CONSTRUCTING AND EVALUATING LARGE-SCALE INFILTRATION SWALES FOR RETAINING AND INFILTRATING ROADWAY STORMWATER RUNOFF

by

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ABSTRACT

Urbanization, characterized by the increase of impervious surfaces including roads, parking lots, and buildings, presents challenges for stormwater management. The expansion of impervious surfaces disrupts natural infiltration processes, leading to increased volumes and peak flow rates of stormwater runoff. These changes necessitate effective management strategies and practices to mitigate the negative consequences such as flooding, streambank erosion, and pollution of waterways.

In response, post-construction stormwater control measures (SCMs) that integrate Low Impact Development (LID) and Green Infrastructure (GI) principles are gaining traction. LID and GI SCMs utilize various sustainable processes, such as evapotranspiration, infiltration, filtration, and water reuse, to mimic pre-development hydrology and manage the quantity and quality of stormwater runoff. The Alabama Department of Transportation (ALDOT) has embraced an infiltration-based LID and GI SCM called infiltration swales for highway runoff management.

Infiltration swales are linear vegetated channels that employ an engineered soil media and check dams to minimize surface discharge and reduce peak flow rates. These vegetated systems mimic predevelopment hydrology by promoting infiltration of stormwater runoff into their media and the underlying native soils, potentially replenishing the local groundwater table. This infiltration process is facilitated by the engineered soil media, a component designed to optimize water permeability while utilizing natural materials.

While infiltration swales are a common stormwater management practice in Alabama, their performance can vary. To address this variability, ALDOT partnered with Auburn University on a two-phase research project to develop a modified infiltration swale design based on the existing ALDOT standard, and to evaluate both swale's infiltration performance. The first phase focused

on developing a modified swale design based on the existing ALDOT standard. The second phase, which forms the basis of this thesis, involved large-scale field testing to compare the performance of the ALDOT and modified swale designs at the Auburn University Stormwater Research Facility.

This research aims to evaluate and compare the infiltration performance of the standard ALDOT infiltration swale design to the newly developed modified swale design. Large-scale infiltration swales were constructed, side-by-side, to facilitate controlled experimentation and monitoring. The evaluation focused on infiltration rates and drawdown times under various scenarios designed to assess the influence of external factors on infiltration performance. These factors included variations in rainfall frequency, underdrain valve settings (open vs. closed), initial soil moisture conditions (wet vs. drier), and seasonal variations. Moisture content sensors were also installed within the swale media and surrounding soil at different depths and locations to track the movement of infiltrated water. Additionally, settlement of the swales was monitored from construction completion, and surface storage volumes were measured. This comprehensive approach, incorporating various tests and measurements, allowed for a robust comparison of the overall infiltration performance between the ALDOT and modified swale designs.

The evaluation revealed significant performance differences between the ALDOT and modified infiltration swales. The ALDOT swale displayed a notably lower average infiltration rate of 1.6 ft/day (0.49 m/day) and a longer average drawdown time of 12.25 hours than the modified swale. The modified swale exhibited a higher average infiltration rate of 5.2 ft/day (1.6 m/day) and a considerably faster average drawdown time of 5.06 hours. These results indicate a statistically significant difference in performance between the two infiltration swale designs. Further analysis concluded that decreased rainfall frequency increased infiltration rates by 1.6

times more for the ALDOT swale and 2.4 times more for the modified swale compared to increased rainfall frequency. Drier soils increased infiltration rates by 1.5 times more for the ALDOT swale and 2.3 times more for the modified swale compared to wetter soils. Closed valve underdrain tests outperformed open valve tests for both swales potentially due to seasonal variation. Colder months were associated with slower infiltration rates while warmer months were associated with enhanced infiltration rates. Warmer months showed improved infiltration rates by 1.7 times more for the ALDOT swale and 2.7 times more for the modified swale compared to colder months. Moisture sensor data revealed an interesting contrast. While the ALDOT swale held 10% more surface water volume compared to the modified swale, the infiltrated water traversed the modified swale media significantly faster, reaching the bottom interface with the native soil in an average of only 0.13 hours (7.6 minutes). In contrast, the ALDOT swale exhibited a much slower travel time, with infiltrated water taking an average of 1.8 hours to reach the bottom. Further evaluation showed that there was no settlement observed in both infiltration swales.

Beyond the core findings on infiltration performance, this thesis accomplished several key milestones. A comprehensive literature review explored factors influencing infiltration-based SCMs, a study on the different infiltration-based SCMs used across the United States by different Departments of Transportation, and studies on grass swales and their average infiltration rates. The project then progressed to a detailed field-scale construction phase. The construction process included geotechnical and soil investigation, site selection, excavation, media material placement, moisture content installation, and site stabilization for both infiltration swale designs. Another major milestone involved constructing and calibrating the testing apparatus used for the subsequent experimentation and evaluation of the two swales. These combined efforts ultimately served two primary objectives: to inform ALDOT on the modified infiltration swale design created, and to provide robust evidence from large-scale experimentation to support the findings on the modified swale's infiltration performance compared to the existing ALDOT swale design.

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CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

The increase in urbanization and population growth has led to a heightened demand for the expansion of highway and roadway networks. According to a report by Transportation for America, the largest 100 urbanized areas in the United States added 30,511 new freeway lane-miles of road between 1993 and 2017, representing a 42% increase. Interestingly, this rate of freeway expansion significantly outstripped the 32% growth in population in those regions over the same period [1]. This development of infrastructure has resulted in a notable increase in impermeable surface cover compared to the natural pre-development area.

Impermeable surfaces are hardened surfaces usually in the form of pavement, asphalt, or concrete that does not allow water to pass through. The presence of impervious surfaces significantly impacts a watershed's runoff characteristics. The rise in impermeability is acknowledged as a key factor contributing to the increase in peak flow and the overall volume of surface stormwater runoff. This is primarily due to reduced infiltration capabilities compared to the predevelopment conditions [2]. According to the Environmental Protection Agency (EPA), when impermeable surfaces reach 10% to 20% of the total area, surface runoff doubles. This trend continues, with a 100% impervious cover resulting in five times more runoff than a forested watershed [3]. As for peak flow increase, some studies have shown that a 10% increase in impervious cover can result in a 30% to 50% increase in peak flow rates [4].

The rise in runoff peak flow and volume is demonstrably linked to several negative environmental consequences. Notably, stormwater runoff acts as a conveyance mechanism for pollutants deposited on highways and roadways. These pollutants are then transported to sensitive habitats and potentially contaminate drinking water sources. Despite comprising only 3% of the landmass in the United States, urban areas generate a significant amount of stormwater pollution. This runoff is estimated to be the leading cause of impairment for a substantial portion of the nation's waterways, affecting 13% of rivers, 18% of lakes, and a troubling 32% of estuaries [4]. Other negative impacts include increased frequency and intensity of flooding, deterioration of urban stream health, excess nutrient and contaminant loading, impacts on biological aquatic organisms, lower local groundwater recharge, and erosion of slopes and streambanks [5], [6].

In response to growing concerns about water quality degradation in the United States, Congress enacted the Clean Water Act (CWA) of 1972. The CWA aimed to restore and maintain the health of the nation's waters by regulating point source discharges and implementing other pollution control measures. Recognizing the significant contribution of stormwater runoff to water quality issues, the CWA was amended in 1987 to establish the National Pollutant Discharge Elimination System (NPDES) program. The NPDES, enforced by the EPA, focused on reducing pollutants from industrial processes and wastewater and municipal sewage discharge [4]. This also laid the groundwork for the Municipal Separate Storm Sewer System (MS4) program which targets stormwater runoff from urbanized areas. It regulates the collection and discharge of stormwater through a network of municipal storm drains, sewers, and other conveyances. The MS4 program applies to municipalities and other designated urban entities, such as universities, hospitals, and airports. The program is further divided into phases, with Phase I targeting larger municipalities and Phase II focusing on smaller ones and specific areas within urbanized areas. It doesn't directly issue permits; however instead, it requires municipalities and other entities to develop and implement Stormwater Management Programs (SWMPs) to control pollution in their stormwater discharges [7]. An SWMP outlines the strategies, policies, and practices that will be implemented to achieve specific water quality objectives.

To achieve effective SWMPs, municipalities and other entities implement stormwater control measures (SCMs), also referred to as best management practices (BMPs). These practices aim to manage stormwater runoff, protect water quality, and mitigate the impacts of urbanization on natural hydrological processes. SCMs are structural or non-structural practices specifically designed to manage stormwater runoff. Structural practices are landscape features designed to counter the increase in peak flow and runoff by detaining, retaining, infiltrating, and/or treating runoff [6]. Some of these SCMs are labeled as "post-construction" which signifies the features are to operate as long-term, permanent solutions well after the construction phase has been concluded. Some SCM types include wetlands, wet ponds, dry detention ponds, infiltration beds, permeable pavement, etc. [8].

In adherence to the requirements of the MS4 program and its associated SWMPs, the Alabama Department of Transportation (ALDOT) utilizes stormwater control measures to manage stormwater runoff and protect public health and the environment. ALDOT uses many different types of SCMs, but a relatively new one they started implementing around the state is called infiltration swales.

1.2 DEFININTIONS AND PURPOSE OF INFILTRATION SWALES

Infiltration swales are a commonly employed SCM implemented by ALDOT along roadways. These linear vegetated channels function by promoting the infiltration of stormwater runoff through an engineered soil media. This infiltration process allows the stormwater to subsequently percolate into the underlying native soils and potentially reach the local groundwater table. This functionality allows infiltration swales to mimic the pre-development hydrology of a site by mitigating the increase in peak flow rates and runoff volumes generated by impervious surfaces. Infiltration swales offer a compelling solution for stormwater management due to their combined capabilities. Their potential for high infiltration rates reduces runoff volumes, while the vegetated channels and check dams promote velocity flow reductions, effectively managing both peak flow rates and total runoff volumes.

Beyond managing peak flow and runoff volume, ALDOT utilizes infiltration swales to comply with MS4 requirements and promote the principles of Low Impact Development (LID) and Green Infrastructure (GI). Both LID and GI share a common goal: managing stormwater runoff in a more sustainable manner that mimics natural hydrology. However, they differ in scope and emphasis. GI encompasses a broader range of practices and elements that utilize natural processes to manage stormwater runoff. These elements, such as parks, rain gardens, and bioswales, often deliver additional environmental and social benefits beyond stormwater management, including improved air quality, habitat creation, and recreational opportunities. GI principles are integrated into the planning and design of communities and infrastructure projects, promoting a holistic approach to urban development. LID, on the other hand, focuses on a specific set of engineered practices designed to manage stormwater runoff close to its source. Examples of LID practices include infiltration trenches, permeable pavements, and bioretention facilities. These practices aim to reduce the overall volume and flow rate of runoff entering traditional conveyance systems. While LID primarily targets stormwater management, some practices can contribute to broader environmental goals when strategically implemented [9], [10].

While ALDOT employs infiltration swales to comply with MS4 regulations and promote sustainable stormwater management, current infiltration swale performance across the state of Alabama suggests that some existing swales may not be functioning optimally in terms of infiltration capacity. To address this challenge, ALDOT has partnered with Auburn University who conducted research on their infiltration swale design with the aim of improving overall stormwater management performance, particularly by enhancing infiltration capabilities.

1.3 RESEARCH OBJECTIVES

This thesis focuses on a large-scale evaluation comparing the infiltration performance of the standard ALDOT infiltration swale design with a newly developed modified swale design created by Auburn University.

The design and evaluation of infiltration swales for retaining and infiltrating roadway stormwater runoff entailed multiple objectives and was divided into two projects: small-scale laboratory testing and large-scale field testing. While Auburn University has already established a modified infiltration swale design through prior small-scale laboratory studies [11], neither this new media design nor the existing ALDOT swale had been subjected to a comprehensive large-scale field evaluation. This research addresses this gap by performing a comparative assessment of infiltration performance through large-scale field experimentation.

The large-scale testing phase involved the construction of field-scale replicas of both the ALDOT and modified infiltration swale designs. This was followed by the development of a comprehensive large-scale testing methodology to facilitate controlled experiments. These experiments aimed to evaluate the infiltration performance of both swale designs under simulated rainfall events. The research tasks needed to achieve this included:

(1) Conducting a literature review to gain a comprehensive understanding of the current infiltration-based LID and GI stormwater control measures and factors that affect infiltration performance.

(2) Constructing both the large-scale ALDOT and modified infiltration swale designs.

(3) Developing a large-scale testing methodology, protocols, and testing apparatus for the constructed ALDOT and modified large-scale infiltration swales.

(4) Performing controlled experiments and recording infiltration performance under different simulated scenarios to create a comparative performance analysis between the ALDOT and modified infiltration swale.

1.4 ORGANIZATION OF THESIS

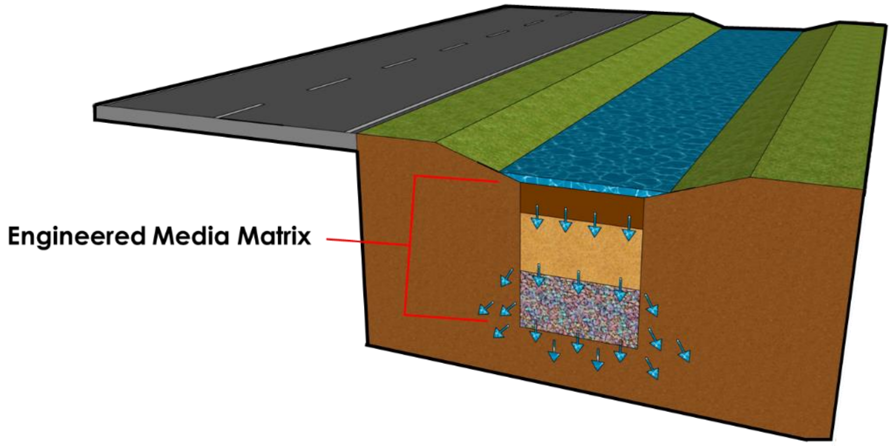
This thesis is divided into six chapters that help illustrate the journey of the construction and evaluation of infiltration swales. Following this chapter, Chapter Two: *Literature Review*, examines the main factors that affect infiltration performance along with an in-depth study of the different infiltration-based SCMs used by other DOTs. Chapter Three: *Swale Design and Construction*, details the protocol and techniques used to construct the field-scale infiltration swales. This chapter additionally includes a comprehensive illustration and dimensioning of the engineered media design. Chapter Four: *Calibration and Testing Methodology*, outlines the various experimental designs, their theoretical background, and the procedures employed to collect data from the infiltration swales. It also covers the calibration of testing apparatus. Chapter Five: *Results and Discussion*, provides all the findings from the performed experiments. Chapter Six: *Conclusion and Recommendations*, provides a summary of the important information collected and found from this study along with limitations and areas for future research.

CHAPTER TWO: LITERATURE REVIEW

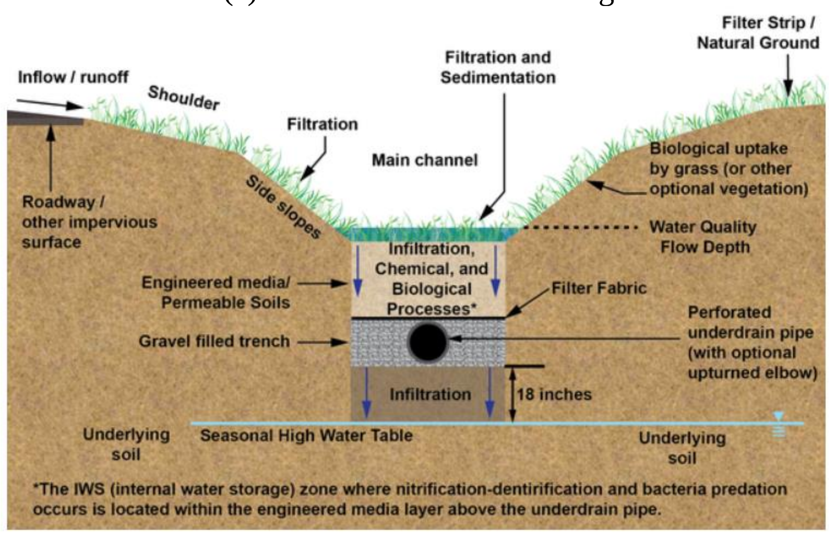
2.1 BACKGROUND

Infiltration swales are a type of post-construction infiltration-based SCM that are used around the United States. While existing literature on the specific infiltration swale design employed in this study may be limited, extensive research exists on grass swales, a closely related SCM. Infiltration swales incorporate engineered media beneath the grass layer to enhance infiltration compared to traditional grass swales. Given their shared core functionality as grass swales with an added infiltration media, findings from grass swale studies can be readily applied to understand the performance of infiltration swales. Infiltration swales, including grass swales, can be effective in reducing the amount of stormwater runoff volumes and peak flows if coordinated, planned, constructed, and maintained correctly. Field studies on grass swales, which lack an engineered media, have documented substantial reductions in runoff volumes through infiltration. These studies report reductions of up to 50% in semi-arid regions with low initial soil moisture content, suggesting the potential effectiveness of infiltration swales in similar conditions [11]. Grass swales and infiltration swales both provide stormwater quantity and quality treatment; however, grass swales can only capture small storm events [2] while infiltration swales, with an added engineered media matrix, potentially can capture small and larger storm events.

In terms of a general design, infiltration swales are a vegetated open channel conveyance system that uses check dams and an engineered media matrix to capture and infiltrate stormwater runoff. The core component of an infiltration swale is the engineered media matrix. The medias can be either heterogeneous (composed of various materials) or homogeneous (uniform material). The ALDOT swale investigated in this study employs a heterogeneous media mixture. Infiltration swales function by promoting permeation of runoff into the engineered soil media matrix. This matrix, comprised of high permeable soil materials, facilitates water movement through its layers and into the underlying native soils, ultimately reaching the local groundwater table. The engineered media matrix has pollutant removal properties; however, water quality research is not within the scope of this thesis. The engineered media matrix is the component of the infiltration swale that is under the base of the swale's channel and is broken into different soil layers to help stimulate infiltration. This ability allows the swale to mimic the pre-hydrology of a site and manage the increase in peak flow and volume of runoff from impervious surfaces through its potential for high infiltration rates over a linear surface area. Figure 2-1(a) shows a general depiction of an infiltration swale and the engineered media matrix component while Figure 2-1(b) shows its functionality.



(a) infiltration swale rendering



(b) general infiltration swale design [12]

Figure 2-1. Infiltration Swale Schematic

Despite the widespread use of post-construction infiltration-based SCMs including infiltration swales across the United States by various departments of transportation (DOTs) and organizations, a lack of standardization exists. This results in diverse interpretations, including variations in nomenclature, design criteria, geometric configurations, media compositions, construction techniques, and maintenance procedures. For instance, other common infiltration-based SCMs include dry detention ponds, grass swales, bioswales, biofiltration swales, media filters, etc. [8]. Some organizations use these SCMs for specific purposes, including focusing on managing the quantity, volume, and peak flow of stormwater runoff or focusing on the quality of runoff by treating and filtering pollutants out.

The focus of this literature review is broken into three parts: (1) using grass swale studies to compare infiltration rates, (2) investigating main factors that affect infiltration-based SCM performance, and (3) investigating other DOT's infiltration-based SCMs to compare to ALDOT's infiltration swale design. To establish a common ground for the subsequent literature, the next section provides definitions for several key terms frequently used within the post-construction stormwater management community.

2.2 GRASS SWALE INFILTRATION RATE STUDIES

Grass swales are vegetated, open-channel ditches that can treat and reduce stormwater runoff [13]. Roadside grass swales are shown to be effective, and studies show mean runoff volume reduction values of 30% [14], 45.7% [15], 33% [16], 47% [17] and 45% [18] [19]. As the vegetation slows down runoff, the native soil can infiltrate and reduce the amount of water generated from impervious surface cover.

Grass swales have limitations, particularly in their ability to handle larger storm events due to restrictions in runoff storage and infiltration capacity. Although grass swales provide stormwater quantity treatment, grass swales can only capture small storm events [2]. Supporting this notion is a study conducted at the University of Maryland that investigated the infiltration capacity of various grass swales over 4.5 years [19]. This study found that smaller storm events 0 to 0.91 in. (0 to 2.3 cm) rainfall depths were entirely infiltrated by the four full-scale grass swales, resulting in no discharge. For moderate storm events 0.91 to 1.3 in. (2.3-3.3 cm) rainfall depths, the swales attenuating both volume and peak flow rates. However, during large storm events exceeding 1.3 in. (3.3 cm) rainfall depth, the swales functioned primarily as conveyance systems. They concluded that if larger storms were to be significantly captured, grass swale designs would need greater storage capacity or become larger. The grass swales showed that they could capture 59% of storms in a year in Maryland [19]. These findings suggest that infiltration swales may present a promising solution due to the enhanced storage capacity facilitated by the engineered soil media. This study demonstrates the efficacy of grass swales in capturing frequent, smaller storm events. However, infiltration swales, with their engineered media matrix designed to promote enhanced infiltration, have the potential to capture both small and large storm events.

This section explores findings from various grass swale studies to establish a baseline for average infiltration rates. Infiltration swales share a core functionality with grass swales, with the addition of an engineered media to enhance infiltration and increase storage. This shared foundation allows to leverage findings from grass swale studies to gain valuable insights into the performance of infiltration swales. This will be achieved by comparing established infiltration rates documented in existing large-scale grass swale studies with the infiltration rates measured from the infiltration swales constructed in this thesis.

2.2.1 Grass Swale Studies

Study #1 conducted a large-scale field experiment adjacent to Maryland highways to compare the infiltration capacities of two common grass swale designs: pretreatment grass filter strips and vegetated check dams. The experiment spanned 4.5 years and analyzed data from 52 storm events. The study employed a rainfall capture approach to determine infiltration rates. This involved recording rainfall data from the 52 storm events and plotting a scatter plot of total rainfall depth versus storm duration. Each data point was then categorized as either fully infiltrated or not infiltrated. Subsequently, a boundary line, known as the fitted capture line, was established to differentiate between captured and non-captured storms. Equation (2-1) depicts the linear equation of this fitted capture line.

$$P_{Swale} = 0.112 \, x \, D + 0.56 \tag{2-1}$$

Where,

P_{Swale} = adjusted total rainfall (in)

D = storm duration (hr.)

Infiltration rates were calculated from Eq.2-1 by plugging in the known duration of each one of the 52 storms to receive a P_{Swale}. This P_{Swale} is then divided by the duration which provided a range of infiltration rates from 0.12 to 0.59 in/hr. (0.3 to 1.5 cm/hr.).

Study #2 used laboratory and large-scale testing on grass swale perforated pipe systems for stormwater management. The large-scale tests used five in situ infiltrometer tests to measure the infiltration rates of five typical grass swales located in Promenade Avenue, City of Nepean, and Ontario, Canada. The infiltrometer was a polyvinyl chloride (PVC) single-ring cylinder pipe that was 7.87 in (20 cm) in diameter shown in Figure 2-2. This apparatus was driven into the soil of the grass swales at five different locations about 0.31 to 0.47 in (8 to 12 mm) deep and infiltration rates were calculated using the constant head method. A constant water head above the infiltrometer single ring cylinder was performed by using a Mariotte siphon. The infiltration rates were determined by calculating the speed of the water level's descent, with measurements recorded every two minutes and each test was completed up to 26 minutes. It is important to mention that at each site the soil type was classified as a sandy silt and resulting in initial infiltration rates varying from 1.18 to 5.12 in/hr. (3 to 13 cm/hr.); however, infiltration rates from 0.39 to 1.18 in/hr. (1 to 3 cm/hr.) were obtained after about 15 to 20 minutes of testing.

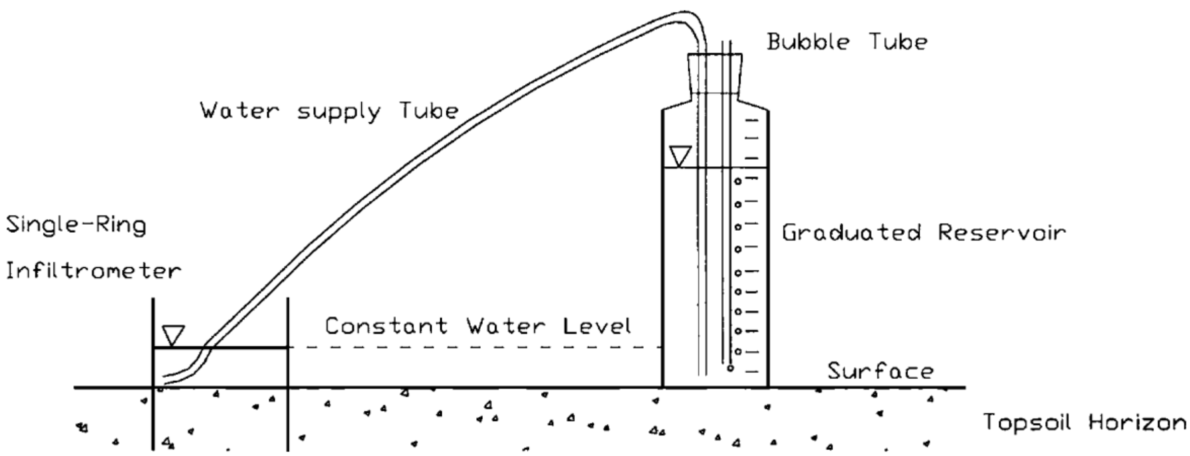


Figure 2-2. Single Ring Infiltrometer and Marionette Siphon Apparatus [2]

Study #3's infiltration rate values were obtained from a dissertation, where experimentation was performed in the Netherlands. The aim of this study was to create an investigation into the performances of different types of SCMs throughout the lower-lying ends of the Netherlands. In the study, they focus on using their own testing method to twelve existing grass swales to obtain infiltration rates. The method involved filling each swale to its maximum water depth, or a minimum of 7.87 in. (20 cm). Once fully inundated, the researchers installed pressure transducers to monitor water level. Infiltration rates were then determined by recording the water height decline in the swale until complete drainage. In coordination with the pressure inducers, they also used hand measurements, underwater camera, and time-lapse photography. Figure 2-3 shows the twelve different grass swales and the infiltrations rates varying from 0.08 m/day to 2.16 m/day (0.26 to 7.1 ft/day) and shows the location, test type, water level, and emptying time. The type of test is either long-term monitoring (L.t.m) or full scale; the difference between the two is l.t.m had pressure inducers installed for longer periods [20].

Municipality	location	type of test	waterlevel [cm]	empty time [min]	infiltration rate [m/day]**
Oostzaan	Doktersbuurt	l.t.m.	10.3	615	0.24
Noordoostpolder	Bant	full scale	33.1	393	1.21
Haren	Vondellaan	l.t.m.	21.2	2755	<u>*0.11*</u>
Haren	Mellensteeg	l.t.m.	12.8	2400	<u>*0.08*</u>
Purmerend	Bloemfontein	full scale	5.6	937	<u>*0.09*</u>
Purmerend	Ismailiastraat	full scale	8.2	823	0.14
Purmerend	Saidweg (oost)	full scale	17	990	0.25
Purmerend	Saidweg (west)	full scale	16.5	981	0.24
Enschede	Ruwenbos	l.t.m.	15.0	1665	0.13
Almelo	Kleef	l.t.m.	5.1	855	<u>*0.09*</u>
Utrecht	Castellumdreef	l.t.m.	17.7	1670	0.15
Arnhem	Burgemeester Matsersingel	l.t.m.	15	100	2.16

*l.t.m= long term monitoring (waterloggers installed for longer period of time).

**Underlined infiltration rates are lower than 0,125 m/d which is needed to empty 25 cm in 48 hours.

Figure 2-3. Infiltration Grass Swale Test Results [20]

Study #4 was conducted on one grass swale in Madison, Wisconsin. To make sure to obtain an accurate infiltration rate, they conducted 108 different infiltrometer measurements within the single grass swale. The 108 infiltration tests were collected using the Modified Philip Dunne (MPD) infiltrometer which can take multiple measurements to calculate the infiltration rate. The researchers used the geometric mean of the 108 infiltration rates to calculate an infiltration rate of 2.8 in/hr. (7.1 cm/hr.). The researcher notifies the reader how spatial variation in the infiltration test causes different infiltration rate results. To obtain an accurate and representative infiltration rate of the swale, the researcher recommends conducting 20 or more infiltration tests. Not much information was provided on how the method was conducted or what test increments and duration were used to calculate the infiltration rates [21].

Study #5 focuses on the effects of initial soil moisture content on the generation of runoff from grass swales located in the residential suburbs of Lulea, Sweden. There are two 30 m (98.4 ft) long swales the researchers investigate and are built adjacent to a two-lane road. Swale #1 was built of mostly loamy fine sand soil, and swale #2 consisted of mostly sandy loam soil. Since the soil classification of swale #2 is more similar the infiltration swale that will be used, the infiltration rate of swale #2 will be used for comparison. The method used to quantify infiltration rates of swale #2 was a double-ring infiltrometer. Nine sample points were taken for each swale at intervals of 3 minutes for every measurement. The study does not explicitly show the duration of the test. Figure 2-4 shows the results for swale #2 and at different parts of the swale the soil classification differs and is not consistently the same soil. Also, the measured infiltration rate also changes from spatial variation and soil type. Focusing on swale #2, the range of values consist of 0.19 to 1.57 in/hr. (0.49 cm/hr. to 4 cm/hr.). The average value listed for grass swale #2 is 0.70 in/hr. (1.78 cm/hr.) this is the infiltration rate value that will be used [22].

Swale 2		
Soil texture WRB	Measured ϕ	Measured K_s (cm/hr)
Silt loam	0.57	2.20
		4.00
Fine sand	0.50	1.90
		1.10
Sandy loam	0.45	2.10
		0.49
Loamy fine sand	0.43	1.58
		2.00
Loamy fine sand	0.52	0.68
Sandy loam	0.50 ± 0.05	1.78 ± 0.98

Figure 2-4. Soil Texture, Porosities, and Hydraulic Conductivities in Swale #2 [22]

2.2.2 Grass Swale Studies Summary

In summary, Table 2-1 shows the five different experimental studies of grass swales for an ease of comparison. This table displays the important take aways from each study on how the author conducted their experiments to measure infiltration rates in grass swales. Table 2-1 lists the average infiltration rate found within the study that will later be compared to the infiltration swales tested in this thesis for comparison.

Table 2-1. Findings Summary of Grass Swale Studies

Studies	Infiltration Test	# of test per swale	Test Duration	Infiltration Rates	Mean Infiltration Rate
Study #1 [19]	Derived from water balance equation	N/A	N/A	0.12 to 0.6 in/hr.	0.709 ft/day
Study #2 [2]	Single Ring Infiltrometer	5	Approx. 25 min	0.4 to 1.2 in/hr.	1.57 ft/day
Study #3 [20]	Full Scale Inundation with pressure inducers	1	100 – 2400 min	3.1 – 85 in/hr.	1.36 ft/day
Study #4 [21]	Modified Philip Dunne Infiltrometer	108	Not Mentioned	2.8 in/hr.	5.6 ft/day
Study #5 [22]	Double Ring Infiltrometer	9	Not Mentioned	0.7 in/hr.	1.4 ft/day

2.3 FACTORS THAT CONTRIBUTE TO FAILURE

Several factors can threaten the effectiveness of infiltration-based SCMs. One major concern is (1) compaction, often caused by construction activities, which reduces soil porosity and hinders infiltration. Another threat is (2) sedimentation from upstream areas, which clogs pores in the media and native soil, decreasing infiltration rates. Finally, neglecting to perform (3) proper native soil testing can lead to selecting unsuitable sites with poor drainage or slow infiltration, ultimately resulting in SCM failure. By understanding these key threats, designers and stakeholders can take preventative measures to ensure the long-term success of infiltration-based SCMs.

2.3.1 Compaction

Compaction is a significant factor contributing to the failure of infiltration-based SCMs and can significantly shorten their lifespan. Even well-suited sites can be rendered ineffective if compaction occurs during construction. A review of Minnesota Department of Transportation's (MnDOT) survey literature identified compaction as the most widespread cause of SCM failure [23]. This issue, despite being readily preventable, remains a leading reason for SCM underperformance. Construction activities such as excavation, mixing, stockpiling, equipment storage, and traffic are the primary culprits behind compaction at construction sites [24].

Compaction reduces soil porosity and increases bulk density, thereby diminishing the available air voids necessary for water to travel and infiltrate through. This not only decreases infiltration rates but also diminishes the soil's water holding capacity and hinders vegetative growth. MnDOT's study correlated increased bulk density with various land-use activities [24].

Table 2-2. Increase in Soil Bulk Density caused by Land Use Activities [24]

Land Use or Activity	Increase in Bulk Density (g/cm^3)	Source
Grazing	0.12 to 0.20	Smith, 1999
Crops	0.25 to 0.35	Smith, 1999
Construction, mass grading	0.34 to 0.35	Randrup, 1998; Lichter and Lindsey, 1994
Construction, no grading	0.2	Lichter and Lindsey, 1994
Construction Traffic	0.17 to 0.40	Lichter and Lindsey. 1994; Smith 1999; Friedman, 1998
Athletic Fields	0.38 to 0.54	Smith, 1999
Urban Lawn and Turf	0.30 to 0.40	Various Sources

A case in point is the Delaware Department of Transportation (DelDOT). They constructed 25 infiltration facilities within the past decade, experiencing a failure rate between 1% and 15%. Notably, compaction was cited as a major factor contributing to these failures [23]. Another instance, Massachusetts Department of Transportation (MassDOT), has built about 250 infiltration facilities within the last 10 years with a 15% to 30% failure rate due to compaction. Lastly, MnDOT reported over 100 infiltration facilities built within the last decade and reported that one of the major factors contributing to a 15% to 30% failure rate was compaction.

The most common practices to prevent compaction are soil ripping (tilling) or adding organics (compost) to the soils. For ripping, when excavating a trench for the media, the excavator will tend to smear the soil pores at the native soil boundary at the bottom of the trench created from the excavator bucket. The operator may be trying to grade the bottom of the trench by smoothing the soils with the excavator bucket. However, this smears and clogs the soils at the boundary layer where the media and native soil meet which decreases the infiltration capacity. The potential for smearing soils increases in occurrence when soils are too wet; so, excavating on a drier day is preferred. To avoid this, it is recommended to ripper the last 6 to 12 in. (15 to 30 cm) of native soils in the trench by using the teeth of the bucket [25]. This will alleviate any compaction that may have occurred during the excavation process and will allow enhanced exfiltration to the native soils. Other ways to avoid compaction includes using only low ground pressure tracked equipment and rubber tire equipment should strictly avoided on the construction site near the infiltration SCMs [24].

Another method to alleviate compaction is adding organic matter to the soils or compost. Composting allows soil particles to aggregate and form larger particles which increases the porosity of the soil and decreases the bulk density. Studies have shown that compost is highly effective and can increase water drainage, increase water retention for plants, and increase infiltration rates. A study performed by Olson shows that adding compost to a residential area soil increases infiltration rates by 3.4 to 6.1 times more [26]. Another literature review created from MnDOT, cited decompaction methods and their associated effectiveness in decreasing compaction which was measured in decreased bulk density. Table 2-3 shows the different methods with their corresponding decompaction results.

Table 2-3. Decrease in Soil Bulk Density caused by Land Use Activities [24]

Land Use or Activity	Decrease in Bulk Density (gms/cm^3)	Source
Tiling of Soil	0.00 to 0.02	Randrup, 1918. Patterson and Bates, 1994
Specialized Soil Loosening	0.05 to 0.15	Rolf, 1998
Selective Grading	0	Randrup, 1998 and Lichter and Lindsey, 1994
Soil Amendments	0.17	Patterson and Bates, 1994
Compost Amendments	0.25 to 0.35	Kolsti et al. 1995
Time	0.2	Legg et al, 1996
Reforestation	0.25 to 0.35	Article 36

Summarizing the Table 2-3, the most effective land use activity for decompaction on average was compost amendments while selective grading and tilling was the lease effective. However, it is important to mention that these studies were performed in the late 1900s and earlier studies prove that ripping and tillage is very effective at alleviating compaction.

Compaction is a readily preventable issue during infiltration-based SCM construction. Implementing preventative measures at this stage is significantly more manageable and cost-effective than attempting to rectify compaction problems later on.

2.3.2 Sedimentation

Sedimentation or media clogging is another significant factor contributing to the failure of infiltration-based SCMs and can significantly shorten their lifespan. Sedimentation mostly occurs during the construction phase of the infiltration SCM; however, post-construction sedimentation is common. Sedimentation causes the media to clog which is defined as the process of reducing porosity, permeability, and infiltration rates due to physical, biological, and chemical processes [27]. If silt or clay particles enter the infiltration SCM before significant vegetation is established, the media will silt over, and the infiltration capacity will decrease significantly. One study used one-dimensional laboratory experiments of gravel media in a column where sediment latent water was introduced to evaluate the effects of sedimentation on the infiltration system. This study showed that the performance of stormwater infiltration systems is highly dependent on the formation of sediment clogging the filter fabric layer interface with the native soils. Especially sediment particle sizes less than 6 μm diameter are the main cause of clogging the filter fabric [27]. A field-scale study of stormwater infiltration systems in Maryland documented that 33% of the 207 facilities evaluated were non-functional due to sedimentation. The study was repeated four years later, and the number of non-functional facilities due to clogging increased to 50% from the original 207 [28]. Another study in France, conducted an analysis by running infiltration experiments on two existing basins, both with and without sediment in the basin’s soil. Figure 2-5 shows the results from one of the basins saturated hydraulic conductivities (infiltration rates) with and without sediment in the soil.

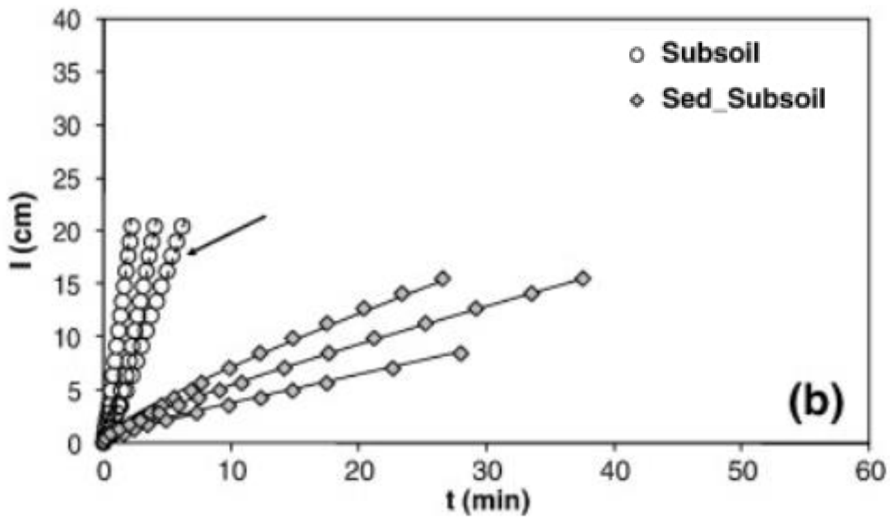


Figure 2-5. Sediment Infiltration Modeling Experiment [29]

The subsoil is the material without sediment depicted in the Figure 2-5 with the circles shown to have a linear relationship with faster infiltration rates. The soil with sediment (Sed-Subsoil) depicted in the Figure 2-5 with squares shown to have a concave relationship with slower infiltration rates. This experiment proved that the settlement of a sediment layer in infiltration basins may trigger a decrease in infiltration of water and decrease the hydraulic performance of a basin [29].

To decrease the chances of sedimentation and clogging from occurring, it is necessary to install erosion and sediment control practices to prevent sediment from entering the excavation trench, media, or surface of the SCM. Some common temporary erosion and sediment control practices used for sedimentation prevention include high-visibility fencing, silt fences, interceptor dikes, temporary curbs, compost socks, buffer zones, and filter berms [30]. Some tips to eliminate sedimentation, is to first grade the site to completion and stabilize the slopes before excavating the infiltration pit for the media. This will decrease the chances for exposed native soils to enter the media chamber. Some other prevention protocols are to protect temporary soil stockpiles from rainfall events and wind erosion. Wind can cause sediment to become airborne and settle into the infiltration swale media [31]. If sediment builds up in any part of the media or surface, it is crucial to remove the accumulated sediment by using the excavator bucket. These are great applications to use to prevent sedimentation from occurring during the construction process of the infiltration-based SCM; however, different techniques are used to ensure sedimentation does not occur post-construction. Post-construction permanent practices to help reduce the chances of sedimentation and clogging are to incorporate a pretreatment facility upstream of the infiltration-based SCM. Pretreatment protects the SCM from trash build-up, solid materials, and particulate matter. As for reducing sedimentation, pretreatment practices including forebays reduce the runoff flow velocity which allows for sediment and solids to drop out [31].

2.3.3 In-Situ Soil Testing

Locations where in-situ soils contain low infiltration rates are a concern for the selection of infiltration-based SCMs. This is because slow infiltration rates caused by the native soil, no matter how high the infiltration rate of the media is, will cause extended surface ponding, damage to vegetation, mosquito breeding, damaged soil structure, and reduce pollutant treatment by the SCM [32]. These soils are called "tight soils" and are defined as soils with infiltration rates less than 0.06 in/hr. (0.15 cm/hr.). Common tight soils with low infiltration capacities are classified as HSG C and HSG D. According to the MnDOT survey and literature review, another large response from nationwide DOTs that caused their infiltration-based SCM to fail were reported to be from poor or no in-situ soil testing at the site. For example, similar to compaction, MassDOT built about 250 infiltration facilities within the last 10 years with a 15% to 30% failure rate due to incorrect assumptions about subsurface soil conditions [23]. Every state organization or DOT has different thresholds for what the native soil infiltration rate should be for the site to be suitable for infiltration-based SCMs. However, from observing multiple organizations and DOTs, most mark HSG A or B as a suitable soil.

A geotechnical investigation is crucial solution to ensure performance for the SCM including subsurface exploration, laboratory testing, soil type classification, and in-situ field infiltration testing [33]. Designers are encouraged to conduct soil evaluation and testing early in the planning and design process so that native soil data at the site can be incorporated into the design or to adjust accordingly [34]. The Pennsylvania Stormwater Best Management Practices Manuel has a great outline for a geotechnical investigation.

The first step is to conduct the background evaluation which includes creating literature review maps of the site, for instance the Natural Resources Conservative Services (NRCS) soil map, existing geology, existing waterbodies, structures, topography, drainage patterns, land uses, etc. A preliminary study of the site is a great start for conducting the preliminary literature review for the infiltration facilities' location; however, most of the time the soils at the site are different from the NRCS web soil survey. It is important to go out to the field and conduct soil tests to confirm the soils found online.

The next step is to create a testing pit or an excavated hole to see the soil profile at the site and overall soil horizon and conditions. Testing pit sizes consist of a width of 2.5 to 3 ft (0.76 to 0.9 m) and depth between 72 to 90 in. (182 to 228 cm) or until bedrock or groundwater is reached [34]. Testing pits are preferred over borings because it allows better visuals of the soil profile while borings are better for initial screening. This is a suitable time to collect soil samples and to take them to the lab for soil classification.

Next step is to perform infiltration tests which can be broken up into field and laboratory test. Field infiltration tests are highly recommended over laboratory infiltration testing because of better representation of the in-situ soil. Also, it is preferable to perform infiltration tests in the field during the wet season of the year, January through June, to obtain infiltration rates that may be more diminished due to the colder and saturated conditions which is also dependent on location [34]. Two common field infiltration tests include the double-ring infiltrometer and percolation tests. While an infiltration test must be performed at least once at the bottom of the excavated trench where the media will be placed, the overall number of tests required for a SCM can vary. According to MnDOT, a minimum of five tests per acre of infiltration SCM is recommended [23]. The double-ring infiltrometer measures the vertical infiltration rate only while the percolation tests provide an infiltration rate that allows water to move through the sides and bottom of the percolation boring. Both tests are great; however, for design purposes, it is recommended to use the double-ring infiltrometer since it will produce a slower infiltration rate compared to the percolation tests and will help preserve the infiltration capacity of the infiltration-based SCM design. There are many other infiltration tests, but the two listed above are more popular than most other tests.

Careful site selection and thorough in-situ soil testing are paramount for the success of infiltration-based SCMs. Overlooking these crucial steps, as evidenced by the high failure rates due to poor soil testing reported by MnDOT and MassDOT, can lead to significant performance issues. A comprehensive geotechnical investigation, including background evaluation, soil profile observation through test pits, and field infiltration testing, is essential to ensure optimal performance and longevity of the SCM. Following established guidelines, such as those outlined in the Pennsylvania Stormwater Best Management Practices Manual, will equip designers with the necessary data to make informed decisions about site suitability and design parameters.

2.4 INFILTRATION-BASED SCMs USED BY US DOTS

This analysis will explore the diverse approaches to post-construction infiltration-based SCMs. Specifically, investigating the design criteria, geometric configurations, and soil media compositions utilized by other DOTs. By understanding these variations, more knowledge on how infiltration-based SCMs are used around the country will aid in the enhancement of ALDOT's infiltration swales overall.

2.4.1 SCMS and BMPS

To establish a clear understanding, it's crucial to differentiate between SCMs and BMPs before exploring their specific variations. BMPs are measures or practices used to reduce the amount of pollution entering surface waters. These practices can be structural or non-structural and may take the form of a process, activity, physical structure, or planning [35]. Non-structural BMPs are preventative practices and procedures that involve management and source controls including policies, ordinances, and educational programs. Structural BMPs are selected by designers and implemented by contractors that control or abate the discharge of pollutants from construction sites. Structural BMPs are stationary and permanent BMPs that are designed, constructed, and maintained to prevent or reduce the discharge of pollutants in stormwater.

SCMs are also known as structural BMPs that are designed, constructed, and maintained to remove pollutants from stormwater runoff by promoting sustainable methods including settling, filtration, evapotranspiration, water reuse, etc. [35]. SCMs focus on mimicking the natural hydrological cycle and pre-development of a site. Common SCMs include wetlands, wet ponds, dry detention ponds, grass swales, permeable pavement, etc.

2.4.2 State of Alabama

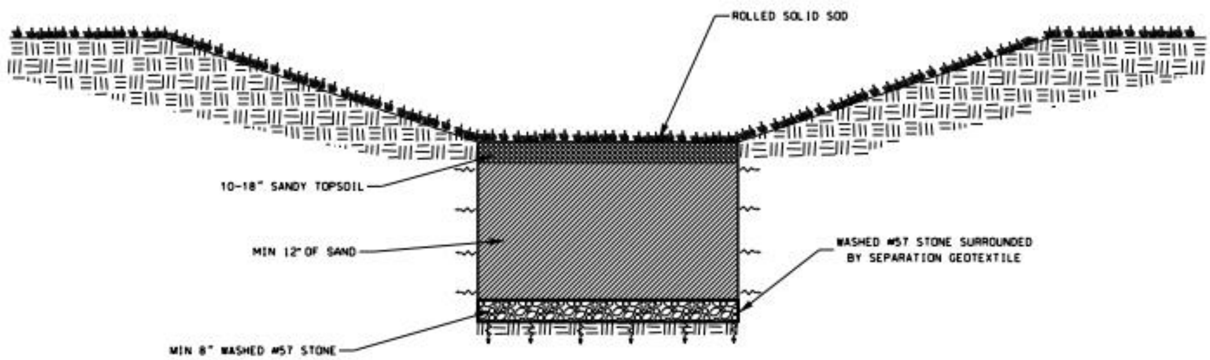
The Alabama Department of Environmental Management (ADEM) plays a critical role in post-construction stormwater management by establishing, enforcing, and creating environmental regulations. Their Low Impact Development (LID) Handbook provides comprehensive guidelines for implementing various SCMs, including site selection, community planning, SCM practices, and retrofits. This handbook is a great source to use for incorporating SCMs across Alabama and breaks up the practices into (1) bioretention cells, (2) constructed stormwater wetlands, (3) permeable pavement, (4) grassed swales, infiltration swales, and wet swales, (5) level spreaders and grassed filter strips, (6) rainwater harvesting, (7) green roofs, and (8) riparian buffers [10]. The infiltration swale design mentioned in the handbook is different from the infiltration swale design that was created by ALDOT and is important to note the ALDOT infiltration swale design is what this thesis focuses on.

While ALDOT and ADEM provide standardized drawings and specifications for the SCMs mentioned, ongoing evaluation of their performance is crucial. This evaluation process allows the two agencies to identify areas for improvement and strengthen their overall stormwater program by addressing any deficiencies in existing post-construction SCMs. This knowledge ensures proper implementation and maintenance of these practices, ultimately helping projects meet current and anticipated stormwater regulations [36].

