 min	2 min	2 min
Bay 2	16 min	16 min	24 min	24 min
Bay 4 Top	4 min	4 min	4 min	4 min
Bay 4 Bottom	4 min	4 min	4 min	4 min
Discharge	16 min	8 min	24 min	24 min

During the second fill, the inflow sampler was again programmed to take a 34 oz. (1.0 L) sample every two minutes during the 30-minute inflow periods for 15 samples. The second, third, fourth, and fifth samplers were programmed to take a composite sample, comprised of a 17 oz. (0.5 L) sample every two minutes during filling, but were transitioned to longer sampling times to capture the basin behavior during the extended dewatering period. Samplers 2-4 were programmed to take a composite sample of a 17 oz. (0.5 L) sample every 75 minutes. This provided water samples from the first 45 hours of dewatering. Sampler 5 followed the same program; however, sampler 5 was programmed to take a sample every 10 minutes when the riser pipe was used for dewatering. This was due to the increased stage level required to dewater from the perforations in the riser pipe. Meanwhile, the skimmer allowed the basin to dewater for approximately 50 hours post-initial fill cycle. Water sampling locations and intervals are shown in Figure 4.13.

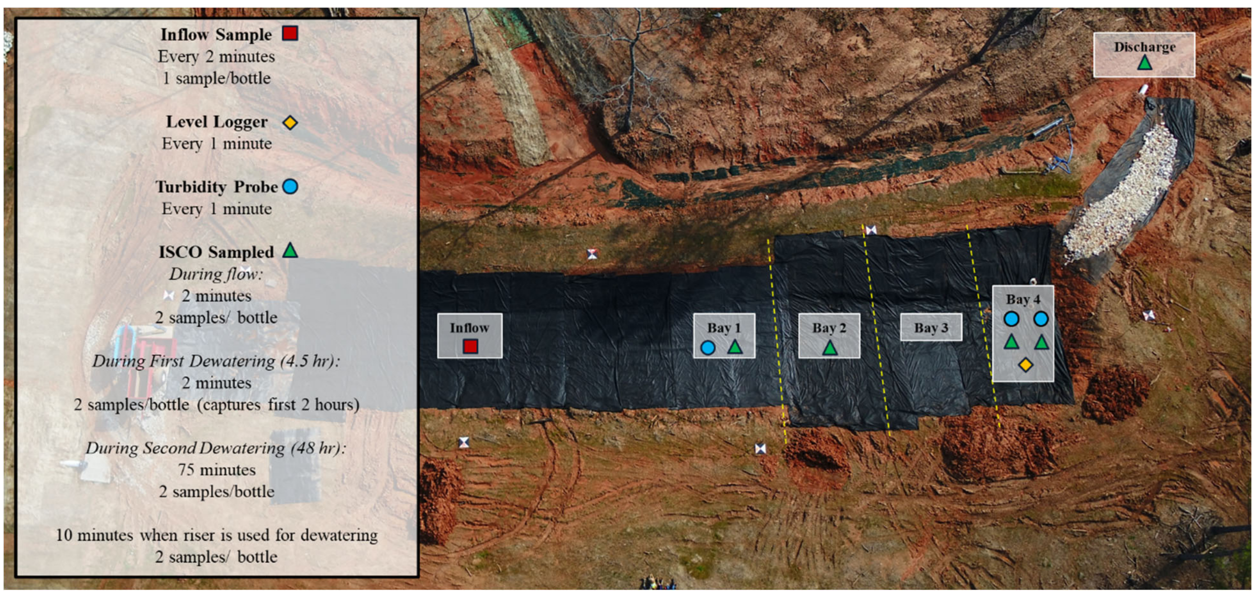


Figure 4.13. Water sampling locations.

Following each series of tests, the sediment basin was drained and the deposited material was dredged out and measured following each series of tests. Five sedimentation gauges were installed in an x-configuration in each bay, and sedimentation depths were measured after the basin was completely drained between tests. The sedimentation gauges were used for observation between tests. Methods to quantify sediment retention are outlined in the following section.

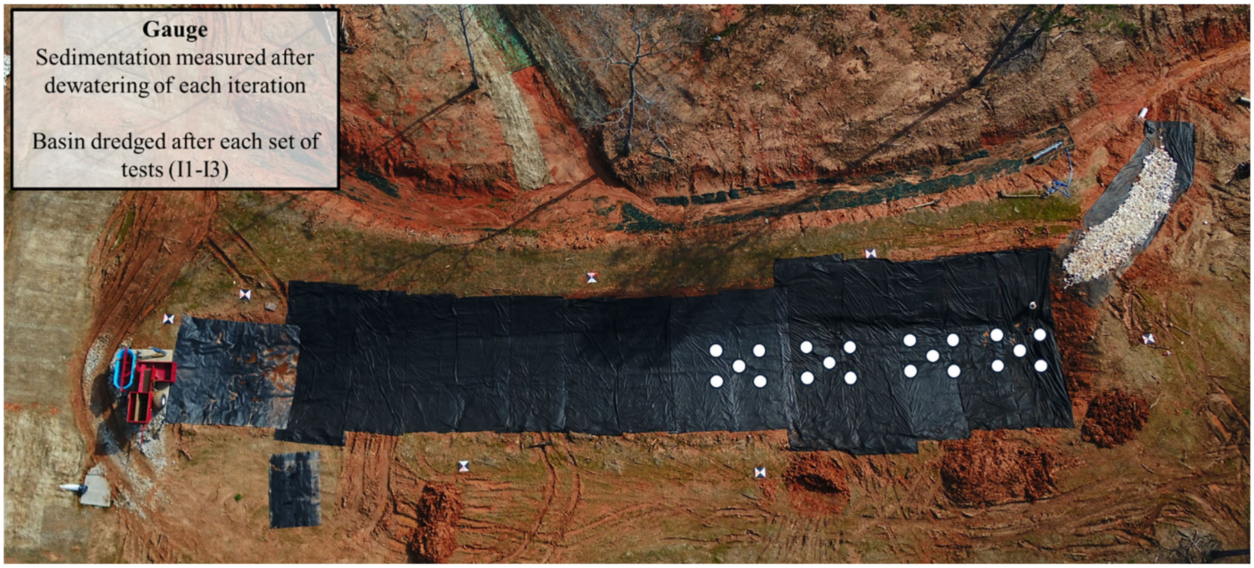


Figure 4.14. Sedimentation gauge configuration.

4.4.7. Sediment Retention Quantification

To quantify sediment retention, the sediment basin was completely drained using a 2 in. (5.1 cm) submersible pump. The deposited material was dredged out and measured following each series of tests. Each bay was dredged and measured independently. Sediment volume and weight were measured by filling a 15.3 ft3 (0.43 m3) metal bin. After volumetric measurements, a 1 ft3 (0.03 m3) sample was taking from the larger bin to correct for the dredged sediment's moisture content.

The bin was filled with the deposited material, and a depth measurement was recorded. The depth measurement was multiplied by the cross-sectional area to result in a total sediment volume. The 1 ft3 (0.03 m3) box was then filled with sediment from the bin. The 1 ft3 (0.03 m3) of sediment was transferred to a metal baking pan and weighed. The weight was corrected to exclude the weight of the empty pan, Wwet. The sediment was dried in an oven for at least 36 hours and reweighed and corrected for weight of empty pan. The dry weight, Wdry, was multiplied by the total volume to estimate the weight of sediment retained in the bay, W1. The water content, Wc, was determined using Eq. 4.5.

$$W_c = \frac{(W_{Wet} - W_{Dry})}{W_{dry}} \qquad \textbf{Eq. 4.5}$$

The geotextile liner captured a portion of the sediment and made it difficult to quantify all deposited sediment. To account for this, a 2 × 2 ft (0.61 × 0.61 m) geotextile square sample was removed from each bay and dried. The representative squares were then weighed and corrected for the weight of the geotextile without deposited material. Each bay was measured for the area, divided by the 4 ft^2 (0.37 m^2) representative square, and multiplied by the resulting weight of each representative square. This result represented the weight of soil retained in the geotextile in each bay, W_2. W_1 and W_2 were combined to estimate the total weight retained in each bay. In between the testing series, the geotextile was pressure washed to remove any captured sediment. The weights were analyzed as a percentage of the total soil weight introduced to the basin during test L1-L3.

4.4.8. Water Quality Analysis

For series S1 and S2, turbidity and total solids analyses were conducted for all water samples. Turbidity was determined using a combination of the HACH® 2100Q Portable Turbidimeter (0-999 NTU) and Hach® TL23 Series Turbidimeter (0- 9,999 NTU). Total solids testing was conducted following ASTM standards D3977-97 *(ASTM 2015).* Sediment concentrations were expected to be above 200 ppm; therefore, the evaporation test method (Test Method A, ASTM D3977-97) was selected. Due to a large number of samples, the analyses were time, labor, and material intensive. The turbidity and total solids concentrations from S2 were plotted and evaluated for a relationship to minimize the impact in the laboratory. After observation, inflow values skewed any relationship. To improve the relationship, the inflow was removed, and sample pairs (turbidity- total solids) were sorted based on turbidity value. The values were split into 10 ranges (0-99, 100-199, 200-299… 900-999, 1000+). Each range was independently evaluated, and samples with outlying total solids concentrations were removed.

The remaining turbidity and total solids values were plotted on the x- and y-axis, respectively, as shown in Figure 4.15 and resulted in a relationship shown in Equation 4.6.

$$y = 0.0417x^{1.34}$$ **Eq. 4.6**

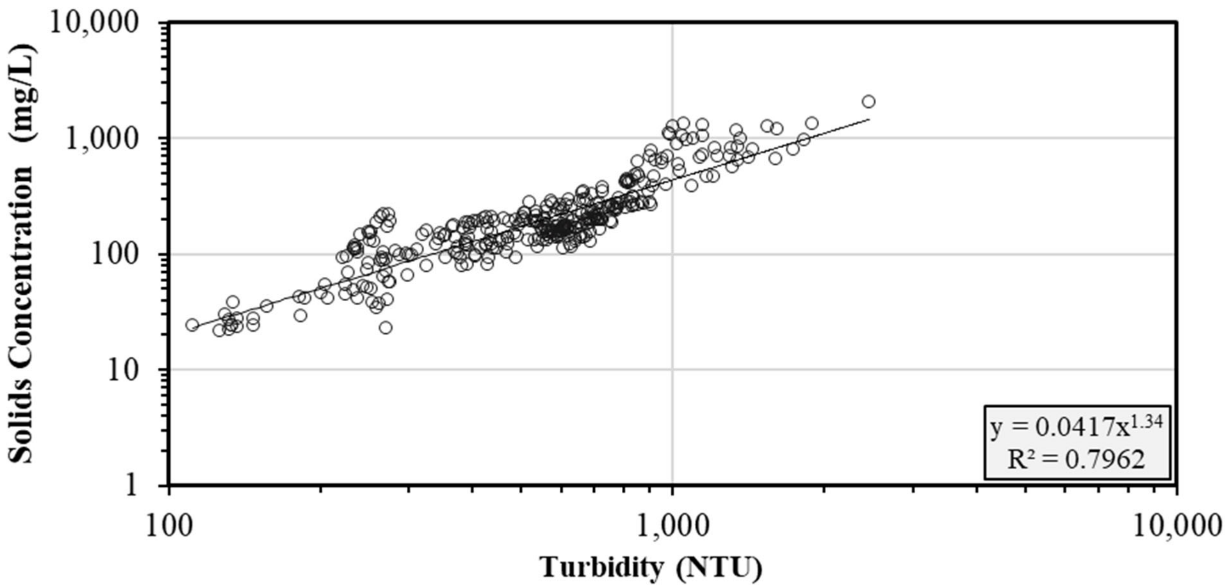


Figure 4.15. Turbidity and total solids relationship.

For the remaining series, inflow water samples were analyzed for turbidity and total solids; however, water samples from locations 2-5 were only analyzed for turbidity, and values were plugged into the relationship shown in Eq. 4.6 to estimate total solids concentrations.

The basin configurations were analyzed for turbidity reduction (%) from the water samples by comparing representative inflow turbidity to turbidities from downstream sampling locations. Representative inflow turbidity for each test (L1-A, L1-B, L2-A, L2-B, L3-A, L3-B) were calculated by averaging the inflow samples from a filling period after removing the outliers.

Outliers were determined as values that were 1.5 times higher or lower than the interquartile range. An example of calculating the representative inflow for the S3 LX-A data set is shown in Table 4.4. This process would be repeated for the second filling period S3 LX-B, etc. The strikethrough text represents an outlier, which was not used in average calculations.

Table 4.4. Example for S3 (lined, IA-soil)

Time (min)	S3: L1-A (NTU)	S3: L2-A (NTU)	S3: L3-A (NTU)	Average (NTU)
2	1,636	1,383	2,793	1,938
4	4,022	1,620	1,431	2,358
6	3,025	1,307	1,656	1,996
8	2,248	1,268	2,854	2,123
10	3,285	~~2,519~~	2,215	2,673
12	1,606	1,173	1,027	1,269
14	1,993	1,228	913	1,378
16	1,564	1,016	1,235	1,272
18	1,195	987	1,257	1,146
20	885	923	1,084	964
22	899	946	918	921
24	875	948	900	908
26	979	1,092	757	943
28	987	1,032	992	1,004
30	1,636	1,383	2,793	1,938
Avg.	**1,800**	**1,148**	**1,431**	**1,460**

The average turbidity values from the samples at the remaining sampling locations were divided by the representative inflow value, subtracted from 1 to determine a turbidity reduction (%), and plotted over the 48-hour observation period. Table 4.5 illustrates the pairings of representative inflow turbidities with discharge time ranges for comparison.

Table 4.5. Turbidity comparison pairs

Inflow Turbidity Value	Compared to Discharge Turbidity Values at Times
Average Turbidity (00:00-00:30)	0:00-2:00
Average Turbidity (5:00-5:30)	5:00-48:00

An example, showing the turbidity reduction analysis for S3 (lined with IA soil) is shown in Table 4.6. Example turbidity reduction calculation for S3 series.

Table 4.6. Example turbidity reduction calculation for S3 series

Time (hh:mm)	**L1-A** *Avg. Inflow 1,800 NTU*	**Turbidity Reduction (%)**	**L2-A** *Avg. Inflow 1,148 NTU*	**Turbidity Reduction (%)**	**L3-A** *Avg. Inflow 1,431 NTU*	**Turbidity Reduction (%)**
00:16	27740	-1,441%	1,148	0%	1,308	9%
00:20	37287	-1,971%	1,344	-17%	1,541	-8%
00:24	1616	10%	921	20%	1,223	15%
00:28	813	55%	818	29%	1,148	20%
00:32	750	58%	727	37%	1,227	14%
00:36	661	63%	674	41%	854	40%
00:40	613	66%	733	36%	896	37%
00:44	585	68%	707	38%	839	41%
00:48	573	68%	719	37%	774	46%
00:52	579	68%	692	40%	769	46%
00:56	509	72%	662	42%	806	44%
01:00	510	72%	632	45%	745	48%
01:04	535	70%	592	48%	693	52%
01:08	473	74%	590	49%	704	51%
01:12	541	70%	575	50%	701	51%
01:16	431	76%	607	47%	705	51%
01:20	462	74%	594	48%	683	52%
01:24	437	76%	577	50%	656	54%
01:28	400	78%	567	51%	644	55%
01:32	405	78%	577	50%	610	57%
01:36	389	78%	564	51%	597	58%
01:40	412	77%	545	53%	610	57%
01:44	395	78%	552	52%	625	56%
01:48	396	78%	405	65%	1,308	9%

Table 4.7. Example turbidity reduction calculation for S3 series

Time (hh:mm)	L1-B *Avg. Inflow 1,193 NTU*	Turbidity Reduction (%)	L2-B *Avg. Inflow 1,588 NTU*	Turbidity Reduction (%)	L3-B *Avg. Inflow 2,712 NTU*	Turbidity Reduction (%)
5:02	270	77%	859	46%	675	75%
5:06	301	75%	851	46%	643	76%
5:10	1,844	-55%	810	49%	717	74%
5:14	2,695	-126%	755	52%	839	69%
5:18	1,918	-61%			1,350	50%
5:22	605	49%			1,416	48%
5:48	575	52%			1,167	57%
6:08	541	55%			1,034	62%
6:28	552	54%			901	67%
6:48	554	54%			758	72%
7:08	519	57%			739	73%
7:28	427	64%			713	74%
8:08	347	71%			687	75%
8:28	355	70%			625	77%
8:48	339	72%			616	77%
9:08	282	76%			610	77%
9:28	264	78%			632	77%
9:48	267	78%			610	77%
10:08	250	79%			607	78%
10:48	222	81%			606	78%

Note: discharge sampler malfunctioned during L2-B sampling, so no discharge values were recorded.

Treatments were evaluated for statistical significance using a traditional multiple linear regression model. Structural treatments (e.g., skimmer, baffles, forebay) were recorded as unique, independent variables using values of 1 if present or 0 if absent for an installation. The dependent variables were turbidity reductions between -100% - 100%. The regression model determined the relative impact of each treatment on turbidity reduction, independent of other treatments. The model equation, as written by Donald et al., (2013), is shown in Eq. 4.7:

$$f(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \qquad \textbf{Eq. 4.7}$$

where,

$f(x)$ = dependent variable (e.g., turbidity reduction [%])
β_0 = coefficient intercept
β_i = ordinary least squares coefficient
x_i = independent variables (e.g., skimmer, baffles, forebay)

Due to the great variability in turbidity the R^2 values were relatively low, but statistical significance was determined based on the p-value at the 95% confidence interval. For analyses, the 30-minutes of flow introduction in LX-A and LX-B were considered the first and second "filling periods." The 30- minutes following, or first hour, was considered "rapid settling," and the remaining dewatering time was considered "polishing."

4.5. Structural Treatments

After conducting a thorough literature review, several sediment basin components and treatments were cataloged and selected for evaluation based on the potential to improve water quality and sediment capture. The treatments selected included lining the basin with geotextile, dewatering surface skimmer, coir flow baffles, rock check dam to create a forebay within the channel, and application of flocculant.

4.5.1. Iowa DOT Configuration

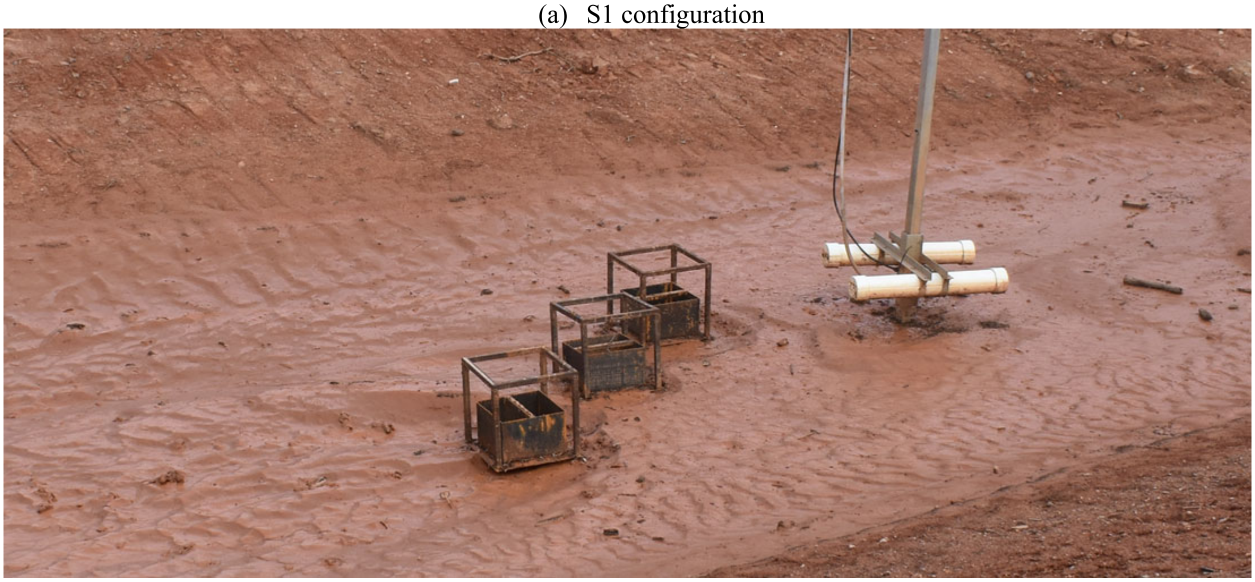
The Iowa DOT has drawings and specifications for the design and construction of temporary sediment control basins used on their sites (Iowa DOT 2018). This configuration is described in the A dewatering mechanism is necessary for treated stormwater to exit the basin without permanent ponding (Thaxton et al., 2004). The USEPA CGP requires dewatering sediment basins from the surface, presumably the least turbid portion of the water column, due to gravitational settling (USEPA 2022). Traditionally, effluent has been discharged through perforated riser pipes, which pull water across a larger portion of the water column. There is contention within the E&SC field if a riser pipe is still considered a surface dewatering mechanism. Instead, floating surface skimmers have become more commonly implemented, sized, and selected based on the desired dewatering rate. Sediment basins are typically designed to detain stormwater for periods ranging between 24 to 72 hours but can be up to seven days (Fang et al., 2015*)*.

An adequate settling time can be determined, and the skimmer can be selected for solid removal prior to discharge (Perez et al., 2016). Various sediment retention rates using a skimmer as the primary dewatering mechanism have been determined in controlled research studies. Examples include (1) Millen et al., found that a skimmer discharged 45% less sediment than a riser pipe (1997) and (2) Jarrett et al., concluded sediment loss from a basin equipped with a perforated riser principal spillway was 1.8 times greater than when a floating surface skimmer was used (2001).

Design section of this proposal and illustrated in Figure 3.2. This configuration was considered S1, or the control installation during testing, and is shown in Figure 4.16a. It is important to note that the S1 installation at the AU-SRF appeared and was expected to perform differently than the Iowa DOT site sediment basins due to the differences in the subgrade. Alabama-native site soil was introduced to the basin rather than the Iowa soil since separating the settled material from subgrade would be difficult without the geotextile lining. While water quality evaluations followed the procedures described above, the sediment retention evaluation was modified since the bounds of dredging would also be difficult without the geotextile. Instead, a pre- and post-test survey was conducted to compare sedimentation.

Three sedimentation cubes were placed every 25 ft (8 m) to capture settled material, which were then measured, dried, and re-measured to account for the shrink-swell due to moisture. These cubes are shown in Figure 4.16(b).

(a) S1 configuration



(b) sedimentation cubes

Figure 4.16. S1 installation at AU-SRF.

4.5.2. Geotextile Lining

Geotextile lining was used for installations S2 and S3. The geotextile lining was expected to stabilize the basin floor. Additional stabilization was expected to reduce erosion of the basin and resuspension of settled particles. An 8 oz. (227 g), non-woven geotextile was secured to the basin with 6 in. (15.2 cm) round top pins. Where necessary, the geotextile was overlapped a minimum of 1.0 ft (30.5 cm). The geotextile liner remained in place for S2-S8 testing. The lined basin is shown in Figure 4.5.

4.5.3. Surface Skimmer

A surface skimmer was the subsequent treatment applied and used for S4 evaluations. Surface skimmers have been adopted by many state environmental regulatory agencies, following section 2.2.12 of the CGP, as the principal dewatering mechanism, replacing the use of perforated riser pipes (ALDOT 2020, NCDOT 2015, TDOT 2020). Section 2.2.12 of the CGP requires stormwater to be withdrawn from the surface unless determined infeasible. Although infeasible cases are rare, exceptions are considered in locations and time when freezing is expected (USEPA 2022).

The skimmer functions by floating at or near the water surface of the basin, allowing dewatering to occur through one or several orifices. Skimmers are sized according to the basin volume and desired detention time. A figure for installation is shown in Figure 4.17

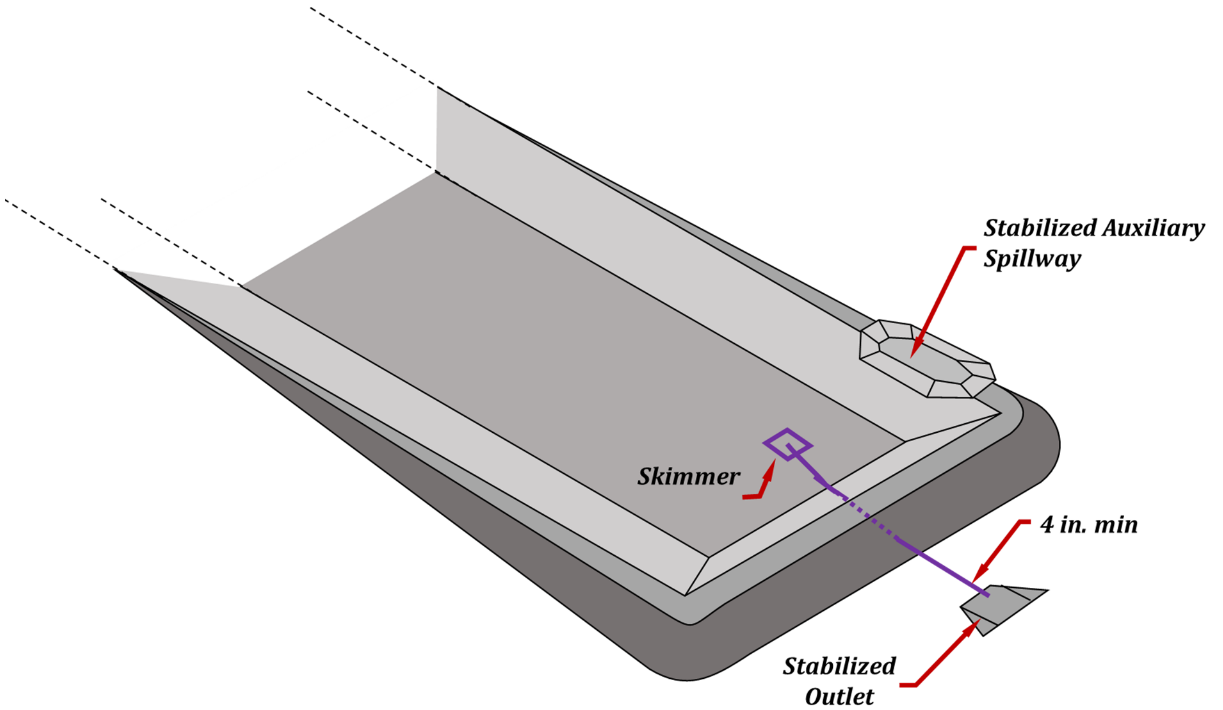
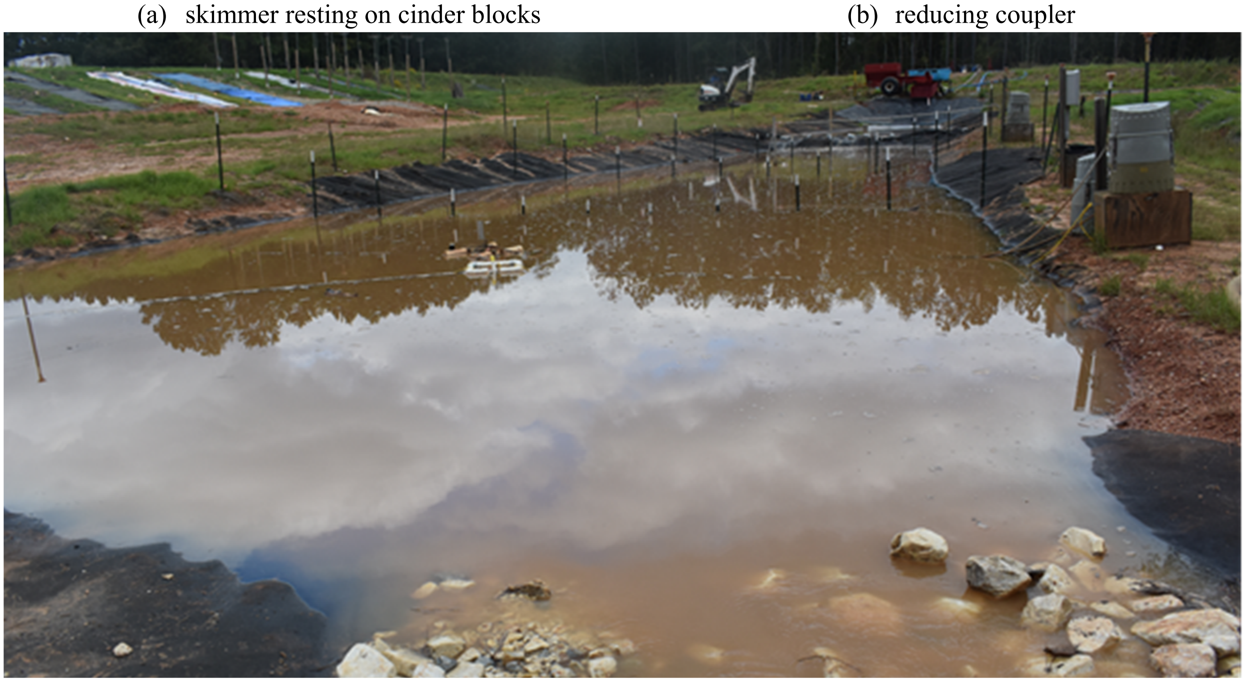


Figure 4.17. Skimmer design.

When used in the basin at the AU-SRF, the floating mechanism was attached to a reducer and then connected to the 12 in. (30.5 cm) outlet. A 2 in. (5.1 cm) Faircloth Skimmer® Surface Drain was used during testing. A dewatering time of 48 hours was used to determine the orifice size, as described in the skimmer's installation directions (J.W. Faircloth & Son, 2007). Using a volume of 3,031 ft3 (86 m3), the required orifice radius was 0.6 in (1.52 cm). Two cinder blocks were used as the skimmer rest to ensure the skimmer would not become stuck in deposited material after complete dewatering. The skimmer installation is shown in Figure 4.18.

(a) skimmer resting on cinder blocks

(b) reducing coupler



(c) dewatering basin

Figure 4.18. Skimmer in the basin at the AU-SRF.

4.5.4. Coir Baffles

A series of three coir baffles were installed for S5, which separated the basin into four bays. The baffles were intended to reduce turbulence and provide lower-velocity flow conditions. The baffles dissipated flow energy, which allowed water to flow across the width of the basin uniformly. This reduces short-circuiting by preventing inflow from moving directly to the outlet and increases the effective width.

For S5 testing, the baffles were installed every quarter-length of the basin. Baffle installation included driving T-posts at least 24 in. (61 cm) into the ground with an extension of at least 48 in. (91 cm) above the basin floor. Wire mesh reinforcement was then tied to the posts, and a double layer of 700-900 g/m2 (2.3-3.0 oz/ft2) coir was attached to the reinforcement. The baffle was secured to the bottom of the basin using staples. A schematic of the baffle installation is shown in Figure 4.19.

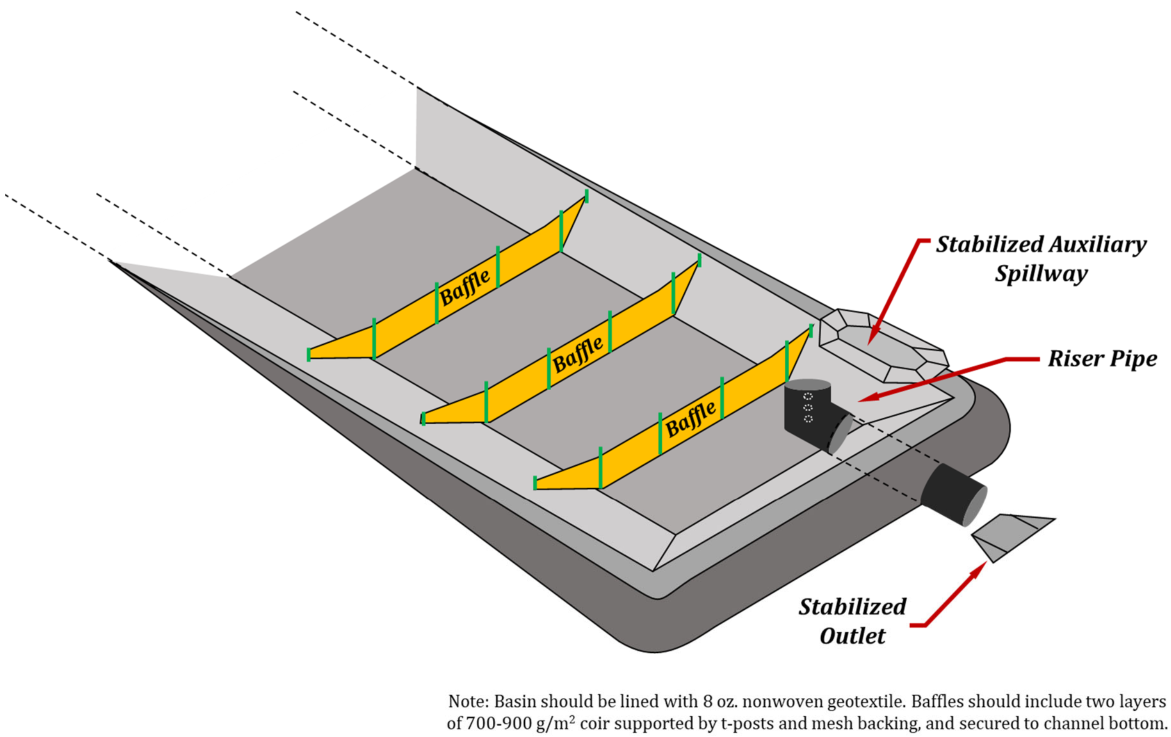
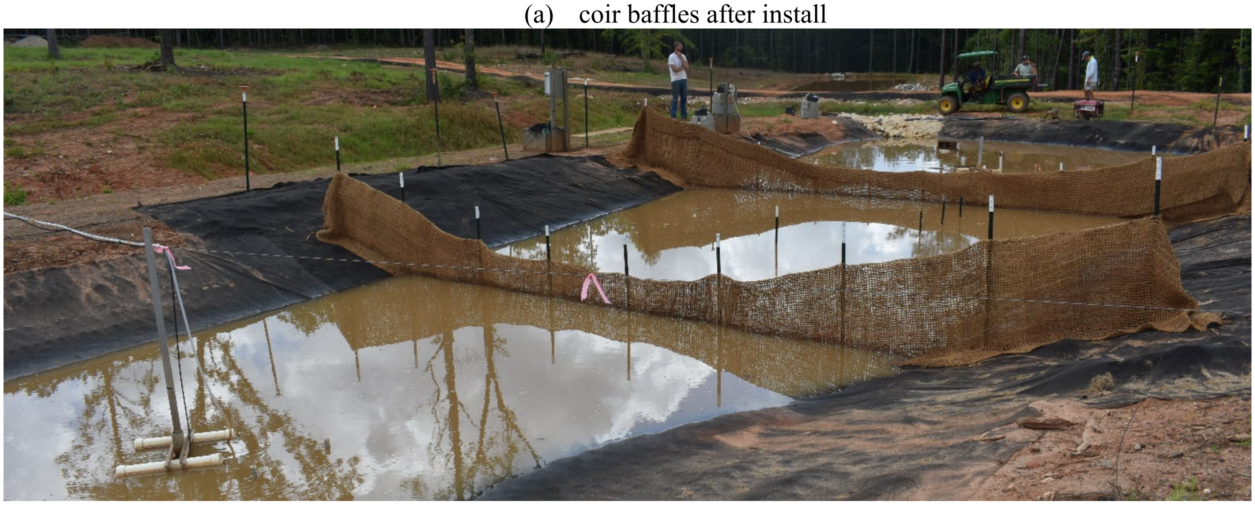


Figure 4.19. Baffles design.

The coir baffles installation is shown in Figure 4.20.

(a) coir baffles after install



(b) coir baffles during flow

Figure 4.20. Coir baffles in basin at the AU-SRF.

4.5.5. Forebay

A forebay was installed for S6 evaluations. A forebay is a section upstream of a sediment basin designed to capture rapidly-settable solids. Forebays can improve the overall capture effectiveness of a sediment basin system while allowing the basin itself only to receive smaller grain-sized particles. This decreases the frequency of dredging and provides additional stormwater storage. An Iowa DOT Rock Check Dam (EC-301) was installed 100 ft (33.3 m) from flow introduction (Iowa DOT 2018). Class D riprap was used, and the rock check dam was covered with an 8 oz (227 g) non-woven geotextile. A schematic is shown in Figure 4.21.

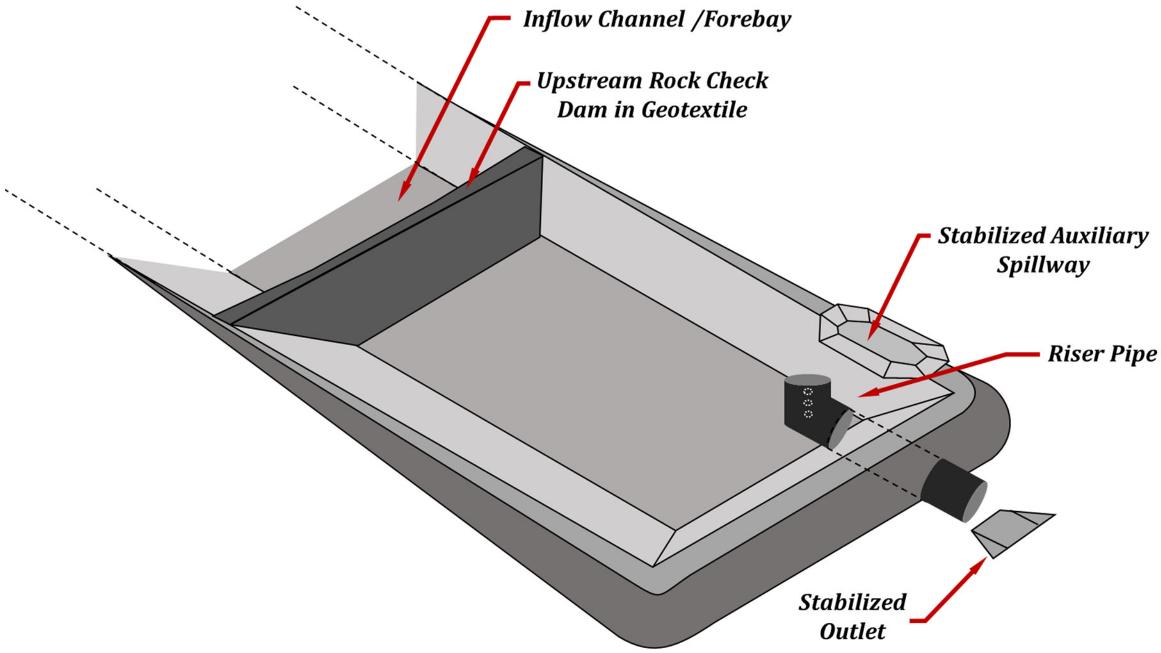
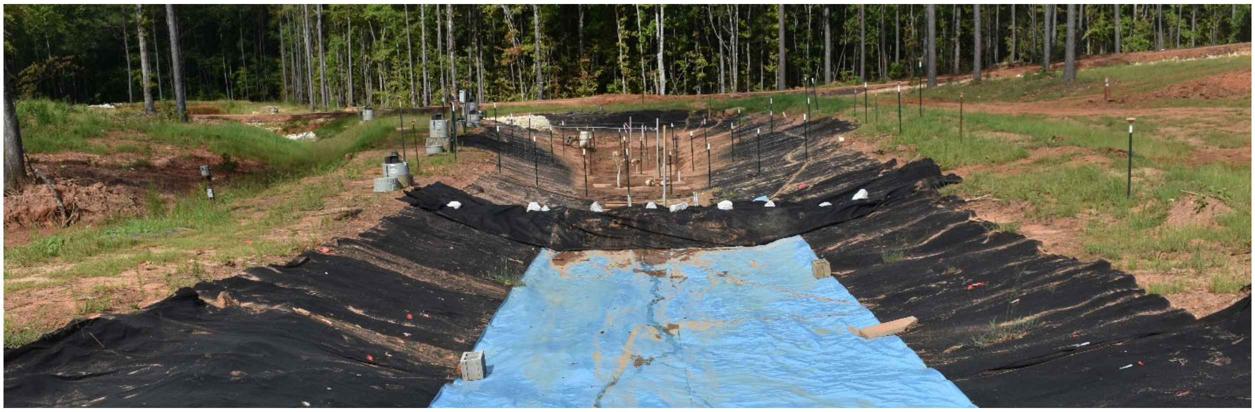


Figure 4.21. Forebay design.

This installation provided approximately 900 ft^3 (25 m^3) of additional storage volume, as shown in Figure 4.22.



(a) forebay installation

(b) forebay during flow

Figure 4.22. Forebay installation.

4.5.6. Most Feasible and Effective Installation

The Most Feasible and Effective Installation (MFE-I) comprised a combination of treatments, including geotextile liner, forebay, and skimmer, and tested for S7. The treatments were selected based on individual effectiveness and feasibility, considering site installation and maintenance. This is shown in Figure 4.23.

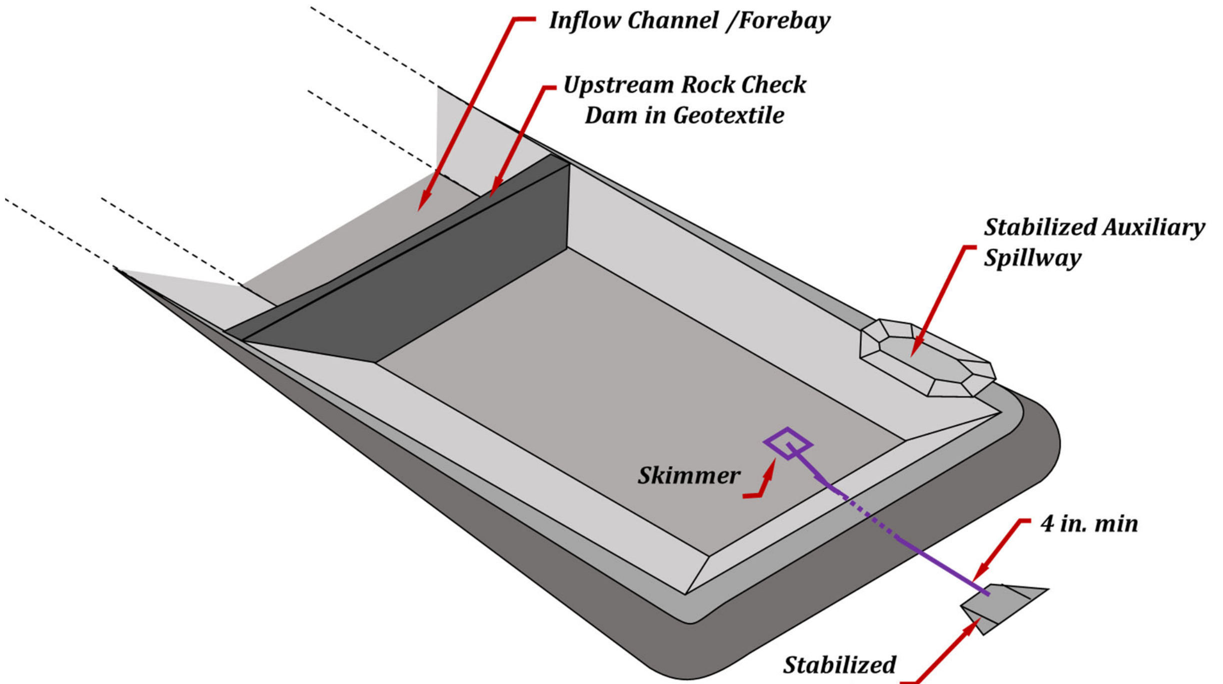


Figure 4.23. MFE-I design.

The MFE-I (S7) configuration was also used for S8 with the addition of flocculant. MFE-I (S7) and MFE-I + Flocculant (S8) are detailed and compared in Chapter Five.

4.6. Results and Discussion

The following section summarizes the findings from the unlined and lined basin configurations tested with Alabama-native soil and the lined, skimmer, baffles, forebay, and combination configurations tested with Iowa-native soil. Each configuration was subjected to six 30-minute filling periods where 1,960 lbs (890 kg) of sediment was introduced. Each configuration was evaluated for sediment retention and water quality improvements.

4.6.1. Sediment Retention

Sediment retention was quantified after each set of testing (6 total filling periods), and methods to evaluate configurations S2-S8 were described in the previous section. Sediment retention by weight for individual bays and the entire system is illustrated in Figure 4.24.

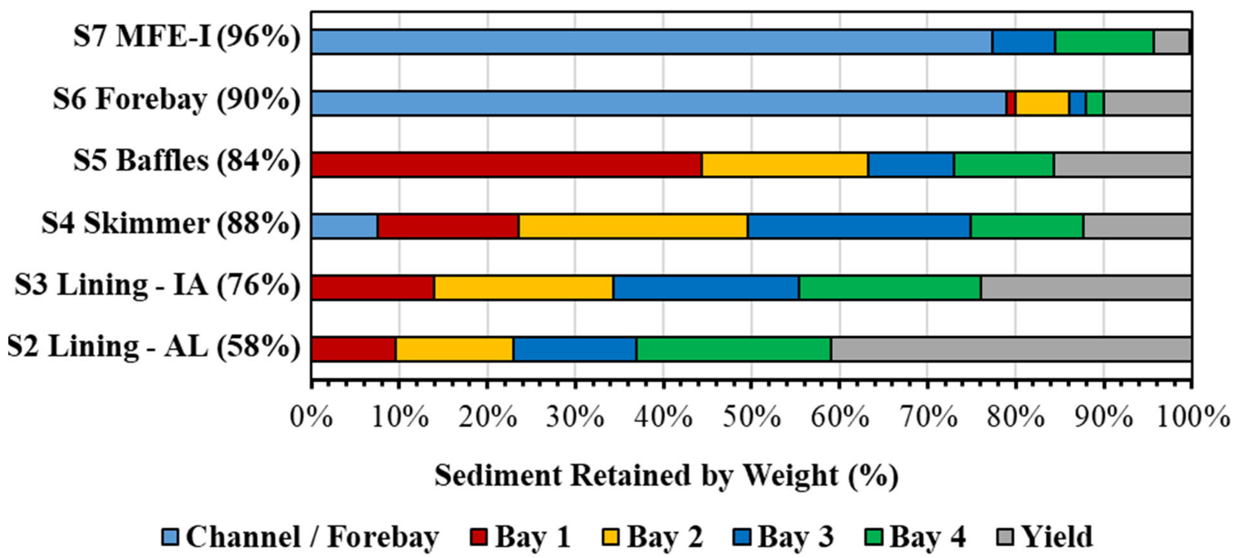


Figure 4.24. Sediment retained by percent weight.

The two-lined configurations were initially compared. More Iowa soil was retained within the basin than Alabama soil. Percent retention was 76% and 59%, respectively. While this was initially counterintuitive due to the fraction of sand present in the Alabama soil and absent from the Iowa soil, the difference was attributed to the Iowa soil being difficult to break down due to the high clay fractions creating colloids for testing at the AU-SRF. Increased particle size typically increases the mass and resulting settling velocity. Although the soil was dried, processed, and shaken through a 0.5 in. (1.27 cm) sieve, colloidal particles may have skewed the gradation compared to the laboratory soil tests.

When the skimmer was installed to dewater the basin, the impoundment depth and length were increased. Consequently, sedimentation occurred over a greater length within the basin and resulted in 88% retention. Sedimentation in the channel due to the skimmer installation is shown in Figure 4.25.

Figure 4.25. In-channel sedimentation due to skimmer installation.

The next treatment applied to the basin was coir baffles, which intercepted and dispersed the inflow across the width of the channels. Based on the sediment retention results, the first two bays captured the largest fraction of settled material, likely the coarsest sediment, shown in Figure 4.26. The sedimentation in Bay 4 with baffles installed was within 2% of the sediment retained when the skimmer was installed. The baffles, or S5 configuration, retained 84% of the introduced sediment by weight.


Figure 4.26. In-channel sedimentation due to coir baffle installation.

Overall sediment retention increased to 90% when the forebay was installed. Sediment retention of 79% occurred within the forebay. This sediment impoundment was visibly coarse after draining, as seen in Figure 4.27.

The forebay exhibited the most sediment capture at 90%, with most of the capture occurring in the forebay. Bay 1 retained the most sediment for the baffle installation. The rock check dam used to create the forebay could also be considered an enhanced first baffle *(NCDOT 2015, IECA 2021)*. The rock check dam and first baffle seemed to function similarly during their respective installations. The first baffle slowed and dissipated flow, which allowed larger particles to settle out in the first bay. Of the 84% of sediment retained, about 45% was captured in the first bay. The rock check dam not only slowed and dissipated flow during the forebay installation but also provided additional storage.

After evaluating sediment retention and water quality improvements and consulting with the Iowa DOT Technical Advisory Committee, the MFE-I, or S7, was developed. This installation included the combination of geotextile lining, a surface skimmer, and a forebay. Baffles were not adopted for the MFE-I (S7) evaluation due to the perceived difficulties with installation, additional material costs, labor, and maintenance considerations. Sediment retention for the MFE-I increased to 96% total capture, with 77% occurring in the forebay. Sediment retention in the forebay was within 2% of each other when comparing the S6 and S7 configurations, validating repeatable and reliable results during large-scale testing.

Figure 4.27. In-channel sedimentation due to forebay installation.

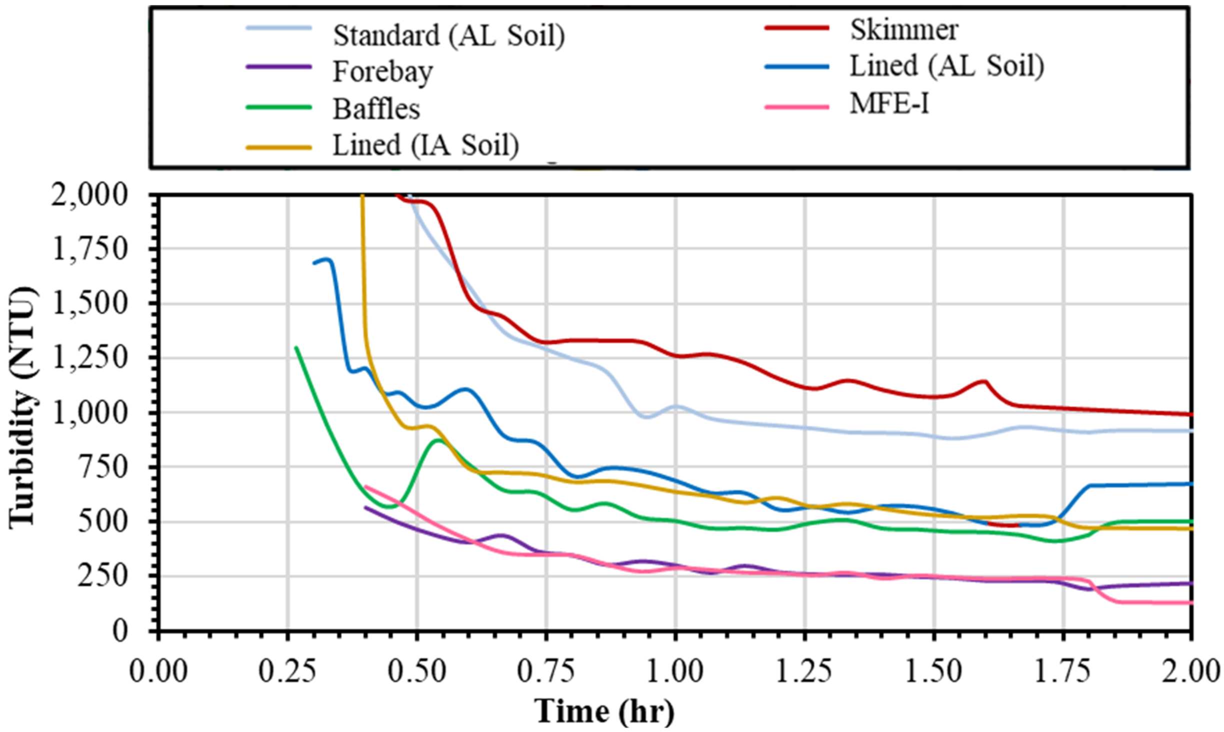
4.6.2. Water Quality

Turbidity was monitored in several locations throughout the basin, however, the most observed and analyzed sampling location was at the discharge outlet of the basin. Figure 4.28

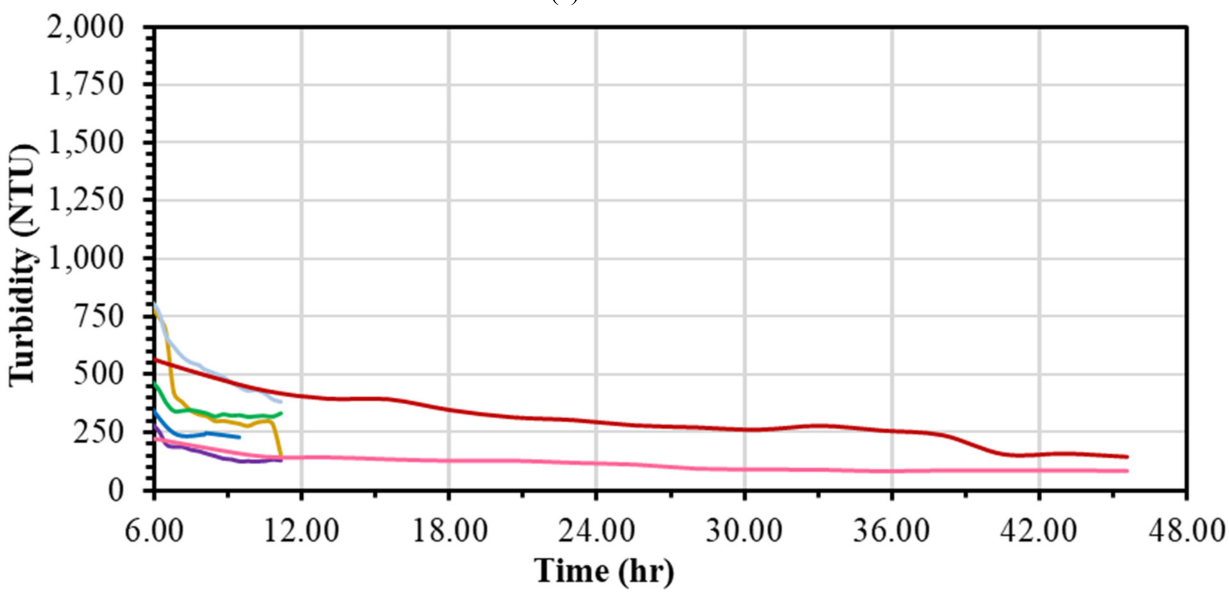
plots the discharge turbidity for all basin configurations. The trends in discharge turbidity largely follow the sediment retention trends, with increased sediment retention corresponding to decreased turbidity. However, the skimmer configuration does not fit into this general trend.