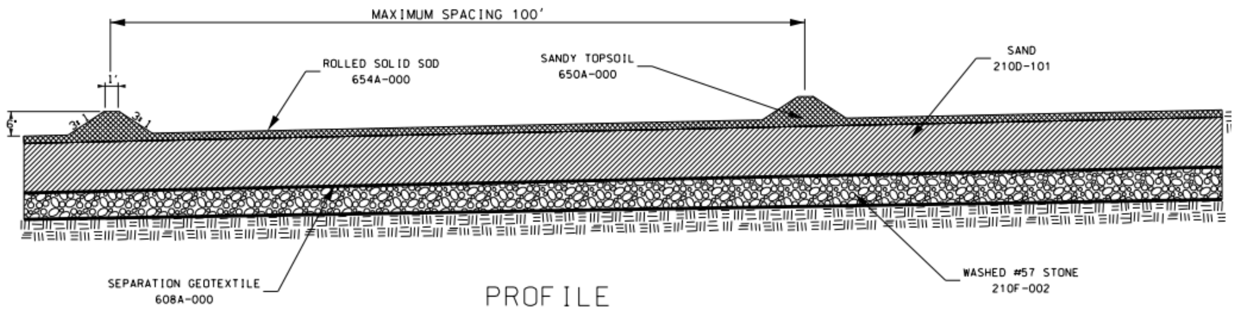
ALDOT currently implements infiltration swales around the state to meet MS4 permit requirements and to promote LID and GI to mitigate the impacts of an increase in impervious surface cover. Infiltration swales are a newer post-construction stormwater management system for the state, ALDOT does not specify details about site selection, design criteria, or maintenance on this SCM. However, the LID handbook lists important design criteria for infiltration swales.

Infiltration swales must have a drainage area of less than or equal to 5 ac (2 ha). The longitudinal slope requirement of the SCM must be less than or equal to 5%. The maximum drawdown time for the surface water is 48 hours [10]. To achieve this drawdown time, it is recommended to perform native soil testing. The recommended native soils should be hydrological soil group (HSG) A or B. The last major design requirement is to make sure the local groundwater table is at least 1 ft (0.3 m) offset from the bottom of the engineered media matrix.

This infiltration swale design is a vegetated lined channel composed of an engineered soil media matrix that lies underneath the bottom of the swale. This component is 4 ft (1.2 m) in width and 5 ft (1.5 m) in depth underneath the surface of the swale. Figure 2-6 shows the ALDOT design: from the top is composed of 1 ft (0.30 m) of sandy topsoil, 2 ft (0.61 m) of fill sand, and 2 ft (0.61 m) of #57 stone. The #57 stone is wrapped on all four sides by a separation geotextile blanket to block smaller soil particles from filling the voids in between the #57 stone. The function of the engineered soil media matrix is to manage the infiltration rate of stormwater runoff and to promote the infiltration of runoff back to the native soil and groundwater table. Figure 2-6(b) shows the profile view of the ALDOT infiltration swale specifications. The infiltration swale is composed of check dams that are spaced out at max every 100 linear ft (30.5 m) which encourage infiltration by slowing the surface flow of water and creating water impoundment. This increases the infiltration by providing more pressure from a higher water head height from the impoundment at each check dam.



(a) cross section



(b) profile view

Figure 2-6. ALDOT Infiltration Swale Schematic

2.4.3 Georgia Department of Transportation

The Georgia Department of Transportation (GDOT) has multiple types of post-construction SCMs that rely on infiltration to capture and treat stormwater runoff. The two types of infiltration-based SCMs similar to infiltration swales are (1) infiltration trench and (2) enhanced dry swales.

An (1) infiltration trench, according to GDOT, is an excavated pit filled in with stone aggregates used to capture stormwater runoff within the swale and to infiltrate the runoff into the surrounding soils from the bottom of the trench and the sides. The infiltration trench's purposes are to form an underground reservoir for stormwater runoff and exfiltrate runoff through the bottom of the trench and sides into the native surrounding soil over a 2-day period. This SCM helps to promote groundwater recharge and is good for small sites with porous native soils. The design criteria to ensure adequate performance include having a native surrounding soil infiltration rate of at least 0.5 in/h (1.3 cm/h), which is HSG A and B.

The infiltration trench design is made up of a total excavation trench depth varying from 3 to 8 ft (0.91 to 2.4 m) and the total width must be less than 25 ft (7.62 m). This excavated pit is then backfilled first with a 6 in. (15.2 cm) deep sand filter layer which serves to promote drainage and prevent compaction of the native soils while the stone aggregate is backfilled above. The next backfilled material placed above the sand layer is aggregate stone with 1.5 to 2.5 in. (3.8 to 6.4 cm) diameter. This layer can vary from 3 to 8 ft (0.91 to 2.4 m). A filter fabric is also lined on all sides and top of the stone layer to prevent sediment from passing into this layer which may cause clogging. The remaining layer placed above the filter fabric is a 6 in. (15 cm) layer of pea gravel. The pea gravel serves to improve sediment filtering and helps with pollutant removal. This layer also can be easily removed and replaced if the SCM begins to clog. An alternative to the pea gravel layer is a permeable topsoil which can be planted with sod. Another component of this SCM is a perforated PVC observation well installed within the trench. This device will allow inspectors to monitor the infiltration performance after a rainfall event. The last main component that must always be paired with an infiltration trench is a pretreatment sediment forebay or grass channel. The forebay helps prevent sediment from entering the infiltration trench which can potentially decrease the infiltration capacity [37]. Figure 2-7 shows a plan and profile view of the GDOT infiltration trench.

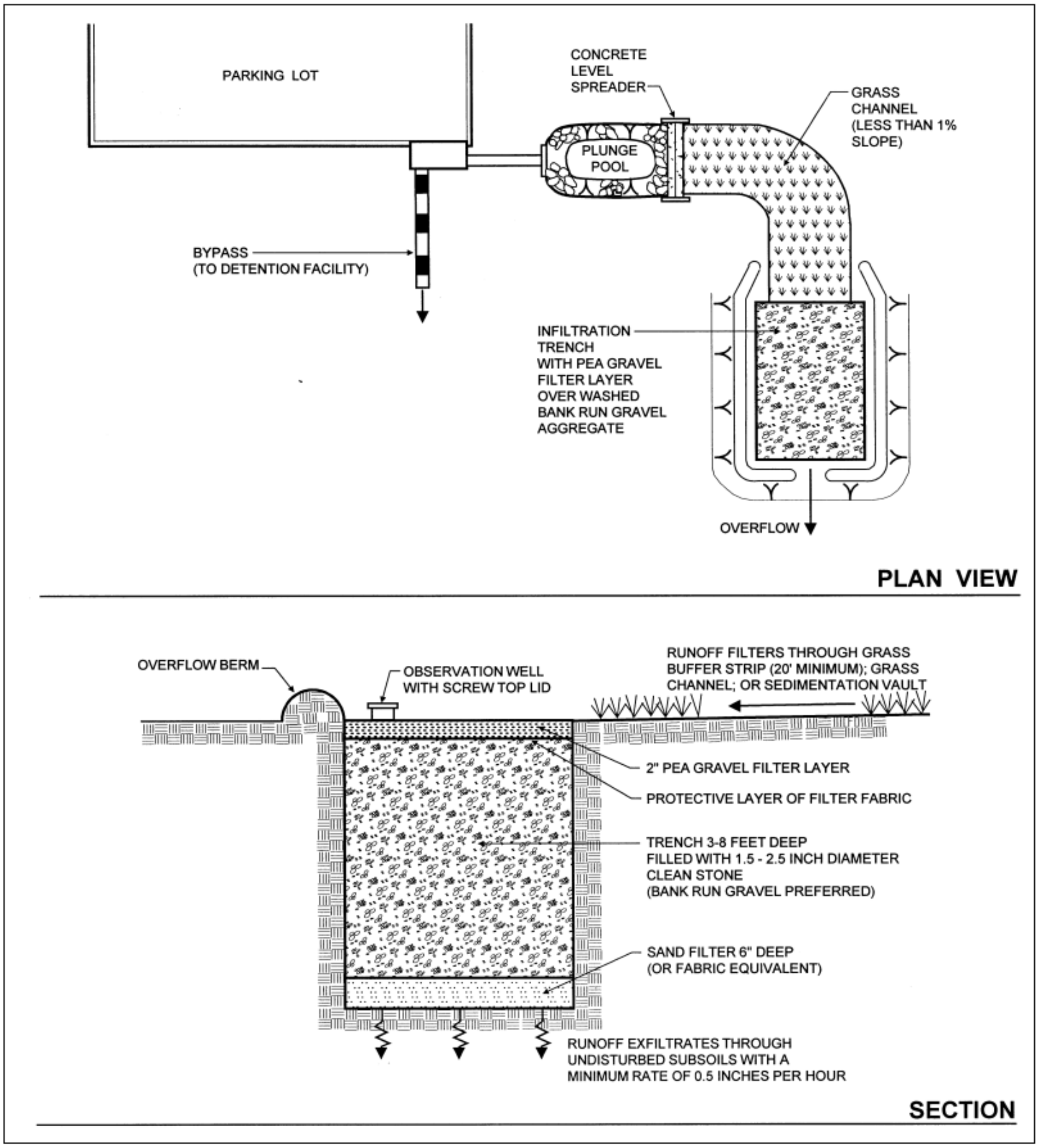


Figure 2-7. GDOT Infiltration Trench Design [37]

An (2) enhanced dry swale is another SCM GDOT uses that is similar infiltration swales. Enhanced dry swales are a vegetated open channel with an engineered media of permeable soils that overlays an underdrain which are designed to convey, capture, and treat stormwater runoff formed by check dams. By using a longitudinal slope less than 4%, forces the runoff to be slowed allowing for more particles to settle and be captured while limiting the effects of erosion. Important design criteria include slopes less than 4%, bottom channel width varying from 2 to 8 ft (0.61 – 2.4 m), 4:1 side slopes or flatter than 2:1, and to be able to convey the 25-year storm event with a minimum of 6 in. (15 cm) of freeboard. Enhanced dry swales primarily rely on infiltration and filtration through an engineered media to provide removal of pollutants from stormwater runoff. Unlike the infiltration trench mentioned above, this SCM does not require native surrounding soils to have a specific infiltration rate since these practices use an underdrain. The maximum ponding time for a dry swale is 48 hours while a 24-hour ponding time is more suitable.

The design of an enhanced dry swale media consists of organic porous soil of at least 30 in. (76 cm) in depth that overlays a 6 in. (15 cm) gravel layer in conjunction with a 4 in. (10 cm) perforated PVC underdrain in the center. The infiltration requirements for the porous soil media are to be at least 1 ft/day (0.3 m/day) and the maximum infiltration rate of 1.5 ft/day (0.45 m/day). Including the infiltration trench, filter fabric is used to separate the organic porous soil and the gravel layer. The last requirements for installation include a forebay for pretreatment and to not load the trench during construction that may cause soil compaction and ripping prior to placing the gravel layer. Figure 2-8 shows a depiction of the plan and cross-section view of the enhanced dry swale [37].

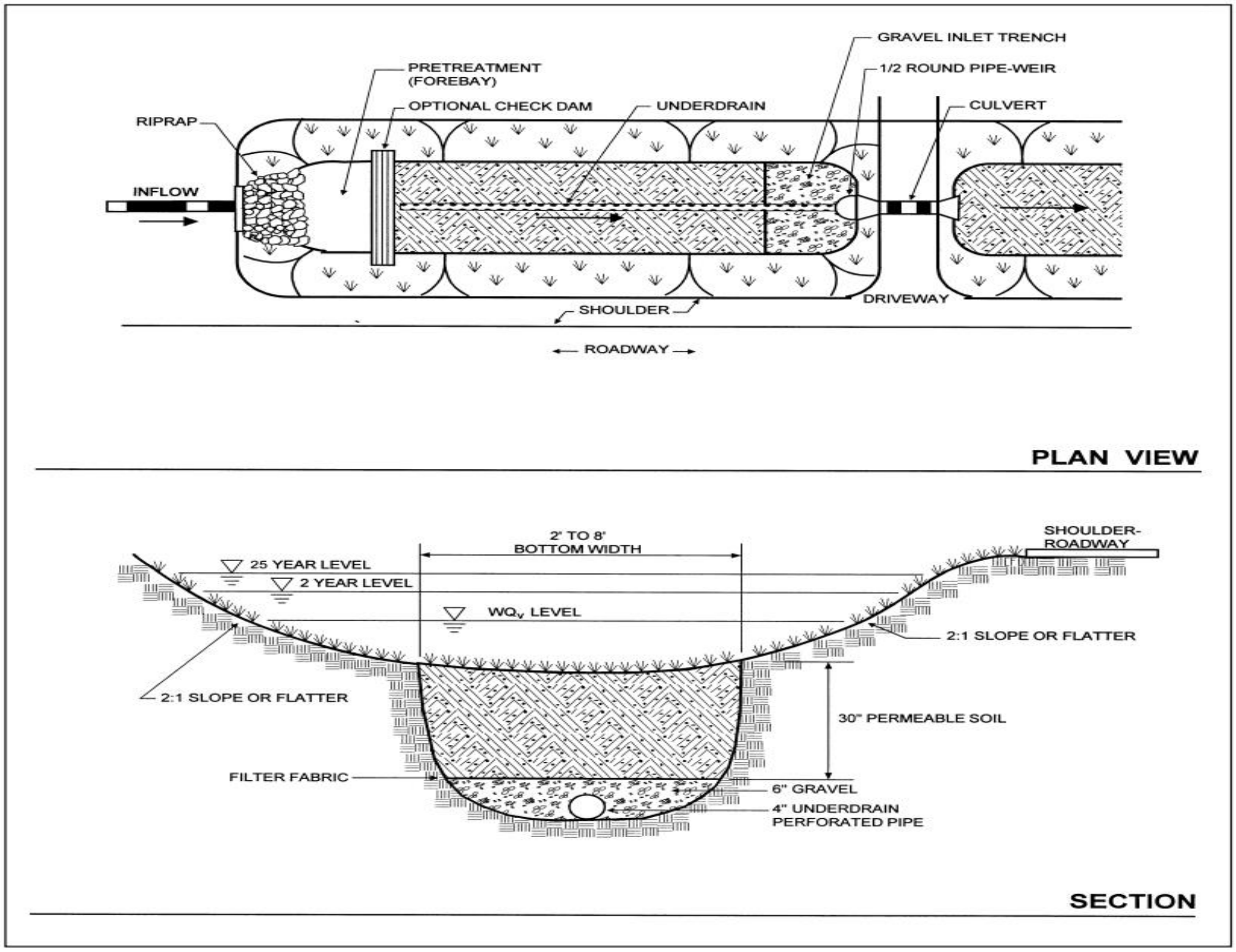


Figure 2-8. GDOT Enhanced Dry Swale Design [37]

2.4.4 Minnesota Department of Transportation

MnDOT has multiple types of post-construction SCMs that use infiltration to capture and treat stormwater runoff. The two types that are similar to ALDOT infiltration swales are (1) infiltration trench and (2) bioinfiltration basin [38].

An (1) infiltration trench according to MnDOT is a shallow excavated trench that is backfilled with stone aggregate which serves as an underground storage of stormwater runoff through the air voids. The depth of the excavated trench can vary from 3 to 6 ft (0.9 to 1.8 m) and the top width being less than 25 ft (7.6 m). The maximum time to drawdown surface runoff is required to be less than 48 hours. Infiltration occurs through exfiltration from the stone aggregate layer into the surrounding permeable native soils. The design criterion used for all infiltration SCM used by MnDOT must have in-situ soil testing and must be HSG A or B with HSG C being acceptable but not preferred. Unlike GDOT, MnDOT requires all infiltration-based SCMs to have native soils as hydrological soil groups A, B, or C while GDOT requires this for practice specific situation.

Including the infiltration trench design proposed by GDOT, MnDOT infiltration trench design is mostly the same. This system is first made up of a 6 in. (15 cm) minimum sand layer at the bottom of the excavated trench. The next layer backfilled is a 3 to 6 ft (0.9 to 1.8 m) layer of washed stone conforming to 1 to 3 in. (2.5 to 7.6 cm) diameter. Similar to GDOT, a filter fabric lines the top and all sides of the stone aggregate layer with the main goal to separate the stone layer and smaller soil particles from clogging. The remaining backfill material is a 4 in. (10 cm) minimum depth pea gravel layer. This system is then paired with a vegetated buffer strip on all sides that serves as pretreatment. The last main component of the infiltration trench is a 4 in. (10 cm) minimum perforated PVC pipe that serves as an observation well with a removable cap. Figure 2-9 shows cross section depiction of the MnDOT infiltration trench.

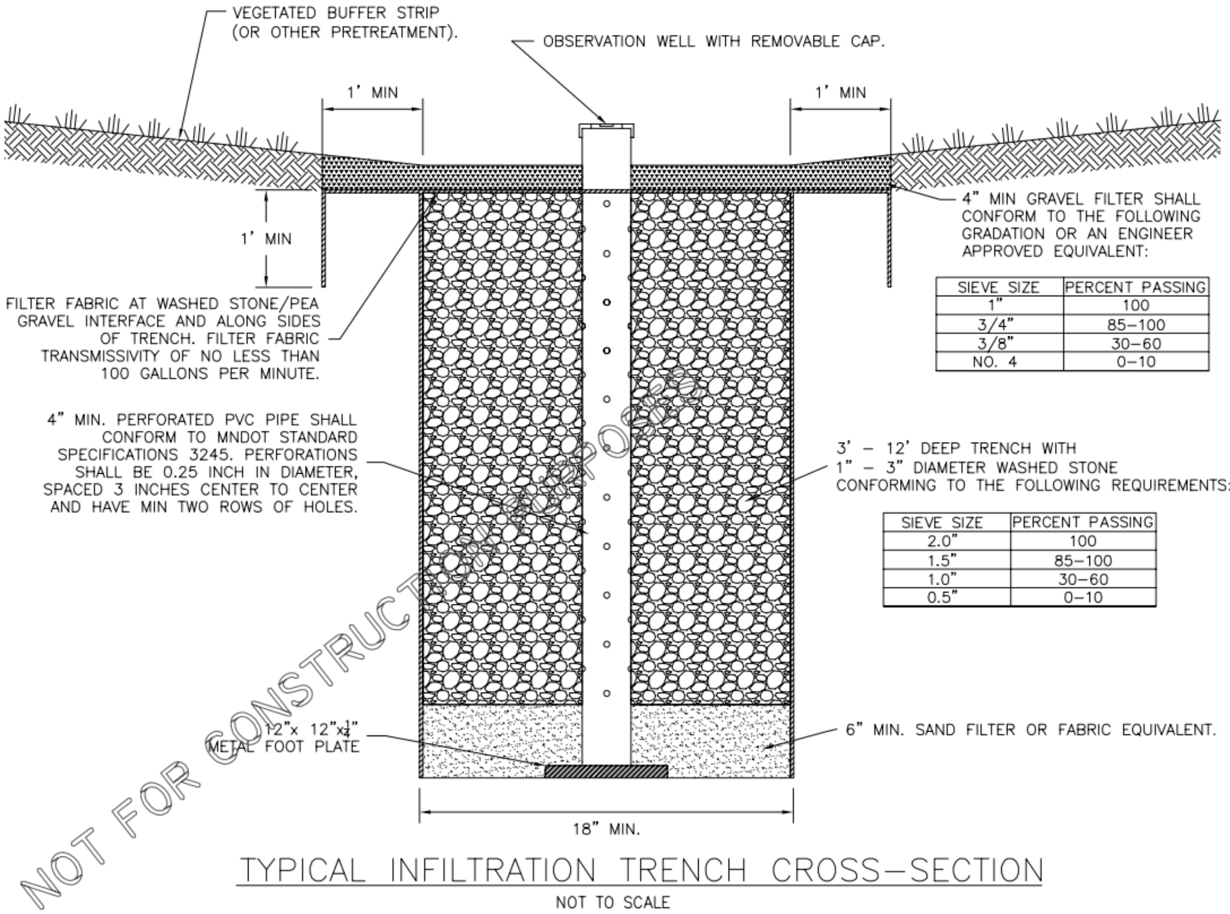


Figure 2-9. MnDOT Infiltration Trench Design [38]

The next SCM MnDOT uses, similar to infiltration swales, are (2) bioinfiltration basins [39]. This infiltration-based SCM often also called rain gardens uses an engineered media and native vegetation to capture, infiltrate, and treat stormwater runoff. Typically, the engineered media and underlying native soil have high infiltration rates that must meet the drawdown requirement of 48 hours. Design criteria include to have in-situ soil to be classified as HSG A, B, or C, drainage area of 5 acres (2 ha) or less, site slopes to be less than 33% but greater than 1%, 3 ft (0.9 m) minimum depth offset from bedrock/groundwater, and to be paired with a pretreatment facility. Bioinfiltration basins use underdrains depending on the HSG of the surrounding soils on site. For instance, an underdrain is used when in-situ soils are HSG C or D only.

For the media designs for the bioinfiltration basin, MnDOT has six different designs depending on the site-specific criteria mainly focusing on stormwater runoff pollutant treatment. These mixes are classified as mix A, B, C, D, E, and F. Mixes C and D are used mostly for filtration practices with an underdrain while mixes A, B, E, and F should not be used when phosphorus is a potential pollutant at the site.

Mix A is called the water quality blend which is a homogenous mixture composed of 60% to 70% sand, 15% to 25% topsoil, and 15% to 25% organic matter. These soil types within the mixture have further requirements and specifications. The advantages of this mixture are that it is likely to absorb more dissolved phosphorous and metals more than mix B and is best for plant growth. However, this mix is likely to leach phosphorus and potential of clogging and long drawdown times [39].

Mix B is called the enhanced filtration blend which is a homogenous mixture of 70% to 80% sand and 15% to 30% organic matter. This mix has further specifications including sand testing and topsoil testing. The advantages of this mixture are that it is easy to mix and least likely to clog; however, it may leach phosphorus and is not the most suitable for plant growth [39].

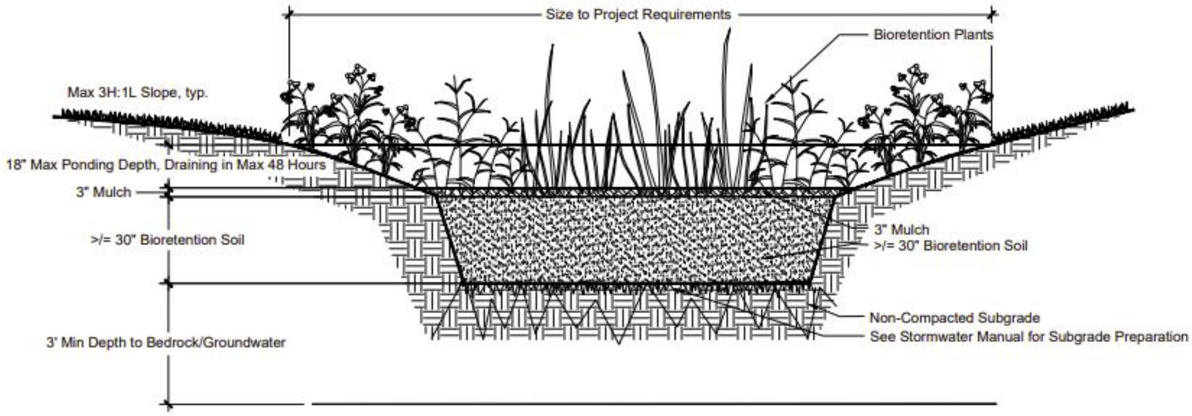
Mix C is called the North Carolina University water quality blend and is a homogenous mixture composed of 85% to 88% by volume of sand, 8% to 12% silt and clays by volume, and 3% to 5% organic matter by volume. This mixture is required if phosphorus is a potential concern at the site paired with an underdrain. The advantages of this mixture are that it is likely to absorb dissolved phosphorus and metals than mix B and is less likely to leach phosphorus; however, it is not suitable for plant growth because it dries out quickly. Also, if placed in cold climates the infiltration rate will significantly decrease due to excess sodium ions and will displace the magnesium and calcium in the soil [39].

Mix D has no name and is a homogenous mixture composed of 50% to 65% of coarse sand, 25% to 35% of topsoil, and 10% to 15% of compost which yields a 2% to 5% organic matter content. Again, this mixture is required to be used if phosphorus is a potential concern at the site paired with an underdrain. The advantages of this mixture are it is best for pollutant removal, moisture retention, and growth for most plants. It is also less likely to leach phosphorus. The disadvantages of this mix is it is harder to find and performs poorly in cold climates [39].

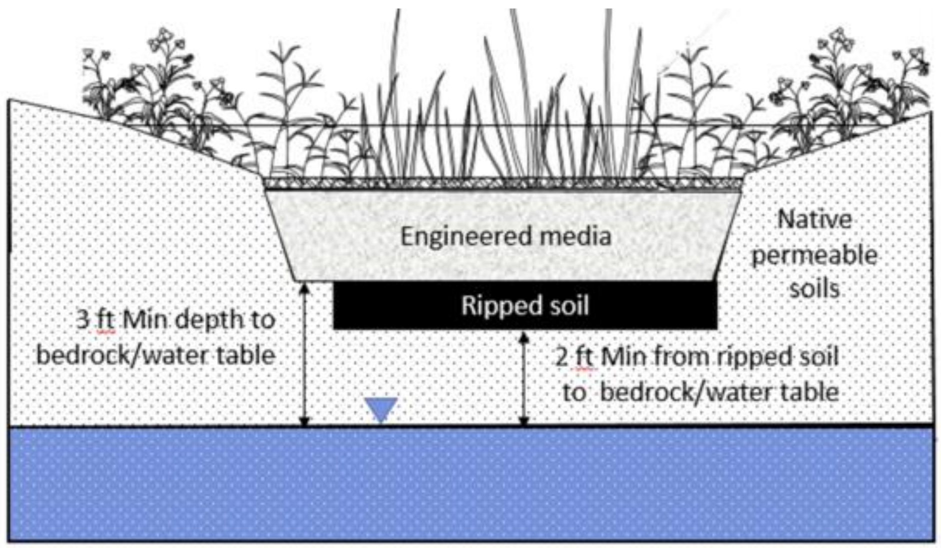
Mix E is called the filter topsoil borrow and is a homogenous mixture composed of 60% to 80% sand and 20% to 40% compost. The sand and compost must meet specific requirements placed by MnDOT. The advantages of this mixture are its high infiltration rates and cost-effectiveness; however, a disadvantage include nutrients decreases for plants overtime [39].

The last mix F is called the custom infiltration basin planting soil and is a homogenous mixture composed of 75% by weight loamy sand and 25% by weight compost. Again, the soils must comply with MnDOT specifications. The advantages of this mixture are it is great for plant growth; however, may contain slower infiltration rates, increases soil compaction, and requires custom mixing [39].

The general design for bioinfiltration basins according to MnDOT is a 33 in. (83 cm) excavated trench. The subgrade of the trench must be decompacted before backfill material is placed. Once the subgrade is prepared, 30 in. (76 cm) of the desired mixture A, B, C, D, E, or F is used depending on the site-specific constraints or present pollutants. The next backfilled material is a 3 in. (7.6 cm) layer of mulch. Side slopes must have a maximum of 3:1 slope and then finished with bioretention plants. Figure 2-10 shows the general cross section of bioinfiltration basins, which can be used interchangeably with the different mixtures A, B, C, D, E, or F.



(a) bioinfiltration cross section



(b) bioinfiltration groundwater separation

Figure 2-10. MnDOT Bioinfiltration Design [40]

2.4.5 North Carolina Department of Transportation

The North Carolina Department of Transportation (NCDOT) has multiple types of post-construction SCMs that use infiltration to capture and treat stormwater runoff. The post-construction SCM that NCDOT uses, most similar to ALDOT infiltration swales, are media filters [41]. Media filters according to NCDOT BMP toolbox, are systems that capture and impound stormwater runoff and allow it to infiltrate and filter through either natural, manufactured, or engineered media to an underdrain. All media filters typically are paired with bypass structures, forebays, basins, media, landscaping, underdrains, outlet control systems, embankments, emergency spillways, and access roads. NCDOT categorizes media filters into two types (1) filtration basin. (grass media filters) and (2) bioretention basin. (landscaped media filters). The main purpose of these two are to reduce peak flows and promote infiltration of stormwater runoff to filter and capture pollutants. During drawdown the media filter removes solids and absorbs pollutants including total suspended solids, nutrients, metals, hydrocarbons, and pathogens. Important design criteria for media filters are to have a minimum of 2 ft (0.61 m) distance from the seasonal high-water table, drainage area of at least 5 acres (2 ha), and site slopes to be less than 20%. Media filters may have an infiltration rate as low as 0.52 in/hr. (1.3 cm/hr.), however, infiltration rates between 1 to 2 in/hr. (2.5 to 5.1 cm/hr.) are desired.

A (1) filtration basin uses media that is mostly composed of coarse sand or reused aggregate that contains organic content to be covered with sod. The media is a homogenous mixture with 95% to 97% coarse sand passing a No.10 sieve and retained on a No.40 sieve. The other component of the mixture consists of 3% to 5% organic matter which is usually pine bark fines. The depth of this media is site specific and pertains to the targeted pollutants but in general the minimum depth is 18 in. (45 cm). All noticeable impounded water inside the basin varying from 12 to 36 in. (30 to 91 cm) should drawdown within 24 hours. Figure 2-11 shows a depiction of NCDOT filtration basin set-up.

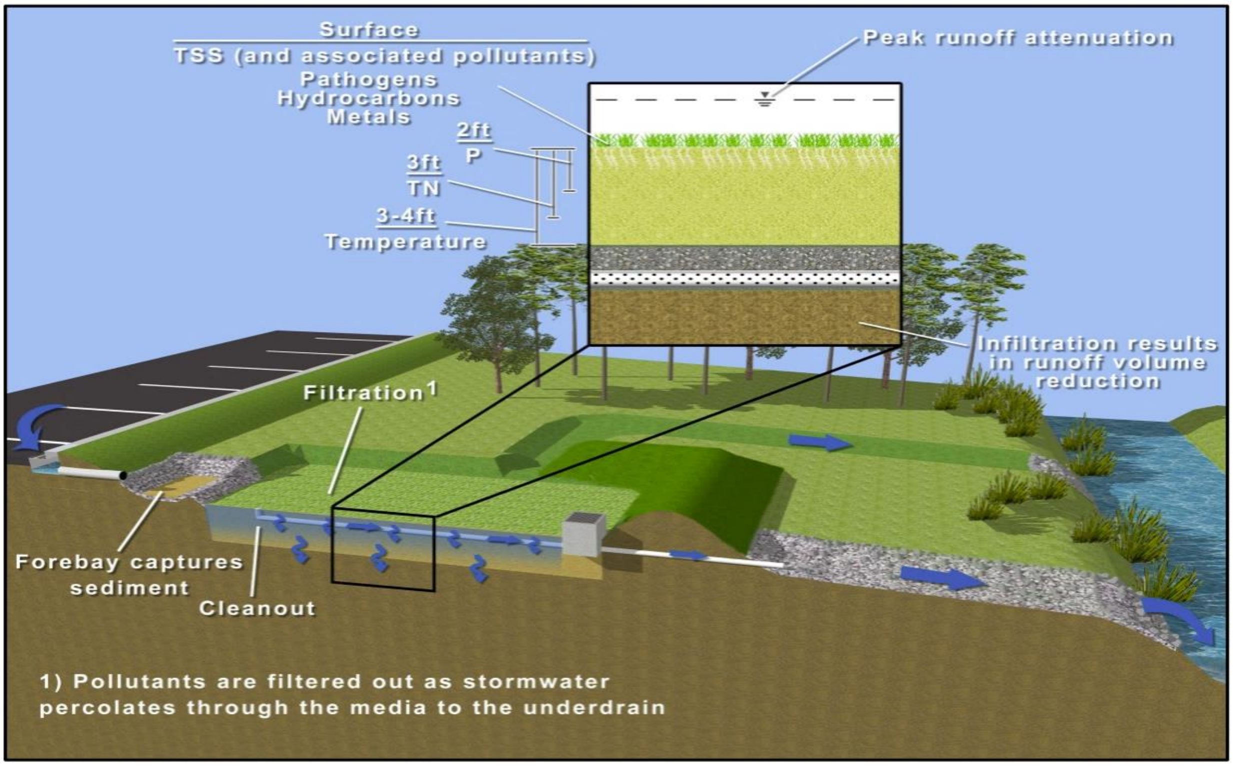


Figure 2-11. NCDOT Filtration Basin Depiction [41]

A (2) bioretention basin uses media that is a homogenous mixture of sand, fines, and organic content to promote plant growth and topped with mulched groundcover. The media is a homogenous mixture made up of 85% to 88% coarse sand passing a No.10 sieve and retained on a No.40 sieve. The other component of the mixture consists of 8% to 12% silt and clay fines, and 3% to 5% organic matter which is usually pine bark fines. The depth of the media is site specific and pertains to the targeted pollutants but in general the minimum depth is 24 in. (60 cm). All noticeable impounded water inside the basin is at a maximum depth of 12 in. (30 cm) should drawdown within 12 hours. This smaller impoundment depth is to make sure the established vegetation is not hindered. This media filter type is designed to drawdown runoff more rapidly than filtration basins to avoid impacts made of the established vegetation. Figure 2-12 shows a depiction of the bioretention basin.

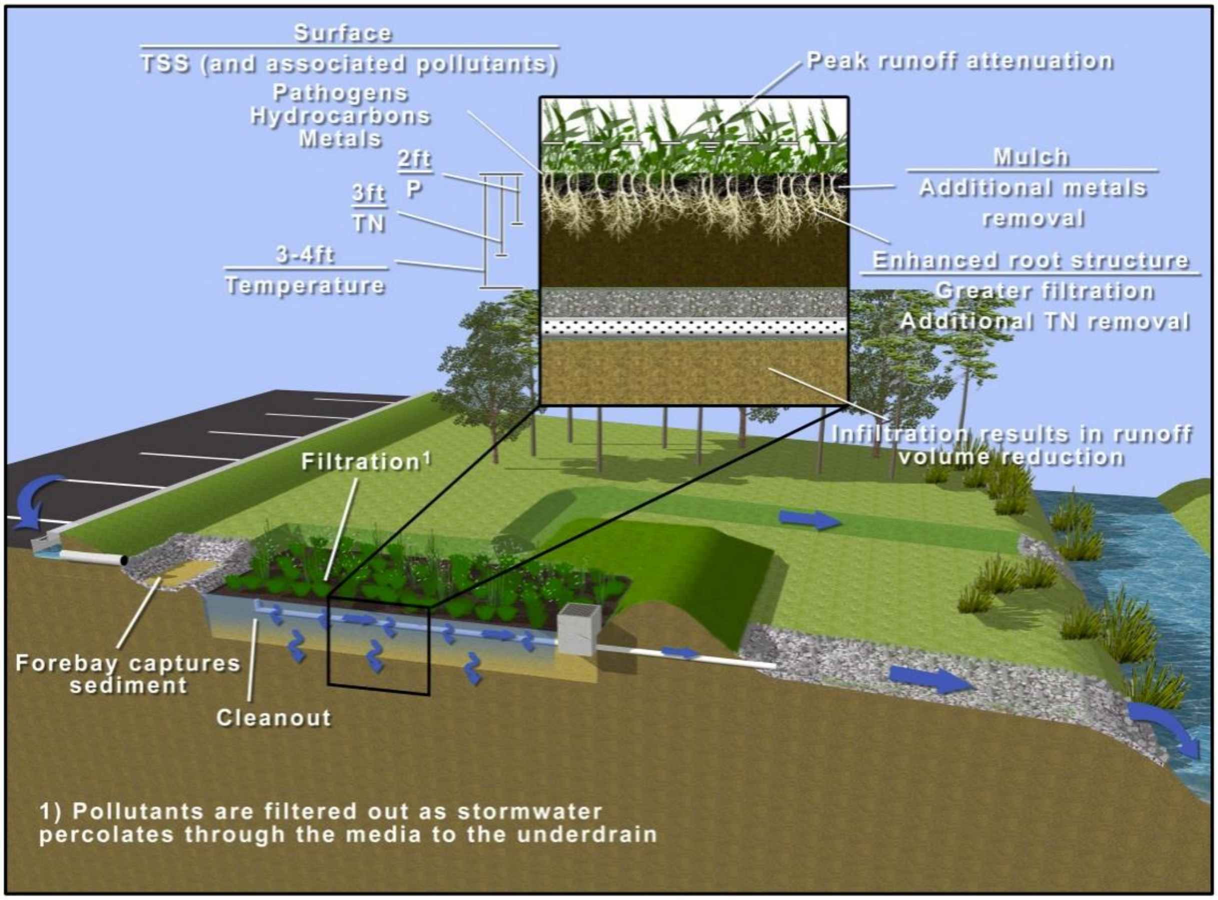


Figure 2-12. NCDOT Bioretention Basin Depiction [41]

2.4.6 Washington State Department of Transportation

The Washington State Department of Transportation (WSDOT) has multiple types of post-construction SCMs that use infiltration to capture and treat stormwater runoff. The post-construction SCM that WSDOT uses, most similar to ALDOT infiltration swales, are called media filter drains [42]. This SCM, according to WSDOT, is classified as a biofiltration BMP. WSDOT uses this type of BMP specifically for stormwater pollutant treatment with some flow control qualities as well. Media filter drains are a linear flow-through runoff treatment device along highways and roadways or other linear depressions. This SCM performs best in flatter areas where side slopes should be less than 25% or 4:1 while longitudinal slopes should be less than 5%. The media filter drains have seven different media designs depending on the type of pollutant removal and specific locations. Media filter drain type two is most similar to the ALDOT infiltration swales and will be covered instead of all media filters. Media filters drain type two is primarily used in highway medians and roadside swales and length is the same as the length of the contributing pavement. According to WSDOT, sheet flow is vital for the function of this SCM and all channelized flows down the base of the media filter drain channel should be minimized. Ensuring slopes less that 4:1 is critical because steeper slopes will increase erosion of the SCM and increase channelized flow.

Components for media filter drain type two from the surface start with sodding with a minimum width of 3 ft (0.91 m) on side slopes and is paired with a 3 in. (7.6 cm) medium seeded compost blanket to promote vegetation growth on the side slopes base of channel. Below the compost blanket is the media drain mix which is a homogeneous mixture of crushed rock, dolomite, gypsum, and perlite that must have a minimum depth of 12 in. (30 cm) and minimum bottom width of 2 ft (0.61 m). The rock provides a structural support component while the other materials in the mix provide pollutant treatment. The estimated initial infiltration rate of the media is 50 in/hr. (127 cm/hr.), and long-term infiltration rate is 28 in/hr. (71 cm/hr.); however, using a safety factor for the long-term infiltration rate, a 10 in/hr. (25 cm/hr.) infiltration rate is used for the design. The last layer is a gravel backfill that includes an underdrain in the middle of the layer. The underdrain pipe size changes depending on the amount of flow predicted to enter the system using the 25-yr design storm. The gravel backfill layer is a minimum of 2 ft (0.61 m) in width and the depth is a minimum of 6 in. (15 cm) above and below the chosen underdrain pipe size. Figure 2-13 shows a visual of the media filter drain type two.

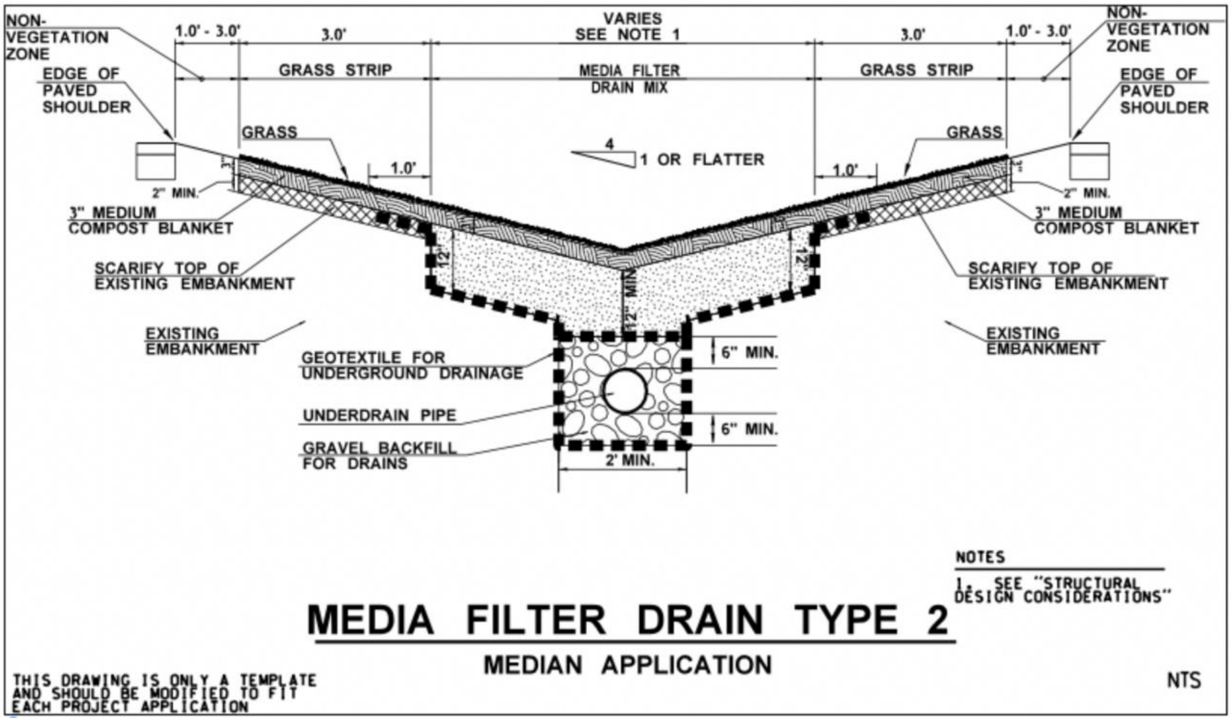


Figure 2-13. WSDOT Media Filter Drain Type 2 [42]

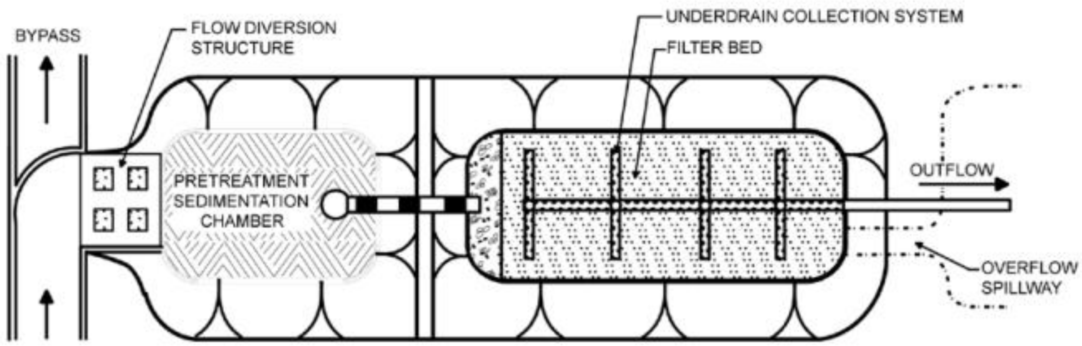
2.4.7 New York State Department of Transportation

The NYSDOT uses multiple types of post-construction SCMs that focus on the use of infiltration to capture and treat stormwater runoff. The post-construction SCM that NYSDOT uses, most similar to ALDOT infiltration swales, are called (1) surface sand filter, (2) organic filter, and (3) dry swale [43]. The dry swale design is the same design as the enhanced dry swale design that GDOT uses, so the two facilities that will be covered for the NYSDOT are the surface sand filter and organic filter.

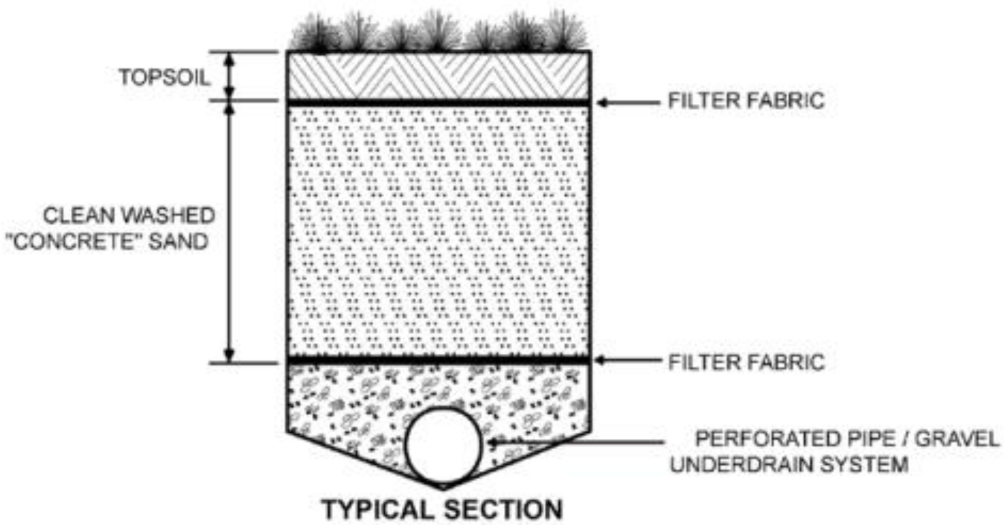
The (1) surface sand filter and the (2) organic filter is a filtering practice which captures and treats stormwater runoff by settling of large soil particles within the forebay and filters and infiltrates the rest of the runoff through the media matrix back into the native soils. Infiltration testing is conducted on the native soils to ensure the site is suitable for these infiltration facilities.

It is required to perform one field infiltration test and one test pit per 200 sq. f (18.6 sq. m). The infiltration rate of the native soil shall be greater than 0.5 in/hr. (1.3 cm/hr.) to use a surface sand filter or organic filter. Any infiltration rate lower is not an acceptable practice. This SCM typically uses a 4 to 6 in. (10 to 15 cm) underdrain to help drain the ten-year design storm. If the SCM is designed to recharge and exfiltrate the native soil, an underdrain shall not be included. Both practices utilize the same required elements of filter media ranging from 1.5 to 3 ft (0.46 to 0.91 m) with sand conforming to ASTM C-33 and organic content being a sand/peat mixture. It is vital for the media to not contain any clay particles especially if geotextile fabric is used. If the SCM is designed for groundwater recharge a geotextile fabric is voided from the bottom of the media. Lastly, the longitudinal slope shall be less than or equal to 2%. Compaction during construction should be minimized and shall decompact the native soils where the media will be backfilled.

The (1) sand surface filter is very similar to the ALDOT infiltration swale designs. The first layer of topsoil shall be at least 3 in. (7.6 cm) and must be tested to make sure that the pH, organic matter, magnesium, phosphorus, potassium, and soluble salts meet specific requirements. A geotextile is placed between the topsoil layer and the next layer of clean washed concrete sand conforming to ASTM C-33. This layer can vary from 1.5 to 3 ft (0.46 to 0.91 m). Another boundary layer of geotextile is placed on the bottom of the sand layer and is not wrapped on all sides of the sand media only the top and bottom. The last layer is the No. 57 gravel layer which is specified to AASGTO M-43. The depth of this layer is unclear; however, most other infiltration practices listed in the NYSDOT manual states at maximum 1 ft (0.3 m) depth of gravel. Figure 2-14 shows the plan and cross-section view of the surface sand filter schematic. This drawing shows an underdrain laying on the bottom of the gravel layer; however, the manual specifically states underdrain are not used if the infiltration rate of the native soil is greater than 0.5 in/hr. (1.3 cm/hr.).



(a) plan view

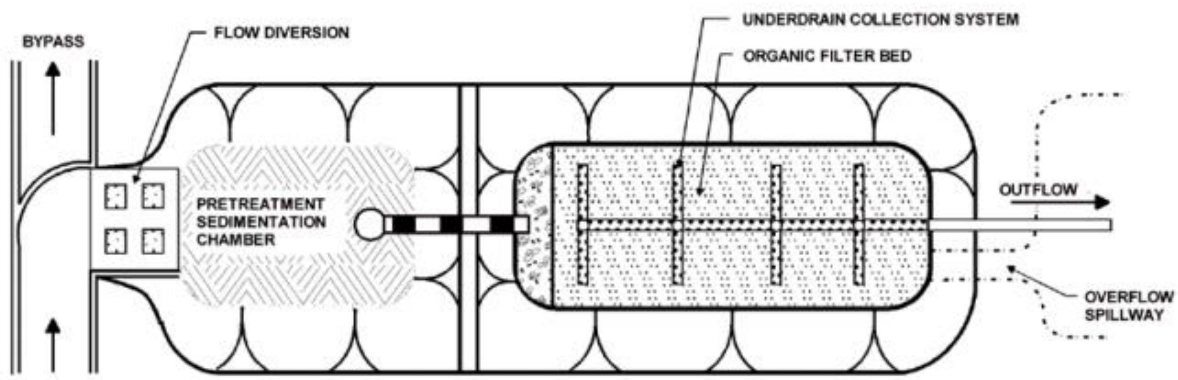


(b) cross-section view

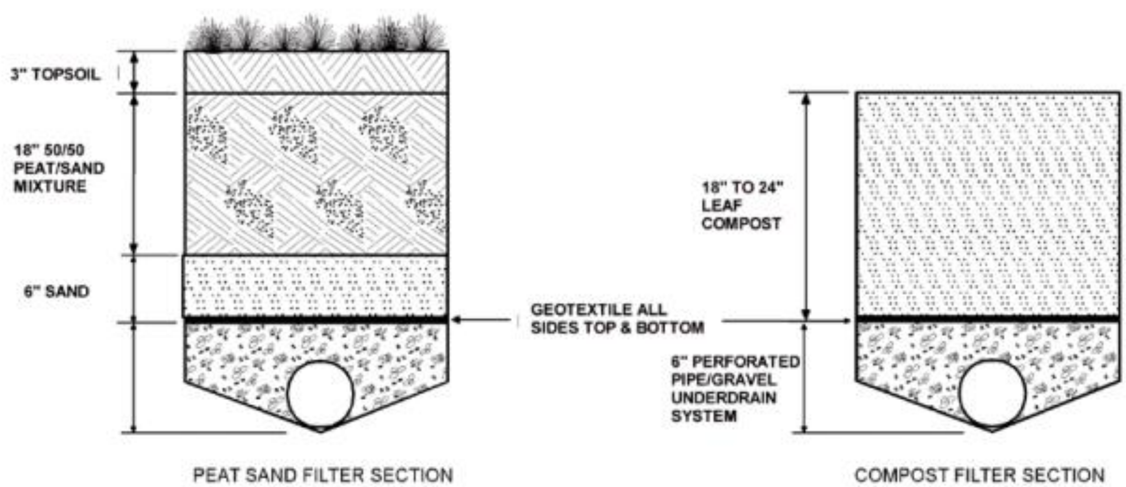
Figure 2-14. NYSDOT Surface Sand Filter Schematic [43]

The (2) organic filter design starts with the first layer of topsoil that shall be at least 3 in. (7.6 cm) and must be tested to make sure that the pH, organic matter, magnesium, phosphorus, potassium, and soluble salts meet specific requirements. The next layer is an 18 in. (45 cm) 50/50 sand/peat homogeneous mixture and a geotextile fabric is not used to separate from the other adjacent layers. The media filter shall use sand with infiltration rates of about 3.5 ft/day (1 m/day) and peat of 2 ft/day (0.61 m/day). An alternative to this layer is an 18 to 24 in. (45 to 60 cm) leaf compost layer. The leaf compost layer shall have an infiltration rate of at least 8.7 ft/day (2.7

m/day). The next layer is a 6 in. (15 cm) washed concrete sand conforming to ASTM C-33 and is followed by a geotextile that will line the sides, top, and bottom of the next No.67 stone gravel layer. Including the surface sand filter, the depth of the gravel layer is not specified; however, 1 ft (0.3 m) is a common depth listed of other NYSDOT practices. The geotextile and underdrain are omitted from the bottom of the gravel layer if the infiltration rate of the native soils is greater than 0.5 in/hr. (1.3 cm/hr.). Figure 2-15 shows the plan and cross-section view of the organic filter SCM.



(a) plan view



(b) cross-section view

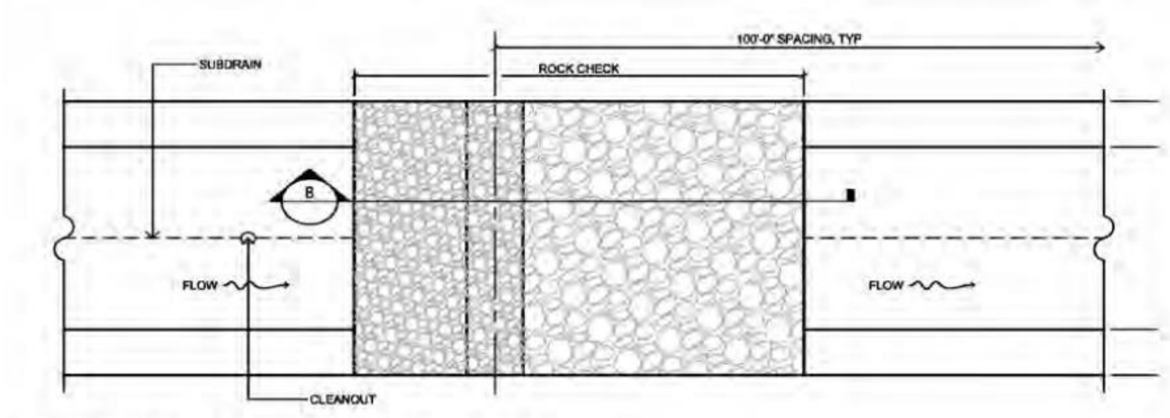
Figure 2-15. NYSDOT Organic Filter Schematic [43]

2.4.8 Iowa Department of Transportation

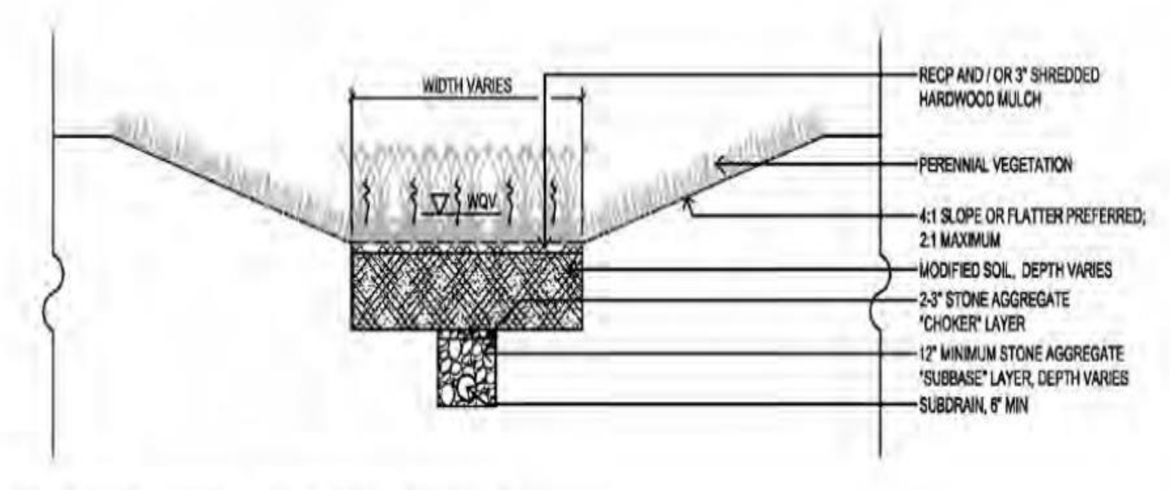
The Iowa Department of Transportation (Iowa DOT) uses a storm water management manual that lists the different post-construction SCMs. The SCM that resembles ALDOT's infiltration swales the most is their bioswales [44]. According to Iowa DOT, bioswales are used for small frequent storms at slower velocities to promote capture, filtration, and infiltration through soil media. This system consists of an open conveyance channel and is located underneath the base of the channel is an engineered media of permeable soils designed to promote stormwater runoff infiltration. Underneath the media is a perforated underdrain if the native soils at the site's location have low infiltration rates. This channel also utilizes rock or earthen check damns to help slow the conveyance of runoff to promote slower velocities, settlement of larger soil particles, and aid infiltration. The longitudinal slope must be smaller than or equal to 2% to minimize the velocity of the runoff. Higher slopes will cause the channel to erode. Also, a geotechnical investigation is required to determine the water table which must at least be 2 ft (0.61 m) below the last layer of the media. Iowa estimates for bioswales to drain down between storm events within 24 hours. This practice is great for right-of-way of roads, parking lots, and residential areas. If this practice is to be used close to gas stations or where spills may occur, the media must be lined in an impermeable fabric.

The geometric design of Iowa's bioswales consists of a trapezoidal cross-section with the bottom width varying from 4 to 8 ft (1.2 to 2.4 m). The channel side slopes must conform to a maximum of 2:1; however, this is not recommended, and 4:1 is the preferred side slope. The longitudinal slope of the SCM works best with a maximum slope of 2%, anything less would be preferred. If the slope is higher than 2% it is recommended to use more check dams to manage the runoff velocities and promote infiltration. The minimum length of the SCM is 100 ft (30.4 m) or as needed to achieve the full water quality volume treatment. The last geometric component is surface storage. The maximum impoundment the bioswale should hold is about 18 in. (45 cm) or an average of 12 in. (30 cm) depth considering the use of check dams.

The design components that make up the engineered media consist of a top layer of 3 in. (7.6 cm) shredded hardwood mulch to help establish perennial vegetation. The next layer is a 6 to 12 in. (15 to 30 cm) deep homogenous mixture of 75% to 90% washed concrete sand, 0% to 10% approved organic matter, and 0% to 25% soil texture conforming to A-horizon characteristics. Below this media layer is a choker aggregate used to separate the media from entering the aggregate subbase. This layer is typically 2 to 3 in. (5.1 to 7.6 cm) deep of clean 0.38 in. (0.96 cm) diameter chips. Below the choker is a 12 in. (30 cm) minimum depth of stone aggregate subbase layer which provides temporary storage after filtration and infiltration of the runoff. This layer is an open-graded aggregate with diameters of 1 to 2 in. (2.5 to 5.1 cm) and a porosity ranging from 35% to 40%. Within this layer resides a perforated underdrain that must have a minimum diameter of 6 in. (15 cm). Sometimes an 8 in. (20 cm) is recommended for aiding maintenance of the underdrain. This pipe is used when native soils have low infiltration rates and can act as a secondary outlet to where native soil infiltrate better. Figure 2-16 shows the depiction of the Iowa Bioswale schematic.



(a) plan view



(b) cross-section view

Figure 2-16. Iowa DOT Bioswale Schematic [44]

2.4.9 California Department of Transportation

The California Department of Transportation (Caltrans) has multiple infiltration-based BMP treatment devices including biofiltration swale (no media), infiltration basin, infiltration trench, sand filters, and bioretention [45]. The BMP that resembles ALDOT infiltration swale the most is the bioretention treatment best management practice (TBMP). This uses an engineered media matrix to manage stormwater runoff more similarly than the other practices they mention.

Bioretention TBMPs use vegetation and an engineered media to promote filtration, infiltration, and storage of stormwater runoff. This practice resembles a basin more than a swale; however, it can easily be configured into different shapes to meet right-of way restrictions. This practice works best adjacent to parking lots, roads, and open spaces. The contributing design drainage area must be less than or equal to 5 acres (2 ha) with 1 acre (0.4 ha) preferred. Two flow types that can enter the bioretention TBMP are sheet flow or concentrated flows from the end of a pipe system. The main purpose of this SCM is to treat the quality of runoff through biochemical processes, plant uptake, absorption from soil particles, and sedimentation. The design treatment volume is based off the water quality volume. Any events larger than the water quality volume should be bypassed around to preserve infiltration capacity. In the middle of the SCM is an overflow riser to allow larger rainfall events to bypass the basin. It is noted that the performance of the bioretention TBMP varies infiltration depending on the native soils surrounding the SCM. Native soil shall also be uncompacted at the bottom of the SCM. If the native soil classifies as a HSG C or D, it is recommended to use a perforated underdrain; however, studies show that underdrain may export excess nutrients in the water. Other design criteria include having side slopes to be as flat as possible at maximum being 3:1. The final grade of the bioretention TBMP should be equal to or less than 2% and check dams are utilized if there is potential for erosion. A geotechnical investigation includes infiltration testing of the native soils at the site. If soils with 2.5 in/hr. (6.4 cm/hr.) are found, then further investigation on the groundwater table is needed to ensure pollutants do not reach the water table. In scenarios where this is a concern, the SCM uses a liner at the bottom of the engineered soil. Caltrans is more concerned with groundwater contamination when using this practice.

The media begins with a 3 in. (7.6 cm) deep layer of non-floating mulch. The next soil media depth ranges from 18 to 24 in. (45 to 60 cm) and must have an infiltration rate of 1 in/hr. (2.5 cm/hr.) with 3 in/hr. (7.6 cm/hr.) being preferred. The main media layer by volume shall be four parts sand, two parts compost, and one part topsoil. Other materials may be added or taken out depending on site specific pollutant removal. Below this layer is a 6 in. (15 cm) deep filter course material. This material is made up of class two permeable material and must comply with a gradation requirement [46]. The specification does not mention the name of the material if it meets the gradation requirement which is a type of course aggregate. This layer is designed to separate the fines from the engineered media from the subsurface drainage layer. The specifications mentioned to not to use filter fabric to separate the layers due to the potential of clogging. Below the filter course layer is the subsurface drainage layer. The last layer is the subsurface drainage layer which is typically used in areas where the native soil infiltration rates are low or classified as HSG C or D. This layer is usually 12 to 24 in. (30 to 60 cm) deep and uses an underdrain to help discharge runoff. The material of this layer but through interpretation is a larger coarse aggregate than the filter course layer. Lastly the drawdown time for the media is a maximum of 36 hours. Figure 2-17 shows the components that make up the Caltrans bioretention TBMPs.

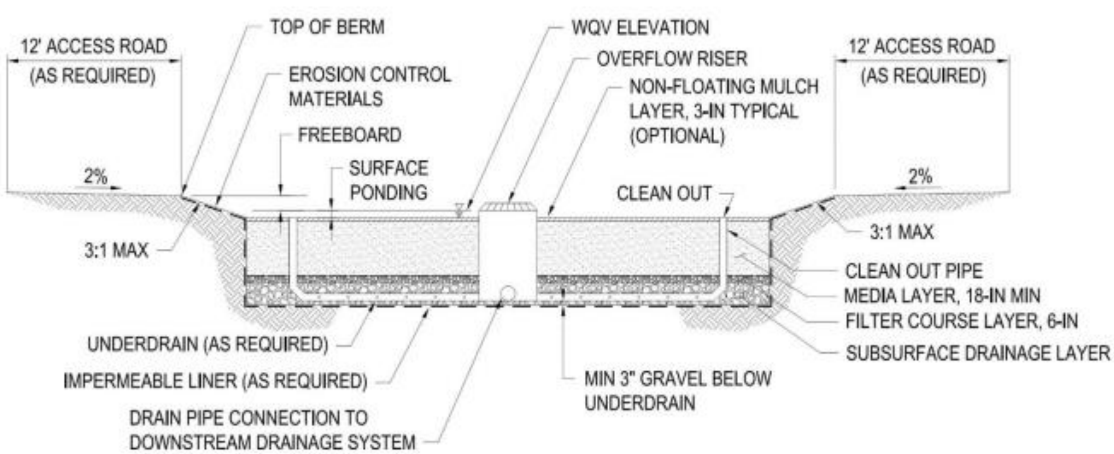


Figure 2-17. Caltrans Bioretention TBMP Schematic [45]

2.4.10 DOT SCM Summary

A review of infiltration-based SCM practices across the United States revealed several key design criteria that influence their performance. These criteria are essential for optimizing infiltration efficiency and ensuring the long-term functionality of these facilities.

- **Longitudinal Slope:** Most reviewed facilities possess relatively flat longitudinal slopes, ranging from 0.5% to a maximum of 5%. State agencies consistently emphasize the importance of a flat slope for promoting infiltration. Lower slopes encourage slower flow velocities, allowing stormwater runoff to linger on the surface and infiltrate into the media. Conversely, steeper slopes create higher velocities that bypass infiltration and can lead to erosion and scour within the SCM.
- **Drainage Area:** The optimal drainage area for infiltration-based SCMs is generally considered to be 5 acres (2 ha) or less. Excessively large drainage areas overwhelm the SCM and compromise its infiltration capacity. Larger areas contribute to higher peak flow velocities, further exacerbating erosion and scour.
- **Native Surrounding Soil:** The infiltration performance of these facilities is significantly influenced by the surrounding native soil. Ideally, the soil should be classified as HSG A or B, with an infiltration rate exceeding 0.5 in/hr. (1.27 cm/hr.). Some states entirely avoid infiltration-based SCMs in areas with HSG C or D soils, while others incorporate underdrains for such sites. Low infiltration rates in native soils prevent timely exfiltration of stormwater runoff from the media before the next storm event, leading to ponding and potential flooding that can take days to resolve.

- **Drawdown Time:** Most state agencies require their infiltration-based SCMs to achieve a complete drawdown within 48 hours. The reviewed literature documented drawdown times ranging from 12 hours (reported for North Carolina's bioretention basins) to a maximum of 48 hours. Drawdown times exceeding 48 hours can lead to increased pollutant concentrations within the stagnant water and create mosquito breeding habitats. The stagnant polluted water can potentially contaminate the groundwater table or other nearby waterways.
- **Depth of Seasonal High Groundwater Table:** The depth of the seasonal high groundwater table significantly impacts the recommended drawdown time. Across the country, reported minimum depths varied from 1 ft (0.3 m) in Alabama to 5 ft (1.5 m) in California. A deeper groundwater table allows infiltrated runoff to exfiltrate and drain from beneath the SCM, facilitating a faster drawdown. Conversely, a shallow groundwater table creates water mounding underground that restricts exfiltration into the native soils, thereby reducing infiltration capacity and potentially causing drawdown times to exceed 48 hours.
- **Check Dams:** Including the benefits of low longitudinal slopes, check dams serve to interrupt flow and reduce flow velocity within the SCM. By creating impoundments, check dams allow the runoff to slow down and make contact with the surface, promoting infiltration. Facilities lacking check dams may experience reduced infiltration due to runoff bypassing the media and continuing downstream.

A summary table consolidating the key findings from this literature review, including the six design criteria and minimum media depth, is presented in Table 2-4.

Table 2-4. Summary of Presented Infiltration-Based SCMs

Agency	Infiltration SCM	Design Criteria	Min. Media Depth
ALDOT	Infiltration Swale	Long. Slope ≤ 5% Drainage Area ≤ 5 ac. (2.02 ha) Native soils HSG A or B Check Dams Groundwater Table ≥ 1 ft (0.305 m) Max. 48 hr. drawdown	30 in. (76.2 cm)
GDOT	Infiltration Trench	Long. Slope ≤ 1% Drainage Area ≤ 5 ac. (2.02 ha) Native soil ≥ 0.5 in/hr. (1.27 cm/hr.) No Check Dams Groundwater Table ≥ 4 ft (1.2 m) Max. 48 hr. drawdown	48 in. (121.9 cm)
	Enhanced Dry Swale	Long. Slope ≤ 4% Drainage Area ≤ 5 ac. (2.02 ha) No Native Soil Restrictions Optional Check Dams Groundwater Table ≥ 2 ft (0.61 m) Max. 48 hr. drawdown	36 in. (91.4 cm)
MnDOT	Infiltration Trench	Long. Slope ≤ 1% Drainage Area ≤ 5 ac. (2.02 ha) Native soil HSG A, B, or C No Check Dams Groundwater Table ≥ 3 ft (0.91 m) Max. 48 hr. drawdown	46 in. (116.8 cm)
	Bioinfiltration Basin		33 in. (83.8 cm)
NCDOT	Filtration Basin	Long. Slope ≤ 0.5% Drainage Area ≤ 5 ac. (2.02 ha) Native soil ≥ 0.52 in/hr. (1.32 cm/hr.) No Check Dams Groundwater Table ≥ 2 ft (0.61 m) Max. 24 hr. drawdown	18 in. (45.7 cm)
	Bioretention Basin	Long. Slope ≤0.5% Drainage Area ≤ 5 ac. (2.02 ha) Native soil ≥ 0.52 in/hr. (1.32 cm/hr.) No Check Dams Groundwater Table ≥ 2 ft (0.61 m) Max. 12 hr. drawdown	24 in. (60.9 cm)
WSDOT	Media Filter Drain	Long. Slope ≤ 5% Drainage Area ≤ 0.12 ac. (0.05 ha) Native soil HSG A or B Flow Spreader, no check dams Groundwater Table ≥ 3 ft (0.91 m) Max. 48 hr. drawdown	33 in. (83.8 cm)
NYDOT	Surface Sand Filter	Long. Slope ≤ 2% Drainage Area ≤ 10 ac. (4.05 ha) Native soil ≥ 0.5 in/hr. (1.27 cm/hr.) No Check Dams Groundwater Table ≥ 3 ft (0.91 m)	33 in. (83.8 cm)
	Organic Filter		39 in. (99.1 cm)

		Max. 48 hr. drawdown	
IOWA DOT	Bioswale	Long. Slope ≤ 2% Drainage Area – small or large Native soil ≥ 0.5 in/hr. (1.27 cm/hr.) Check Dams Groundwater Table ≥ 2 ft (0.61 m) Max. 12 hr. drawdown	23 in. (58.4 cm)
Caltrans	Bioretention TBMP	Long. Slope ≤ 2% Drainage Area ≤ 5 ac. (2.02 ha) Native soil HSG A or B Check Dams Groundwater Table ≥ 5 ft (1.5 m) Max. 36 hr. drawdown	39 in. (99.1 cm)

2.5 SUMMARY

This review delves into the mechanics of infiltration swales, highlighting the critical role of each component in facilitating infiltration. It identifies three key factors that can compromise long-term performance – compaction, sedimentation, and inadequate pre-construction soil testing. Recognizing these potential challenges allows designers and stakeholders to implement preventative measures, ensuring the sustained effectiveness of infiltration-based SCMs.

Furthermore, the review explores various infiltration-based SCMs employed by DOTs across the nation. This exploration focuses on different infiltration-based SCM types, their design criteria for optimal performance and longevity, along with media design specifications and dimensions.

Based on the findings from this investigation, the review concludes with key recommendations that will ensure effective long-term performance. These recommendations include a longitudinal slope between 0.5% and 1% for optimal infiltration, a drainage area no larger than 5 acres, surrounding soil that infiltrates water well (HSG A or B), a surface drawdown time of 24 hours (with 48 hours still acceptable), groundwater that sits at least 3 feet below the swale (the deeper the table the better), and the use of check dams within the swale to improve infiltration and minimize erosion.

CHAPTER THREE: SWALE DESIGN AND CONSTRUCTION

3.1 INTRODUCTION

This chapter outlines the ALDOT and modified infiltration swale designs and will present a detailed comparison discussing the rationale behind the changes made to the existing ALDOT infiltration swale design to create the modified infiltration swale through findings made from small-scale testing.

This section will also delve into the construction process for the field-scale infiltration swale testing. The construction process consists of site selection process, swale layout, excavation, filling materials, installing sensors, grading, sodding, and placing the introductory system. The construction phase of the infiltration swale project served as the foundation for subsequent performance evaluation. This critical stage comprised a series of planned and executed steps, ensuring a strong platform for data collection and analysis.

3.2 TESTING FACILITY

Construction and testing of the infiltration swales were conducted at the Auburn University Stormwater Research Facility (AU-SRF) located adjacent to the pavement test track site from the National Center for Asphalt Technology (NCAT) in Opelika, Alabama. The AU-SRF is a 10-acre (0.03 km^2) property which provides ample area for testing and researching erosion, sediment control, and stormwater management practices. The facility also serves as a training facility to educate designers, contractors, and inspectors in proper design, installation, maintenance, and inspection practices [47].

The AU-SRF currently has a variety of research projects for testing erosion control practices such as simulated rainfall simulators, sediment basins, inlet protection practices, sediment barrier testing, and much more. Due to the expansion of the property, there was plenty of area to construct and assess the two infiltration swales in the expanded area. Both infiltration swales were constructed on the southeast side of the property outlined in blue in Figure 3-1. The expanded area of the facility also includes an upper and lower pond which are used for pumping water out of for testing. The upper pond is larger and can approximately hold 138,000 ft^3 (3,907 m^3) and the lower pond can approximately hold 34,000 ft^3 (962.7 m^3). These ponds are also depicted in Figure 3-1 along with the AU-SRF original area and expanded area. To conduct some of the infiltration swale testing water was pumped from the upper pond into both swales since the upper pond is adjacent to the infiltration swale designated area.

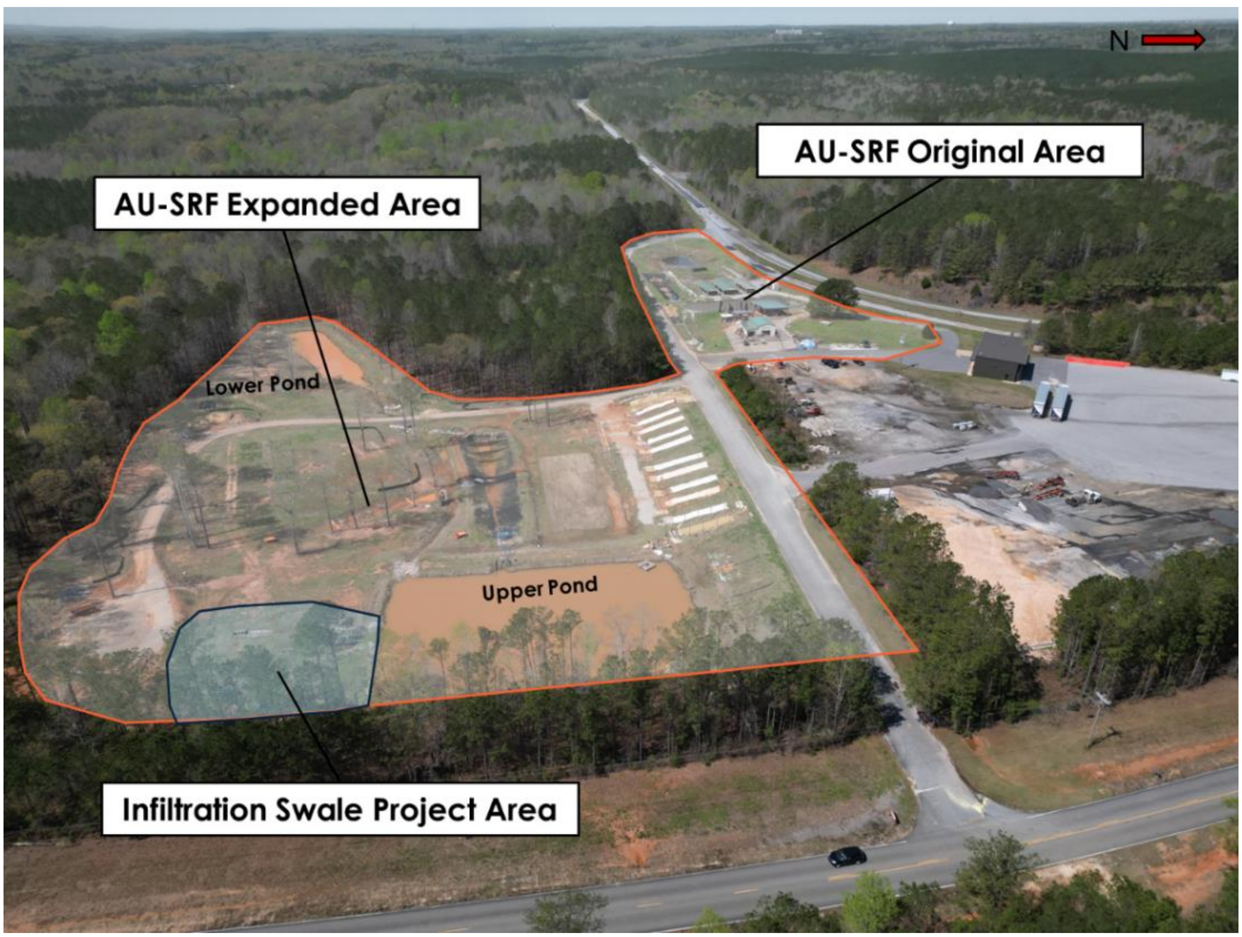


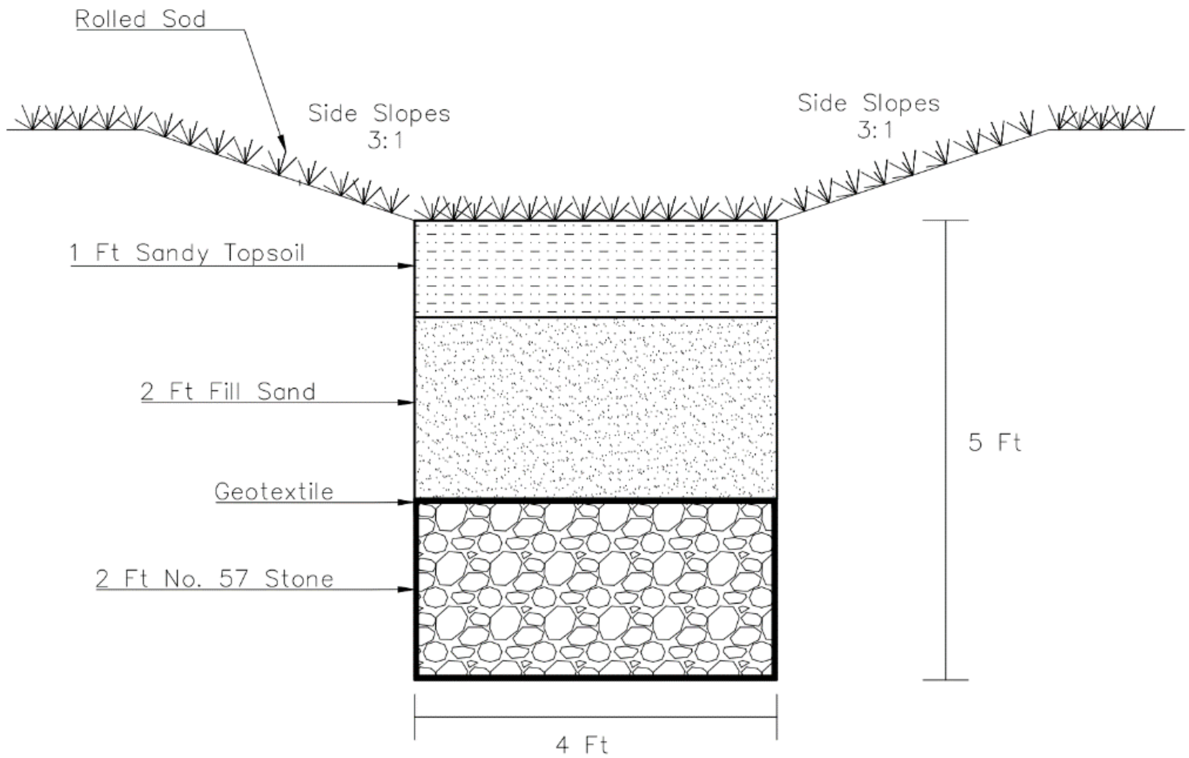
Figure 3-1. AU-SRF Facility

3.3 INFILTRATION SWALE DESIGN

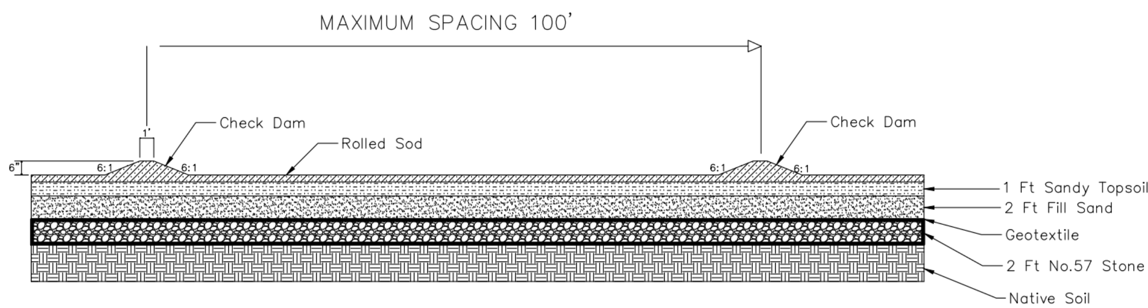
The infiltration swale design process is essential to understand how the engineered media matrix affects the functionality and the infiltration performance. The ALDOT infiltration swale design is an existing design currently used across the state of Alabama and was provided to Auburn University for testing and enhancement. The ALDOT infiltration swale design was used in small-scale laboratory testing to evaluate the limiting factors hindering the performance of its infiltration speed and capacity. Through small-scale testing, two key factors were altered and evaluated: (1) existing and new media materials and (2) material depth dimension modifications. These two factors were used to see what kind of changes increased the infiltration capacity. There were multiple modified media designs that were tested through small-scale testing and the chosen media design will be shown in this section along with the justification behind the specific changes made to the existing ALDOT infiltration swale design.

3.3.1 Field-Scale ALDOT Infiltration Swale Design

ALDOT currently implements infiltration swales across Alabama adjacent to highways and roadways. Many of these SCMs function as designed; however, many also fall short of sufficient performance and functionality. Figure 3-2 represents the current ALDOT infiltration swale design.



(a) cross section



(b) profile view

Figure 3-2. ALDOT Infiltration Swale Field-Scale Drawing

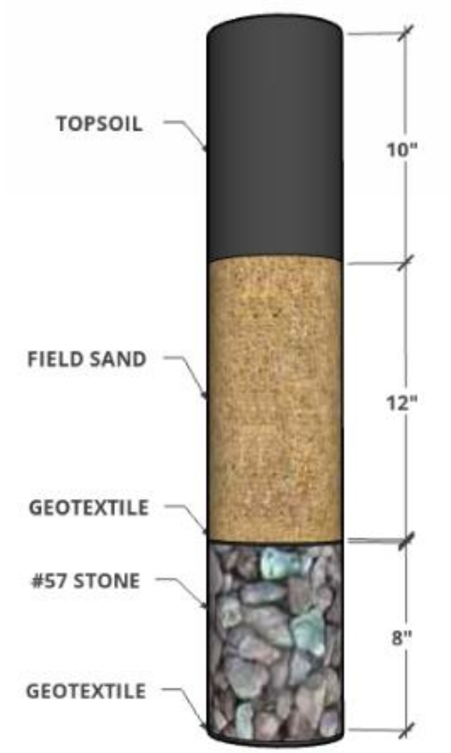
This infiltration swale design is a vegetated lined channel composed of an engineered soil media matrix that lies underneath the bottom of the swale. This component is 4 ft (1.2 m) in width and 5 ft (1.5 m) in depth underneath the surface of the swale's channel. Figure 3-2(a) from the top is composed of 1 ft (0.3 m) of sandy topsoil, 2 ft (0.6 m) of fill sand, and 2 ft (0.6 m) of #57 stone. The #57 stone layer is wrapped on all four sides by a separation geotextile fabric to block any smaller soil particles from filling the air voids in between the #57 stone.

The function of the engineered soil media matrix is to manage the infiltration rate of stormwater runoff and to promote infiltration of runoff back to the native soil and groundwater table. Figure 3-2(b) shows the profile view of the ALDOT infiltration swale which is designed for a 1% longitudinal slope. Also, there are 6 in. (15 cm) earthen check dams that are spaced out at a maximum of every 100 linear ft (30.5 m). The check dams are added to the design to help infiltration by slowing the channelized runoff and creating water impoundment. This increases the infiltration by providing more pressure from a higher water head height from the impoundment at each check dam and slows the channelized water down to give it time to infiltrate rather than flow on the surface.

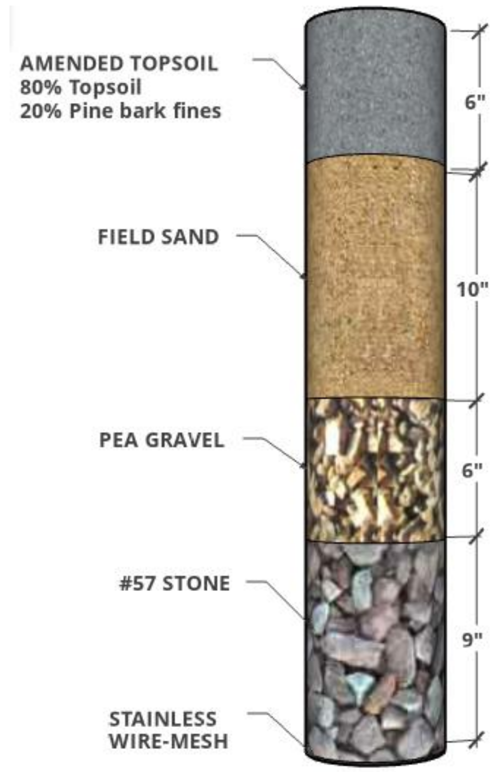
3.3.2 Small-Scale Modified Infiltration Swale Design

Before introducing the modified infiltration design, it is important to understand the small-scale testing portion of the project performed. Small-scale testing of the infiltration swale design in more detail was performed separately by Diego Armando Ramírez Flórez [48], this section will summarize some of the major findings.

Small-scale testing encompassed using a 2.5 ft (0.76 m) long cylindrical 6 in. (15 cm) PVC apparatus scaled down to fit the field-scale engineered media matrix designs. These cylindrical apparatuses were used to test multiple media designs simultaneously, most importantly infiltration test. This consisted of the modified permeability constant head test (ASTM D2434) and falling infiltration rate test. These two tests were used to measure the infiltration rates of the ALDOT infiltration swale design and different engineered media matrix designs. Figure 3-3 shows the small-scale engineered media matrix ALDOT design and the chosen modified infiltration swale design.



(a) ALDOT infiltration swale design



(b) modified infiltration swale design

Figure 3-3. Small-Scale Testing Designs [48]

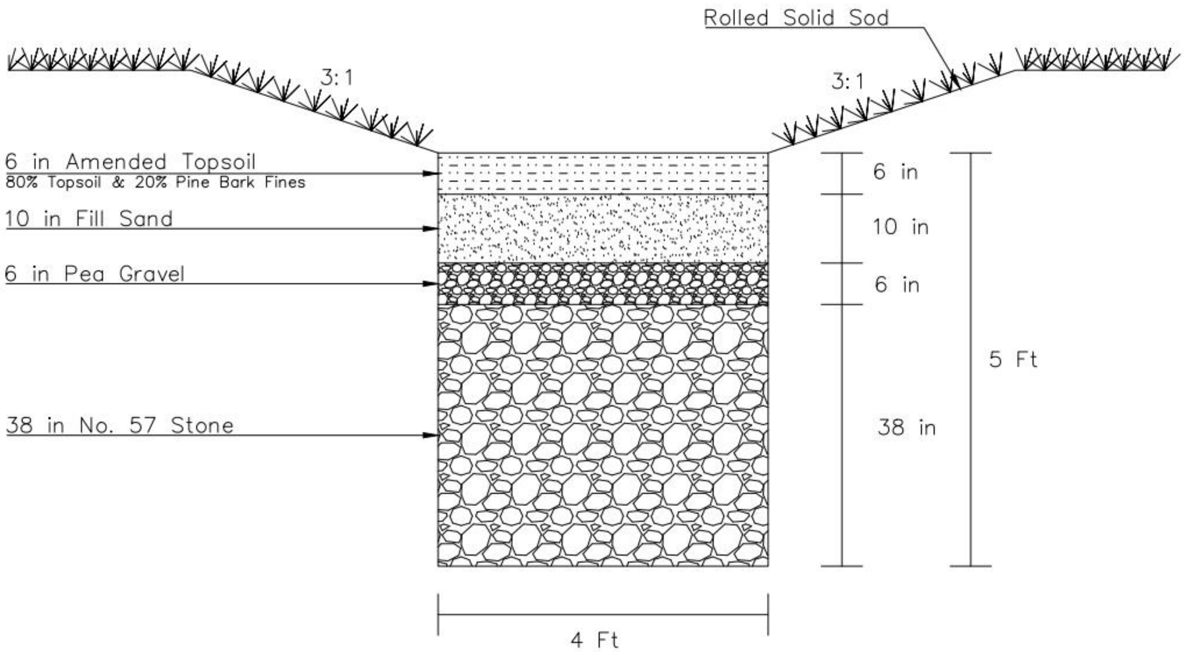
The chosen modified infiltration swale design included 6 in. (15 cm) of an amended topsoil (80% topsoil and 20% pine bark fines), 10 in. (25 cm) of field sand, 6 in. (15 cm) of pea gravel, and 9 in. (23 cm) of #57 stone. One of the major findings found from this small-scale study was that the ALDOT topsoil was one of the major limiting factors affecting the infiltration capacity. The topsoil layer was found to have an infiltration rate of less than 1.0 ft/day (0.30 m/day) which is lower than the minimum requirement specified in the LID Manual [10]. To enhance the ALDOT topsoil, this layer's depth was decreased to 6 in. (15 cm) instead of 10 in. (25 cm) and amended with 20% pine bark fines and 80% of the original topsoil by weight. This amended topsoil yielded an infiltration rate that was 7.25 times faster than the ALDOT swale's infiltration rate solely from pine bark fines amendment and decreasing the amount of topsoil [48]

Another major finding was the geotextile layer decreased infiltration rates. This was caused by fine soil particles from the sand layer migrating to the geotextile after running water through which ended up clogging the geotextile. To alleviate the reduction in infiltration rate capacity caused by the geotextile, a new 6 in. (15 cm) pea gravel layer was used as a substitute. The addition of the pea gravel layer yielded an infiltration rate 2.66 times faster than ALDOT's design solely from using pea gravel rather than the geotextile. Further analysis showed that minimal amounts of sand particles were penetrating through the pea gravel layer, and the pea gravel functioned as a great boundary layer separating the sand and the #57 stone [48]

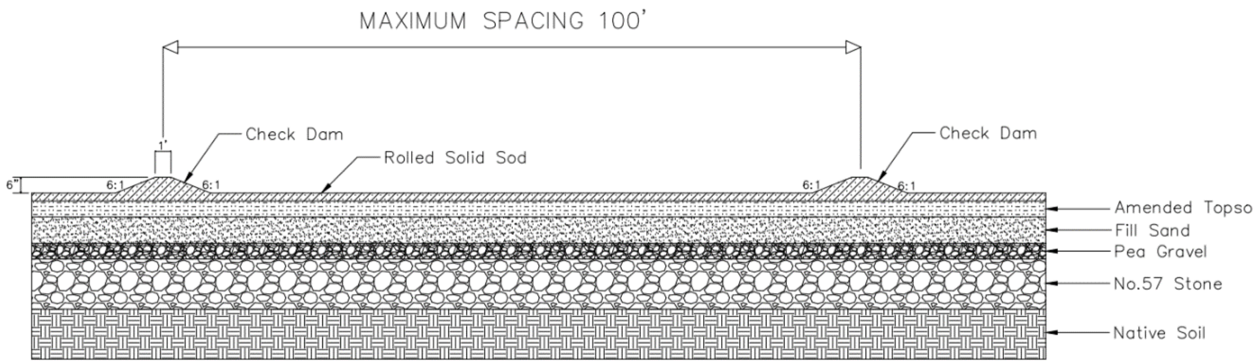
One other major finding was to increase the amount of material of #57 stone layer. This layer alone had the fastest infiltration rate because of its large air voids and high porosity results. The topsoil layer and the fill sand layer volumes were decreased to create more space mostly for the pea gravel layer but the #57 stone.

3.3.3 Field-Scale Modified Infiltration Swale Design

The next step was to take the small-scale modified infiltration swale design and scale it up to fit a field-scale engineered media matrix depth of 5 ft (1.5 m). The final field-scale modified infiltration swale design is shown in Figure 3-4.



(a) cross section



(b) profile view

Figure 3-4. Modified Infiltration Swale Field-Scale Drawing

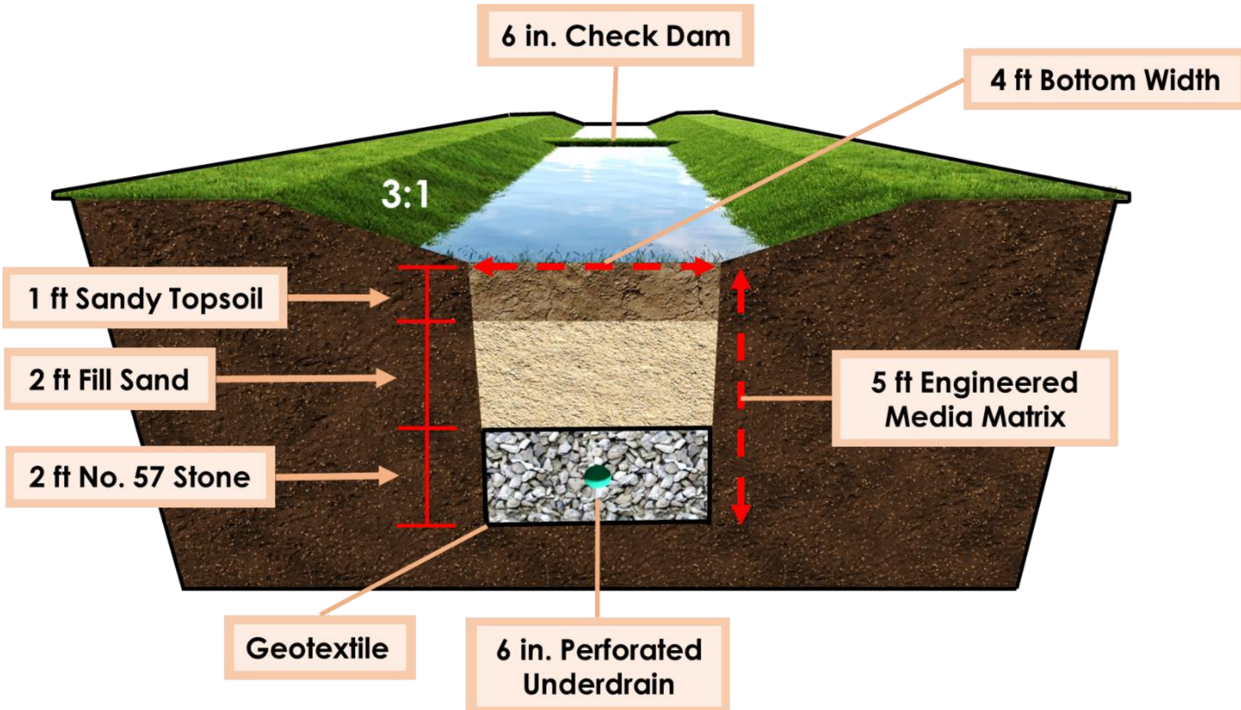
Figure 3-4 shows the modified swale design through a cross section and profile view. Focusing on the cross section, the field-scale design of the modified infiltration swale starts with a 6 in. (15 cm) of amended topsoil (80% pine bark fines and 20% topsoil). The next layer consists of 10 in. (25 cm) of filled sand material. Then for the geotextile replacement is the 6 in. (15 cm) of pea gravel and increased #57 stone layer that is 38 in. (97 cm).

Figure 3-4(b) shows the profile view of the modified infiltration swale at a 1% longitudinal slope and shows the 6 in. (15 cm) earthen check dams that are spaced out at the maximum of every 100 linear ft (30.5 m).

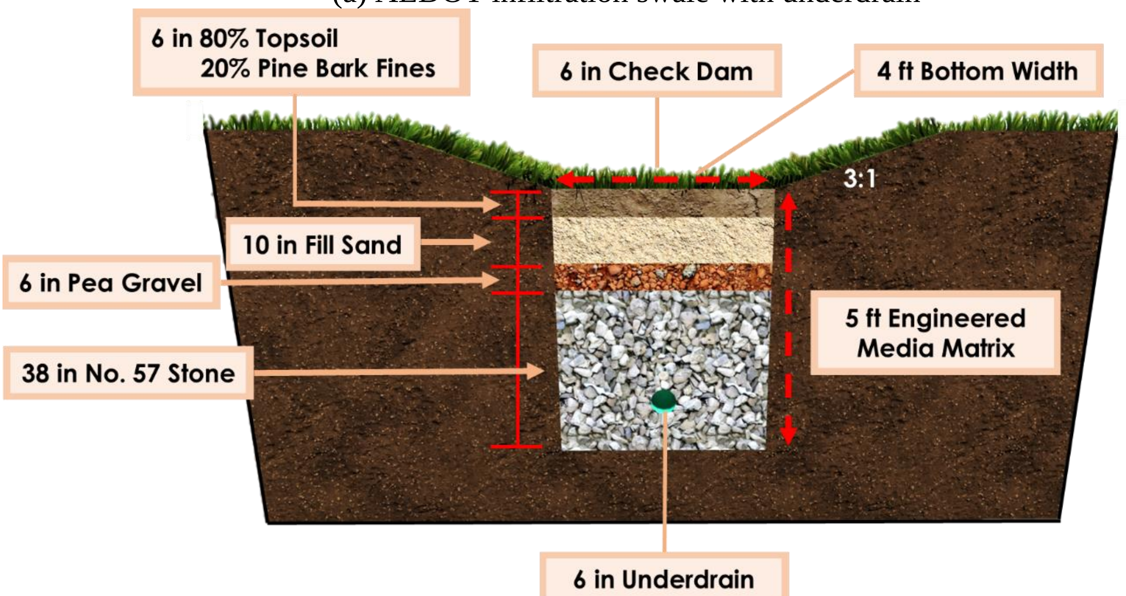
3.4 INFILTRATION SWALE CONSTRUCTION

The construction of the infiltration swales at the AU-SRF site followed a sequential approach. The ALDOT infiltration swale was built first, serving as a valuable pilot project. This initial construction phase provided essential field data and performance insights that ultimately informed a more effective build of the modified infiltration swale.