The increased turbidity with the skimmer installed was not expected and did not follow the expected behavior, as described in the literature *(Millen et al., 1997 and Jarret et al., 2001)*. After closer examination, turbidity reduction differences were observed between the sampling location at the top of Bay 4 and the discharge for the skimmer, or S4, installation. Although the turbidity was increased during the initial dewatering period, the skimmer was still included in the MFE-I, or S7 configuration, considering the increased sediment retention resulting from its installation and the ability to allow turbidity to decrease beyond the other treatments by decreasing flowrate as shown in Figure 4.28(b).

The forebay provided an additional 900 ft^3 (25 m^3) of storage volume and impounded water until it overtopped the rock check dam. The discharge dispersed flow across the channel and slowed the velocity, which decreased the volume reaching the basin during the filling period; thus, discharge did not start until later into the filling period, as shown in Figure 4.28.



(a) 0:00-2:00 hr



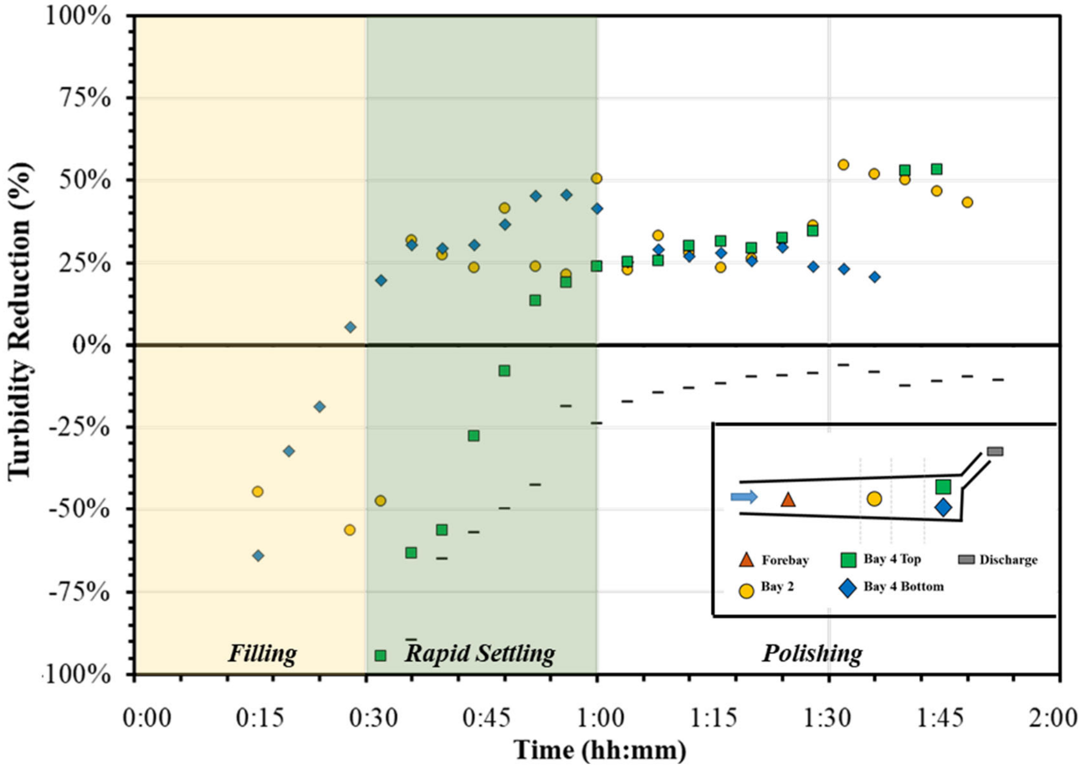
(b) 6:00-48:00 hr

Figure 4.28. Turbidity during monitoring of structural treatments

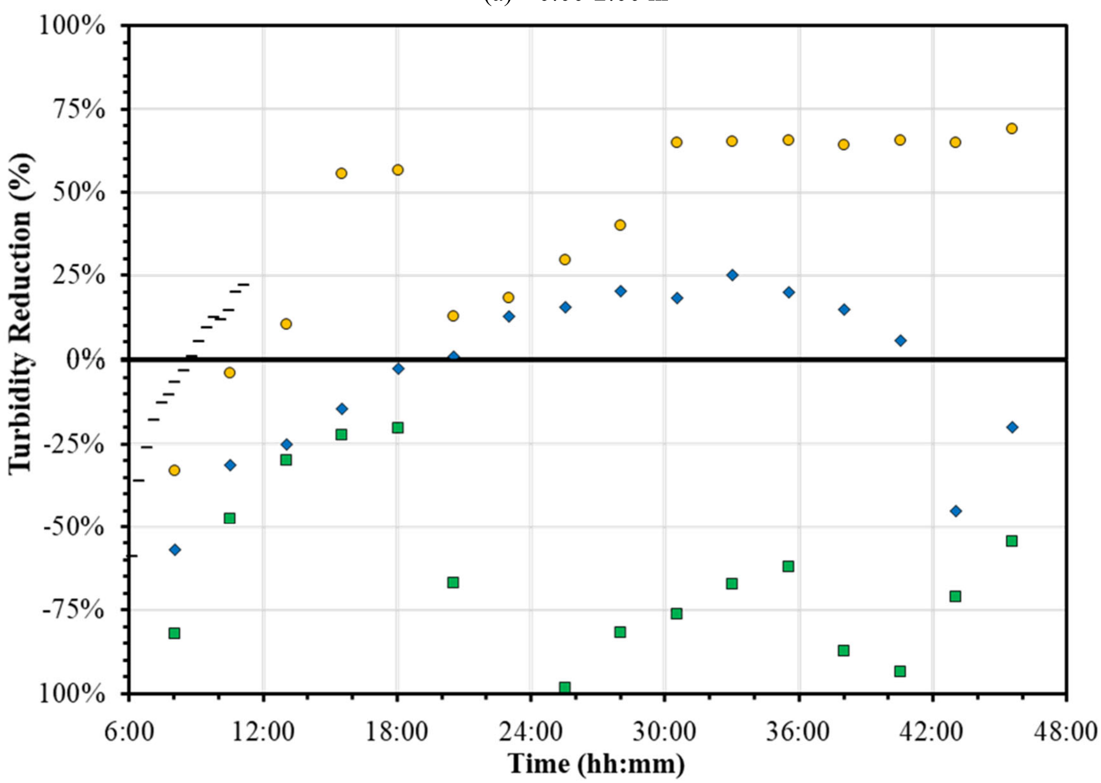
In addition to the increased sediment retention, the sediment basin was dewatered over the 48-hour monitoring period when the skimmer was installed instead of the traditional perforated riser pipe. The skimmer had a lower, terminal dewatering point, or permanent pool at approximately 2 ft (0.61 m), as dictated by the invert of the discharge pipe through the earthen berm. As a result, the basin stage was drawn further down with the skimmer installed, which allowed increased stormwater storage for subsequent filling or storm events.

When the riser pipe was used, the basin stage quickly raised and thus consumed a large portion of the basin volume. The basin was only able to dewater through the orifices but eventually was impounded to reach the top of the riser pipe, and the total diameter of the 12 in. (0.30 m) pipe was overcome with the flow. As a result, the auxiliary spillway was never utilized during controlled testing, as it would take an increased volume of runoff to do so. The basin quickly dewatered when the stage was above the pipe elevation but slowed to a more controlled rate when only discharging through the orifices. The permanent pool, or stage, for the riser pipe and forebay with riser pipe installations, equalized at approximately 3 ft (1 m), reached in 12 hours.

Although sediment retention was not quantified for the unlined S1 configuration, water samples were taken in Bay 2, Bay 4 Top and Bottom, and Discharge locations. As shown in Figure 4.29(a), the discharge turbidity reduction was negative during the first filling, rapid settling, and polishing period, indicating the turbidity was higher at discharge than average inflow. This observation was similar to the field observations documented in Performance during Field-Monitoring. Increased turbidity could have been due to the resuspension of fine particles or the additional sediment load resulting from channel erosion during high flow. Turbidity reduction was the lowest following the filling period and slowly increased. Turbidity reduction reached 0% by nine hours after the first fill and nearly 25% after twelve hours when dewatering through the riser pipe was completed. Turbidity reduction was highest in Bay 2 but did not follow a pattern in Bay 4.



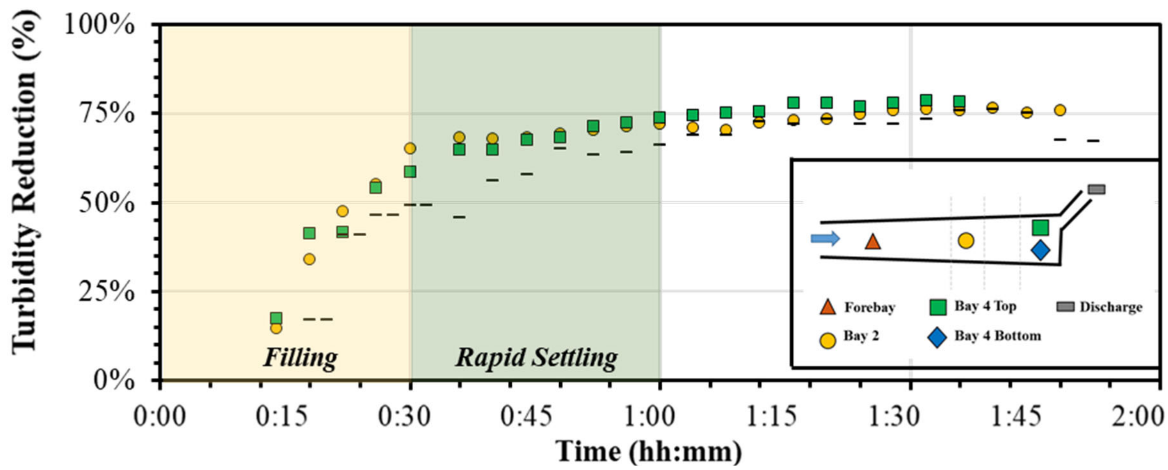
(a) 0:00-2:00 hr



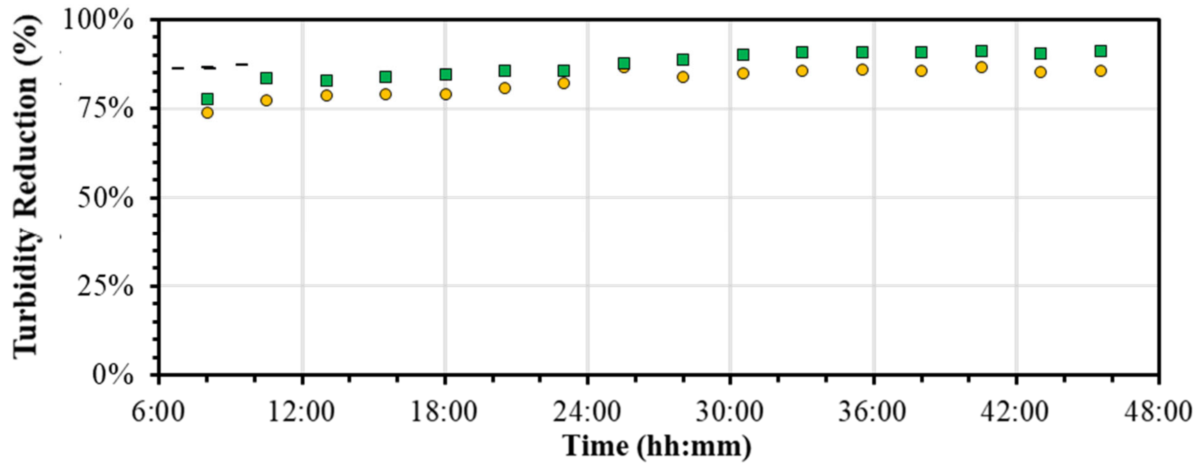
(b) 6:00-48:00 hr

Figure 4.29. Turbidity reduction during unlined testing (AL soil).

Turbidity reduction from S1 was compared to the lined S2 configuration and subject to Alabama-native sediment-laden flow. Discharge turbidity reduction was positive throughout basin monitoring and more closely followed the turbidity reduction trends of Bay 2 and Bay 4. Turbidity reduction was above 75% when dewatering commenced; however, Bay 2 and Bay 4 were continuously monitored and indicated potential removals up to 90%.



(a) 0:00-2:00 hr



(b) 6:00-48:00 hr

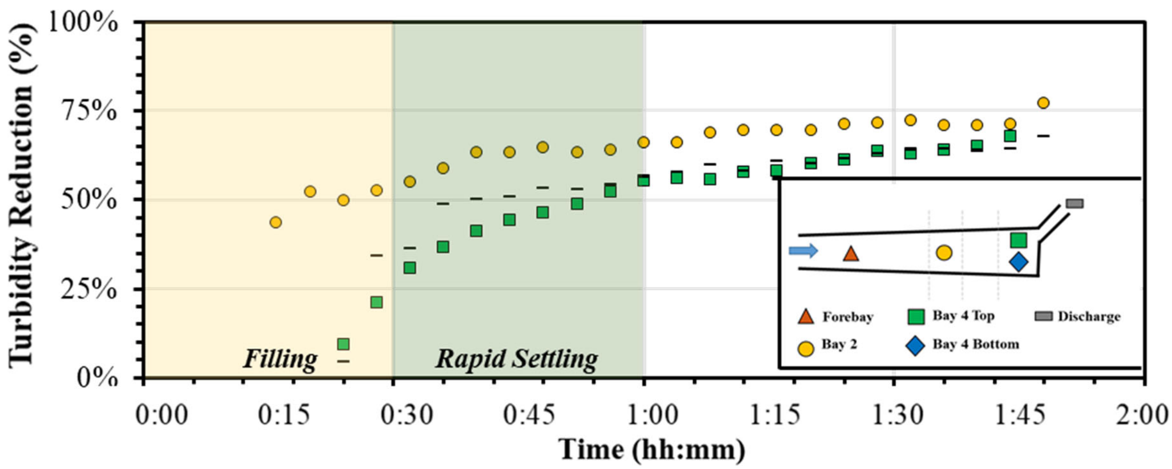
Figure 4.30. Turbidity reduction during lined testing (AL soil).

Turbidity reductions at discharge for the S1 and S2 configuration were compared using a traditional regression model for statistical relevance, with S1 as the base case. The lining was considered an independent value and proved to be statistically significant. Turbidity reduction was estimated to be significantly higher when the geotextile lining was implemented during all periods of the test, as indicated by the coefficient in Table 4.8. The predicted increase in turbidity reduction is hypothesized to be in response to a decreased sediment load by minimizing channel erosion, since the geotextile aided in stabilization. This is due to the highest coefficient for the geotextile lining occurring during the filling period, when channel erosion is most likely to occur.

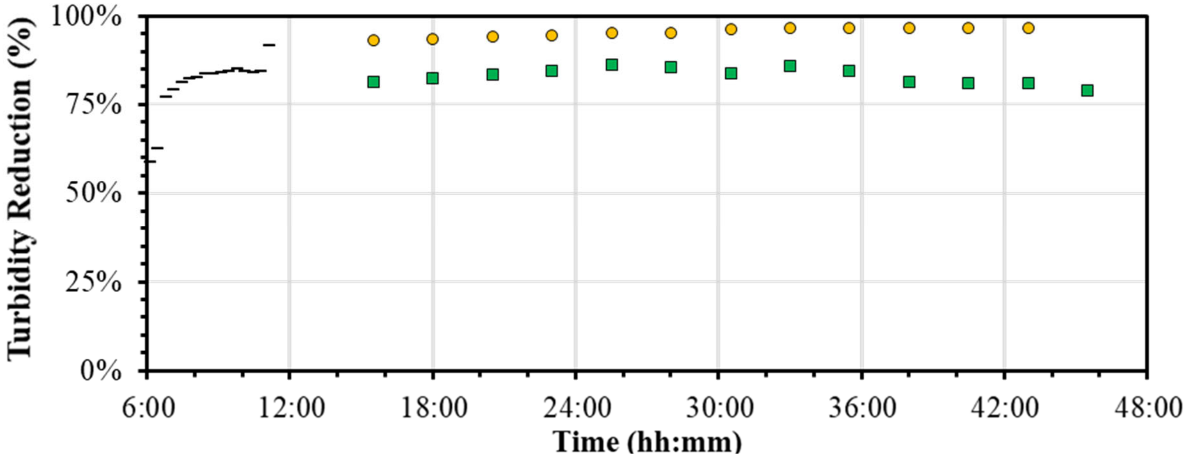
Table 4.8. Linear regression model comparing S2 and S1

Test Period	Treatments	Coefficients	P-value
Entire Test	**Intercept**	-0.52	1.63 E-27
$R^2 = 0.68$	**Geotextile Lining**	1.17	6.49 E-58
Filling	**Intercept**	-1.42	5.14 E-24
$R^2 = 0.71$	**Geotextile Lining**	2.00	3.57 E-28
Rapid Settling	**Intercept**	-0.49	1.71 E-09
$R^2 = 0.75$	**Geotextile Lining**	1.09	2.23 E-15
Polishing	**Intercept**	-0.18	5.53 E-05
$R^2 = 0.74$	**Geotextile Lining**	0.90	2.22 E-26

The S2 configuration was re-evaluated using Iowa- native soils for the S3 configuration. Turbidity reduction for the S3 configuration is shown in Figure 4.31. Discharge turbidity reduction followed Bay 2 and 4 trends but was not as high as the S2 configuration. The decreased turbidity reduction values were expected when Iowa-native soil was introduced due to an increased fraction of fine particles.



(a) 0:00-2:00 hr



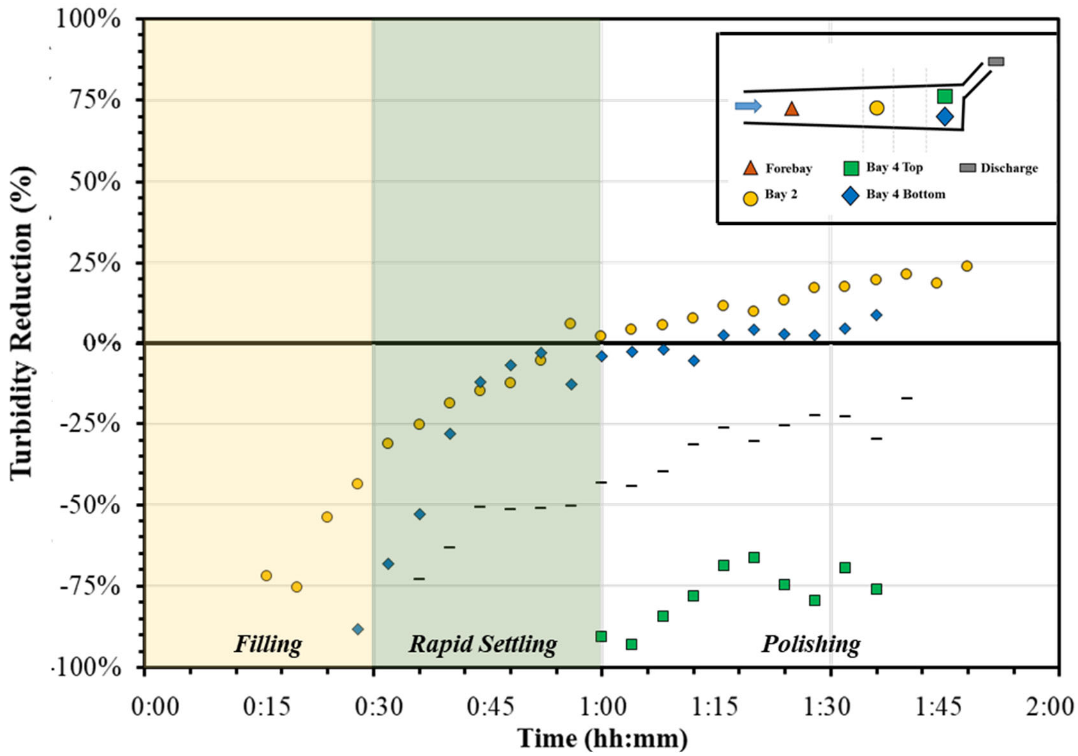
(b) 6:00-48:00 hr

Figure 4.31. Turbidity reduction during lined testing (IA soil).

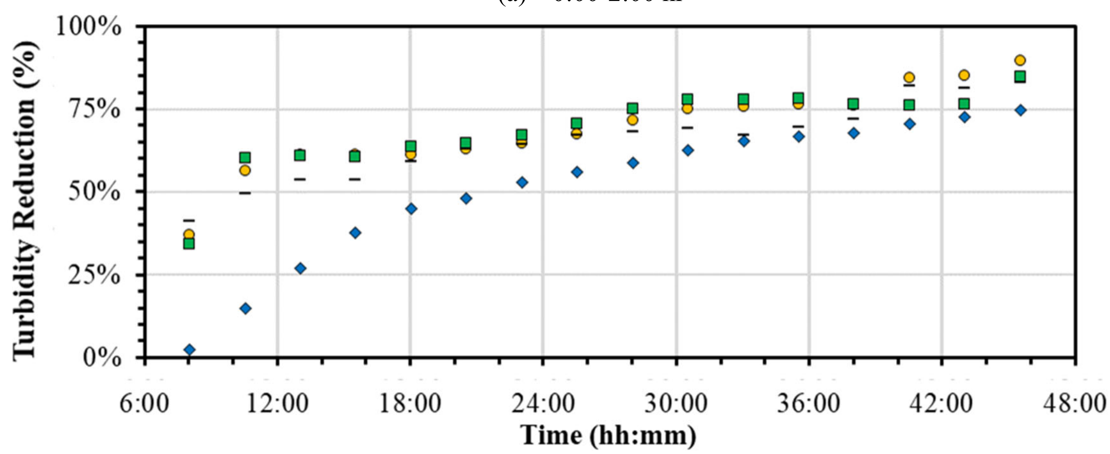
An additional linear regression was modeled to evaluate the significance of using Iowa-native soil instead of Alabama soil. The regression model returned low R^2 values during the, indicating a lacking relationship; however, the Iowa-native material was statistically significant in each period of testing. Table 4.9 provides a summary of the estimated model. The testing regimen then compares individual structural treatments, including the skimmer, baffles, and forebay testing shown in Figure 4.32, Figure 4.33, and Figure 4.34, respectively.

Table 4.9. Linear Regression model comparing S3 and S2

Test Period	Treatments	Coefficients	P-value
Entire Test	**Intercept**	0.65	3.40 E-119
$R^2 = 0.03$	**Iowa Soil**	-0.07	2.00 E-3
Filling	**Intercept**	0.58	5.59 E-02
$R^2 = 0.06$	**Iowa Soil**	-1.39	1.01 E-02
Rapid Settling	**Intercept**	0.59	3.40 E-24
$R^2 = 0.12$	**Iowa Soil**	-0.11	1.51 E-02
Polishing	**Intercept**	0.72	3.58 E-66
$R^2 = 0.05$	**Iowa Soil**	-0.06	1.37 E-02



(a) 0:00-2:00 hr

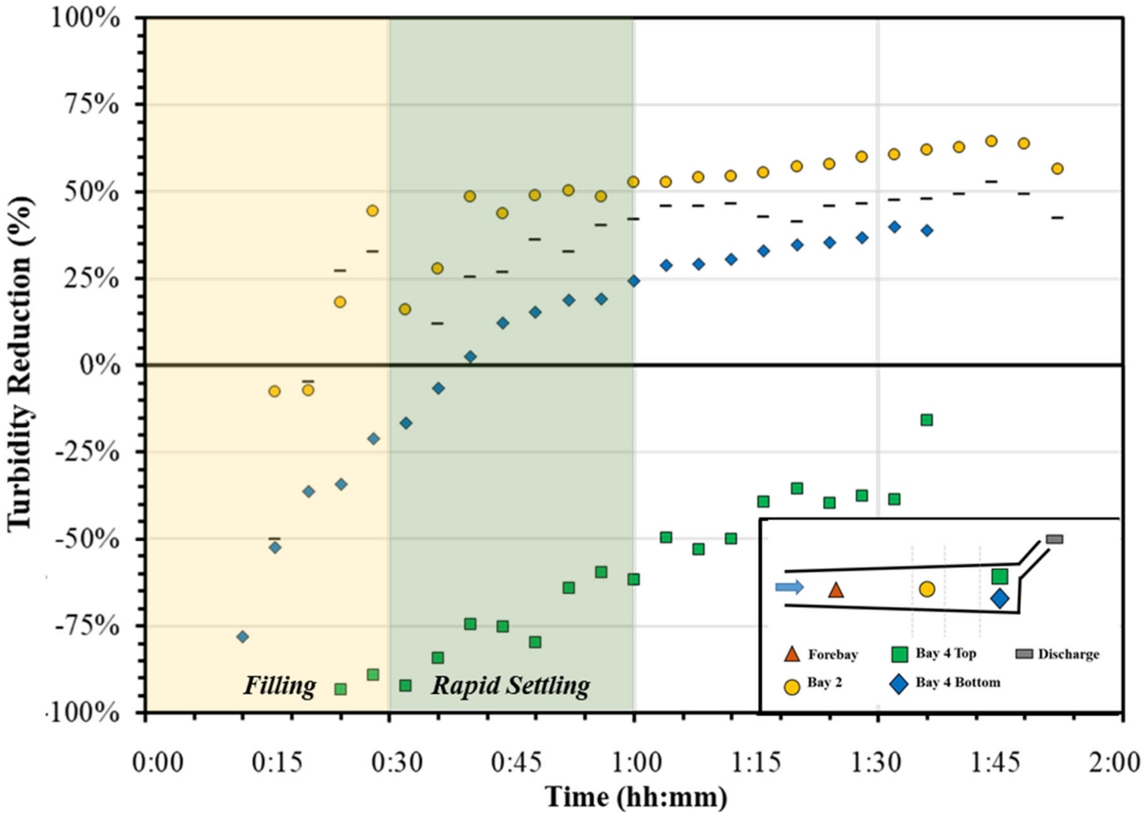


(b) 6:00-48:00 hr

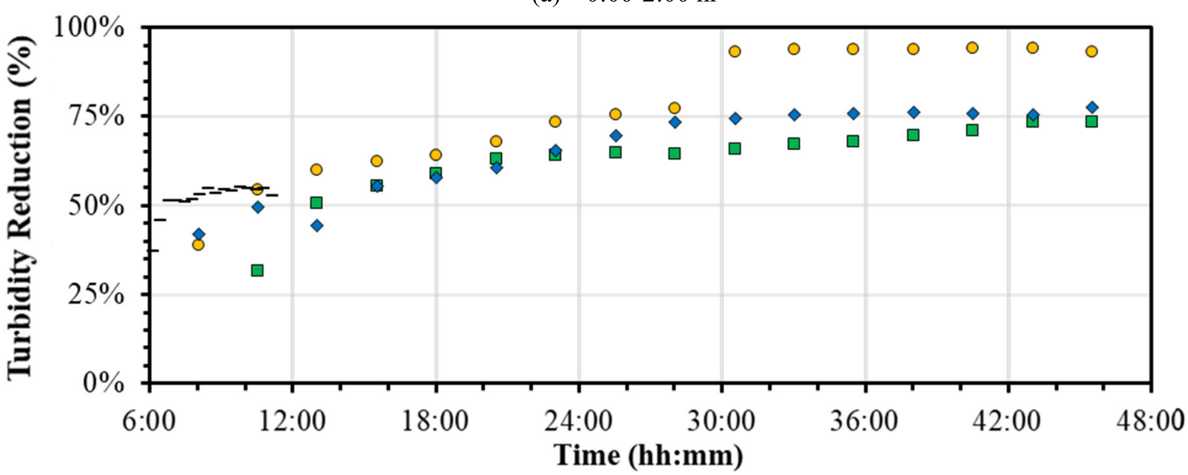
Figure 4.32. Turbidity reduction during skimmer testing (IA soil).

Although the discharge turbidity reduction was negative during the first filling, rapid settling, and polishing periods of S4, the turbidity reduction percentages were positive throughout the second polishing period. The discharge turbidity reduction split the turbidity reduction comparisons between the top and bottom of Bay 4.

Similar to the S4 performance, the S5 discharge turbidity reduction was negative during the first filling, rapid settling, and polishing periods; however, the turbidity reduction percentages were positive throughout the second polishing period but did not reach removal percentages experienced during the S5 configuration. There was a shift in trend between the top and bottom sampling locations in Bay 4 during the first filling, rapid settling, and polishing period, as seen in Figure 4.33. This may be because the coarse particles were captured in earlier bays, leaving just the finest particles, the slowest to drop from suspension, in Bay 4. In the extended dewatering period, differences in turbidity reductions between the two sampling locations were decreased.



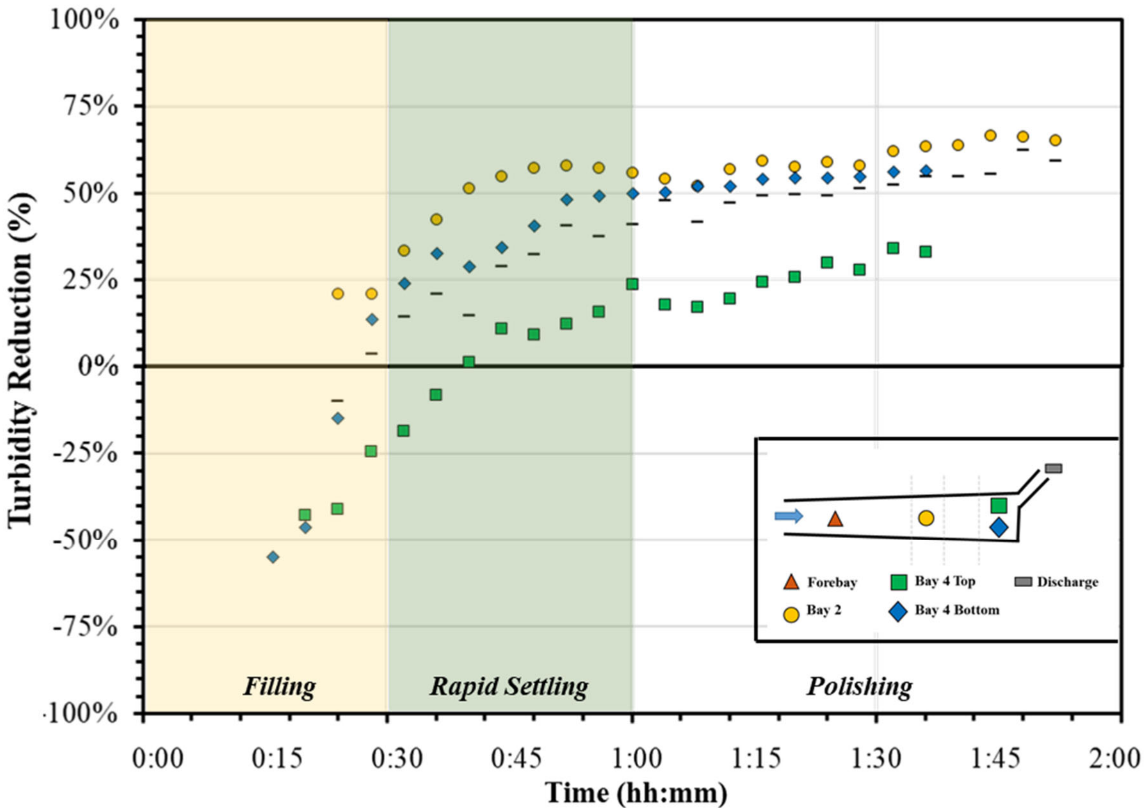
(a) 0:00-2:00 hr



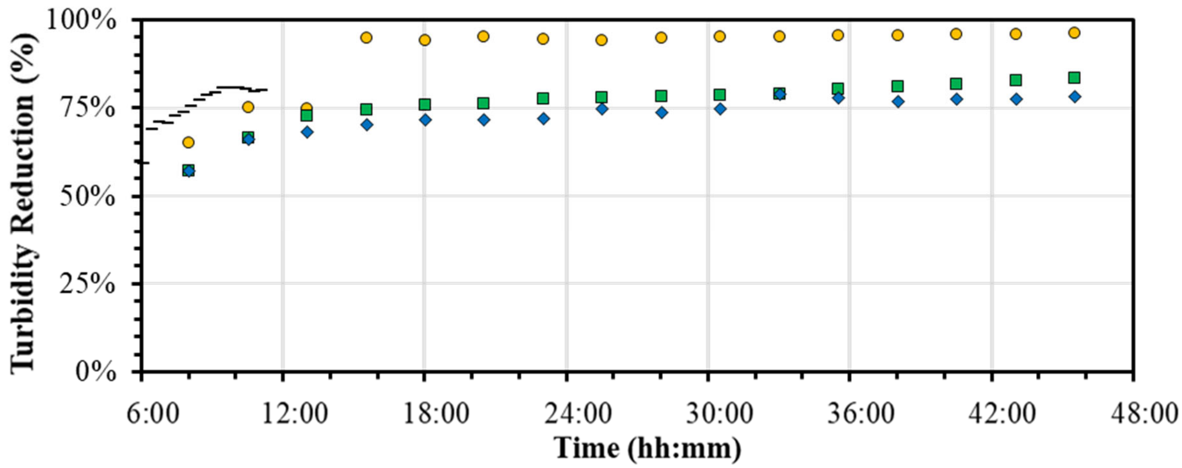
(b) 6:00-48:00 hr

Figure 4.33. Turbidity reduction during baffles testing (IA soil).

The final evaluated structural treatment was the forebay, with the greatest sediment retention and the lowest turbidity values of all individual structural treatments. The discharge turbidity reduction percentages were positive, even during the first filling period, and reached 80% before dewatering commenced.



(a) 0:00-2:00 hr



(b) 6:00-48:00 hr

Figure 4.34. Turbidity reduction during forebay testing (IA soil).

As hypothesized, the turbidity reduction decreased for all configurations as time increased in the second extended polishing period. Interestingly, Bay 2 seemingly had the highest, consistent turbidity reduction in the polishing periods, consistent with Perez *(2016),* despite the differences in channel geometry. Dewatering from the top of Bay 2 may yield the greatest turbidity reduction before offsite discharge.

The MFE-I (S7) configuration was recommended based on the individual structural treatments' sediment retention and water quality improvements and included the geotextile lining, skimmer, and forebay. A linear regression model was developed to evaluate the statistical significance of the structural treatments on turbidity reduction and followed the model described in 4.4.8 Water Quality Analysis. Results from the S7 configuration were also included when developing the model.

Table 4.10. Linear regression model for structural treatments

Test Period	Treatments	Coefficients	P-value
Entire Test	**Intercept**	0.44	8.15 E-28
$R^2 = 0.13$	**Skimmer**	-0.35	2.69 E-15
	Baffles	-0.25	1.89 E-05
	Forebay	0.19	1.47 E-05
Filling	**Intercept**	-1.01	1.16 E-02
$R^2 = 0.08$	**Skimmer**	-0.53	2.53 E-01[a]
	Baffles	0.89	1.55 E-01[a]
	Forebay	1.54	1.06 E-03
Rapid Settling	**Intercept**	0.24	1.85 E-02
$R^2 = 0.31$	**Skimmer**	-0.82	2.23 E-10
	Baffles	-0.24	1.18 E-01[a]
	Forebay	0.33	6.65 E-03
Polishing	**Intercept**	0.56	4.41 E-38
$R^2 = 0.15$	**Skimmer**	-0.28	2.13 E-10
	Baffles	-0.28	2.19 E-06
	Forebay	0.14	1.57 E-03

Note: [a] indicates not statistically significant at 95% confidence.

Despite the low R^2 value, indicating a weak relationship, the forebay was statistically significant, based on the p-value, during all periods of the test and aided in turbidity reduction. Based on the model, the skimmer and baffles were expected to decrease turbidity reduction percentage or increase turbidity; however, the baffles were not statistically significant during the filling and rapid settling periods of the test. The skimmer was not significant during filling. All points were considered in the linear regression model to increase the accuracy and prediction of the basin's behavior as a system during and after a storm event.

MFE-I (S7) was also used for S8 evaluations, with the addition of flocculant. The sediment retention and water quality performance of the MFE-I (S7) and MFE-I + Flocculant (S8) are detailed and compared in Chapter Five.

5. CHAPTER FIVE: UPSTREAM FLOCCULANT APPLICATION

5.1. Introduction

Settling fine sized soil particles (i.e., clay and silt) requires long detention times that exceed typical sediment basin treatment conditions. Chemical treatments such as coagulants and flocculants have the potential to bond finer particles to create larger flocs that gravitationally settle more rapidly. Sediment basins present an opportunity to introduce chemical flocculant in construction stormwater management plans and capture the flocs before offsite discharge. Flocculant has the potential to improve sediment capture within the basin and decrease required detention time to achieve certain discharge water quality standards, including TSS and turbidity goals. Proper contact and mixing time are required for the flocculant to be fully activated and effective. There is little known about the effects if the flocculant is not appropriately mixed with runoff and bonded to chemicals. This research effort aimed to quantify the benefits of sediment capture, turbidity reduction, and residual flocculant concentrations from the basin discharge.

Kazaz et al., reported that 39% of state DOTs apply flocculant during construction in a recent state of the practice survey, and 54% of those rely on manufacturer guidance for implementation *(2021)*. Flocculant application is especially prevalent in states where numeric effluent discharge limitations exist, such as North Carolina where turbidity cannot exceed more than 50 NTU above background levels and New Jersey where 80% of TSS must be removed from construction runoff (*North Carolina Department of Environmental Quality 2019*, *New Jersey Department of Environmental Protection 2004*).

Although various flocculant types are used in stormwater treatment, including synthetic flocculants; inorganic flocculants; bio/natural flocculants; and stimuli-responsive flocculants, synthetic flocculants are the most commercially available and applied within the industry. Synthetic flocculants are categorized according to their net positive / negative charge or as cationic

/ anionic, respectively cationic flocculant application is typically avoided due to the potential of binding with the negatively charged hemoglobin in fish gills, resulting in fish kills *(USEPA 2005)*. Anionic flocculant is more widely applied as environmental toxicity implications occur at higher concentrations.

Polyacrylamide (PAM), a flocculant type, is most commonly used in construction stormwater and is available in various forms, including granular, emulsion, and blocks. Selecting the appropriate PAM for site soils is essential for performance and efficiency. It is common practice for several jar tests to be conducted, which compare settling and water quality characteristics in response to PAM application for a specific site soil. When applied to a construction site, PAM is typically applied by spreading granular powder on upstream practices or placing blocks in a conveyance channel to allow for proper contact and mixing time.

If properly introduced, chemical flocculant can drastically decrease turbidity levels by increasing the settling velocity. Flocculant is particularly helpful in sediment basin efficiency by reducing the settling time from several hours to minutes (*Fang et al., 2015, Kang et al., 2015*). Bhardwaj and McLaughlin (*2008*) determined that the addition of flocculant reduces turbidity up to 66 to 88% when actively and passively dosed, respectively. Despite the potential to enhance construction stormwater management programs, Kazaz et al., *(2021)* reported that 31 state DOTs do not permit the use of flocculants on active sites. When further questioned why flocculants were prohibited, 50% of these states responded that the current E&SC practices were sufficient, and 35% responded that there was a perceived risk for receiving waterbodies *(2021)*. This research aimed to compare the performance of the sediment basin with and without the presence of flocculant. Additionally, residual testing was conducted on samples from the sediment basin effluent to quantify the concentration of flocculant being discharged.

5.2. Materials and Methods

This section describes the method employed to select a flocculant to introduce to the basin, performance comparisons of the MFE-I with and without flocculant, and procedures to quantify residual concentrations in sediment basin effluent. A combination of innovative laboratory and large-scale testing techniques was implemented. This research was a collaborative effort, developing from dosage and application research concurrently conducted by B. Kazaz, M.A. Perez, W.N. Donald, X. Fang, and J. Shaw for ALDOT.

5.3. Flocculant Selection

Flocculants were selected based on a methodology developed by Kazaz et al., *(2022b)*. Iowa native soil was classified as USCS Sandy Lean Clay and AASHTO Clayey Soil, as described in 4.3 Materials and Methods of this report. Sediment-laden samples were made by mixing the soil with 3.8 oz (1,000 mL) of water to achieve turbidity of 1500 NTU (± 300 NTU). Fourteen flocculant products were mixed with the independent solutions and compared for the most favorable settling and water quality improvements. Flocculants were ranked on a points system, which considered floc size, formation time, settling rate, and effluent color. Flocculant products compared in the study included eight commercially available polyacrylamides, sodium montmorillonite, two chitosan-based flocculants, agricultural gypsum, and alum-based products.

Floc sizes were visually observed, compared to known particle diameters, categorized into eight particle size ranges. The categories and point allocations are shown in Table 5.1.

Table 5.1. Floc size point allocation

Size (mm)	3.01-4.50	2.26-3.00	1.51-2.25	1.01-1.50	0.76-1.00	0.51-0.75	0.30-0.50	0-0.29
Points	10	9	8	7	6	5	4	0

After mixing the flocculant into the sediment-laden samples, the time taken for flocs to form was recorded and categorized into 11-time ranges. The categories and point allocations are shown in Table 5.2.

Table 5.2. Floc formation time point allocation

Time (s)	0-10	11-20	21-40	41-50	51-60	61-80	81-100	101-120	121-140	141-160	>160
Points	10	9	8	7	6	5	4	3	2	1	0

Flocs were visually observed during settling for several minutes. Several time measurements since settling started and corresponding depths in the water column were recorded to determine settling velocity. The settling velocity was averaged for each sample and categorized into 11 ranges. The categories and point allocations are shown in Table 5.3.

Table 5.3. Floc settling velocity point allocation

Vel (in./hr)	>3501	3,001-3,500	2,501-3,000	2,001-2,500	1,500-2,000	1,001-1,500	801-1,000	601-800	401-600	201-400	0-200
Points	10	9	8	7	6	5	4	3	2	1	0

The effluent color was compared with five categories of control colors. The categories and point allocations are shown in Table 5.4.

Table 5.4. Effluent color point allocation

Size (mm)	1 (Clear)	2 (Light yellow)	3 (Dark Yellow)	4 (Brown)	5 (Dark Brown)
Points	10	8	6	4	0

The points allocated in each category were summed for an individual flocculant and ranked. The top-three best-performing products were considered for use in large-scale testing. If more than one flocculant had the same number of points, the flocculant was selected on availability in flocculant blocks, as desired by the research sponsor for ease of application and cost. Based on the match test results, the H_{30} Floc Flat, a semi-hydrated flocculant block from Carolina Hydrologic, was selected for sediment basin testing.

5.3.1. Flocculant Installation

Flocculant was applied to the basin under the MFE-I configuration. Although flocculants are also available in granular, emulsion, and sock forms, blocks were selected for ease of application. Flocculant blocks were placed and secured in the channel upstream of the rock check dam to ensure ample contact and mixing time before reaching the forebay. Sediment-laden flow was diverted to the center of the channel using rock gabions to maximize contact with the flocculant blocks. Flocculant blocks were secured to the channel using t-posts and sod staples, as shown in Figure 5.1a. The blocks under flow conditions are also shown in Figure 5.1(b).

Since the blocks were semi-hydrated, the manufacturer suggested storing or covering the blocks with trash bags in between runs to minimize the effects of drying out from the sun. While researchers wanted to evaluate the sediment retention and water quality benefits of flocculant application, it was important all research was practical and implementable for the research sponsor. Researchers understood that it would be difficult to adequately cover and uncover all flocculant blocks on-site at the appropriate times. The two smaller blocks are shown in Figure 5.1(a) were used to compare if a block was covered instead of left in the elements within the channel. All testing MFE-I testing was conducted between November 16 and December 15, 2021, and the blocks were subjected to approximately 19,000 ft^3 (538 m^3), during testing. Between tests, the blocks were measured for length, width, height, circumference, and weight to compare degradation.

(a) placement in channel

(b) under flow conditions

Figure 5.1. Flocculant block installation.

5.3.2. Sediment Retention and Water Quality Effects

Sediment retention and water quality behavior were measured following the methods outlined in 4.3 Materials and Methods, subsections Data Collection and Sediment Retention Quantification. Turbidity reduction was evaluated using the linear regression model described in Chapter 4 with the addition of flocculant as an independent variable. An additional model was developed, comparing just the MFE-I (S7) and MFE-I + Flocculant (S8) installations. Additionally, the differences of average turbidity during the filling, rapid settling, and polishing periods for the S7 and S8 configurations were evaluated for statistical relevance at the 95% confidence interval, using two-tailed equal variance t-tests

Sediment retention was compared to that of the MFE-I (S7) as a system and within individual bays. In addition, a particle size analysis was conducted using the Malvern Mastersizer 3000, a laser diffraction particle size analyzer, on settled material from the forebay, Bay 3, and Bay 4 with and without the presence of flocculant. It was noted that the Malvern Mastersizer 3000 provided more accurate results for silts and clays, so the deposited material was dried and passed through the number 18 sieve to remove particles greater than 1.0 mm.

The Malvern Mastersizer 3000 was initially employed to compare particle sizes with and without flocculant, with the hypothesis that the flocculant would create larger particle sizes. The settled, dried, and sieved material was added to a beaker of deionized water until the Malvern Mastersizer 3000 reached an obscuration percentage between 15-20%. The Malvern Mastersizer 3000 provided five individual particle size analyses for each sample and an average curve. An analysis was considered accurate if the percent error between analyses was less than 5%; however, the percent errors were much greater when water was used as the dispersant. Only the last three of the five analyses could be used for each sample. The error in the first two runs was likely due to residual material in the machine from previous samples, causing some clogging within the machine.

Sodium hexametaphosphate, a dispersant, was added to all samples to improve the function of the machine and the accuracy of results. After the dispersant was added, the samples were sonicated for at least 24 hours before being processed in the Mastersizer 3000. The addition of the dispersant would allow the smallest particle sizes to be observed. It was hypothesized that the flocculant would aid in the capture of finer particles. Results from the particle size analyses were plotted by size against percent volume in the sample.

Although sediment retention and captured particle size are important metrics for sediment basin performance, water quality was hypothesized to be more sensitive to flocculant application. Water quality behavior was measured following the methods outlined in 4.3 Materials and Methods, with slight modifications. Due to the forebay causing an impoundment overtaking the automated inflow sampling location, inflow samples were hand sampled at the outfall of the mixing trough into the channel. An additional hand sampling location was added to capture the water quality overtopping the forebay and entering the basin. The sampling frequency was every two minutes during MFE-I testing and every three minutes during the MFE-I + Flocculant testing due to the addition of a hand sampling location downstream of the flocculant block for residual testing infeasible to hand sample three locations every two minutes.

Discharge turbidities were plotted for an initial visual comparison of water quality being discharged from the basin with and without the application of flocculant. Further analysis included averaging the inflow turbidity measurements for each set of tests (MFE-I and MFE-I + Flocculant) from 0- 30 minutes to get representative inflow turbidity for each test, following the procedures outlined in Chapter Four: In-Channel Sediment Basin Performance Improvements through Large-

Scale Testing. As an example, the inflow turbidities and corresponding time stamps for the MFE-I+ Flocculant set are shown in Table 5.5. The turbidity values were averaged and resulted in a representative inflow value of 753 NTU.

Table 5.5. Example for MFE-I1 + Flocculant (S8)

Time (min)	S8: L1-A (NTU)	S8: L2-A (NTU)	S8: L3-A (NTU)	Average (NTU)
3	363	174	169	235
6	932	724	728	795
9	596	1,710	1,731	1,346
12	584	432	432	483
15	884	1,280	1,293	1,152
18	520	449	449	473
21	522	556	557	545
24	234	706	710	550
27	562	1,454	1,470	1,162
30	324	1,013	1,021	786
Avg.	**552**	**850**	**856**	**753**

Turbidities at the remaining sampling locations were divided by the representative inflow value, subtracted from 1 to determine a turbidity reduction, and plotted over the 48-hour observation period. For numerical comparisons, the turbidities were averaged and corrected for outliers, following the same procedure described for inflow and illustrated in Table 5.5 for the filling, rapid settling, and polishing periods. These values are reported as turbidity reduction compared to inflow. The pairings to calculate turbidity reduction are shown in Table 4.5.

5.3.3. Residual Testing

Although flocculants can significantly reduce sediment concentrations in stormwater effluent, high residual flocculant concentrations can potentially impact aquatic life downstream of an application site. Kazaz et al., *(2022a)* determined a method to detect residual concentrations by comparing the settling velocities of site samples with residual flocculants and to the settling velocities observed using known, dosed flocculant concentrations. Residual testing for this project followed the methods detailed by Kazaz et al., *(2022a),* using the selected PAM-based flocculant product, which was installed in block form in the sediment basin. Dosed concentrations ranged from 0-40,000% of the manufacturer's dosage recommendation of 5 μg/L to create the residual curves. The residual curve is displayed in Figure 5.2.

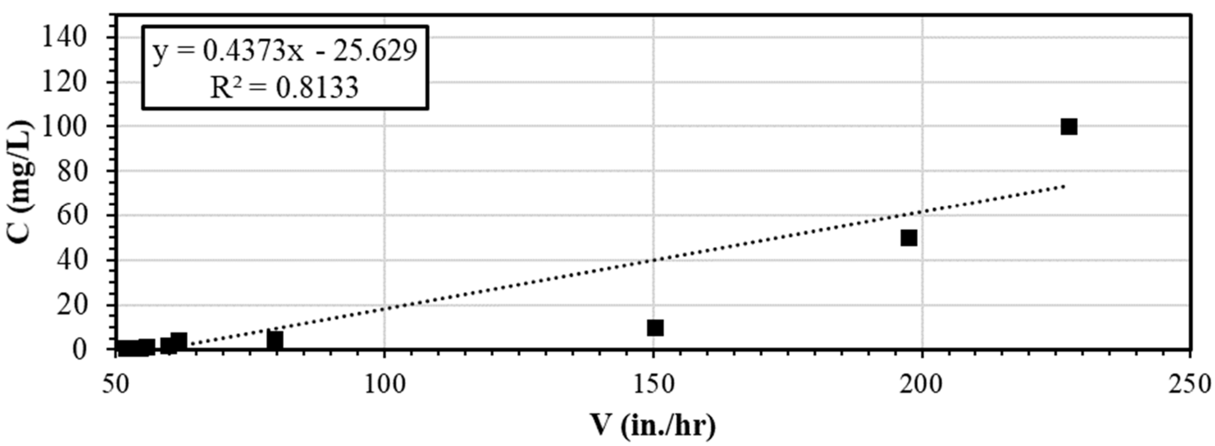


Figure 5.2. Residual curve for selected PAM flocculant.

5.4. Results and Discussion

While flocculants can decrease sediment concentrations, it is essential that appropriate flocculant selection, application, and dosage techniques are used. If improperly dosed or mismanaged, flocculants can harm the receiving water's health. This section summarizes flocculant selection, water quality and sediment retention improvements, and residual concentrations. Flocculant identification and residual concentration results from this study are products of the testing procedures outlined in Kazaz et al., *(2022b).*

5.4.1. Flocculant Selection and Installation

In total, fourteen flocculants were added to solutions using Iowa-native soil and deionized water. The flocculants were ranked on a points system, which considered floc size, formation time, settling rate, and effluent color, and are shown in Table 5.6. When compared, three of the flocculants achieved exactly the same amount of points, which are bolded below.

Table 5.6. Total flocculant point allocation

Product	**Color**	**Pts.**	**Floc Formation** mm:ss	**Pts.**	**Size Floc** mm	**Pts.**	**Settling Rate** in./hr (cm/hr)	**Pts.**	**Total Pts.**
1	1	10	0:00	10	1.0-1.5	7	653 (1,659)	3	30
2	1	10	0:00	10	1.0-1.5	7	440 (1,118)	2	29
3	1	10	0:07	10	1.0-1.5	7	759 (1,928)	3	30
4	3	6	0:00	10	1.5-2.25	8	80 (203)	0	24
5	1	10	0:04	10	0.75-1.0	6	1,050 (2,667)	5	31
6	2	8	0:03	10	1.0-1.5	7	215 (546)	1	26
7	2	8	0:00	10	1.0-1.5	7	145 (368)	0	25
8	1	10	0:05	10	1.0-1.5	7	622 (1,580)	3	30
9	1	10	0:07	10	0.75-1.0	6	1,125 (2,858)	5	31
10	1	10	0:00	10	1.0-1.5	7	975 (2,477)	4	31
11	2	8	0:38	8	2.25-3.0	9	56 (142)	0	25
12	1	10	1:02	5	1.5-2.25	8	59 (150)	0	23
13	1	10	0:11	9	1.5-2.25	8	65 (165)	0	27
14	1	10	0:00	10	1.0-1.5	7	476 (1,209)	2	29

Product 10 was excluded from the study as it caused a rapid change in pH, as observed by B. Kazaz, which could be detrimental to receiving waterbodies. PAMs were the two best performing flocculants (Products 5 and 9). The manufacturers of the two products were contacted, and the chemical composition of the flocculants was requested in block form.

PAM is widely used in construction stormwater management and are available in various compositions. Many of the tested flocculants are widely applied and may perform well across many soil types; similarly, soils may respond well to multiple flocculants. If a soil responds well to many flocculant types, it is suggested to consider application and maintenance plan and cost. Product 9 was available in block form in this testing, which was the desired dosing mechanism, and therefore used in the channel for all MFE-I +Flocculant testing.

Despite tracking the length, width, height, circumference, and weight of the two blocks left covered and uncovered to evaluate degradation, some limitations made the experimental results challenging to evaluate. The results are shown in Table 5.7.

Table 5.7. Measured dimensions of flocculant blocks

Parameter	Uncovered			Covered		
	MFE-I + F01	**MFE-I + F02**	**MFE-I + F03**	**MFE-I + F01**	**MFE-I + F02**	**MFE-I + F03**
Length in. (cm)	7.25 (18.4)	8 (20.32)	9.5 (24.1)	8 (20.32)	8 (20.32)	9 (22.9)
Width in. (cm)	5 (12.7)	4.5 (11.4)	5 (12.7)	4.75 (12.1)	5 (12.7)	5.5 (14.0)
Height in. (cm)	2.75 (7.0)	2.75 (7.0)	2.75 (7.0)	3 (7.6)	3 (7.6)	2.5 (6.4)
Circumference in. (cm)	-	16 (40.6)	13.25 (33.7)	-	16.25 (41.3)	13.5 (34.3)
Weight lb. (kg)	4 (1.8)	5.2 (2.4)	5 (2.3)	4.4 (2.0)	6 (2.7)	5 (2.7)

After examining results, it was evident there was no clear trend. The measurements of the blocks were dependent on shrink-swell due to moisture content, and the blocks could not be oven-dried without losing their effectiveness during testing. Additionally, sediment would adhere to the flocculant blocks in between testing, creating a “caking” effect. This affected the length, width, height, and circumference measurements. Additionally, this caking layer protected the uncovered flocculant block from elements. Caking was scraped from the flocculant blocks after measurements but before the next test. According to manufacturer guidance on flow capabilities, the one-month evaluation subjected the blocks to less than 20% of the sediment-laden flow the blocks were capable of treating. Additional lab-based research is suggested to examine degradation over the block's suggested lifetime, using controlled flow and sediment introduction and environmental chambers.