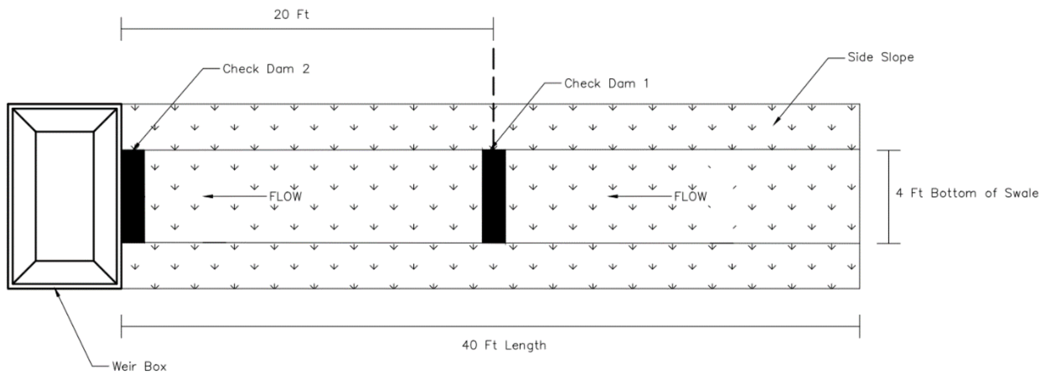
The modified infiltration swale was the second and final swale to be built at the AU-SRF. While the ALDOT swale was being built, the modified infiltration swale alternative media designs were still undergoing small-scale testing. However, once the modified media design was selected the construction encompassed the same procedure as the ALDOT infiltration swale. This included channel shaping and layout, excavation, filling materials, moisture content sensor installation, grading, sodding, and introductory system set-up. The designs specific for research and for construction are shown in Figure 3-5.



(a) ALDOT infiltration swale with underdrain



(b) modified infiltration swale with underdrain



(c) plan view for both swales

Figure 3-5. Research Swale Construction Drawings

For construction at the AU-SRF the length chosen for both infiltration swale was 40 ft (12 m) with check dams at the 20 ft (6.1 m) and 40 ft (12 m) mark. Another change made from the original design is the addition of a 6 in. (15 cm) perforated underdrain pipe placed in the #57 stone layer shown in Figure 3-5(a) and Figure 3-5(b). This underdrain is not included in the ALDOT design and the purpose for adding it is to be able to measure the flow and volume of water infiltrated for simulated and natural rainfall events.

This chapter details a breakdown of the construction stages, along with the quality assurance measures implemented to mitigate factors that could potentially hinder infiltration performance.

3.4.1 Geotechnical Investigation

Prior to initiating construction of the ALDOT and modified infiltration swales at the AU-SRF, a thorough geotechnical pre-investigation is crucial. Figure 3-1 depicts the designated areas at the AU-SRF used for infiltration swale construction. These areas served as the location for extracting and conducting the field and laboratory soil tests.

This investigation serves to confirm the suitability of the underlying native soils for optimal infiltration swale performance. The subsurface exploration will encompass both field and laboratory testing of the native soils. The primary area of interest is the deepest section of the engineered media matrix, where infiltration will predominantly occur between the final layer of the matrix and the in-situ soils.

Conducting field and laboratory soil testing for infiltration-based SCMs is essential. If a site has slow infiltration rates, it can lead to extended drainage times exceeding 48 hours. This timeframe often represents a critical threshold during which regulatory agencies may require alternative stormwater management solutions. Verifying the adequacy of in-situ soil infiltration is paramount for also optimizing the overall long-term performance of the infiltration swales. This ensures efficient drainage of the engineered media matrix, allowing for exfiltration into the native soil and ultimately, the local groundwater table.

Following the Minnesota Department of Transportation (MnDOT) guidelines, a soil boring and excavation pit were employed within the boundaries of the planned infiltration-based SCMs. These procedures facilitate the classification of native soil types and the determination of their infiltration rates. Notably, MnDOT recommends one boring and one excavation pit for projects with a surface area less than 1000 ft^2 (92.9 m^2), which aligns perfectly with the size of the planned infiltration swales which are approximately 160 ft^2 (14.9 m^2) each [49].

3.4.1.1 AU-SRF Field Boring Sample Collection

The geotechnical investigation at the AU-SRF employed a two-phased approach for collecting soil samples within the designated infiltration swale construction area.

- **Phase 1: Shallow Soil Sampling (0-4 ft)**

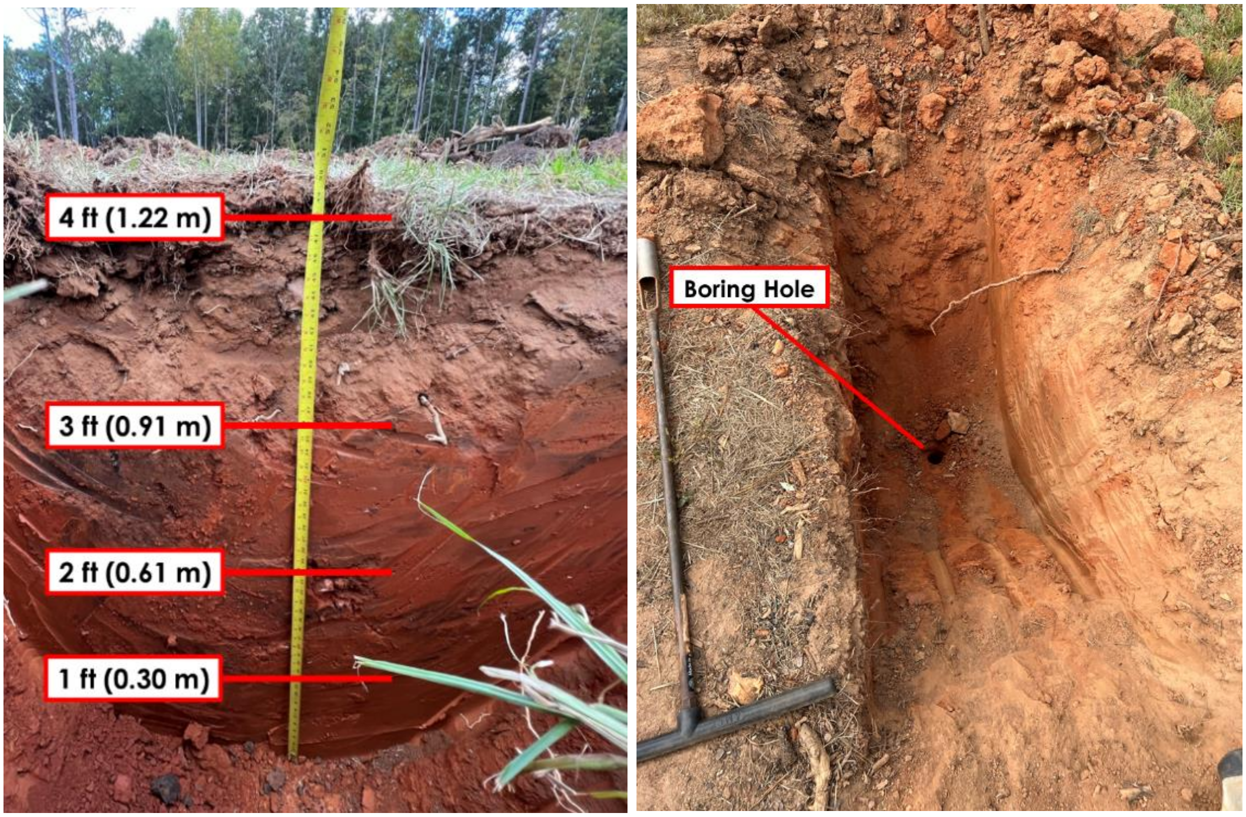
A handheld soil auger with a 6 in. (15 cm) increment collection capability was utilized to extract soil samples from the surface down to a depth of 4 ft (1.2 m). This method provides a safe and efficient means of collecting samples from shallow depths.

- **Phase 2: Deep Soil Sampling (4-9 ft)**

To access soil samples beyond the reach of the handheld auger, a mini excavator was used to create a 4 ft (1.2 m) deep excavation pit. This depth falls within the Occupational Safety and Health Administration (OSHA) guidelines for safe excavation without requiring additional shoring or trench boxes (typically required at depths exceeding 5 ft (1.5 m). Soil samples were then retrieved from the bottom of the excavation pit.

- **Final Depth Increment (8-9 ft)**

The final foot of the soil profile 8-9 ft (2.4-2.7 m) was accessed by extending the mini excavator pit by an additional foot. This allowed for the collection of a complete soil profile up to the depth of 9 ft (2.7 m). Figure 3-6 visually depicts the boring process, the 4 ft (1.2 m) deep excavation pit used for deeper sample collection, and the resulting soil profile at the selected site.



(a) soil profile and soil horizon (b) 4 ft (1.22 m) pit boring

Figure 3-6. Soil Collection and Soil Profiling

3.4.1.2 Soil Laboratory Testing

A critical component of soil classification for the infiltration swales is grain size analysis. This standard test method, conducted in accordance with ASTM C136, measures the distribution of particle sizes within a soil sample. The resulting data provides essential information for estimating infiltration rates within the swale system. Grain size distribution significantly impacts a soil's permeability, which directly influences how quickly water can infiltrate through the material. Soils with a higher proportion of coarse particles (sands, gravels) generally exhibit faster infiltration rates compared to those dominated by finer particles (silts, clays). The native soil results are found in Chapter 5.

3.4.1.3 Infiltration Field Testing

To obtain a more accurate representation of field conditions compared to laboratory samples, a double-ring infiltrometer test (ASTM D3385) was employed. This standardized field test method measures the infiltration rate of the in-situ soil, minimizing disturbances that may occur during sample collection.

While infiltration testing at various depths is valuable, the most critical location for testing is the interface between the engineered media matrix and the native soil. This zone is where infiltrated water exits the engineered media and enters the underlying native soil profile. Figure 3-7 visually depicts the double-ring infiltrometer field test performed at the surface and at the interface boundary.

(a) surface test (b) pit test

Figure 3-7. Double-Ring Infiltrometer

Once the geotechnical investigation results of the site were confirmed, construction of the ALDOT and modified infiltration swales commenced. Geotechnical investigations for site selection for infiltration-based SCMs are vital and are required to ensure long-term infiltration performance as poor or no soil testing is one of the main factors hindering the infiltration performance. Other important tests to consider for optimal performance are percolation tests, establishing the groundwater table, and falling and constant head lab testing. Infiltration results found in Chapter 5.

3.4.2 Site Layout and Preparation

The construction process for both infiltration swale systems commenced with site preparation and layout. This initial stage involved using wooden stakes, tape measures, strings, and spray paint to delineate both of the swale's length of 40 ft (12 m), bottom width of 4 ft (1.2 m), and 3:1 side slope. The spray-painted lines in Figure 3-8 show the boundary of the engineered media matrix component and is where the exaction commenced. Prior to excavation, an automatic laser level was employed to measure the surface elevations at the upstream and downstream ends of the swale’s layout. This ensured a longitudinal slope of 1% for optimal flow.

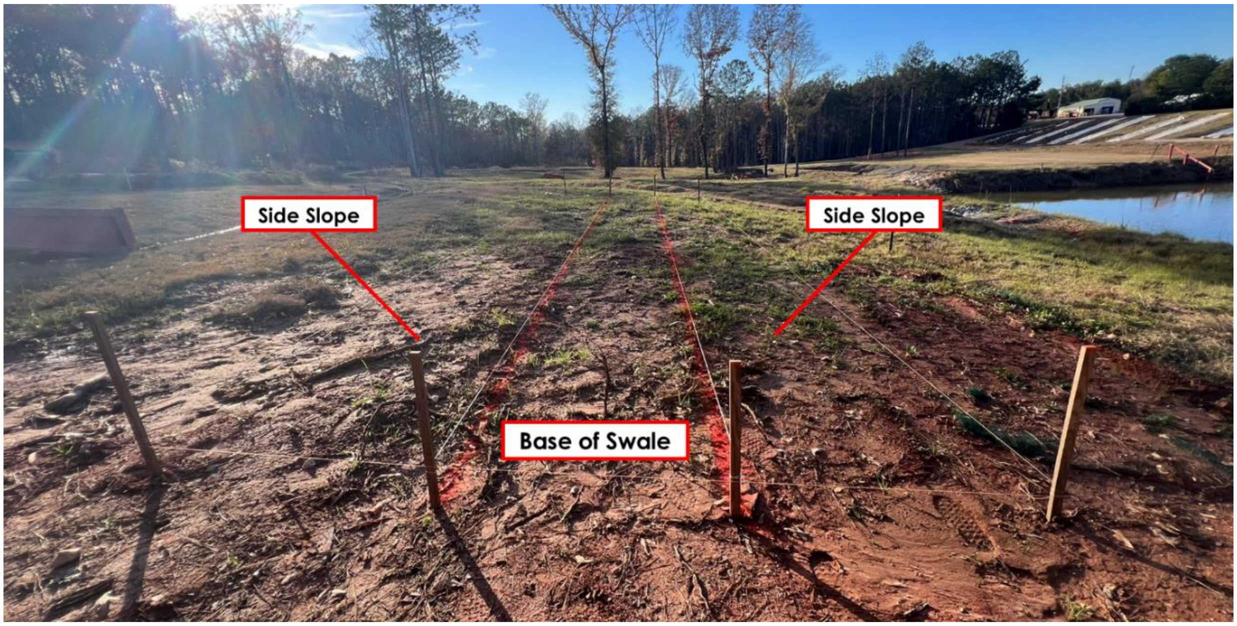


Figure 3-8. Swale Layout

Another important aspect for quality assurance during the construction process was to build a sediment diversion berm to function as a protective boundary where sediment and silts would be caught from rain events before entering the engineered media matrix or excavation pit. This is vital to ensure infiltration swale performance for smaller soil particles including clay and silt will clog the media and ruin the performance of the infiltration swale. The diversion berm layout is shown in Figure 3-9.

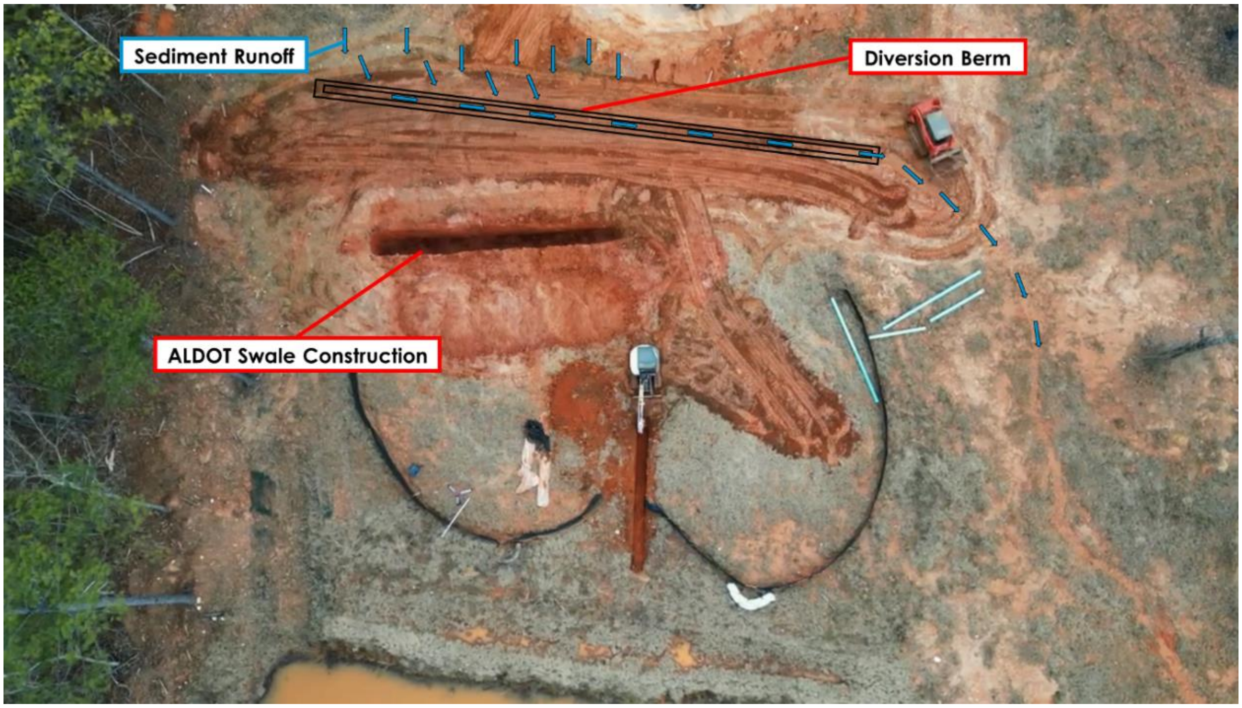


Figure 3-9. Diversion Berm

3.4.3 Excavation

Following site preparation, a 6.5 ft (1.9 m) deep trench for the engineered media matrix was excavated, starting from the downstream end, and progressing upstream. Next, utilizing a pre-established reference point on the surface, the down stream's final base surface elevation in the excavated pit was established by measuring 1 ft (0.30 m) below the pre-established datum. This elevation served as the base for the downstream channel surface. The upstream surface elevation was marked with spray paint by calculating a 4.8 in. (12 cm) difference from the downstream elevation line to achieve the desired 1% slope over the 40 ft (12 m) length. String was then used to connect the upstream and downstream elevation lines, which was subsequently spray painted to mark the entire channel's bottom surface. Once the channel bottom elevation was established, the mini excavator was used to create side slopes with a 3:1 inclination. An automatic laser level verified and marked the side slope measurements on the surface. Lastly, a trench for the underdrain pipe was excavated foe the pipe to daylight and allow water to drain away from the swale, ensuring a 1% to 2% downward slope for proper drainage. Figure 3-10 shows the excavation process.

(a) excavated media body (b) trench for underdrain

Figure 3-10. Excavation Process

3.4.4 Engineered Media Matrix and Underdrain Placement

The next phase of construction focused on the placement of the engineered media matrix and underdrain installation. Reference elevations for each media layer were marked based on the surface datum to ensure a 1% slope during filling within the excavation pit. The ALDOT infiltration swale first fill material was the geotextile fabric, following filling the first foot (0.30 m) off the bottom of excavation pit with #57 stone, forming a foundation for the underdrain pipe positioned in the center of this stone layer. After the underdrain was positioned, the rest of the #57 stone was filled forming a total fill of 2 ft (0.61 m). The geotextile fabric was sealed on all four sides of the #57 stone per ALDOT specifications. The next layer was to then fill in the 2 ft (0.61 m) of fill sand. The last layer to install was the 1 ft (0.30 m) of topsoil. Figure 3-11 shows the fill process for the ALDOT swale.

(a) pipe and #57 stone

(b) sealed geotextile

(c) sand layer

(d) topsoil layer

Figure 3-11. ALDOT's Engineered Media Matrix Installation

The modified infiltration swale's first fill material was a foot (0.30 m) of #57 stone, forming a foundation for the underdrain. The underdrain is installed in the exact same location for both swales. After the underdrain was positioned, the rest of the #57 stone was filled forming a total fill of 3.2 ft (0.97 m) or 38 in. (97 cm). The next layer was to then fill 6 in. (15 cm) of the pea gravel layer which was replacing the geotextile. The next fill layer was 10 in. (25 cm) of fill sand, and the last layer to install was 6 in. (15.2 cm) of amended topsoil. Figure 3-12 shows the fill process for the modified infiltration swale.

(a) pipe and #57 stone

(b) pea gravel layer

(c) sand layer

(d) amended soil layer

Figure 3-12. Modified Swale's Engineered Media Matrix Installation

3.4.5 Weir Boxes Installation

While installing the engineered media matrix, a surface weir box at the downstream end for both swales was installed. Also, an underdrain weir box for both swales was installed at the underdrain outlet point. The surface weir box installation process entailed excavating pits adjacent to the downstream of each swale. The surface weir box was then placed inside the hole using the mini excavator and was then leveled and backfilled with the native soil. The same process was conducted for the underdrain box for each swale's underdrain outlet. This construction installation process is shown in Figure 3-13.

(a) surface box placed

(b) backfilled

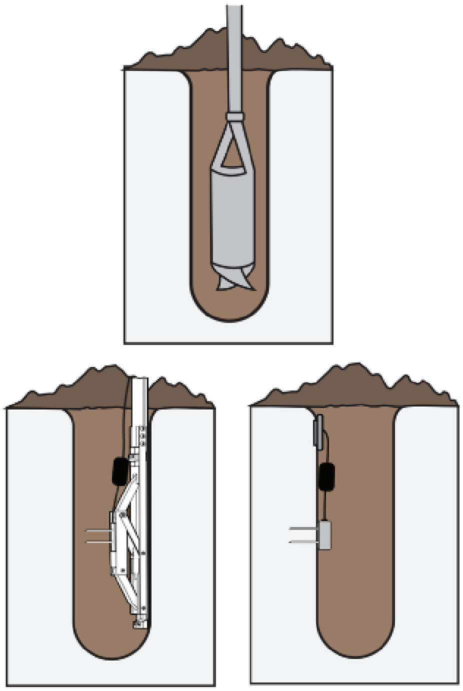
(c) underdrain box

(d) backfilled

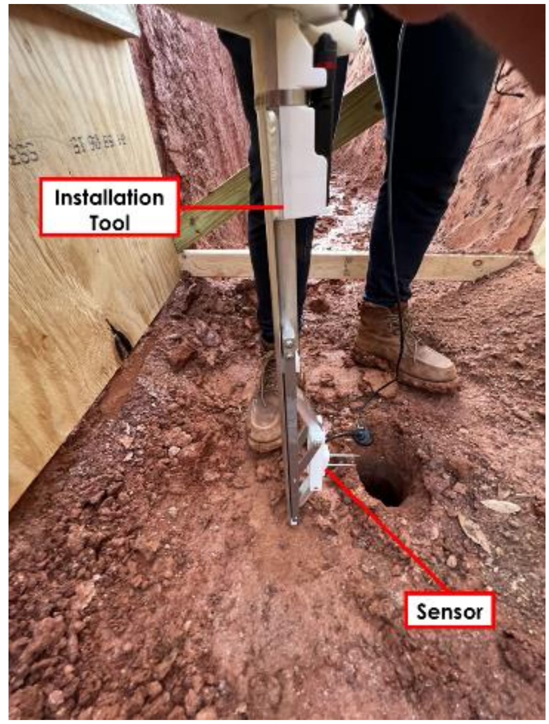
Figure 3-13. Weir box Installation

3.4.6 Moisture Content Installation

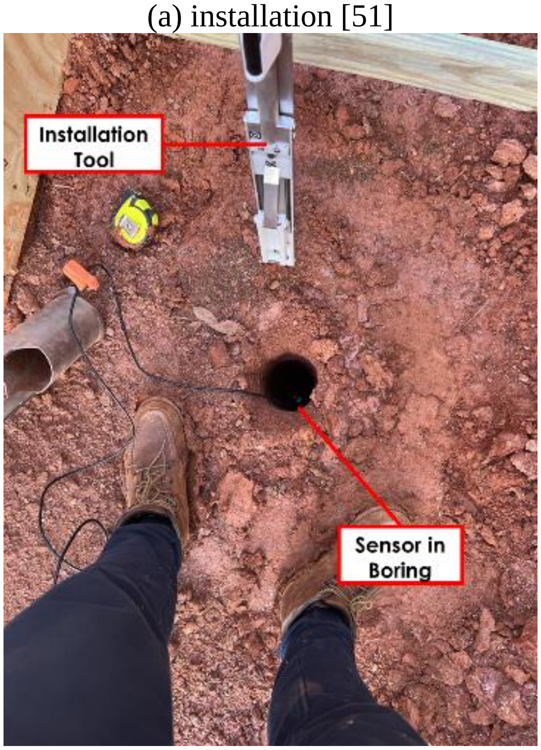
Before any materials were filled into the exaction pit for the engineered media matrix, five moisture content sensors were installed in both infiltration swales. The moisture content sensors are to be used for testing once the infiltration swales are fully constructed. More information on moisture content sensor locations and methodology is available in Chapter 4. The method to install the sensors included using a handheld auger to dig a boring hole. Next, was to use a specific installation tool that allowed for the sensor to be installed perpendicular to the inside of the boring walls and makes sure to eliminate air gaps for installation. Once installed the sensor inside the boring was then backfilled and compacted. Installation for sensors at higher elevations was installed in the media by hand and backfilled with the excavator using the next fill material. Each sensor has a wire attached and connects to a single control box where data is stored and exported for testing. Figure 3-14 shows this process of moisture content sensors installation.



(a) installation [51]



(b) installation set-up



(c) sensor installed

(d) control box

Figure 3-14. Moisture Content Sensor Installation

3.4.7 Final Grading and Sodding

Upon completion of the engineered media matrix installation, the construction process focused on final touches and vegetation establishment. A final touch to add was the earthen check dams. Using topsoil, two earthen check dams were constructed: one at the 20 ft (6.1 m) midpoint and another at the downstream end (40 ft or 12 m) for both swales. The remaining topsoil was used to create final grading across the side slopes and shoulders of the swale, facilitating sod establishment. Subsequently, Bermuda Tifway sod was used to cover both swales. The sod was compacted and rolled only on the side slopes and shoulders. It was essential to avoid compaction of the media, so the infiltration capacity does not decrease.

3

(a) final grading

(b) sodding

(c) rolled sod

(d) stabilized sod

Figure 3-15. Final Grading and Sodding

3.5 SUMMARY

This chapter delineates the construction process for the ALDOT and modified infiltration swales, outlining the specific steps involved in their development. Key stages included site investigation, preparation, excavation, installation of the engineered media matrix, and final landscaping with vegetation establishment. These procedures laid the groundwork for subsequent experimental analyses.

CHAPTER FOUR: CALIIBRATION AND METHODOLOGY

4.1 INTRODUCTION

This chapter outlines the methodologies, calibrations, and procedures employed to conduct a comprehensive evaluation of large-scale infiltration swales. The evaluation focused on two swales: an ALDOT infiltration swale and a modified infiltration swale.

4.1.1 Experimental Design

The infiltration swales were subjected to a rigorous testing regimen encompassing infiltration rate and drawdown tests, evaluations at various flow rates, moisture content sensor monitoring, and surface settlement monitoring. Maintaining meticulous consistency throughout the experimental setup and preparation for each test run was paramount to ensure the reliability and accuracy of the collected data.

4.1.2 Methodology Objectives

The primary purpose of the testing methodology was to aid in the accuracy in conducting a comparative assessment of the ALDOT and modified infiltration swales. This evaluation aimed to comprehensively assess the overall performance of both swales, with a particular focus on their infiltration capacities for ensuring long-term effectiveness. The testing aimed to elucidate the factors influencing infiltration swale performance, thereby informing potential improvements and future research directions for swale design and implementation. The primary performance metric for the swales was their comparative infiltration rates and capacities to detain and store stormwater runoff generated by simulated and natural rainfall events.

4.2 WATER INTRODUCTION

To evaluate the performance of infiltration swales in managing highway and roadway stormwater runoff, a system was designed to replicate channelized flow conditions within the swales. An introductory flow tank was used for both infiltration swales and was an essential part of testing to control the amount of flow that was being introduced and pumped into the infiltration swale's channel. The introductory flow system, designed to deliver a controlled volume of water into the infiltration swale, plays a critical role in establishing a mass balance system later. The introductory flow tank allows for precise tracking of influent water volumes entering the swale, which will be differentiated from effluent discharged water as runoff or infiltrated stormwater later.

4.2.1 Introductory Flow System

Two blue plastic introductory flow tanks, each with a 300-gallon (1,136 L) capacity, were used for the corresponding infiltration swale being tested. These tanks facilitated the introduction of water into each swale for evaluation and testing. The two flow tanks are comprised of four key components: inlet ports, a wooden baffle dissipater, rectangular weir opening, and a pumping system.

There are six 4 in. (10 cm) inlet ports on the backside of the introductory flow tub that are openings that can be connected to a flexible hose through PVC and steel attachments. The six inlet ports can be capped and sealed depending on the number of hoses and flow needed for testing. For purposes of this project, only one inlet port with its associated hose and pump was required to reach the adequate flow rates for both infiltration swales.

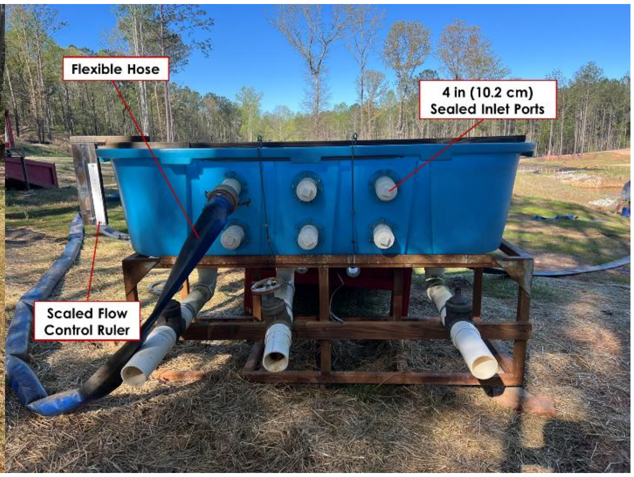
The wooden baffle is a perforated thin board placed inside the center of the tank and is the length of the inside diameter of the tank. The perforated wooden baffle functions as a hydraulic energy dissipater, mitigating the high-velocity flow and intense water pressure originating from the supply hose. The baffle effectively reduces the flow velocity and intensity within the influent flow tank, ensuring a steady and uniform outflow through the weir opening located on the front side.

The rectangle weir opening on the frontside of the tank faces the infiltration swale and is the component of the tank that controls the amount of flow entering the infiltration swale channel. The weir opening plate is accompanied by a scalar flow control ruler. This ruler facilitates the direct measurement of discharge based on the observed water level within the introductory flow tank. This correlation is established through a 0.25 in. (0.64 cm) clear plastic standpipe connected to the tank's bottom. The water level observed in the standpipe reflects the flow rate produced by the pumping system feeding the blue introductory flow tank.

The last main component of the introductory flow system for the infiltration swale test channels is the pump set-up. Water is pumped from the upper pond from the AU-SRF expanded area shown in Figure 3-1 into the introductory flow tub by a DuroMax portable engine pump (Model No. XP650WP). There is one pump used per infiltration swale and its corresponding introductory blue tank. The pumps use a 4 in. (10 cm) inlet port to connect to a single 4 in. (10 cm) hose**.** Figure 4-1 shows the four main components of the water introduction system used to add accurate flow amounts to the infiltration swales for tests.

The flow calibration process for the introductory flow tank included filling the inside of the tank up with water until just below the weir opening. This water level inside the tub should correspond to 0 ft^3/s (0 m^3/s) on the scaled flow control ruler. Any deviation from a perfectly level introductory flow tank would result in inaccurate flow readings on the scaled flow control ruler, potentially indicating values below or exceeding 0 ft^3/s (0 m^3/s). Ensuring a level introductory blue flow tank was therefore crucial for the functionality of the water introduction system prior to testing.

(a) introductory flow tub (front)



(b) introductory flow tub (back)

(c) pump

(d) wooden perforated baffle

Figure 4-1. Components for Introductory Flow System

4.3 SURFACE AND UNDERDRAIN WEIR BOX

The ALDOT infiltration swale and the modified infiltration swale test set-up included having their own surface and underdrain weir boxes. These wooden weir boxes were vital for infiltration swale testing. They can measure the volume of water and flow leaving an infiltration swale through either bypassed runoff on the surface of the swale or flow leaving the system through infiltration into the engineered soil media matrix.

4.3.1 Surface Weir Box

There are two surface weir boxes, one for the ALDOT infiltration swale and another for the modified infiltration swale. The surface weir box's purpose is to specifically measure the flow and volume of water leaving the infiltration swale specifically as runoff or bypassed water during tests. This is an essential component of the mass balance testing being set up.

4.3.1.1 Surface Weir Box Design

The design of the rectangular surface weir boxes, one for the ALDOT swale and another for the modified swale, prioritized sufficient capacity to accommodate the anticipated flow exiting the downstream end of each infiltration swale. A flow amount of 3 ft^3/s (0.09 m^3/s) was used as the maximum amount that would enter the infiltration swales from the introductory flow tank. This known flow was chosen because infiltration swales are designed for flow rates that originate from impervious surface of highways and roads. For example, throughout the testing process the highest flow rate used occurred around 0.60 ft^3/s (0.02 m^3/s). Given the predetermined design flow rate and the implementation of a rectangular weir opening, equation (4-1) facilitates the iterative adjustment of the weir width and water depth to achieve a target flow rate of approximately 3 ft^3/s (0.09 m^3/s),

$$Q = CL_W h_o^{\frac{3}{2}} \tag{4-1}$$

Where $Q =$ discharge flow (ft^3/s [m^3/s]); $C = 3.33$ discharge coefficient from Fundamentals of Engineering handbook; L = effective length of crest (ft [m]); $h_o =$ depth of flow above elevation of crest (ft [m]). With the established values for Q and C the chosen L_W was 0.6 ft (0.18 m) and the maximum value of h_o to achieve 3 ft^3/s (0.09 m^3/s) was 16 in. (41 cm). The final dimensions of the surface weir boxes included 2 ft (0.61 m) inside width, 6 ft (1.8 m) inside length, and 2 ft (0.61 m) inside depth shown in Figure 4-2.

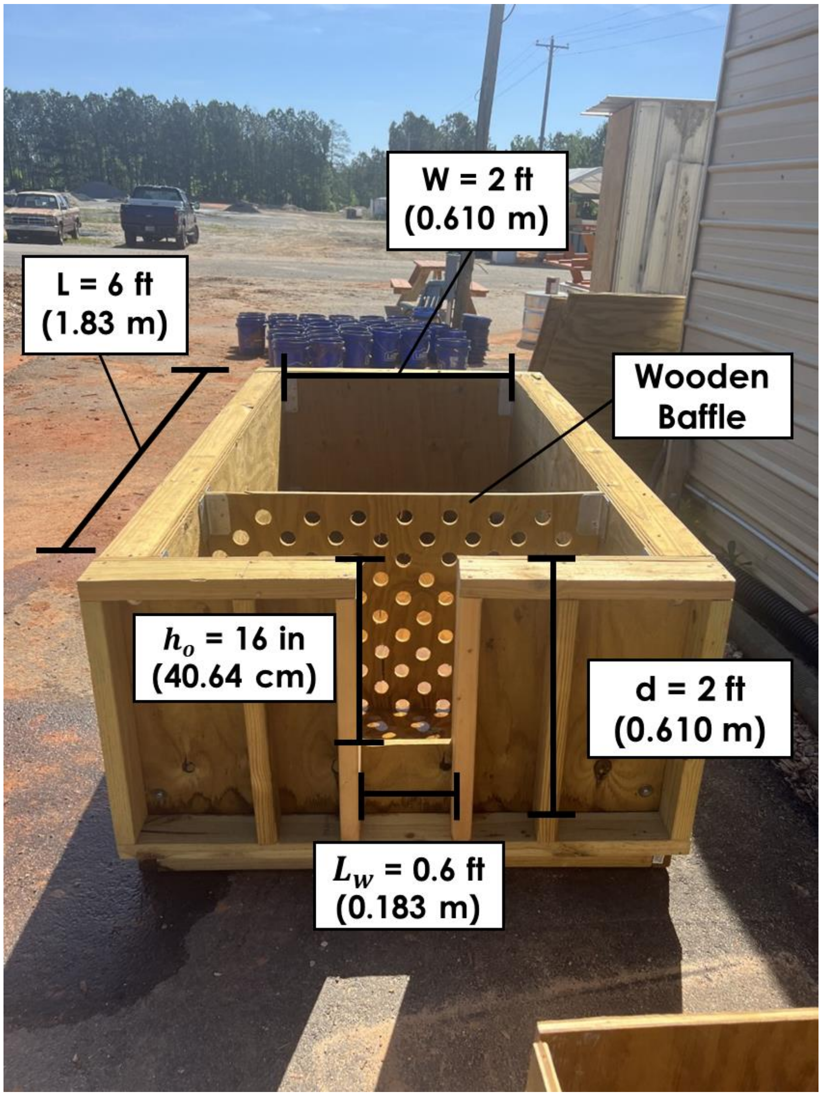


Figure 4-2. Surface Weir Box Depiction

Another crucial component of the surface weir box is a wooden baffle positioned perpendicular to the flow path within the rectangular box. This baffle functions as an energy dissipater, mitigating the turbulence of the incoming water. A level water surface over the weir crest is essential for ensuring accurate flow measurements exiting the surface weir box.

4.3.1.2 Surface Weir Box Calibration

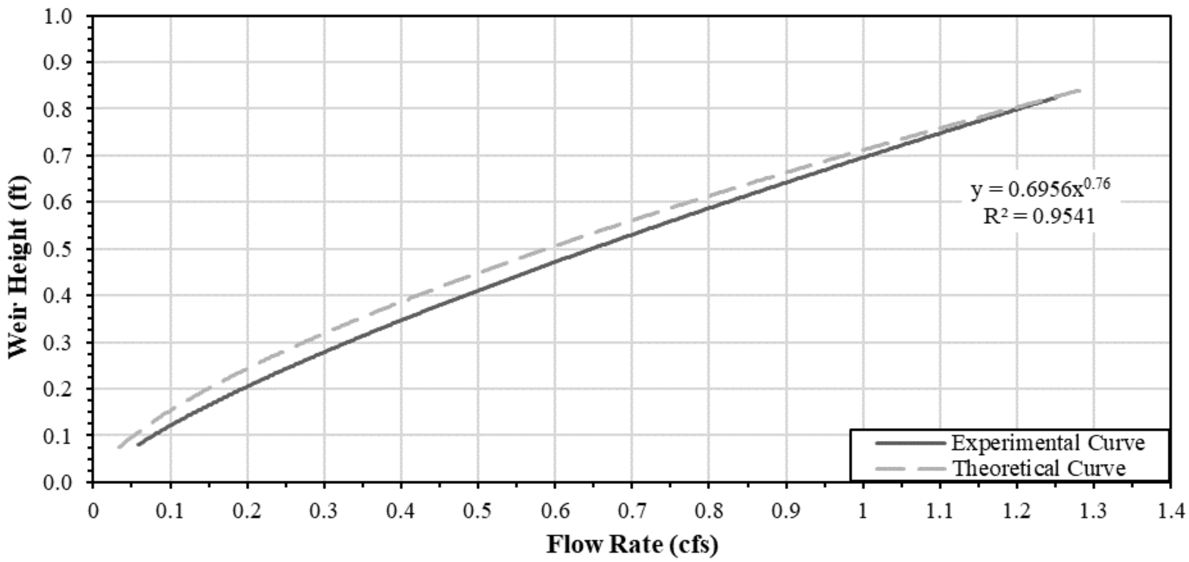
Following the installation of each surface weir box at the downstream end of its respective infiltration swale, a calibration process was conducted. This involved pumping water into the boxes at predetermined, incremental flow rates. Each flow rate corresponded to a specific water level measured above the weir crest. Water flowing over the weir crest was collected, measured, and timed to calculate the flow rate at that water level in the weir box shown in Figure 4-3.

(a) surface weir box water depth measurement

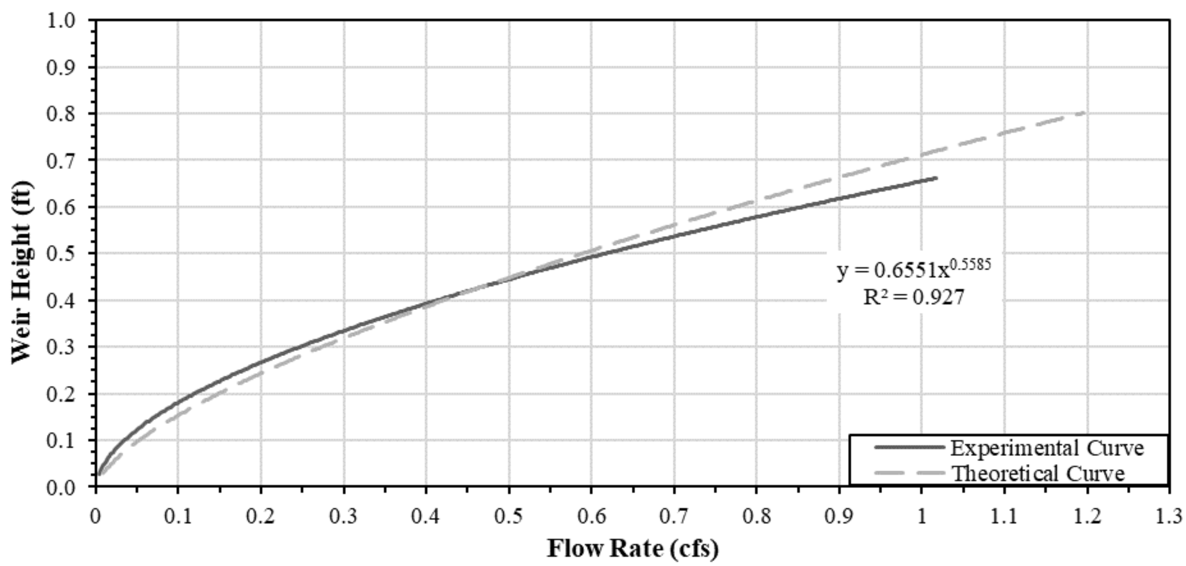
(b) surface weir box collected water

Figure 4-3. ALDOT Surface Weir Box Field Calibration

The experimentally determined flow rates derived from the collected data were plotted for comparison with a theoretical flow curve. By recording the depth of water over the crest, the corresponding volume of water captured for that water depth, and the time it took to capture volume of water was all used to calculate the flow leaving the weir box. These same known values recorded during the experiment were plugged into the theoretical equation (4-1) shown above and plotted against each other. The power curve equations derived from the surface weir box calibration data presented in Figure 4-4(a) and (b) were subsequently employed during testing. This involved inputting the known weir crest height as the y-variable and solving the equation for the x-variable, which represents flow rate. Flow measurements were then obtained over small, timed intervals to determine the total volume exiting the underdrain weir box.



(a) ALDOT surface rectangular weir box



(b) modified swale surface rectangular weir box

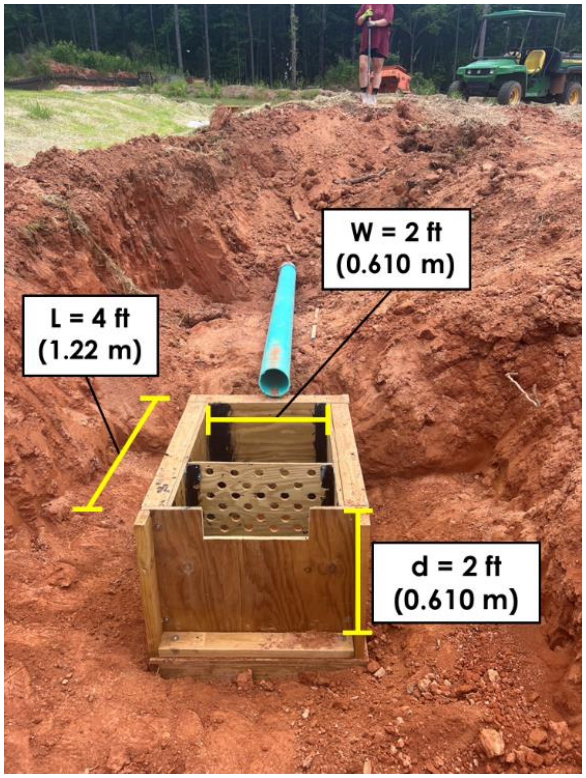
Figure 4-4. Calibration Curve for Surface Weir Boxes

4.3.1.3 Underdrain Weir Box

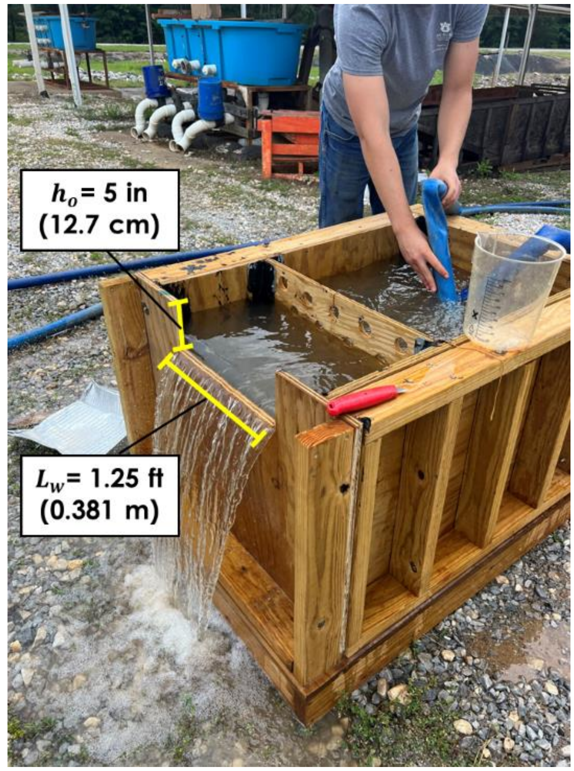
Similar to the surface weir boxes, two underdrain weir boxes were constructed – one for the ALDOT infiltration swale and another for the modified infiltration swale. This section delves into the design and implementation of these underdrain weir boxes. Their primary function is to precisely quantify the volume and flow rate of infiltrated water exiting the infiltration swales during testing. This data acquisition is crucial for the establishment of a mass balance within the testing framework.

4.3.1.4 Underdrain Weir Box Design

Following the design principles applied to the surface weir boxes, the underdrain weir boxes were constructed with identical dimensions and weir openings, ensuring consistent performance between the two systems. Based on the anticipated flow rate exiting the underdrain pipe of each infiltration swale, the maximum design capacity for these underdrain weir boxes was established at 1 ft^3/s (0.03 m^3/s). The underdrain weir boxes are designed for a lower maximum flow rate compared to the surface weir boxes. This is because they exclusively capture the infiltrated water channeled through the perforated underdrain pipe located at the base of each infiltration swale's engineered media matrix. The anticipated flow rate exiting the underdrain pipe is expected to be lower compared to the surface runoff measured by the surface weir box during testing. Using equation (4-1) with a maximum flow rate of 1 ft^3/s (0.03 m^3/s), the underdrain weir box L_W was 1.25 ft (0.38 m) and the maximum value of h_o to achieve 1 ft^3/s (0.03 m^3/s) was 5 in. (13 cm). The final dimensions of the underdrain weir boxes included 2 ft (0.61 m) inside width, 4 ft (1.2 m) inside length, and 2 ft (0.61 m) inside depth shown in Figure 4-5.



(a) underdrain weir box dimensions



(b) underdrain weir opening dimensions

Figure 4-5. Underdrain Weir Box

Another crucial component of the underdrain weir box, mentioned for the surface weir boxes, is the wooden baffle positioned perpendicular to the flow path within the rectangular box. This baffle functions as an energy dissipater, mitigating the turbulence of the incoming water.

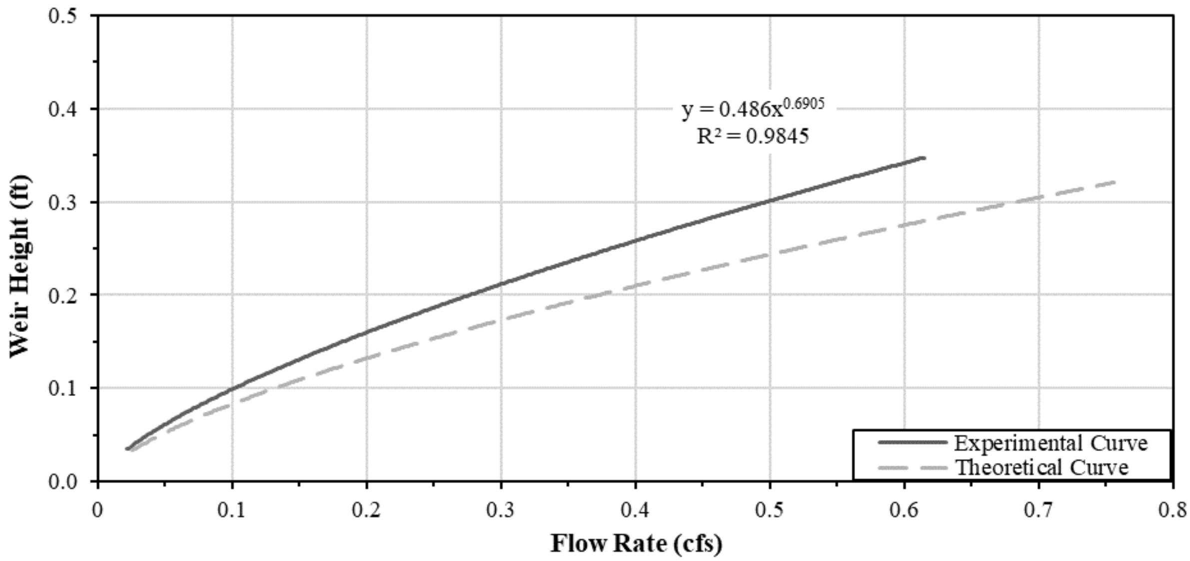
4.3.1.5 Underdrain Weir Box Calibration

Once each of the underdrain weir boxes were installed where their infiltration swale’s underdrain daylighted, the weir box was calibrated similar to the surface weir boxes. This involved pumping water into the boxes at predetermined, incremental flow rates. Each flow rate corresponded to a specific water level measured above the weir crest. Water flowing over the weir crest was collected, measured, and timed to calculate the flow rate at that water level in the weir box shown in Figure 4-6.

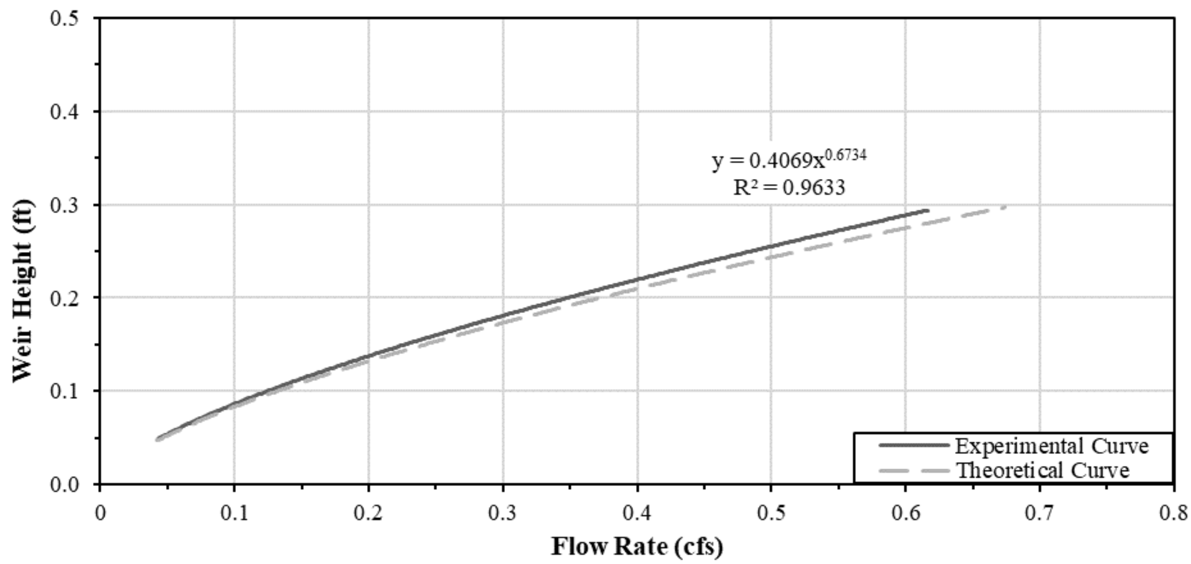
(a) ALDOT underdrain weir box test (b) modified swale underdrain weir box test

Figure 4-6. Underdrain Weir Boxes Field Calibration

Similar to the surface weir box calibrations, the underdrain weir box performance was evaluated by plotting the experimentally determined flow rates against a theoretical flow curve (equation 4-1). This involved recording water depth over the crest, corresponding captured volume, and time to capture the volume. These known values were then used in equation (4-1) to calculate the theoretical flow rate, which was subsequently plotted for comparison with the measured data. The power curve equations derived from the underdrain weir box calibration data presented in Figure 4-7(a) and (b) were subsequently employed during testing. This involved inputting the known weir crest height as the y-variable and solving the equation for the x-variable, which represents flow rate. Flow measurements were then obtained over small, timed intervals to determine the total volume exiting the underdrain weir box.



(a) ALDOT underdrain rectangular weir box



(b) modified swale underdrain rectangular weir box

Figure 4-7. Calibration Curve for Underdrain Weir Boxes

4.3.2 Water Pressure Inducer

Each weir box was equipped with a Solinst levelogger 5th generation, a self-contained water level data logger. Utilizing infrared data transfer and a long-lasting lithium battery, this device records up to 150,000 temperature and water level measurements. The levelogger automatically logs water level changes over time, storing data internally for download to online software and subsequent export to Excel. Notably, the logger employs a pressure sensor to measure water pressure relative to its zero point, coupled with data from a separate barometric pressure sensor (barologger). Downloaded together, the combined pressure readings enable the levelogger to automatically calculate and record water level over time.

Each weir box has an installed 9 in. (23 cm) perforated PVC pipe that holds a single levelogger. The levelogger is housed within a perforated PVC casing. This perforation allows the water to reach the pressure sensor, enabling accurate water level readings despite the logger's fixed position within the weir box. The set-up is shown in Figure 4-8 and is installed on the frontside of the perforated wooden baffle, closest to the weir opening. This location ensures it measures the non-turbulent water surface after it has passed through the baffle, rather than the turbulent flow on the backside.

Figure 4-8. Levelogger Weir Box Installation

The purpose of installing one water levelogger per weir box is to record the water level passing over the weir opening every 15 seconds. This water level recorded at every 15 seconds is then inputted into the corresponding calibration curve weir box equations. Inputting the weir water height into the corresponding equations allows to solve for the flow leaving the weir box at each timed interval. This flow can then be transcribed to a volume of water that is leaving the corresponding weir box. This is a vital part of the set-up of the mass-balance system by measuring the water that is leaving the infiltration swales by either from the surface weir box as by-passed water or the underdrain weir box as infiltrated water. The exiting water flow and volume amount will then be differentiated from the known amount of water that is being pumped onto the swales from the introductory flow system.

4.3.3 Plastic Liner Calibration Check

To ensure the calibration of the surface weir boxes and introductory flow tanks were correct, plastic fabric was used to cover the entire length and width of the infiltration swales. The impermeable plastic fabric lining served to prevent infiltration of influent water into the underlying soil media. Instead, all influent water was directed to flow over towards the surface weir box for collection and measurement. Figure 4-9(b) shows the ALDOT infiltration swale lined with plastic and water flowing into the surface weir box.

(a) scalar flow ruler

(b) plastic liner

Figure 4-9. Plastic Liner Calibration

A flow rate of 0.55 ft^3/s (0.02 m^3/s), established using the scaled flow ruler on the water introduction system, was pumped into the swale for a duration of 30 minutes. A levelogger positioned within the surface weir box continuously recorded the water height over the weir crest throughout the test. This ensured continuous monitoring of water inflow to the swale and outflow through the weir box. With the predetermined flow rate and duration of the pumping process known, the total volume of water introduced into the system could be accurately calculated. Once the introduced flow volume was found, the levelogger data was extracted to find the amount of water volume that exited the infiltration swale. Figure 4-10 shows the water level of the surface weir box during this test.

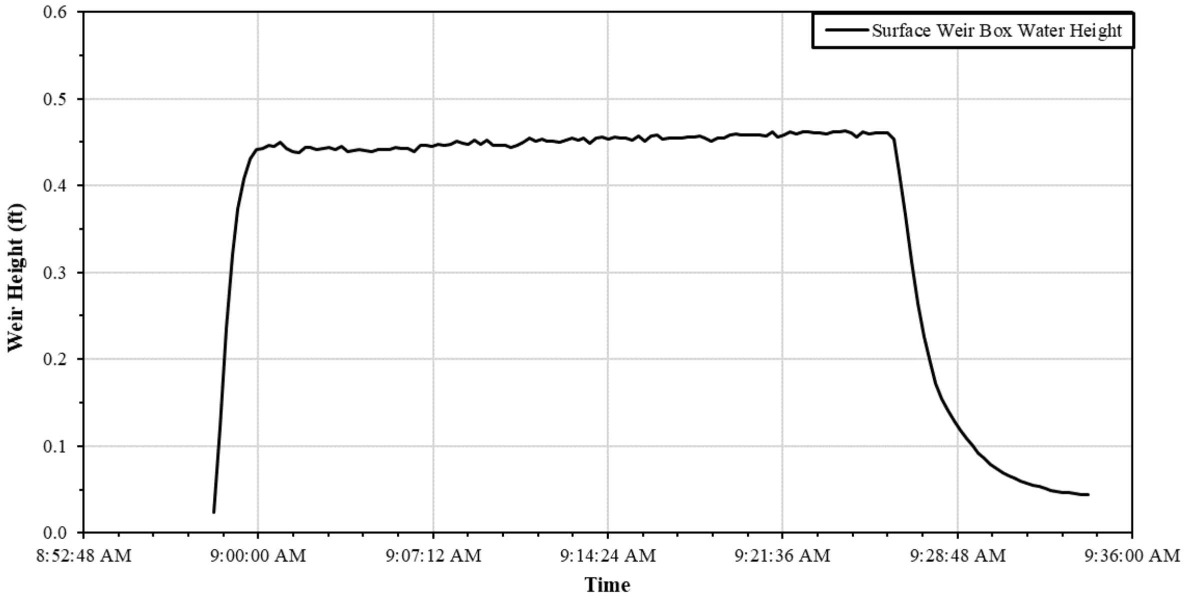


Figure 4-10. Surface Weir Box Water Height

The water level in the weir box was then subtracted from the crest height to solely get the value of water level over the crest. This value was then plugged into the equation from Figure 4-4 to obtain the flow amount for that water level over the crest for every 15 seconds. The water level data collected by the Levelogger was processed at 15 second intervals to determine the incremental volume exiting the weir box throughout the test. The sum of these incremental volumes yielded the total outflow volume. The experiment measured an inflow volume of 1039 ft^3 (29.4 m^3) to the infiltration swale, while the total outflow volume exiting the surface weir box was 987 ft^3 (27.9 m^3). The difference of 52.5 ft^3 (1.49 m^3) represents the volume of water retained within the swale as surface storage. According to this calibration 95% of the water was bypassed intro the surface weir box and 5% was captured in the swale's surface. This test confirmed the accuracy of the water introductory system flow amount, and the accuracy of the surface weir boxes for both infiltration swales.

4.4 SURFACE STORAGE VOLUME

Building upon the observation in the previous section that both the ALDOT and modified infiltration swales, while lined with an impermeable geomembrane, reached their maximum storage capacity without overflowing into the surface weir boxes, a procedure was devised to quantify the precise volume of water the infiltration swales can retain at the surface. To determine the volume of surface water storage within the infiltration swales, a manual pumping system was employed. This system utilized a pump and a calibrated container with a known volume of approximately 5 ft^3 (0.14 m^3). The number of full containers required to empty the surface water was then used to calculate the total volume of water stored. This was performed for both infiltration swales which were both made up of two storage surfaces called zone one and zone two. Figure 4-11 shows the work conducted to measure the volume for the surface storage volume and results in chapter 5.

(a) dewatering surface water (b) 5 ft³ (0.14 m³) drum

Figure 4-11. Measuring Surface Storage Volume

4.5 INFILTRATION AND DRAWDOWN EXPERIMENTS

The infiltration and drawdown experiment are a critical component of the infiltration swale evaluation process. This test quantifies two key parameters: infiltration rates and drawdown times. Infiltration rates indicate the swale's capacity to accept influent water, while drawdown times reflect the rate at which the stored water drains from the system. By analyzing these parameters, we can determine which infiltration swale exhibits superior performance in terms of water infiltration efficiency. Infiltration and drawdown experiments all use the same procedure for testing and are divided into different tests to evaluate the performance: (1) one-day versus three-day dry periods, (2) open versus closed valve underdrains, (3) colder versus warmer months, (4) wet versus drier soils test, (5) overall performance. These different experiments were performed to help better understand how the infiltration swales perform under different scenarios that may happen in practical situations when implemented. For instance, infiltration swales located in areas with high or low frequency of rainfall, agencies that use underdrains with infiltration swales, and infiltration swales performance present with pre-wetted soils or drier soils. Furthermore, this section will discuss the set-up process and methodology of the infiltration and drawdown testing.

4.5.1 Experimental Set-Up

Figure 4-12 shows the modified and ALDOT infiltration swale experimental set-up in an aerial view. In the figure, the modified infiltration swale area is denoted by the red boxes and callouts, while the ALDOT infiltration swale area is represented by the orange boxes and callouts. Even though the modified infiltration swale has a different engineered media matrix design than the ALDOT infiltration swale design, all other components of the experiment are kept the same. For example, the swale channel length of 40 ft (12 m), swale bottom width of 4 ft (1.2 m), side slopes of 3:1, and both earthen check dam heights. Other factors that are kept the same are the water introductory flow systems, surface weir boxes, and the underdrain weir boxes.

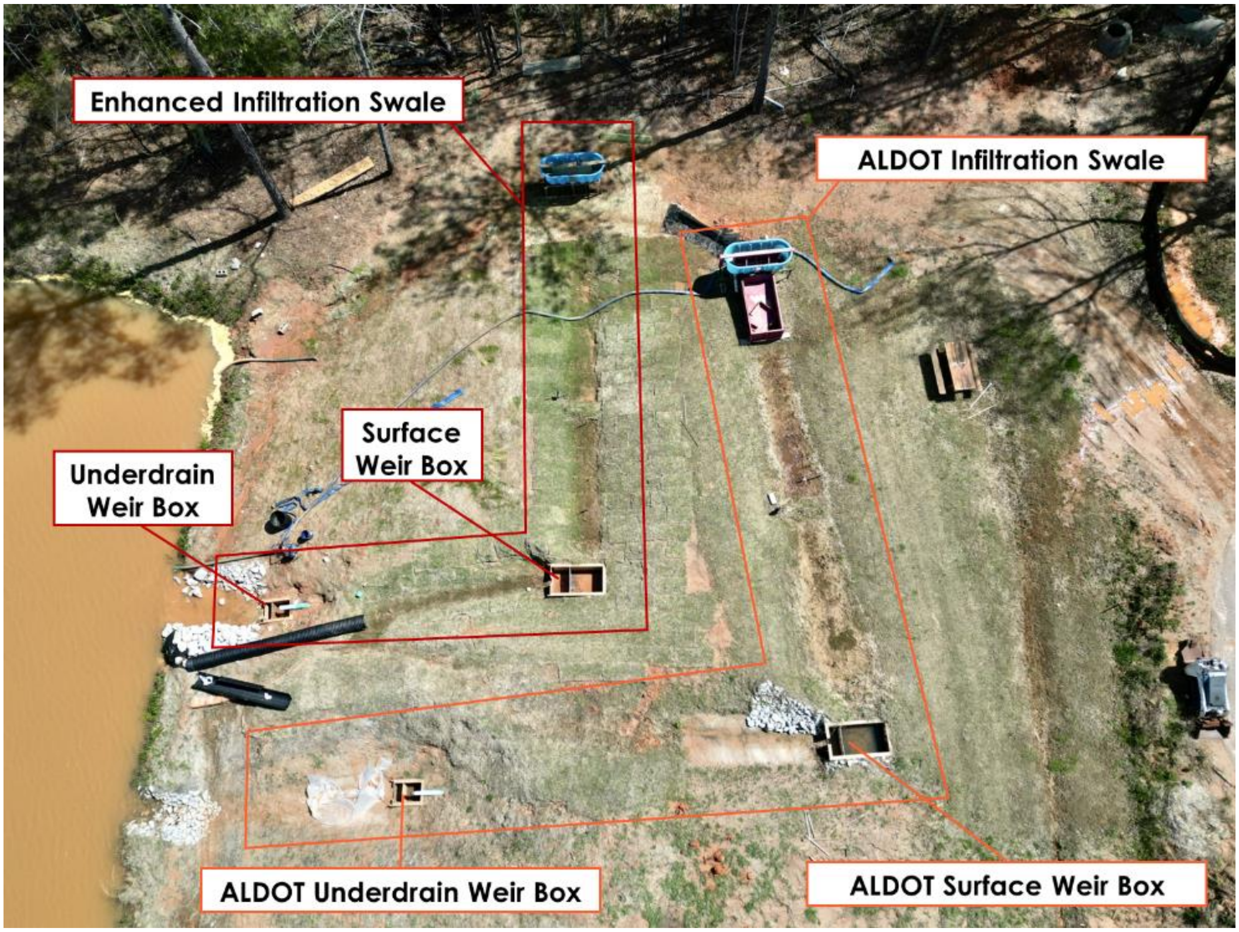


Figure 4-12. Aerial View of Infiltration Swale Set-Up

4.5.2 Experimental Procedure

The experimental procedure for infiltration rate and drawdown time testing starts with the introductory flow systems at the upstream part of the swale. This system introduces a constant, predetermined flow rate of approximately 0.38 ft^3/s (0.01 m^3/s) into the first zone of the infiltration swale. The flow rate of 0.38 ft^3/s (0.01 m^3/s) was chosen because it represents the maximum

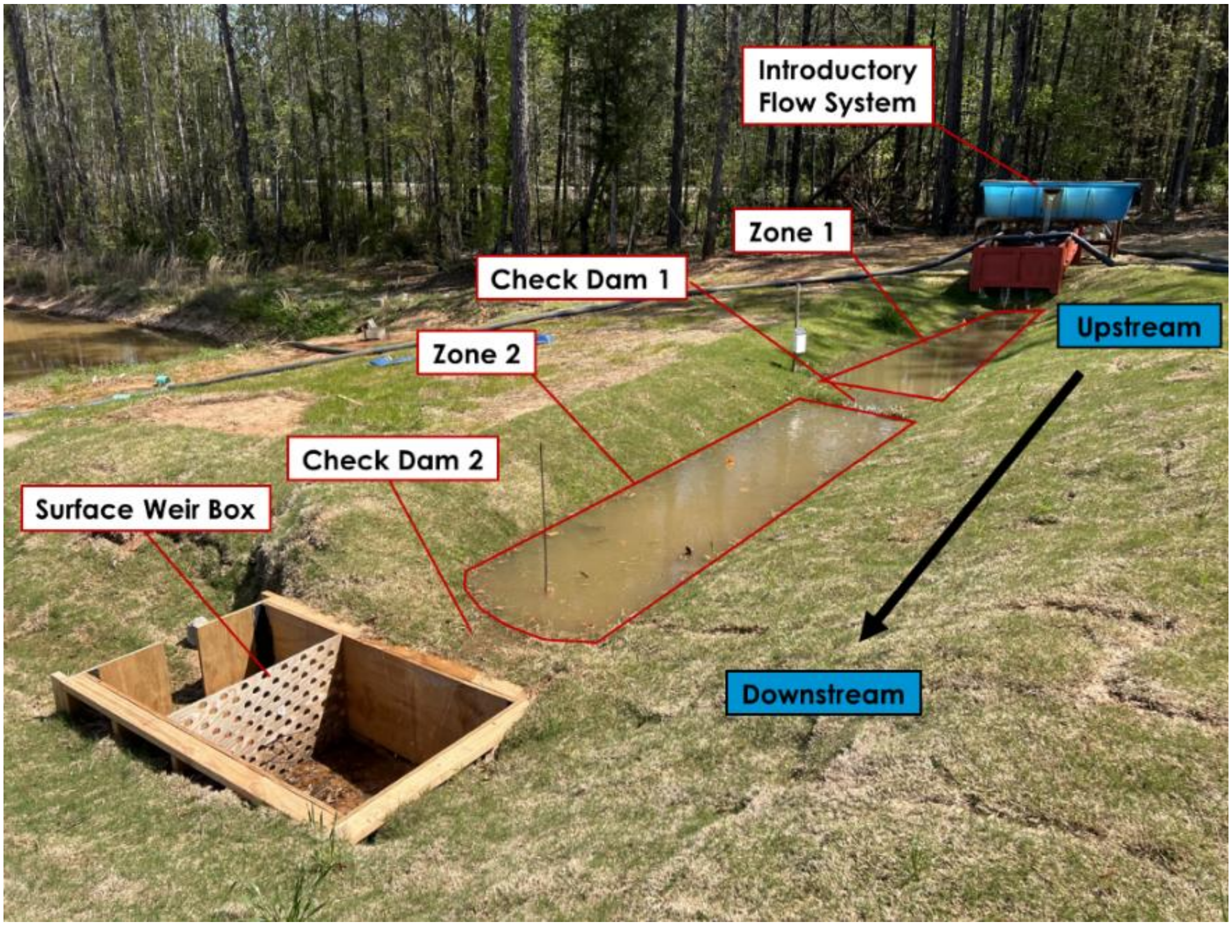


Figure 4-13. Infiltration Swale Set-Up

capacity of the water it can pump. Zone one represents the first body of water the swale holds before checking dam one shown in Figure 4-13.

Infiltration rate testing for each infiltration swale followed a prescribed protocol. The inlet flow system was activated, introducing a constant flow rate of 0.38 ft^3/s (0.01 m^3/s) into zone one of the swales. This flow rate represented the maximum capacity of the pump. The test proceeded as water accumulated within zone one. Once the water level surpassed the designated height of check dam one, excess water overtopped the dam and entered zone two, the second designated water storage zone.

The key measurement points for initiating flow shutoff occurred when Zone 2 achieved complete water storage capacity, signified by the absence of overflow into the surface weir box. While minimal overflow into the weir box might occasionally occur during testing, the protocol prioritized minimizing such occurrences. This emphasis stemmed from the critical need for accurate infiltration rate determination.

Infiltration rates are calculated based on the volume of water infiltrated through the swale media, not including water overflowing into the weir box. Overflow would lead to faster and inaccurate infiltration rate calculations. Consequently, infiltration rate testing commenced only after overflow into the surface weir box ceased entirely, indicating zone two had reached its maximum water depth.

Figure 4-14 illustrates two scenarios within the infiltration swale. Figure 4-14(a) depicts an overflow event, where the swale holds excessive water that spills into the surface weir box. Figure 4-14(b) portrays the optimal scenario for initiating the test, where the water level remains within the swale and does not overflow into the weir box.

(a) overflow into the weir box (b) no overflow into the weir box

Figure 4-14. Overflow into Surface Weir Box

Once zone two within each infiltration swale achieved complete water storage capacity, as established above, the infiltration rate testing commenced. During this phase, continuous water level measurements were collected at 15 second intervals using a levelogger positioned at the deepest point (downstream end) of zone two in each swale. This strategic placement ensured that infiltration rates were captured at the location with the maximum water depth and the longest anticipated drainage time. Consequently, this approach yielded the most accurate infiltration rate data, reflecting the behavior of a completely filled swale throughout the drainage process. Figure 4-15 shows the location in zone two of the levelogger placement and close-up images of the perforated PVC casing that holds the levelogger.

(a) levelogger in PVC casing

(b) levelogger

(c) levelogger location

Figure 4-15. Levelogger Location in Infiltration Swales

To facilitate a robust comparison of infiltration rates and drawdown times between the ALDOT and modified infiltration swales, both test procedures were initiated simultaneously. This synchronized approach aimed to minimize the influence of external factors that could potentially skew the results and compromise the evaluation of individual swale performance. Environmental conditions, such as variations in cloud cover, can impact infiltration rates. For example, sunny days often lead to increased evaporation and heating of the surface water storage, while cloudy days experience considerably less evaporation. By conducting the tests concurrently, the impact of these external factors on the performance of both the ALDOT and modified swales was effectively mitigated, yielding more reliable data for comparative analysis. Figure 4-16 shows both infiltration swales side-by-side during an infiltration and drawdown test.

(a) view from the downstream

(b) view from the upstream

Figure 4-16. Infiltration and Drawdown Experiment

4.5.3 Infiltration Rate and Drawdown Data Collection

Upon complete drainage of the infiltration swales, signifying the test's conclusion, the leveloggers were retrieved from each swale. The data collected during the testing period was then downloaded and transferred to Excel spreadsheets for further analysis. The downloaded data encompassed three key parameters for each time point: date, time of measurement, and corresponding water height within the swale.

The primary objective of this analysis was to determine the total drawdown time (time taken for complete drainage) and the associated infiltration rate for each infiltration swale test. To calculate the infiltration rate for an individual test, the following steps were undertaken:

1. **Initial Water Height:** The initial water height, representing a completely full swale (approximately 0.70 ft or 0.21 m), was identified from the downloaded data set.
2. **Final Water Height:** A water height of 0 ft (0 m), signifying an empty swale, was designated as the final data point.
3. **Water Height Difference:** The difference between the initial and final water heights was calculated.
4. **Drawdown Time:** The total time it took for the swale to drain from the initial water height (0.70 ft or 0.21 m) to the final water height (0 ft or 0 m) was extracted from the downloaded data. This value served as the drawdown time for the specific test.
5. **Infiltration Rate Calculation:** Finally, the average infiltration rate (I) was determined using the following equation (4-2) formula:

$$I = \frac{(inital\ water\ height - final\ water\ height)}{drawdown\ time} \tag{4-2}$$

This formula calculates the average infiltration rate throughout the entire drawdown process. The drawdown time obtained in step 4 is directly incorporated into the infiltration rate calculation (step 5).

4.5.4 One-Day versus Three-Day Dry Period Infiltration Test

This infiltration and drawdown experiment is the one-day dry period versus the three-day dry period testing. The one-day dry period represents filling up both swales at the same time and letting them drain one day after another. For instance, the swales were filled up completely with water once on Monday, Tuesday, Wednesday, and Thursday for the one-day dry period. For the three-day dry period, the swales were filled up at the same time but were filled every three days. For instance, both swales were filled up on Monday and the next time they were filled was on that Thursday and so on. The one-day dry period experiment represents a higher frequency of rainfall events. This represents dramatic rainfall events that would mimic a worst-case scenario if it rained every day for four to five days in a row. The three-day dry period experiment represents a normal rainfall frequency. The duration of three days in between filling the swales up was chosen because historical rain data from Montgomery, AL, on average showed rainfall events occur every three days. The one-day set-up will showcase both infiltration swale's performance for an extreme rainfall event week while the three-day setup will showcase a more practical representation of performance if the infiltration swale was implemented in Central Alabama.

It is noteworthy to mention that these tests were performed in trying to avoid actual rainfall from interrupting or skewing the infiltration rates and drawdown times. The timing of these tests included monitoring the weather and finding a forecast that had no rain for days or weeks which were difficult to find living on the east coast. Lastly, all tests were conducted with the underdrain valve open unless mentioned otherwise.

4.5.5 Open versus Closed Valve Underdrains

This is the next infiltration experiment that analyzes the performance of both infiltration swales under varying underdrain configurations. Specifically, the comparison investigates the impact of a closed underdrain valve (no underdrain functionality) on infiltration rates and drawdown times compared to an open underdrain valve (functioning underdrain). This evaluation aims to determine the influence of the underdrain system on the swale's ability to infiltrate stormwater and achieve acceptable drawdown times without the underdrain's active contribution. According to established principles, open underdrain valves allow infiltrated water to readily enter the underdrain system and discharge quickly, facilitating faster drawdown and potentially higher infiltration rates. Conversely, closed valves restrict underdrain discharge, forcing water to infiltrate solely into the native soil, potentially leading to slower drawdown and infiltration.

4.5.6 Colder versus Warmer Months

Infiltration rates and drawdown times can be influenced by various environmental factors, including temperature. To assess the potential impact of seasonal variations, this section analyzes the infiltration data from the ALDOT and modified infiltration swales with respect to the corresponding test months in Auburn, Alabama. By categorizing the data into colder and warmer months, we aim to investigate whether seasonal temperature fluctuations have a significant influence on the infiltration performance of the swales.

4.5.7 Wet versus Drier Underlying Soils

This section examines the influence of initial media and native soil moisture conditions on the performance of infiltration swales for all open valve tests. The analysis compares the swales' behavior under two scenarios: one with pre-wetted underlying media and soil, and another with drier underlying media and soil. Tests were classified as drier if it was the first day for each of the one-day dry period test, while subsequent days within that period were classified as wet. All tests within the three-day dry period tests were considered drier due to the three-day interval between rain events. All other tests were classified based on the presence of rainfall before the test commenced.

4.5.8 Overall Infiltration Performance Comparison

This section presents a comprehensive analysis of infiltration performance data collected from both the ALDOT swale and the modified swale. Given that the majority of infiltration tests were conducted with open underdrain valves, this analysis will exclusively focus on this configuration to maximize the sample size and ensure a more robust comparison between the ALDOT swale and the modified swale. By comparing the infiltration rates and drawdown times observed in these tests, we aim to establish a clear understanding of the relative performance of each swale design.

This comparative analysis is crucial for drawing definitive conclusions about the overall effectiveness of each swale. Ultimately, the results will help us determine which swale design exhibits superior infiltration capabilities and achieves faster drawdown times. This information is vital for guiding future design and implementation decisions for infiltration swales in stormwater management applications.

4.5.9 Statistical Analysis

The overall infiltration performance, including comparisons of wet versus drier soil conditions, open versus closed valve underdrains, one-day versus three-day dry period tests, and moisture content results, were analyzed using two-sample unpaired t-test. This analysis compared the infiltration rates of the ALDOT swale and the modified swale to determine if the observed differences were statistically significant (greater for one swale or not statistically different). The two versions of the two-sample t-test used were the pooled variance for all the results except for the open valve and closed valve test used the Welch's T-test because of variances. Statistical analysis set-ups comparing two average infiltration rates used version 1 shown in Table 4-1 while moisture content results used version 2. Lastly, the sample sizes of each ALDOT or modified swale was also incorporated into the analysis.

Table 4-1. T-Test Set-Up

Version	Tails	Effect	Effect Size	Significance Level (α):	Effect Type
(1)	Left (H_1: $\mu_1<\mu_{2+d}$)	Medium	0.5	0.05	Standardized Effect Size
(2)	Two (H_1: $\mu_1\neq\mu_{2+d}$)	Medium	0.5	0.05	Standardized Effect Size

To assess the relative influence of various factors on infiltration rates, a multiple linear regression (MLR) analysis was conducted for both the ALDOT and modified swales. The MLR model separates the independent factors to evaluate the effects on the dependent variable. This method allows to identify what factors had the most significant impact on the dependent variable which is the infiltration rate for each test. The independent variables that are being investigated include seasonal variation which is represented as water temperature (°F) that was pumped into the swales for each test, wet or drier soil which is represented with soil moisture content (%), and valve condition (open or closed). This model develops partial regression coefficients that report how strongly that independent variable affects the dependent. A significance level of $\alpha = 0.05$, corresponding to a 95% confidence interval, was adopted for both swales in the MLR. The MLR model used for the analysis is shown in Equation 4-3.

$$f(x) = \beta_0 + \beta_{1X1} + \beta_{2X2} + \cdots + \beta_{nXn} \tag{4-3}$$

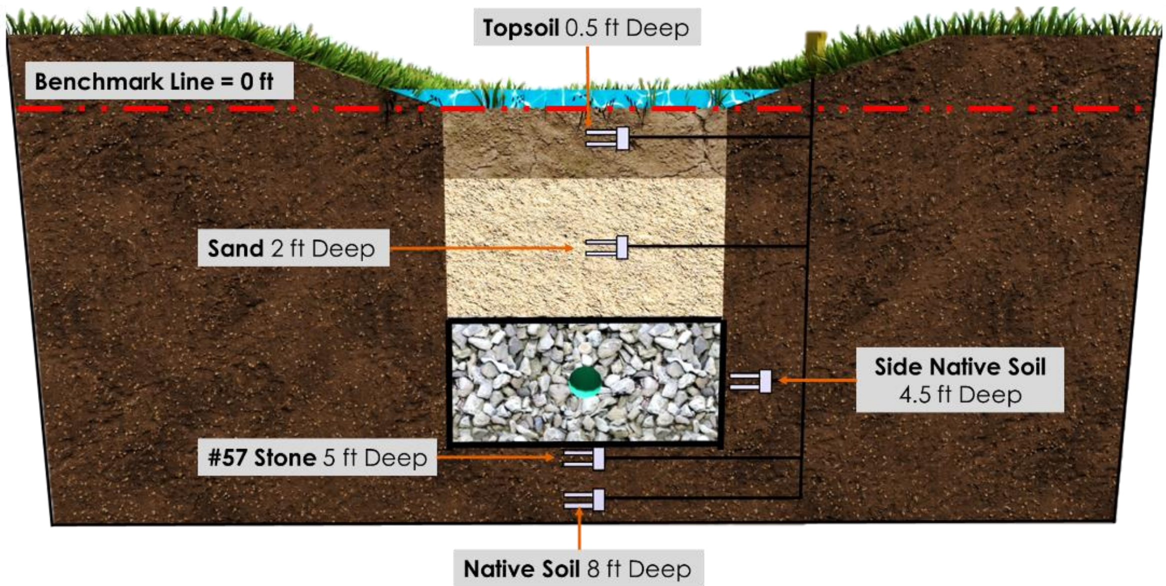
Where $f(x) =$ dependent variable (infiltration rate (ft/day)); $X_i =$ independent variables (e.g., water temperature, soil moisture content, and open/closed valve); β_i = the ordinary least squares coefficients.

4.6 SOIL MOISTURE MONITORING

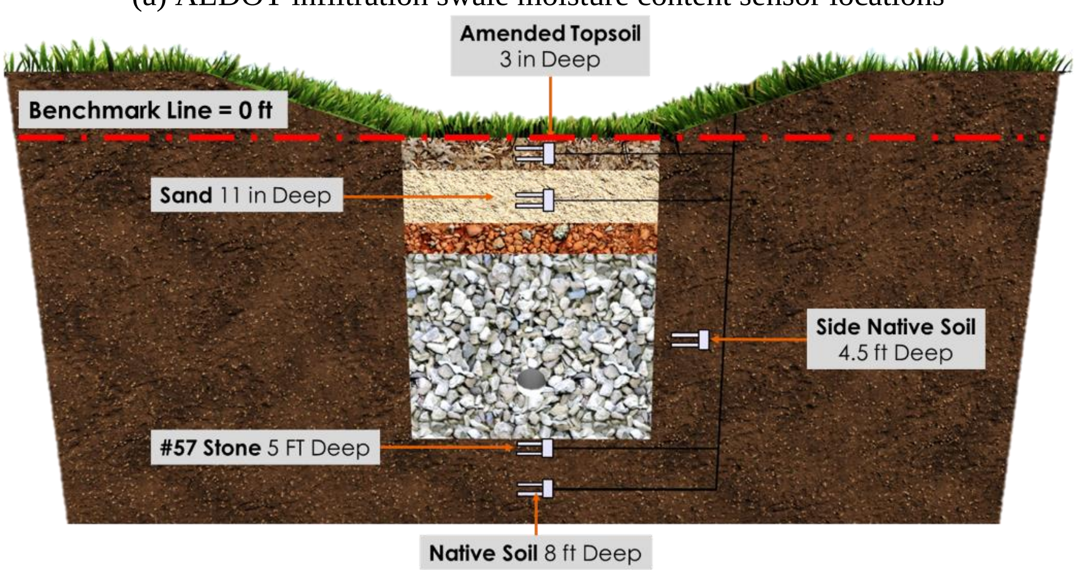
In conjunction with the infiltration rate and drawdown testing, soil moisture content was monitored within both the engineered media matrix and the surrounding native soils of the ALDOT and modified infiltration swales. The installation and configuration of the moisture content sensors were detailed in Chapter 3. The inclusion of these sensors played a crucial role in comprehensively assessing the infiltration swale performance. They provided real-time data on the moisture content of specific soil layers during infiltration testing. The moisture content sensors tracked the infiltration and subsequent movement of water within the subsurface. By monitoring the sensors response patterns at their specific locations, it was possible to extract the time it took for infiltrated water to reach different depths and areas of the media and surrounding native soils. These times were then cross referenced between the ALDOT and modified swale to evaluate the infiltration efficiency of their media design.

4.6.1 Moisture Content Sensor Placement

The selection of sensor locations within the infiltration swales was critical for obtaining representative moisture content data from specific soil layers. A detailed illustration of the sensor locations within both the ALDOT and modified swales is provided in Figure 4-17.



(a) ALDOT infiltration swale moisture content sensor locations



(b) modified infiltration swale moisture content sensor locations

Figure 4-17. Moisture Content Sensor Locations (not to scale)

The primary factor guiding sensor placement was ensuring optimal contact between the sensor probes and the target soil or media of interest. Consequently, sensors were positioned directly in the center of their designated soil layer. As depicted in Figure 4-17, for a comprehensive comparison of the infiltration swale media performance, sensors were installed within each distinct media layer of both swales. All sensor depths and horizontal offsets were referenced from a benchmark zero point established at the base of the swale channel. Figure 4-17 shows that for optimal comparison of the ALDOT and modified infiltration swale medias, sensors were placed in each soil media layer. All sensors' depths and locations are from the benchmark zero at the bottom of the swale's channel surface.

4.6.2 Sensor Depths

Sensor depths varied between the ALDOT and modified swales due to differences in media layer thicknesses. The first sensor in the ALDOT swale was positioned at a depth of 0.5 ft (0.15 m) from the surface, while the corresponding sensor in the modified swale was located at 0.25 ft (0.08 m). The second sensor, targeting the sand layer, was placed at a depth of 2 ft (0.6 m) in the ALDOT swale and 0.92 ft (0.28 m) in the modified swale. The deepest sensor, positioned identically in both swales, was located 3 ft (0.9 m) above the bottom of the engineered media matrix, translating to a total depth of 8 ft (2.4 m) from the base of the swale channel. This sensor placement aimed to determine whether infiltrated water remained within the engineered media matrix or infiltrated deeper into the surrounding native soils, potentially contributing to groundwater recharge.

4.6.2.1 Native Soil Monitoring

To assess potential horizontal infiltration from the engineered media matrix into the surrounding native soil, a sensor was installed in both swales at a depth of 4.5 ft (1.4 m) and with a horizontal offset of 1.5 ft (0.48 m) from the edge of the engineered media.

4.6.2.2 #57 Stone Layer Considerations

The large air voids within the #57 stone layer presented a challenge for sensor placement. Effective moisture content measurement necessitates full contact between the sensor probes and the surrounding soil. To address this limitation, sensors were not placed directly within the #57 stone layer but instead positioned in the native soil directly beneath this layer in both swales. This placement allowed for monitoring the amount of water infiltrating through the final layer of the engineered media at a depth of 5 ft (1.5 m).

4.6.3 Moisture Content Sensors Data Collection

Two independent data acquisition systems were established, one designated for the ALDOT infiltration swale and the other for the modified infiltration swale. Each system monitored a network of five moisture content sensors strategically installed within its respective swale. Following sensor installation, the data collection parameters were configured for each system. The sensors were programmed to record data at 5-minute intervals, capturing the following parameters for each time point: date, time, and volumetric water content (VWC) expressed as a percentage (%).

The VWC readings ranged from 0%, signifying completely dry soil, to a maximum value of 64%, representing soil saturation (100% VWC). It is important to acknowledge that sensor readings can vary between different soil types, even with identical water content. This variation arises from the inherent properties and characteristics of each soil type. For example, clay soils exhibit a greater capacity for water retention and absorption compared to sand soils. Consequently, a clay soil layer will register a higher VWC reading compared to a sand layer under identical water application conditions, as the sand allows for faster drainage and lower moisture content readings from the sensors.

Data collection commenced upon initiating the infiltration rate and drawdown testing. As water was introduced simultaneously into both infiltration swales, the moisture content sensors awaited the arrival of infiltrating water within the engineered media matrix and surrounding native soils. Due to the time required for water to travel through the media and reach each sensor, data download did not occur immediately following complete drainage of the swale surface water. Even after surface water depletion, infiltration continues through the engineered media and into the native soils. Therefore, allowing sufficient time for water to reach the deepest sensors was critical.

The process for downloading sensor data was straightforward. It involved directly connecting the data logger to the control box of the corresponding moisture content sensor system, which housed all collected data points. The data was then downloaded and exported into Excel spreadsheets for further analysis.

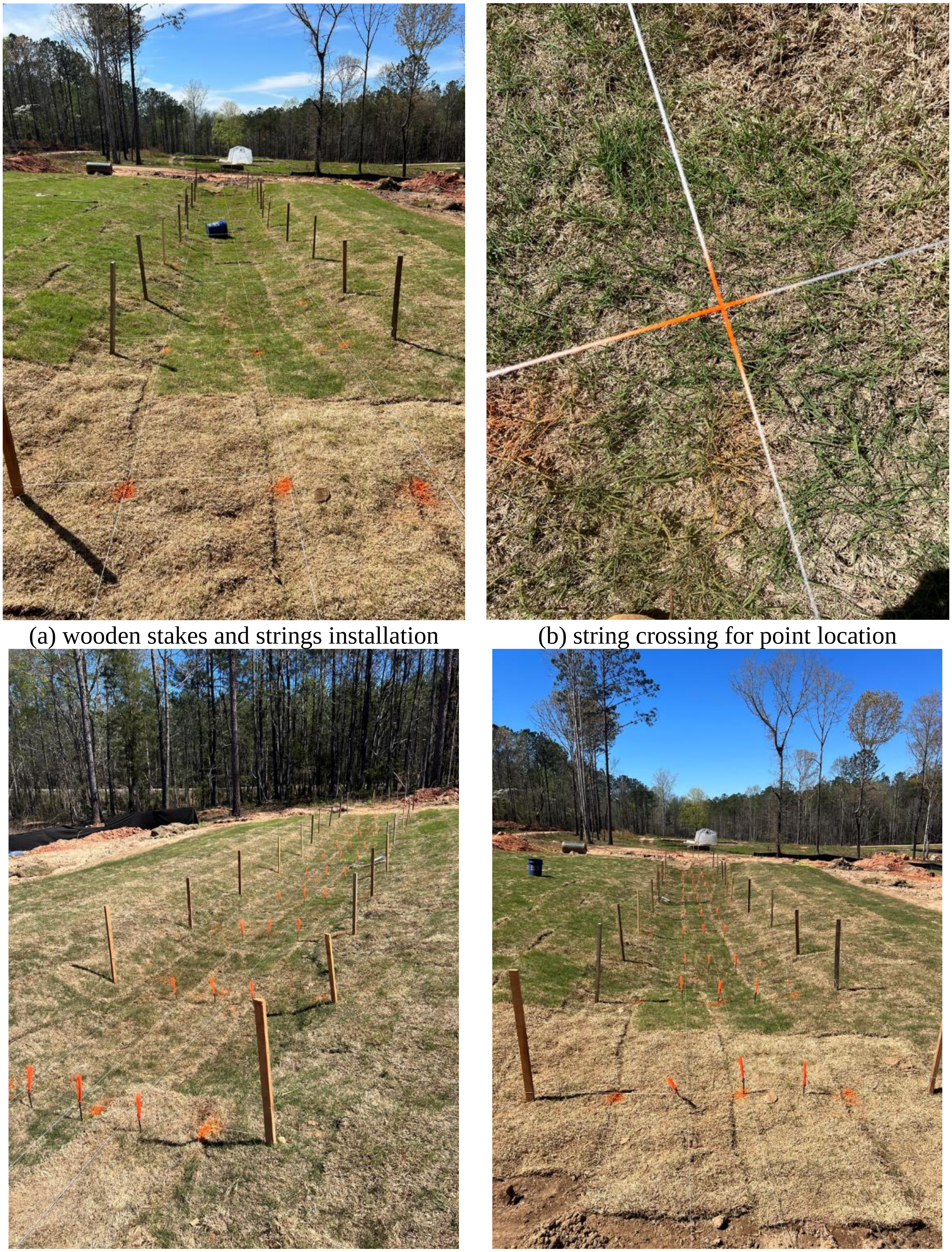
4.7 SETTLEMENT MONITORING

In addition to infiltration rate and drawdown testing, an evaluation of the infiltration swales' settlement characteristics was undertaken. This assessment aimed to track the vertical displacement (settlement) of both the ALDOT and modified infiltration swales over an extended period following construction.

Monitoring settlement is crucial because it can impact infiltration rates over time. Consolidation and settlement processes within the engineered media matrix can lead to a reduction in the overall volume of air voids. As these air voids decrease in size and quantity, the available storage capacity for infiltrating water diminishes. Furthermore, excessive settlement can contribute to clogging of the engineered media, further hindering infiltration. Therefore, settlement measurements for both swales were recorded throughout the project duration.

4.7.1 Settlement Measurement Points

Settlement measurements for the infiltration swales needed an established network of fixed reference points throughout the length of each swale's bottom channel. Given the swale dimensions of 40 ft (12 m) in length and 4 ft (1.2 m) in bottom channel width, reference points were installed in cross-sections spaced at 5 ft (1.5 m) intervals along the channel. Each cross-section comprised three reference points: one at the center and one offset by 2 ft (0.6 m) to either side (left and right). The specific locations of these points are illustrated in Figure 4-18**.**



(a) wooden stakes and strings installation (b) string crossing for point location

(c) orange steel nail installation (d) settlement set-up completion

Figure 4-18. Settlement Point Set-Up

To establish the reference points, the following procedures were implemented. A tape measure was used to mark and install wooden stakes every 5 ft (1.5 m) along the longitudinal direction (parallel to the channel length) on both sides of the swale channel. The center point of the channel bottom width was identified and marked using wooden stakes placed at both the upstream and downstream ends of the swale. Wooden stakes were installed at an offset of 2 ft (0.6 m) to the left and right of the center point to establish the remaining two points within each cross-section. Strings were used to connect corresponding wooden stakes across the channel width, ensuring all points within a cross-section were aligned. The intersection points of the strings were marked with orange spray paint for improved visibility. Steel nails with bright orange markers were driven into the ground at each spray-painted location (refer to Figure 4-18(c)). These permanent markers facilitated easy visual identification during subsequent settlement measurements and allowed the nails to settle along with the swale bottom over time.

4.7.2 Settlement Test

Following the establishment of the settlement measurement points (Section 2.5.1), monthly elevation measurements were obtained at each point for both infiltration swales. An automatic level laser survey instrument was employed to precisely measure the elevation of each reference point. A total of 24 points were installed and subsequently measured on a monthly basis commencing from the completion of swale construction.

It is important to note that the automatic level was not positioned at the same location for each monthly measurement. To address this, two permanent, external reference points were established outside the swale perimeter at locations unaffected by settlement. These fixed points served as the benchmark for all subsequent monthly settlement measurements. Figure 4-19 presents an aerial view of the ALDOT infiltration swale, illustrating the distribution of the 24 settlement points and the two external benchmark points.

Figure 4-19. Settlement Points

Elevation at each reference point was measured sequentially using the automatic level laser. The measured elevations were then documented in an Excel spreadsheet for further analysis. This process facilitated the pairing of corresponding points across each month's data set, enabling the identification of any elevation changes over time.

Following data transcription, the recorded elevations were converted from their original units to feet (meters) for consistency. Furthermore, an average elevation was calculated for each cross-section by averaging the individual elevations of the three points within that section. To determine the settlement at each cross-section, the average cross-section elevation was subtracted from the corresponding elevation measured at one of the two external fixed reference points.

Finally, the calculated settlement values for each cross-section were plotted on a monthly basis to visualize the settlement trends over time.

4.8 SUMMARY

This chapter outlines the methodologies utilized for a comprehensive evaluation of infiltration swale performance. A variety of calibrations, experiments, and instrumentation were employed. Key components of the methodology included calibration of the water introduction system and weir boxes, implementation of levelogger water induction devices, and the establishment of methodologies for measuring infiltration rates, drawdown times, soil moisture content, and settlement. These methods, described in detail, form the foundation for the infiltration swale results presented in Chapter 5.