5.4.2. Sediment Retention and Water Quality Improvements

Sediment retention was measured following the methods outlined in Chapter 4. The sediment retained was quantified for each section of the basin and the entire system. Sediment retention was compared for the MFE-I with and without flocculant. A visual display of the results is illustrated in Figure 5.3.

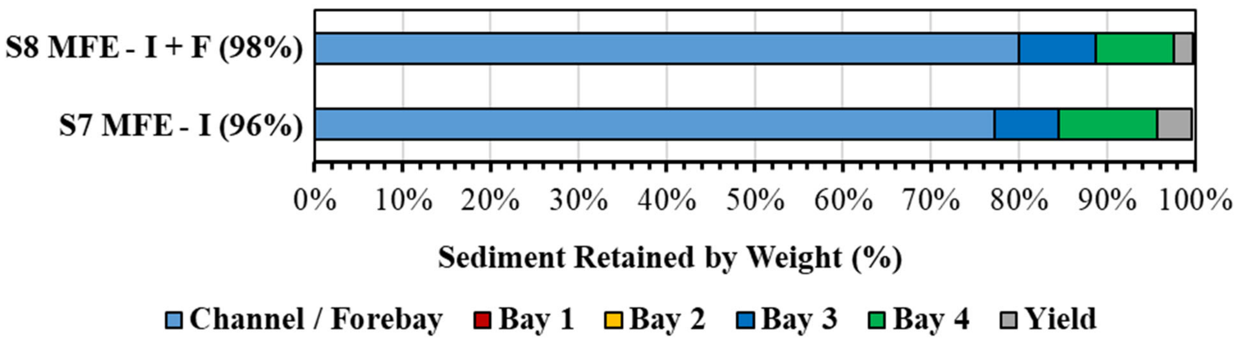


Figure 5.3. Sediment retained by percent weight.

The MFE-I had 77% sediment capture by weight in the forebay, 7% in Bay 3, and 11% in Bay 4. When flocculant was applied, sediment capture increased by 3% in the forebay, 2% in Bay 3, and decreased by 2% in Bay 4. The basin captured 96% of sediment by weight without flocculant and 98% when flocculant was applied.

The settled material from the forebay, Bay 3, and Bay 4 from MFE-I and MFE-I + Flocculant Testing were preserved, dried, sieved, and analyzed for particle size. Table 5.8 displays the D10, D50, and D90 for each sample. Figure 5.4 displays the particle sizes when deionized water was used to suspend the samples.

Table 5.8. Particle size analysis with deionized water buffer

Parameter	FB-MFE-I	FB-MFE-I + Flocculant	B3-MFE-I	B3-MFE-I + Flocculant	B4-MFE-I	B4-MFE-I + Flocculant
D_{10} (μm)	3.17	3.48	2.76	2.42	2.79	2.73
D_{50} (μm)	25.9	27.2	21.7	16.7	19.1	16.5
D_{90} (μm)	74.6	80.4	66.1	57.7	57.9	63.3

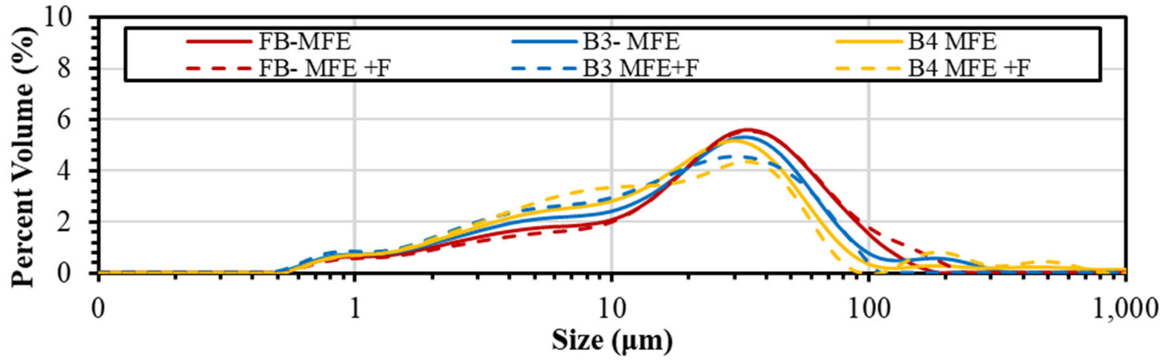


Figure 5.4. Particle size analysis with deionized water buffer.

Some general trends were observed from this analysis, confirming that the largest grain sizes were captured early in the basin and decreased as the flow path progressed. For example, the largest grains were captured in the forebay, followed by Bay 3 and Bay 4. However, the analysis was not very revealing of grain size comparisons when flocculant was and was not applied. In the following analyses, sodium hexametaphosphate was used to disperse the samples, with the intent to capture the smallest grain sizes for all samples. Table 5.9 displays the D_{10}, D_{50}, and D_{90} for each sample. Figure 5.5 displays the particle sizes when dispersant was used to soak and suspend the samples.

Table 5.9. Particle size analysis with sodium hexametaphosphate buffer

Parameter	FB-MFE-I	FB-MFE-I + Flocculant	B3-MFE-I	B3-MFE-I + Flocculant	B4-MFE-I	B4-MFE-I + Flocculant
D_{10} (µm)	1.72	1.00	1.02	0.747	1.48	0.95
D_{50} (µm)	11.7	4.37	4.85	2.96	8.28	4.59
D_{90} (µm)	54.3	15.5	17.9	8.05	36.0	14.3

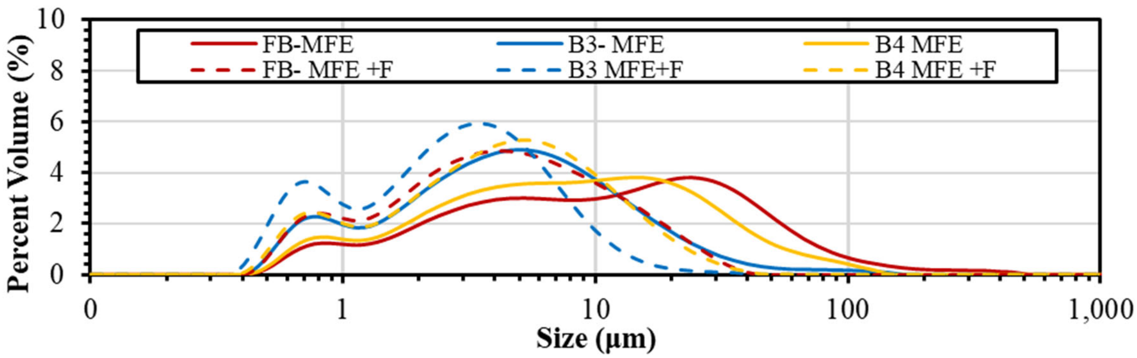


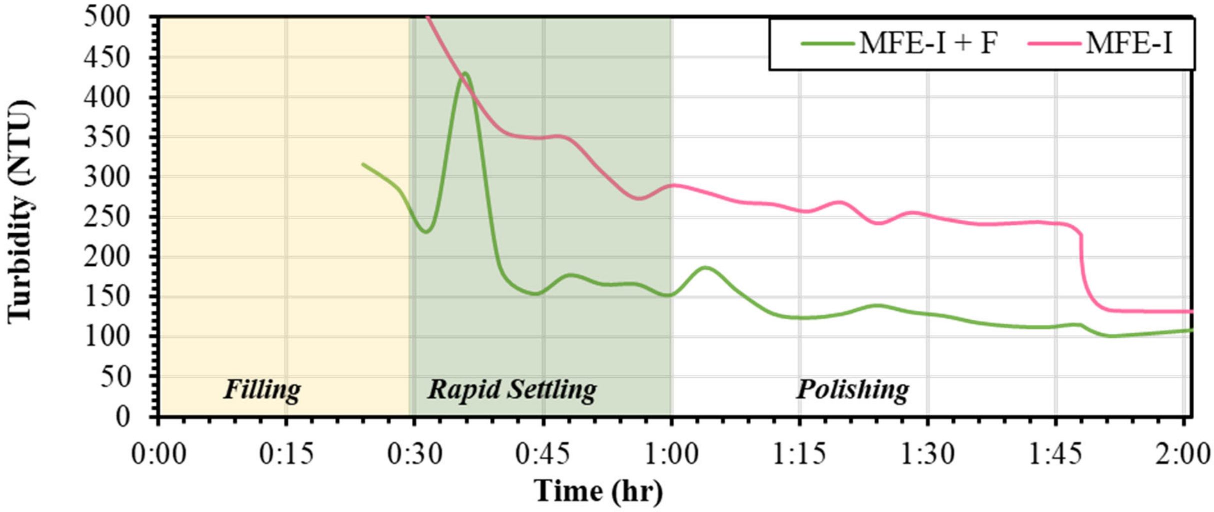
Figure 5.5. Particle size analysis with sodium hexametaphosphate buffer.

This analysis confirmed the hypothesis, indicating that the addition of flocculant captures the finest particles, which are most likely to remain suspended within the water column. The addition of flocculant provides an opportunity to aggregate the finest particles, increasing the overall particle diameter, which would promote settling, according to Stoke's Law. The capture of these particles was presumed to be correlated to a reduction in turbidity.

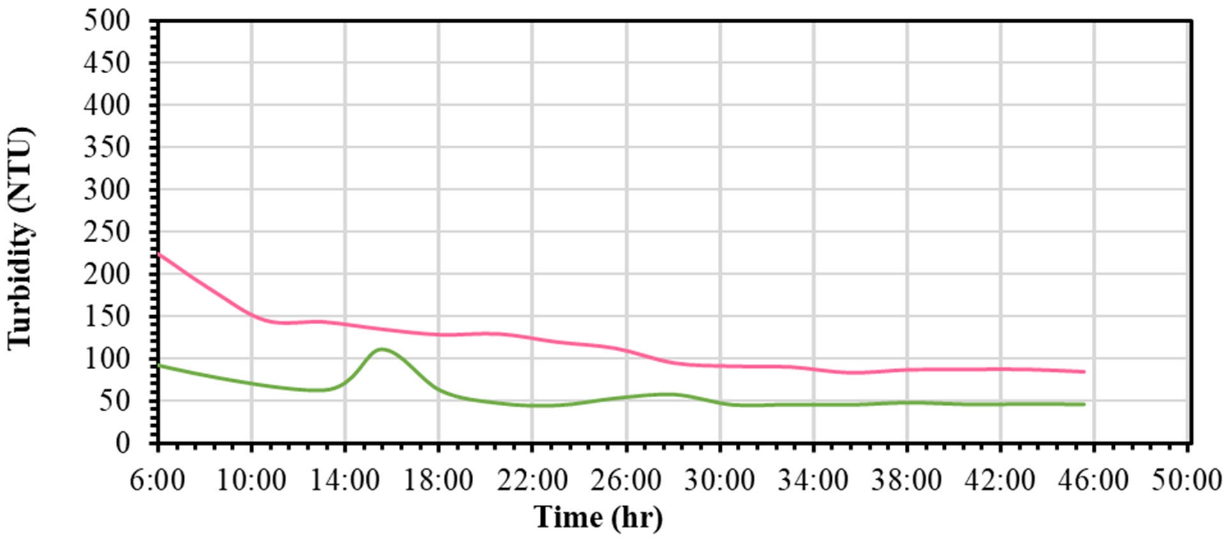
Despite sediment retention and particle size capture being important metrics for the sediment basin performance and indicating enhanced performance due to flocculant, water quality was hypothesized to be more sensitive to flocculant application. Turbidity measurements were compared at various locations in the basin to quantify the water quality impacts. Figure 5.6 illustrates the average discharge turbidity during MFE-I testing without flocculant in pink and with flocculant in green.

As indicated in the Results and Discussion section of Chapter Four: In-Channel Sediment Basin Performance Improvements through Large-Scale Testing, the 30-minutes of flow introduction in LX-A and LX-B are considered the first and second "filling periods." The 30-minutes following, or first hour, is considered "rapid settling," and the remaining dewatering time is considered "polishing." During the rapid settling period, discharge turbidity values are approximately 100 NTU lower when flocculant is applied. The difference in turbidity decreases to approximately 50 NTU during the polishing period, but further analysis was conducted to compare the discharge and inflow water quality more precisely.

The average inflow for MEF-I and MFE-I + Flocculant Testing was 334 and 753 NTU, respectively, during first fill testing, and 440 and 430 NTU, during the second fill testing. Inflow turbidity was affected by material deposited in the mixing trough washing out, background turbidity in the supply pond, and soil introduction parameters. As displayed in Table 5.5, inflow turbidity values for MFE-I+F02 and F03 were higher than F01, causing the average to be higher. Although the background turbidity of the supply pond would vary, it was always under 150 NTU. Differences in first flush inflow turbidity were most likely due to residual soil from previous testing being stuck or deposited in the sediment hopper and mixing trough. While all soil was air-dried and sieved in the same fashion, soil introduction was highly variable due to weather and soil moisture content affecting the consistent performance of the sediment hopper. In higher moisture, the hopper would clog, forcing hand introduction until the clog was relieved.



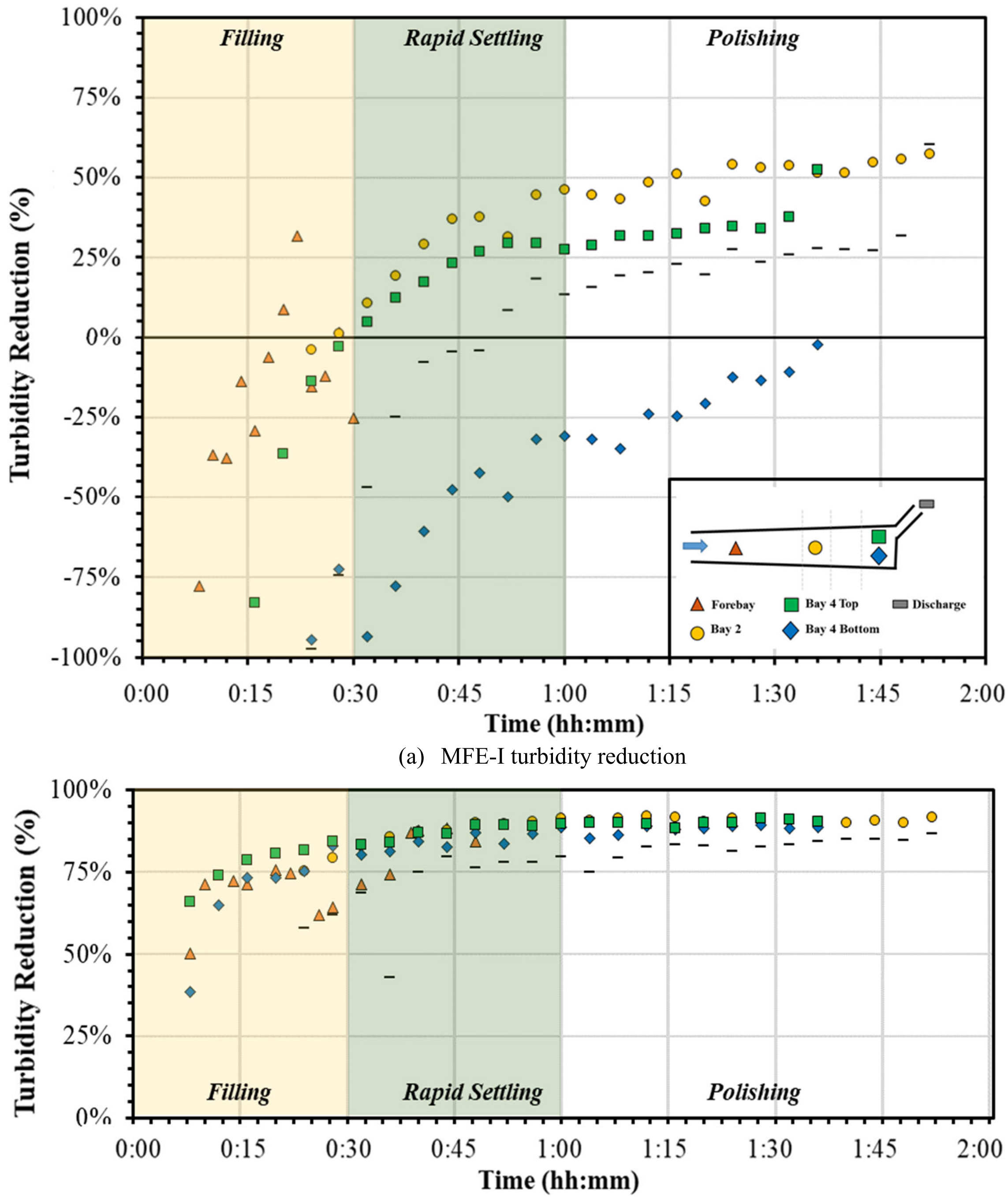
(a) 0:00-2:00 hr



(b) 6:00-48:00 hr

Figure 5.6. Observed turbidity with flocculant application.

The turbidity reduction from samples overtopping the forebay in Bay 2, the bottom of Bay 4, the top of Bay 4, and the discharge from 0:00-2:00 hr are displayed in Figure 5.7. These measurements were recorded after the first filling period. It is important to note the y-axis on the graphs, the turbidity reduction for MFE-I is graphed to -100%. Any value less than 0% indicates the water samples taken had higher turbidity than the average inflow.



(a) MFE-I turbidity reduction

(b) MFE-I + Flocculant turbidity reduction

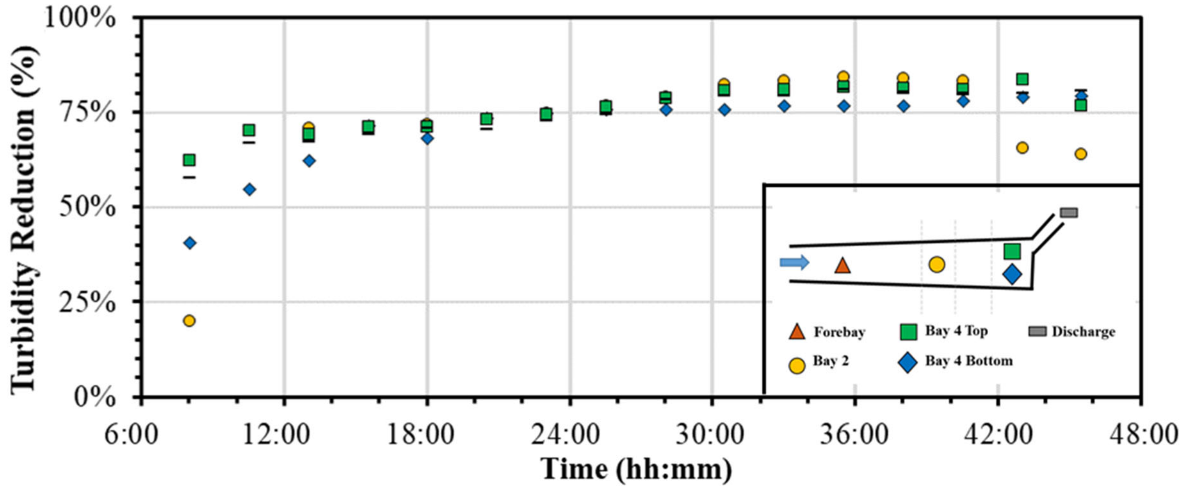
Figure 5.7. Turbidity reduction 0:00-2:00 hr.

Without flocculant, turbidity improvements at discharge did not occur until after flow introduction ended. However, turbidity improvements immediately started when flocculant was applied, as shown in Figure 5.7(b). Turbidity was reduced by 50% during the rapid settling period and reached 87% removal by the end of the two-hour monitoring period compared to 30% removal when no flocculant was applied. The discharge turbidity ranged between 102-187 NTU in hours 1:00-2:00 with flocculant and 133-290 NTU without flocculant.

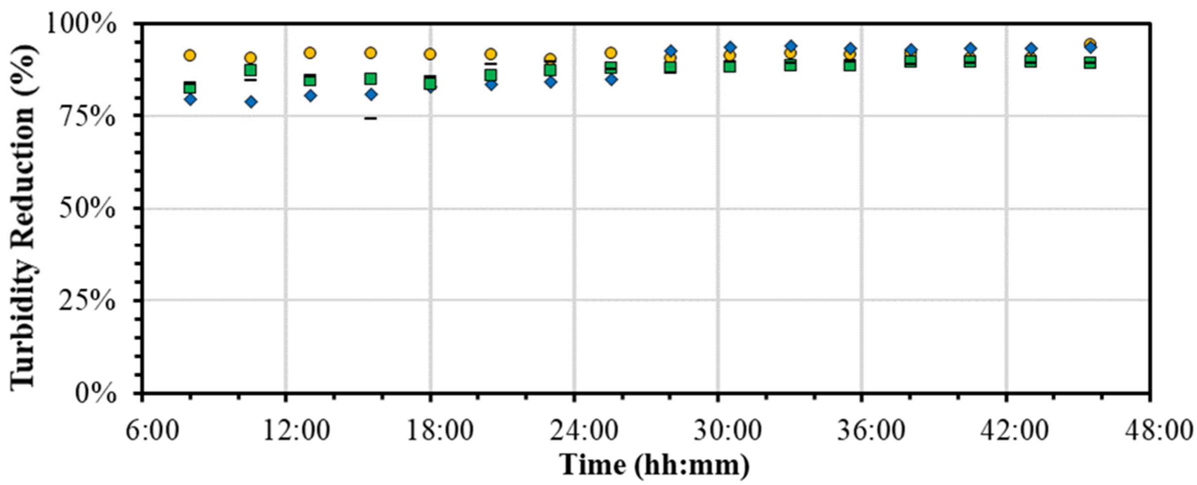
The basin behavior was more similar across all sampling locations when flocculant was applied; however, the turbidity reduction was more variable between sampling locations when flocculant was not applied. In theory, the samples taken at the top of Bay 4 and discharge would have similar turbidity values since a skimmer was used for dewatering the basin, but as shown in Figure 5.7(a), Bay 4 had a greater turbidity reduction than observed at discharge. The skimmer was installed to the 12 in. (31 cm) discharge pipe through the earthen berm, as shown in Figure 4.18. The discharge sampling location was roughly 3 ft (1 m) into the downstream pipe. The discrepancy in turbidity reduction without flocculant could have been due to deposition occurring in the 12 in. (31 cm) dewatering pipe, which was installed with no slope.

Additionally, there was armoring at the outfall of the dewatering pipe to avoid downstream erosion. This armoring decreased flow velocity and created a small impoundment at discharge, allowing some settling, and affecting measurements. However, the same effects would likely be observed during field implementation.

The second fill occurred at 5:00 hours. Water quality following this test was observed for up to 48 hours to evaluate the effects of prolonged detention. Figure 5.8 displays the turbidity reduction from samples overtopping the forebay in Bay 2, the bottom of Bay 4, the top of Bay 4, and the discharge during the polishing period from 6:00-48:00.



(a) MFE-I turbidity reduction



(b) MFE-I + Flocculant turbidity reduction

Figure 5.8. Turbidity reduction 6:00-48:00 hr.

Without flocculant application, turbidity reduction at discharge reached 80% after 36 hours in the basin. However, discharge turbidity reduction reached 80% immediately following the first and second filling periods. After 23 hours of detention, turbidity was reduced by 90% with flocculant, indicating that detention times may be decreased if flocculant is applied, and the same turbidity reduction can be achieved as prolonged detention times in sediment basins without flocculant application. At the end of the 48 hours, the discharge turbidities were 46 and 85 NTU, with and without the application of flocculant.

When flocculant was added to the linear regression model, the base case being S3 configuration, as described in Chapter Four: In-Channel Sediment Basin Performance Improvements through Large-Scale Testing Water Quality Analysis, the R^2 of the estimated model ranged between 0.11-0.42, depending on test period. Although these R^2 values still did not indicate a well-fit line, flocculant was statistically significant during the rapid settling and polishing periods. The coefficients and p-values are shown in Table 5.10.

Table 5.10. Linear regression model for structural and chemical treatments

Test Period	Treatments	Coefficients	P-value
Entire Test	**Intercept**	0.44	9.90 E-33
$R^2 = 0.24$	**Skimmer**	-0.35	7.22 E-18
	Baffles	-0.25	3.19 E-06
	Forebay	0.19	2.38 E-06
	Flocculant	0.54	2.49 E-25
Filling	**Intercept**	-1.01	6.37 E-03
$R^2 = 0.11$	**Skimmer**	-0.53	2.16 E-01[a]
	Baffles	0.89	1.24 E-01[a]
	Forebay	1.54	4.00 E-04
	Flocculant	0.71	2.43 E-01[a]
Rapid Settling	**Intercept**	0.24	1.13 E-02
$R^2 = 0.42$	**Skimmer**	-0.82	8.17 E-12
	Baffles	-0.24	9.26 E-02[a]
	Forebay	0.33	3.52 E-03
	Flocculant	1.04	7.19 E-11
Polishing	**Intercept**	0.56	6.42 E-46
$R^2 = 0.29$	**Skimmer**	-0.28	2.56 E-12
	Baffles	-0.28	1.81 E-07
	Forebay	0.14	4.94 E-04
	Flocculant	0.45	2.02 E-18

Note: [a] indicates not statistically significant at 95% confidence.

When MFE-I + Flocculant was independently compared to MFE-I (base case), the R^2 of the estimated model increased, indicating a stronger correlation between flocculant application and turbidity reduction. Flocculant was again statistically significant. The components of the linear regression model are displayed in Table 5.11.

Table 5.11. Linear regression model comparing S7 and S8

Test Period	Treatments	Coefficients	P-value
Entire Test	**Intercept**	0.40	2.99 E-47
$R^2 = 0.38$	**Flocculant**	0.42	1.99 E-30
Filling	**Intercept**	0.24	5.40 E-03
$R^2 = 0.23$	**Flocculant**	0.46	2.85 E-04
Rapid Settling	**Intercept**	0.01	8.13 E-01
$R^2 = 0.63$	**Flocculant**	0.77	1.31 E-11
Polishing	**Intercept**	0.49	8.72 E-54
$R^2 = 0.46$	**Flocculant**	0.38	1.23 E-25

Additional numerical turbidity comparisons are shown in Table 5.12 and Table 5.13. The turbidity values at each location were compared to the inflow values to determine the statistical significance of turbidity reduction at the 95% confidence interval, using two-tailed equal variance t-tests.

Table 5.12. Average turbidity during MFE-I testing (NTU)

First Fill Avg. Inflow Turbidity: 334 NTU	**Forebay**	**Bay 2**	**Bay 4 Bot.**	**Bay 4 Top**	**Discharge**
Filling Period (0:00-0:30)	393	338	1364[b]	5781	621[b]
Rapid Settling (00:31- 1:00)	-	227[a]	515[b]	262	354
Polishing (1:00+)	-	164[a]	399	223[a]	254[a]

Second Fill Avg Inflow Turbidity: 440 NTU	**Forebay**	**Bay 2**	**Bay 4 Bot**	**Bay 4 Top**	**Discharge**
Filling (5:00-5:30)	406	290[a]	266[a]	178[a]	188[a]
Rapid Settling (00:31- 1:00)	-	182	257	187	231
Polishing (1:00+)	-	108[a]	112[a]	107[a]	113[a]

Note: [a] indicates significant turbidity reduction, and [b] indicates significant turbidity increase, compared to inflow, at the 95% CI

During the filling and rapid settling periods associated with the first fill testing, there was an increase in turbidity compared to the inflow. While there was an observed decrease in turbidity following the second fill, turbidities never reached below 100 NTU. Hand samples overtopping the forebay were completed at 30 minutes. Thus, there was no data during the rapid settling and polishing periods; however, it was observed that the forebay continued dewatering for approximately 10-minutes post inflow. Hand samples were taken up to 40 minutes during MFE-I + Flocculant testing. Thus, the data is displayed in Table 5.13.

Table 5.13. Average turbidity during MFE-I + Flocculant testing (NTU)

First Fill Avg. Inflow Turbidity: 753 NTU	**Forebay**	**Bay 2**	**Bay 4 Bot.**	**Bay 4 Top**	**Discharge**
Filling (0:00-0:30)	224[a]	171[a]	240[a]	169[a]	302
Rapid Setting (00:31- 1:00)	134[a]	89[a]	118[a]	96[a]	178[a]
Polishing (1:00+)	-	68[a]	90[a]	73[a]	125[a]

Second Fill Avg. Inflow Turbidity: 430 NTU	**Forebay**	**Bay 2**	**Bay 4 Bot.**	**Bay 4 Top**	**Discharge**
Filling (5:00-5:30)	134[a]	69[a]	108[a]	88[a]	101[a]
Rapid Settling (00:31- 1:00)	92[a]	61	103	84	95
Polishing (1:00+)	-	38[a]	53[a]	55[a]	53[a]

Note: [a] indicates significant turbidity reduction, compared to inflow, at the 95% CI

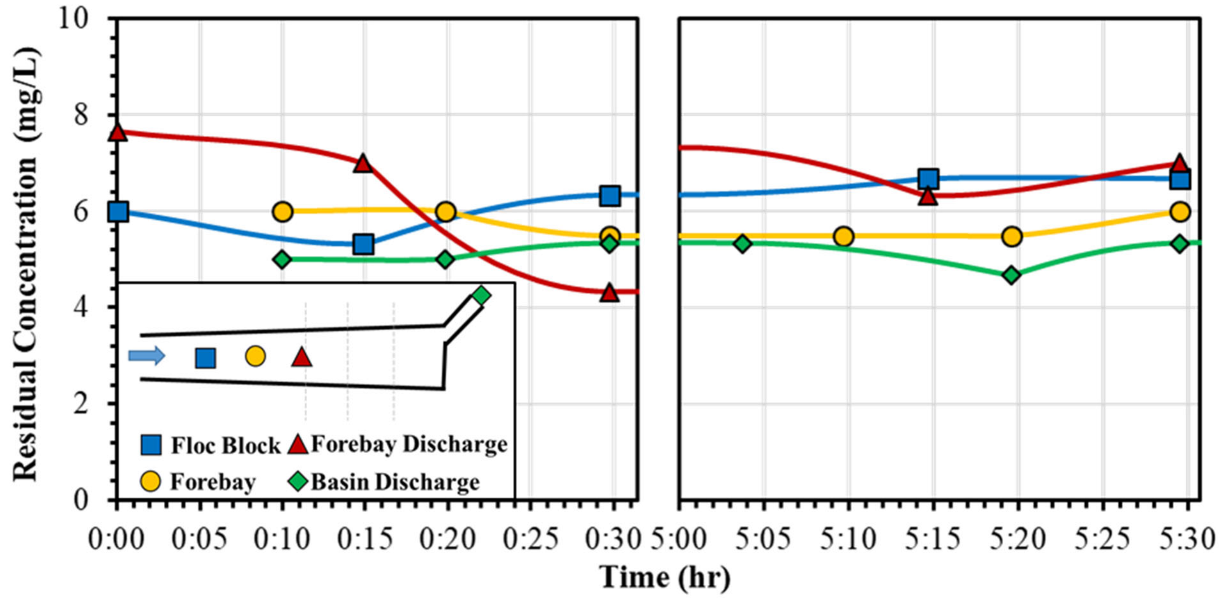
Following the second filling period, turbidities were reduced to 101 NTU, or less, at discharge and reached as low as 45 during extended dewatering. MFE-I and MFE-I + Flocculant were compared at each sampling location and time period using two-tailed equal variance t-tests. In all comparisons, MFE-I + Flocculant had significantly less turbidity at the 95% confidence interval.

5.4.3. Residual Concentrations

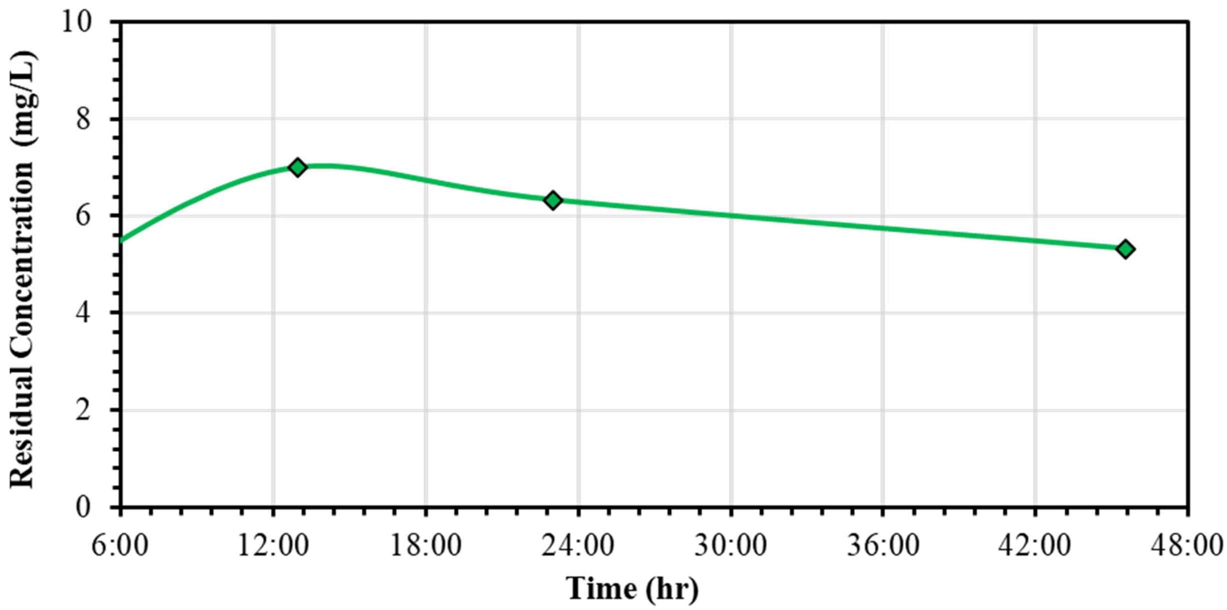
Although flocculant significantly impacted water quality, improved sediment retention, and fine grain size capture, the downstream effects of flocculant dosing were unknown. Manufacturer guidance was referenced for application, maintenance, and toxicity limits. Since flocculant blocks were used for the application, it was difficult to measure the inflow dosage compared to granular or emulsion forms. The manufacturer's guidance recommended one semi-hydrated, five-pound (2.27 kg) flocculant block to treat 800,000 gallons (128,000 ft^3 [3,625 m^3]) of sediment-laden flow but provided little information regarding the chemical makeup.

Residual concentrations were determined for several water samples by comparing the settling velocities of site samples with residual flocculants and to the settling velocities observed using known, dosed flocculant concentrations, as described in Kazaz et al., *(2022b)*. The method developed by Kazaz would allow residual testing to be conducted in the field, provided the known concentrations, such as the one shown in Figure 5.2, are created in advance.

Water samples for residual testing were taken during inflow directly downstream of the flocculant block, within the forebay, discharging from the forebay, and discharging from the basin. Discharge samples were analyzed for residual flocculant concentrations throughout the 48-hour dewatering period. The residual concentration plots are displayed in Figure 5.9.



(a) average residual flocculant concentrations in discharge during filling periods



(b) average residual flocculant concentrations in discharge during dewatering

Figure 5.9. Average residual concentrations.

Residual concentrations never exceeded 8 mg/L but, on average, remain roughly 6 mg/L. It was important to compare these concentrations with the manufacturer's material safety data sheet (MSDS). This particular product had an MSDS that did not provide a toxicity concentration but indicated that it was unlikely to be toxic to fish, algae, and daphnia even at high concentrations, due to low solubility. However, the product had unknown chronic toxicity and was not readily biodegradable, so proper management of flocculated and settled material on a site is important to consider. The acute toxicity report indicated that the product was non-toxic for humans, dermally or orally *(Carolina Hydrologic 2016)*. Although this particular flocculant product does not seem to be a threat to receiving waters during sediment basin testing, continued match, application, and dosage testing is being conducted by B. Kazaz, M.A. Perez, W.N. Donald, X. Fang, and J. Shaw for ALDOT for implementation guidance.

6. CHAPTER SIX: IN-CHANNEL SEDIMENT BASIN DESIGN TOOL

The large-scale testing effort described in the previous two chapters provided performance data for structural and chemical components, which indicated enhanced sediment capture and turbidity reduction within an in-channel sediment basin; however, the in-channel sediment basin configuration and several of its components are anticipated to be newly introduced to design specifications. An Excel-based tool was developed to aid in design and implementation of in-channel sediment basins. The Excel tool considers basin geometry and dewatering systems to determine detention volume and discharge characteristics. These characteristics can also be applied to a specific storm event, if the user elects to input a hydrograph. Additionally, the tool includes a section to input a specific soil gradation to determine if flocculant should be applied. Flocculant application is suggested if less than 80% of the sediment is predicted to settle within the desired dewatering time. Additional outputs include skimmer size selection, orifice diameter, plots of the channel cross-section at the earthen berm, stage-storage curve, and stage-discharge curve for design tables and reports. The user input is shown in Figure 6.1. Red text specifies areas for user input, red outline indicates a drop-down list for user selection, and the black text is output. Graphical outputs are described in the following section.

In-Channel Sediment Basin Design Tool

User Provided Input Paramters (Red)

Project & Location:	Designer:	Date:

Channel Configuration	
Foreslope (H:V)	3.50
Backslope (H:V)	3.00
Channel Bottom Width (ft)	10.00
Longitudinal Slope (%)	3.00%

Dam/ Auxiliary Spillway Configuration	
Top of Dam (ft)	4.50
Slope of Dam Face (%)	200.00%
Spillway Width (ft)	4.00
Spillway Height (ft)	4.00

Dewatering System	
Dewatering Structure	Skimmer
Desired Dewatering Time (days)	3
Riser Elevation (ft)	3.00
Riser Diameter (in.)	12.00
Elevation of Orifice Row 1 (in.)	24.00
Elevation of Orifice Row 2 (in.)	26.00
Elevation of Orifice Row 3 (in.)	28.00
Orifices in Row	4.00
Orifice Diameter (in.)	1.00
Skimmer	
Skimmer rest or pipe invert elevation (in.)	6.00

Site Soil Gradation		
Sieve No.	(mm)	% Finer
4	4.7500	100%
10	2.0000	96%
20	0.8500	89%
40	0.4250	80%
60	0.2500	75%
100	0.1500	68%
120	0.1250	61%
200	0.0750	62%
Pan- Hydrometer Analysis	0.0522	61%
	0.0379	57%
	0.0279	52%
	0.0213	40%
	0.0156	34%
	0.0118	28%
	0.0085	24%
	0.0061	22%
	0.0043	20%
	0.0031	19%
	0.0025	18%
	0.0022	18%
	0.0013	17%
	0.0009	15%

Expected Temperature in Basin (°F)	70

Hydrograph Routing	
Route Hydrograph?	Yes
Initial Discharge Elevation (ft)	0.50

User Input Hydrograph	
Time (hr)	Q_{in} (ft^3/s)
0.00	0
0.02	0
0.03	0
0.05	0
0.07	0
0.08	0
0.10	0
0.12	0
0.13	0
0.15	0
0.17	0
0.18	0
0.20	0
0.22	0
0.23	0
0.25	0
0.27	0

Storage	
Standing Pool (ft^3)	91.46
Stormwater Storage (ft^3)	8,840.54
Aux. Spillway Flow (ft^3)	3,020.68

Skimmer	
Skimmer Size (in.)	2
Orifice Diameter (in.)	1.41

Flocculant	
Settled Sediment (%)	79.90%
Apply Flocculant?	Yes

Notes

This tool is to be used for design guidance only. The engineer of record is responsible for final design. Dam height is limited to 5 ft, as maximum specified in 3.4.6 of IECA Sediment Basin Design Standard (2021). Skimmer is limited to design for the Faircloth Skimmer. If the skimmer size or orifice diameter results in #N/A, dewatering time must be increased. Inflow hydrograph is limited to 2000 time step entries. Flocculant suggested if settled sediment is less than 80%.

Figure 6.1. User input in spreadsheet-based tool.

6.1. Geometry and Volume

Although the Iowa DOT, for whom this research was conducted, has a standard in-channel sediment basin design *(EC-601, Iowa DOT, 2018),* the channel environments are expected to vary across sites. Additionally, it is anticipated that if the in-channel sediment basin design is adopted elsewhere, the channel design may need to be modified. Altering the channel design affects the detention volume. The first consideration of the tool was to estimate the available storage in the basin and develop a stage-storage curve for design tabulation. The tool requests the user to input the channel geometry, including the foreslope, backslope, channel bottom width, longitudinal slope, dam height, and the width of the auxiliary spillway. Next to the requested inputs, the Iowa DOT standard roadside ditch and temporary sediment control basin geometries are listed for reference. The auxiliary spillway height was calculated, subtracting six inches from the dam height, as specified by the Iowa DOT temporary sediment control basin design. Similarly, the top of the riser was calculated by subtracting 1.5 ft (0.45 m) from the dam height, if applicable, as specified by the Iowa DOT temporary sediment control basin design *(EC-601, Iowa DOT, 2018).* This design is included in Figure 3.2.

Detention volume characteristics, including impoundment length, surface area, and storage volume, are calculated based on the user input channel geometry over stage increments of 0.1 ft (3.0 cm). For a detailed illustration of basin behavior, the basin's stage increments were set to 0.1 ft (3.0 cm). The impoundment length is determined by dividing the stage by the user-input longitudinal slope. Next, the surface area is calculated following the surface component in the volume equation of the Iowa DOT Roadside Detail Temporary Sediment Control Basin Tabulation (100-33). The equation is shown in Eq. 6.1.

$$SA = \left(\frac{1}{4} \times FS \times h^2\right) + \left(\frac{1}{2} \times CB \times h\right) + \left(\frac{1}{4} \times BS \times h^2\right) \qquad \textbf{Eq. 6.1}$$

where,

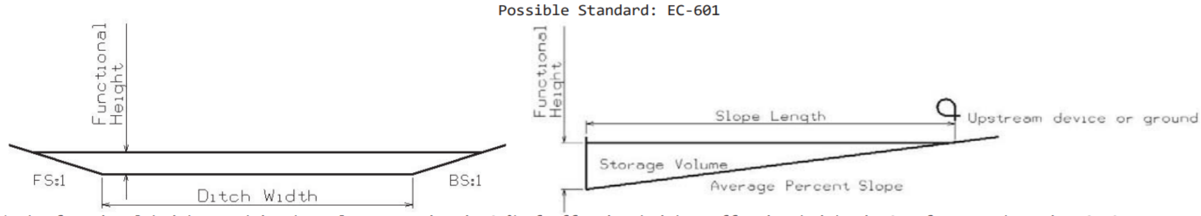
SA = surface area (ft^2)
FS = foreslope (X:1)
BS = backslope (Y:1)
CB = channel bottom width (ft)
h = basin stage (ft)

The storage is determined by multiplying the surface area equation by the impoundment length, as shown in the Iowa DOT 100-33 in Figure 6.2; however, the tool also considers the volume directly upstream of the sloped earthen dam, rather than assuming an exactly vertical depth at the dam.

100-33
10-16-18

TEMPORARY SEDIMENT CONTROL BASIN

Possible Standard: EC-601



* The functional height used in the volume equation is 95% of effective height. Effective height is 2.5 feet as shown in EC-601.
* Volume equation: [(1/4(FS*H^2))+(DW*H)+(1/4*(BS*H^2))]*(H/Avg%Slope)

Basin No.	Location		Bid Items			Stormwater Storage Volume Summary					Remarks
	Station	Side	Installation	Maintenance	Removal	Foreslope	Backslope	Ditch Width	Average % Slope	Volume*	
			Each	Each	Each	FS:1	BS:1	FT		CF	

Figure 6.2. Temporary sediment control basin tabulation *(Iowa DOT 2018).*

The stage-storage curve is automatically plotted at 0.1 ft (3.0 cm) increments, with a displayed best-fit equation and R^2 value to gauge the strength of the relationship. An example of the stage-storage curve is shown in Figure 6.3.

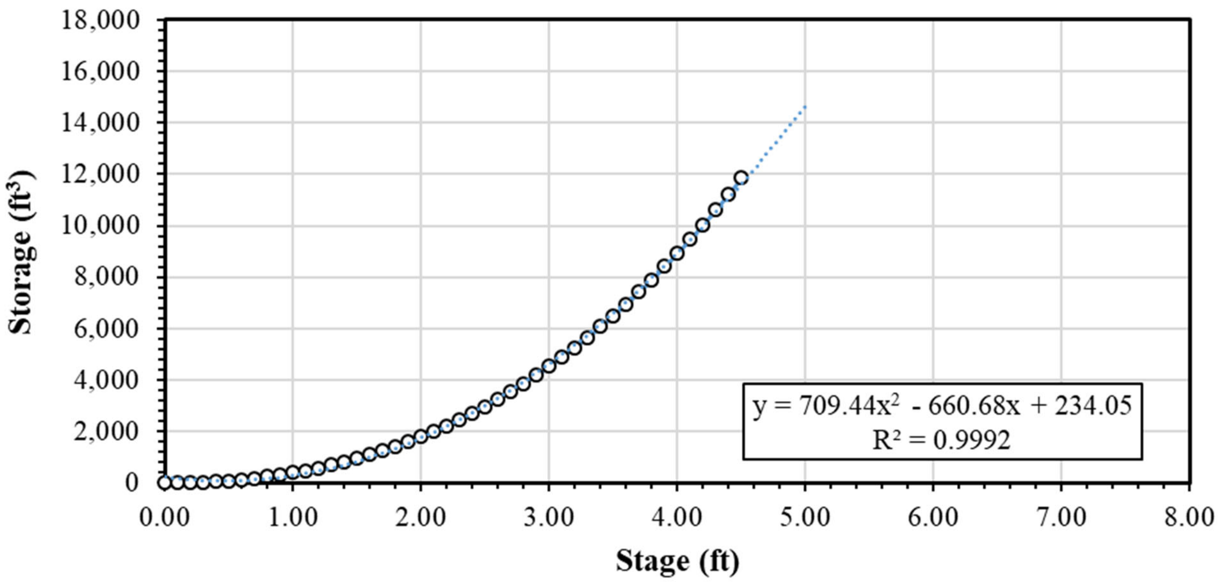


Figure 6.3. Plotted stage-storage curve.

6.2. DEWATERING

The second portion of the tool allowed the user to select a dewatering system. The user could toggle between a rock spillway, riser pipe, and skimmer. Outputs from this portion of the tool included a stage-discharge curve. The discharge was calculated according to the system selected. The flow over the rock spillway followed the broad-crested weir relationship, shown in Eq. 6.2 *(Finnemore and Franzini 2002)*.

$$Q = L \times \sqrt{g} \times \left(\frac{2}{3}\right)^{\frac{3}{2}} \times (h - H)^{\frac{3}{2}} \qquad \textbf{Eq. 6.2}$$

where,

Q = flow over weir (ft^3/s))
L = spillway width (ft)
g = acceleration of gravity (32.2 ft/s^2)
H = height of spillway (ft)
h = basin stage (ft)

No additional user input was required outside the basin geometry block if the rock spillway was selected. This spillway type would allow users to apply the tool for the detention created behind rock check dams, or the component of the forebay in this research, and the flow over an auxiliary spillway. The rock spillway was included because it served as the auxiliary spillway for the riser pipe and skimmer dewatering systems. Additionally, this would be the outlet type for the silt basins.

As shown in EC-601, the traditional dewatering pipe was also included as a dewatering option. If the riser pipe was the selected system, the tool requested the diameter of the riser pipe and orifices. Additional user input included the elevation of each orifice row and the count of orifices at a single elevation. Equations 7E-12.01 and 7E-12.02 from the Iowa Statewide Urban Design and Specifications were used to calculate weir and orifice flow. Weir flow was considered when the stage in the basin was greater than the top of the riser pipe's elevation. Rows of orifices were incorporated into the discharge as the stage in the basin overcame their elevation. The equations are shown in Eq. 6.3 and Eq. 6.4.

$$Q = 10.5 \times d \times h^{\frac{2}{3}} \quad \textbf{Eq. 6.3}$$

$$Q = 0.6 \times A \times \sqrt{2 \times g \times H} \quad \textbf{Eq. 6.4}$$

where,

Q = flow through (ft^3/s))
d = riser diameter (ft)
g = acceleration of gravity (32.2 ft/s^2)
H = allowable head over riser (ft)
A = open orifice area (ft^2)

The skimmer from the MFE-I installation was included as the third dewatering system option. If this option was selected, the user was requested to input the desired dewatering time in days, skimmer rest, or pipe invert elevation, which would govern the water level available to drain through the skimmer. Skimmer design was based on calculations for Faircloth skimmers, as used in the large-scale research effort. The tool outputs the skimmer size and orifice diameter based on user input. The skimmer maximum flow capacities, orifice factors, and skimmer heads were referenced in the tool, following the Faircloth Technical Sizing Instructions *(2007)*. The skimmer orifice was calculated by dividing the basin volume, determined by the geometry, by the skimmer factor. This calculation provided the required open orifice area, which the orifice diameter was then calculated from using the area of a circle. The discharge from the skimmer was calculated by substituting the orifice area into Eq. 6.4.

A stage-discharge curve auto-populates based on the dewatering system selected and input parameters. An example, using the riser pipe, is shown in Figure 6.4

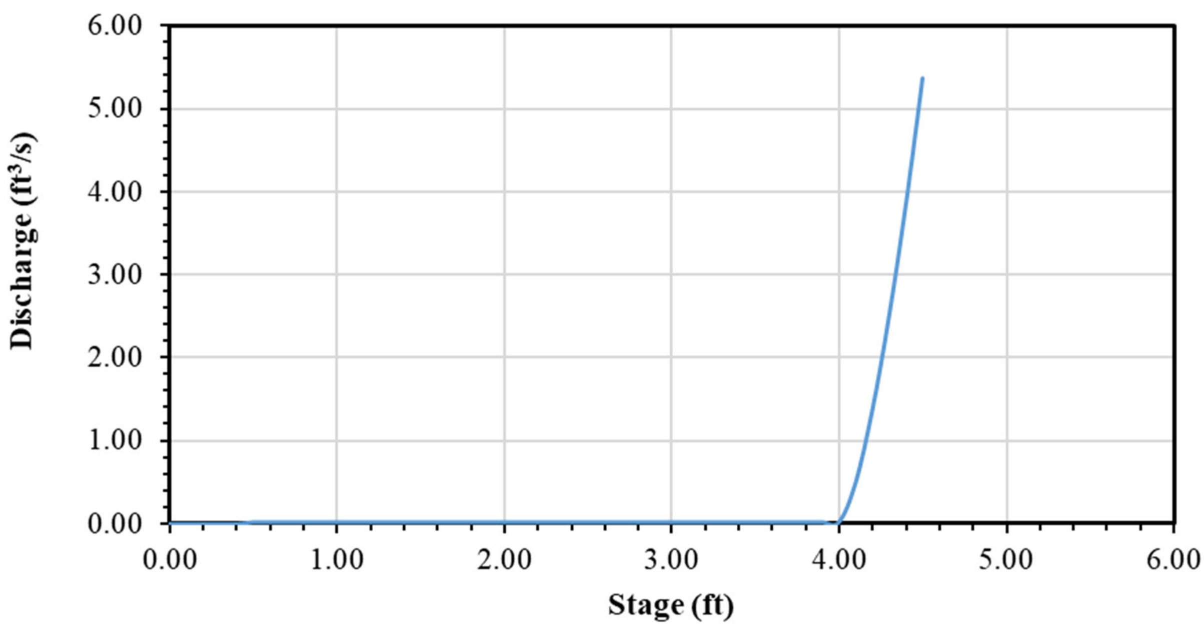


Figure 6.4. Stage discharge curve.

Additionally, a schematic of the basin cross-section at the dam is populated based on the geometry and dewatering user input. An example, using the riser pipe, is shown in Figure 6.5.

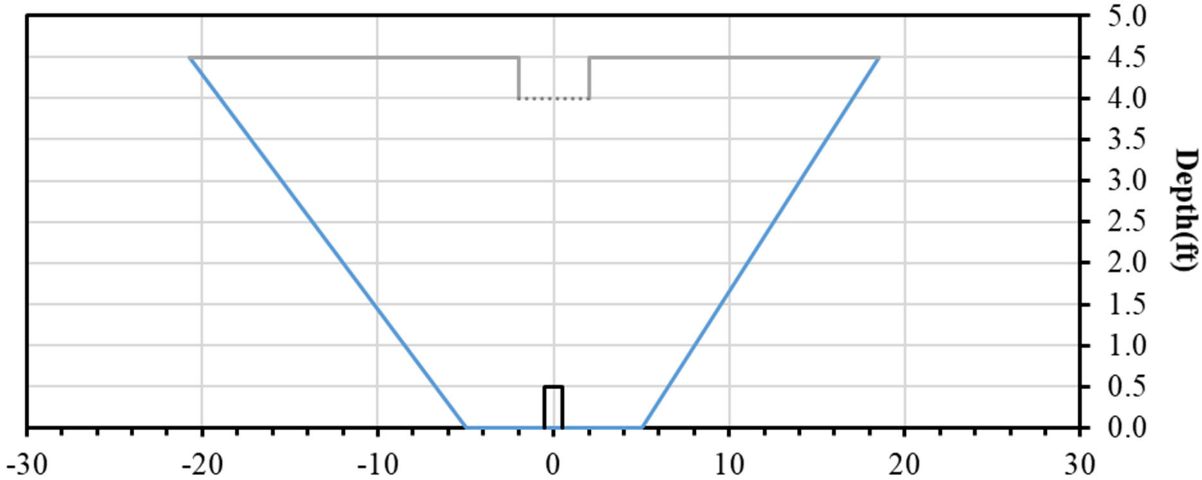
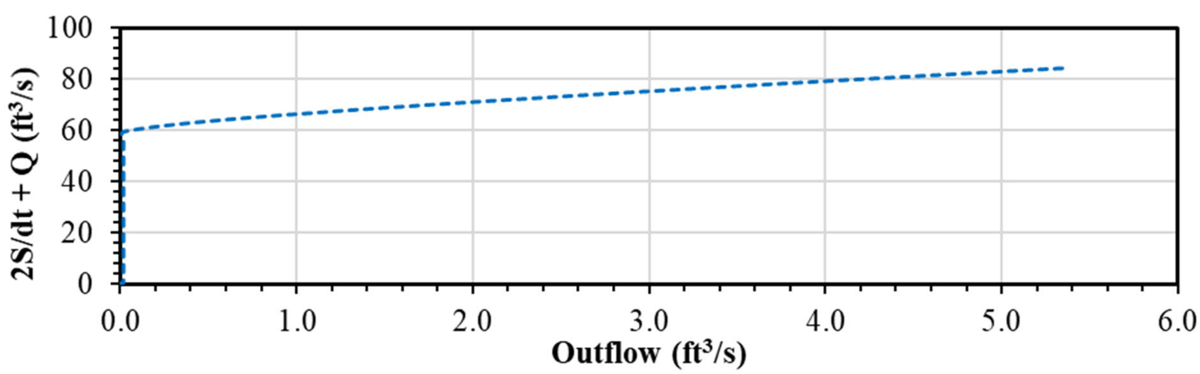
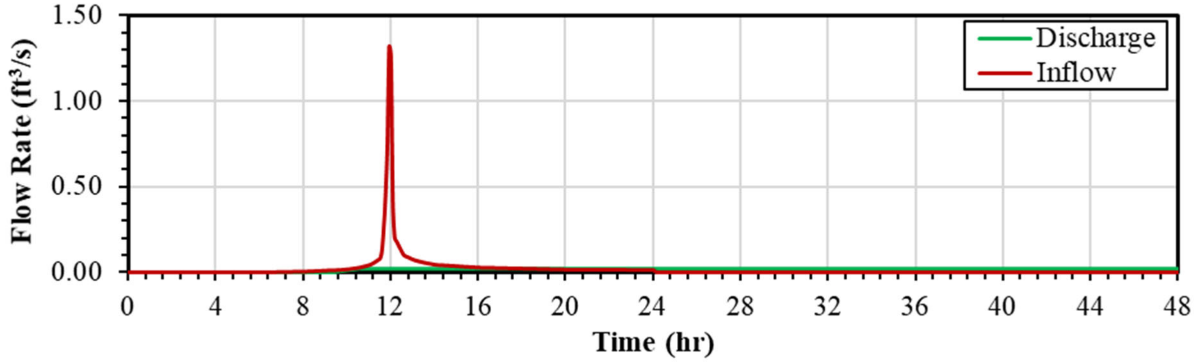


Figure 6.5. Basin cross section schematic.