CHAPTER FIVE: RESULTS AND DISCUSSION

5.1 OVERVIEW

This chapter details and compares the infiltration performance of the traditional ALDOT swale to the modified swale. The lists below summarize different sections and results that are evaluated and discussed in this chapter:

- **Geotechnical and Native Soil Testing:** this section characterizes and classifies the underlying native soil and its infiltration properties to ensure the site is proper for infiltration swales.
- **Infiltration and Drawdown Evaluation:** explores how factors including simulated rainfall frequency (one-day vs. three-day dry period), underdrain configuration (open vs. closed valve), seasonal variation (colder vs. warmer months), initial moisture content (wet vs. drier), and overall performance comparison affect infiltration rates and drawdown times in both swales.
- **Overall Performance:** this section compares the overall infiltration efficiency of the two swales.
- **Statistical Analysis:** explores the MLR results and what factors had the most effect on infiltration rates.
- **Surface Storage Volumes:** assess the surface storage volume capacity and any discrepancies between the ALDOT and modified swales.
- **Moisture Content Sensor Evaluation:** data from moisture sensors installed within the swales provide insights into water movement patterns through the media layers.
- **Settlement Evaluation:** this section examines potential changes in surface elevation over time due to media compaction, which can impact infiltration capacity.

By analyzing these results, valuable insights into the effectiveness of each swale design and identify areas for potential improvement.

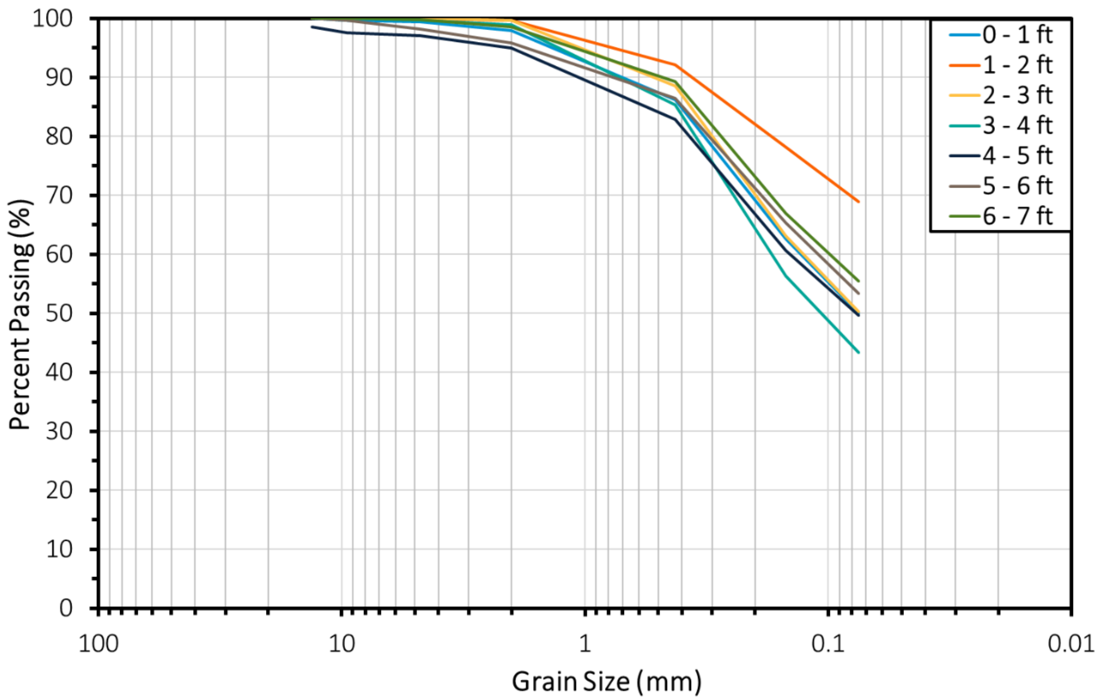
5.2 GEOTECHNICAL AND NATIVE SOIL CLASSIFICATION

This section integrates the findings from the construction phase (Chapter 4) with laboratory soil testing results and field infiltration data to evaluate the suitability of the native soil for an infiltration-based SCM. Determining site suitability for infiltration practices is crucial for ensuring the long-term effectiveness and functionality of infiltration swales. By carefully considering these factors and integrating the data from laboratory analysis and field testing, an informed decision can be made about the suitability of the site, for an alternative SCM may be needed for poor native soils.

5.2.1 Soil Laboratory Testing

Figure 5-1 presents the collected soil profile from 0 to 9 ft (2.7 m) depths displayed in transparent plastic bags. The figure additionally incorporates the corresponding grain size results for each sample depth up to 7 ft (2.1 m). This combined visualization aids in comprehending the relationship between soil texture (as determined by grain size) and depth within the profile.

(a) boring profile



(b) grain size results

Figure 5-1. Native Soil Results

This analysis revealed that the in-situ soil at the AU-SRF site can be classified as a silty loam based on its particle size distribution and usage of a laser-induced spectroscopy.

Knowledge of the soil texture (silty loam) allows us to leverage the Minnesota Department of Transportation (MnDOT) HSG classification system Table 5-1. This system categorizes soils based on their infiltration rate and drainage characteristics. Table 5-1 presents the MnDOT HSG table, listing soil groups A through D, their corresponding infiltration rates, and associated soil textures.

Table 5-1. Hydrological Soil Table (MnDOT) [39]

Hydrologic Soil Group	Infiltration Rate (in/hr)	Infiltration Rate (cm/hr)	Soil Textures
A	1.63	4.14	Silty Gravels Gravelly Sands Sand
	0.8	2.03	Sand Loamy Sand Sandy Loam
B	0.45	1.14	Silt Sands
	0.3	0.76	Loam Silt Loam
C	0.2	0.51	Sandy Clay Loam Silts
D	0.06	0.15	Clay Loam Silty Clay Loam Sandy Clay Silt Clay Clay

The classification of the soils at the site were silty loam soils as identified through the grain size analysis. Using Table 5-1, silty loam soils fall within the HSG B classification. This indicates the location is suitable for constructing infiltration swales, as HSG groups A and B are recommended by most DOTs across the country. HSG C soils may also be acceptable if they can achieve complete drainage within 48 hours.

5.2.2 Field Infiltration Soil Testing

While the laboratory analysis classified the in-situ soil as a silty loam, potentially corresponding to an HSG B, field testing is crucial for verifying the actual infiltration rate at the designated infiltration swale construction site. This approach ensures long-term performance by confirming the suitability of the native soil for optimal infiltration.

Table 5-2. Double-Ring Results

Time	Initial Depth (cm)	Final Depth (cm)	Infiltration Rate (cm/half-hr)	Infiltration Rate (cm/hr)	Infiltration Rate (cm/hr)
0-30	4	2.5	1.5	3	**1.4**
30-60	2.5	1.9	0.6	1.2	
60-90	1.9	1.5	0.4	0.8	
90-120	1.5	1	0.5	1	
120-150	1	0.6	0.4	0.8	
150-180	4	3.4	0.6	1.2	
180-110	3.4	2.5	0.9	1.8	
110-140	2.5	1.8	0.7	1.4	
140-170	1.8	1.2	0.6	1.2	
140-170	1.2	0.6	0.6	1.2	

As indicated in Table 5-2, the infiltration rate for this deepest layer averaged approximately 0.55 in/hr. (1.4 cm/hr.) based on the average of the last four readings. To account for potential variations and ensure long-term infiltration performance, a safety factor of two is often applied to field-measured infiltration rates. Dividing the raw infiltration rate by two results in a safety factor infiltration rate of. 0.28 in/hr. (0.7 cm/hr.). It is confirmed that the in-situ soil at the AU-SRF site sits between HSG B and C; however, 0.28 in/hr. (0.7 cm/hr.) sits closer to the HSG B class according to Table 5-1. This finding is close to the preliminary classification based on the soil texture classification (silty loam) determined through grain size analysis.

5.3 INFILTRATION AND DRAWDOWN EVALUATION

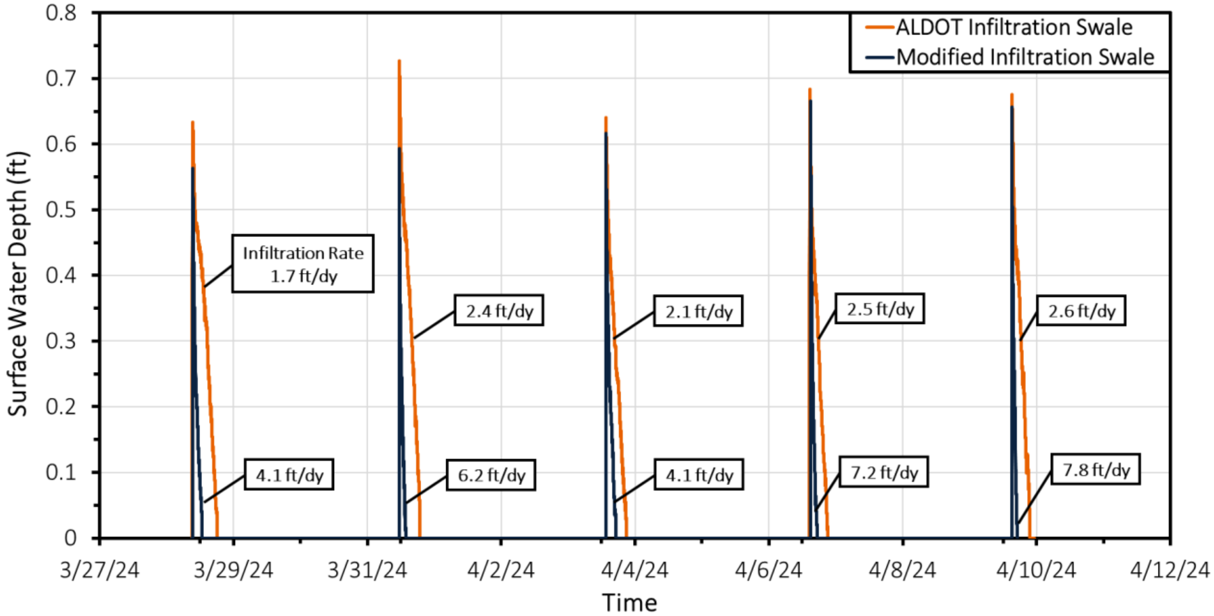
A series of tests were conducted on both swales, focusing on two parameters infiltration rates and drawdown times. These two parameters are key findings in evaluating the performance of the ALDOT and the modified infiltration swale. This section is divided into four different result sections to evaluate the performance: (1) one-day dry period versus three-day dry period,

(2) open versus closed valve underdrains, (3) wet versus drier underlying soil, (4) overall infiltration performance comparison. These four different experiments were performed to help better understand how the infiltration swales perform under different scenarios that may happen in practical situations when implemented. For instance, (1) infiltration swales located in areas with high or low frequency of rainfall, (2) agencies that use underdrains with infiltration swales, and (3) infiltration swales performance present with pre-wetted soils or drier soils. The testing methodology for all three experiments is the same as mentioned in Chapter 4, which entailed filling both swales up completely with water simultaneously and using the levelogger to record infiltration rates and drawdown times till both swale's surfaces drained fully.

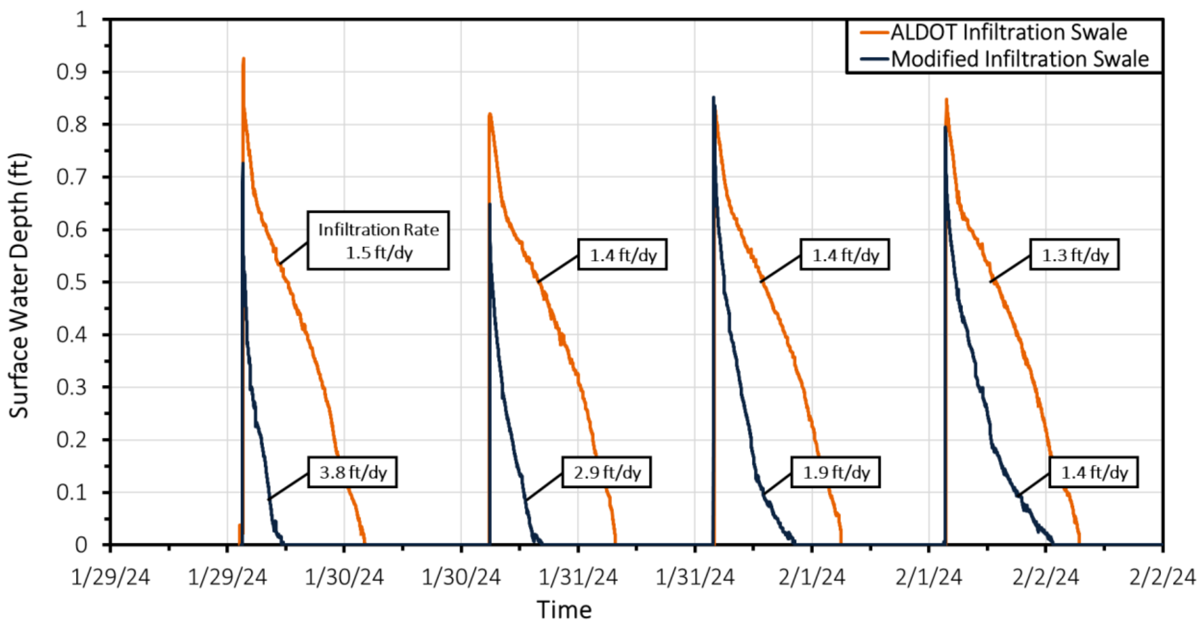
5.3.1 One-Day vs Three-Day Dry Periods

The experiment compared infiltration and drawdown performance under two simulated rainfall frequencies: one-day and three-day dry periods. The one-day scenario represents frequent rainfall events, while the three-day scenario reflects a more typical pattern based on historical Montgomery rain data. All tests were conducted under drier conditions to avoid real rain interference and used open underdrains unless otherwise specified.

Figure 5-2 illustrates the results collected from performing the one-day dry period versus the three-day dry period tests. This figure shows the surface water depth of the infiltration swales on the y-axis and time on the x-axis. The orange line represents the data collected from the ALDOT swale and the dark blue line represents the data collected from the modified infiltration swale. Figure 5-2(a) shows the results collected from the three-day dry period tests and Figure 5-2(b) shows the results for the one-day dry period. Figure 5-2(b) had four tests performed because the last day for the one-day tests was a natural rainfall event that was not simulated and was excluded.



(a) three-day dry period



(b) one-day dry period

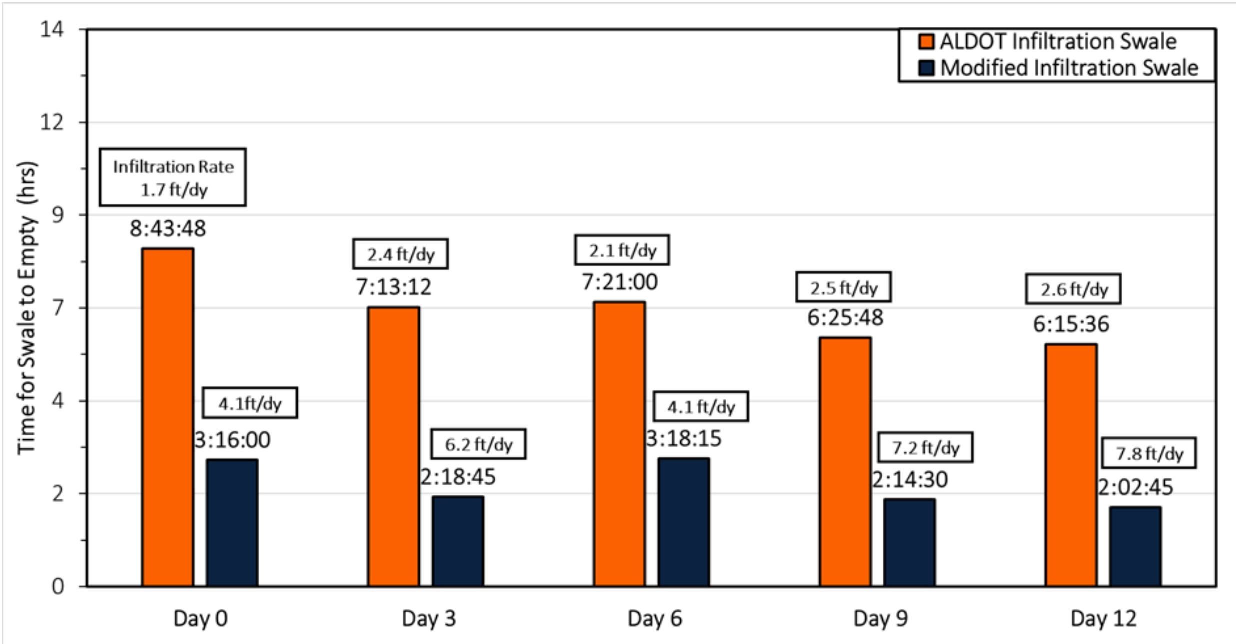
Figure 5-2. Dry Period Infiltration Rate Comparison

Focusing on the three-day interval infiltration rates first in Figure 5-2(a), the ALDOT swale exhibited an average infiltration rate of 2.26 ft/day (0.69 m/day), while the modified swale demonstrated a significantly higher rate of 5.88 ft/day (1.79 m/day), representing an approximately 2.6-fold increase. A two-sample t-test with pooled variance confirmed a statistically significant difference ($p = 0.0008807$) between the infiltration rates of the two swales, rejecting the null hypothesis at the 95% confidence level. Figure 5-2(a) three-day dry period test results showed that the modified swale outperformed the ALDOT swale. Focusing on the ALDOT swale, the infiltration rate recorded for the first test was 1.7 ft/day (0.52 m/day) while the following infiltration rates increased and stayed consistent within the range of 2.1 ft/day (0.64 m/day) to 2.6 ft/day (0.79 m/day). This consistent infiltration rate showed that the ALDOT infiltration swale can recover and maintain high infiltration rates for rain events that occur every three days. Now observing the modified infiltration swale, the infiltration rate recorded for the first test was 4.1 ft/day (1.2 m/day) while the following days were also consistently high infiltration rates. Even though it decreased on the third test, this infiltration rate is almost double the infiltration rates recorded from the ALDOT infiltration swale. The modified infiltration rate maintained high infiltration rates and showed it can recover and maintain remarkably high infiltration rates for rain events that occur every three days. Comparing them side by side, the modified infiltration swale had infiltration rates that were 2.6 times faster than the ALDOT infiltration swale on average; however, both showed adequate infiltration rates that are acceptable. The three-day results show that both infiltration swales were able to fully drain and even maintain a consistent or increased infiltration rate through the testing duration.

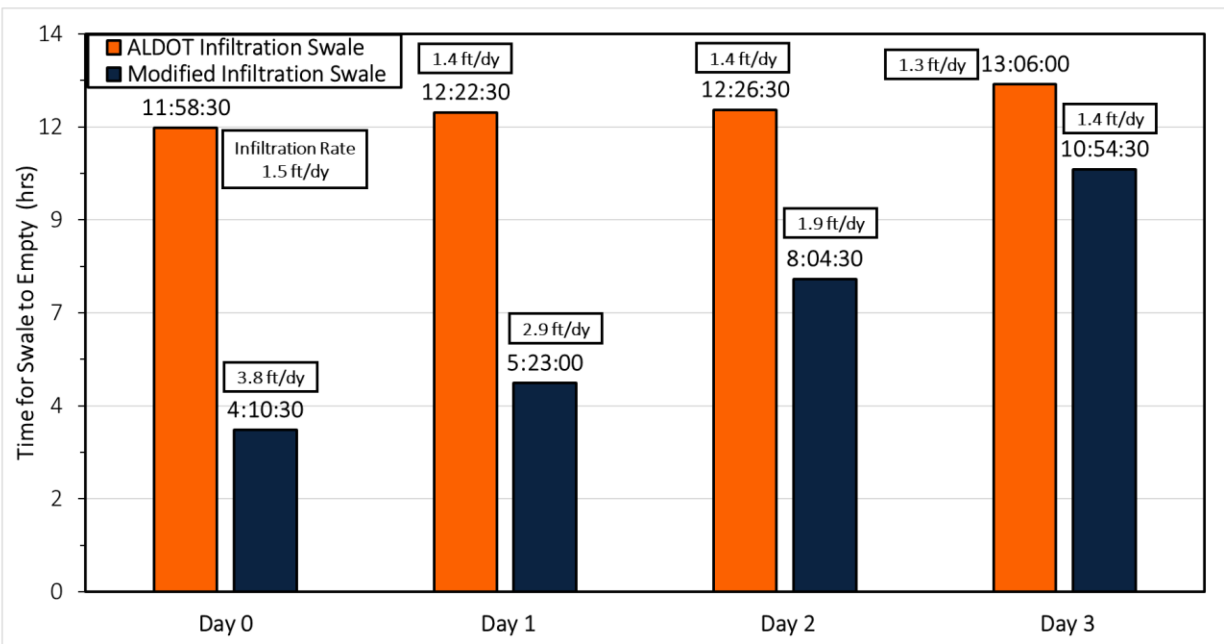
Focusing on Figure 5-2(b) one-day dry period test results showed that the modified swale had faster infiltration rates, with averages of 2.5 ft/day (0.76 m/day) for the modified and 1.4 ft/day (0.43 m/day) for ALDOT, respectively, representing an approximate 1.8-fold increase. A two-sample t-test with pooled variance confirmed a statistically significant difference between the two swales (p = 0.04285), rejecting the null hypothesis at the 95% confidence level. The one-day dry period test represents a more extreme rainfall event to show how well the infiltration swales can recover. The ALDOT infiltration swale recorded an infiltration rate of 1.5 ft/day (0.46 m/day) for the first test and the following rates were close and consistent. This shows that the ALDOT infiltration swale infiltration rates did not decrease with increased soil moisture content from water being infiltrated every day. The infiltration rates are barely just above the required 1 ft/day (0.3 m/day) required by most DOTs across the country. This is cutting it close to the threshold and literature shows that over time the infiltration rates will slow down further from use. The modified infiltration rate recorded for the first test was 3.8 ft/day (1.2 m/day) and the following infiltration rates decreased after each day. The first three infiltration rates are high infiltration rates; however, the last infiltration rate of 1.4 ft/day (0.43 m/day) is around the consistent infiltration rate for the ALDOT swale. This means the performance of the modified swale matches the ALDOT swale when the fourth day of rain occurred. The one-day dry period test showed that the modified infiltration swale outperformed the ALDOT infiltration swale for the first three days, but on the fourth day matched the performance of the ALDOT infiltration swale. Again, both swales drained within the 1 ft/day (0.3 m/day) and showed acceptable performance; however, the ALDOT infiltration rates were cutting it close.

Summarizing Figure 5-2, the ALDOT swale's infiltration rates on average increased from the one-day interval to the three-day interval by a factor of approximately 1.6. The modified swale's infiltration rates on average increased from the one-day interval to the three-day interval by a factor of approximately 2.3. The main take away from comparing infiltration swale from the three- day test to the one-day test is that increased rainfall frequency decreased infiltration rates for both swales. Lasty, the test shows that both swales can sustain infiltration performance for the three-day interval while for the one-day interval the infiltration performance decreases after each test.

Figure 5-3 presents the same three-day and one-day tests shown in Figure 5-2, but instead of the infiltration rates, it represents the drawdown times to empty from being full of water. Figure 5-3(a) shows the results from the three-day dry period tests and Figure 5-3(b) shows the results from the one-day dry period test. The infiltration rate of each test is above each bar.



(a) three-day dry period



(b) one-day dry period

Figure 5-3. Dry Period Drawdown Time Comparison

Observing the Figure 5-3(a), the three-day dry period bar graph, the ALDOT swale achieved complete drainage in an average of approximately 7 hours. The modified swale achieved complete drainage in an average of approximately 2.6 hours. The modified swale drained roughly 2.7 times faster than the ALDOT swale and both swales showed consistent times across each test. The ALDOT swale drawdown times were consistent for each test varying from 6.3 hours to 7.35 hours. These drawdown times are considered fast times and represent adequate performance. However, the modified infiltration swale significantly outperformed the ALDOT swale with consistent drawdown times varying from 2.03 hours to 3.3 hours which is almost triple the speed of the ALDOT swale. Once again Figure 5-3(a), shows that both swales can recover and keep consistent performance for the three-day interval.

Observing the Figure 5-3(b), the one-day dry period bar graph, the ALDOT swale achieved complete drainage in an average of approximately 12.5 hours. The modified swale achieved complete drainage in an average of approximately 7.1 hours. The modified swale drained roughly 1.8 times faster than the ALDOT swale, and drawdown times remained consistent for the ALDOT swale and increased for modified. The ALDOT swale drawdown times, similar to the infiltration rates, were consistent for each test varying from 11.97 hours to 13.1 hours even though the times were predicted to be longer after each test since the rainfall frequency increased. These drawdown times are still considered fast times and represent adequate performance since they are less than 24 hours. The modified infiltration swale outperformed the ALDOT swale with drawdown times increasing after each rainfall event varying from 4.17 hours to 10.9 hours. This increase in rainfall frequency to one day affected the modified infiltration swale more than the ALDOT swale; however, the modified swale still showed enhanced performance. The ALDOT times staying consistent, for the one-day dry period is explained in the underdrain influence section in 5.3.1.1.

Overall, despite the longer drawdown times under more frequent rainfall, it's important to note that both swales achieved complete drainage within 24 hours for all test scenarios. A key takeaway is the clear impact of rainfall frequency on drawdown times. When subjected to more frequent rainfall events, one-day dry period, both swales exhibited longer drawdown rates and reduced infiltration rates compared to the three-day day period. This is expected as the soil has less time to dry between rain events. Results also provide evidence that both swales recover infiltration performance for the three-day dry period which is the average historical time interval for rainfall events in central Alabama.

5.3.1.1 Underdrain Influence Discussion

Noteworthy mentions from Figure 5-2(b) and Figure 5-3(b), the one-day dry period tests, the ALDOT infiltration rates and drawdown times were consistent over the four days while the modified infiltration rates and drawdown times slowed after each test.

The distinct discharge patterns observed between the ALDOT and modified swales under identical underdrain conditions suggest potential differences in media performance. While the modified swale demonstrated consistent underdrain discharge after each test, the ALDOT swale exhibited no discharge. This disparity may be attributed to media infiltration rates and seepage into the native soil. It is predicted that ALDOT's low infiltration rates from the topsoil and sand layers into the gravel layer, coupled with the relatively low seepage rate of the native soils, did not allow infiltrated water to impound within the gravel layer to the level sufficient to flow into the underdrain. The addition of the geotextile fabric between the sand and the gravel layer is another obstacle that may cause slow infiltration into the gravel layer. Geotextiles clogging was found in the small-scale testing [50] and is backed by evidence from literature reporting clogging occurs most at the geotextile fabric layer [27] .

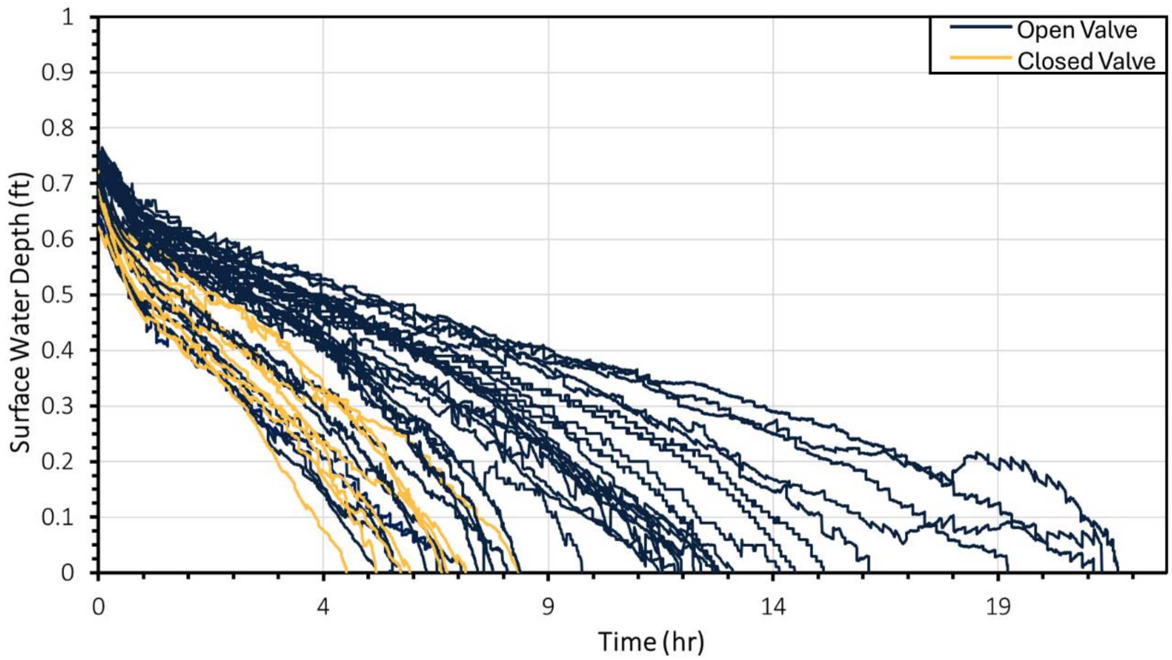
To further validate these findings, ongoing research at Auburn University is utilizing data collected from the large-scale infiltration swale experiments to develop predictive models. By simulating various hydrologic conditions, including known media infiltration rates, underdrain elevation, surface storage volumes, and native soil seepage rates (0.3 to 1.2 inches per hour), the models have demonstrated a similar underdrain flow behavior to that observed in the field. Specifically, the model predicted no flow through the underdrain pipe for the ALDOT swale, aligning with the experimental results. These models have the potential to further support and refine the conclusions drawn from this study. However, this modeling effort is ongoing and requires additional development and validation.

The following test series will be conducted with both valves on the underdrain closed. This will ensure the swales function as designed, allowing for a more accurate assessment of their infiltration rates and drawdown times under real-world conditions.

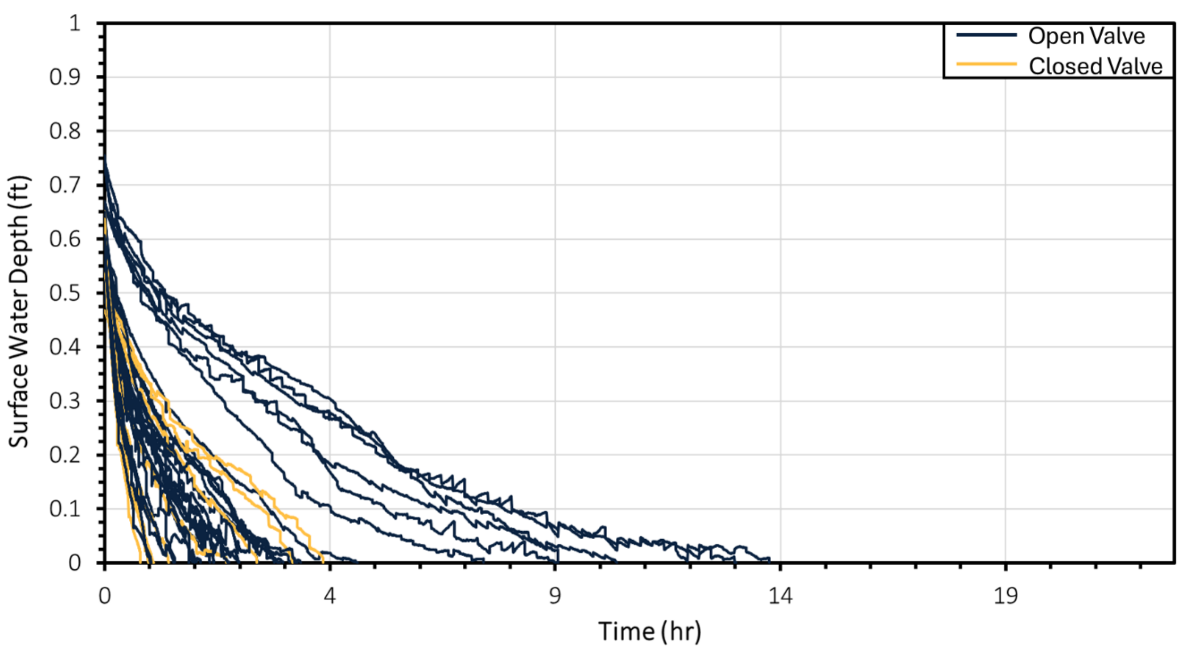
5.3.2 Open vs Closed Valve Underdrain

This section examines the impact of underdrain valve configuration (open versus closed) on infiltration swale performance. The analysis focuses on how the underdrain system influences infiltration rates and drawdown times without its active contribution (closed valve). Open underdrains likely promote faster drawdown and potentially higher infiltration rates by allowing infiltrated water to readily discharge. Conversely, closed underdrains may hinder these processes by restricting water discharge.

Figure 5-4(a) depicts the results from the ALDOT swale tests and Figure 5-4(b) shows the results from the modified swale tests. Yellow lines represent the valve was closed during the test and the blue line represent the valve was open during the test.



(a) ALDOT swale



(b) modified swale

Figure 5-4. Open vs. Closed Valve Underdrains Comparison

The ALDOT swale, Figure 5-4(a), for the open valve configuration (n=32), an average infiltration rate of 1.6 ft/day (0.49 m/day) and an average drawdown time of 12 hours were observed. Conversely, the closed valve configuration (n=8) demonstrated a higher average infiltration rate of 2.5 ft/day (0.76 m/day) and a shorter average drawdown time of 6.97 hours. A Welch's t-test revealed a statistically significant difference (p=0.0002279) between the two conditions, with the closed valve configuration exhibiting superior performance.

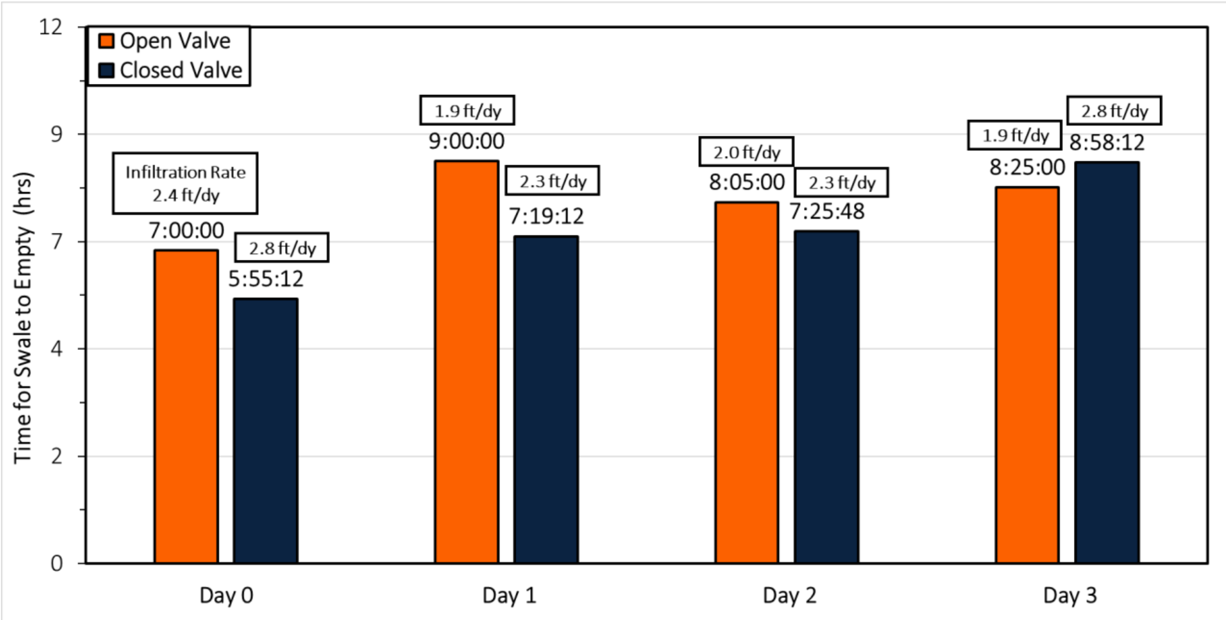
Contrary to the prediction, the open underdrain valve configuration did not demonstrate improved infiltration rates or drawdown times compared to the closed valve configuration. As previously mentioned, the ALDOT underdrain system exhibited no observable discharge during tests with an open valve. Consequently, the data collected from the ALDOT swale for open and closed valve tests cannot be definitively used to isolate the influence of the underdrain on the swale's performance. Also, most of the open valve tests were performed in the winter with colder temperatures. Further investigation of seasonal variation on the open valve and closed valve comparison is shown further below where the open and closed valve tests were performed in the same month in Figure 5-5.

The modified swale, Figure 5-4(b), exhibited significantly higher performance metrics compared to the ALDOT swale. Under the open valve condition (n=27), it achieved an average infiltration rate of 5.2 ft/day (1.6 m/day) and an average drawdown time of 5 hours. When the underdrain valve was closed (n=8), performance was further enhanced, with an average infiltration rate of 9.5 ft/day (2.9 m/day) and a reduced drawdown time of 2.3 hours. A Welch's t-test indicated a no statistical significance difference in infiltration rates between the open and closed valve conditions for the modified swale (p=0.01112). The sample average of open valve infiltration rates is smaller than the sample average of closed valve, but not small enough to be statistically significant.

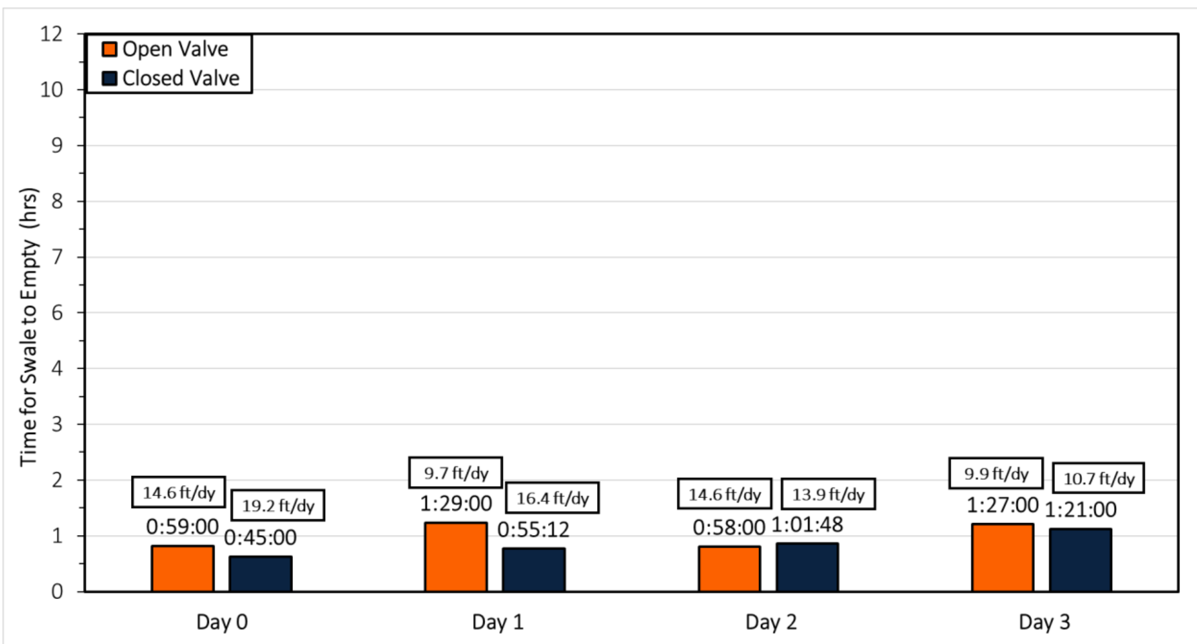
The results for the modified swale, Figure 5-4(b), deviate from the anticipated trend, similar to the findings from the ALDOT swale. The modified swale exhibited slower infiltration performance on average with an open underdrain valve compared to a closed valve. Unlike the ALDOT swale, the modified swale's underdrain system functioned as designed, with significant discharge observed during open valve tests.

A potential explanation for this unexpected outcome in the modified swale results may lie in the seasonal timing of the tests. As Figure 5-4(b) indicates, open valve tests were primarily conducted during the winter months (January to March) in Auburn, AL, when temperatures are lower. Lower winter temperatures can lead to increased water viscosity, and fluids with higher viscosity tend to infiltrate slower than those with lower viscosity. Conversely, the closed valve tests were conducted in April and June, coinciding with warmer temperatures and higher sunlight exposure. Warmer temperatures are associated with decreased water viscosity, potentially contributing to the faster infiltration observed in these closed valve tests. The next results below perform open and closed valve test within the same month to investigate any changes in performance of the valve within the same season.

Figure 5-5 shows a one-day dry period testing over four days for an open valve and closed valve. The closed valve test was performed from 6/7/2024 to 6/10/2024 and the open valve the week after from 6/13/2024 to 6/16/2024.



(a) ALDOT swale



(b) modified swale

Figure 5-5. Open vs. Closed Valve One-Day Dry Period Comparison

A closer examination of the open and closed valve test results for the ALDOT swale (Figure 5-5(a)) reveals a narrower range of performance between the two configurations compared to previous observations. The difference between the sample average of open valve and closed valve is not big enough to be statistically significant. The p-value equals 0.3502, this means that the chance of type I error, rejecting a correct H_0, is too high: 0.3502 (35.02%). While the closed valve again exhibited slightly faster performance with an average drawdown time of 7.4 hours and an average infiltration rate of 2.3 ft/day (0.7 m/day), these values are closer to those achieved by the open valve with average drawdown time of 8.1 hours and average infiltration rate of 2.1 ft/day (0.64 m/day). Notably, the open valve tests were conducted only two days following the completion of the closed valve tests. This temporal proximity raises the possibility that residual soil moisture from the closed valve tests may have influenced the performance of the open valve tests, potentially leading to slower infiltration rates in the latter case.

Overall, the findings suggest that the underdrain system in the ALDOT swale does not function as intended. The observed results likely represent a scenario where both configurations essentially performed under closed valve conditions due to the lack of observed discharge from the underdrain.

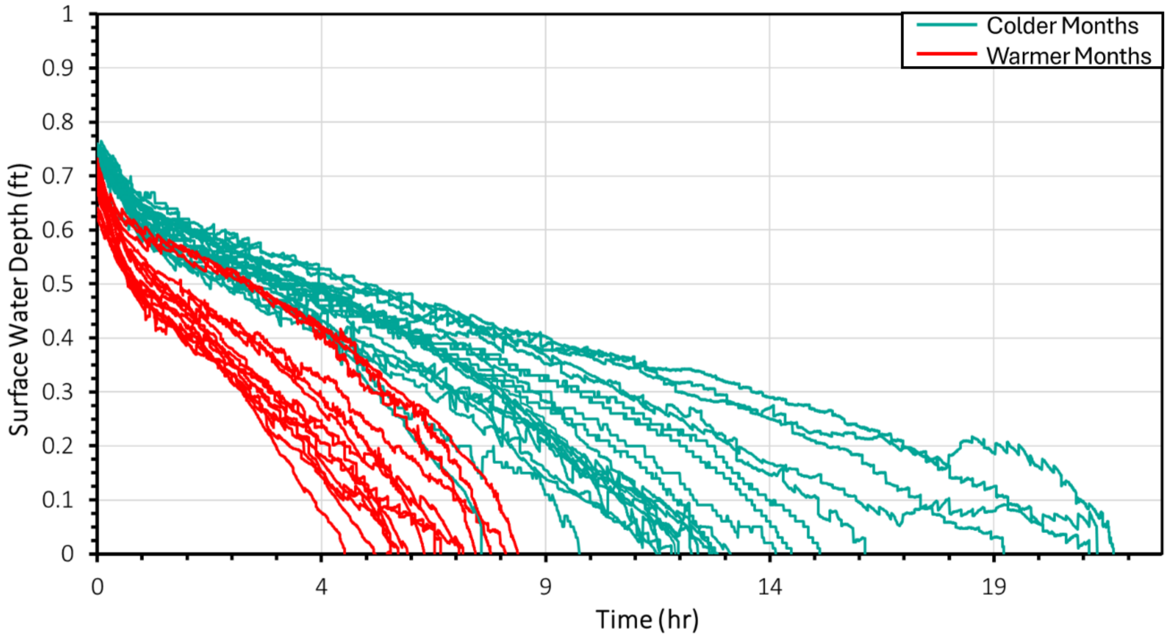
Observing Figure 5-5(b), the modified swale's valve comparison, similar to the ALDOT swale, the closed valve configuration exhibited marginally superior performance with an average drawdown time of 1 hour and an average infiltration rate of 15 ft/day (4.6 m/day) compared to the open valve (average drawdown time: 1.2 hours, average infiltration rate: 12.3 ft/day (3.7 m/day). The difference between the sample average of open valve and closed valve is not big enough to be statistically significant. The p-value equals 0.2749, this means that the chance of type I error, rejecting a correct H_0, is too high: 0.2749 (27.49%). The test statistic T equals -1.2014, which is in the 95% region of acceptance: [-2.4469: 2.4469]. As observed in the ALDOT swale tests, the open valve tests were conducted shortly after the completion of the closed valve tests (two days). This temporal proximity might have influenced the open valve results, with residual soil moisture from the preceding closed valve tests potentially leading to slightly slower infiltration rates.

However, unlike the ALDOT swale, the modified swale underdrain system appears to function as designed. This is evidenced by the observed decrease in infiltration rates and drawdown times following each test in the closed valve configuration, which aligns with the expected trend of reduced performance over subsequent tests due to increased soil moisture. Interestingly, the open valve tests do not exhibit a clear pattern, with Day 2 even showing slightly better performance compared to other days. This might be due to the two tests performed before Day 2, potentially leading to a temporary increase in effective porosity within the media.

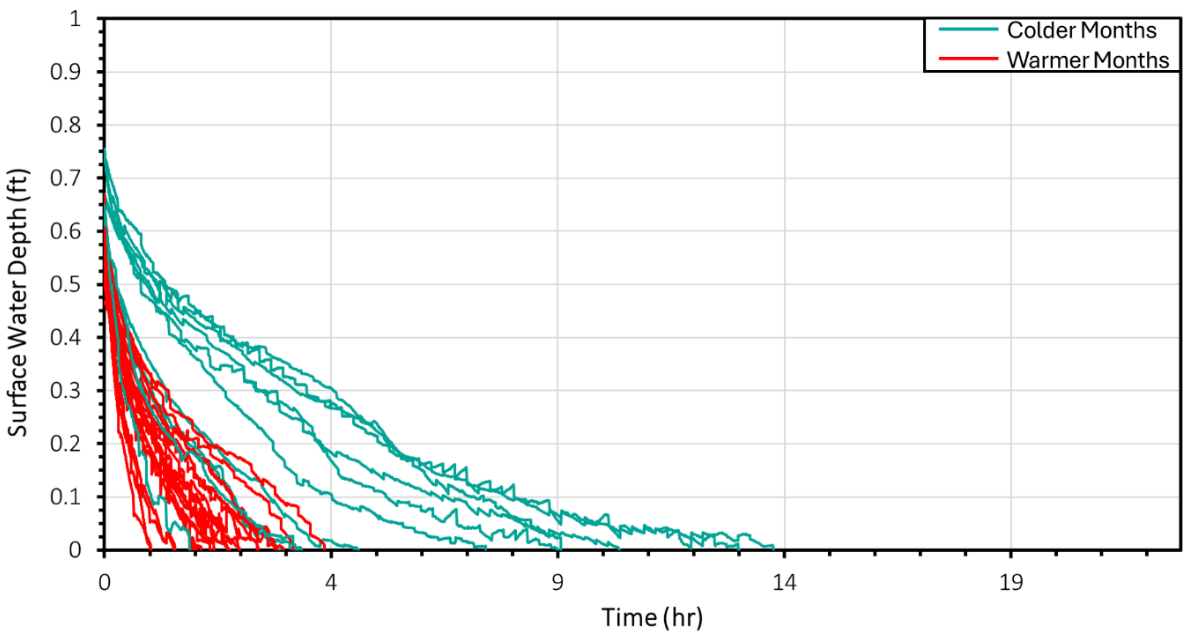
Notably, the performance metrics (infiltration rate and drawdown time) for both open and closed valve tests conducted in June are relatively similar. This suggests that the underdrain may not have had a significant impact on infiltration performance during this specific month. It is important to acknowledge the limitations of this study, particularly the lack of data from closed valve tests conducted in colder months. Future investigations exploring the influence of the modified swale's underdrain on performance could benefit from incorporating additional environmental factors such as water temperature, soil temperature at various depths, and sunlight exposure at the swale surface. Analyzing these additional parameters alongside infiltration data might provide more conclusive evidence regarding the influence of seasonal variations on infiltration performance in the modified swale.

5.3.3 Seasonal Variation

Figure 5-5 explores the potential influence of seasonal temperature variations on infiltration rates. To investigate this concept further, the infiltration data obtained from the existing ALDOT and modified infiltration swale open/closed valve tests (Figure 5-4) were utilized. In Figure 5-6, each data curve is linked to a specific calendar month, and the curves are categorized based on the corresponding season in Auburn, Alabama (colder vs. warmer). The teal-colored curves represent infiltration tests conducted during the colder months (late November to mid-March), while the red-colored curves depict tests performed during the warmer months (late March to June).



(a) ALDOT swale



(b) modified swale

Figure 5-6. Seasonal Variation Comparison

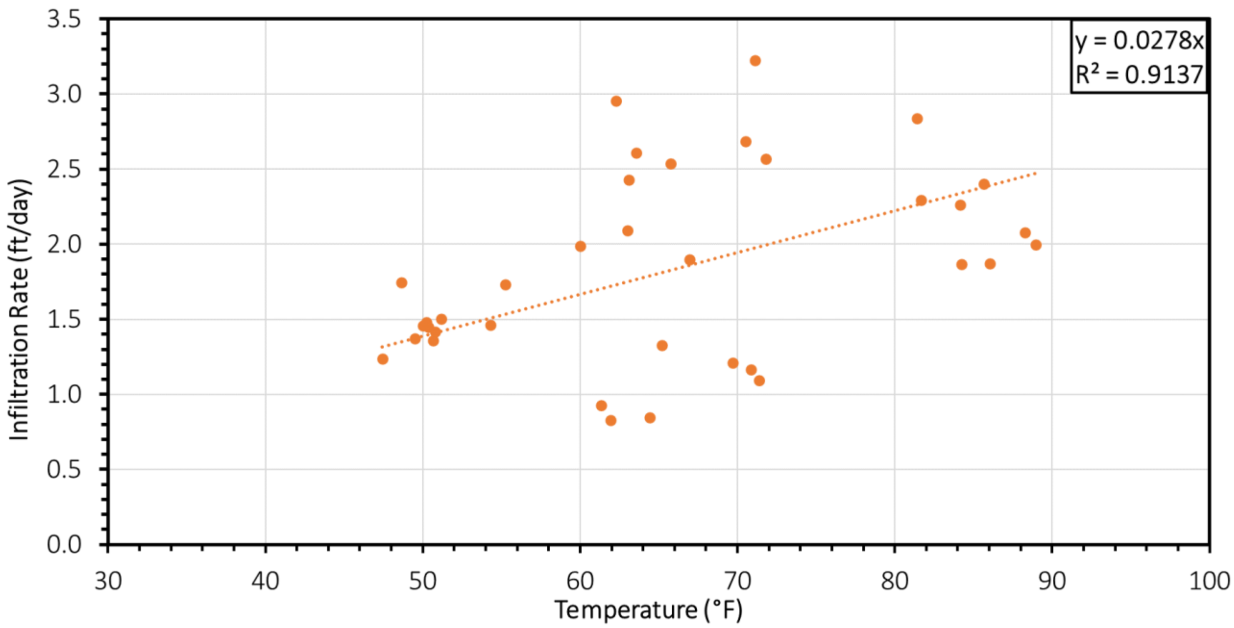
The ALDOT swale**,** Figure 5-6(a), exhibited seasonal variations in infiltration performance. During colder months (n=21), the average infiltration rate was 1.3 ft/day (0.39 m/day) with an average drawdown time of 14.4 hours. Conversely, warmer months (n=11) demonstrated improved performance, with an average infiltration rate of 2.2 ft/day (0.67 m/day) and a reduced drawdown time of 7.5 hours.

The modified swale, Figure 5-6(b), demonstrated a pronounced seasonal influence on its performance. During colder months (n=12), the swale exhibited an average infiltration rate of 2.7 ft/day (0.82 m/day) and an average drawdown time of 8.5 hours. In contrast, warmer months (n=15) saw a significant increase in performance, with an average infiltration rate of 7.2 ft/day (2.2 m/day) and a reduced drawdown time of 2.3 hours.

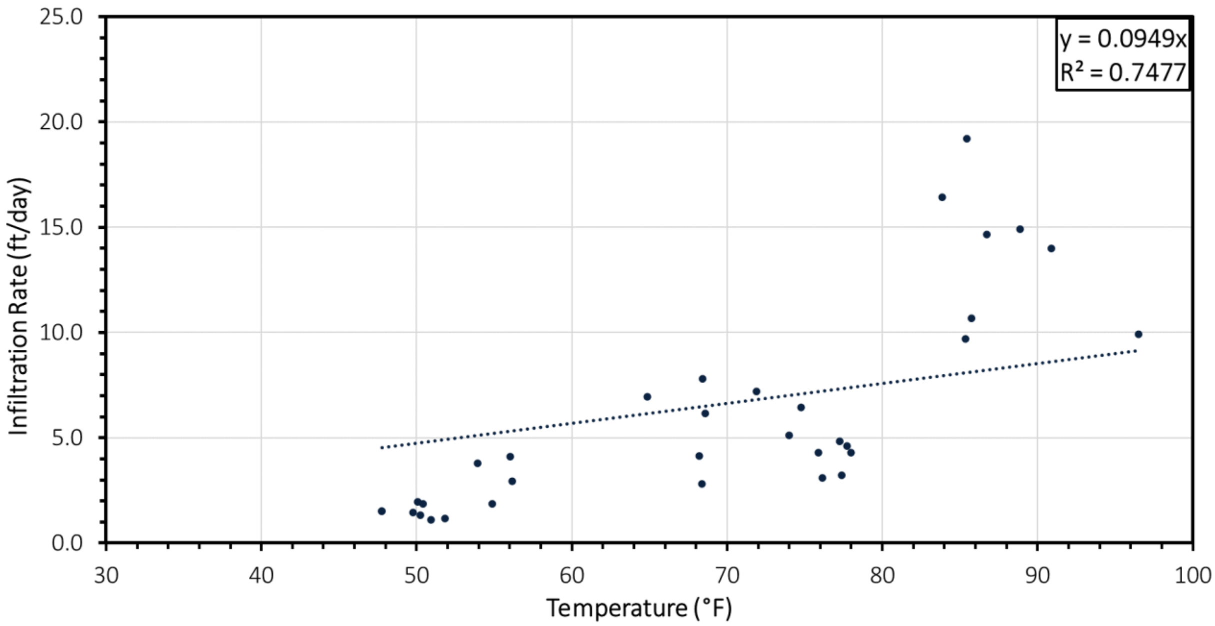
The results from Figure 5-6 reveal a distinct pattern: colder months are associated with slower infiltration rates and longer drawdown times for both swales. Conversely, warmer months exhibit enhanced infiltration rates and faster drawdown times. The ALDOT swale displayed nearly doubled infiltration rates and drawdown times in warmer months compared to colder months. Notably, the modified infiltration swale demonstrated a more dramatic seasonal effect. Warmer months yielded nearly four times faster infiltration rates and drawdown times in the modified swale compared to colder months. These findings suggest that while both swales exhibit improved performance in warmer temperatures, the modified infiltration swale design experiences a greater relative increase in infiltration capacity.

The impact of seasonal variations on swale performance is further evidenced by the drainage time data collected during one-day dry period tests. The modified swale exhibited a clear trend of decreasing drainage times throughout the year, with values ranging from 4.2 to 10.9 hours in January, 2 to 3.8 hours in May, and 0.9 to 1.5 hours in June. The overall pattern indicates faster drainage times from warmer months. To further evaluate seasonal variation, a linear regression was conducted for both swales showing the correlation of water temperature pumped into the swale versus the infiltration rate found when the test was completed. Observing

Figure 5-7 illustrates a stronger correlation between water temperature and infiltration rate for the ALDOT swale compared to the modified swale, as indicated by R-squared values of 0.91 and 0.75, respectively.



(a) all ALDOT swale tests



(b) all modified swale tests

Figure 5-7. Water Temperature vs Infiltration Rates

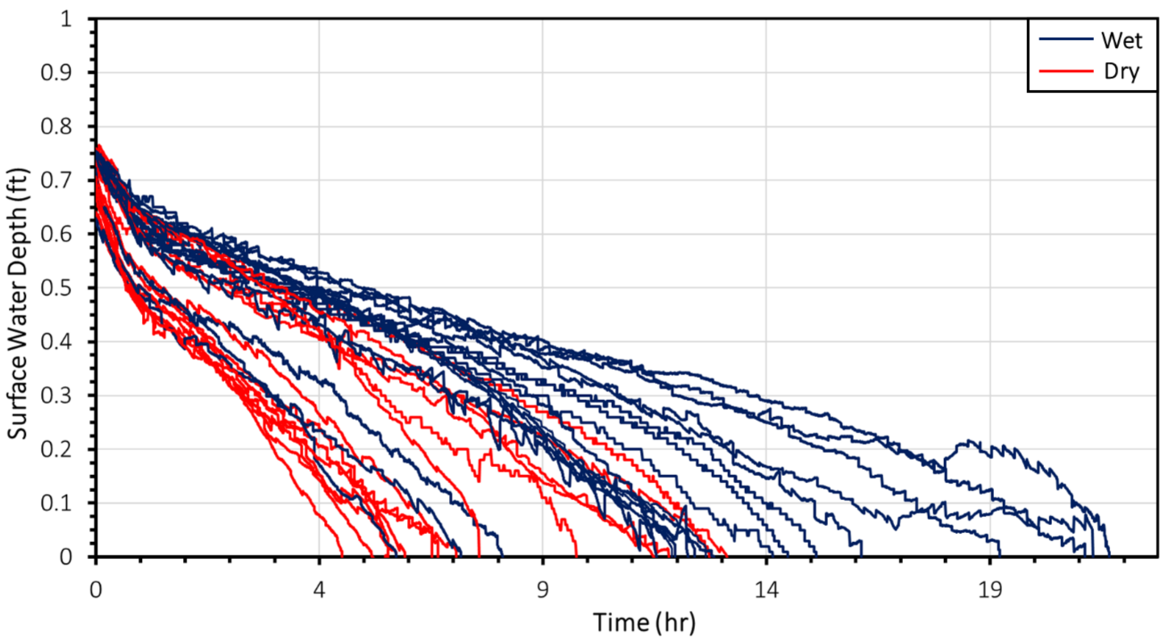
While the R-squared value for the modified swale indicates a moderate correlation, it nonetheless contributes to the overall understanding of seasonal influences on infiltration performance for both swale types. To further elucidate these seasonal patterns, continued data collection throughout the subsequent year is recommended. This would allow for a more robust evaluation of the observed seasonal trends in infiltration rates and drawdown times. By replicating the findings across multiple winter seasons, we can strengthen the confidence in the observed relationship between temperature and infiltration performance.

5.3.4 Wet versus Drier Underlying Soils

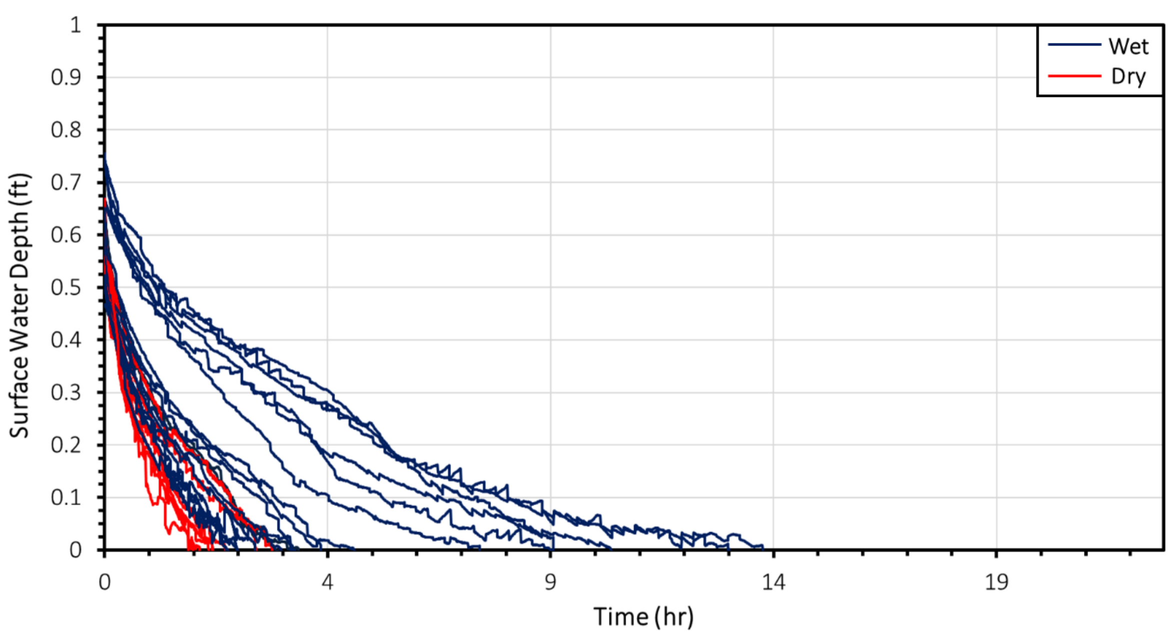
This section analyzes how initial moisture content (wet vs. drier) in the swale media and native soil affects infiltration performance under open valves. It compares pre-wetted scenarios to drier conditions. Notably, only the first day of each one-day dry period is considered drier, while subsequent days are considered wet. All three-day dry period tests are considered drier due to the longer interval between rain events.

Figure 5-8 presents red curves representing the drier test, while blue curves represent the wet test. Established research suggests a negative correlation between infiltration capacity and increased soil moisture [51]. This well-established principle is demonstrably evident in Figure 5-8(a). It reveals a clear trend where tests conducted under initial wetted conditions (presumably corresponding to later days within the testing period) exhibit demonstrably longer drawdown times compared to those with drier initial conditions (likely corresponding to the first day of each testing period). This observation aligns with the established principle, suggesting that soils with increased moisture exhibit a slower infiltration rate, resulting in extended drawdown times.

While Figure 5-8(a) aligns with established principles regarding the impact of initial moisture content, Figure 5-8(b) presents a contrasting observation. Notably, Figure 5-8(b) includes wet test data points with drawdown times comparable to those observed in drier tests. This seemingly contradicts the expected negative correlation between infiltration and soil moisture. This unexpected finding warrants further investigation to elucidate potential explanations. One possibility is that the modified swale's design or material composition may mitigate the influence of soil moisture to a greater extent compared to the ALDOT swale. Future research could explore the specific mechanisms by which the modified swale design might achieve this effect.



(a) ALDOT swale



(b) modified swale

Figure 5-8. Wet vs. Drier Soils

The ALDOT swale, Figure 5-8(a), exhibited varying performance under different soil moisture conditions. In wet soil conditions (n=20), the average infiltration rate was 1.4 ft/day (0.43 m/day) with an average drawdown time of 13.7 hours. Conversely, drier soil conditions (n=13) resulted in improved performance, with an average infiltration rate of 2.1 ft/day (0.64 m/day) and a reduced drawdown time of 8.72 hours. A two-sample t-test with pooled variance confirmed a statistically significant difference (p=0.0002872) between the two soil moisture conditions, with drier soils demonstrating superior infiltration characteristics.

Figure 5-8(a) provides compelling evidence regarding the influence of initial soil moisture conditions on the ALDOT swale's performance. The drier test data points cluster in the bottom left corner of the graph, signifying both faster drawdown times and higher infiltration rates. Conversely, the wet test data points tend to concentrate towards the upper right portion of the Figure 5-8(a), indicating slower drawdown times and lower infiltration rates. While outliers exist in both categories, the overall trend suggests a clear separation between the two datasets. The findings are further corroborated by numerical data, demonstrating a statistically significant difference between the average wet soil infiltration rate and the average drier soil infiltration rate. The sample average infiltration rate under wet soil conditions is demonstrably lower than the sample average under drier soil conditions. The data further indicates that drier soil conditions within the ALDOT swale lead to an average drawdown time reduction of approximately 5 hours and an infiltration rate increase of 1.5 times compared to wet soil conditions. These findings highlight the importance of managing soil moisture content to optimize the performance of the ALDOT swale.

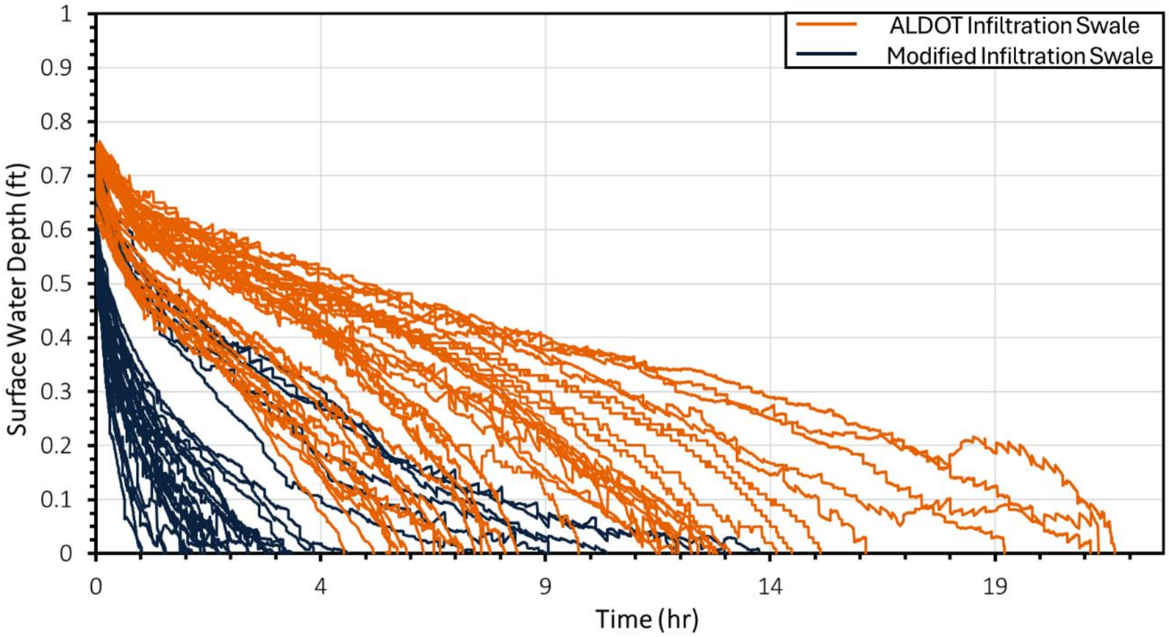
The modified swale, Figure 5-8(b), demonstrated a strong sensitivity to soil moisture conditions. Under wet soil conditions (n=13), the swale exhibited an average infiltration rate of 2.5 ft/day (0.76 m/day) with an average drawdown time of 8.1 hours. In contrast, drier soil conditions (n=11) led to significantly improved performance, with an average infiltration rate of 5.8 ft/day (1.8 m/day) and a reduced drawdown time of 2.7 hours. A two-sample t-test with pooled variance confirmed a highly statistically significant difference (p=0.000004164) between the two conditions, with drier soils facilitating superior infiltration capacity.

Figure 5-8(b) reveals interesting insights regarding the impact of initial soil moisture content on the modified swale's performance. Similarly the ALDOT swale, a trend is evident where drier soil test data points generally cluster towards the bottom left corner of the graph, indicating faster drawdown times and higher infiltration rates. However, a key distinction emerges when compared to the ALDOT swale. The modified swale exhibits a larger number of wet soil test data points that achieve drawdown times comparable to those observed for drier tests. However, the results still demonstrate a statistically significant difference between the average wet soil infiltration rates and the average drier soil infiltration rates. The sample average infiltration rate under wet soil conditions is demonstrably lower than the sample average under drier soil conditions. While drier tests on average demonstrate a performance advantage, with a reduction in drawdown time of approximately 4.6 hours and an infiltration rate increase of 2.1 times compared to wet tests, the modified swale seems to be less susceptible to the negative infiltration consequences from increased soil moisture compared to the ALDOT swale.

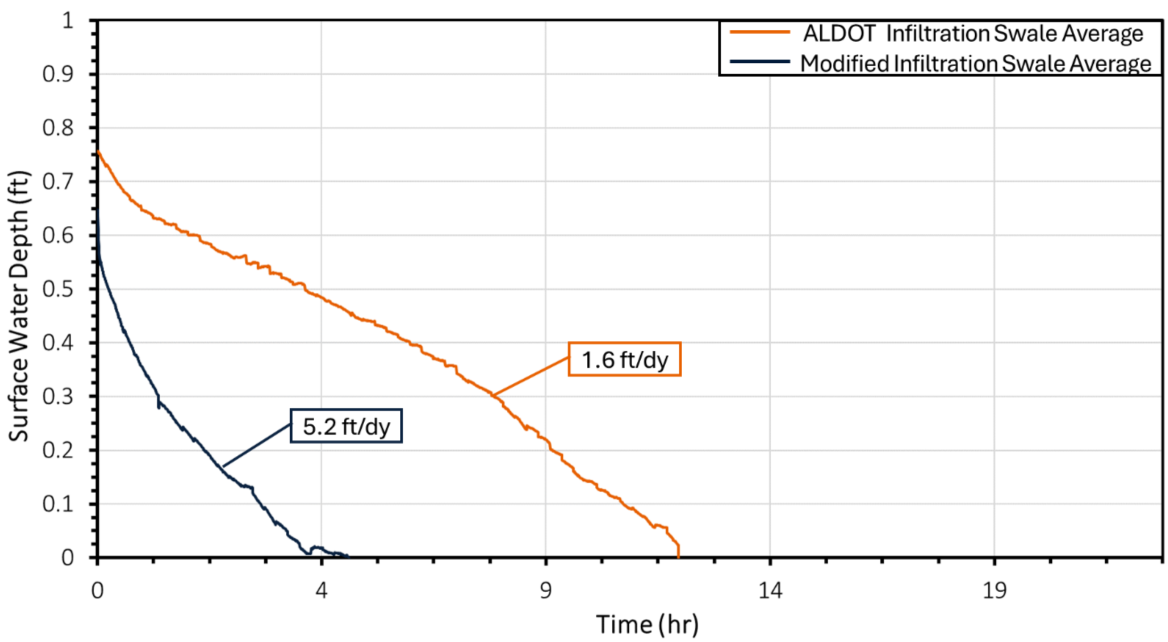
5.3.5 Overall Infiltration Performance Comparison

This section presents a comprehensive analysis of infiltration performance data collected from both the ALDOT swale and the modified swale. Given that the majority of infiltration tests were conducted with open underdrain valves, this analysis will exclusively focus on this configuration to maximize the sample size and ensure a more robust comparison between the ALDOT swale and the modified swale. By comparing the infiltration rates and drawdown times observed in these tests, we aim to establish a clear understanding of the relative performance of each swale design.

Figure 5-9(a) presents a comprehensive comparison of all infiltration tests conducted on both swales. The orange line represents the ALDOT swale test data, while the blue line corresponds to the modified swale test data. A clear distinction is evident between the two swales' performance profiles. Notably, the fastest drawdown times and infiltration rates observed for the ALDOT swale coincide with the slowest drawdown times and infiltration rates exhibited by the modified swale. This indicates an inverse relationship, where peak performance in one swale aligns with the lowest performance in the other. Furthermore, the Figure 5-9(a) demonstrates that the modified swale's fastest infiltration performance surpasses any recorded value for the ALDOT swale.



(a) ALDOT swale vs. modified swale tests



(b) average performances

Figure 5-9. ALDOT and Modified Swale Overall Infiltration Performance

Figure 5-9(b) shows the average drawdown time with its corresponding infiltration rate for both swales. The data reveals a significant difference in performance. The average of ALDOT's infiltration rates is less than the average of the modified's infiltration rates. In other words, the sample average of ALDOT is less than the sample average of the modified, and the difference is big enough to be statistically significant. The p-value equals 9.974e-7, this means that the chance of type I error (rejecting a correct H_0) is small: 9.974e-7 (0.0001%). The test statistic T equals -5.2936, which is not in the 95% region of acceptance: [-1.672: ∞].

The ALDOT swale exhibits an average drawdown time of approximately 12.25 hours, while the modified swale achieves an average drawdown time of 5.06 hours. This translates to an average drawdown time advantage of 7.19 hours for the modified swale. Similarly, the average infiltration rate for the ALDOT swale is approximately 1.6 ft/day (0.49 m/day), whereas the modified swale displays an average infiltration rate of 5.2 ft/day (1.6 m/day). This represents an improvement in infiltration rate of approximately 3.25 times for the modified swale compared to the ALDOT swale.

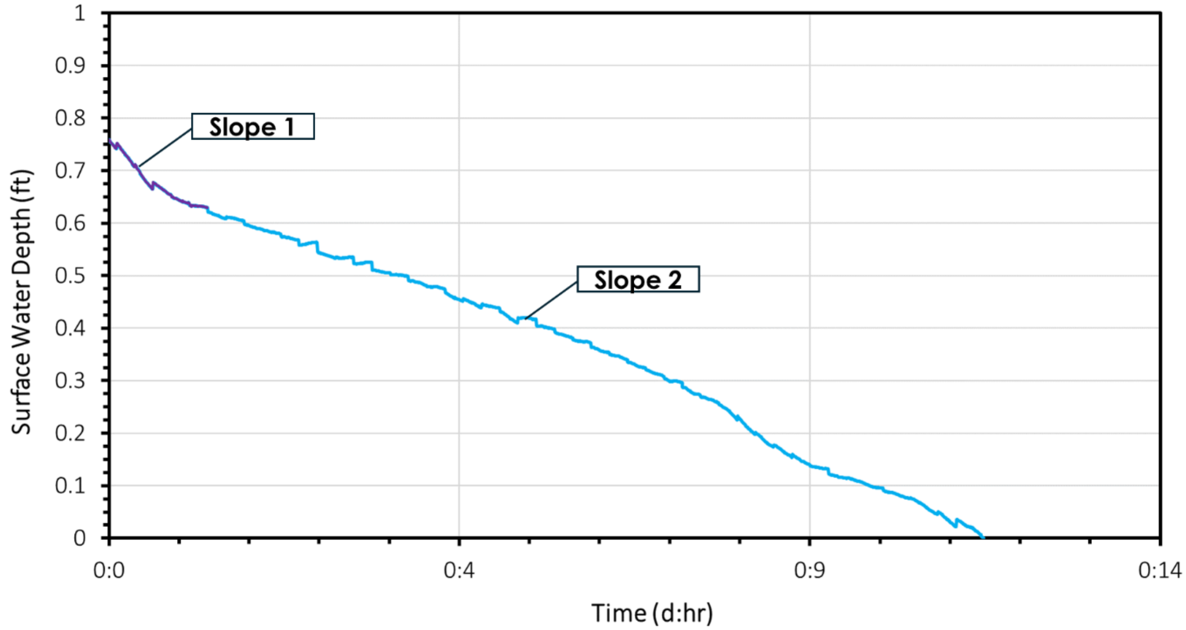
To quantify the water storage capacity of each swale, a topographic survey was conducted to determine the volume-depth relationship. This analysis enabled the calculation of potential water storage for both swales. The ALDOT and modified swales were capable of storing an average of 96.1 ft^3 (2.7 m^3) and 134 ft^3 (3.8 m^3) of water per day, respectively. These findings underscore the superior water storage capacity of the modified swale, contributing to its enhanced overall performance.

5.3.6 Infiltration Media Mechanics Analysis

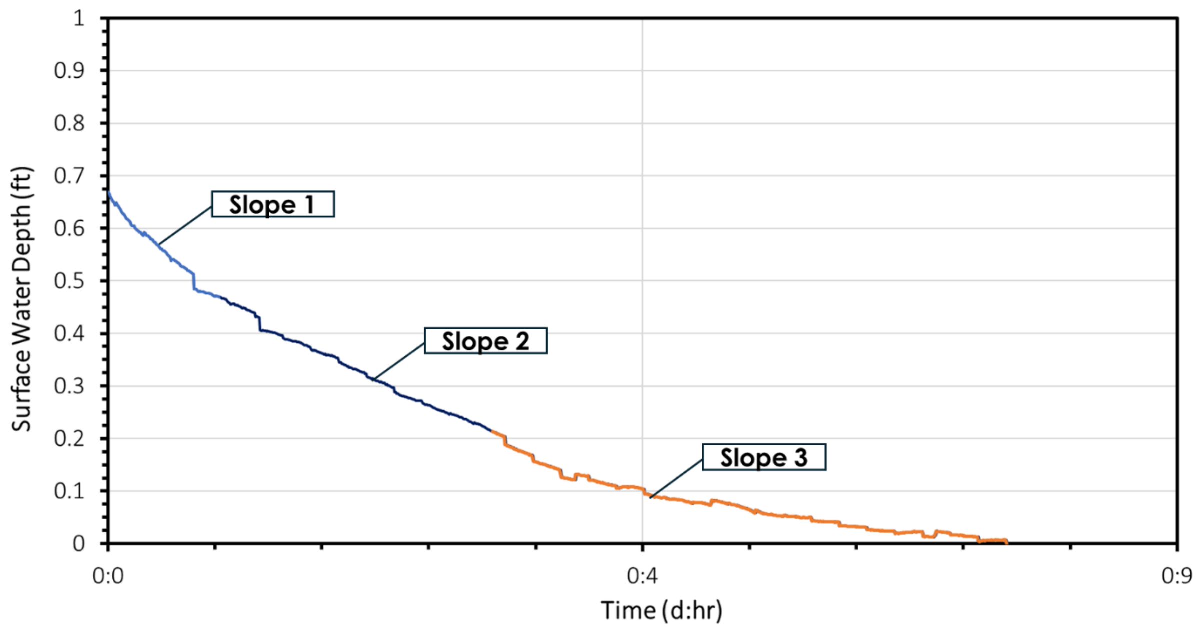
After analyzing the overall performance of both swales, the drawdown curves reveal distinct patterns for the two swale designs. The ALDOT swale exhibited a generally linear and concave downward trend, indicating a relatively consistent infiltration rate over time. In contrast, the modified swale displayed a steeper, concave upward curve, suggesting a more rapid infiltration rate during the initial stages of the drawdown process. These patterns, visualized in

Figure 5-9(a), highlight the differential infiltration behaviors of the two swale designs. This indicates that both swales are not made up of just one infiltration rate but multiple infiltration rates at different times.

Figure 5-10 presents representative drawdown curves for the ALDOT and modified swales. The ALDOT swale drawdown curve, Figure 5-10(a), exhibits two distinct phases: an initial rapid drawdown phase (slope 1) followed by a prolonged, slower phase (slope 2). Slope 1 has an infiltration rate of 2.4 ft/day (0.73 m/day) and slope 2 has an infiltration rate of 1.2 ft/day (0.37 m/day). The modified swale drawdown curve, Figure 5-10(b), demonstrates a pattern with three discernible phases: a rapid initial drawdown (slope 1), an intermediate phase (slope 2), and a final phase of slower drawdown (slope 3). Slope 1 has an infiltration rate of 19.1 ft/day (5.82 m/day), slope 2 is 6.4 ft/day (1.9 m/day), and slope 3 is 2.4 ft/day (0.73 m/day). These patterns suggest that infiltration rates decreased over time for both swale types, likely due to increasing soil saturation and decreasing hydraulic head.



(a) ALDOT swale



(b) modified swale

Figure 5-10. Swale Infiltration Rates Change Over Time

The calculation of average infiltration rates was based on initial and final depths over drainage time. This method assumes a linear drawdown, which is not representative of the observed data. While the ALDOT swale exhibited a more linear drawdown pattern, the modified swale demonstrated a nonlinear behavior with multiple drawdown phases. This highlights the dynamic nature of infiltration processes and shows that infiltration rates change over time and are not made up of a single infiltration rate.

5.3.7 Statistical Analysis

To identify the factors influencing infiltration rates, a MLR analysis was performed on both swale's dataset. The model incorporated soil moisture content, underdrain valve status (open or closed), and water temperature as independent variables. Results, Table 5-3, indicate that both water temperature (p-value = 1.23E-09) and soil moisture content (p-value = 1.57E-05) significantly influenced infiltration rates. Conversely, the underdrain valve status (open or closed) did not exhibit a statistically significant effect on infiltration performance. This finding may be attributed to the inherently high infiltration capacity of the modified swale media, which minimized the impact of underdrain conditions.

Table 5-3. Modified Swale MLR Results

Variables	Coefficients	p-value
Intercept	21.3	<0.001
Temperature Range (°F)	0.279	<0.001
Moisture Content (%)	-1.09	<0.001
Valve Condition	-0.202	0.861

[a]Comparison to effects of base at 95% confidence level and p-value <0.05

A MLR analysis was also performed on the ALDOT swale's dataset. Results, Table 5-4, indicate that both soil moisture content (p-value = 7.53E-07) and valve condition (p-value = 0.002) significantly influenced infiltration rates. Conversely, the water temperature did not exhibit a statistically significant effect on infiltration performance. This finding may be attributed to the inherently slower infiltration capacity of the modified swale media, which may have minimized the impact of water temperature.

Table 5-4. ALDOT Swale MLR Results

Variables	Coefficients	p-value
Intercept	3.83	<0.001
Temperature Range (°F)	0.005	0.351
Moisture Content (%)	-0.249	<0.001
Valve Condition	0.565	0.002

[a]Comparison to effects of base at 95% confidence level and p-value <0.05

5.3.8 Grass Swale vs Infiltration Swale Performance Comparison

A comparative analysis was conducted to assess the infiltration performance of infiltration swales relative to traditional grass swales. This analysis involved comparing the average infiltration rates reported in the literature for grass swales to those measured for the ALDOT and modified infiltration swales in this study. The infiltration rates reported for the five grass swale studies were as follows: 0.709 ft/day (0.22 m/day) [19], 1.57 ft/day (0.48 m/day) [2], 1.36 ft/day (0.41 m/day) [20], 5.6 ft/day (1.71 m/day) [21], and 1.40 ft/day (0.43 m/day) [22].

The ALDOT and modified infiltration swale designs exhibited infiltration capacities exceeding those observed in all the reviewed grass swale studies with the exception of study four. This study reported an average infiltration rate of 5.6 ft/day (1.7 m/day), which surpassed the performance of the ALDOT infiltration swale but yielded comparable results to the modified infiltration swale. Also, the ALDOT swale infiltration rate showed similar results to study two. Studies one, two, four, and five employed infiltrometer tests from smaller-scale methodologies, such as the modified Philip Dunne infiltrometer and the double ring infiltrometer. In contrast, Study three utilized a methodology more closely resembling the approach adopted in this thesis. This method involved completely filling the swales with water and recording the infiltration rate as the water drained. Consequently, focusing on studying three's infiltration rate average and comparing it to the infiltration swales tested in this study offers a more accurate comparison due to the shared methodological foundation. Study three reported an average infiltration rate of 1.36 ft/day (0.42 m/day), which aligns closely with the performance of the ALDOT swale. However, the modified swale's significantly higher average of 5.6 ft/day surpasses the infiltration rate observed in study three.

These findings suggest that infiltration swales, particularly those incorporating the modified media design, may offer a superior solution for stormwater runoff management. In comparison to traditional grass swales, which primarily function to capture smaller storm events, both the ALDOT and, more significantly, the modified infiltration swales demonstrate the potential to infiltrate a greater volume of runoff, even from larger storm events.

5.4 SURFACE STORAGE INFLUENCE

The observed disparity in drawdown times and infiltration rates between the ALDOT and modified swales can likely be attributed, at least in part, to a difference in water storage capacity within zone two. Table 5-5(a) shows the data collected for the surface storage volume of the modified infiltration swale zone 2 and Table 5-5(b) for the ALDOT infiltration swale zone 2.

Table 5-5. Surface Storage Volumes of Infiltration Swales

Zone 2			
#	Depth (in)	Depth (ft)	Volume (ft^3)
1	21.5	1.79	4.9
2	21.5	1.79	4.9
3	21.5	1.79	4.9
4	21.5	1.79	4.9
5	21.5	1.79	4.9
6	10	0.83	2.2
	Volume (ft^3) =		26.7

(a) modified infiltration swale surface storage volume

Zone 2			
#	Depth (in)	Depth (ft)	Volume (ft^3)
1	21.5	1.79	4.9
2	21.5	1.79	4.9
3	21.5	1.79	4.9
4	21.5	1.79	4.9
5	21.5	1.79	4.9
6	21.5	1.79	4.9
7	4	0.33	0.8
	Volume (ft^3) =		30.2

(b) ALDOT infiltration swale surface storage volume

The total surface storage for the modified infiltration swale is about 49.3 ft^3 (1.40 m^3) and 57.2 ft^3 (1.62 m^3) for the ALDOT infiltration swale. However, data collection for infiltration and drawdown measurements was exclusively conducted within zone 2, which is what Table 5-5 represents. The ALDOT swale zone two possesses an increased storage capacity of 3.5 ft^3 (0.08 m^3) compared to the modified swale. The percentage difference between the zone's two surface volumes is about 10.6%.

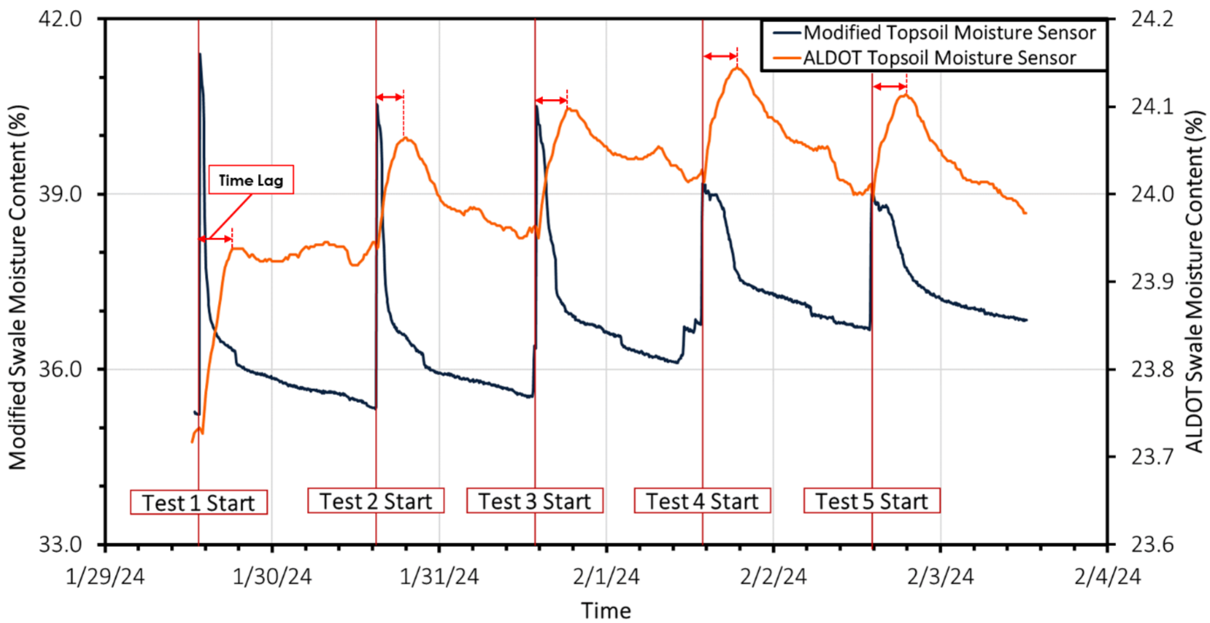
Ideally, the surface storage volumes of the infiltration swales would prefer minimal variation. However, on-site slope constraints encountered during construction limited the ability to create exact replicas. Nonetheless, the measured surface storage volumes demonstrate acceptable. This highlights the inherent variability encountered during real-world construction projects, where achieving perfect uniformity in infiltration swales can be difficult.

5.5 MOISTURE CONTENT SENSOR EVALUATION

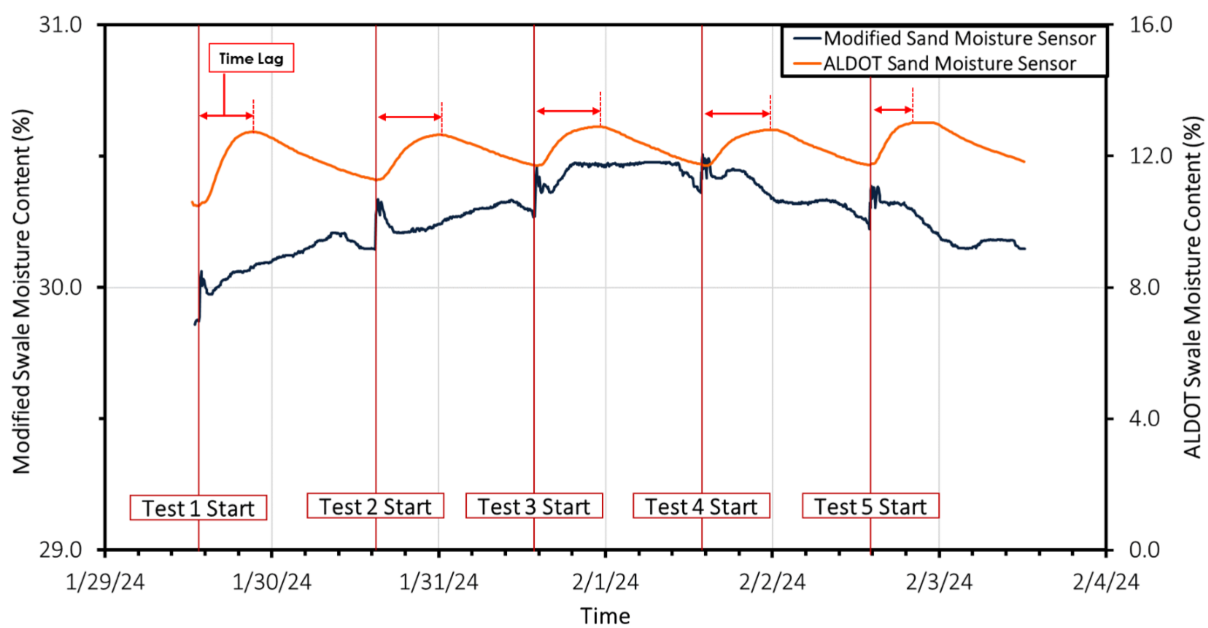
This section analyzes the data collected from the moisture content sensors installed within both infiltration swales. While the sensor responses confirm activation upon water introduction and subsequent infiltration into the soil layers, the absolute moisture content values appear unreliable. Inconsistencies are observed in the numeric data between sensors positioned within the same soil media which potentially represents that infiltrated water was moving through the media through paths of least resistance which could be at various locations in the media that did not intercept where the sensors were located. This is evidenced by the need for separate y-axes in Figure 5-11 to visualize the responses from the ALDOT and modified swale sensors. If the sensors shared the same y-axis, it would be hard to visualize the response in the sensors from infiltrated water since the moisture content sensors percentage fluctuations are at completely different ranges and scales.

5.5.1 One-Day Dry Period

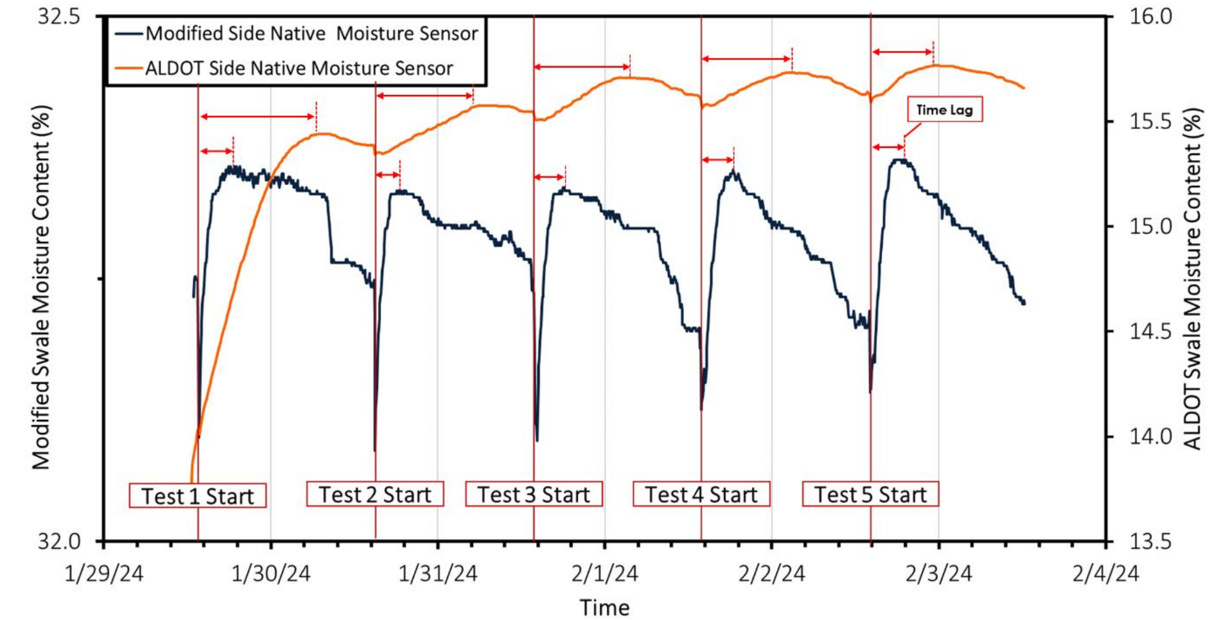
Figure 5-11 presents the recorded volumetric moisture content (%) for the ALDOT swale and modified swale during one-day dry period tests. The data from these moisture content sensors provides valuable insights into the temporal dynamics of water infiltration within the swale media and native soils at various depths. The figure depicts the moisture content profiles for both swales, segmented by sensor location: topsoil, sand layer, #57 stone layer, side native soil, and deep native soil. The specific depths and placements of each sensor were detailed in Chapter 4. The vertical red lines on the time axis indicate the start of each test. The peaks observed in Figure 5-11 represent the maximum volume of water detected by the sensor. The time difference between the vertical red line and the corresponding peak on the sensor data curve represents the time lag for that sensor. In essence, the time lag signifies the duration it takes for water to infiltrate and fully saturate the sensor. This time lag analysis can provide valuable insights into the amount of time it takes water to infiltrate to specific layers. The time lag is represented as double sided red arrows in the Figure 5-11.