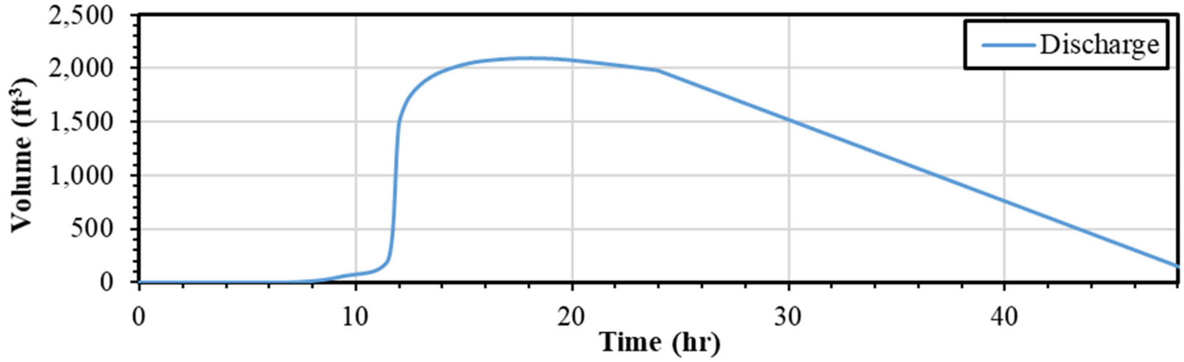
The user may also input time and flow rate into available hydrograph parameters. If the user elects to input a hydrograph, the tool relies on the Muskingum Routing method at 5 min (300 second) time steps to model the hydrological flow into and discharged from the basin. This method considers the discharge capacity of the selected dewatering device. When routing is utilized, the tool supplies users with a created storage indication curve used to predict discharge, an inflow and discharge hydrograph, and the basin's volume over time to illustrate dewatering. Examples of the graphical outputs are shown in Figure 6.6.



(a) storage indication curve



(b) inflow and discharge hydrograph



(c) dewatering behavior

Figure 6.6. Hydrograph routing graphical output.

6.3. Sediment Capture and Flocculant

The last portion of the tool allows the user to input a soil gradation from a combined sieve and hydrometer analysis. Additionally, the tool allows the user to adjust the expected water temperature, starting with freezing, in the basin to adjust settling calculations. If no temperature is selected, 70 °F (20 °C) is the default. To predict settling, Stoke's Law was applied to determine if a particular sediment particle size class would settle within the user-specified dewatering time. If no dewatering time is specified, three days is considered the default. Stoke's law, was used to estimate the settling velocities of particles based on diameter, following the form of:

$$V = \frac{g\left(\frac{\rho_1}{\rho_w} - 1\right) d^2}{18\nu}$$ **Eq. 6.5**

where,

V = flow through (m^3/s))
ρ_w = density of water
g = acceleration of gravity (9.81 m/s^2)
ρ_1 = density of particle (kg/m^3)
d = particle diameter (mm)
ν = kinematic viscosity

The settling velocity for each particle size class was multiplied by the desired dewatering time to determine a settling distance. If the settling distance was greater than the user-input spillway height, or maximum stage level, the particle size class was assumed to be settled. If the settling distance was less than the spillway height, the particle size class was considered to be still suspended. If more than 20% of all sediment was still considered to be suspended, flocculant application was recommended. The settling distance was auto-populated based on soil gradation, basin geometry and conditionally formatted to indicate the particle classes that settled in green and were suspended in red. Additionally, the soil gradation was plotted with the particle size classes that settled in green and particle size classes suspended in red. The color-coded soil gradation plot is shown in Figure 6.7. If flocculant is recommended, users may reference the flocculant selection tool described by Kazaz et al., *(2022b).*

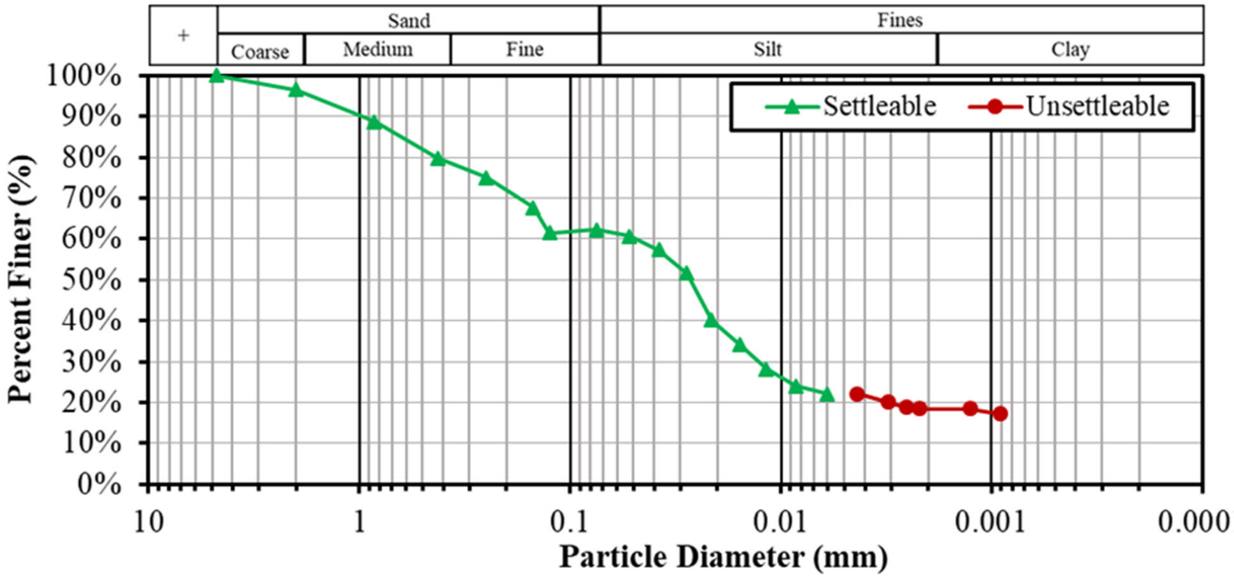


Figure 6.7. Particle settling estimation.

This tool is expected to aid the Iowa DOT in implementing new technologies to improve sediment capture and turbidity reduction, including the skimmer, forebay, and flocculant application. Additionally, the tool is anticipated to aid other state agencies and construction operators when adopting the in-channel sediment basin design configuration. Outputs provide skimmer sizing, cross-sectional schematics with the dewatering system, stage-storage and stage-discharge curves, which may be used in design tabulations and reports.

7. CHAPTER SEVEN: POST CONSTRUCTION AND SMART STORMWATER SYSTEMS

While construction stormwater presents unique pollution potential to receiving waterways, post-construction stormwater management plans, or PCSWMP, are also essential to maintain downstream water health *(City of Detroit 2019, Omaha Stormwater 2021, City of Clive 2019)*. The expansion of urban centers and rapid development result in impervious landscapes, which affect infiltration and evapotranspiration processes *(Kerkez et al., 2016)*. The disruption in these processes causes increased runoff and, often, flash flooding events. These events have increased flow velocity, volume, and contaminants that aging stormwater infrastructure systems are unable to capacitate *(Kerkez et al., 2016)*.

Hawley and Vietz *(2016)* emphasize the acceleration and extent of channel erosion and sediment transport due to urbanization. Maillan et al., *(2009)* monitored an urban, suburban, and rural stream and showed the urban stream had the highest biochemical oxygen demand (BOD), orthophosphate, total suspended sediment (TSS), surfactant concentrations, and fecal coliform yield. The study also showed the percentage of the watershed development and percent impervious landscape were strongly correlated with BOD, orthophosphate, and surfactant concentrations *(Mallin et al., 2016).*

Green infrastructure practices, such as permeable pavements, bioswales, and infiltration ponds, aim to reconnect some of the natural infiltration systems and alleviate the downstream water quantity and quality consequences *(USEPA 2022)*; however, green infrastructure is often statically designed while aiming to address dynamic flows and contaminant loads *(Kerkez et al., 2016)*. In recent years, "smart" stormwater solutions and systems have been developed to adjust to real-time storm and flow events dynamically. These systems rely on sensors and automated controls to adapt a PCSWMP for an individual, or series, of events *(Mullapudi et al., 2016)*.

7.1. SMART STORMWATER STRUCTURES

Traditionally, stormwater infrastructure has been designed to host events based on historical rainfall data, but as the climate changes, the frequency and intensity of storm events are increasing in most continental regions of the world *(Wuebbles et al., 2017)*. Smart stormwater practices provide an opportunity to retrofit or redesign stormwater infrastructure to be dynamic and adaptive to more intense and frequent storm events *(Mullapudi et al., 2016)*. Components of smart stormwater systems include sensors, actuated control valves, and dynamic gates *(Kerkez et al., 2016)*. Such components may be involved on a singular outlet, such as a detention pond, to control discharges locally *(Kerkez et al., 2016).* These systems are typically designed on a site-by-site basis, often to ensure that post-development discharges mimic pre-development discharge *(City of Clive 2019).*

Recent studies have considered the application of smart stormwater systems across a catchment *(Kerkez et al., 2016, Li et al., 2019, Shishegar et al., 2021).* These systems involve instrumenting various water quality and quantity sensors within a watershed *(Shishegar et al., 2021).* Real-time control, as presented in Shishegar et al., *(2021)*, combines predicted and observed data, including meteorological forecasting data, historical precipitation data, and observed weather conditions, across a watershed and adjusts actuators accordingly. Smart stormwater systems can adjust to reduce peak flows and allow extended detention time for enhanced settling of sediment and sediment-bound particles.

Shishegar et al., *(2021)* used a modified version of the EPA's Stormwater Management Model, better known as SWMMM. SWMMM is an open-source, public Windows-based software *(USEPA 2022)*. Using the modified model, researchers conducted a case study on a mid-size municipality in Quebec, Canada, on an 840,000 ac (340,000 ha) watershed. A static and smart stormwater system were compared using 2013 rainfall data. The smart stormwater decreased mean peak flows by 59% and increased detention time by 21 hours, on average *(Shishegar et al., 2021)*.

7.2. Performance Evaluations of Automated Outlet Structures

One example of a smart stormwater system includes automated outlet structures. An example of this is Flood-Con's Patented Automated Flood Control (AFC), an outlet control device designed to control the discharge from a traditional outlet control structure. The AFC functions by using measured rainfall and local site hydrologic parameters to determine and control discharge rates by automatically adjusting the release rate on an individual storm basis, allowing designers to implement smaller detention basins while achieving discharge rates of pre-developed conditions. Similar to most smart stormwater systems, controlled discharge flow rates are a well-recognized benefit; however, water quality impacts are not well understood.

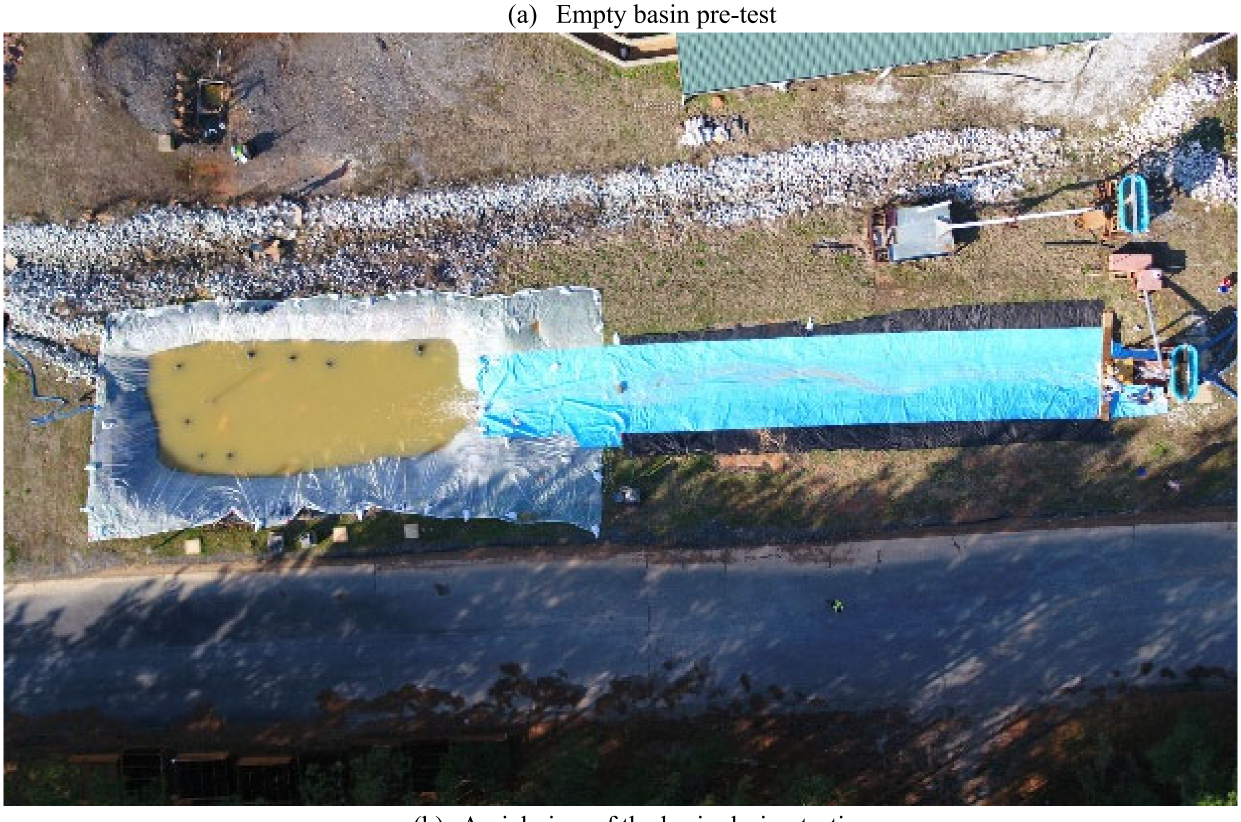
Flood-Con requested a performance evaluation of the AFC to gain designers' and regulators' recognition as a viable practice for low impact development (LID). In Alabama, the LID Manual indicates that a practice must capture 80% of TSS from the runoff resulting from the first 1.0 to 1.5 in. (2.5 to 3.8 cm) of rainfall, or the first flush event *(Alabama Department of Environmental Management and Alabama Cooperative Extension System 2017)*. The AFC is most likely to implemented on dry or wet detention pond. Dry and wet ponds provide up to 60% and 80% TSS removal, repectively, as claimed by the International Stormwater BMP Database *(International Stormwater BMP Database 2016)*. The AFC would be especially useful in the industry if performance evaluations indicated that it enhanced TSS removal in a dry detention pond from 60 to 80% to achieve the required performance specified in the AL LID Manual.

The Technology Acceptance and Reciprocity Partnership (TARP) developed a testing protocol for testing stormwater practices, which has been recognized and endorsed by several states. The TARP Tier II Stormwater Protocol provides specific recommendations for simulated stormwater used for product testing. The protocol uses field testing to determine product effectiveness and provides guidance for site selection. The TARP protocol calls for mean influent concentration to fall within a range of 100-300 mg/L *(TARP 2003)*. A testing methodology was adapted and modified to be performed at the AU-SRF to evaluate the water quantity and quality in response to the AFC, or other outlet structure, installed. The following section outlines the design and calibration of the large-scale testing apparatus. Performance evaluations are ongoing at the AU-SRF.

7.2.1. Methodology

The FloodCon Automated Outlet Structure testing was conducted on a retrofitted sediment basin at the AU-SRF. The basin had two primary components, including a 90 ft (27 m) inflow channel armored with tied concrete block and a 2,790 ft^3 (79 m^3) geotextile-lined, trapezoidal basin. Detained stormwater could impound up to 3.5 ft (1.0 m) before overtopping the auxiliary spillway. Prior to FloodCon product testing, the inflow channel and basin were lined with an impermeable plastic liner to prevent infiltration during testing, emulating a post-construction dry-detention pond, as shown in Figure 7.1.

(a) Empty basin pre-test



(b) Aerial view of the basin during testing

Figure 7.1. Post-construction testing basin at AU-SRF.

7.2.1.1. Flow and Sediment Introduction Rates

Sediment introduction aimed to simulate a 1.5 in. (3.75 cm) rainfall across a 0.6 ac (0.2 ha) contributing area with 90% impervious area. Water was introduced through the inflow tub to the channel at 0.75 ft^3/s (0.02 m^3/s) rate for 60 minutes to achieve 2,700 ft^3 (76.46 m^3) of total volume or completely fill the existing basin. As outlined in the TARP protocol, influent sediment concentrations were targeted to fall on the lower end of the 100-300 mg/L range (TARP 2003). Since FloodCon first aimed to test AFC in Alabama, an Alabama Sandy Loam was used for sediment introduction. Prior to introduction, the loam was passed through the number 60 sieve to represent the particle sizes expected from post-construction runoff. To achieve 100 mg/L, a soil introduction rate of 0.28 lb/min (0.13 kg/sec) was expected, or 16.9 total lb (7.7 kg) during a one-hour test. The sediment introduction rate was calibrated in a series of control tests.

7.2.1.2. Flow and Sediment Introduction Apparatus

Flow was introduced into the testing apparatus using the method described in the Flow and Sediment Introduction Apparatus section in Chapter Four: In-Channel Sediment Basin Performance Improvements through Large-Scale Testing. The desired flow rate for testing was achieved using a four-stage introduction apparatus. This setup included a pump system, adjustable equalizing tank, and a discharge weir to monitor inflow which fed to a soil-water mixing trough to create sediment-laden flow. The flow introduction system is shown in Figure 7.2**.**

Since the targeted sediment concentrations were relatively low compared to the traditional testing at the AU-SRF, new introduction methods were explored. A low-speed grain auger was first used but did not produce the targeted sediment concentration. Hand feeding was attempted but caused sediment surges during sampling. A sediment feeding method was eventually determined through an iterative calibration process. The final process implemented hand-feeding through an adjustable density cone to avoid irregularities in sediment concentration. Hand-feeding rates were confirmed by the research assistant shaking the appropriate amount of pre-weighed sediment over 60 seconds, monitored on a stopwatch.

Figure 7.2. Water introduction system for post-construction basin.

7.2.1.3. Dewatering system

A 4.0 in. (10.2 cm) diameter schedule 40 PVC pipe was used for dewatering and could be adapted for several dewatering scenarios. The dewatering mechanism was installed at a nine-inch (23.9 cm) elevation above the channel floor, on the basin side. Due to this elevation, the basin did not start discharging until approximately 5 min. after flow introduction started. If desired, the AFC could be fitted on the pipe on the downstream side of the basin, as shown in Figure 7.3.

(a) basin side of dewatering pipe (b) downstream dewatering pipe

Figure 7.3. Dewatering system on post-construction basin.

During calibration and control testing, the 4.0 in. (10.2 cm) pipe was capped with a 3D printed acrylic plate with varying orifice sizes, and the AFC was not installed. The desired dewatering time was 48 hours. Initially, an orifice of 0.67 in. (1.70 cm) was selected. After an iterative process of measuring dewatering rates, eventually, a 0.70 in. (1.78 cm) orifice was installed for a controlled dewatering rate of 0.16 ft^3/s (0.020 m^3/s).

Once calibration and control tests were completed, the next series of testing would leave the 4.0 in. (10.16 cm) pipe fully open, relying on the FloodCon Automated Outlet Structure installed downstream for dewatering adjustments. Additional configurations, which may be tested, are included in the following section, titled, Anticipated Next Steps.

7.2.1.4. Sampling Regime

Testing intended to verify: 1) basin discharge rates and 2) turbidity and TSS Reduction. This section describes the instrumentation and sampling regime used for calibration and, eventually, performance evaluations.

7.2.1.4.1. Sampling Regime

A set of Solonist M5 Levelogger and M 1.5 Barologger were used to monitor the stage of the basin, which was correlated to a volume using the stage-storage relationship defined in Perez *(2016),* and shown in Eq. 7.1.

$$y = 14.982x^4 - 133.06x^3 + 532.33x^2 - 77.82x - 0.2051 \quad \textbf{Eq. 7.1}$$

The Levelogger was installed at the discharge end of the basin, level with the dewatering orifice, to monitor the stage of the basin throughout testing. A Solonist Barologger was installed next to the basin to record and adjust for atmospheric pressure. The loggers recorded data every 1 minute during testing and 48 hours after dewatering. Discharge rates were calculated by comparing storage volumes over time.

7.2.1.4.2. Water Quality

Three Teledyne ISCO 6712 automated samplers were deployed in the channel and basin to collect 24, 1 L (33.8 fl oz) samples each throughout the filling and dewatering periods of the test. The first sampler was used to collect inflow samples in the inflow channel approximately 60 ft (18.3 m) from the mixing trough, as shown in Figure 7.4**.** A 500 mL (16.9 fl. oz) inflow sample was pulled every 2 min. Two samples were collected in a single bottle for a total of 1,000 mL (33.8 fl oz) total sample. Inflow samples were taken throughout water and sediment introduction (60 minutes). The second and third sampler inflow suction tubes were attached to the PVC dewatering mechanism, as shown in Figure 7.4**.** The second sampler was programmed with the same sampling interval as the first sampler. The second sampler collected discharge samples from time 0 to time 1 hour and 40 min. The third sampler then started sampling at 1 hour 40 minutes and pulled a 500 mL (16.9 fl. oz) sample every hour for 48 hours. Like the other two-level samplers, two samples were taken per bottle for a 1,000 mL (33.8 fl. oz) total sample. In between tests, the basin was flushed to remove deposited sediment.

(a) ISCO inflow sampling location

(b) ISCO discharge sampling location

Figure 7.4. Water sampling locations.

7.2.1.5. Post-Test Water Sample Analysis

During testing, 15 inflow samples and 48 discharge samples were collected. Each sample was evaluated for turbidity and total suspended solids. Turbidity was determined using a combination of the HACH® 2100Q Portable Turbidimeter (0-999 NTU). Total solids testing was conducted following ASTM standards D3977-97 (ASTM 2015). Inflow sample TSS concentrations were averaged. A test was considered valid if the average TSS concentration was between 100-300 mg/L. Discharge TSS values were averaged for the 60- minute filling, 60- minute rapid settling, and remaining polishing periods. These averages were compared to the inflow sediment concentrations to understand TSS reduction.

Mass balance was employed to quantify the amount of sediment retained in the basin, using measured TSS concentrations and flow rate. The flow inflow rate was monitored and recorded over the 60-minute testing frame and converted to units L/s. The inflow sediment introduction considered both theoretical and measured sediment quantities. For example, if 35 lb (16 kg) of sediment was introduced with 2,700 ft^3 (76 m^3), the theoretical inflow sediment concentration would be uniformly 208 mg/L; however, the TSS measurements for the inflow samples were used to compare the experimental with the theoretical sediment concentrations. To calculate the total sediment mass introduced, the concentration, C_{in} (mg/L), was multiplied by the inflow rate, Q_{in} (L/s), resulting in $Q_{in}C_{in}$ (mg/s). $Q_{in}C_{in}$ was averaged over a singular time step (5 minutes at inflow), and multiplied by the time elapsed (300 s), which resulted in a mass, m, of mg. The mass was summed over 60 minutes to result in the total. This is shown in Eq. 7.2 through Eq. 7.4.

$$Q_{in} \times C_{in} = (QC)_{in} \qquad \text{Eq. 7.2}$$

$$\frac{(QC)_{in(n_1)} + (QC)_{in(n_2)}}{2} \times (T_{n_1} - T_{n_2}) = m_{in\,(n)} \qquad \text{Eq. 7.3}$$

$$\sum m_{in} = M_{in} \qquad \text{Eq. 7.4}$$

where,

Q_{in} = inflow rate (L/s)
C_{in} = inflow concentration (mg/L)
T = Time (seconds)
m = mass introduced in time step (mg)
M = total mass (mg)
ν = kinematic viscosity (1.00E-06 m^2/s)

Outflow mass was calculated using the same method; however, discharge rate (Q_{out}) was calculated using a stage-discharge relationship from the recorded Levelogger data for each test. The discharge concentration, C_{out} (mg/L), was determined using the TSS measurements from the discharge water samples. The outflow mass was compared to the inflow mass to result in a percent retained in the basin.

7.2.2. Control Tests

In total, eight calibration tests were conducted, adjusting the outflow orifice size to achieve the desired dewatering time of 48 hours and the target inflow concentration of 100-300 mg/L. After several calibration tests, an orifice size of 0.70 in. (1.78 cm) was selected for the dewatering cap. The target inflow sediment concentration was eventually achieved by introducing 35 lb. (15.88 kg) of sieved soil throughout the 60-minute testing window. To ensure a consistent introduction rate, one volumetric pound of sediment was passed through the adjustable density over a 1.5 minute period until all 35 lb (16 kg) were introduced.

The discharge TSS concentrations from the three control tests, TC01, TC02, and TC03, are plotted in Figure 7.5.

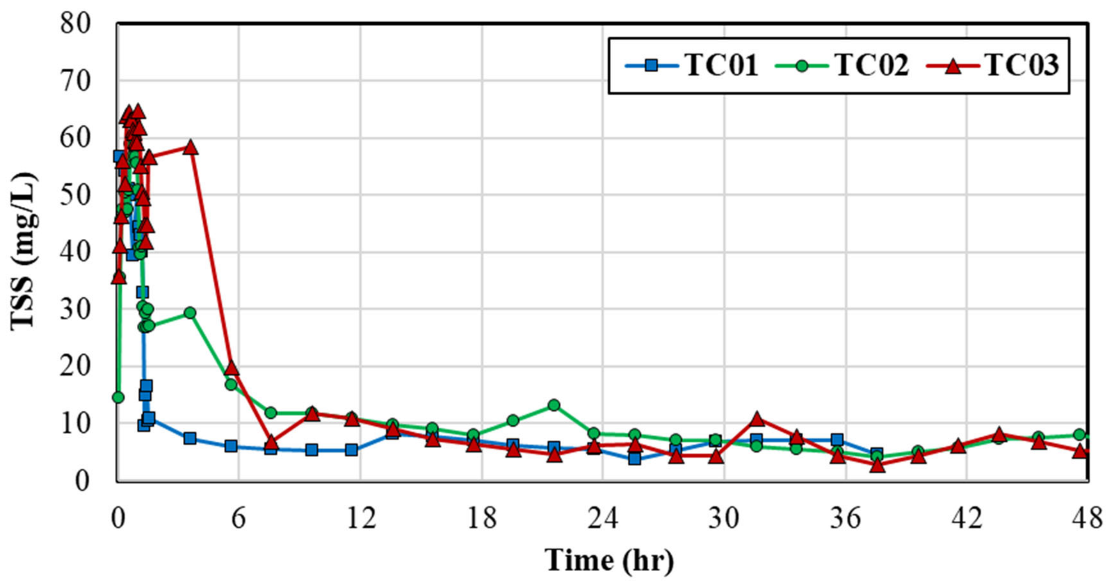


Figure 7.5. Flood-Con discharge TSS during control testing.

The inflow TSS concentrations were within 20 mg/L of each other for the three control tests (206, 199, 219 mg/L, for test FC01, FC02, and FC03, respectively). The average TSS reduction was consistent across all periods; however, total dewatering time decreased. This is likely due to pinholes created in the basin lining and around the dewatering pipe created during basin cleanouts. The TSS reduction from the filling, rapid settling, and polishing periods are recorded in Table 7.1.

Table 7.1. TSS reduction during Flood-Con control testing

TEST	Filling (0-1 hr)	Rapid Settling (1-2 hr)	Polishing (2- 48 hr.)	Dewatering Time (hr)
FC01	76%	80%	96%	43.6
FC02	75%	84%	95%	42.5
FC03	74%	77%	96%	41.3

Mass balance was used to quantify the total mass of sediment retained in the basin. Mass was converted from milligrams to pounds and recorded in Table 7.2.

Table 7.2. Sediment introduced and retained based on mass balance

TEST	Target Inflow Mass (lb)	Measured Inflow Mass (lb)	Outflow Mass (lb)	Target Mass Retained (%)	Measured Mass Retained (%)
FC01	35.0	17.9	2.1	94%	88%
FC02	35.0	30.6	2.0	94%	94%
FC03	35.0	34.9	2.2	94%	94%

In the first control test, only 17.9 of the 35.0 introduced pounds (8.1-15.9 kg) of sediment were accounted for in measurements, which was likely due to observed windy conditions carrying the sediment at introduction. Total sediment retention is comparable to the TSS reduction at polishing displayed in Table 7.1. The consistent and comparable results between the three control tests confirmed that the testing method was feasible and repeatable for product evaluation.

7.2.3. Anticipated Next Steps

Control testing, or S1, as shown in Figure 7.6, has been completed. The next series of testing will include the installation of AFC, on the downstream outlet pipe. In the event the AFC does not achieve the targeted treatment goal of 80% TSS removal, additional configurations can be evaluated (i.e. S3-S5), as needed, to achieve 80% TSS reduction. Configuration S3 is intended to evaluate the AFC while dewatering from the surface of the basin. Configuration S4 will evaluate the AFC in combination with an upstream post-construction stormwater practice installed within the channel of the basin. Configuration S5 will combine the upstream BMP with surface dewatering to evaluate the combined treatment efficiency. The potential series of testing is shown in Figure 7.6.

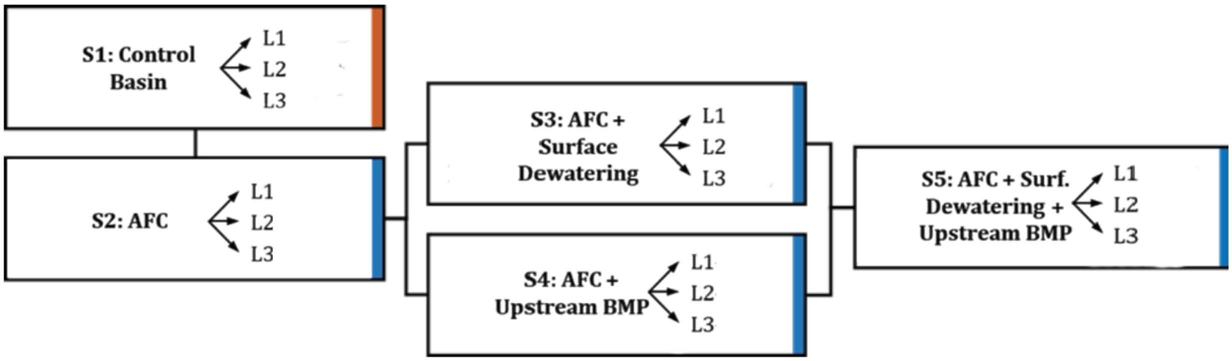


Figure 7.6. Proposed AFC testing regime.

In addition to AFC testing, the lined basin can now support testing of additional post-construction management practices and verify the performance of emerging smart stormwater systems. Testing for a post-construction skimmer, manufactured by Faircloth, has recently started. Performance evaluations may highlight the need for technological improvements or help validate models, which will inform water quality and quantity benefits locally, or in a catchment when smart stormwater systems are implemented.

8. CHAPTER EIGHT: CONCLUSIONS AND IMPACT

8.1. Introduction

As the natural world is continually developed and the climate changes, water resources face new challenges, including an increase in polluted-runoff resulting from more frequent and intense storm events. Thus, stormwater management design and implementation have become a required and vital component of construction and post-construction site plans. Concurrently, stormwater regulations have become more stringent, outlining specific water quality or quantity benchmarks to be met on a site. The research described in this dissertation focused on the scientifically-designed performance evaluations for commonly implemented stormwater strategies. Various existing performance evaluation methods were described, and additional analysis included a cost assessment, an important factor in project planning and management for construction operators. Further research included in this dissertation investigated and provided improvements for an alternative, in-channel sediment basin that utilizes existing site channels to treat sediment-laden stormwater. Improvements included structural and chemical treatments. Finally, a large-scale testing methodology was developed to evaluate outlet structures for post-construction implementation.

8.2. Conclusions and Impact

This section summarizes the conclusions of the research investigated and reported in this dissertation. In addition to this dissertation, findings from this research have, and continue to be, disseminated in comprehensive reports, technology transfers, and peer-reviewed journals. The dissemination of these findings is anticipated to provide the stormwater industry with practical and implementable designs that have been evaluated and validated through scientific, repeatable testing methods.

8.2.1. Performance and Cost Assessments of Erosion and Sediment Control Technologies and Implementation

The second chapter cataloged the existing erosion and sediment control research, testing methods, and cost metrics associated with the industry to fulfill the first two objectives of this dissertation. The emergence of E&SC research initially began in the early 2000s and was conducted through field-testing methods; however, the dynamics of a developing construction site presented challenges for attributable and replicable practice evaluations. There has since been a shift to controlled testing, with AU-SRF significantly contributing to the existing E&SC knowledge base. This chapter documents development and capabilities of the AU-SRF Expansion to continue promoting the mission of environmental stewardship. Although E&SC testing methods are continually developed and advanced at the AU-SRF and similar facilities, the evaluations often focus primarily on performance and exclude the cost associated with implementation.

A thorough cost assessment of the implemented practices, or industry, has not been conducted for nearly two decades. The current cost information has not been adjusted for inflation applied to materials, labor, or mobilization. This chapter included a case study on ditch checks, which outlined a method to assess the cost-benefit of enhanced practices implemented in the field. Silt fence and wattle ditch check installations, tested using large-scale methods, were evaluated for sediment retention and structural observations on an active site. Cost estimates for each practice were estimated by summing the cost of each design component based on specifications. The estimated cost was divided by the average sediment retention, creating a metric of cost per volume. This metric allows construction operators, such as cost-conscious departments of transportation to compare E&SC based on cost and performance. In the case study, an enhanced silt fence ditch check cost 15% more than the standard design but retained 400% more sediment. Ultimately, the cost per volume was 28% of the standard design. The nature of this comparison provides designers and operators with information when assessing the SWPPP performance, resource preservation, and project budget.

Additionally, estimated costs were used to develop an Excel tool titled, *CheckSpread. CheckSpread* accepts user-input channel geometries and desired ditch check type to provide spacing, quantity, and cost estimates. *CheckSpread* is intended to aid designers by selecting ditch checks considering channel characteristics and cost. While CheckSpread currently includes cost estimates from early 2020 for wattle, silt fence, and rock ditch check installations, the tool could be updated and customized. The framework, including methods for cost estimation and ditch check design principles, is included to guide the development of a similar tool. It is expected that the methodology presented will aid additional state agencies and designers in developing similar tools for ease in design and proper implementation, based on the design principles validated through E&SC research.

8.2.2. In-Channel Sediment Basin Performance Improvements through Large-Scale Testing

Traditional sediment basins are designed with an excavated pond with dead and live storage volume designations and have exhibited up to 90% capture of suspended solids in controlled research studies (*Fennessy and Jarrett 1997, Bidelspach et al., 2004*, *Perez et al., 2016*). However, an alternative sediment basin design, relying on existing site conveyance structures, has been implemented on sites. As a result of the use of existing infrastructure, installation time and costs are reduced. In-channel basins provide an opportunity to maximize length-to-width flow ratios but lack performance-based design. Results from field monitoring indicated that the in-channel basins had negligible treatment in the field during active construction; however, the dynamics of the site made it difficult to define the cause. It was suspected that channel and basin erosion added to the sediment load, lacking maintenance resulted in resuspension of previously settled material, and inadequacies in the dewatering system caused increased turbidity at basin discharge. Additionally, the basin sizing and installation failed to consider contributing drainage areas and relied heavily on ditch checks and perimeter controls to provide additional storage. Field findings indicated that upstream practices failed, contributing additional flow and sediment loads to the basin. While these field observations were essential to understanding a real-world site and case study, they also highlighted the need for large-scale, reproducible sediment basin testing techniques to improve current practice and field performance

The third objective of this dissertation was achieved by developing a large-scale in-channel sediment basin to evaluate water quality and sediment retention performance in response to structural sediment basin treatments. Structural treatments included (1) geotextile lining, (2) a floating surface skimmer, (3) porous flow baffles, and (4) an upstream forebay. The components were installed individually and as a system. The evaluated system with the best sediment retention and turbidity reduction performance included a geotextile liner, forebay, and skimmer. Baffles were not included in the system due to installation costs, effort, and maintenance challenges.

The geotextile liner stabilized the channel to reduce erosion within the channel. With the use of a skimmer, dewatering can occur over an extended period to promote settling, decrease discharge rates, alleviate pressure applied to receiving waters, and provide additional stormwater storage for subsequent storms. The forebay created detention to capture rapidly settable solids and increased the storage volume by nearly 33%. The forebay was accessibly located to ease cleanout requirements and extend times between basin dredging. This alternative basin design captured up to 96% of the sediment introduced and reduced discharge turbidity by nearly four times compared to the unlined standard. This research is expected to provide an alternative basin design backed by performance data from large-scale testing.

8.2.3. Upstream Flocculant and Downstream Impacts

Following the performance evaluations of the sediment basin in response to the structural components, flocculant blocks were added to the inflow channel, and water quality and sediment retention were quantified, satisfying the fourth objective of this dissertation. In total, 13 flocculant products were applied to sediment-laden samples. The sediment used in the samples was Iowa-native soil to ensure an appropriate product was selected for application in large-scale testing. Based on the designated point system, three flocculants received 31 points. Another three products received 30 points. Although all of these products would have likely provided similar results, the product eventually used in large-scale testing was selected based on the availability in block form, the desired application mechanism of the research sponsor.

Sediment retention in the system increased by 2% when flocculant was used, and the D_{50} decreased by nearly 50% in all areas of the basin, validating that the finer particles can be captured when flocculant is applied. The turbidity was significantly reduced when flocculant was applied in the basin. The estimated turbidity reduction was significanly more with flocculant, based on a linear regression model comparing the MFE-I and MFE-I + Flocculant. Flocculant had a coefficient of 0.42 in the model. Residual concentrations were measured following the methods outlined by Kazaz et al., (*2022)* to ensure there would not be harmful downstream effects if this flocculant was applied on site. At discharge, residual concentration never exceeded 8 mg/L but averaged 6 mg/L. Due to the product's low solubility, the MSDS indicated it was unlikely to be toxic to aquatic life even at high concentrations.

The findings of this research are expected to provide an example of the water quality benefits and serve as scientific-based evidence for the adoption of flocculant in construction stormwater management. While the method for detection of residual concentration is attributed to Kazaz et al., (*2022)*, this research effort provides evidence that, if properly dosed, flocculant sorbs to the aggregated particles and drops from suspension rather than being discharged to receiving waters. The detected concentrations in this study would not be harmful to receiving waters by the metrics provided in the manufacturer's safety data sheets (MSDS).

8.2.4. In-Channel Sediment Basin Design Tool

A spreadsheet-based tool was developed to aid in implementing in-channel sediment basins and the various structural and components that enhanced sediment capture and turbidity reduction, as indicated through large-scale testing results. The development of this tool satisfied the fifth objective of this dissertation, to provide design guidance for the implementation of in-channel sediment basins. Users are prompted to input basin geometry and desired dewatering systems to determine detention volume and discharge characteristics and are provided with skimmer size selection, orifice diameter, plots of the channel cross-section at the earthen berm, stage-storage curve, and stage-discharge curve for design tables and reports. Additionally, the tool recommends if flocculant should be applied. Flocculant application is suggested if less than 80% of the sediment load is predicted to settle within the desired dewatering time, determined by a user-input soil gradation.

The tool allows designers to size an in-channel sediment basin within a particular channel environment and evaluate the discharge from various mechanisms. Three dewatering systems are considered in the basin- a rock spillway, a traditional perforated riser, and a Faircloth skimmer. The rock spillway option allows designers to determine the volume and discharge of detention behind a rock check dam, considered a forebay in large-scale testing. Additionally, this outlet type allows the tools to be applied to silt basins, which were highly relied upon in the Tama U.S. 30 case study referenced in this dissertation.

8.2.5. Post Construction Stormwater and Smart Stormwater Systems

In addition to construction stormwater management, there has been a surge of low-impact development design to minimize the impact of development on receiving waterways in a catchment. Like construction stormwater management, specifications for low-impact development vary between states. In Alabama, a practice must capture 80% of TSS from the runoff resulting from the first 1.0 to 1.5 in. (2.5 to 3.8 cm) of rainfall, or the first flush event. Although the International Stormwater BMP Database provides industry-recognized TSS reduction data for several traditional LID practices, emerging LID systems lack performance data. This research's final objective was satisfied by creating and calibrating a large-scale detention system to install and evaluate emerging post-construction outlet systems.

The system's calibration at the AU-SRF required 35 lb (16 kg) of sediment to be introduced with 2,700 ft^3 (76 m^3) to achieve a target concentration between 100-300 mg/L. The control outlet, before device installation, consisted of a 0.70 in. (1.78 cm) orifice to achieve a dewatering rate of 0.16 ft^3/s (0.020 m^3/s) over 48 hours. TSS was observed and reported over time, but the mass balance analysis was relied on to quantify sediment retention in the system. Next, the evaluated outlet structure, such as the AFC, will be installed and evaluated. Performance evaluations may highlight the need for technological improvements or help validate models, which will inform water quality and quantity benefits locally, or in a catchment when smart stormwater systems are implemented.

8.3. LIMITATIONS AND RECOMMENDED FURTHER RESEARCH

The section describes the limitations and important considerations for the research included in this dissertation. Additional research concepts are introduced that may expand or strengthen the existing knowledge base.

8.3.1. Performance and Cost Assessments of Erosion and Sediment Control Technologies and Implementation

The cost estimate was developed considering the geometry of the depressed highway median described. Quantity discrepancies between materials estimated and installed on-site may exist. Researchers were not responsible for field installations, and installations could have deviated from design; however, based on inspection, differences were minor and did not affect the performance and field monitoring of the practices. Multiple replicates of the standard and modified practices were installed on-site for repeatable results but had varying topography, contributing areas, soil type, etc. The labor cost analysis relies heavily on the cost difference between the reported, all-inclusive DOT cost and estimated raw material cost. Estimated silt fence labor costs are meager. It is speculated that when silt fence materials are purchased in bulk for such a large construction site, material costs may be decreased, allocating more funds to labor. While the modified silt fence ditch check installation is more involved than the standard design, the material length requirement decreases by 50%, driving costs down. Combined cost estimates and field performance provide general trends for the ditch checks installed on the Iowa DOT site.

Future research may consider an exact bill of materials upon installation and track the performance of each installation. Additional efforts to track functionality, maintenance, and replacements on the evaluated practices would add to the existing knowledge base. Literature regarding current E&SC spending, particularly on highway construction sites, should be updated and expanded to inform state agencies and their constituents.

8.3.2. In-Channel Sediment Basin Performance Improvements through Large-Scale Testing

The findings from the large-scale testing effort are limited by the flow and sediment introduction rates subjected to the basin. The evaluations were conducted under known flow and sediment introduction rates based on historical data; however, storm intensities and frequencies are increasing due to a changing climate. The field performance of the tested basin configurations will likely vary based on these factors. The AU-SRF in-channel sediment basin was 3,031 ft^3 (86 m^3) and was determined to represent a 0.84 ac (0.34 ha) treatment area. Sediment basins may treat up to 10 drainage acres, and the configuration, particularly the skimmer, may need to be adjusted to dewater the required increased volume.

Despite evaluating an Iowa DOT design, the large-scale in-channel sediment basin testing was conducted in Alabama. Although Iowa-native soil was used for the majority of the controlled testing, the subgrade of the basin was Alabama site soil. The standard basin specification did not include a liner; therefore, the subgrade was exposed during control testing. Soil erodibility should be accounted for, as it affects the channel erosion behavior and thus additional sediment load. Future controlled testing may account for the variability in soil erodibility in in MUSLE calculations. Site soil was also used for sediment introduction in unlined and lined large-scale testing configurations. Soil gradations indicated the Iowa- and Alabama- native soils were similar in coarse sand and fine silt and clay fractions but different in fine sands and coarse silts fractions. Sand fractions above 0.85 mm or the #20 sieve, and below 0.02mm, were within 5% of one another. Differences in gradation likely affected the suspension and settling behaviors. Although the staged testing regimen allowed the comparisons to build on one another, it was difficult to compare large-scale testing results to the pilot field-monitoring effort. Part of the performance of the in-channel sediment basin will be dependent on site soil characteristics.

Additionally, sediment retention was measured using a combination of volume and weight, which allowed for moisture corrections. Sediment quantification was manageable when the geotextile liner was installed, separating settled material from the subgrade; however, the methods did not apply to standard installation testing when a liner was not installed. Instead, a survey was conducted pre-and post- series. When the surveys were compared, sediment retention results indicated that more sediment was retained than introduced due to the swell of the soil. Since standard testing was conducted during the winter, the soil never dried enough to get accurate results. Although sample depth measurements and moisture contents were recorded and applied for correction, the sediment retention results for the standard test were skewed. Instead, turbidity reduction was compared to classify the performance.

The MFE-I design should be installed on-site, monitored, and compared to results from the pilot study in another phase of the project. Additionally, upstream ditch checks should be installed, and the system should be analyzed holistically to understand the treatment train.

8.3.3. Upstream Flocculant Application

Although sediment-laden samples were dosed with various flocculants at the bench scale, only one PAM product was selected for the large-scale sediment basin testing. Although PAM is widely applied in construction stormwater management, turbidity reduction and sediment grain-size capture are highly dependent on the interaction of a particular flocculant and site soil. Results from this study may be used as an example of sediment retention and water quality benefits if the appropriate flocculant is selected; however, the bench-scale evaluation is essential for selection.

Sediment retention and turbidity reduction may not be reproducible if another flocculant, soil type, or application mechanism is used. In this study, three flocculant products received the same number of points with 31 points. Another three products received 30 points. Although one product was selected for large-scale testing based on its block form, real-world site constraints such as cost and availability may benefit from selecting various, similarly-performing products. Further testing should include a sensitivity analysis to understand the water quality impact of using flocculants with certain point designations

In this testing, flocculant blocks were used to dose sediment-laden inflow with flocculant. Flocculant blocks are easily applied, but tracking the concentration of flocculant applied to the inflow was challenging. Additional lab-based research is suggested to examine degradation, estimate dosed concentrations, and determine flocculant blocks' longevity and maintenance requirements. Additional research may be conducted using controlled flow, sediment introduction, and environmental chambers to emulate changing site weather and drying conditions.

The residual concentration determination was conducted following the methods of Kazaz et al., (*2022)* for field detection; however, the methods are observational based on settling gradient, timing, and results likely vary based on the executor of the procedure. Additionally, a specific soil was required for the analysis. Since inflow concentration was challenging to track due to the application mechanism, residual concentration comparisons were impossible.

8.3.4. In-Channel Sediment Basin Design Tool

The spreadsheet-based tool is anticipated to help in the adoption of in-channel sediment basin and several of the structural and chemical components tested through the large-scale testing efforts described in this dissertation. The outputs of this tool are expected to aid communication in design and installation. The tool is currently limited to a trapezoidal channel geometry.

Additionally, the dewatering systems are limited. Although numerous skimmer systems exist, the current tool only considers the design parameters from Faircloth (2007). Future iterations of this tool may also allow the skimmer type to be selected for dewatering comparisons. Cost comparison between skimmers of similar sizing and drawdown time may also be included.

Although additional spillway geometries exist for forebay and auxiliary spillway design, the rock spillway is considered a broad-crested weir. Currently, a designer would need to conduct at least two iterations in the tool if a rock check dam was being implemented to create a forebay upstream of a detention basin. Further improvements to the tool may include the forebay into the basin design. Similarly, the current tool only recommends if flocculant should be applied; however, Kazaz (2022c) created a tool to aid in flocculant selection. These tools may be linked in the future, and a flocculant recommendation may be based on soil type from benchmark soils if determined to be applicable through testing.

8.3.5. Post Construction Stormwater and Smart Stormwater Systems

The basin designed to evaluate post-construction outlet structures at the AU-SRF is completely lined with an impervious plastic liner, eliminating the effects of infiltration expected on a site. The current methodology evaluates the water quality improvements under the designated filling and sediment concentration conditions. However, systems like the Flood-Con's Patented Automated Flood Control (AFC) adjust and release detained flow based on a site's measured rainfall and local hydrologic parameters. The system may be monitored over a staged-testing series to evaluate the water quality at various inflow, release rates, and detention times. Similarly, the outlet control structures may also be monitored in series to understand impacts on a catchment if multiple devices are installed. TSS reduction may be achieved singularly or as a system. While TSS is observed and reported over the testing time, mass balance is used to report sediment retention in the basin due to the outlet structure. The current methodology is expected to provide performance evaluation results to appropriately design and install smart stormwater systems.

8.4. Acknowledgments

This research is based on studies sponsored by the Iowa Department of Transportation, Flood-Con, and Faircloth Skimmer. The author gratefully acknowledges this financial support. The findings, opinions, and conclusions expressed in this dissertation are those of the author and do not necessarily reflect the views of the sponsors.

9. REFERENCES

1. About AU-ESCTF. 2021. Samuel Ginn College of Engineering, Research Centers, Auburn University Erosion and Sediment Control Test Facility. https://www.eng.auburn.edu/research/centers/auesctf/about-us/index.html. Accessed July 1st, 2021.

2. Alabama Department of Environmental Management and Alabama Cooperative Extension System. 2017. Low Impact Development Handbook for the State of Alabama. Auburn, AL.

3. Albert, J. R. 2001. "Designing Sedimentation Basins for Better Sediment Capture." Soil Erosion Research for the 21st Century, Proc. Int. Symp. Honolulu, HI.

4. ALDOT. 2020. Standard and Special Drawings for Highway Construction. Alabama Department of Transportation. Montgomery, AL.

5. American Public Health Association, American Water Works Association, and Water Environment Federation. 1999. Standard Methods for the Examination of Water and Wastewater. Washington, D.C.

6. ASTM Standard D7208-06. 2006. Standard Test Method for Determination of Temporary Ditch Check Performance in Protecting Earthen Channels from Stormwater-induced Erosion. ASTM International, West Conshohocken, PA.

7. ASTM Standard D7351-07. 2007. Standard Test Methods for Determination of Sediment Retention Device Effectiveness in Sheet Flow Applications. ASTM International, West Conshohocken, Pa.

8. ASTM Standard D6459-15. 2015. Standard Test Method for Determination of Rolled Erosion Control Product Performance in Protecting Hillslopes from Rainfall-Induced Erosion; ASTM: West Conshohocken, PA, USA.

9. ASTM Standard C136-01. 2017. Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM International, West Conshohocken, Pa.

10. ASTM Standard D5141-11. 2018. Standard Test Method for Determining Filtering Efficiency and Flow Rate of the Filtration Component of a Sediment Retention Device. ASTM International, West Conshohocken, PA.

11. ASTM Standard D4318-17e1. 2018. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International. West Conshohocken, PA, USA.

12. ASTM Standard D3977-97(2019). 2019. Standard Test Methods for Determining Sediment Concentration in Water Samples. ASTM International. West Conshohocken, PA, USA.

13. ASTM Standard D7928-21e1. 2021. Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. ASTM

International, West Conshohocken, PA.

1. Barfield, B. J., and M. Clar. 1985. Development of New Design Criteria for Sediment Traps and Basins. Maryland Resource Administration. Annapolis, MD.

2. Basham, D. L., Zech, W. C., Donald, W. N., and M. A. Perez. 2019. “Design and Construction of Full-Scale Testing Apparatus for Evaluating Performance of Catch Basin Inserts.” ASCE Journal of Sustainable Water in the Built Environment, 5(1). doi.org/10.1061/JSWBAY.0000868.

3. Bhattarai R., Kalita, P., Garcia, C. B. and P. Schumacher. 2016. Evaluation of Ditch Checks for Sediment Retention. Illinois Center for Transportation. Rantoul, IL.

4. Bidelspach, D. A. and A. R. Jarret. 2004. Electro-mechanical outlet flow control device delays sediment basin dewatering. Applied Engineering in Agriculture 20: 759-763.

5. Bidelspach, D. A., and A. R. Jarrett, et al., 2004. Influence of increasing the delay time between the inflow and outflow hydrographs of a sediment basin.Transactions of the American Society of Agricultural Engineers 47: 439-444.

6. Boyd, C. E., and F. Lichtkoppler. 1979. “Turbidity and Color.” Water Quality Management in Pond Fish Culture. International Center for Aquaculture Agricultural Experiment Station, Auburn, AL.

7. Bugg, R. A., Donald, W. N., Zech, W. C., and M. A. Perez. 2017. “Improvements in Standardized Testing for Evaluating Sediment Barrier Performance: Design of a Full-Scale Testing Apparatus.” ASCE Journal of Irrigation and Drainage Engineering, 143 (8) doi.org/10.1061/(ASCE)IR.1943-4774.0001194

8. Bugg, R., Donald, W. N., Zech, W. C., M. A. Perez. 2017. “Performance Evaluations of Three Silt Fence Practices Using a Full-Scale Testing Apparatus.” Water, 9(7):502. doi.org/10.3390/w9070502.

9. Carolina Hydrologic. 2016. HydroFlocFlat 5 lb Material Safety Data Sheet. Charleston, SC.

10. Chapman, J. M., Proulx, C. L., Veilleux, M. A. N., Levert, C., Bliss, S., Andre, M., Lapointe, N. W. R., and S. J. Cooke. 2014. “Clear as mud: A meta-analysis on the effects of sedimentation on freshwater fish and the effectiveness of sediment-control measures.” Water Research.

11. Chen, C. N. 1975. Design of Sediment Retention Basins. National Symposium on Urban Hydrology and Sediment Control. Lexington, KY.

12. City of Clive. 2019. Clive Stormwater Management Manual. Clive, IA.

13. City of Detroit Water and Sewage Department. 2019. Stormwater Management Design Manual. Detroit, MI.

14. City of Omaha. 2021. Post Construction Stormwater Management Planning Document. Omaha, NE.

15. Donald, W. N., Zech, W. C., Perez, M. A., and X. Fang. 2013. "Ditch Check Installation Evaluations of Wheat Straw Wattles Used for Velocity Reduction." Transportation Research Record, 2358(1): 69-78. doi.org/10.3141/2358-08.

16. Donald, W. N., Zech, W. C., and X. Fang. 2014. "Comparative Evaluation of Wattle Ditch Checks Composed of Differing Materials and Properties." ASCE Journal of Irrigation and Drainage Engineering, 142(2). doi.org/10.1061/(ASCE)IR.1943-4774.0000794.

17. Donald, W. N., Zech, W. C., Perez, M. A., and X. Fang. 2015. "Evaluation and Modification of Wire-Backed Nonwoven Geotextile Silt Fence for Use as a Ditch Check." ASCE Journal of Irrigation and Drainage Engineering, 141(2). doi.org/10.1061/(ASCE)IR.1943-4774.0000959.

18. Donald W. N., Zech, W. C., Fang, X., and M. A. Perez. 2016. "A Hydraulic Method to Evaluate the Performance of Ditch Check Practices and Products." ASCE Journal of Hydrologic Engineering, doi.org/10.1061/(ASCE)HE.1943-5584.0001311.

19. Fang, X., Zech, W. C., and C. P. Logan. 2015. "Stormwater field evaluation and its challenges of a sediment basin with skimmer and baffles at a highway construction site." Water, 7(7):3407–30. doi.org/10.3390/w7073407

20. Federal Reserve Bank of Minneapolis. 2022. Inflation Calculator. https://www.minneapolisfed.org/about-us/monetary-policy/inflation-calculator Accessed March 21, 2022.

21. Fennessey, L. A. J. and A. R. Jarrett (1997). Influence of principal spillway geometry and permanent pool depth on sediment retention of sedimentation basins. Transactions of the American Society of Agricultural Engineers 40: 53-59.

22. Fifield, J. S. 2015. Designing effective sediment basins and traps. Part 1: The myth of capturing 3, 600 cubic feet per acre. Stormwater, Forester Press, Santa Barbara, CA.

23. Finnegan, E. J., and J. B. Franzini. 2002. Fluid Mechanics with Engineering Applications. McGraw Hill. New York, NY.

24. Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J. L. and P. S. Mikkelsen. 2015. "SUDS, LID, BMPs, WSUD and more–The evolution and application of terminology surrounding urban drainage." Urban water journal,12(7), pp.525-542. doi.org/10.1080/1573062X.2014.916314

25. Goldman, S. J., Jackson, K., and T. A. Bursztynsky. 1986. Erosion and Sediment Control Handbook, McGraw-Hill, New York, NY.

26. Gogo-Abite, I. and M. Chopra. 2013. "Performance evaluation of two silt fence geotextiles using a tilting test-bed with simulated rainfall." Geotextiles and Geomembranes, 39:30–8. doi.org/10.1016/j.geotexmem.2013.07.001.

27. Hawley, R. J., and G. J. Vietz. 2016. "Addressing the urban stream disturbance regime." Freshwater Science 35, no. 1, pp. 278-292. doi.org/10.1086/684647

28. Hazen, A. 1904. "On Sedimentation." Transactions of ASCE, Vol. 53, No. 980, pp. 45–88.

29. Iowa Department of Natural Resources. 2018. Understanding Impaired Waters. Des Moines, IA.

30. Iowa Department of Transportation. 2019. Design Manual, Cross-Sections. Ames, IA.

31. Iowa Department of Transportation. 2017. Standard Road Plan Erosion Control Standards. Ames, IA.

32. Iowa Statewide Urban Design and Specifications. 2020. Iowa SUDAS Design Manual. Iowa State University, Ames, IA.

33. International Erosion Control Association. 2021. Temporary Sediment Basin Standard. Aurora, CO.

34. International Stormwater BMP Database. 2016. BMP Database Summary Statistics. Denver, CO.

35. Jarrett, A.R. 2001. Designing Sedimentation Basins for Better Sediment Capture. ASABE Soil Erosion Research for the 21st Century. Honolulu, HI.

36. Johnson, A. K., Claman, D. R., and J. A. Christiansen. 2017. Tama County Grading Plans. Iowa Department of Transportation. Ames, IA.

37. Julien, P. Y. 2018. River Mechanics: 2nd Editions. Cambridge University Press. doi.org/10.1017/9781316107072.

38. J.W Faircloth & Son Inc. 2007. Determining the Skimmer Size and the Required Orifice for the Faircloth Skimmer Surface Drain. Hillsborough, NC.

39. Kang, J., King, S., and R. A. Mclaughlin. 2014. "Sediment Basin Design Criteria for Flocculated Sediment." Transactions of the ASABE, Vol. 7004, pp. 861–867.

40. Kang, J., King, S. E., and R. A. McLaughlin. 2015. "Flocculated Sediments Can Reduce the Size of Sediment Basin at Construction Sites." Journal of Environmental Management, Vol. 166, 2016, pp. 450–456. doi.org/10.1016/j.jenvman.2015.10.049

41. Kaufman, H. M. 2000. "Erosion Control at Construction Sites: The Science–Policy Gap." Journal of Environmental Management. 26(1) 89–97. doi.org/10.1007/s002670010073

42. Kazaz, B., Poddar, S., Arabi, S., Perez, M. A., Sharma, A., and J. B. Whitman. 2021. “Deep Learning-Based Object Detection for Unmanned Aerial Systems (UAS) Based Inspections of Construction Stormwater Practices.” Sensors. doi.org/10.3390/s21082834.

43. Kazaz, B., Perez, M. A., and W. N. Donald. 2021. “State-of-the-Practice Review on the Use of Flocculants for Construction Stormwater Management in the United States.” Transportation Research Record, 2675(7):248-258. doi.org/10.1177/0361198121995192.

44. Kazaz, B., Schussler, J. C., Dickey, L. C., and Perez, M. A. 2022. Soil Loss Risk Analysis for Construction Activities, Transportation Research Record. doi.org/10.1177/03611981221075027.

45. Kazaz, B., Perez, M. A., Donald, W. N., Fang, X., J. N. Shaw. 2022. “Detection of Residual Flocculant Concentrations in Construction Stormwater Runoff.” Transportation Research Record. doi.org/10.1177/03611981221077985.

46. Kazaz, B. 2022. “Improvements in Construction Stormwater Treatment Using Flocculants” [Doctoral Dissertation Under review]. Auburn University. Auburn, AL

47. Kerkez, B., Gruden, C., Lewis, M., Montestruque, L., Quigley, M., Wong, B., Bedig, A., Kertesz, R., Braun, T., Cadwalader, O. and A. Poresky. 2016. “Smarter stormwater systems.” Environmental Science & Technology, 50 (14), 7267-7273 doi.org/10.1021/acs.est.5b05870.

48. Lake, D. W. 2016. Cost Analysis of Erosion and Sediment Control Practices, Appendix C. New York State Standards and Specifications for Erosion and Sediment Control. Albany, NY.

49. Landphair, H. C., Mcfalls, J. A., Peterson, B. E., and M. Li. 1997. Alternatives to Silt Fence for Temporary Sediment Control at Highway Construction Sites: Guidelines for TXDOT. Austin, TX.

50. Li, J., Burian, S. and C. Oroza. 2019. “Exploring the potential for simulating system-level controlled smart stormwater system.” In World Environmental and Water Resources Congress. American Society of Civil Engineers. pp. 46-56. Reston, VA.

51. Liu, L., Perez, M. A., and J. B. Whitman. 2020. “Evaluation of Lamella Settlers for Treating Suspended Sediment.” Water. doi.org/10.3390/w12102705.

52. Liu, L., Perez, M. A., Whitman, J. B., and W. N. Donald. 2021. “SILTspread: Performance-Based Approach for the Design and Installation of Silt Fence Sediment Barriers.” ASCE Journal of Irrigation and Drainage Engineering, 147(10). doi.org/10.1061/(ASCE)IR.1943-4774.0001608.

53. Mallin, M. A., Johnson, V. L. and Ensign, S. H. 2009. “Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream.” Environmental monitoring and assessment, 159(1), pp.475-491. doi.org/10.1007/s10661-008-0644-4

54. Mullapudi, A., Wong, B. P. and B. Kerkez. 2017. “Emerging investigators series: building a

theory for smart stormwater systems." Environmental Science: Water Research & Technology, 3(1), pp.66-77. doi.org/10.1039/C6EW00211K

55. McCaleb, M. M., and R. A. Mclaughlin. 2008. "Sediment Trapping by Five Different Sediment Detention Devices on Construction Sites." Transactions of the ASABE, Vol. 51, No. 5, pp. 1613–1621.

56. McLaughlin, R. A., King, S. E., and G. D. Jennings. 2009. "Improving Construction Site Runoff Quality with Fiber Check Dams and Polyacrylamide." Journal of Soil and Water Conservation, 64(2), 144–154. doi.org/10.2489/jswc.64.2.144.

57. McLaughlin R.A., Hayes, S. A., Clinton, D. L., McCaleb, M. S., G. D. Jennings. 2009. "Water Quality Improvements Using Modified Sediment Control Systems on Construction Sites." Transactionsof the ASABE, Vol. 52, No. 6, pp. 1859–1867.

58. McLaughlin, R. A., Rajbhandari, N., Hunt, W. F., Line, D. E., Sheffield, R. E., and N. M. White. 2013. "The Sediment and Erosion Control Research and Education Facility at North Carolina State University." Presented at Soil Erosion Research for the 21st Century. doi.org/10.13031/2013.3197.

59. Millen, J. A., Jarrett, A. R., and J. W. Faircloth. 1997. "Experimental Evaluation of Sedimentation Basin Performance for Alternative Dewatering Systems." American Society of Agricultural Engineers,Vol. 40, No. 4, pp. 1087–1095.

60. Mitchell, G. F., Shad M. S., and T. Masada. 1991. "Erosion and Sediment Control Practices in Highway Construction." Presented at Erosion Control: A Global Perspective, International Erosion Control Assn. Proceedings of Conference XXII, Orlando, Florida USA, Feb. 20-22, 1991, pp. 57-67.

61. Mitchell, G. F., Guo, T., and N. Igiz. 2003. "How Much Does Erosion and Sediment Control for DOT Projects Cost?" Stormwater.

62. NCEES. 2020. FE Reference Handbook 10.0.1. ISBN: 978-1-947801-11-0.

63. NCDENR. 2019. NCDENR Stormwater BMP Manual. Raleigh, NC.

64. NDOT. 2015. Erosion & Sediment Control Design and Construction Manual. North Carolina Department of Transportation. Raleigh, NC.

65. NJ DEP. 2004. New Jersey Stormwater Best Management Practices Manual. Trenton, NJ.

66. Ohio EPA. 2013. General Permit Authorization for Stormwater Discharges Associated with Construction Activity Under the National Pollutant Discharge Elimination System. Columbus, OH.

67. ODOT (Ohio Department of Transportation) 2016. Standard Hydraulic Construction Drawing: Catch basin No. 3A. Columbus, OH.

68. ODOT (Ohio Department of Transportation). 2018. Vol. 2 of Location & Design manual. Columbus, OH.

69. Perez, M. A., Zech W. C., Donald, W. N., and X. Fang. 2015. “Methodology for Evaluating Inlet Protection Practices Using Large-Scale Testing Techniques.” ASCE Journal of Hydrologic Engineering, 20(4). doi.org/10.1061/(ASCE)HE.1943-5584.0001019.

70. Perez, M. A., Zech, W. C., Donald, W. N., and X. Fang. 2015. “Installation Enhancements to Common Inlet Protection Practices Using Large-Scale Testing Techniques.” Transportation Research Record, 2521: 151–161. doi.org/10.3141/2521-16

71. Perez, M. A., Zech, W. C., Donald, W. N., and X. Fang. 2016. “Design Methodology for the Selection of Temporary Erosion and Sediment Control Practices Based on Regional Hydrological Conditions.” ASCE Journal of Hydrologic Engineering, 21(4). doi.org/10.1061/(ASCE)HE.1943-5584.0001328.

72. Perez M. A., Zech, W. C., and W. N. Donald. 2015. “Using Unmanned Aerial Vehicles to Conduct Site Inspections of Erosion and Sediment Control Practices and Track Project Progression.” Transportation Research Record, 2528(1):38-48. doi.org/10.3141/2528-05.

73. Perez, M. A., Zech, W. C., Donald, W. N, and X. Fang. 2016. “SEDspread: A Sediment Basin Design Tool for Construction Sites.” ASCE Journal of Irrigation and Drainage Engineering, 142(12): 04016064-1-11. doi.org/10.1061/(ASCE)IR.1943-4774.0001099.

74. Perez, M. A., Zech, W. C., Fang, X., and J. G. Vasconcelos. 2016. “Methodology and Development of a Large-Scale Sediment Basin for Performance Testing.” ASCE Journal of Irrigation and Drainage Engineering, Vol. 142, No. 10, p. 04016042. doi.org/10.1061/(ASCE)IR.1943-4774.0001052

75. Perez, M. A. 2016. Improvements in the Design and Application of Erosion and Sediment Control Technologies for the Construction Industry. Auburn University. Auburn, AL.

76. Perez, M. A., Zech, W. C., Vasconcelos, J. G., and X. Fang. 2019. “Large-scale performance testing of temporary sediment basin treatments and high-rate lamella settlers.” Water, 11(2). doi.org/10.3390/w11020316.

77. Perez, M. A., Zech, W. C., Donald, W. N., Turochy, R., and B. G. Fagan. 2019. “Transferring Innovative Erosion and Sediment Control Research Results into Industry Practice.” Water, 11(12): 2549. doi.org/10.3390/w11122549

78. Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., and R. Blair. 1995. “Environmental and Economic Costs of Soil Erosion and Conservation Benefits.” Science, 264 (5201):1117–1123.

79. Pitt, R., Clark, S. E., & Lake, D. W. 2007. Construction site erosion and sediment controls: Planning, design and performance. DEStech Publications, Inc.

80. Ricks, M. D., Wilson, W. T., Zech, W. C., Fang, X., and W. N. Donald. 2020. “Evaluation of

Hydromulches as an Erosion Control Measure Using Laboratory-Scale Experiments." Water, 12 (515). doi.org/10.3390/w12020515.

81. Ricks, M. D., Horne, M. S., Faulker, B., Zech, W. C., Fang, X., Donald, W. N., and M. A. Perez. 2019 "Design of a Pressurized Rainfall Simulator for Evaluating Performance of Erosion Control Practices." Water, 11 (2386). doi.org/10.3390/w11112386.

82. Schussler, J. C., Perez, M. A., Cetin, B., and J. B. Whitman. 2020. "Field Monitoring of Erosion and Sediment Control Practices and Development of Additional Iowa DOT Design Manual Guidance." Final Report. Ames, IA.

83. Schussler, J. C., Kazaz, B., Perez, M. A., Whitman, J. B., and B. Cetin. 2021. "Field Evaluation of Wattle and Silt Fence Ditch Checks." Transportation Research Record. doi.org/10.1177/0361198121992073.

84. Schussler, J. C., Perez, M. A., Donald, W. N., Whitman, J. B., Zech, W. C., Fang, X., and B. Fagan. 2022. A Decade of Research in Review: The Auburn University Stormwater Research Facility, Transportation Research Record. doi.org/10.1177/03611981221076449.

85. Shishegar, S., Duchesne, S., Pelletier, G., and R. Ghorbani. "A smart predictive framework for system-level stormwater management optimization." Journal of Environmental Management, Volume 278, Part 1. 2021. doi.org/10.1016/j.jenvman.2020.111505.

86. Shoemaker, A. L., Zech, W. C., and T. P. Clement. 2012. "Laboratory-Scale Evaluation of Anionic Polyacrylamide as an Erosion and Sediment Control Measure on Steep-Sloped Construction Sites." Transactions of the ASABE, 55(3): 809-820.

87. Skogerboe, Dustin. 2020. Email to Jaime Schussler. 27 January 2020.

88. Tang, Z., Sharif, M., Lim, K. J., Engel, B. A., Choi, J., and K. M. Sullivan. 2004. "A Web-based DSS for Erosion Control Structure Planning." Applied Engineering in Agriculture, 20(5). doi.org/10.13031/2013.17451

89. TDOT. 2020. Erosion Prevention and Sediment Control. Tennessee Department of Transportation Standard Roadway Drawings. Nashville, TN.

90. The Technology Acceptance Reciprocity Partnership. 2003. Protocol for Stormwater BestManagement Practice Demonstrations.

91. Thaxton, C. S., Calantoni, J. and R. A. Mclaughlin. 2004. "Hydrodynamic Assessment of Various Types of Baffles in a Sediment Retention Pond." Transactions of the ASABE, Vol. 47, No. 3, pp. 741–750.

92. Troxel, C. F. 2013. Life Cycle Analysis of Sediment Control Devices. Georgia Institute of Technology. Atlanta, GA.

93. U.S. Department of Agriculture Forest Services. 2006. Erosion Control Treatment Selection Guide. Washington, D.C.

94. USDA. 1986. Urban hydrology for small watersheds TR-55. Technical Release. United States Department for Agriculture Soil Conservation Service, Washington DC.

95. USEPA. 1972. Guidelines for Erosion and Sediment Control Planning and Implementation. Washington, D.C.

96. USEPA. 1973. Comparative Costs of Erosion and Sediment Control, Construction Activities. Washington, D.C.

97. USEPA. 1992. Federal register. Final NPDES general permits for stormwater discharges from construction sites; notice. Washington, DC.

98. USEPA. 2005. National Management Measures to Control Nonpoint Source Pollution from Urban Areas. Washington, D.C.

99. USEPA. 2022. National Pollutant Discharge Elimination System Construction General Permit (CGP) for Stormwater Discharges from Construction Activities. Washington, D.C.

100. USEPA. 2020. Water Quality Assessment and TMDL Information. Washington, D.C.

101. USEPA. 2022 Stormwater Management Model. Washington, D.C.

102. USEPA. 2022 Green Infrastructure. Washington, D.C.

103. USEPA. 2005. National Management Measures to Control Nonpoint Source Pollution from Urban Areas. Washington, D.C.

104. Western Australia Water watch. 2011. Water Quality and Macroinvertebrates. East Perth, Perth, Australia.

105. Whitman, J. B., Zech, W. C, Donald, W. N., and J. J. LaMondia. 2018. "Full-Scale Performance Evaluations of Various Wire-Backed and Nonwoven Silt Fence Installation Configurations." Transportation Research Record. doi.org/10.1177/0361198118758029.

106. Whitman, J. B., Zech, W. C, and W. N. Donald. 2019. "Improvements in Small-Scale Standardized Testing of Geotextiles used in Silt Fence Applications." Geotextiles and Geomembranes. doi.org/10.1016/j.geotexmem.2019.04.002.

107. Whitman, J. B., Zech, W. C, and W. N. Donald. 2019. "Full-Scale Performance Evaluations of Innovative and Manufactured Sediment Barrier Practices." Transportation Research Record. doi.org/10.1177/0361198119827905.

108. Whitman, J. B., Perez, M. A., Zech, W. C, and W. N. Donald. 2020. "Practical Silt Fence Design Enhancements for Effective Dewatering and Stability." Transportation Research Record. doi.org/10.1177/0361198119827905.

109. Whitman, J. B., Schussler, J. C., Perez, M. A., L. Liu. 2021. "Hydraulic Performance Evaluation of Wattles used for Erosion and Sediment Control." ASCE Journal of Irrigation and Drainage. 147(7). doi.org/10.1061/(ASCE)IR.1943-4774.0001586.

110. Wossink, A., Mitasova, H., and R. A. McLaughlin. 2005. "The Cost Effectiveness of Standard and Alternative Sediment and Turbidity Control Systems on Construction Sites in North Carolina." Water Resources Research Institute of The University of North Carolina, Raleigh, N.C.

111. Wuebbles, D. J., Easterling, D. R., Hayhoe, K., Knutson, T., Kopp, R. E., Kossin, J. P., Kunkel, K. E., LeGrande, A. N., Mears, C., Sweet, W. V., Taylor, P. C., Vose, R. S., and M. F. Wehner. 2017. "2017: Our globally changing climate." In Climate Science Special Report: Fourth National Climate Assessment, Volume I, pp. 35-72. doi.org/10.7930/J08S4N35.

112. Zech, W. C., Halverson, J. L., and T. P. Clement. 2008. "Intermediate-Scale Experiments to Evaluate Silt Fence Designs to Control Sediment Discharge from Highway Construction Sites." ASCE Journal of Hydrologic Engineering, 13(6): 497-504. doi.org/10.1061/(ASCE)1084-0699(2008)13:6(497)

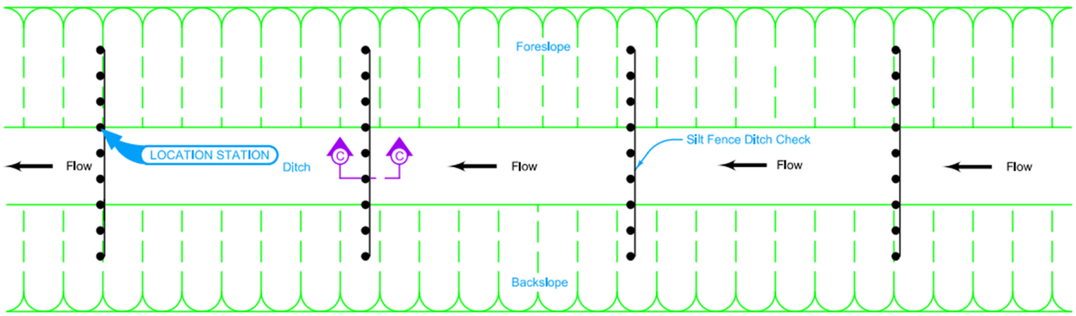
113. Zech, W. C., McDonald, J. S., and T. P. Clement. 2009. "Field Evaluation of Silt Fence Tieback Systems at a Highway Construction Site." ASCE Practice Periodical and Structural Design and Construction, 14 (3). doi.org/10.1061/(ASCE)1084-0680(2009)14:3(105).

114. Zech, W. C., Halverson, J. L., and T. P. Clement. 2007. "Development of Silt Fence Tieback Design Methodology for Highway Construction Installations." Transportation Research Record, 2011(1), 21–28. doi.org/10.3141/2011-03.

115. Zhu, T., Lund, J. R., Jenkins, M. W., Marques, G. F. and R. S. Ritzema. 2007. "Climate change, urbanization, and optimal long-term floodplain protection." Water Resources Research, 43(6). doi.org/10.1029/2004WR00351

10. APPENDICES

APPENDIX A
IOWA STANDARD HIGHWAY DRAWINGS FOR EROSION AND SEDIMENT CONTROL



PLAN FOR DITCH CHECK (TYPE 1) (12)

(1) Secure top of engineering fabric to steel posts using cable ties (50 lb.) or wire passing through or encompassing the belt. See attachment to post.

(2) For manual installation only, fold engineering fabric along bottom of trench.

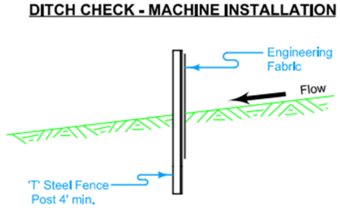
(3) Embed all posts 28 inches below the ground line.

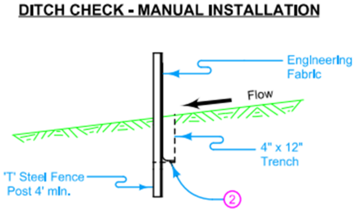
(4) Locate posts at toe of foreslope and toe of backslope and space remaining posts equally.

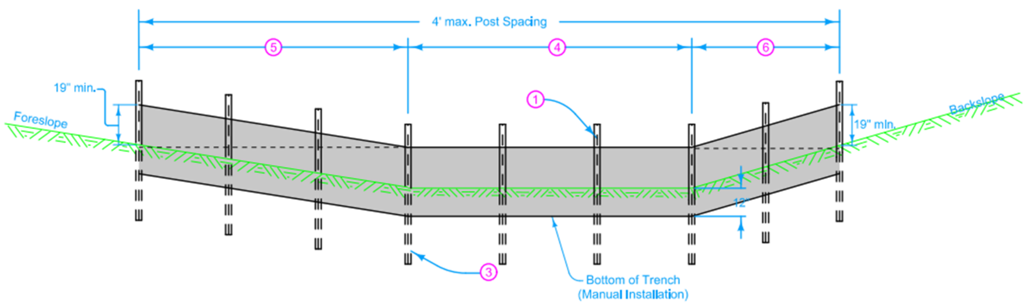
(5) Minimum end span (in feet) = 2 X Foreslope (H:V).

(6) Minimum end span (in feet) = 2 X Backslope (H:V).

(12) Refer to Tab. 100-18







FRONT VIEW

IOWADOT

STANDARD ROAD PLAN

REVISION	
5	10-15-19

EC-201

SHEET 2 of 6

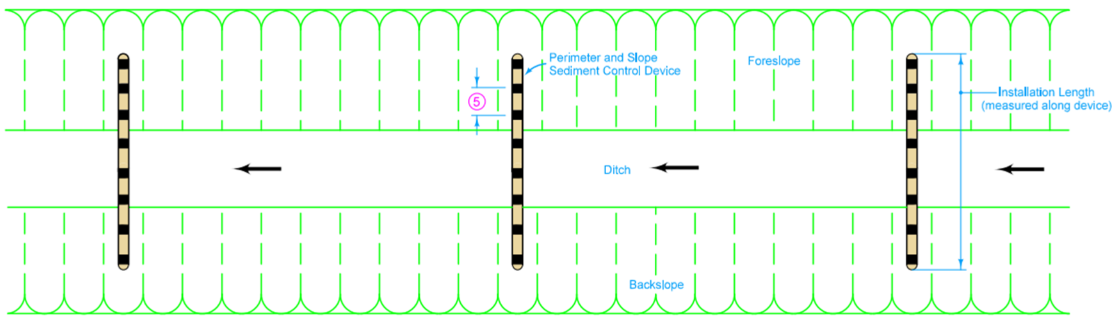
REVISIONS: Modified circle note 1.

APPROVED BY DESIGN METHODS ENGINEER

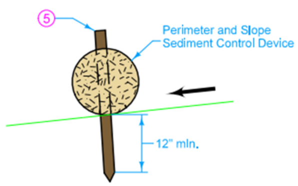
SILT FENCE

⑤ Space 1" X 1" wood stakes at 2 foot maximum spacing.

⑥ Install Ditch Protection perpendicular to ditch. Overlap joints per Detail 'A'.



DITCH PROTECTION ⑥



INSTALLATION IN DITCH

LEGEND

- Contour Lines
- Flow
- Wood Stake ⑤

IOWA DOT

STANDARD ROAD PLAN

REVISION	
3	04-18-17

EC-204

SHEET 3 of 3

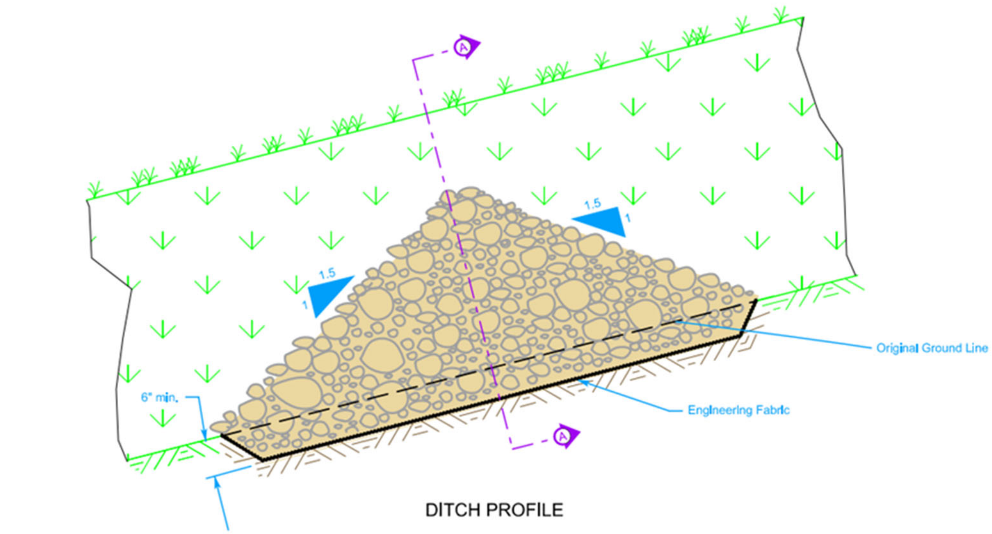
REVISIONS: Added Designer Info button. Modified notes to remove wattles and filter socks. Removed overlap joint on Ditch Protection view on page 3.

Brian Smith

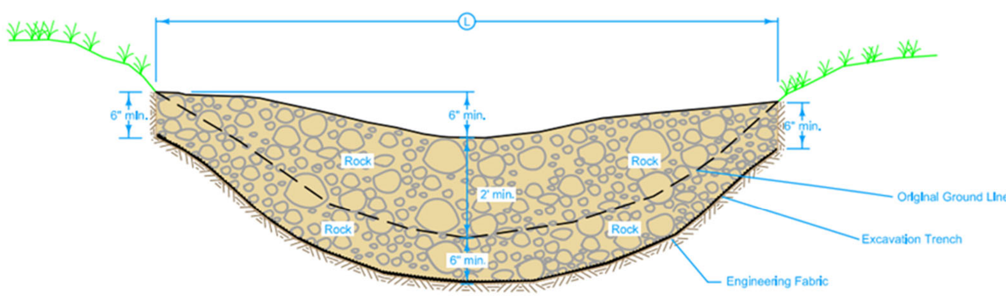
APPROVED BY DESIGN METHODS ENGINEER

PERIMETER AND SLOPE SEDIMENT CONTROL DEVICES

Use Class D Revetment to construct Rock Check Dam.



DITCH PROFILE



SECTION A-A

Possible Contract Items:
- Rock Check Dam
- Maintenance of Rock Check Dam
- Removal of Rock Check Dam

Possible Tabulation:
- 100-32

IOWA DOT

STANDARD ROAD PLAN

REVISION	
New	10-16-18

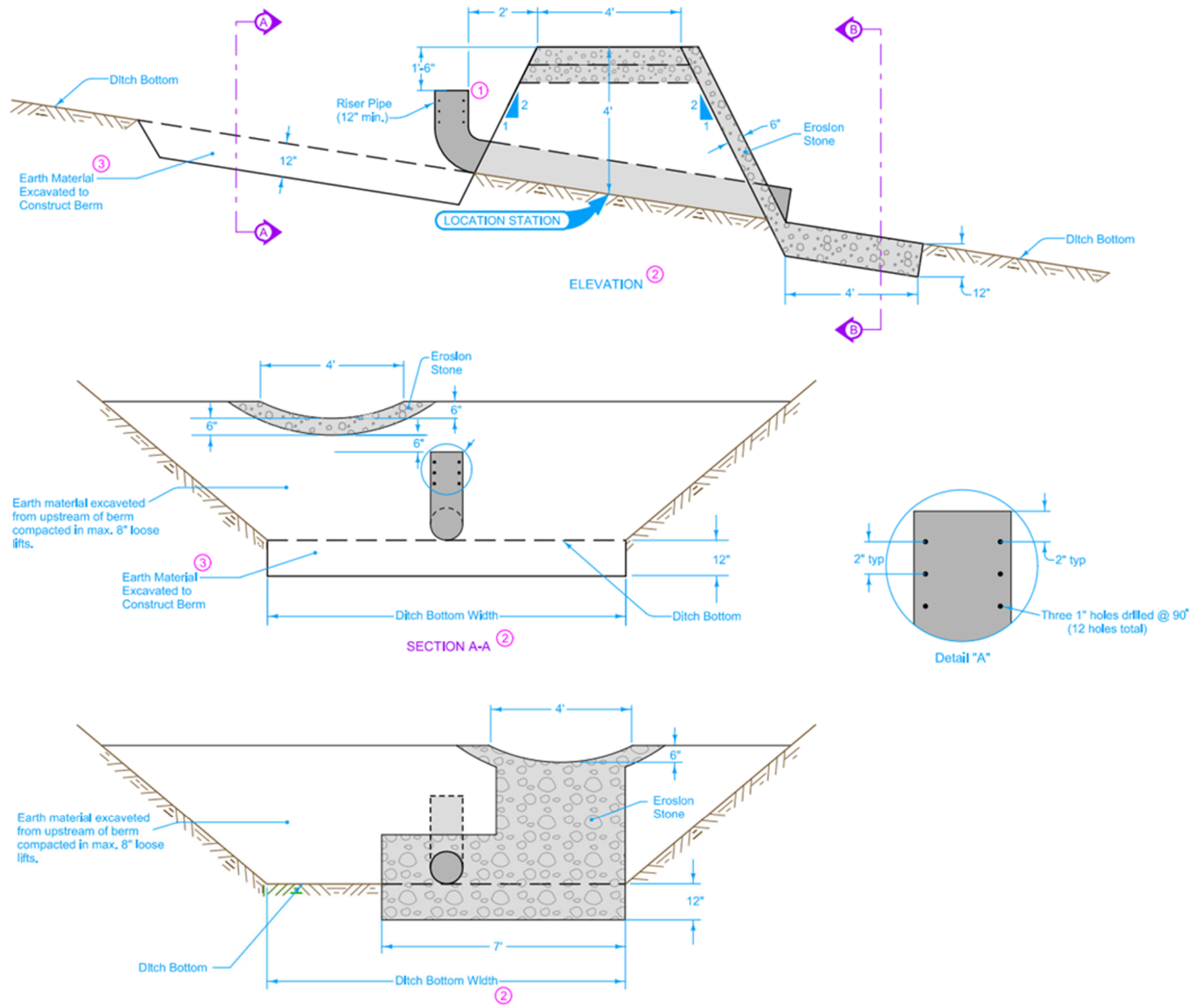
EC-302

SHEET 1 of 1

REVISIONS: New. Replaces Design Detail 570-2.

APPROVED BY DESIGN METHODS ENGINEER

ROCK CHECK DAM



1. Ensure Riser Pipe remains vertical.
2. Dimensions shown are minimums.
3. When Temporary Sediment Control Basin is removed, if basin has not silted in to designed ditch grade, use topsoil to bring up to designed ditch grade.

Possible Contract Items:
- Temporary Sediment Control Basin
- Maintenance of Temporary Sediment Control Basin
- Removal of Temporary Sediment Control Basin

Incidental to Temporary Sediment Control Basin:
- Erosion Stone
- Pipe
- Excavated Earth Material

Possible Tabulation:
- 100-33

IOWA DOT

STANDARD ROAD PLAN

REVISION	
New	10-16-18

EC-601

SHEET 1 of 1

REVISIONS: New. Replaces Design Detail 570-3

APPROVED BY DESIGN METHODS ENGINEER

TEMPORARY SEDIMENT CONTROL BASIN

IOWA DOT
Office of Design

3G-1

Roadway Ditches

Design Manual
Chapter 1
Cross Sections
Originally Issued: 09-13-12
Revised: 11-16-17

Ditches are described as having a depth that is measured from profile grade and bottoms that typically have a normal cross slope of 0%. The normal ditch depth for rural highways is 5 feet and the normal ditch width is 10 feet. For divided roadways, the median ditch depth is 4 feet, as defined by 'M' in Figure 1 below.

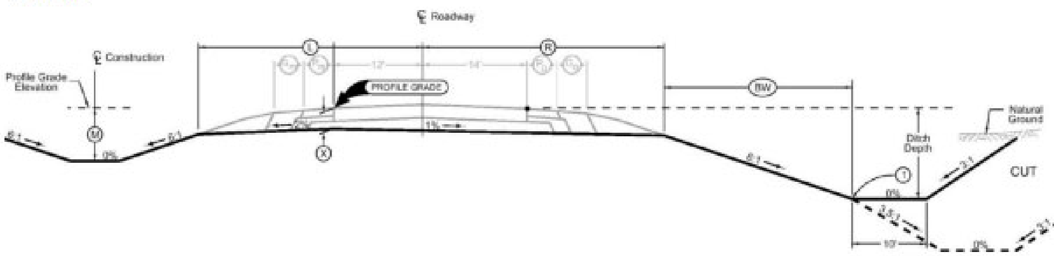


Figure 1: Typical cross section of a normal ditch.

Ditching Guidelines

Consider the following guidelines when determining ditching for a project:

- The proposed drainage layout should conform to the existing drainage pattern.
    - Avoid crossing ridge lines with ditch grades whenever possible.
    - Legal problems can arise when drainage is taken from its existing drainage area and diverted into another drainage area
- Consider impacts to underground utilities.
- When water is draining from a cut section to a fill section, consideration should be given to carrying the water to the draw in a special ditch to contain flow and avoid silt accumulating in an adjacent field. Refer to Road Design Detail 4204 for more information on special ditches.
- If adjusting ditch width, always make width increase with the direction of flow. Erosion may occur if ditch width decreases with increasing flow.
- Limit the length of variable ditches used to tie into structures to no more than 100 feet, except in isolated cases.
- Careful consideration should be given to ditching in critical areas, e.g. front yards, etc.
- 'V' ditches are less desirable than flat bottom ditches due to erosive tendencies; however, they can be used where site conditions are restrictive.
- When the backslope is 10 feet or higher, an intercepting ditch may be necessary. Refer to Section 3G-2 and Road Design Details 4101 and 4102 for more information regarding intercepting ditches.
- If the backslope exceeds 25 feet, or if foreslope or backslope stability is required, refer to Road Design Detail 4104 and Section 3J-1.
- Review ditching for possible letdown structures when roadway grade exceeds 5%.

- Consider the following guidelines relating to the use of ditch grades:
    - Refer to Section 20D-2 for guidance on proper naming conventions for ditch grades in design files.
    - Compute ditch grades to tenths of a percent and elevations to tenths of a foot.
    - Minimum acceptable ditch grades range from 0.2% to 1.0%.
    - Desirable ditch grades range from 1.0% to 3.0%.
    - Do not run ditch grades closer than +/-25 feet to a draw or waterway. This will allow for minor adjustments of the flowline without re-ditching.
    - The minimum desirable ditch depth is 3 feet.
    - Minimum acceptable ditch depth is 2 feet. This is to allow for proper installation and function of longitudinal subdrains.
- Show ditch description on plan sheets as outlined in Section 1F-5b.
    - If ditch width is something other than standard, indicate the width in the ditch description on the ditch bar graph.

Permanent Erosion Control Guidelines

The Roadside Development Section in the Office of Design typically designs permanent erosion control projects for the Department.

Temporary Erosion Control Guidelines

Temporary sediment control devices such as silt fence, ditch checks, and perimeter and slope sediment control devices are used to control sediment on new projects until permanent seeding is established. Temporary erosion control measures also include silt ditches, silt dikes, and silt basins as outlined in Standard Road Plan EW-403. Refer to Section 10C-1 for additional information on these temporary erosion control measures, as well as additional measures.

Refer to Section 2602 of the Standard Specifications for information relating to water pollution control (soil erosion).

APPENDIX B
MATERIAL COSTS USED IN CHECKSPREAD DEVELOPMENT

Practice	Name	Description	Cost: Des Moines, Iowa	Cost: Des Moines, Iowa	Cost: Birmingham, Alabama	Cost: Illinois	Cost: Avg.
Silt Fence Ditch Check/ Perimeter Control	SF Engineering Fabric, 36 in.	woven, 150 lbs grab strength (Iowa DOT 4196.01.B.1), minimum 36 in. wide	$ 0.08	*$ 0.28 ft.* [A]	$ 0.03 ft.	$ 0.13 ft.	$ 0.08
	Studded T-Post, 4 ft	Painted, 1.33 lbs/ ft. (Iowa DOT 4154.09)	$ 3.25 ea	$ 2.95 ea.	$ 4.00 ea.	*$ 19.00* ea	$ 3.40
	MOD Studded T-Post, 4 ft	Unpainted, 1.25 lbs/ ft	$ 2.50 ea		$ 3.00 ea.		$ 2.75
	Cable Ties, 50 lb	50 lbs		$ 0.02 ea			$ 0.02
	Sod Staples, 6 in.	11 gauge metal, 6 in. (15 cm) long by 1 in. (2.5 cm) U-shaped staples	$ 0.03 ea	$ 0.04 ea	$ 0.03 ea.		$ 0.03
	Welded Wire Fence, 18 in.	14 gauge steel wire mesh with a minimum 6 in. by 6 in.			$ 0.89 ft.		$ 0.89
	C-Ring Ties, 1 in.	1 in. (1.7 cm), 16 gauge, galvanized steel.			$ 0.03 ea.		$ 0.03
	Silt Saver WBSF				$ 0.70 lf		$ 0.70
Wattle	Wooden Stakes, 36 in.	1 x 1 in. , 36 in. long	$ 0.80 ea	$ 0.52 ea	$ 0.55 ea.		$ 0.62
	Excelsior Wattle, 10 ft	20 in. Wattle	$ 2.45 ft.	$ 2.00 ft.	$ 2.85 ft.	*$ 9.00* ft	$ 2.43
	Special Ditch Protection, 8 ft	Wood Excelsior Mat, single net	$ 46.50 rl	$ 55.00 rl	$ 44.40 rl.		$ 48.63
Basins	Erosion Stone	6 in. nominal size. Broken limestone, dolomite, quartzite, granite, or concrete (Iowa DOT 4130.03-.05					$ 56.03
	Riser Pipe	12 in. corrugated pipe			$ 7.45 ft.	$ 1,400.00 ea	$ 703.73
	Coir Baffles	700-900 g/m^2 coir erosion blanket, min 36 in. wide			$ 195.00 rl.		$ 195.00
	Surface Skimmer	4 in.			$ 1,328.00 ea		$ 1,328.00
	PVC Outlet	4 in.					
Various Wattles Fills	Excelsior	20 in., 10 ft.	$ 2.45 ft.	$ 2.00 ft.	$ 2.85 ft.		$ 2.43
	Wheat Straw w/ netting	20 in., 10 ft.	$ 2.35 ft.		$ 2.25 ft.		$ 2.30
	Wood chip w/ sock	20 in., 10 ft.			$ 6.00 ft.		$ 6.00
	Coconut coir	12 in., 10 ft.				$ 6.27 ft.	$ 6.27
	Premium coconut coir	12 in., 10 ft.				$ 7.04 ft.	$ 7.04
	Miscanthus **[B]**	12 in., 10 ft.					$ 1.75
	GeoHay **[B]**	20 in., 10 ft.					$ 4.13
RCD	Class D Erosion Stone **[C]**	Limestone/ dolomite/ quatzite/ granite				$ 44.93 cyd.	$ 56.03

Notes: [A] denotes values outside of inner quartile range, and thus were not included in calculating average cost
[B] cost received directly from manufacturer
[C] mobilization cost was added for up to 30 miles.

APPENDIX C
WATER QUALITY LABORATORY PROCEDURES

TURBIDITY AND TOTAL SOLIDS PROCESSING PROCEDURES

Turbidity Analysis

Step 1: Prepare lab space with stirring plate and turbidimeter. Prepare ample DI water should the samples require dilution.

Step 2: Confirm turbidimeter readings using standard samples (10, 20, 100, and 800 NTU). If outside of threshold, recalibrate turbidimeter.
Step 3: Vigorously shake ISCO sample bottle to resuspend any settled solids. Transfer contents to a 1000 mL beaker, insert stir bar, and place on stir plate. Continue mixing until sample appears to be homogeneous.
Step 4: Set pipette to 7.5 mL and carefully extract 15 mL from the sample to fill turbidity cell to line. Cap the cell. Using a soft cloth, wipe the cell to ensure there is no residue on the outside.

Step 5: Place the cell into the turbidimeter, matching the arrow on the cell to the arrow on the turbidimeter. Secure the cell and read the NTU value. If the value is over range, proceed to Step 6.
Step 6: If the sample is outside of the range, dilute the sample 1:2 by mixing 25 mL of the sample with 25 mL of deionized water in a beaker using the stir plate.
Step 7: Repeat steps 4 through 6 as necessary.

Dilution Note: If the sample is still outside of ranger after dilution, transfer the sample from the cell and add another 25 mL of water and reread. Continue this process until you get a reading. The dilution factor will be DF=(NTU)×(x+1), where x is the amount of times 25 mL of water is added. For example, DF=(NTU)×(2+1) after two dilutions are performed.

Total Suspended Solids Processing Procedures

1. **Step 1:** Prepare glassware, deionized water, filtering apparatus, scales, turbidimeter, and vacuum pump.
2. **Step 2:** Prepare and label the required crinkle dishes and place filter membranes on each dish using clean tweezers. Do not use fingers.
3. **Step 3:** Prewash filter membranes by placing the filter disc on the filter holder of the filter apparatus with the wrinkled side upward, gridded side down. Attach the top funnel portion of the magnetic filter holder. Apply 10 mL of deionized water and provide suction to filter through membrane. Remove washed filter and place on corresponding crinkle dish. Repeat for all membranes.
4. **Step 4:** Place washed membranes in the oven at 103˚C for one hour. Remove crinkle dishes and membranes from the drying oven and place in a desiccator and allow to cool to room temperature.
5. **Step 5:** Weigh the crinkle dish and filter using an analytical balance. Record weight to the nearest 0.0001 g.

6. **Step 6:** Use tweezers to place the corresponding filter membrane on the filtering apparatus.

7. **Step 7:** Pipette 25 mL of diluted solution and place in apparatus.

8. **Step 8:** Filter sample through membrane using the vacuum pump. Rinse the filtrate on the filter with three 10 mL portions of deionized water.

9. **Step 9:** Slowly release the vacuum on the filtering apparatus. Gently remove the filter disc using the tweezers.

10. **Step 10:** Place the filter disc on its corresponding crinkle dish.

11. **Step 11:** Place membranes in the oven at 103˚C for one hour. Remove crinkle dishes and membranes from the drying oven and place in a desiccator and allow to cool to room temperature.

12. **Step 12:** Weigh the crinkle dish and filter using an analytical balance. Record weight to the nearest 0.0001 g.

<u>Total Solids Processing Procedures</u>

Step 1: Allow all collected samples to be refrigerated for a minimum of 24 hours to allow sediment to settle out. After at least 24 hours, continue with the experiment

Step 2: Mark and weigh all evaporating dishes. Record the mass to the nearest 0.0001g.

Step 3: Using a vacuum pump and flask, vacuum the supernatant from the samples using a hose with a j- hook attachment. Vacuum the maximum amount of water without disturbing the sediment. Retain supernatant in the flask and record the volume.
Step 4: Measure the remaining water in the original sample bottle by marking the water level line.

Step 5: Use DI water to wash the sediment and remaining water into an evaporating dish.

Step 6: With the empty sample bottle, refill the bottle to the marked level line. Transfer the water to a graduated cylinder and record the volume.

Step 7: Bake the samples in a laboratory oven at 210 ºF (99) for 3 hours. Ensuring that the water has evaporated, increase the temperature to 221 ºF (105) for another 2 hours.

Step 8: After the samples have completed baking, weigh the dishes with the samples to the nearest 0.0001 gram. Discard the sediment.

The following steps are to determine the dissolved solids correction factor.

Step 9: Weigh empty evaporating dishes. Record the mass.

Step 10: Transfer a measured volume (100 mL), using a pipette, from the supernatant from Step 3 to an evaporating dish.
Step 10: Dry the samples as defined in Step 7.

Step 11: After baking, record the mass of the dish and sample to the nearest 0.0001 g and discard the sample.

Step 12: Calculate the dissolved solids correction factor using:

$$DSc = (DS/Va) \times Vs$$

where
DSc =Dissolved-Solids Correction,
(g) DS =Weight of Dissolved
Solids, (g)
Va =Sample Volume for Dissolved Solids,
(mL) Vs =Volume of Supernatant with
Sediment, (mL)

Step 13: Subtract this correction factor from the net weight.

Step 14: Divide the net weight of the sediment by the net weight of the sample, multiply the quotient by 1,000,000. This will provide a sediment concentration result in parts per million.

Repeat this process for each sample taken.

APPENDIX D
FAIRCLOTH SKIMMER TECHNICAL SIZING GUIDANCE

Determining the Skimmer Size and the Required Orifice for the *Faircloth Skimmer®* Surface Drain

November 2007

Important note: *The orifice sizing chart in the Pennsylvania Erosion Control Manual and reproduced in the North Carolina Design Manual **DOES NOT APPLY** to our skimmers. It will give the wrong size orifice and not specify which size skimmer is required. Please use the information below to choose the size skimmer required for the basin volume provided and determine the orifice size required for the drawdown time, typically 4-7 days in Pennsylvania and 3 days in North Carolina.*

The **size** of a Faircloth Skimmer®, for example a 4" skimmer, refers to the maximum diameter of the skimmer inlet. The inlet on each of the 8 sizes offered can be reduced to adjust the flow rate by cutting a hole or ***orifice*** in a plug using an adjustable cutter (both supplied).

Determining the skimmer size needed and the orifice for that skimmer required to drain the sediment basin's volume in the required time involves two steps: **First**, determining the size skimmer required based on the volume to be drained and the number of days to drain it; and **Second,** calculate the orifice size to adjust the flow rate and "customize" the skimmer for the basin's volume. *The second step is not always necessary* if the flow rate for the skimmer with the inlet wide open equals or is close to the flow rate required for the basin volume and the drawdown time.

Both the skimmer size and the required orifice radius for the skimmer should be shown for each basin on the erosion and sediment control plan. Make it clear that the dimension is either the radius or the diameter. It is also helpful to give the basin volume in case there are questions. During the skimmer installation the required orifice can be cut in the plastic plug using the supplied adjustable cutter and installed in the skimmer using the instructions provided.

The plan review and enforcement authority may require the calculations showing that the skimmer used can drain the basin in the required time.

Determining the Skimmer Size

Step 1. Below are approximate **skimmer maximum flow capacities** based on typical draw down requirements, which can vary between States and jurisdictions and watersheds. If one 6" skimmer does not provide enough capacity, multiple skimmers can be used to drain the basin. For drawdown times not shown, multiply the 24-hour figure by the number of days required.

Example: A basin's volume is 29,600 cubic feet and it must be drained in 3 days. A 3" skimmer with the inlet wide open will work perfectly. (Actually, the chart below gives 29,322 cubic feet but this is well within the accuracy of the calculations and the basin's constructed volume.)
Example: A basin's volume is 39,000 cubic feet and it must be drained in 3 days. The 3"

skimmer is too small; a 4" skimmer has enough capacity but it is too large, so the inlet will need to be reduced using step 2 to adjust the flow rate for the basin's volume. (It needs a 3.2" diameter orifice.)

1½" skimmer: with a 1½" head	1,728 cubic feet in **24 hours** 3,456 cubic feet in **2 days** 5,184 cubic feet in **3 days**	6,912 cubic feet in **4 days** 12,096 cubic feet in **7 days**
2" skimmer: with a 2" head	3,283 cubic feet in **24 hours** 6,566 cubic feet in **2 days** 9,849 cubic feet in **3 days**	13,132 cubic feet in **4 days** 22,982 cubic feet in **7 days**
2½" skimmer: with a 2.5" head	6,234 cubic feet in **24 hours** 12,468 cubic feet in **2 days** 18,702 cubic feet in **3 days**	24,936 cubic feet in **4 days** 43,638 cubic feet in **7 days**
3" skimmer: with a 3" head	9,774 cubic feet in **24 hours** 19,547 cubic feet in **2 days** 29,322 cubic feet in **3 days**	39,096 cubic feet in **4 days** 68,415 cubic feet in **7 days**
4" skimmer: with a 4" head	20,109 cubic feet in **24 hours** 40,218 cubic feet in **2 days** 60,327 cubic feet in **3 days**	80,436 cubic feet in **4 days** 140,763 cubic feet in **7 days**
5" skimmer: with a 4" head	32,832 cubic feet in **24 hours** 65,664 cubic feet in **2 days** 98,496 cubic feet in **3 days**	131,328 cubic feet in **4 days** 229,824 cubic feet in **7 days**
6" skimmer: with a 5" head	51,840 cubic feet in **24 hours** 103,680 cubic feet in **2 days** 155,520 cubic feet in **3 days**	207,360 cubic feet in **4 days** 362,880 cubic feet in **7 days**
8" skimmer: with a 6" head	97,978 cubic feet in **24 hours** 195,956 cubic feet in **2 days** 293,934 cubic feet in **3 days**	391,912 cubic feet in **4 days** 685,846 cubic feet in **7 days**

Determining the Orifice

Step 2. To determine the orifice required to reduce the flow rate for the basin's volume and the number of days to drain the basin, simply use the formula volume ÷ **factor** (from the chart below) for the same size skimmer chosen in the first step and the same number of days. This calculation will give the **area** of the required orifice. Then calculate the orifice radius using Area = πr^2 and solving for *r*, $r = \sqrt{(Area/3.14)}$ .The supplied cutter can be adjusted to this radius to cut the orifice in the plug. The instructions with the plug and cutter has a ruler divided into tenths of inches. Again, this step is not always necessary as explained above.

An alternative method is to use the orifice equation with the head for a particular skimmer shown on the previous page and determine the orifice needed to give the required flow for the volume and draw down time. C = 0.59 is used in this chart.

Example: A 4" skimmer is the smallest skimmer that will drain 39,000 cubic feet in 3 days but a 4" inlet will drain the basin too fast (in 1.9 days) To determine the orifice required use the factor of 4,803 from the chart below for a 4" skimmer and a drawdown time of 3 days. 39,000 cubic feet ÷ 4,803 = 8.12 square inches of orifice required. Calculate the orifice radius using Area = πr^2 and solving for r, $r = \sqrt{(8.12/3.14)}$ and r = 1.61". As a practical matter 1.6" is about as close as the cutter can be adjusted and the orifice cut..

Factors (in cubic feet of flow per square inch of opening through a **round** orifice with the head for that skimmer and for the drawdown times shown) for determining the **orifice radius** for a basin's volume to be drained. This quick method works because the orifice is centered and has a constant head (given above in Step 1).

1½" skimmer:	960 to drain in **24 hours**	3,840 to drain in **4 days**
	1,920 to drain in **2 days**	6,720 to drain in **7 days**
	2,880 to drain in **3 days**	
2" skimmer:	1,123 to drain in **24 hours**	4,492 to drain in **4 days**
	2,246 to drain in **2 days**	7,861 to drain in **7 days**
	3,369 to drain in **3 days**	
2½" skimmer:	1,270 to drain in **24 hours**	5,080 to drain in **4 days**
Revised 11-6-07	2,540 to drain in **2 days**	8,890 to drain in **7 days**
	3,810 to drain in **3 days**	
3" skimmer:	1,382 to drain in **24 hours**	5,528 to drain in **4 days**
	2,765 to drain in **2 days**	9,677 to drain in **7 days**
	4,146 to drain in **3 days**	
4" skimmer:	1,601 to drain in **24 hours**	6,404 to drain in **4 days**
Revised 11-6-07	3,202 to drain in **2 days**	11,207 to drain in **7 days**
	4,803 to drain in **3 days**	
5" skimmer:	1,642 to drain in **24 hours**	6,568 to drain in **4 days**
	3,283 to drain in **2 days**	11,491 to drain in **7 days**
	4,926 to drain in **3 days**	
6" skimmer:	1,814 to drain in **24 hours**	7,256 to drain in **4 days**
	3,628 to drain in **2 days**	12,701 to drain in **7 days**
	5,442 to drain in **3 days**	
8" skimmer:	1,987 to drain in **24 hours**	7,948 to drain in **4 days**
	3,974 to drain in **2 days**	13,909 to drain in **7 days**
	5,961 to drain in **3 days**	

J. W. Faircloth & Son, Inc.
Post Office Box 789
Hillsborough, North Carolina 27278

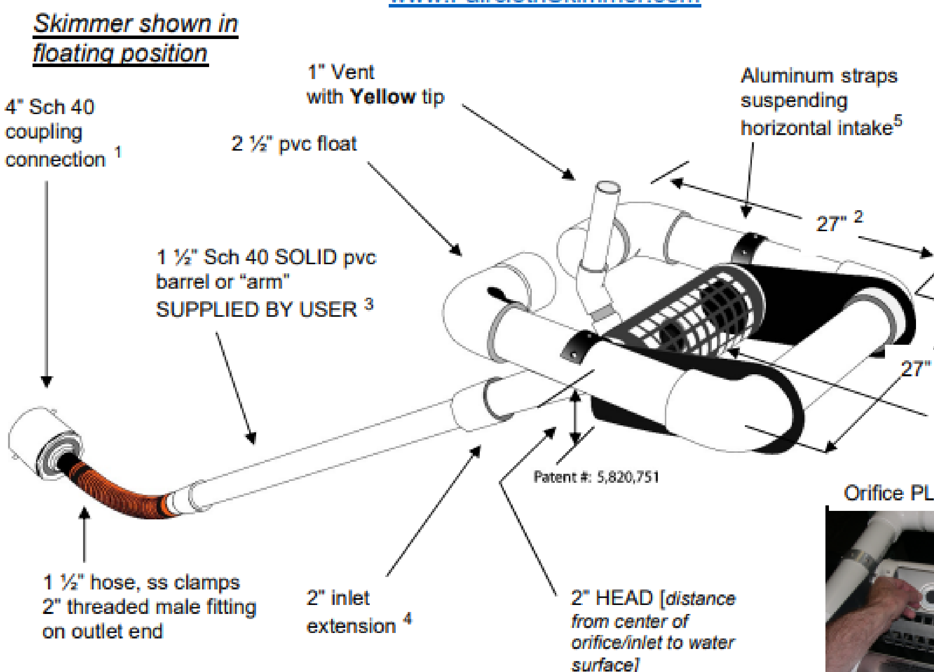
Telephone (919) 732-1244 FAX (919) 732-1266

FairclothSkimmer.com

2" Faircloth Skimmer® Cut Sheet

J. W. Faircloth & Son, Inc.

www.FairclothSkimmer.com



Orifice PLUG for inlet[6]

1. Skimmer can be attached to a straight 4" sch 40 pipe through the dam but the pipe may need to be anchored to the bottom at the connection so it is secure. Coupling can be removed and hose attached to outlet using the threaded 2" fitting. Typical methods used: a) on a metal structure a steel stub out welded on the side at the bottom with a 2" threaded coupling or reducer(s); b) a concrete structure with a hole or orifice at the bottom - use a steel plate with a hole cut in it and coupling welded to it that will fit over the hole in the concrete and bolted to the structure with sealant; or c) grout a 4" pvc pipe in a hole in the concrete to connect the skimmer.

2. Dimensions are approximate, not intended as plans for construction.

3. Barrel (solid, not foam core pipe) should be 1.4 times the depth of water with a minimum length of 6' so the inlet can be pulled to the side for maintenance. If more than 8' long, weight may have to be added to inlet to counter the increased buoyancy.

4. Orifice/inlet tapers down from 2" maximum inlet to a 1 ½" barrel and hose. Barrel is smaller to reduce buoyancy and tendency to lift inlet but is sufficient for flow through inlet because of slope. The orifice/inlet can be reduced using the plug and cutter provided to control the outflow rate – see #6.

5. Horizontal intake is 4" pipe between the straps with aluminum screen door for access to the inlet and orifice inside.

6. **Capacity:** 3,283 cubic feet per day maximum with 2" inlet and 2" head. Inlet can be reduced by installing a smaller orifice using the plug and cutter provided to adjust flow rate for the particular drawdown time required. Please use the sizing template available at www.fairclothskimmer.com .

7. Ships assembled. User glues inlet extension and barrel, installs vent, cuts orifice in plug and attaches to outlet pipe or structure. Includes float, flexible hose with fittings, rope, orifice plug & cutter. Does NOT include 1 ½" Sch 40 SOLID pvc barrel or "arm" SUPPLIED BY USER.

2inchCut 5-1-19

APPENDIX D

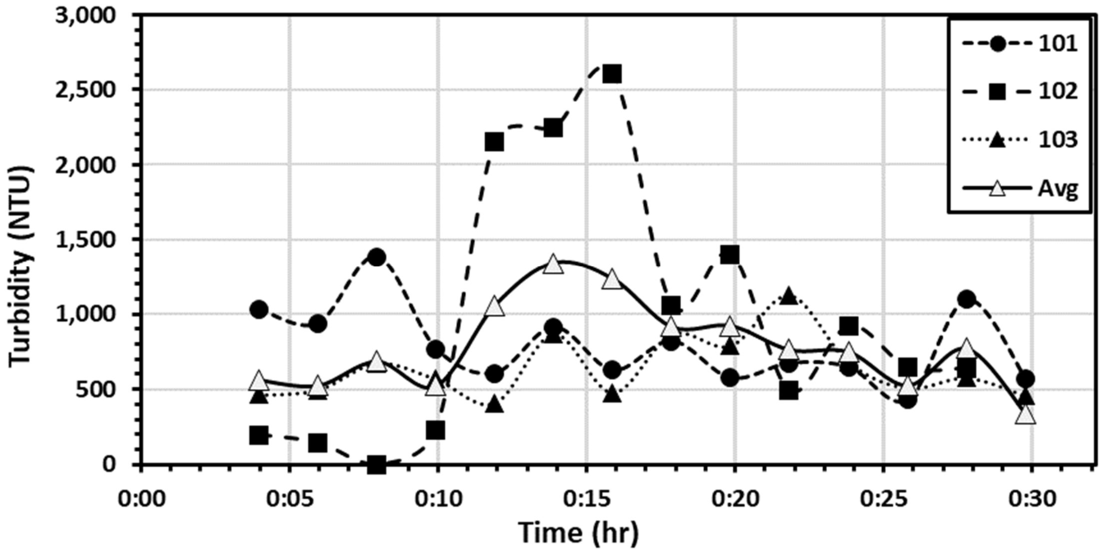
TURBIDITY MEASUREMENTS BASED ON LOCATION DURING EACH TEST

Key for Iowa DOT Testing Code (XYZ)

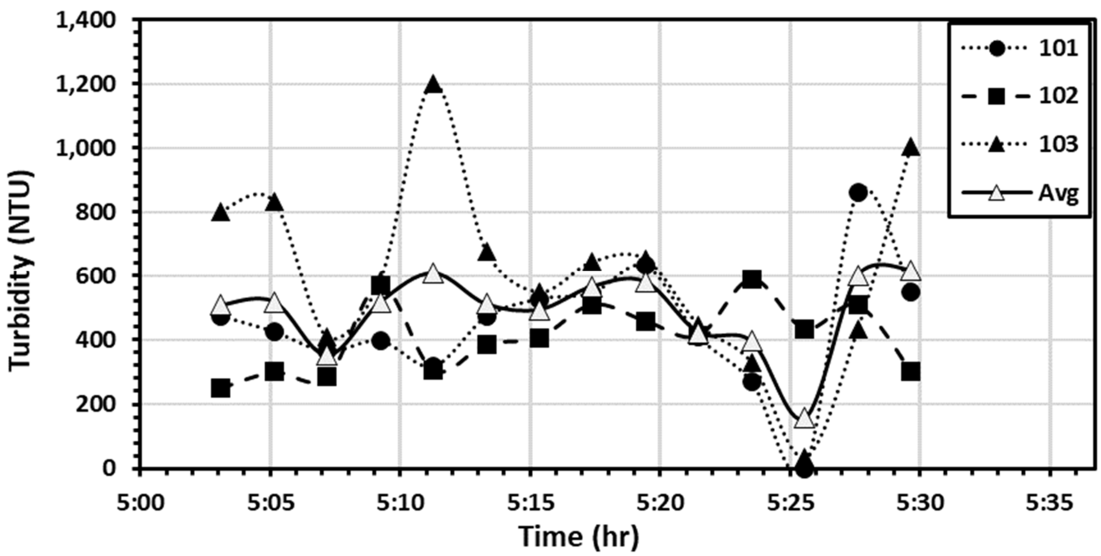
X		Y		Y	
Treatment	**#**	**Soil**	**#**	**Iteration**	**#**
Calibration	0	AL	0	L-1	1
Unlined	1	IA	1	L-2	2
Geotextile	2			L-3	3
Skimmer	3				
Baffles	4				
Forebay	5				
MFE	7				
MFE + Flocc	8				

Note y-axis changes for observation on turbidity variance between tests.

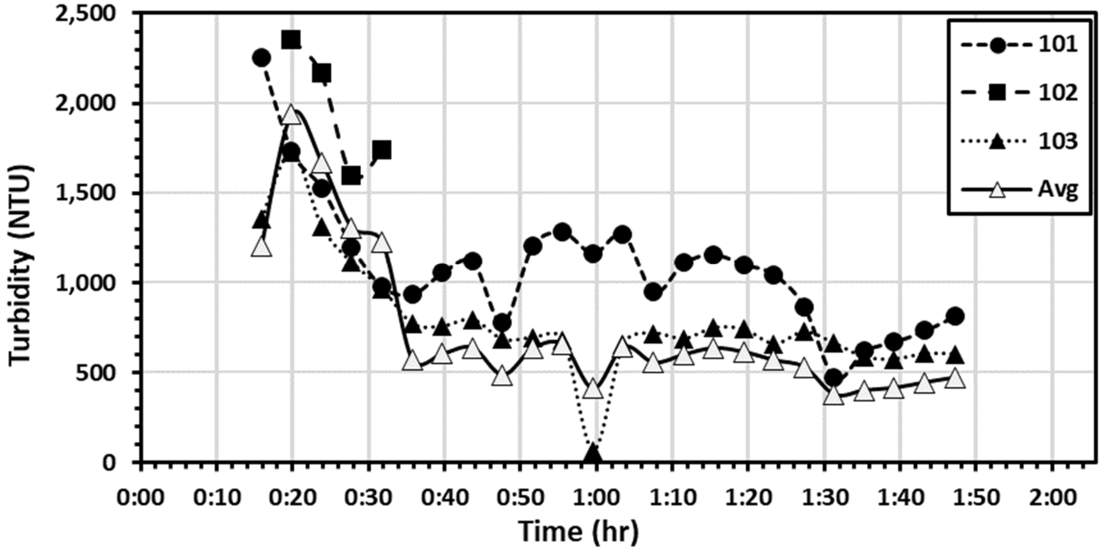
S1- Unlined Testing with Alabama Soil (Standard)



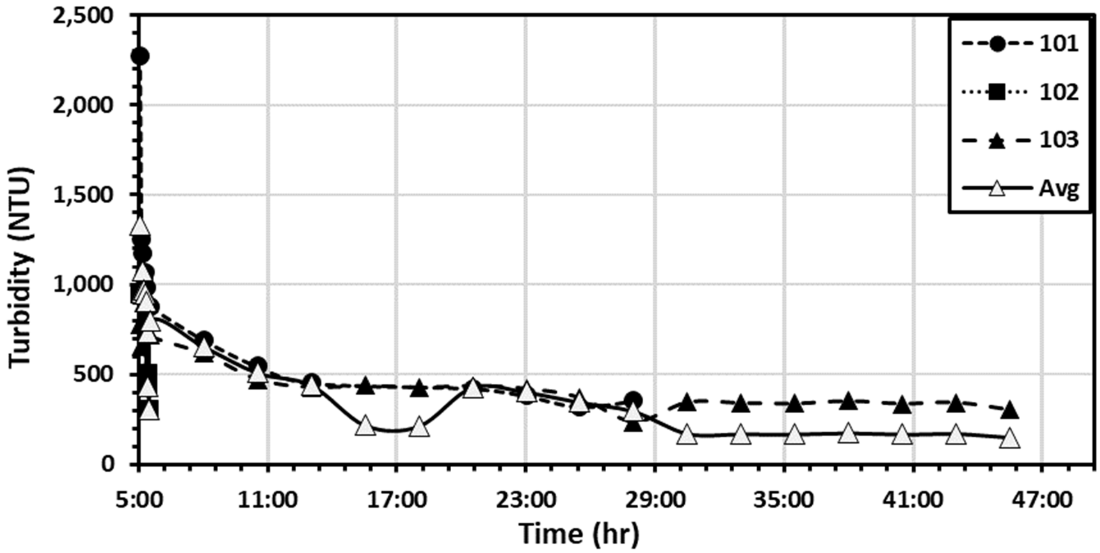
Inflow Sampling Location



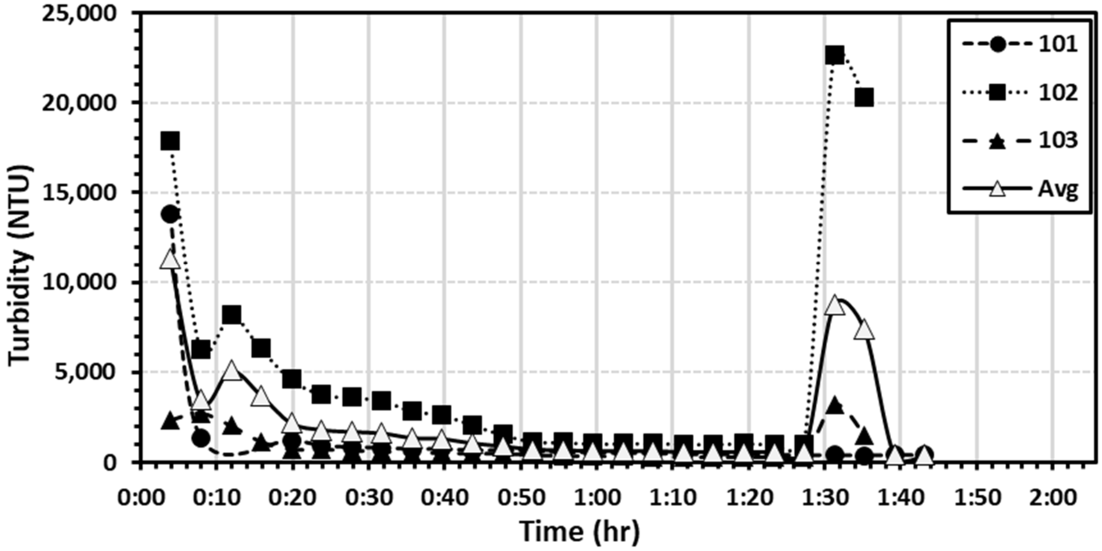
Inflow Sampling Location



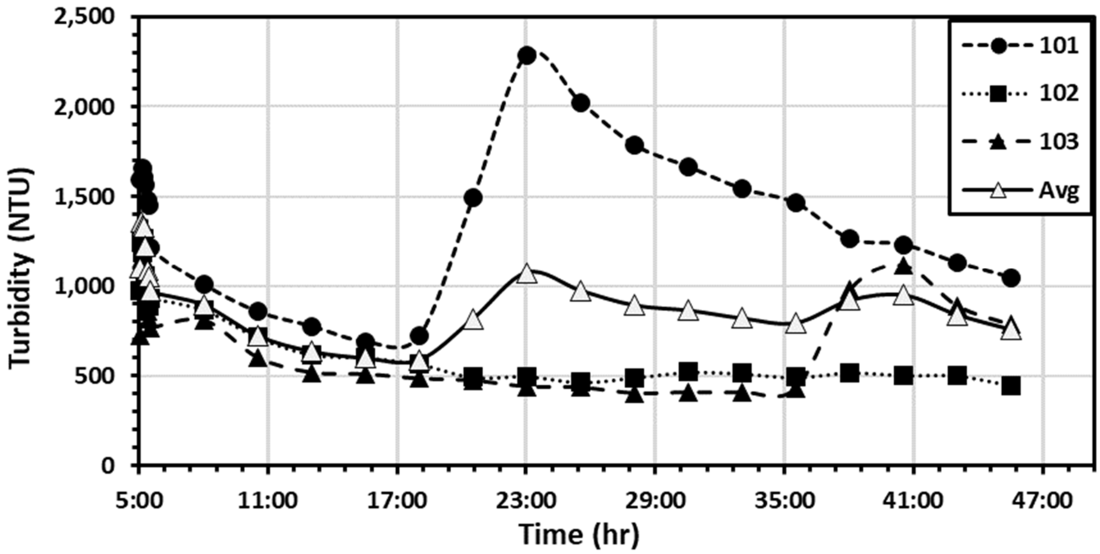
Bay 2 Sampling Location



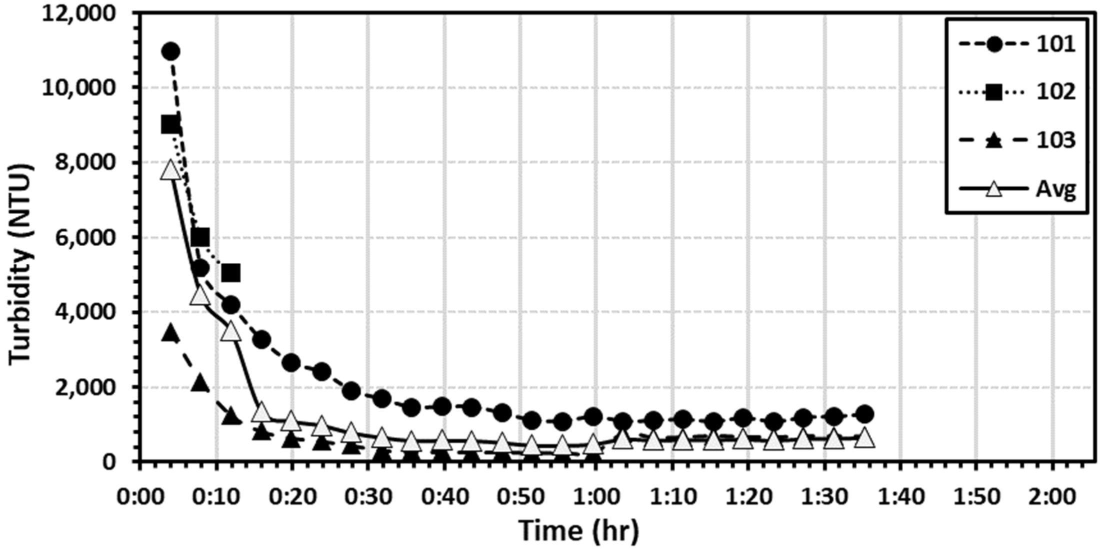
Bay 2 Sampling Location



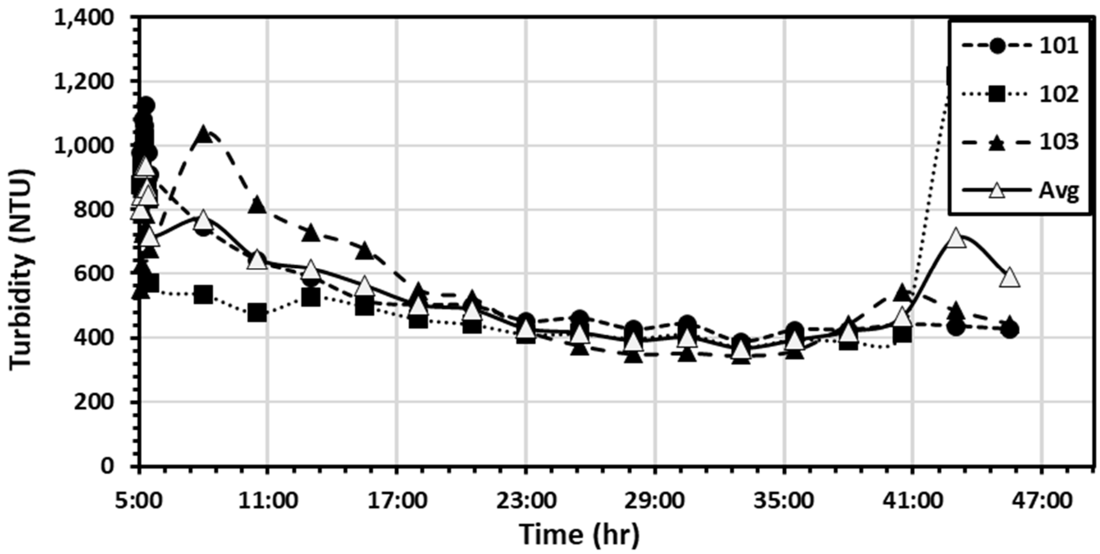
Bay 4 Bottom Sampling Location



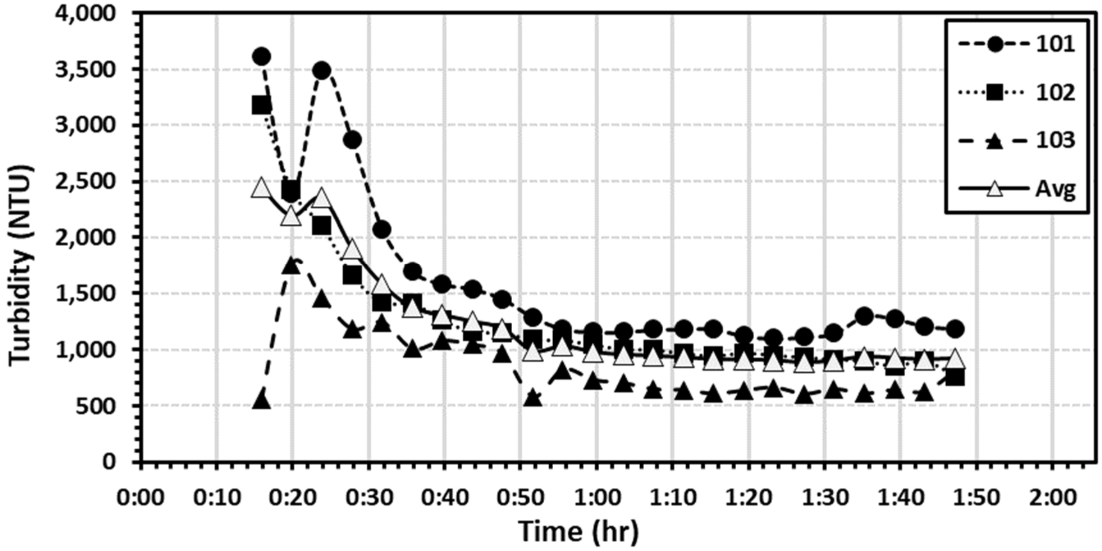
Bay 4 Bottom Sampling Location



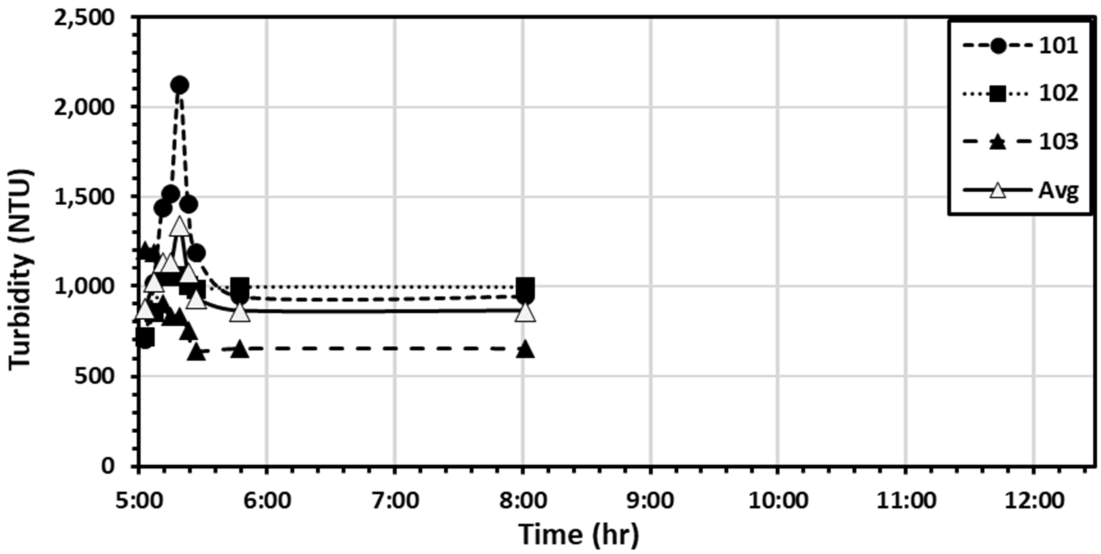
Bay 4 Top Sampling Location



Bay 4 Top Sampling Location

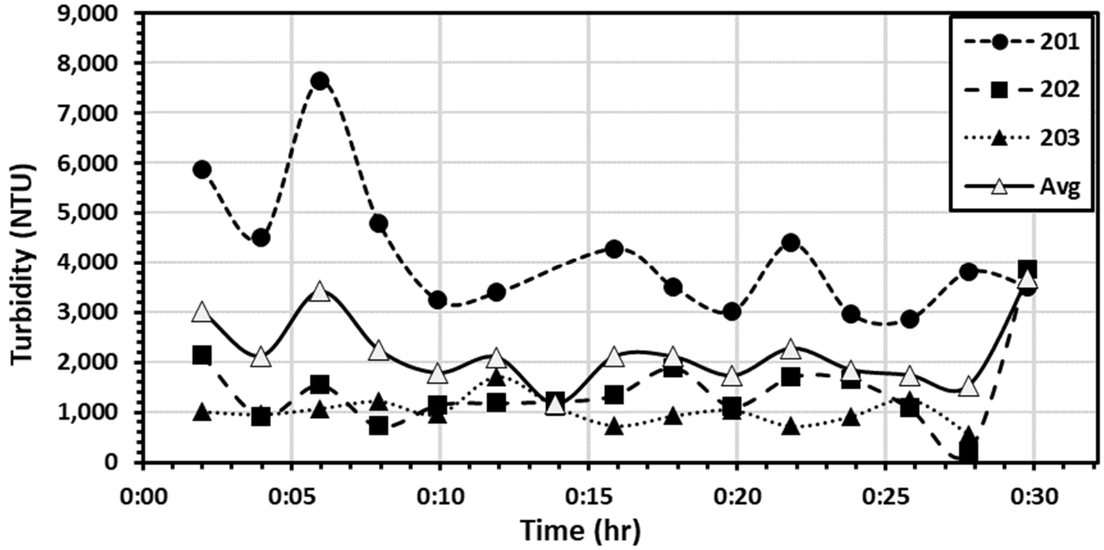


Discharge Sampling Location

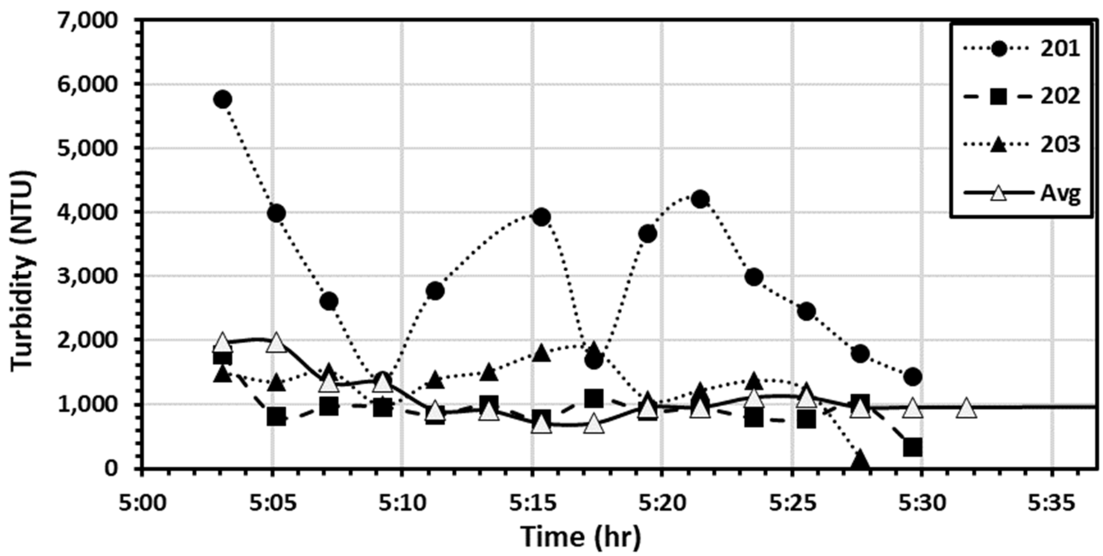


Discharge Sampling Location

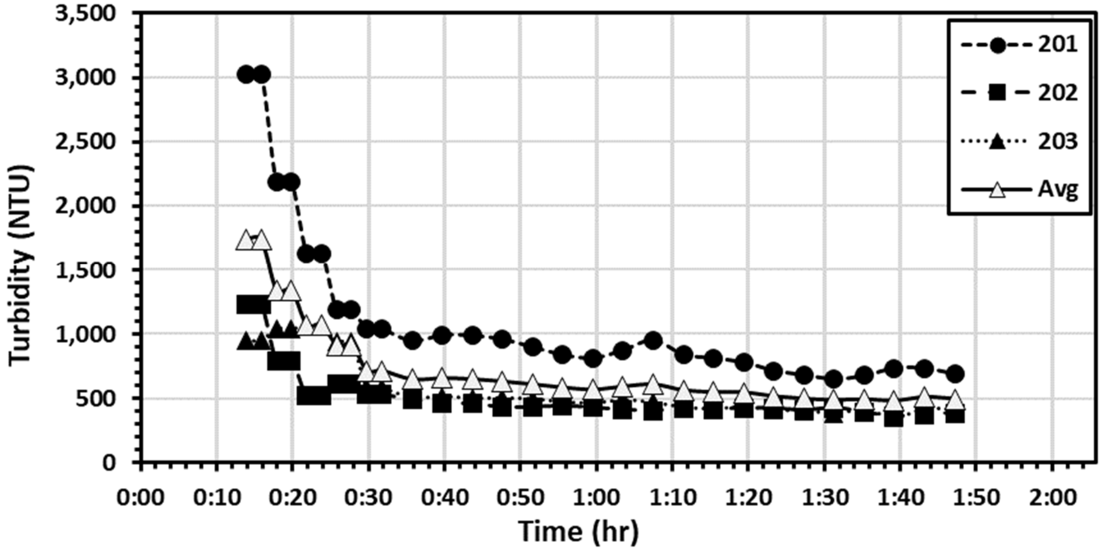
S2-Lined Testing with Alabama Soil



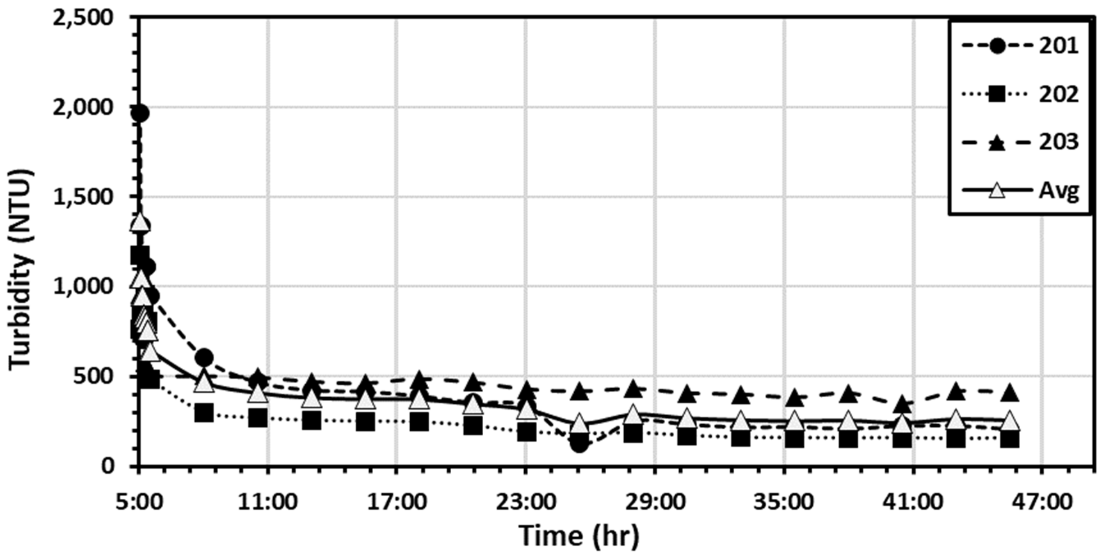
Inflow Sampling Location



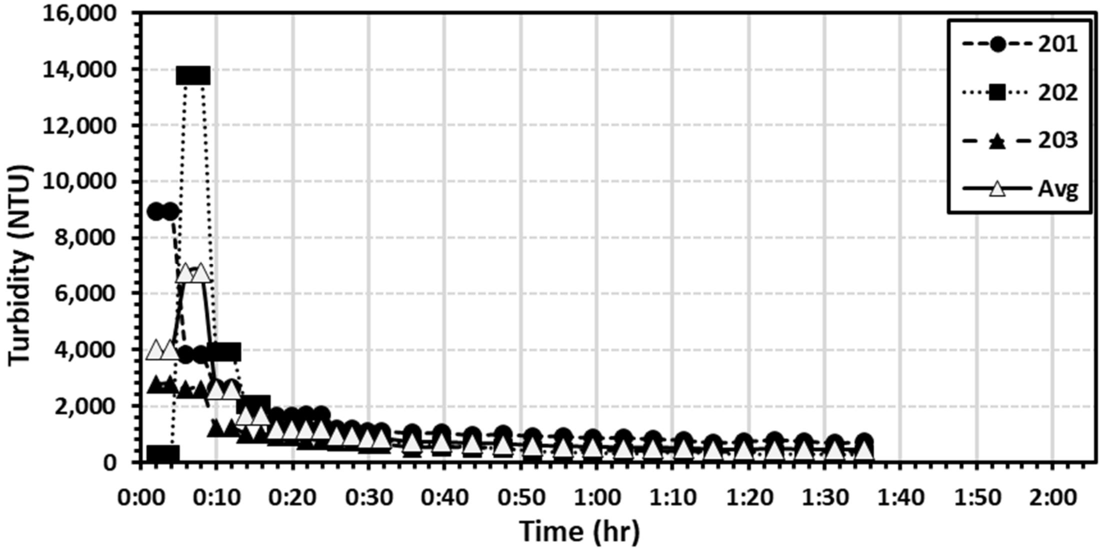
Inflow Sampling Location



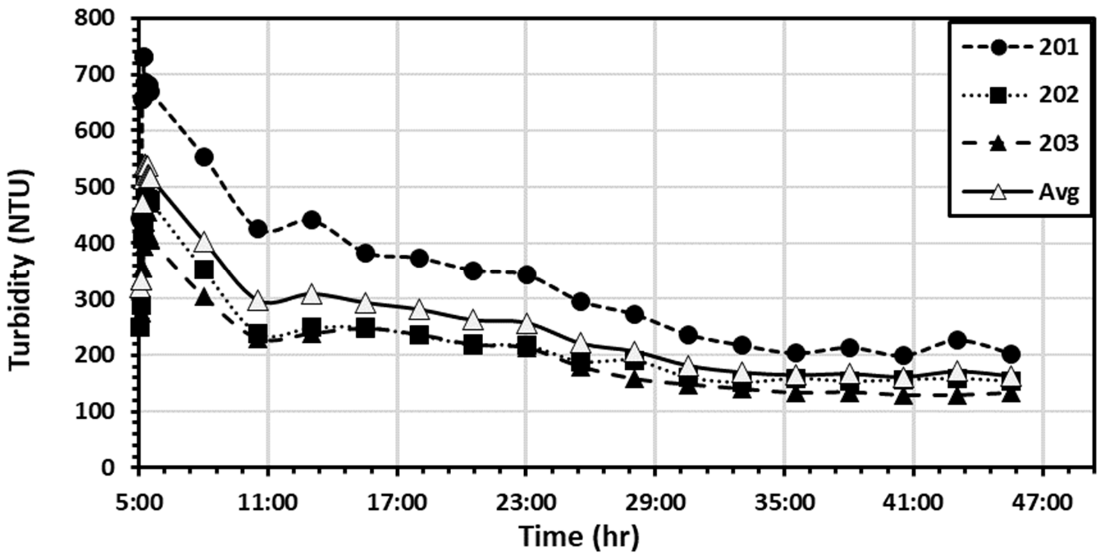
Bay 2 Sampling Location



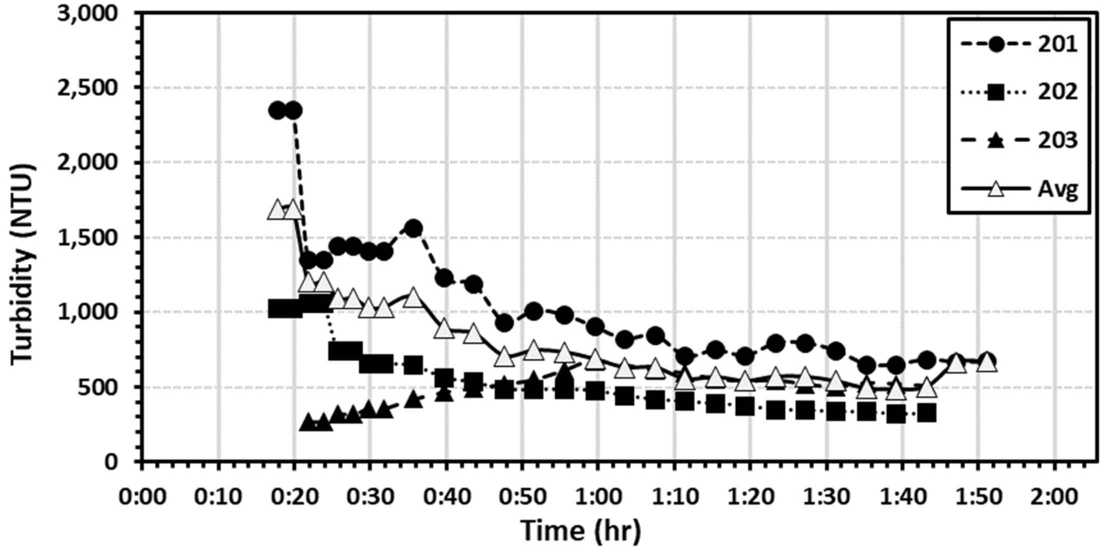
Bay 2 Sampling Location



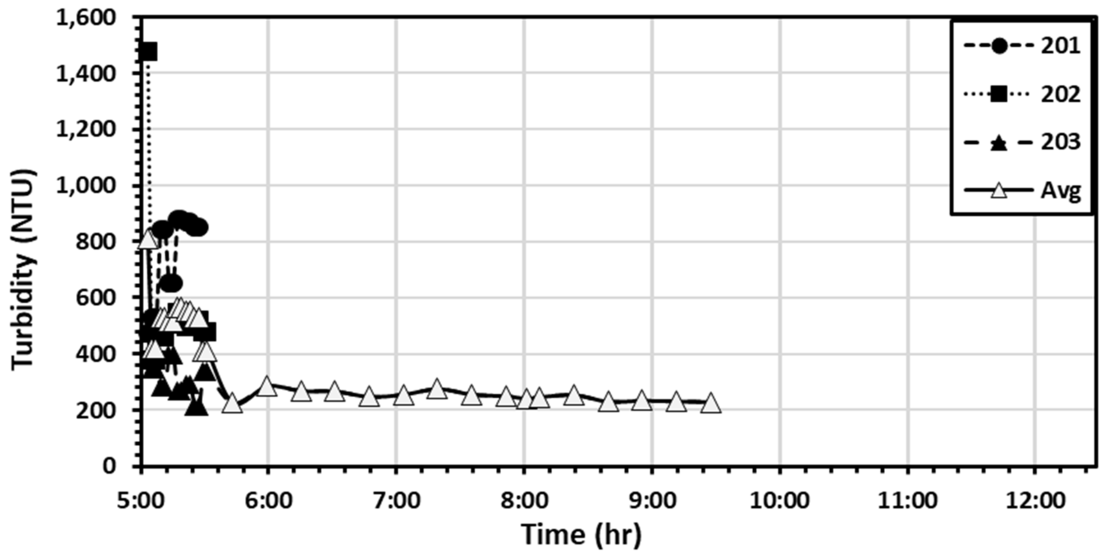
Bay 4 Top Sampling Location



Bay 4 Top Sampling Location

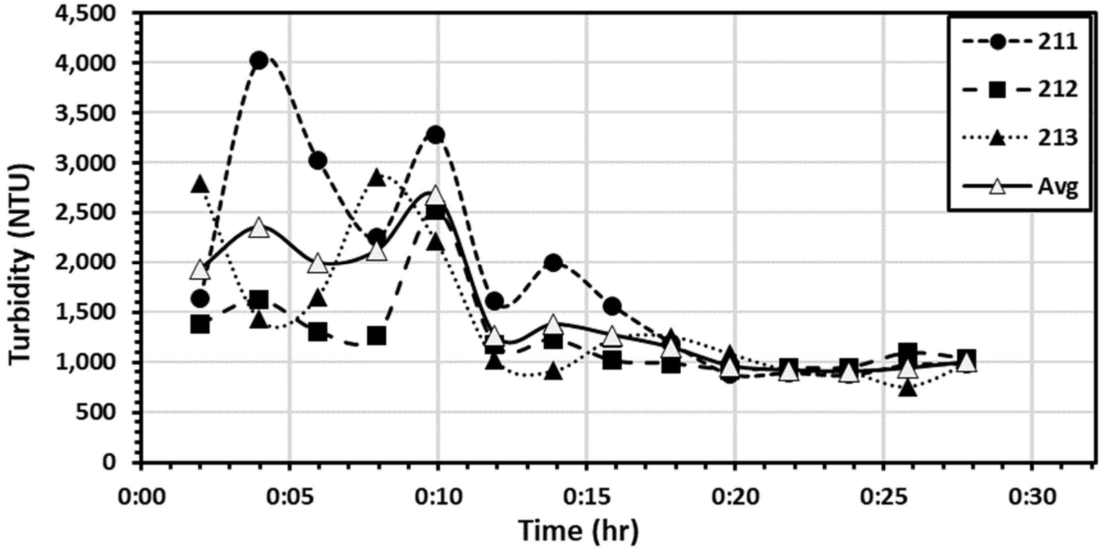


Discharge Sampling Location

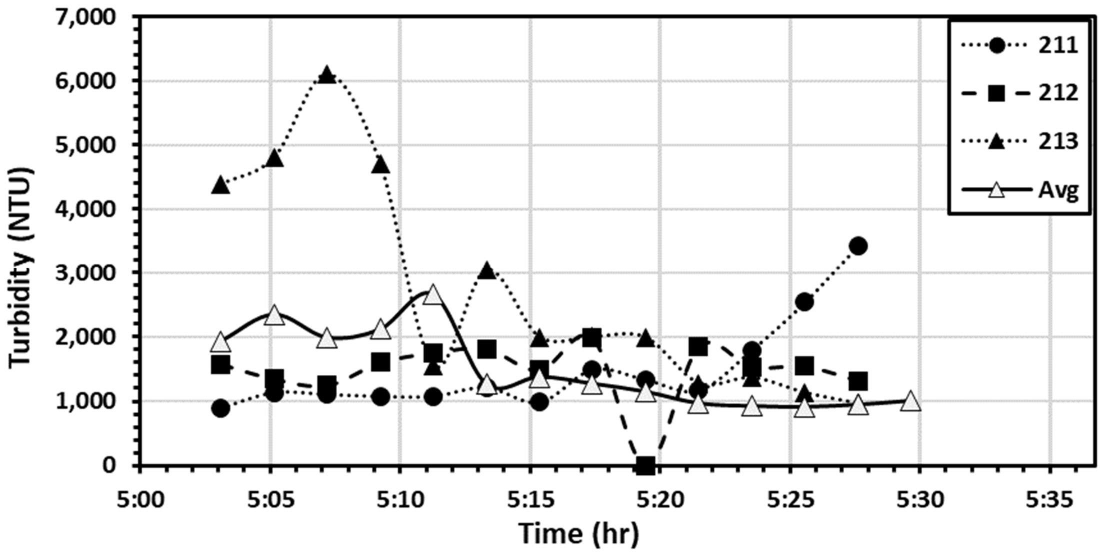


Discharge Sampling Location

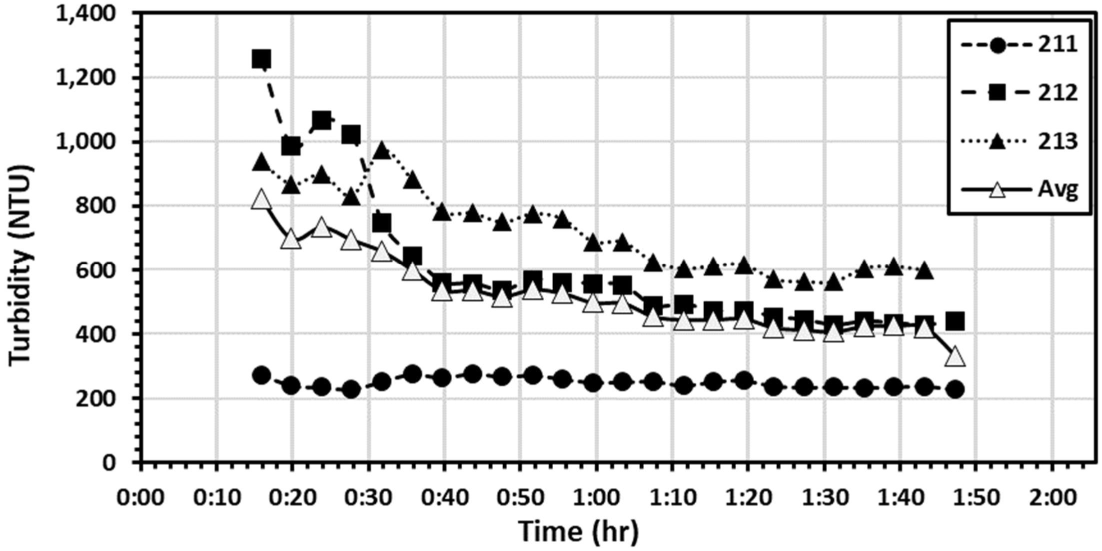
S3-Lined Testing with Iowa Soil



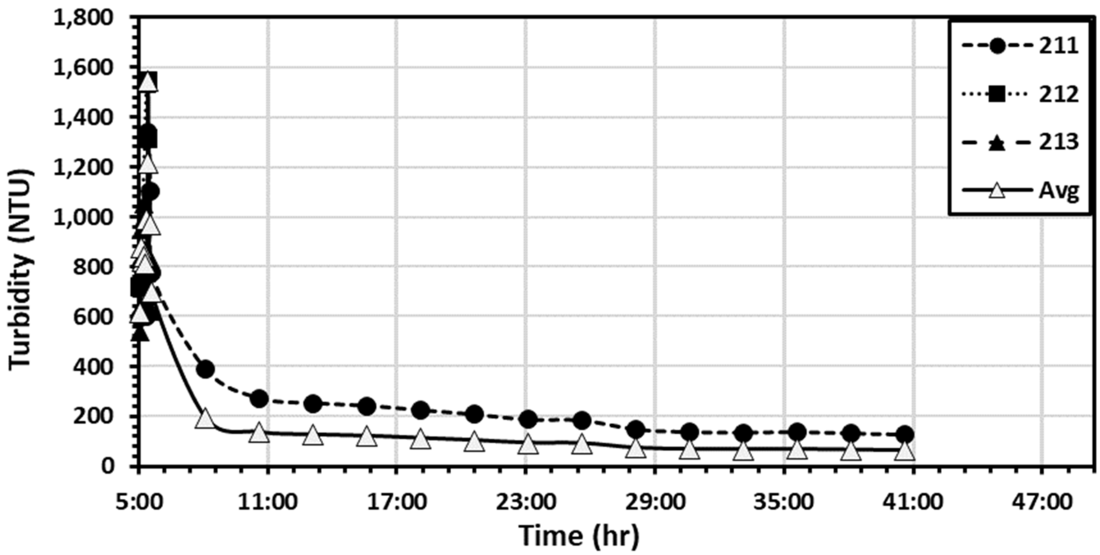
Inflow Sampling Location



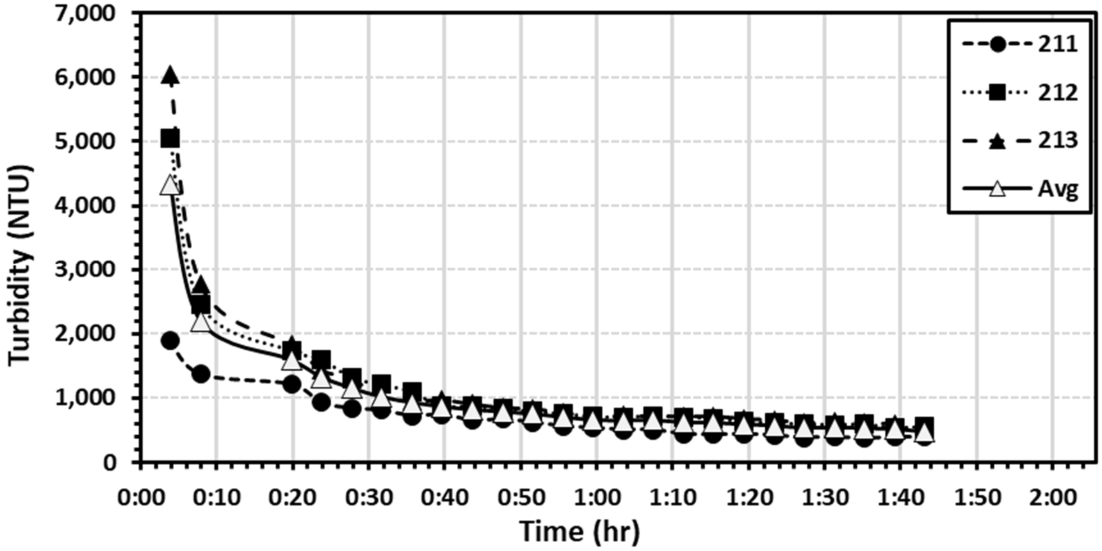
Inflow Sampling Location



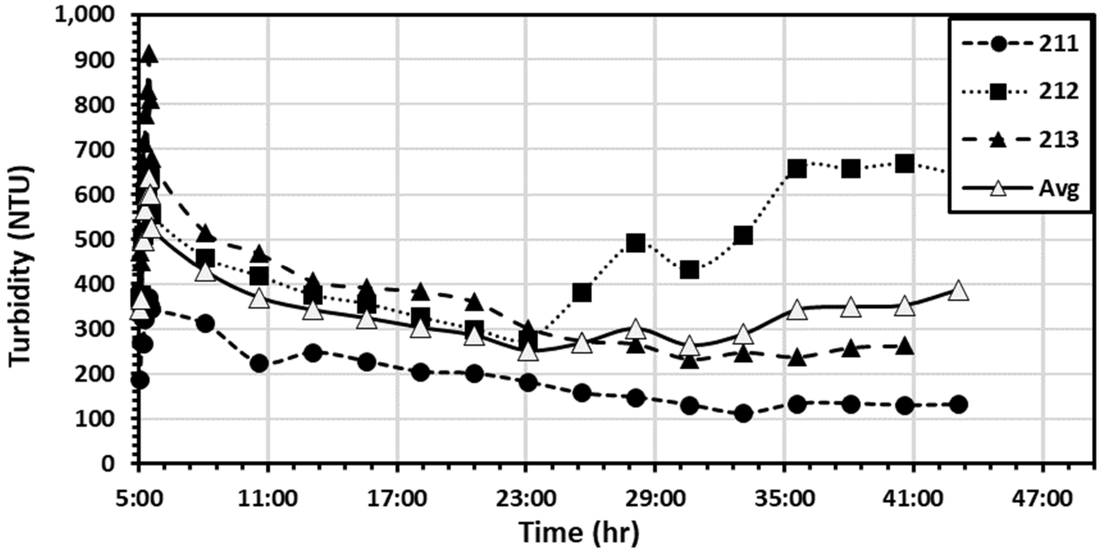
Bay 2 Sampling Location



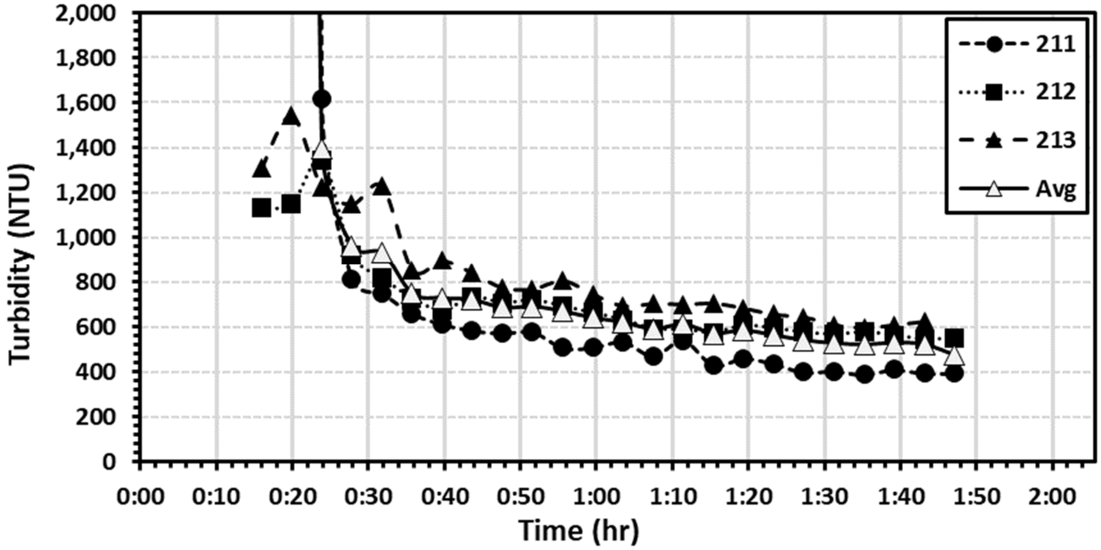
Bay 2 Sampling Location



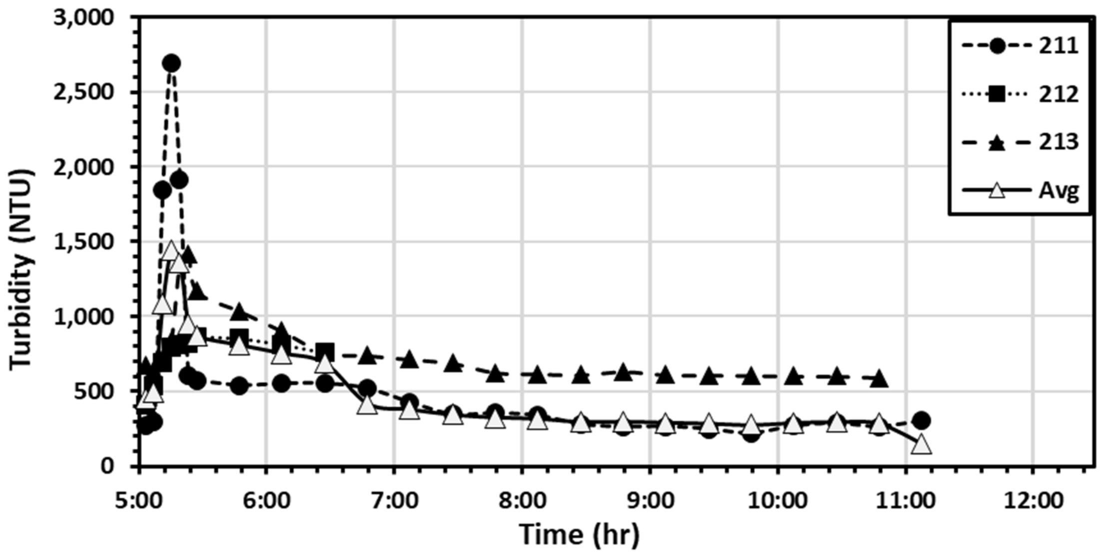
Bay 4 Top Sampling Location



Bay 4 Top Sampling Location

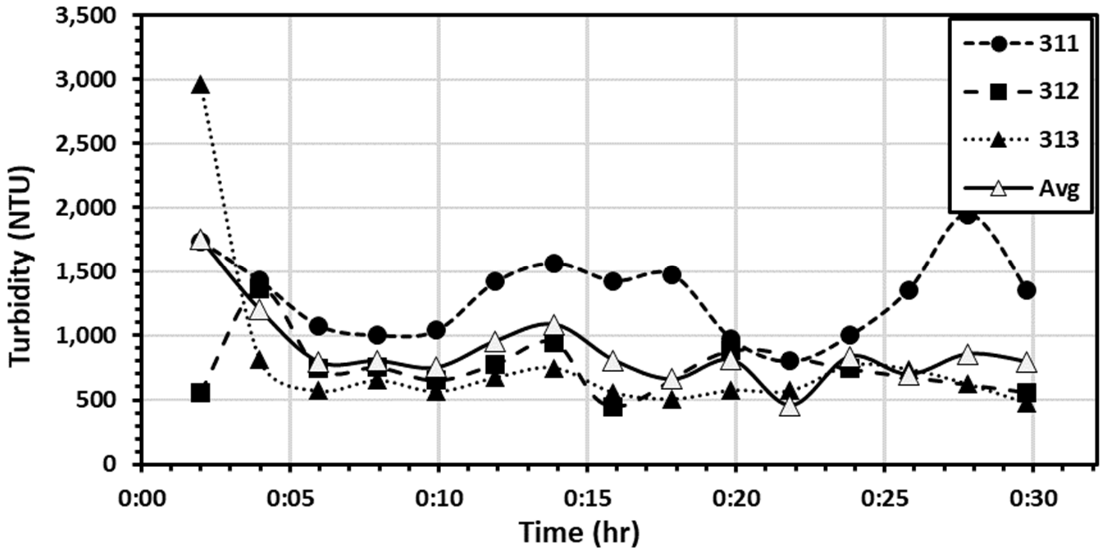


Discharge Sampling Location

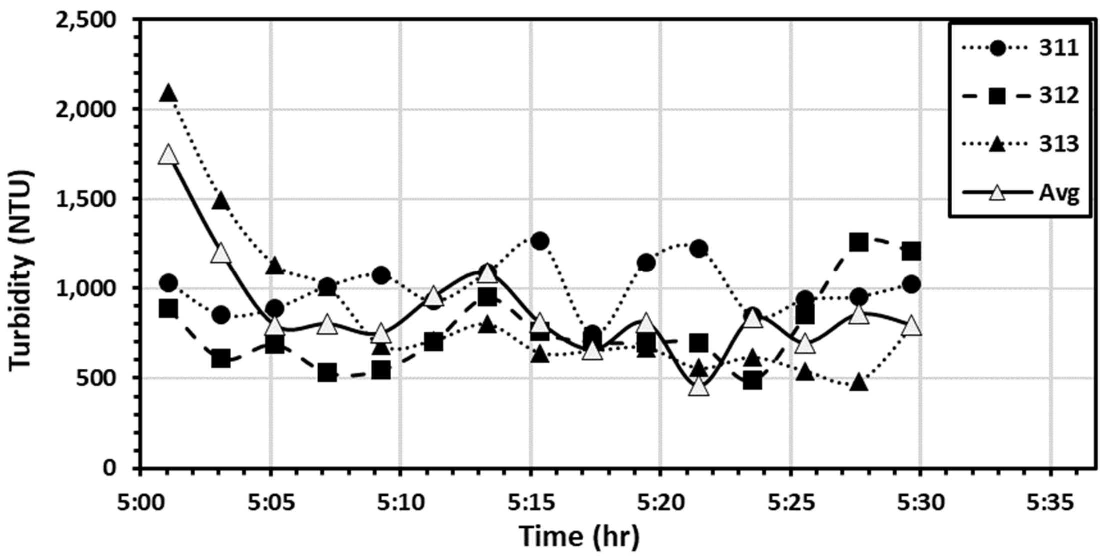


Discharge Sampling Location

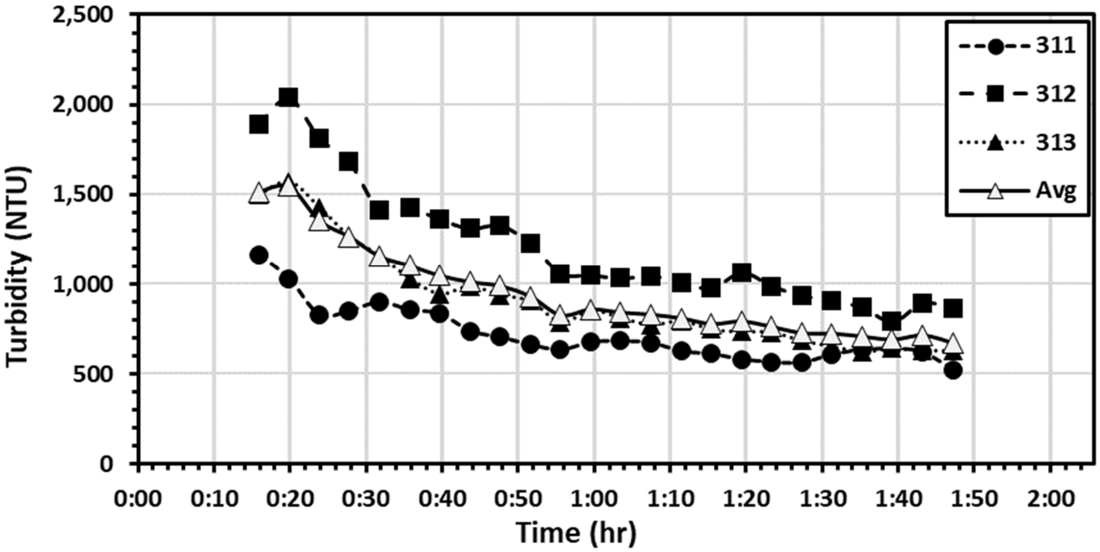
S4-Lined Testing with Skimmer



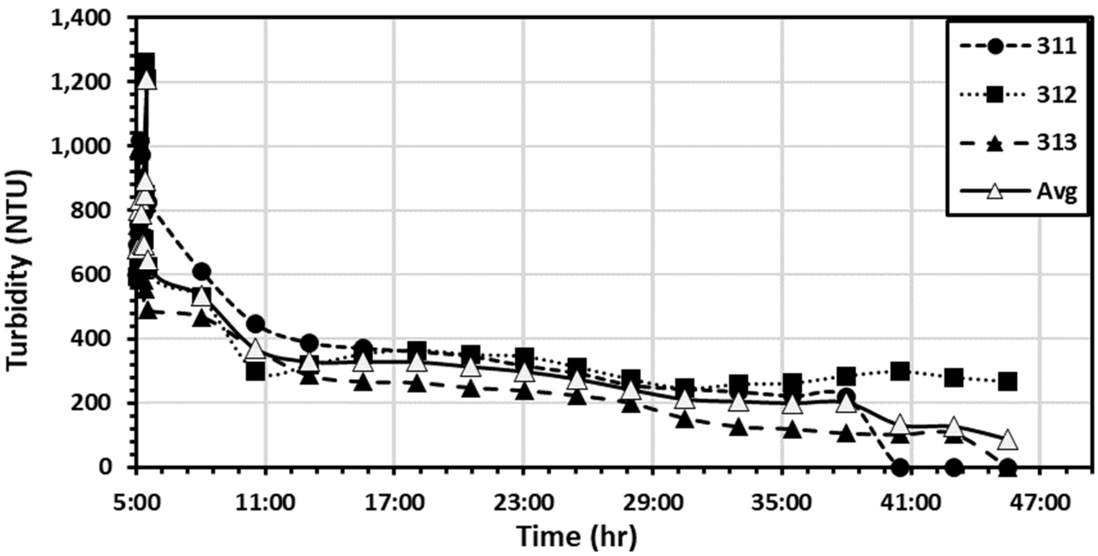
Inflow Sampling Location



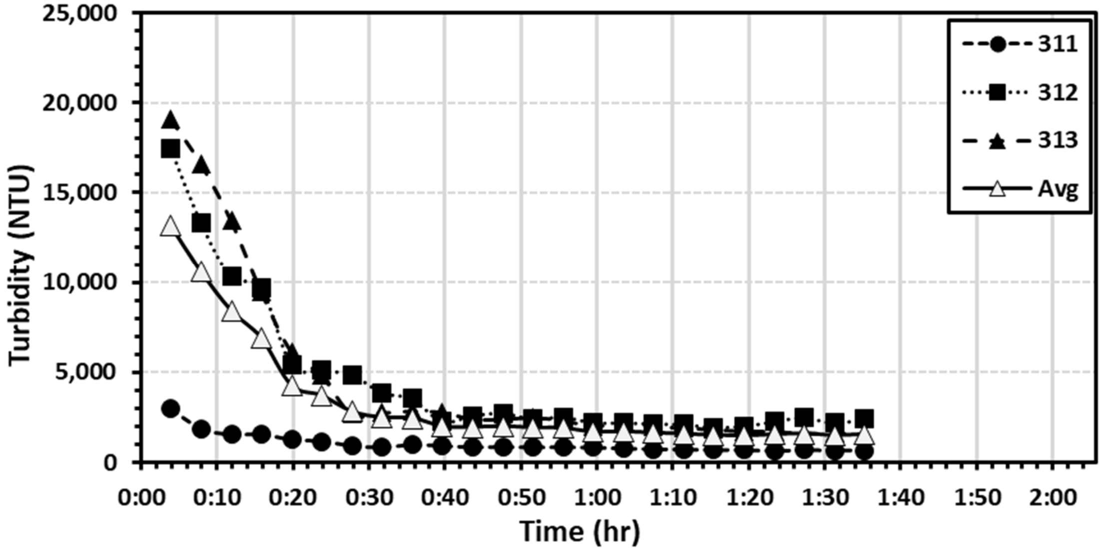
Inflow Sampling Location



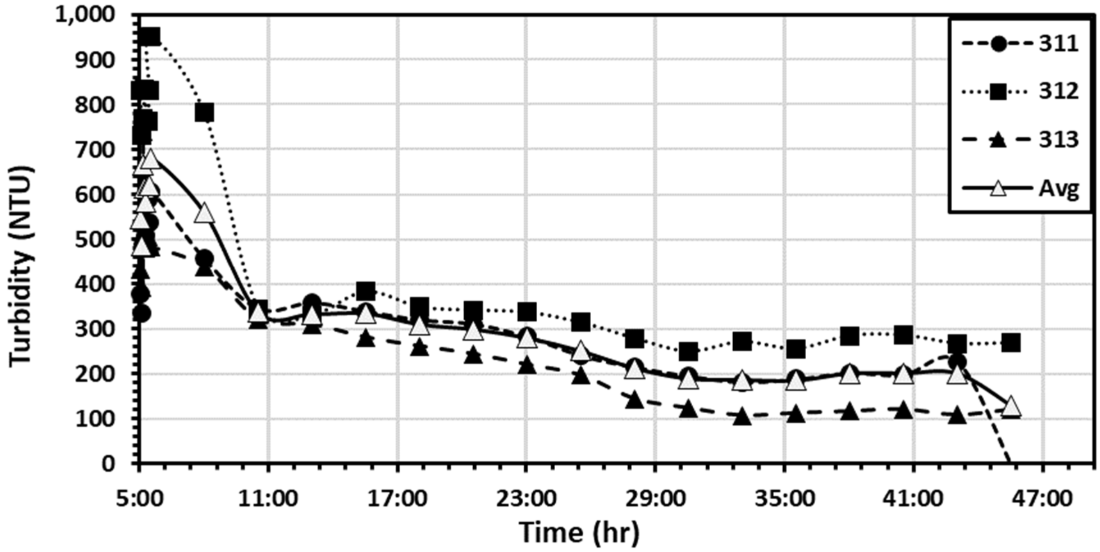
Bay 2 Sampling Location



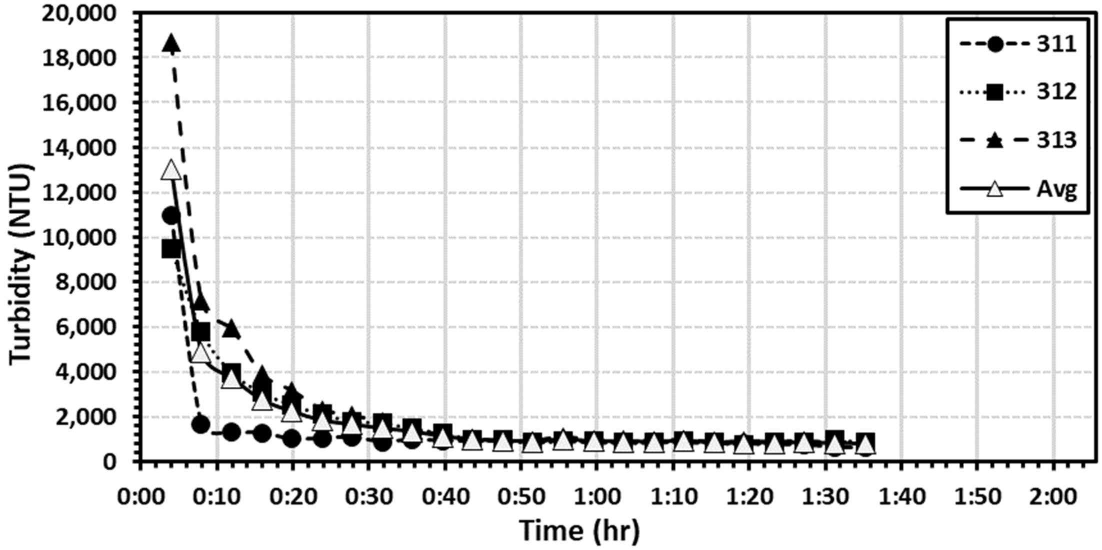
Bay 2 Sampling Location



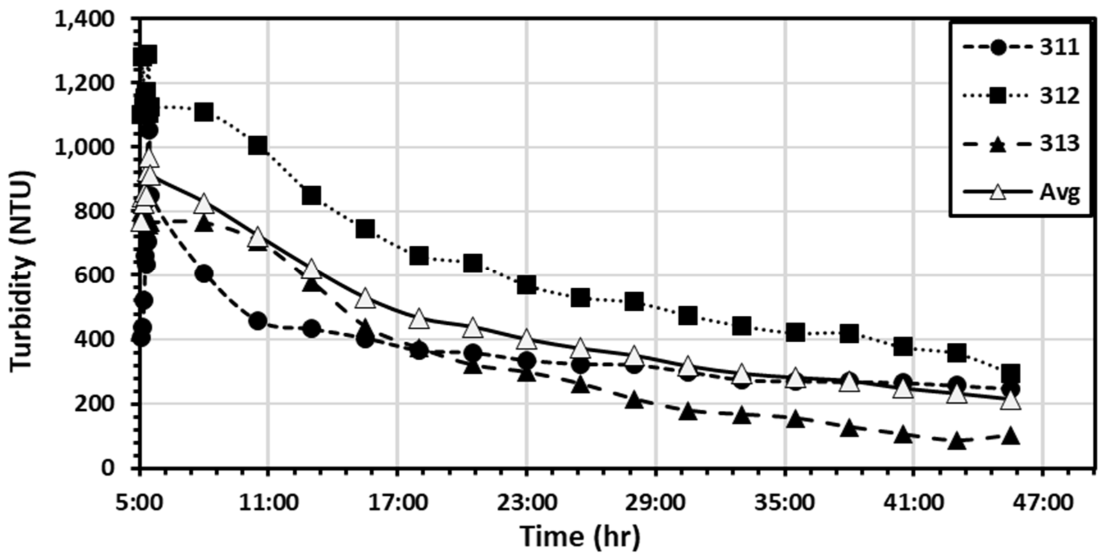
Bay 4 Bottom Sampling Location



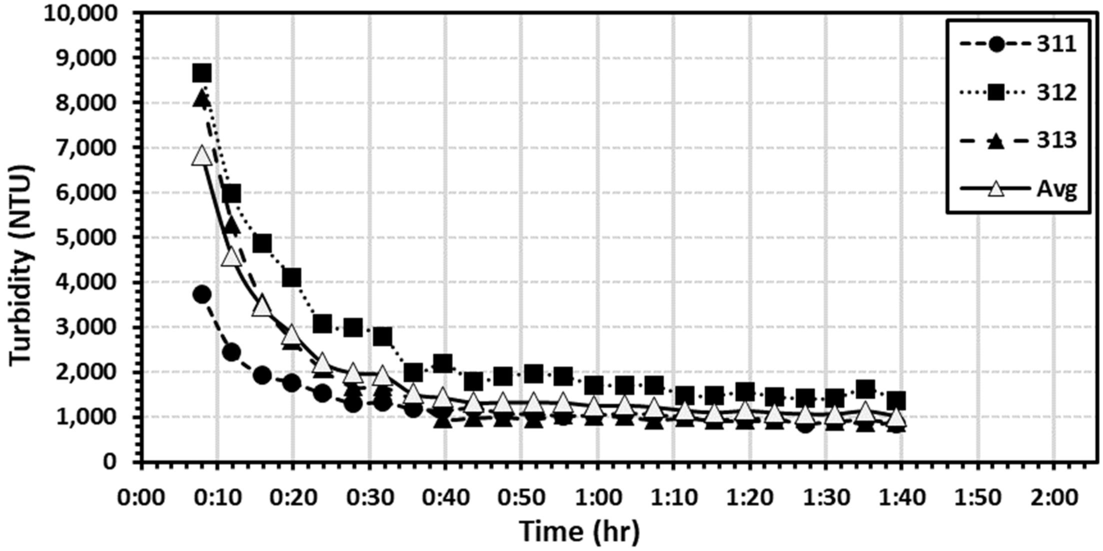
Bay 4 Bottom Sampling Location



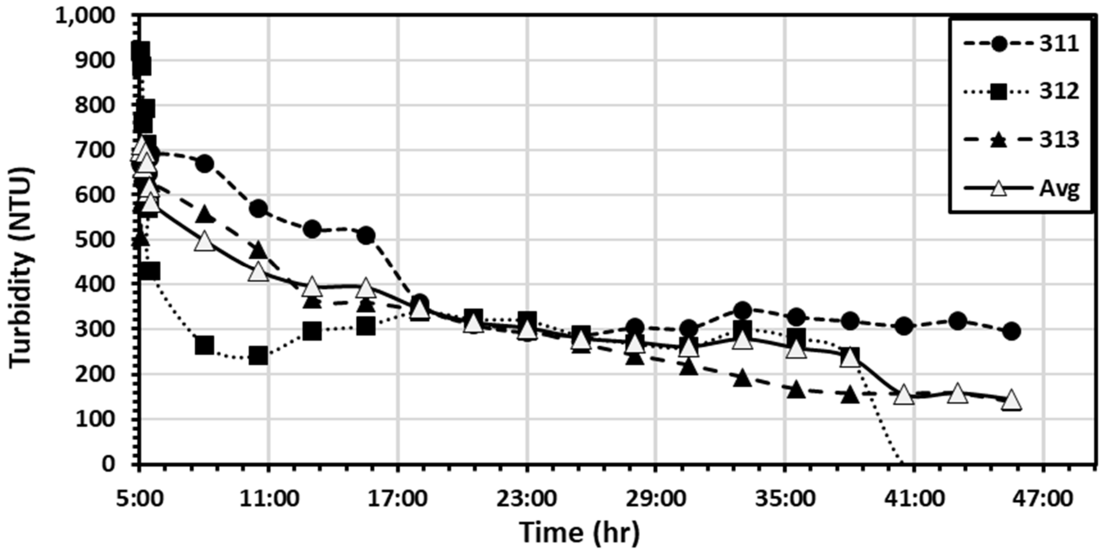
Bay 4 Top Sampling Location



Bay 4 Top Sampling Location

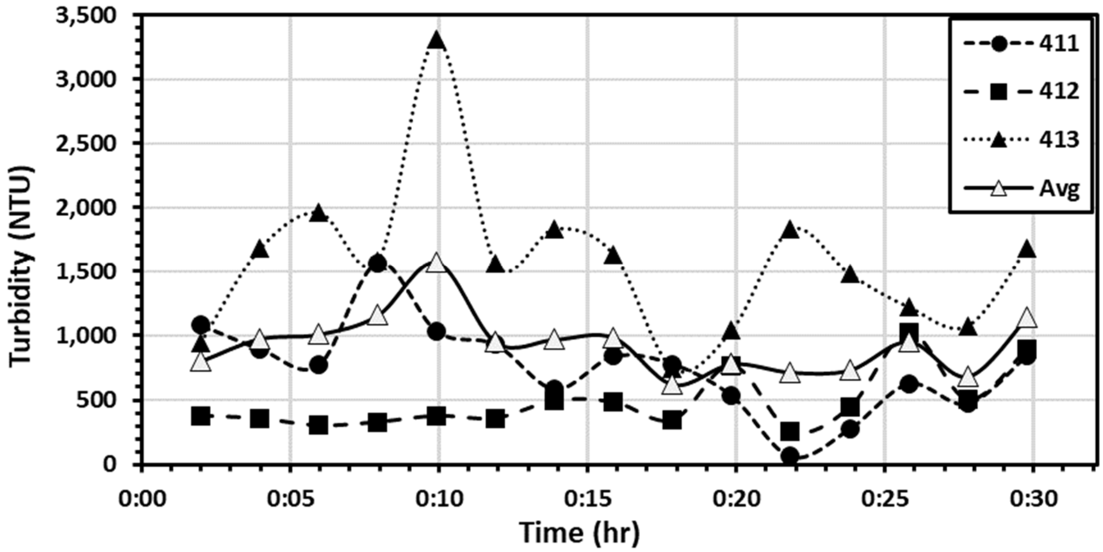


Discharge Sampling Location

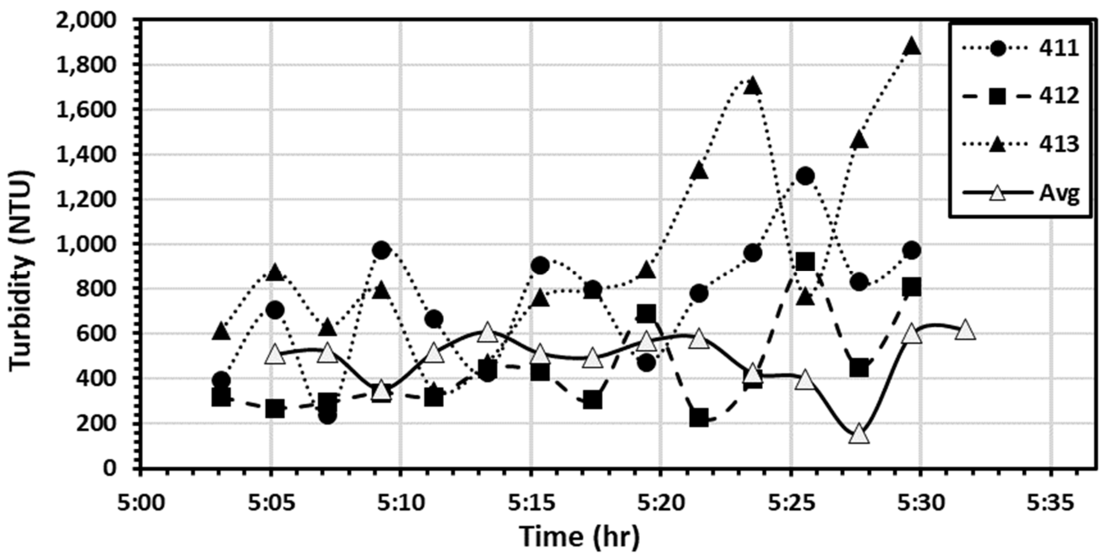


Discharge Sampling Location

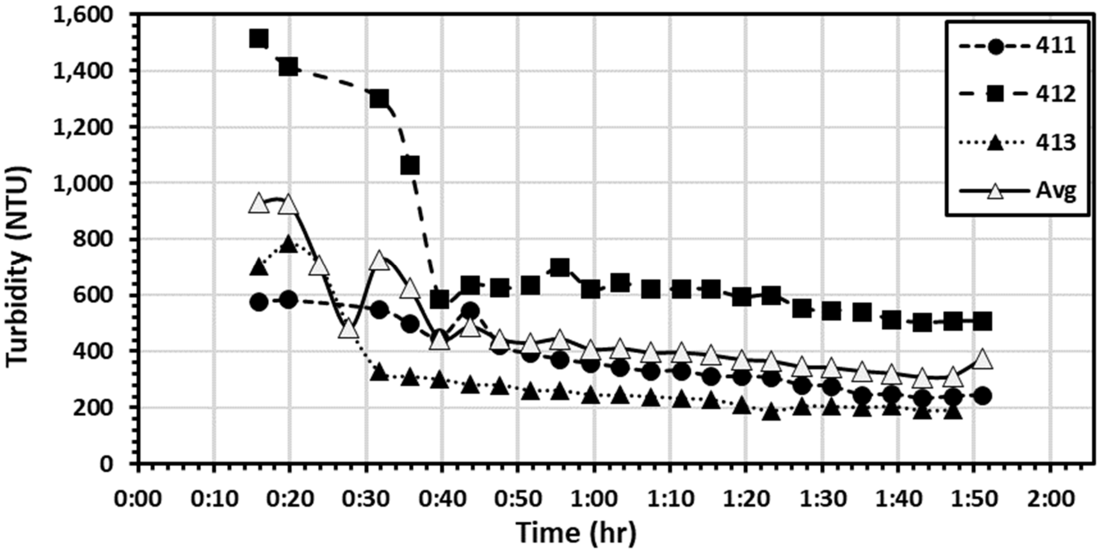
S5-Lined Testing with Baffles



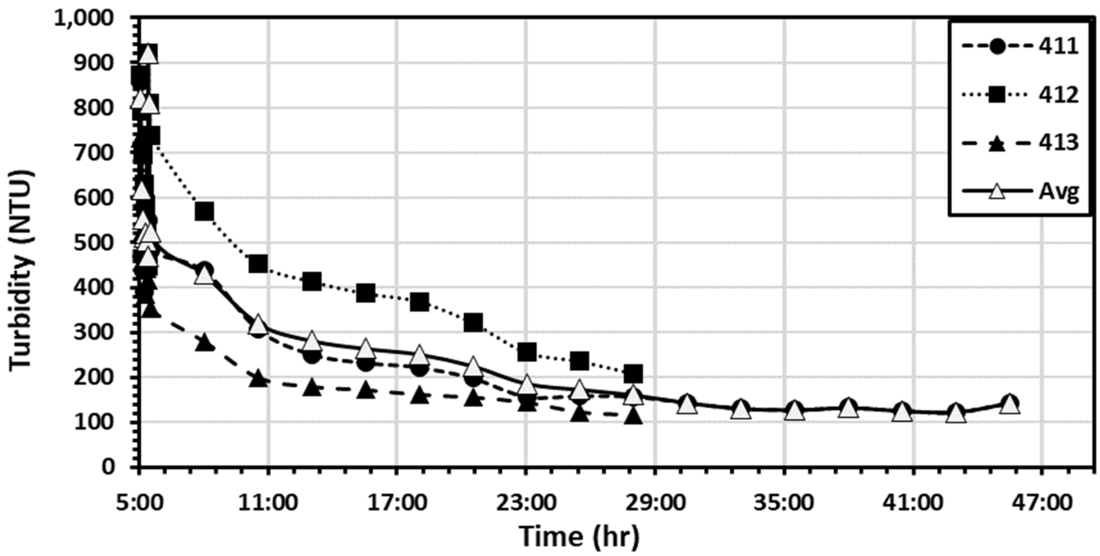
Inflow Sampling Location



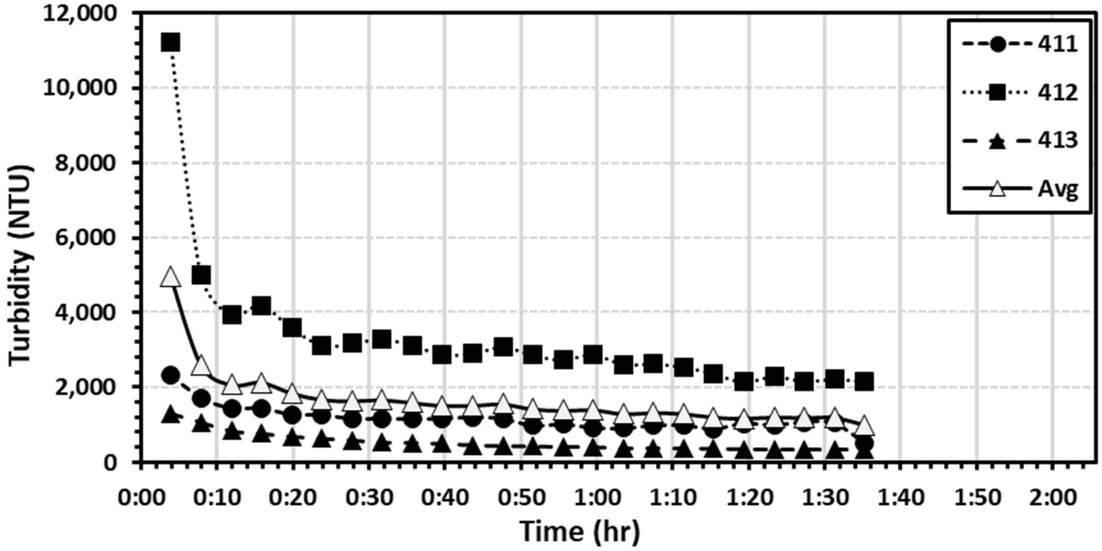
Inflow Sampling Location



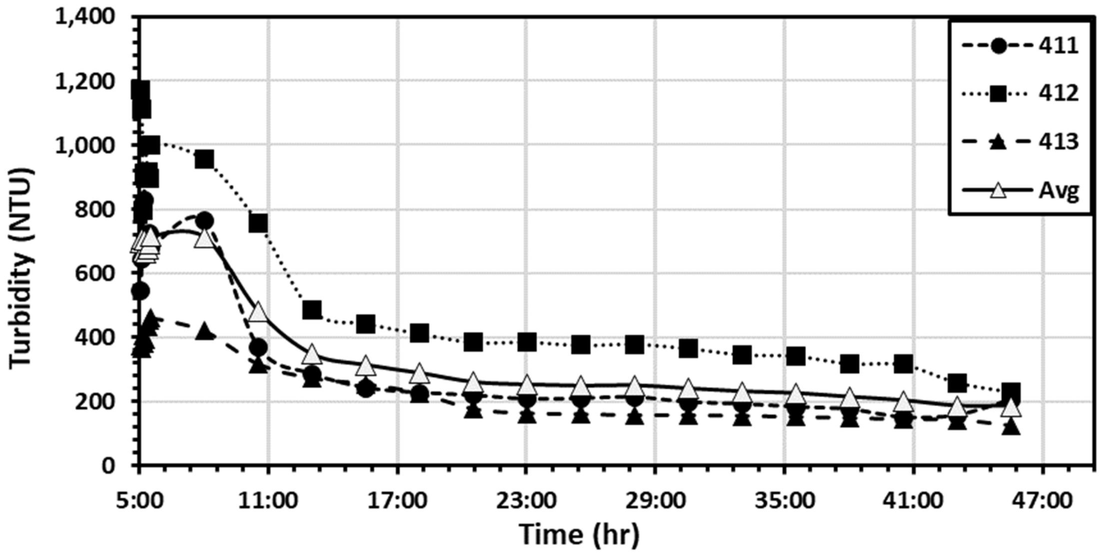
Bay 2 Sampling Location



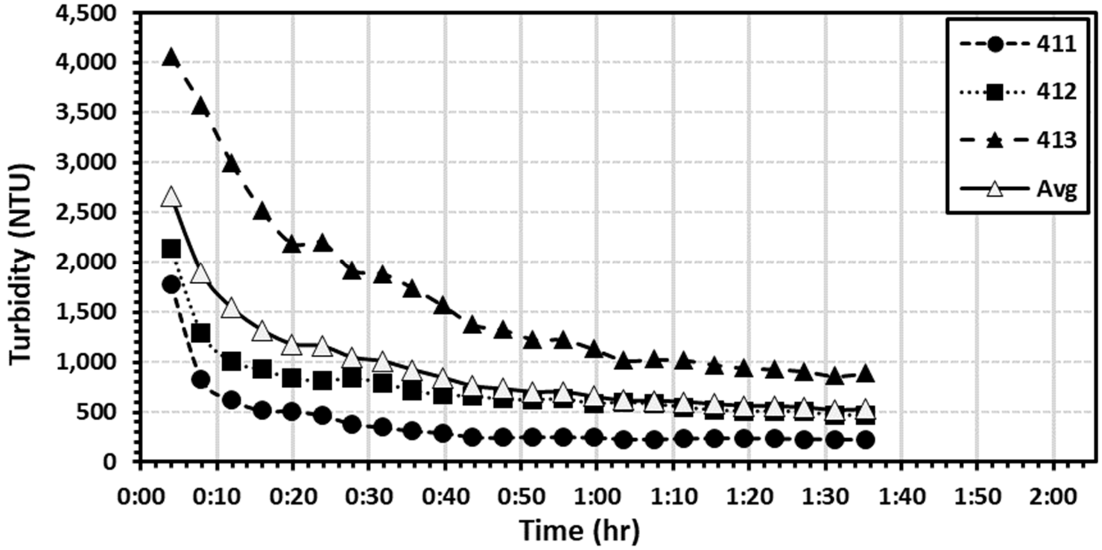
Bay 2 Sampling Location



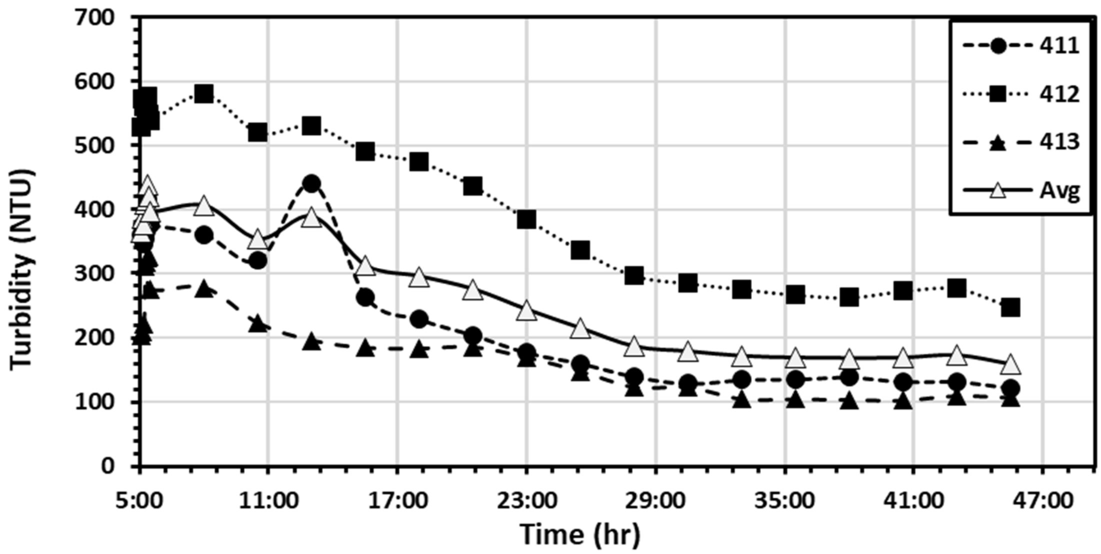
Bay 4 Bottom Sampling Location



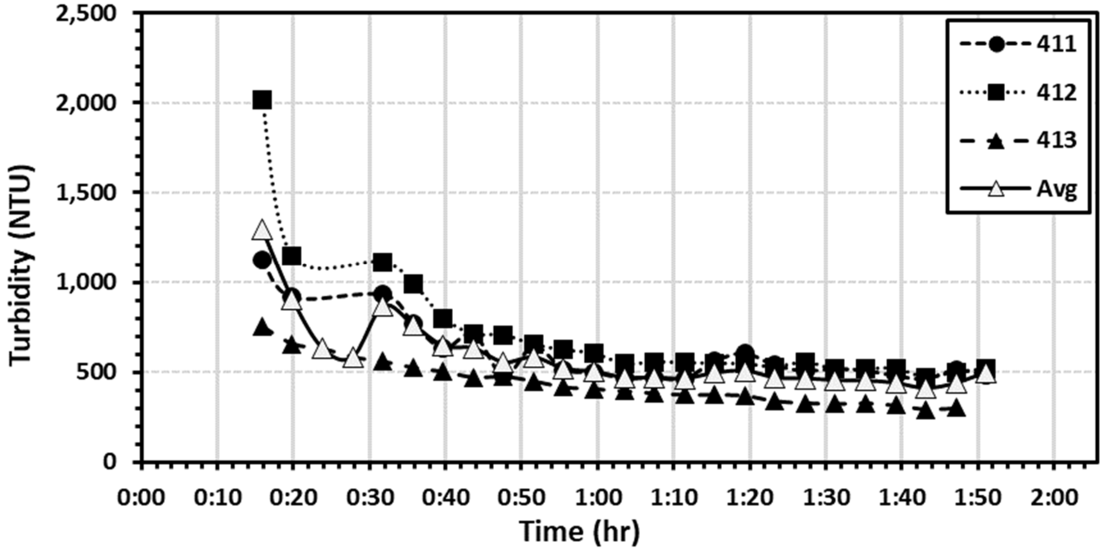
Bay 4 Bottom Sampling Location



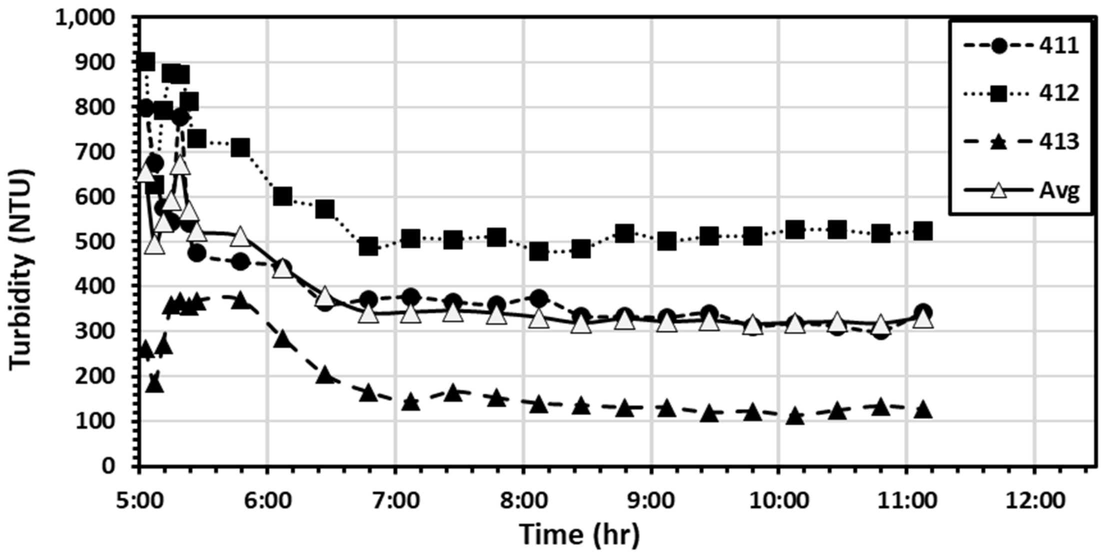
Bay 4 Top Sampling Location



Bay 4 Top Sampling Location

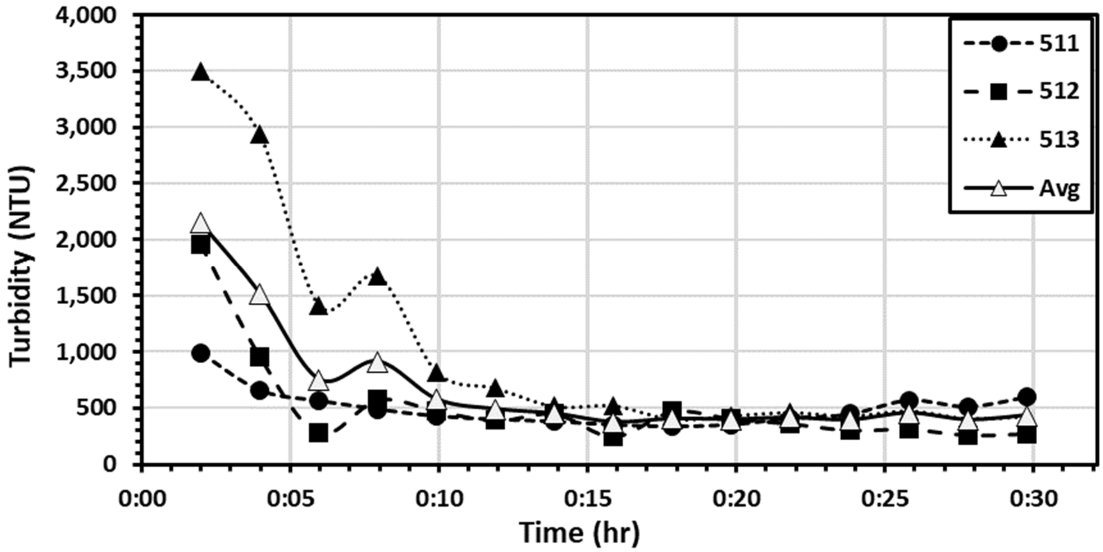


Discharge Sampling Location

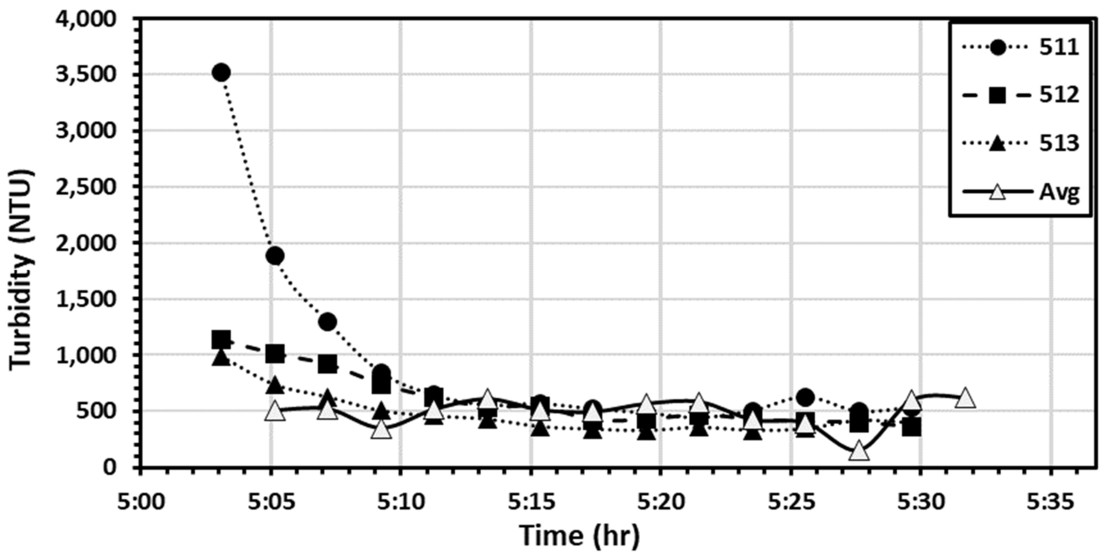


Discharge Sampling Location

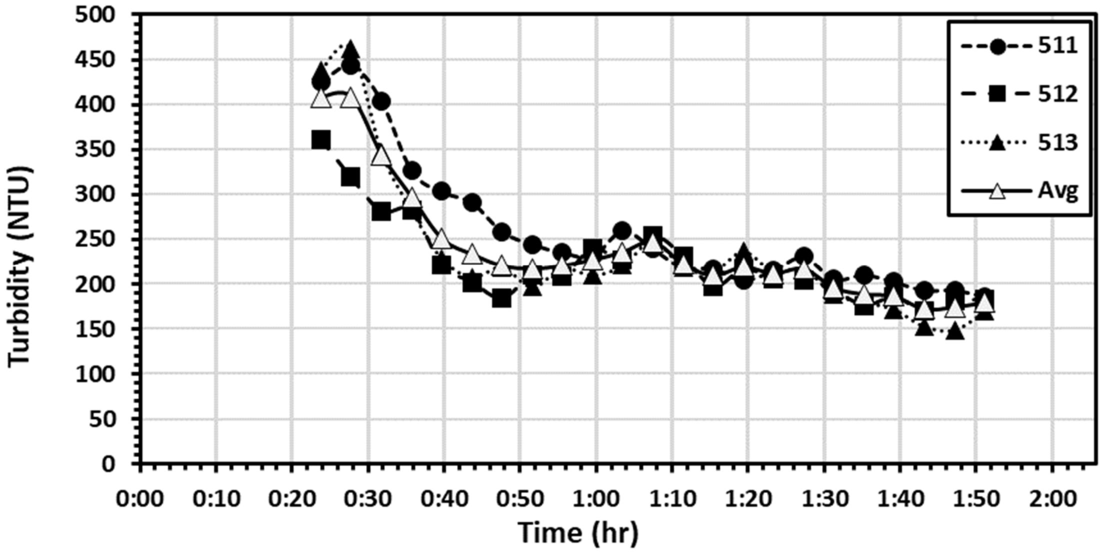
S6-Lined Testing with Forebay



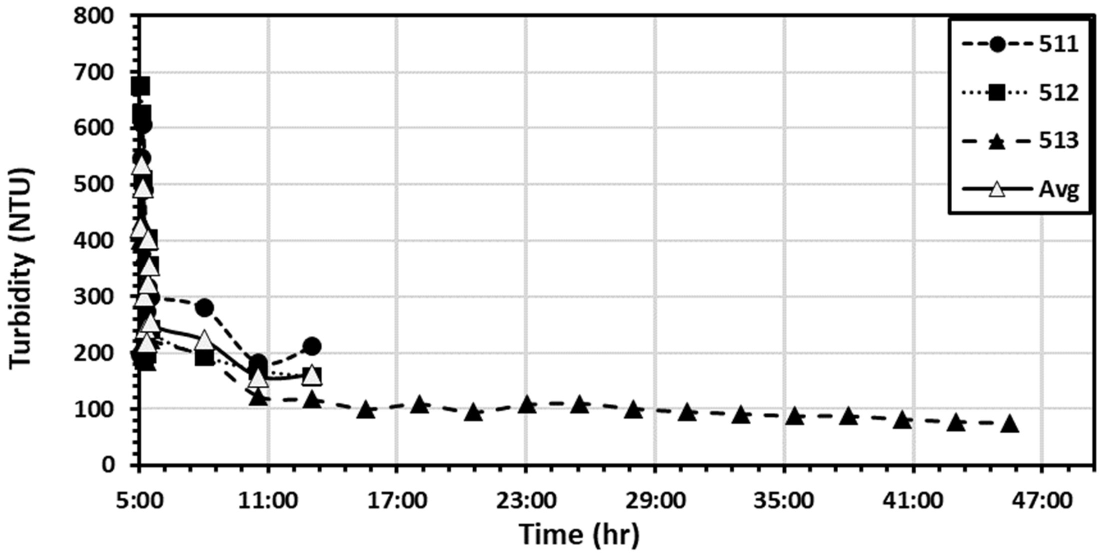
Inflow Sampling Location



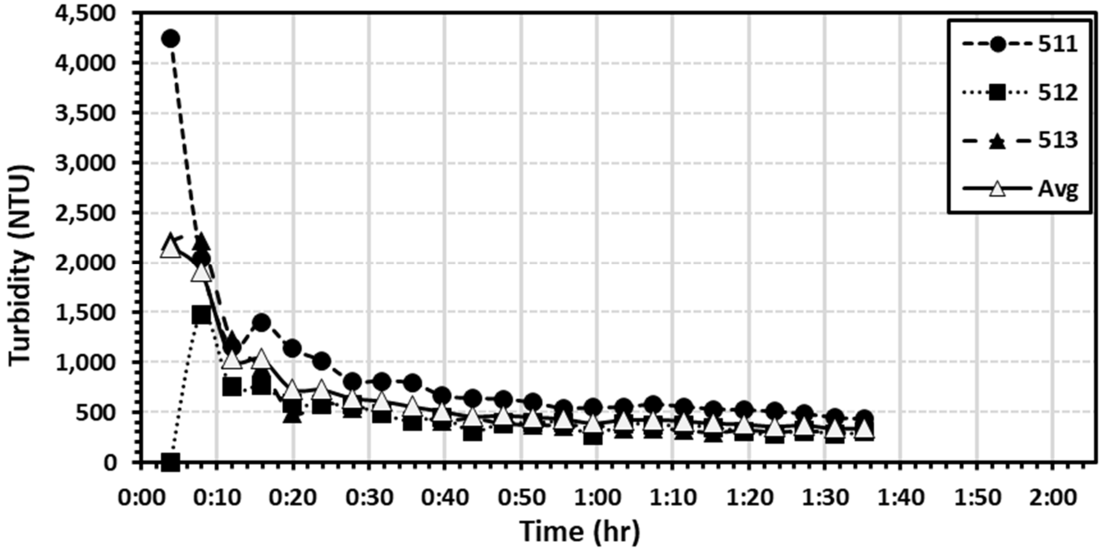
Inflow Sampling Location



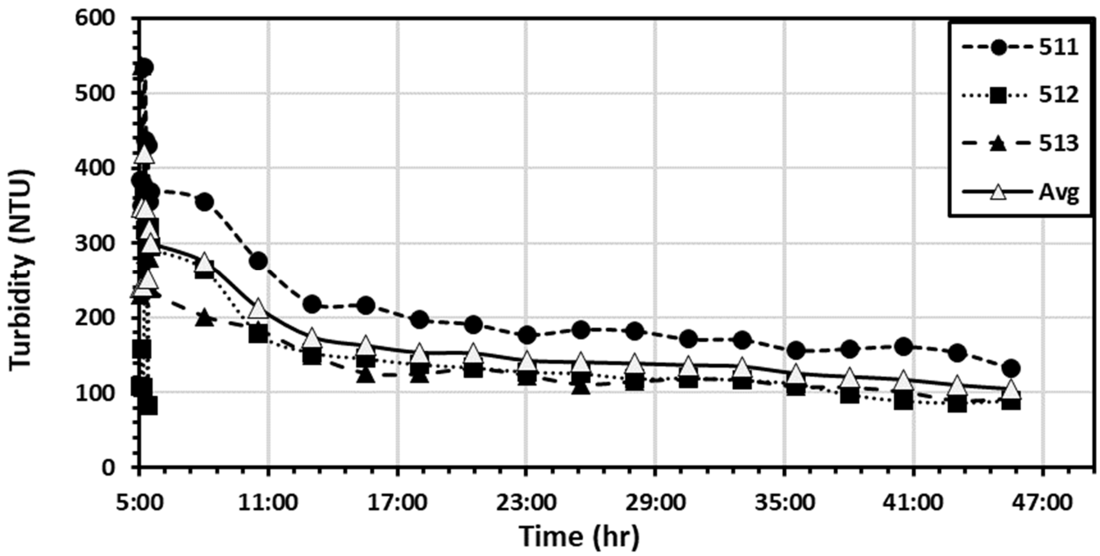
Bay 2 Sampling Location



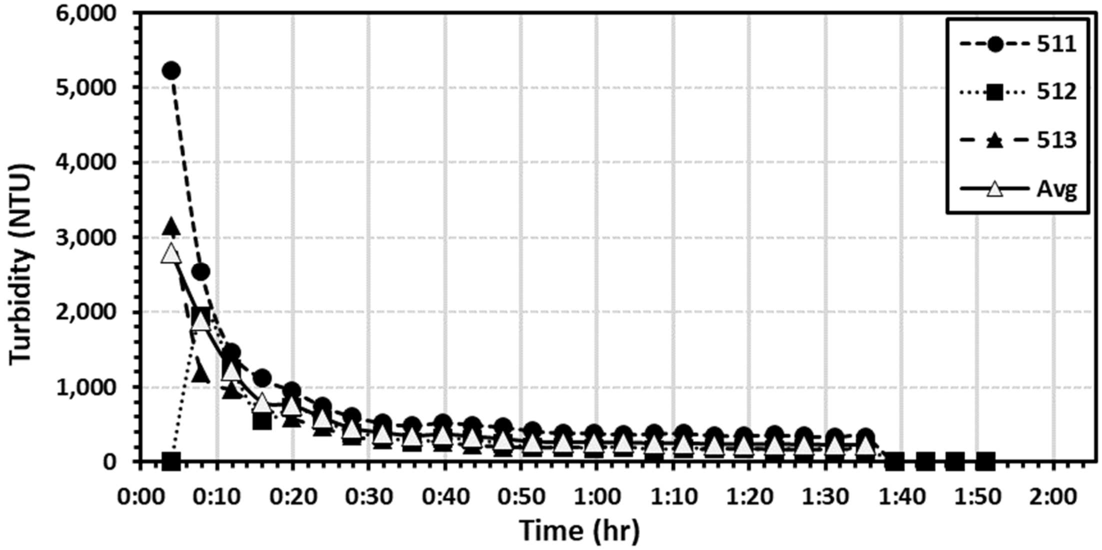
Bay 2 Sampling Location



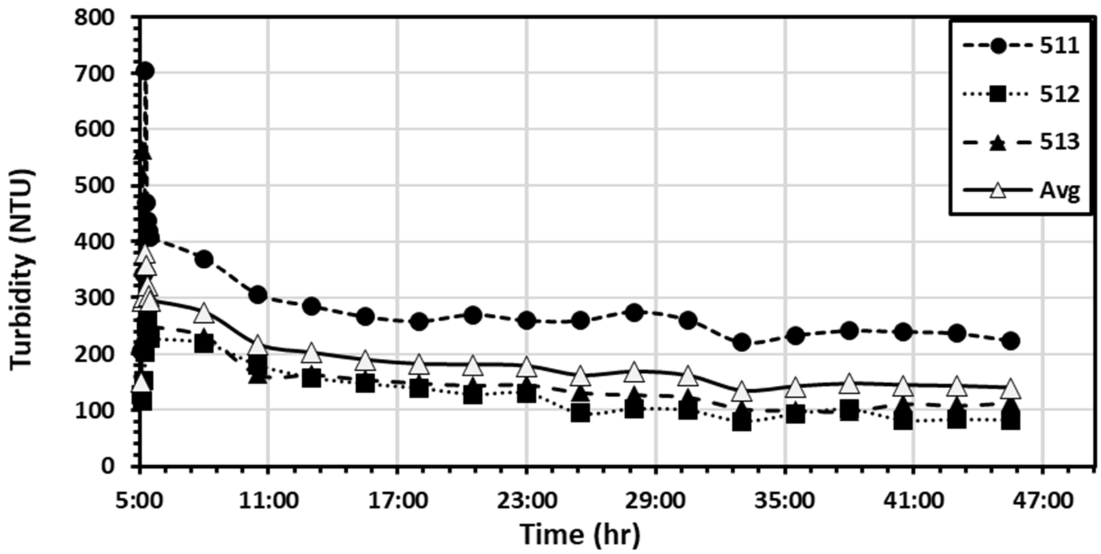
Bay 4 Bottom Sampling Location



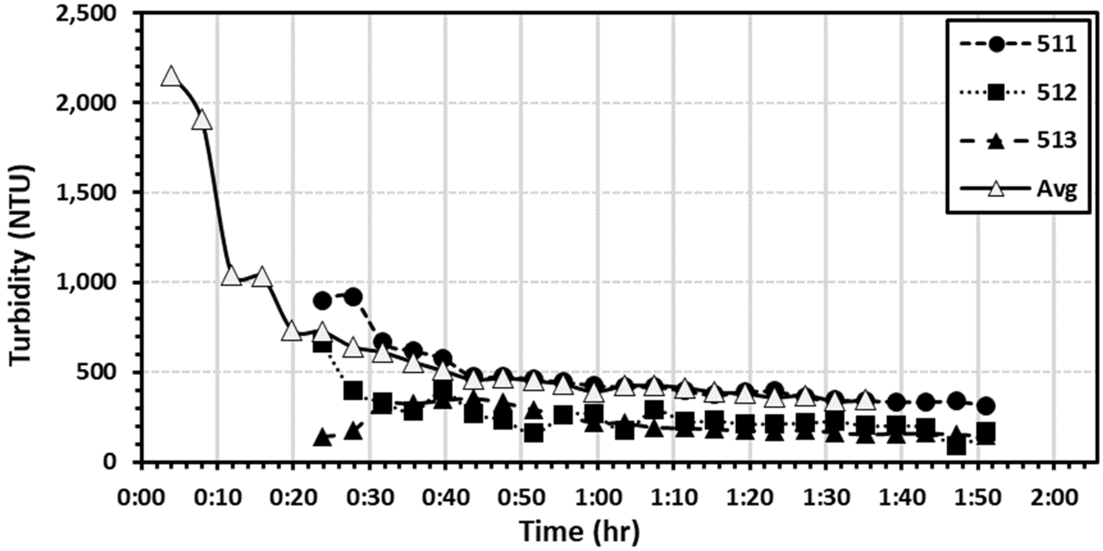
Bay 4 Bottom Sampling Location



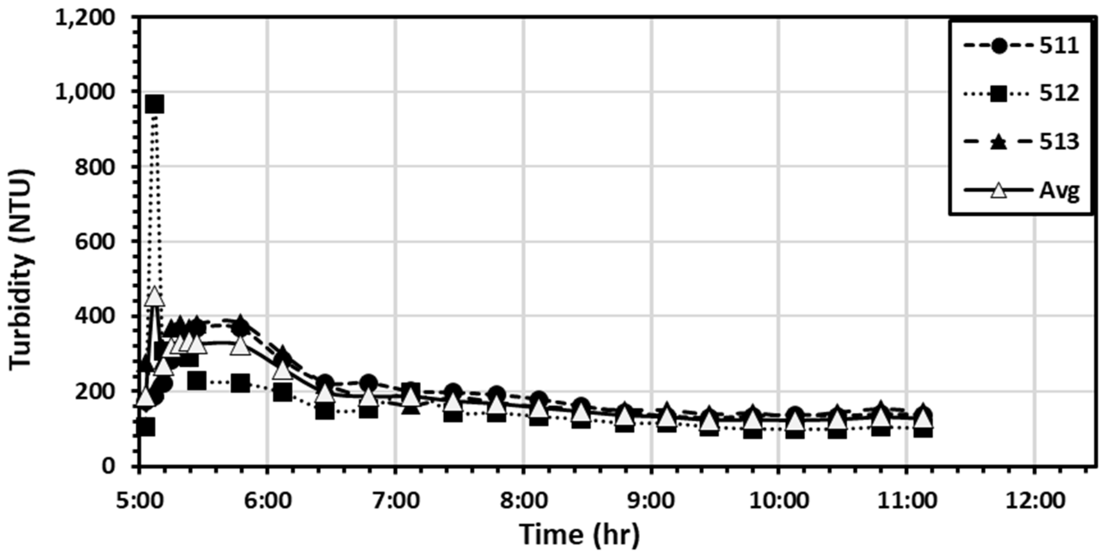
Bay 4 Top Sampling Location



Bay 4 Top Sampling Location

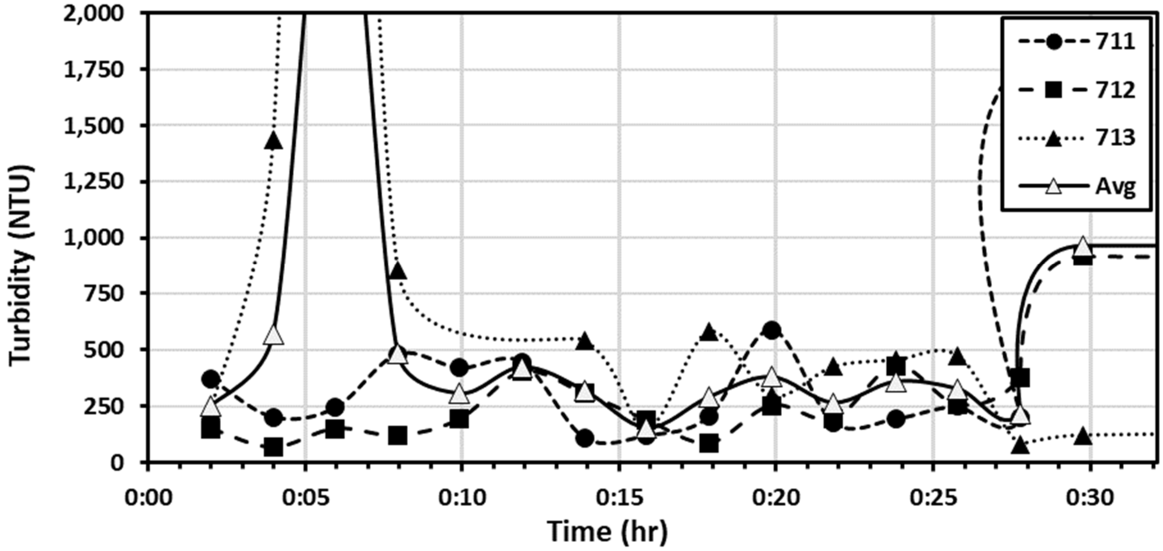


Discharge Sampling Location

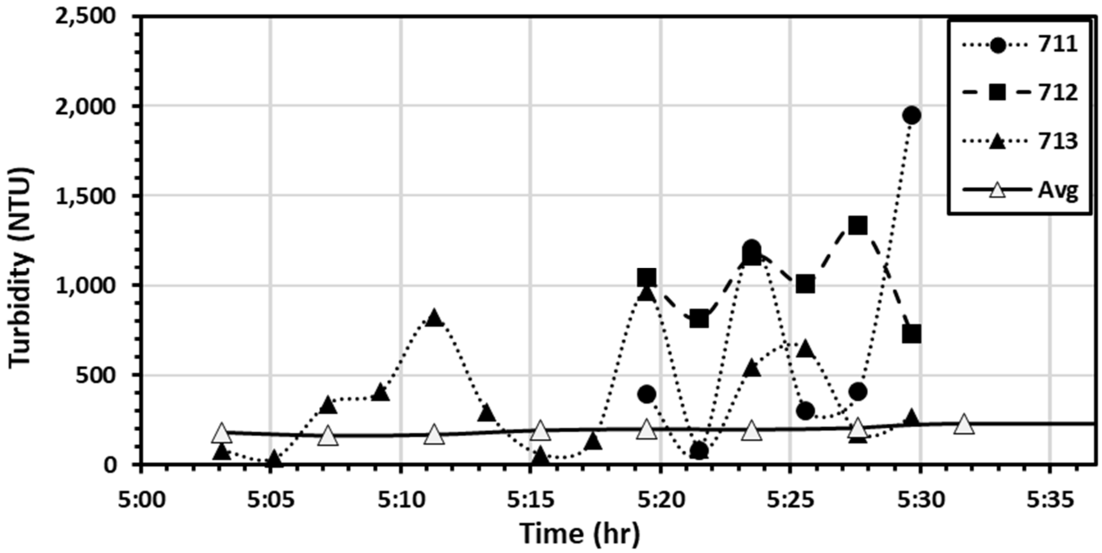


Discharge Sampling Location

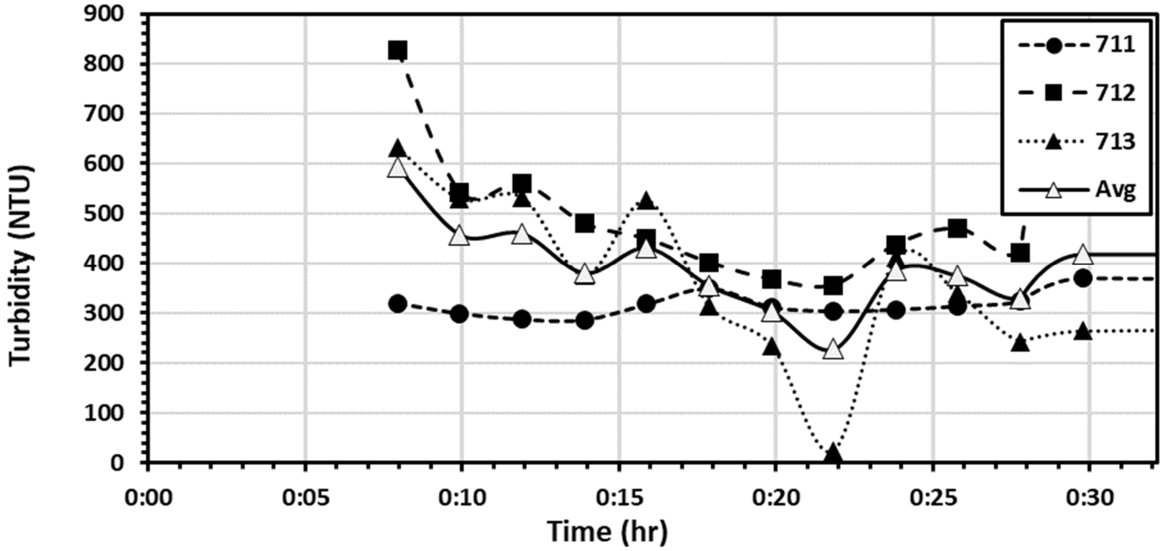
S7-MFE-I Testing



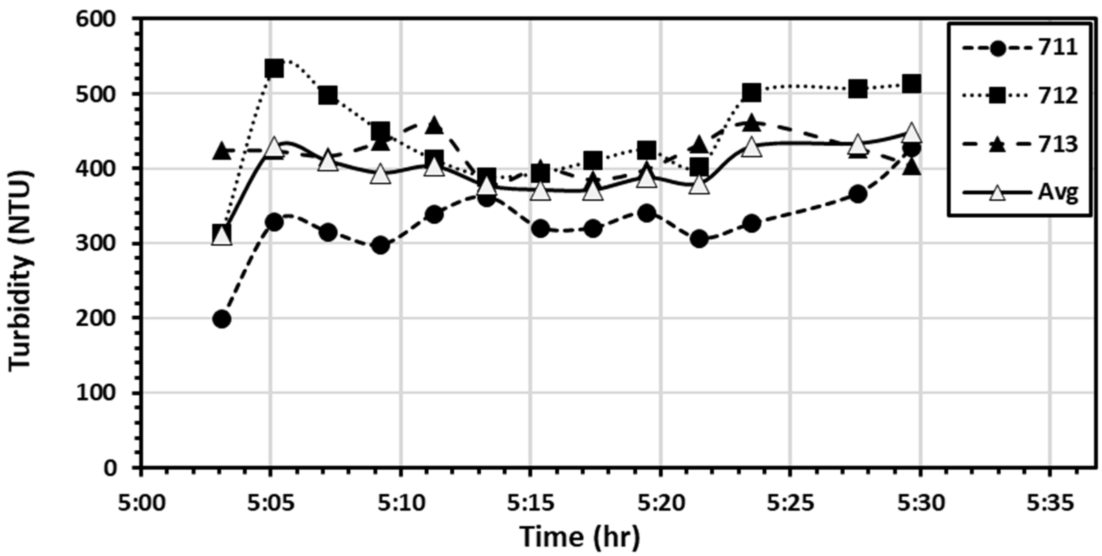
Inflow Sampling Location



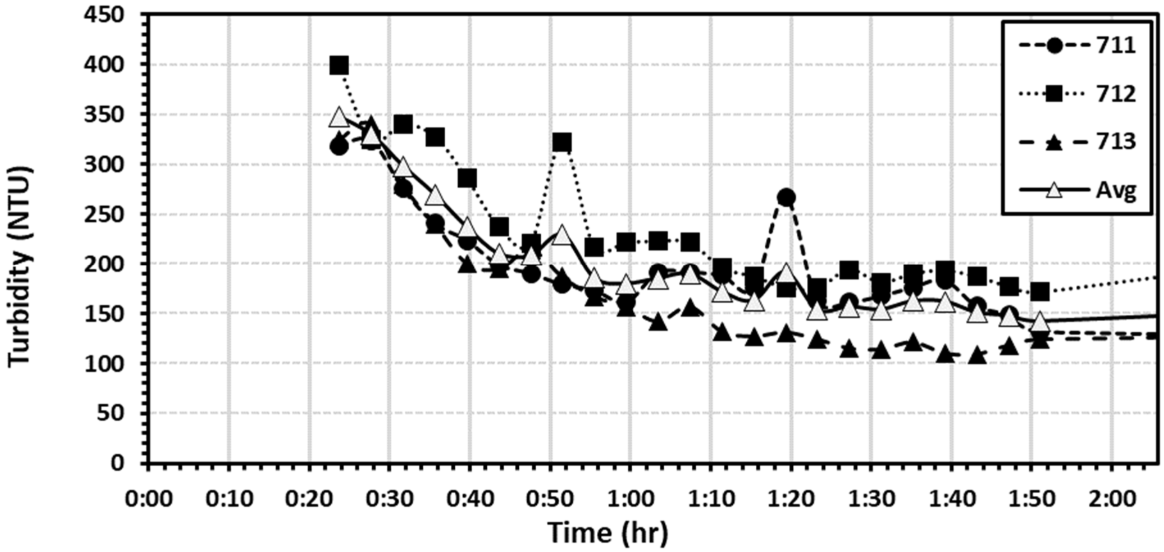
Inflow Sampling Location



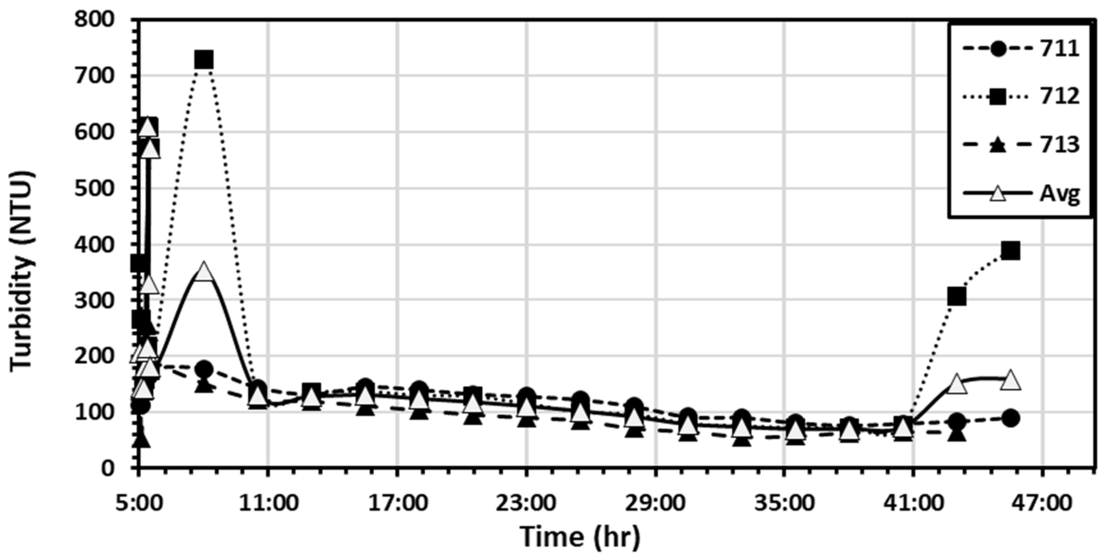
Forebay Sampling Location



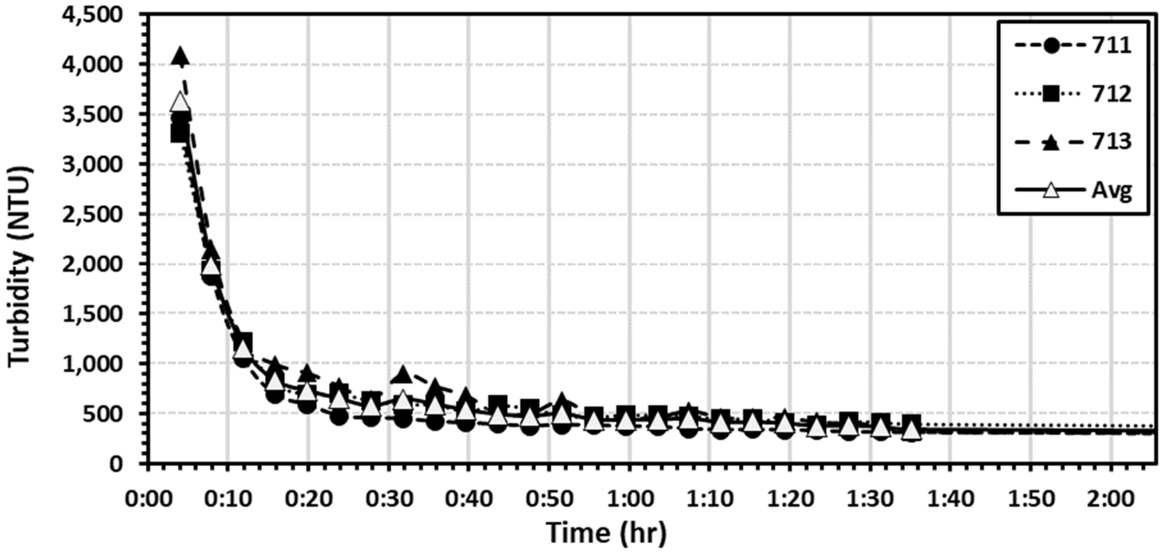
Forebay Sampling Location



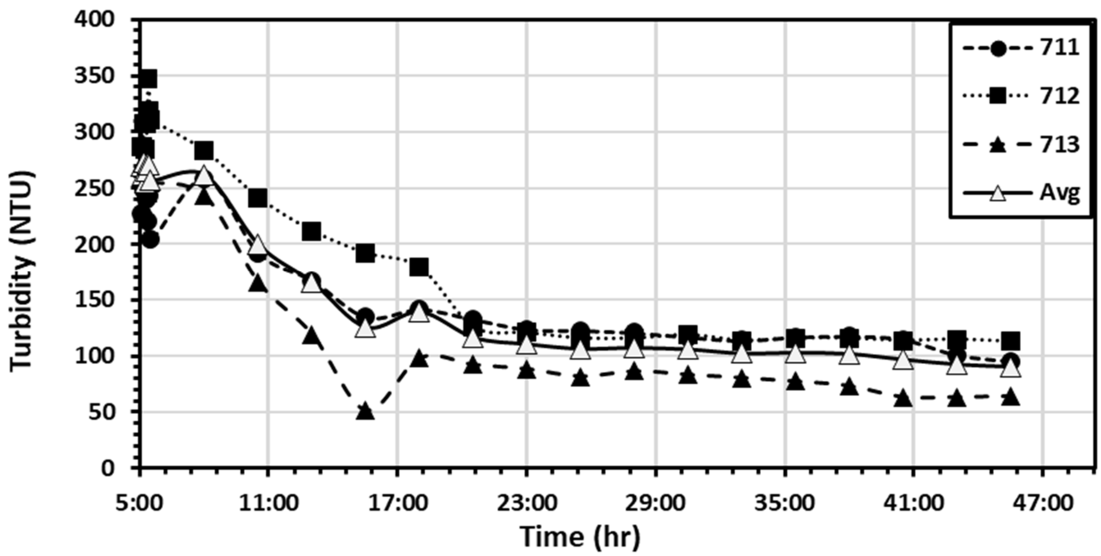
Bay 2 Sampling Location



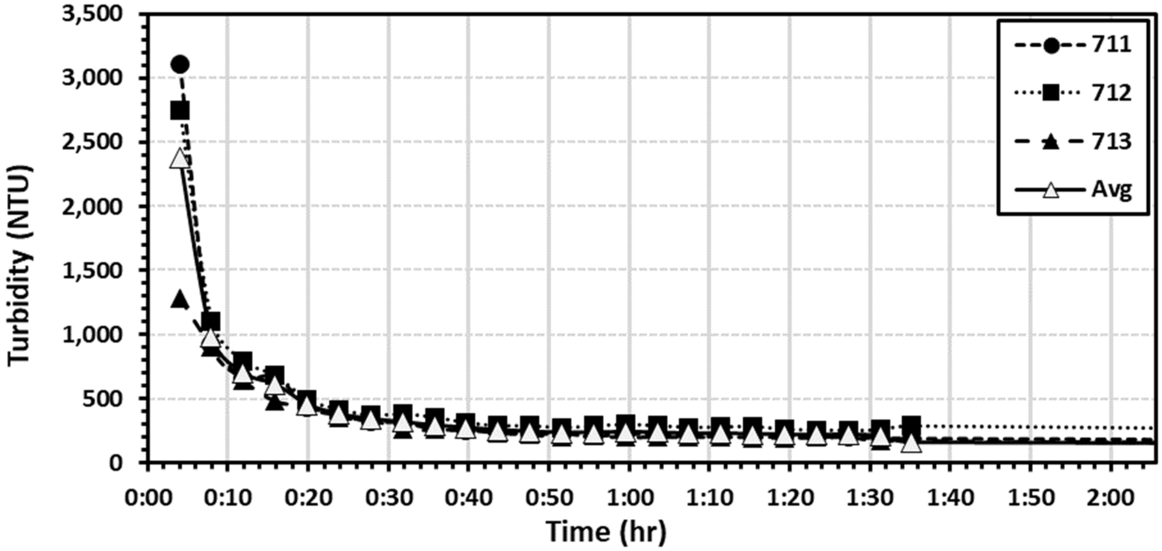
Bay 2 Sampling Location



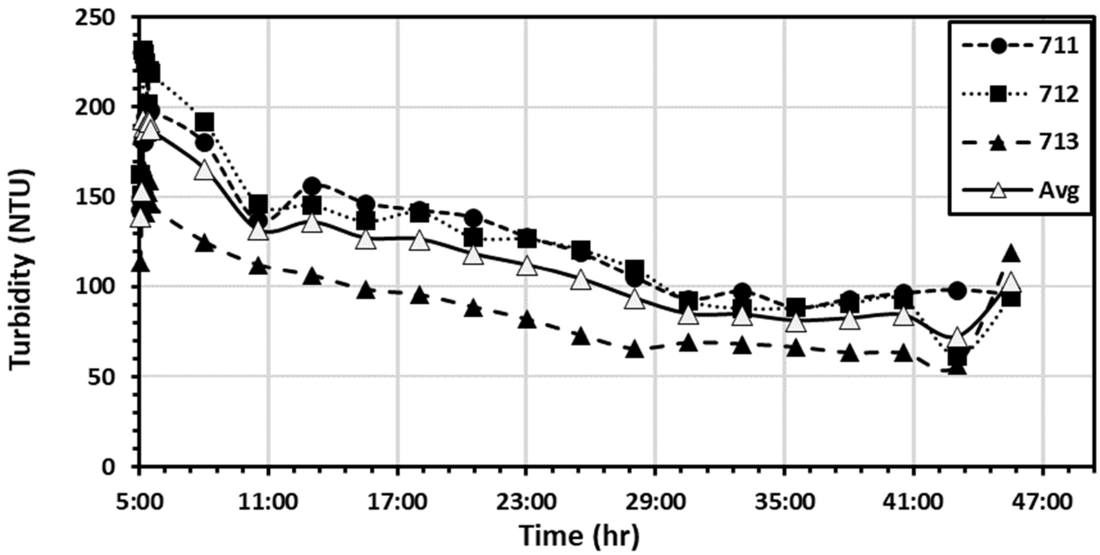
Bay 4 Bottom Sampling Location



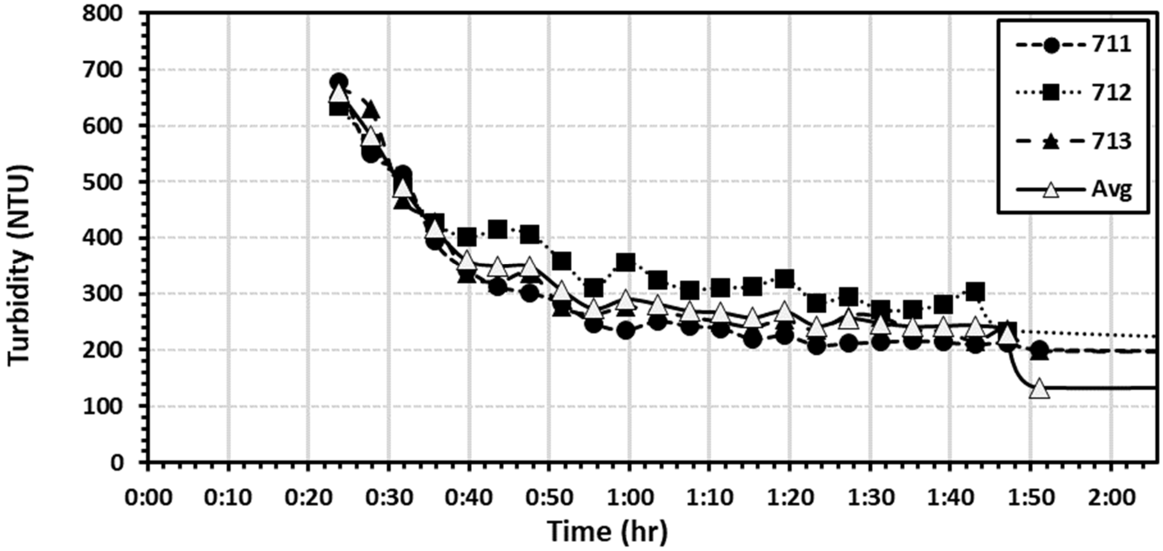
Bay 4 Bottom Sampling Location



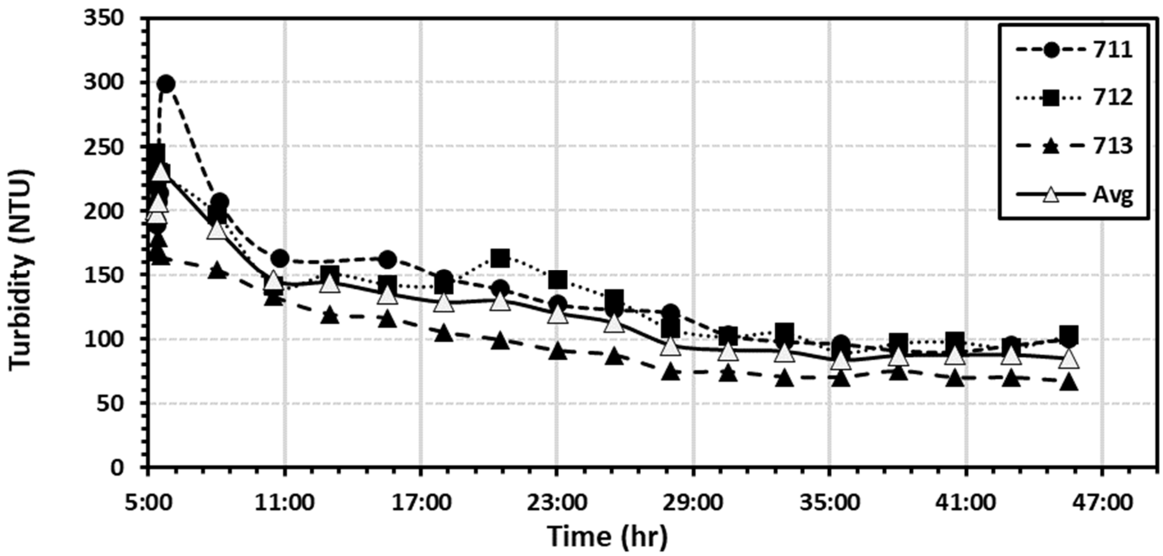
Bay 4 Top Sampling Location



Bay 4 Top Sampling Location

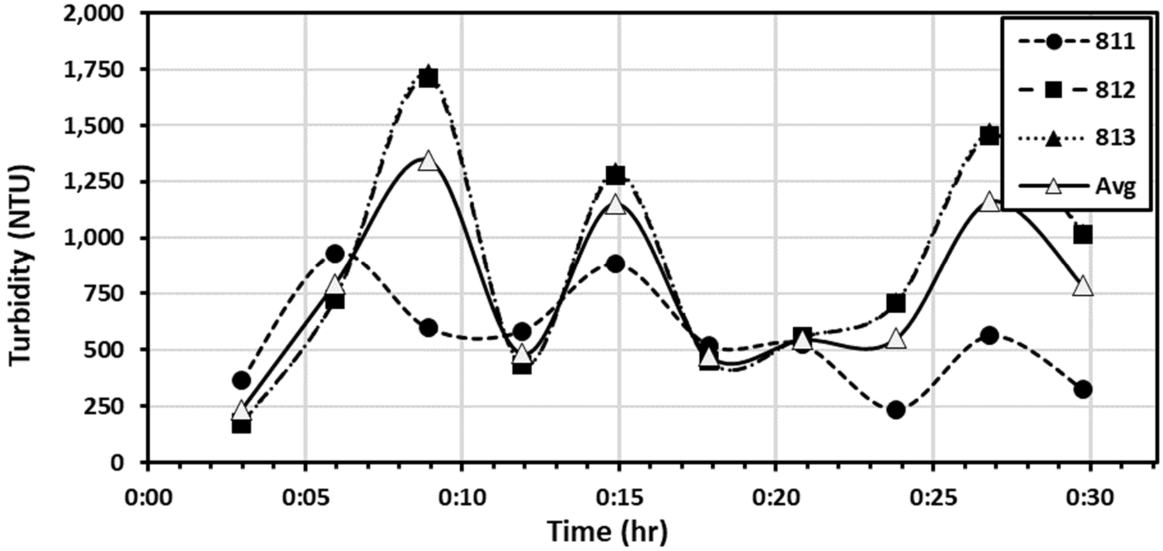


Discharge Sampling Location

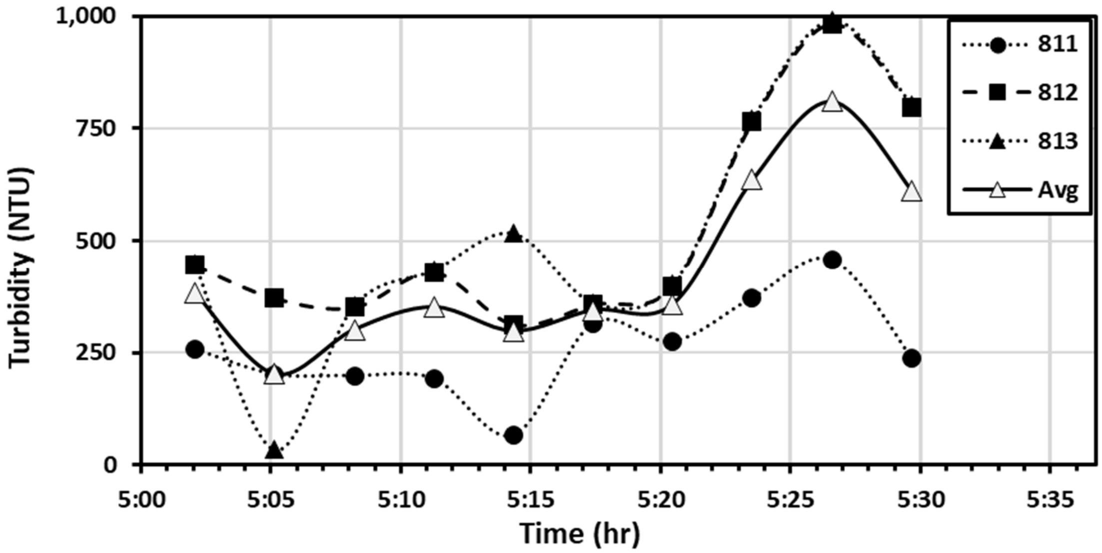


Discharge Sampling Location

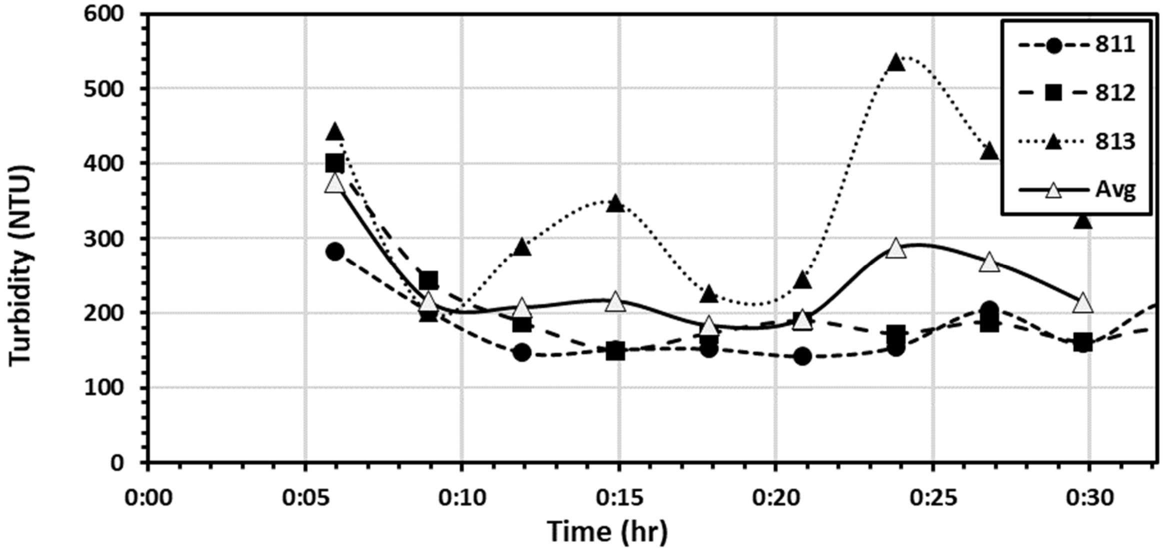
S8-MFE-I +Flocculant Testing



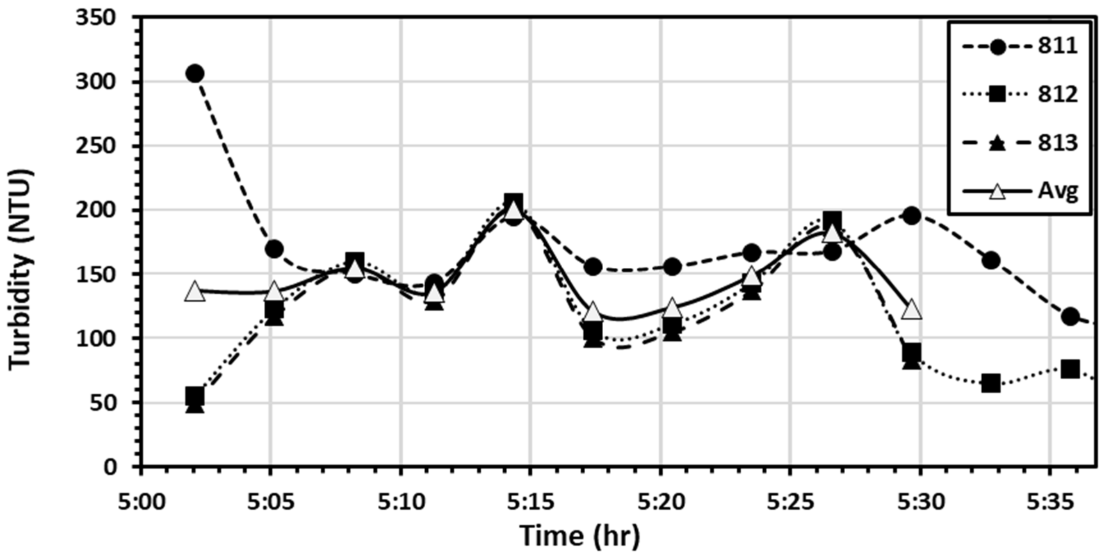
Inflow Sampling Location



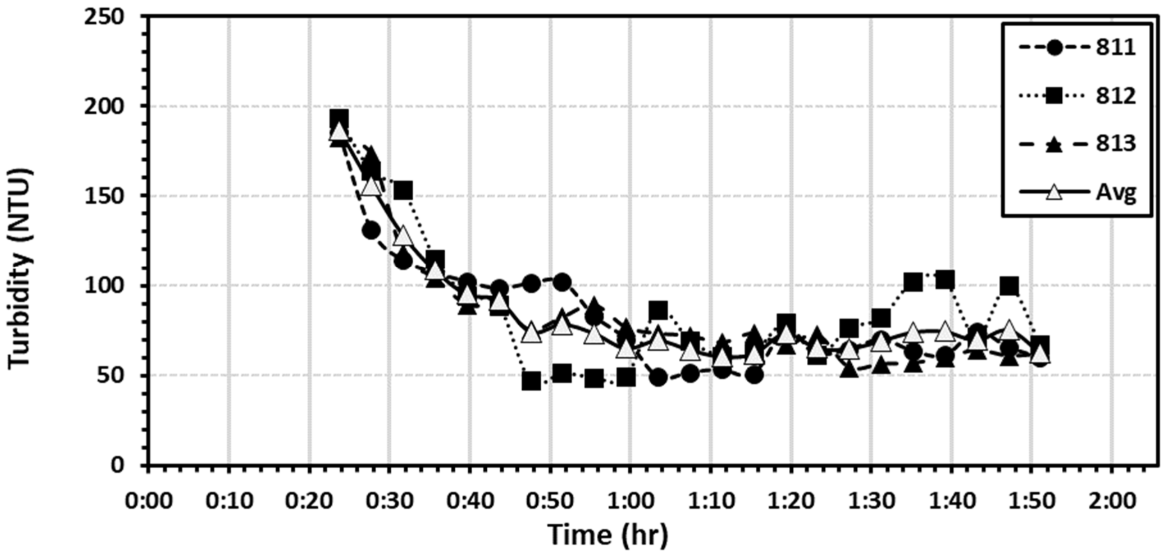
Inflow Sampling Location



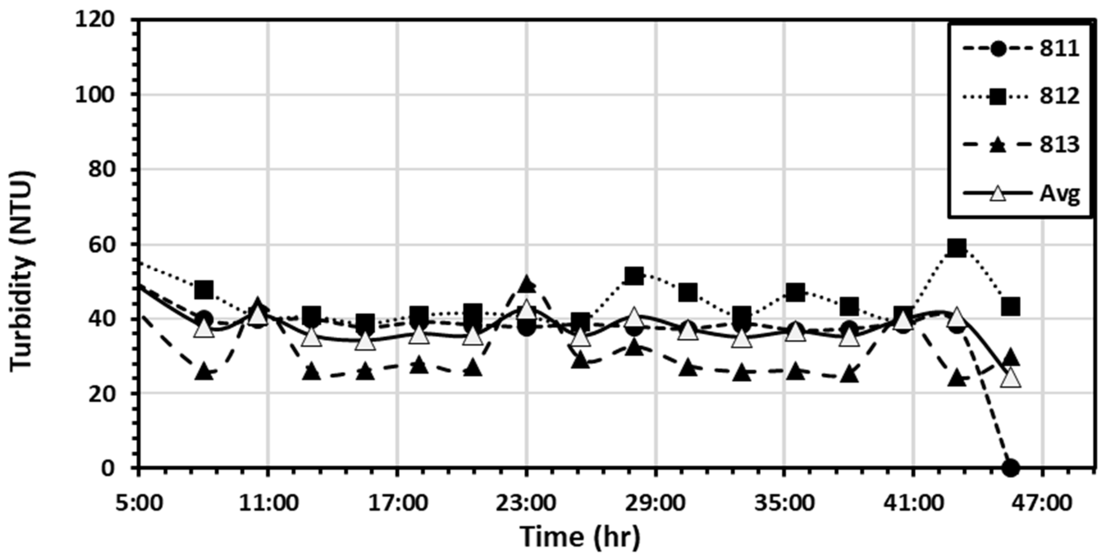
Forebay Sampling Location



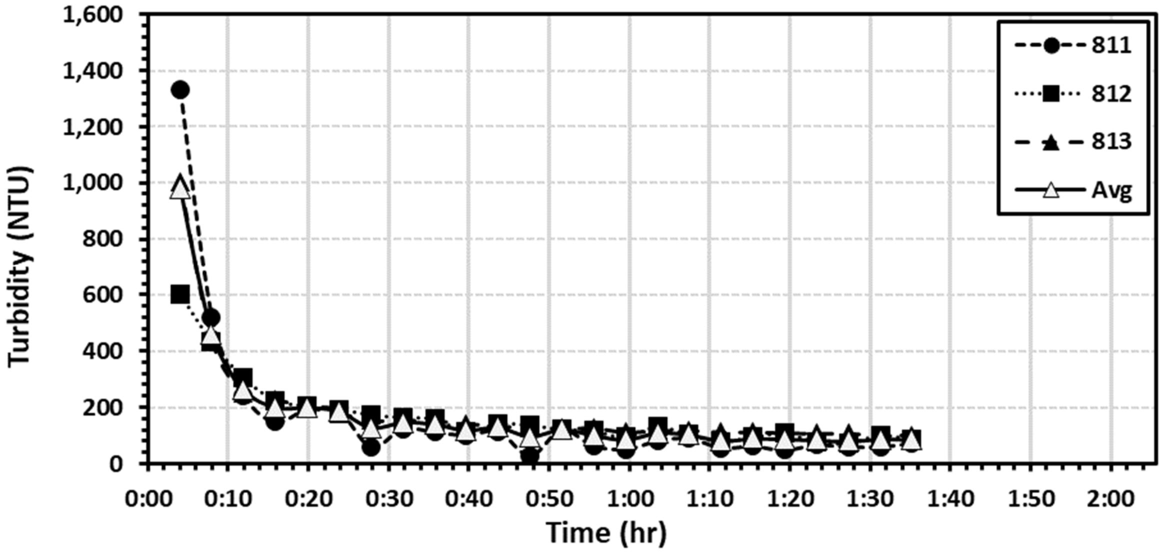
Forebay Sampling Location



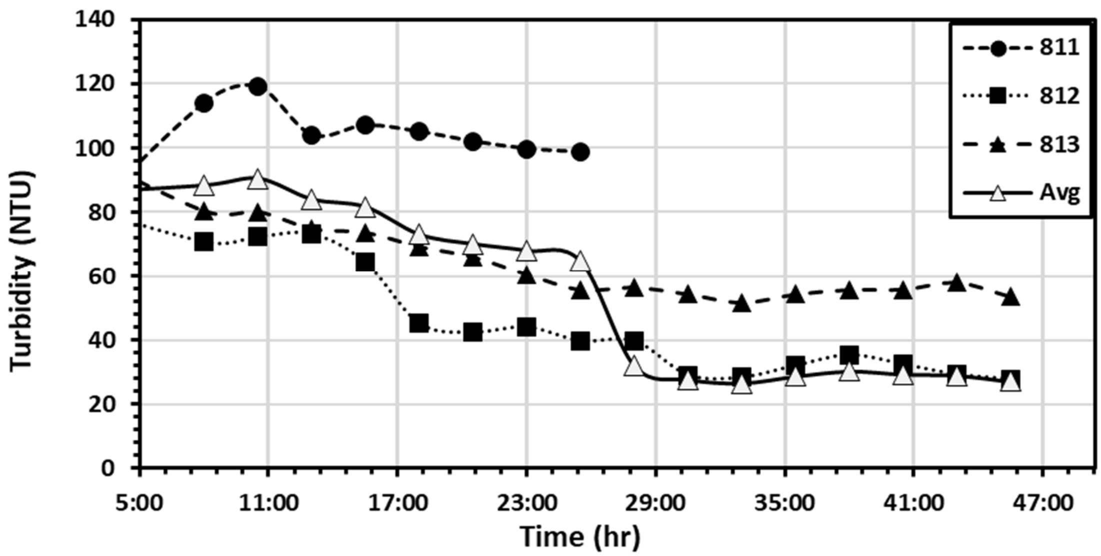
Bay 2 Sampling Location



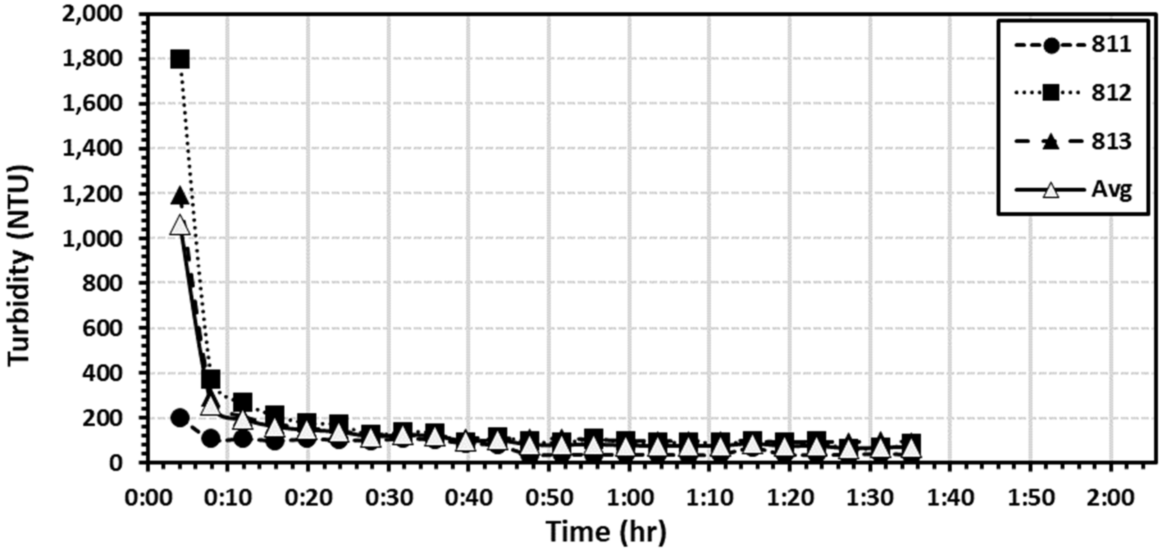
Bay 2 Sampling Location



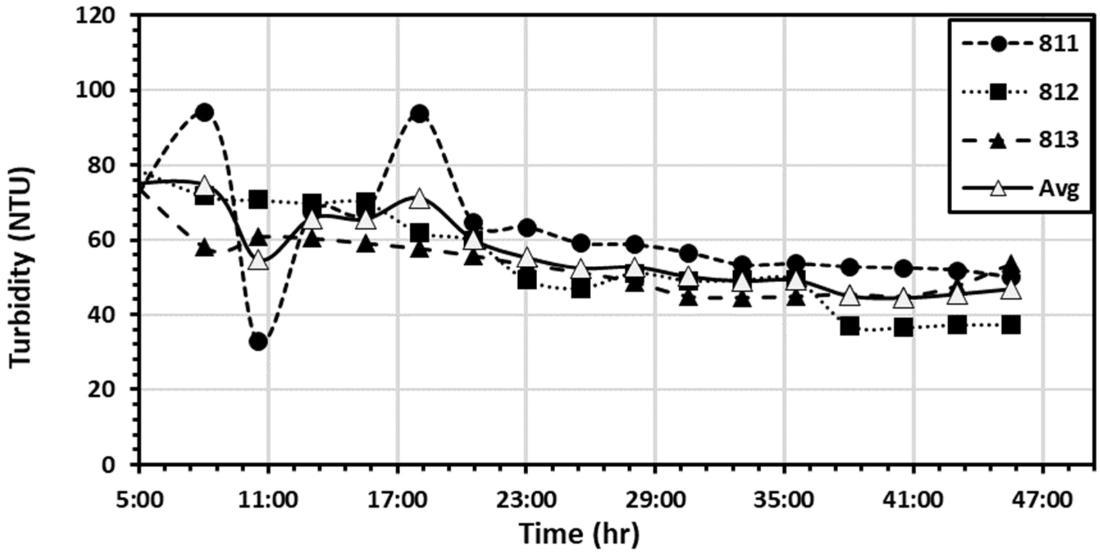
Bay 4 Bottom Sampling Location



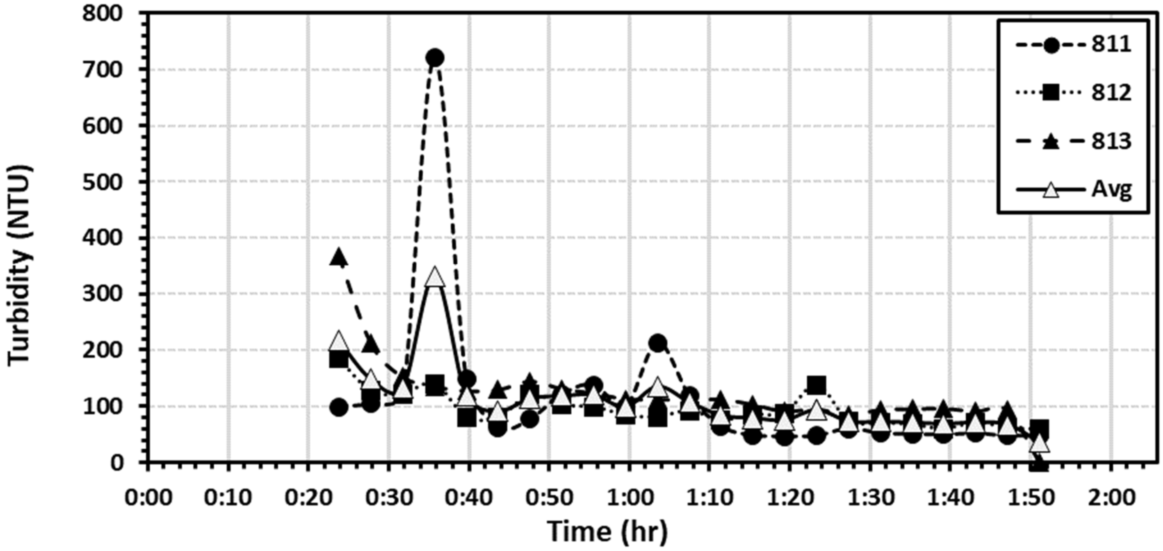
Bay 4 Bottom Sampling Location



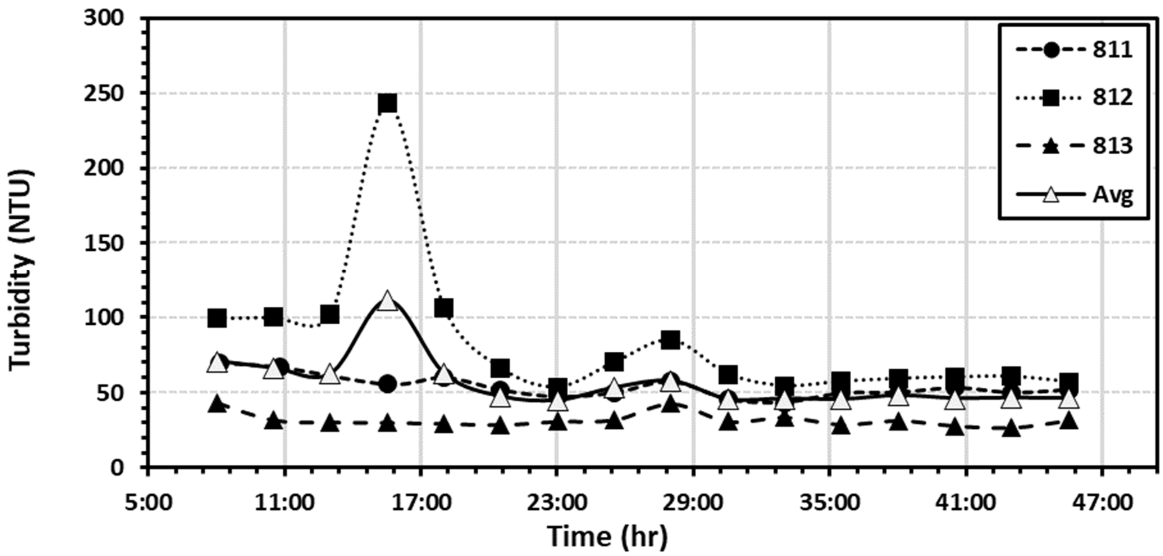
Bay 4 Top Sampling Location



Bay 4 Top Sampling Location



Discharge Sampling Location



Discharge Sampling Location