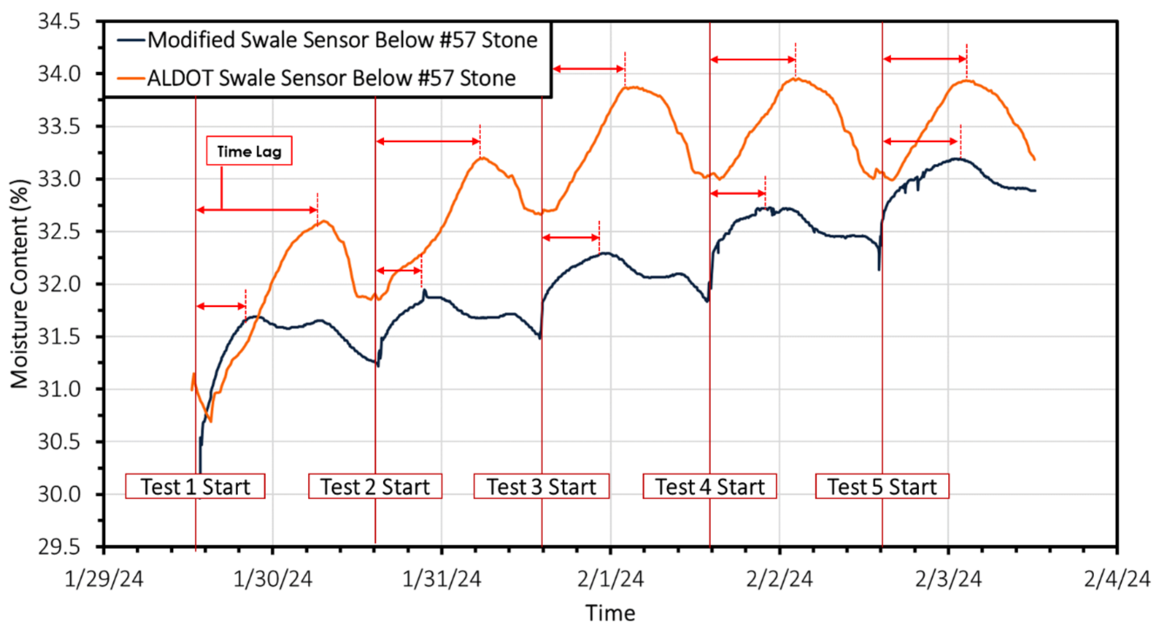
(a) topsoil layer moisture content



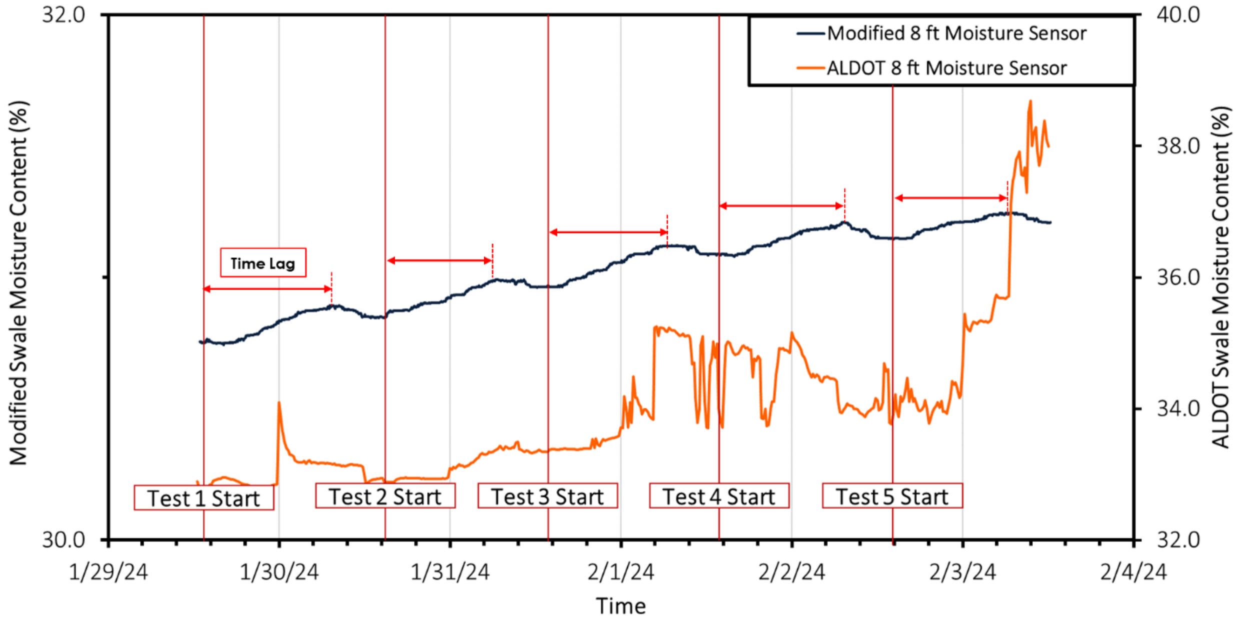
(b) sand layer moisture content



(c) side native soil moisture content



(d) sensor below #57 stone



(e) 8 ft deep layer

Figure 5-11. Moisture Contents Between ALDOT and Modified Swale Media Layers

From Figure 5-11, moisture content sensors were installed at various depths to monitor water movement in the ALDOT swale. A sensor placed at a depth of 6 inches (15.2 cm) within the topsoil registered a water travel time of 4.75 hours. At a depth of 24 inches (60.9 cm) within the sand layer, the travel time increased to 8.6 hours. Within the native soil, a sensor located at a depth of 4.5 feet (1.4 meters) showed travel time of 14.4 hours. The sensors placed below the #57 stone layer at a depth of 5 feet (1.5 meters) recorded a travel time of 14.6 hours. The deepest sensor, situated at 8 feet (2.4 meters), did not record a measurable water arrival time.

From Figure 5-11, the modified swale, demonstrated faster travel times at each sensor's location. A sensor at a depth of 3 inches (7.6 cm) within the topsoil recorded a travel time of just 0.2 hours. At a depth of 11 inches (27.9 cm) within the sand layer, the travel time increased to 0.68 hours. Within the native soil, a sensor located at a depth of 4.5 feet (1.4 meters) measured a travel time of 4.42 hours. The sensors placed below the #57 stone layer at a depth of 5 feet

(1.5 meters) recorded a travel time of 9.13 hours. The deepest sensor at 8 feet (2.4 meters) registered a travel time of 17.67 hours.

The analysis of time lag data for each sensor layer verifies the findings from the infiltration rates and drawdown section, supporting the notion of higher infiltration efficiency and overall performance in the modified swale compared to the ALDOT swale. Examining each layer individually, the modified swale's topsoil sensor recorded the maximum infiltrated water volume 4.55 hours earlier than the ALDOT swale sensor. Similarly, the modified swale's sand layer sensor detected peak infiltration 7.92 hours ahead of the corresponding sensor in the ALDOT swale. The topsoil and sand moisture content sensors in the modified swale exhibit a rapid response to infiltrated water. This is evident from the peak readings in moisture content data, which appear to coincide with (or immediately follow) the red vertical lines representing the start time of each test. The side native soil and #57 stone layer sensors in the modified swale also exhibited earlier responses, reaching peak infiltration volumes of 9.98 and 5.47 hours sooner, respectively, compared to their counterparts in the ALDOT swale. However, data from the 8 ft (2.24 m) deep sensor are excluded from the comparative analysis due to malfunctioning in the ALDOT swale at that location, rendering infiltration times for that layer unreliable.

It's important to note that due to design modifications in the modified swale, the depths of the topsoil and sand layer sensors differ between the two swales, despite being installed centrally within their respective layers. This difference arises from the reduced media depth in the modified swale design. Consequently, direct comparisons of sensor data for these two layers are not feasible.

In contrast, the side native soil and #57 stone layer sensors in both swales occupy identical locations and depths. Examining Figure 5-11(d), the #57 stone layer which shares the same y-axis, shows a consistent pattern that emerges in the modified swale's moisture content profiles following each test. These profiles exhibit a steeper concave shape compared to the milder concave shape observed in the ALDOT swale profiles. This steeper initial rise in moisture content for the modified swale suggests that infiltrated water transits pass the sensors more rapidly compared to the ALDOT swale. The gentler slope in the ALDOT profiles indicates a slower movement of infiltrated water through the media.

The #57 stone in both swales are the best sensors for comparison since they are at the same depth, location, and are at the bottom of the media. Figure 5-12 reflects the same tests from Figure 5-11(d) of the #57 stone sensors in both swales; however, Figure 5-12 shows the time lag between the start of the one-day dry period test to the time the sensor recorded the first initial rise in moisture content. This time presented represents the time it takes the #57 stone sensor to sense the first of the infiltrated water that passed through all the different layers of the media and made it to the bottom of the media.

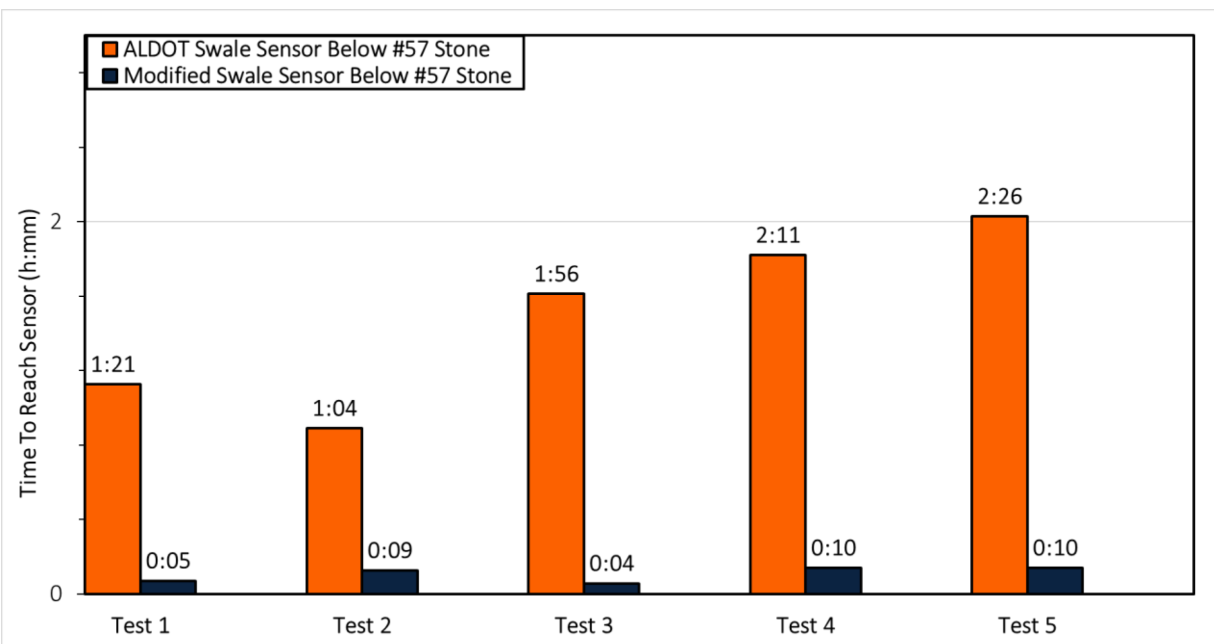


Figure 5-12. Sensor Below #57 Stone Times

Figure 5-12 shows the modified #57 stone sensor in blue and the ALDOT sensor in orange. The modified infiltration swale shows times averaging 0.13 hours while ALDOT swale shows an average time of 1.8 hours. These findings provide evidence that the modified swale media demonstrates superior infiltration efficiency. Notably, despite having a reduced surface storage capacity (3.5 ft^3 or 0.08 m^3 less than the ALDOT swale), the modified swale allows infiltrated water to pass through the media and reach the bottom of the #57 stone layer more quickly than the ALDOT swale by 1.67 hours faster. The sample average of the modified swale is less than the sample average of the ALDOT swale, and the difference is big enough to be statistically significant. The p-value equals 0.0000941, this means that the chance of type I error (rejecting a correct H_0) is small: 0.0000941 (0.0094%). This suggests that the modified swale design promotes faster infiltration despite a smaller storage volume. Another interesting pattern shown in Figure 5-12 is that the ALDOT sensor time increases after each test, except test one, which represents that the underdrain for the ALDOT swale was not functioning as designed since both swales were open valved.

5.5.1.1 Moisture Content Sensor Limitations

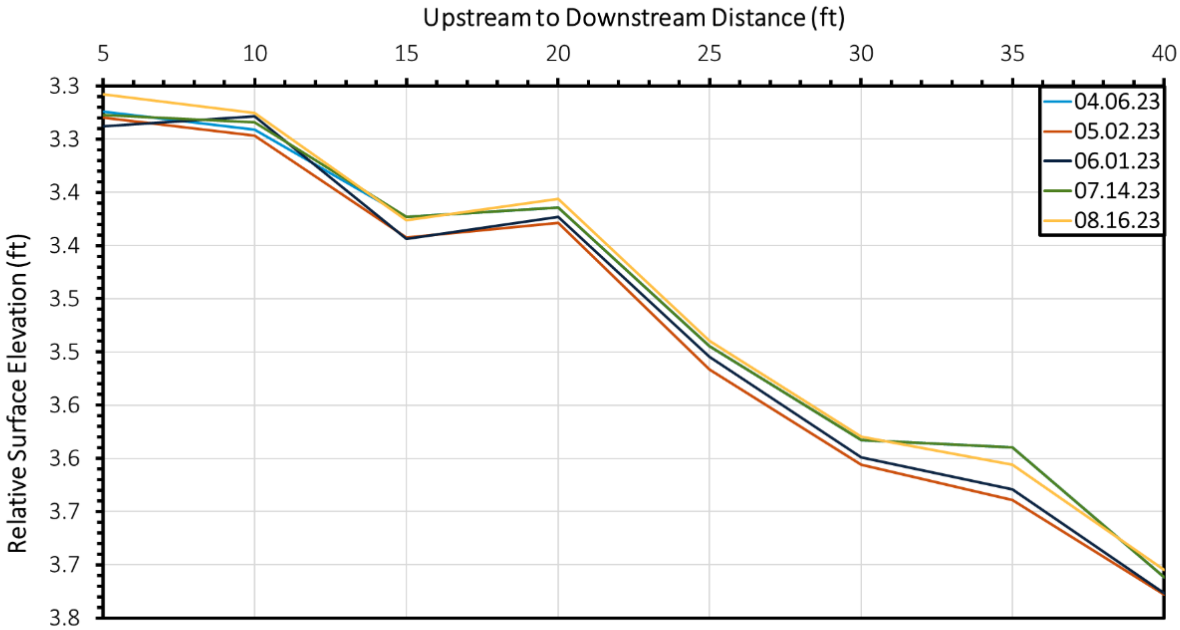
The observed discrepancies in the numerical data between sensors positioned within the same soil media warrant consideration of potential spatial variability in infiltration patterns. Infiltrating water may preferentially exploit pathways of least resistance within the media. These flow paths could deviate from the specific locations where the sensors are installed. Consequently, sensors might not always capture the peak infiltration events at a particular depth, leading to inconsistencies in the recorded moisture content values. The moisture content sensors seemed to be unreliable and further investigation with more sensors installed within a cross-section and throughout the length of the swale's media is needed for confirmation of results.

5.6 SETTLEMENT EVALUATION

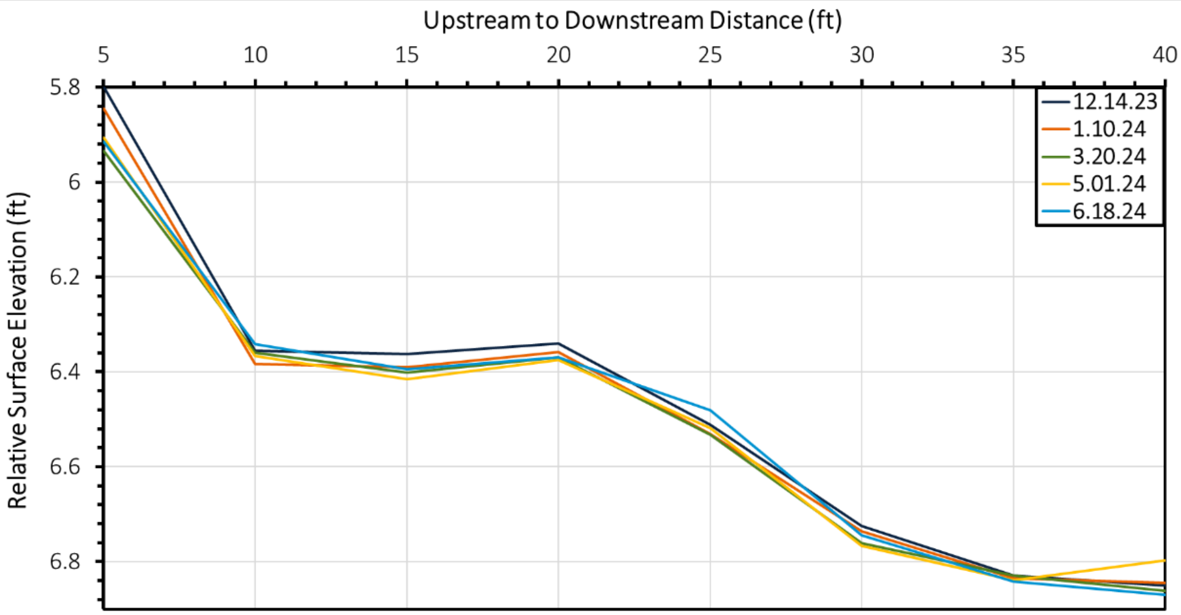
Settlement testing was conducted on both the ALDOT and modified swales to assess potential surface elevation changes following media installation and sod stabilization. Monitoring settlement is crucial as media compaction can decrease infiltration capacity. Figure 5-13 presents the settlement data collected throughout the first year after installation for each swale (ALDOT installed in 2023, modified swale installed in 2024). The x-axis represents the longitudinal distance along the swale bed in 5 ft (1.5 m) increments, moving from upstream (left) to downstream (right). Each colored line on Figure 5-13 depicts the settlement measurements for a specific month.

The results from both swales consistently show negligible settlement across the entire swale surface at each 5 ft increment throughout the monitoring period. All data points for each month in both swales cluster closely around a common baseline, indicating minimal changes in surface elevation. This finding suggests that neither swale experienced significant settlement within the first six months following installation.

While this initial data is promising, further monitoring is recommended to determine if settlement might occur at a later stage. Nonetheless, the current results indicate that both the ALDOT and modified swale designs effectively maintained their initial surface elevations during the first six months after construction.



(a) ALDOT swale settlement



(b) modified swale settlement

Figure 5-13. Swale Settlement Comparison

5.7 SUMMARY

The native soil lab and field infiltration tests classified the native soil as silty loam based on grain size analysis and field infiltration rates of 0.28 in/hr. (0.7 cm/hr.) to confirm a HSG B soil.

Evaluating the infiltration performance for the one-day and the three-day dry periods, the modified swale consistently outperformed the ALDOT swale in infiltration rates and drawdown times under different conditions. Increased rainfall frequency (shorter dry period) negatively impacted both swales, reducing infiltration rates and increasing drawdown times. The modified swale's drawdown times were more affected by increased frequency compared to the ALDOT swale. Despite longer drawdown times under frequent rainfall, both swales fully drained within 24 hours for all tests.

Evaluating the infiltration performance for the open and closed valves, the closed valve configuration exhibited slightly better performance (faster drawdown and higher infiltration rates) compared to the open valve in both swales. Seasonal variations potentially influenced performance. Open valve tests conducted in colder months (winter) showed slower infiltration compared to closed valve tests in warmer months (April, June). This could be due to temperature affecting water viscosity. More correlation needed to confirm relationship. Closed and open valve tests conducted in June showed similar performance, suggesting the underdrain may not have had a significant impact during the same season; however, underdrains could have a higher effect on performance in colder months.

Evaluating the infiltration performance for seasonal variation, colder months showed slower infiltration and longer drawdown times for both infiltration swales (ALDOT and modified). Warmer months, conversely, saw increased infiltration rates and faster drawdown times.

Evaluating the infiltration performance for wet and drier soils, both swales exhibited slower drawdown times and lower infiltration rates under wet soil initial conditions compared to drier conditions. The modified swale appeared less susceptible to the negative effects of soil moisture on infiltration compared to the ALDOT swale. This suggests the modified swale's design or material composition may mitigate moisture influence.

Evaluating the overall infiltration performance, the average infiltration rate for the ALDOT swale is approximately 1.6 ft/day (0.49 m/day), whereas the modified swale displays an average infiltration rate of 5.2 ft/day (1.6 m/day). This represents an improvement in infiltration rate of approximately 3.25 times for the modified swale compared to the ALDOT swale.

Evaluating the moisture content sensors, sensor data confirmed water infiltration, but absolute moisture content values were unreliable. This is likely because water preferentially flowed through paths of least resistance, potentially missing some sensors. The time it took for water to reach sensors (time lag) was consistently lower for the modified swale compared to the ALDOT swale at all depths except the deepest layer (unreliable data due to sensor malfunction in the ALDOT swale). The #57 stone layer sensor data (at the same depth in both swales) revealed a steeper initial rise in moisture content for the modified swale, suggesting faster water movement. Despite having a smaller surface storage capacity, the modified swale allowed water to reach the bottom #57 stone layer sensor significantly faster (1.7 hours) compared to the ALDOT swale. This suggests the modified swale design promotes faster infiltration.

Evaluating the settlement of both swales, neither swale experienced significant settlement within the first six months following installation.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 INTRODUCTION

Urbanization and population growth drive the expansion of highway and road networks. This infrastructure development results in an increase in impervious surface cover compared to natural pre-development conditions. This rise in impervious cover is a well-documented factor contributing to increased peak flow rates and total volume of stormwater runoff. Reduced infiltration capacity compared to pre-development conditions is the primary cause.

The increased peak flow and volume of stormwater runoff pose environmental threats. Pollutants from roadways are transported to sensitive habitats and drinking water sources, while flooding events become more frequent and intense, damaging infrastructure and jeopardizing public safety. Urban streams suffer due to habitat degradation and altered flow regimes, while excess nutrients and contaminants contribute to water quality decline, harming aquatic life. Local groundwater recharge diminishes, and erosion of slopes and streambanks leads to infrastructure damage and habitat loss.

To address these stormwater runoff problems, municipalities and other entities employ SCMs to manage runoff, protect water quality, and mitigate the impact of urbanization on natural hydrological processes. ALDOT utilizes different types of SCMs to comply with MS4 permits and SWMPs. This thesis focuses on ALDOT's infiltration-based SCM called infiltration swales. Infiltration swales mimic pre-development hydrology by mitigating the increase in peak flow rates and runoff volumes generated by impervious surfaces due to their high infiltration capacity achieved over a linear surface area. This makes them an attractive solution for stormwater runoff management.

While ALDOT employs infiltration swales to comply with MS4 regulations and promote LID and GI principles, research suggests that some existing swales in Alabama may not be functioning optimally in terms of infiltration capacity. To address this challenge, ALDOT has partnered with Auburn University to conduct research on infiltration swale design with the aim of improving overall stormwater management performance, particularly by enhancing infiltration capabilities.

6.2 LITERATURE REVIEW

The literature review delves into the mechanics of infiltration swales, explaining their components and their role in infiltration. It identifies three key factors that can negatively impact long-term performance: compaction, sedimentation, and inadequate pre-construction soil testing. Recognizing these threats allows designers and stakeholders to implement preventative measures and ensure the long-term effectiveness of infiltration-based SCMs.

Furthermore, the review investigates various infiltration-based SCMs employed by Departments of Transportation (DOTs) across the country. This investigation explores different types of SCMs, their design criteria for optimal performance and longevity, along with media design specifications and dimensions.

Drawing upon the findings of this investigation, the review concludes with recommendations for key design criteria to ensure effective long-term performance. These recommendations include: a longitudinal slope of 0.5% to 1% for optimal infiltration, a drainage area of 5 acres (2.02 ha) or less, surrounding native soils classified as Hydrologic Soil Group (HSG) A or B for better suitability, a drawdown time of 24 hours (although 48 hours is acceptable), a minimum groundwater table depth of 3 ft (0.9 m) below the SCM (with greater depth being preferable), and the incorporation of check dams to enhance infiltration and minimize erosion impacts.

6.3 SWALE DESIGNS AND CONSTRUCTION

This chapter outlined the existing ALDOT infiltration swale design and presents a detailed comparison with a modified design, discussing the rationale behind the modifications based on small-scale testing findings. Media dimensions and materials can be found in this chapter. Additionally, the chapter delves into the meticulous construction process for the field-scale infiltration swales, encompassing site selection, layout, excavation, material selection and placement, sensor installation, grading, sodding, and introductory system installation. This critical construction phase serves as the foundation for subsequent performance evaluation, ensuring a robust platform for data collection and analysis.

6.4 FIELD-SCALE TESTING METHODOLOGY

This chapter detailed the comprehensive evaluation methodologies employed to assess the performance of the field-scale infiltration swales. These methodologies, encompassing calibrations, experiments, and instrumentation, directly addressed the infiltration swale results presented in Chapter 5. Specific topics included the water introduction system, surface and underdrain weir box calibrations, levelogger water induction devices, infiltration rate and drawdown methodology, soil moisture content sensor methodology, and settlement methodology. This meticulous approach ensured the collection of reliable data for subsequent analysis.

6.5 INFILTRATION SWALES PERFORMANCE EVALUATION

This chapter delved into the findings made from the comparison of the infiltration performance between the ALDOT sand the modified infiltration swales. While this chapter explored a range of findings across various project aspects, this section concentrated on the core comparative analysis derived from the infiltration testing. The modified infiltration swale exhibited a significant improvement in performance compared to the ALDOT swale. The average drawdown time for the ALDOT swale was approximately 12 hours, while the modified swale achieved a notably faster drawdown time of 4.75 hours. This translates to a 7.25-hour advantage for the modified swale in terms of drainage efficiency. Similarly, the infiltration rate of the ALDOT swale averaged around 1.6 ft/day (0.49 m/day). In contrast, the modified swale boasted a significantly higher average infiltration rate of 4 ft/day (1.2 m/day). This represents an impressive 2.5-fold improvement in infiltration capacity for the modified swale.

As expected, both swales displayed slower drainage and lower infiltration rates under wetter soil conditions compared to drier conditions. Interestingly, the closed valve configuration yielded slightly better performance in both swales, with faster drawdown and higher infiltration rates. Seasonal variations potentially influenced performance as well. Increased rainfall frequency (shorter dry period) negatively impacted both swales, while colder winter months (open valve tests) exhibited slower infiltration compared to warmer months (closed valve tests) – potentially due to temperature affecting water viscosity. While the modified swale demonstrated superior infiltration performance compared to the ALDOT swale, both designs achieved complete drainage within 24 hours for all tests. This is a noteworthy finding, as typical drawdown time requirements are set at 48 hours. Both swales exceeded these requirements, suggesting their effectiveness in managing stormwater runoff. Reasons for existing infiltration swales not performing as designed can be from site specific factors during construction including compaction and sedimentation, along with conducting poor or no soil testing at the site to confirm native soils as HSG A or B.

After showing the results for the MLR statistical analysis, the significant factors that affected the infiltration rate for the modified swale were the water temperature and the soil moisture content. This means pertaining to the modified infiltration swale, there is 95% confidence that the soil moisture content and the temperature of infiltrated water affects the infiltration rates, while the valve condition does not exhibit a statistically significant effect. This finding may be attributed to the inherently high infiltration capacity of the modified swale media, which minimized the impact of underdrain conditions. The significant factors that affected the infiltration rate for the ALDOT swale were the soil moisture content and the valve condition. This means pertaining to the ALDOT infiltration swale, there is 95% confidence that the soil moisture content and the valve condition affects the infiltration rates, while the water temperature does not exhibit a statistically significant effect. This finding may be attributed to the slow infiltration rate properties of the topsoil layer and geotextile potential for clogging which limits the infiltration rates.

6.6 LIMITATIONS AND RECOMMENDED FUTURE RESEARCH

Throughout the journey of this project there were some unforeseen complications in the study. This section is to provide insight into some of these complications, limitations, and improvements for future research to be conducted with infiltration-based SCM testing.

One of the key challenges encountered during this project was achieving identical surface storage volumes within the infiltration swales due to limitations imposed by the on-site slope constraints. While both swales hold similar water volumes, the ALDOT swale exhibited a slightly higher capacity (3.5 ft^3 or 0.08 m^3 in zone two) compared to the modified swale. This discrepancy introduced a potential confounding variable when directly comparing infiltration rates and drawdown times. However, the findings from the moisture content sensors provided justification for the modified infiltration performance of the improved media. Despite the slight volume difference in zone two, it is unlikely that this marginal disparity would have significantly impacted the drawdown and infiltration rates observed in the ALDOT swale. Further investigation is required to substantiate this hypothesis.

This study acknowledges two other key limitations. First, a larger sample size of infiltration rate tests with the underdrain valve closed is warranted. Most of the infiltration and drawdown data were derived from open valve tests. A more comprehensive dataset with closed valve tests would be necessary to definitively establish the impact of underdrain configuration (open versus closed) on infiltration performance. Especially since the underdrain complications with the ALDOT infiltration swale are not functioning as designed. Secondly, investigating seasonal variations through infiltration testing with different water, air, and soil temperatures is recommended. Analyzing these additional parameters could potentially reveal relationships between these factors and infiltration rates.

Future research should focus on developing effective retrofit strategies for underperforming infiltration swales. Identifying and implementing modifications to improve the hydraulic performance of existing swales would be an impactful contribution. Some research methods may include how to effectively remove and backfill replacement material for the media, adding injection ports, and/or adding access points.

The performance monitoring of the infiltration swales identified limitations with the moisture content sensors. The measured values deviated from expectations, potentially due to spatial variability within the water flow paths and their intersection with the sensor locations. Infiltrating water may have preferentially traveled through areas not directly monitored by the sensors. To address this limitation, future studies should employ a denser network of moisture content sensors installed in different cross-sections at the same depths. This would enhance data collection and facilitate a more comprehensive understanding of the spatial distribution of moisture content within the swales.

DICLAIMER

It is important to note that the findings, opinions, and conclusions presented here are solely my own and do not necessarily reflect the official views of ALDOT. However, I am deeply appreciative of the opportunity to contribute to their ongoing efforts in sustainable infrastructure development.

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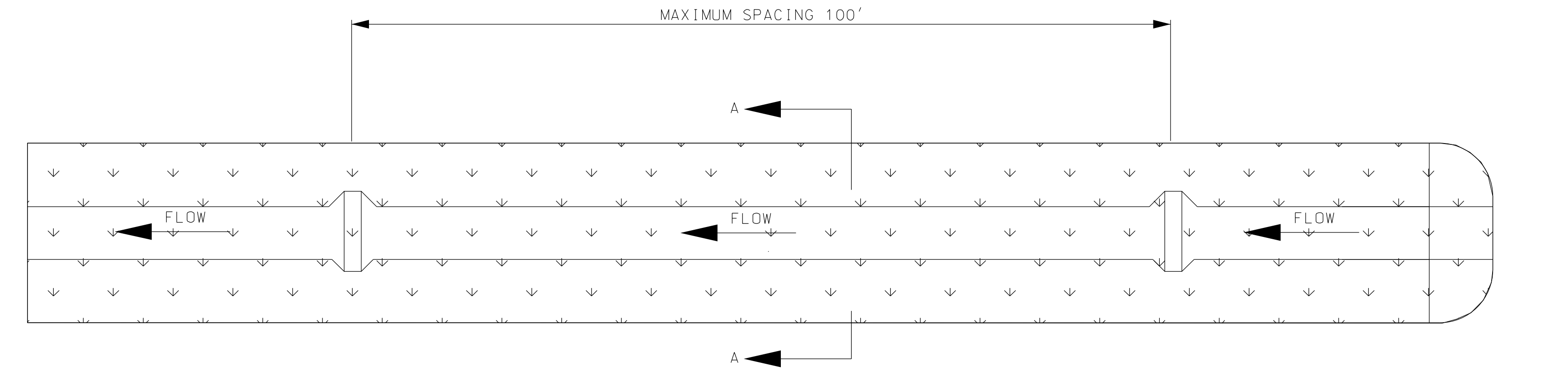
APPENDICES

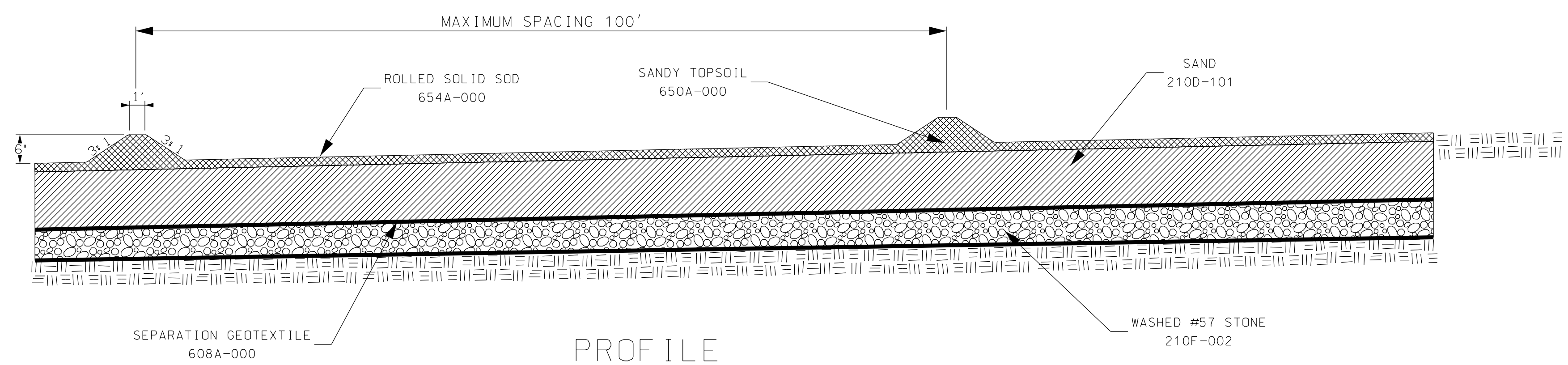
APPENDIX A

INFILTRATION SWALE SPECIFICATIONS

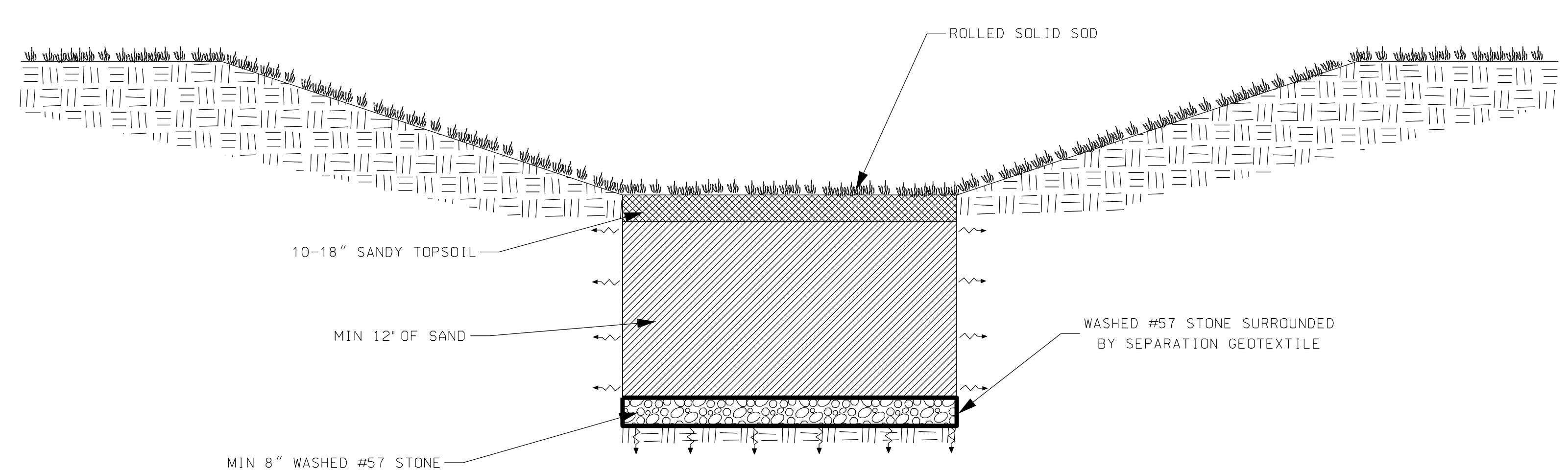
REFERENCE PROJECT NO	FISCAL YEAR	SHEET NO



PLAN VIEW



PROFILE



SECTION A-A

NOTES:

1. EXCAVATION FOR THE INFILTRATION SWALE SHALL NOT OCCUR UNTIL ALL UPSTREAM DISTURBED AREAS ARE STABILIZED AND THE TRENCH PROTECTED FROM SEDIMENTATION DURING ITS CONSTRUCTION.
2. AVOID OVER EXCAVATION AND COMPACTION IN THE BOTTOM OF THE TRENCH BED DURING CONSTRUCTION.
3. GEOMETRY OF THE INFILTRATION SWALE SHALL MATCH THE PROPOSED DITCH.
4. SAND SHALL MEET THE REQUIREMENTS OF ALDOT STANDARD SPECIFICATION SECTION 826.02 (b)
5. BEGIN WITH BERMS AT THE BOTTOM OF DITCH RUNS APPROX. 10' FROM DOWNSTREAM STRUCTURES.
6. BERMS SHALL BE PLACED SO THAT THE TOP OF THE DOWNSTREAM BERM IS THE SAME HEIGHT AS THE TOE OF THE UPSTREAM BERM.

--SPECIFICATIONS--
CURRENT ALABAMA DEPARTMENT OF TRANSPORTATION

REVISIONS

1. Added to CADD on 07-10-2015 by W.D.H.
2. Revised on 08-15-2017 by J.M.M.

ALABAMA DEPARTMENT OF TRANSPORTATION
1409 COLISEUM BOULEVARD
MONTGOMERY, AL 36130-3050

DESIGN BUREAU SPECIAL DRAWING

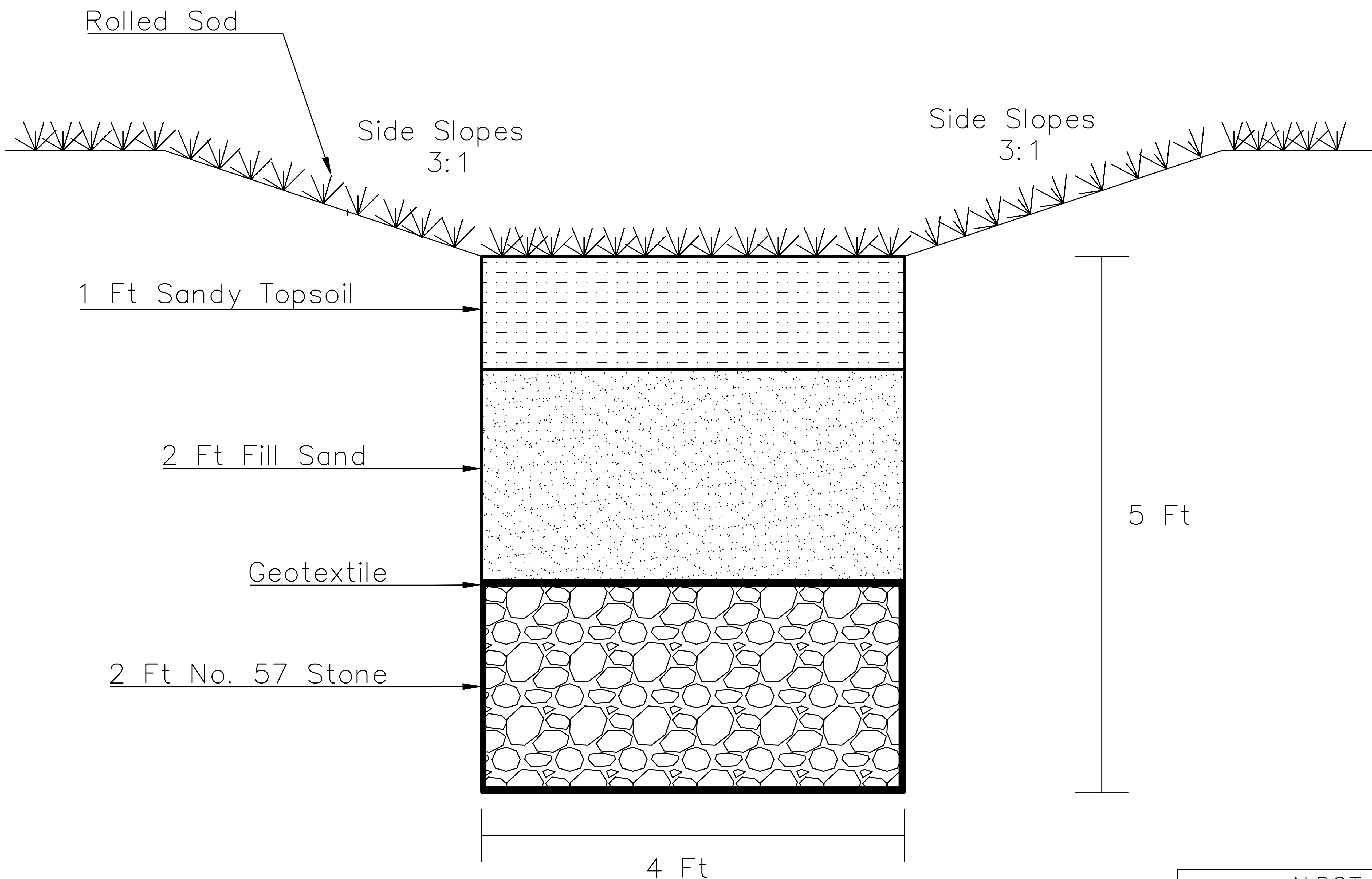
INFILTRATION SWALE

Bureau Std Engr L.V.S.
DATE DRAWN:________ DATE DRAWN:____

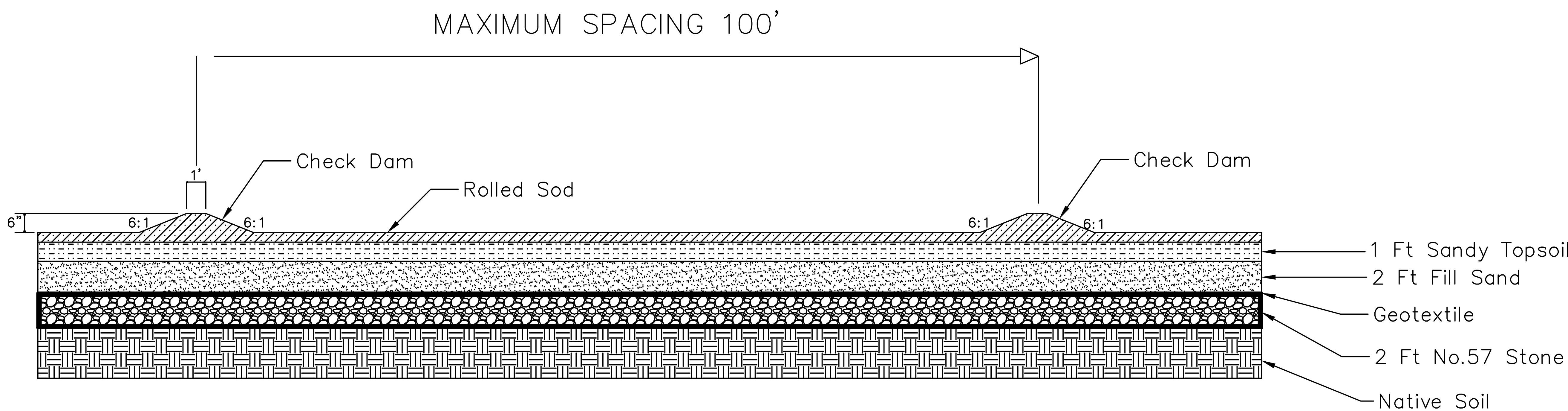
SPECIAL DRAWING NO
SPECIAL DETAIL

INDEX NO
##

NOT TO SCALE



		ALDOT Infiltration Swale Cross Section
	Not to Scale	Date: 05/10/24 Drawn By: Parker Austin



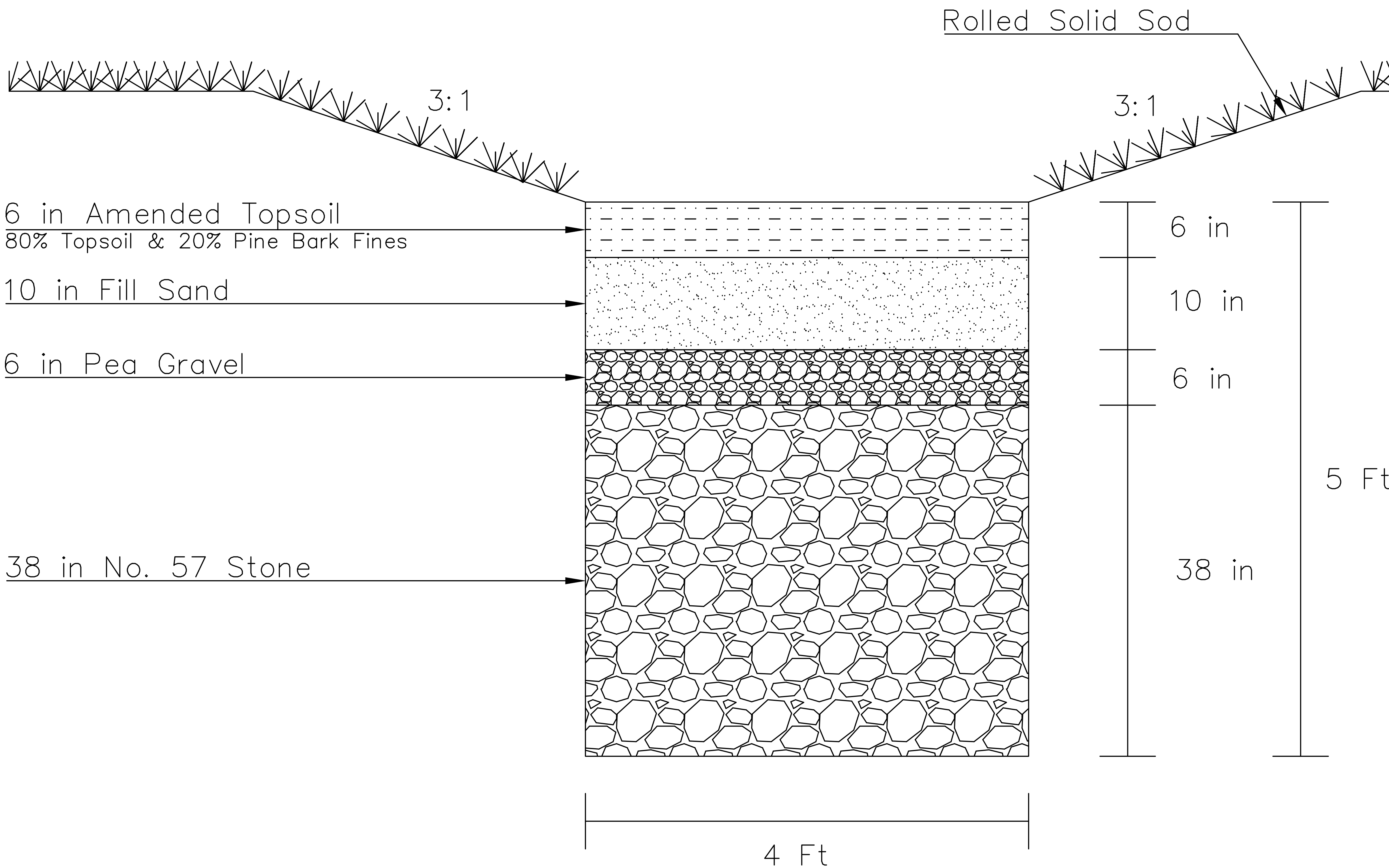
PROFILE

ALDOT
Infiltration Swale
Profile View

Not to Scale

Date: 05/10/24

Drawn By: Parker Austin

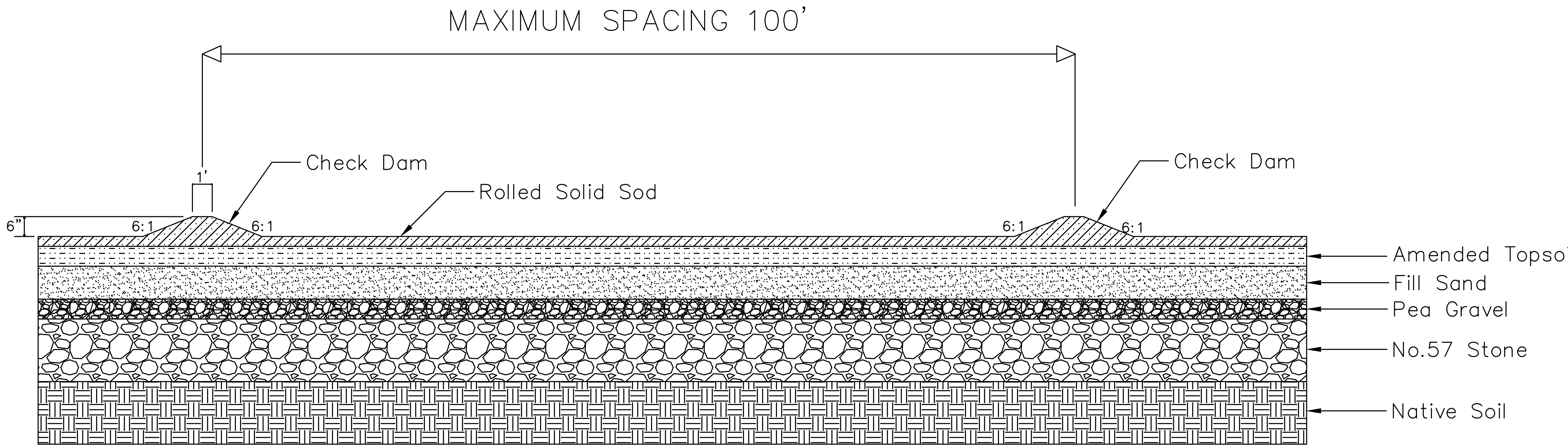


Modified Infiltration Swale
Profile View

Not to Scale

Date: 05/10/24

Drawn By: Parker Austin



Modified Infiltration Swale
Profile View

Not to Scale

Date: 05/10/24

Drawn By: Parker Austin

APPENDIX B

EXPERIMENTAL DATA

ALDOT Infiltration Swale Infiltration Test

Zone 2: Data Points

Data Point	Valve	Wet or Dry	Start Date	Time Start	End Date	Time End	Initial Depth (ft)	Final Depth (ft)	Time Interval (hr)	Time (d:hr:mm:ss)	Rate (ft/dy)	Rate (ft/hr)
1	Open	DRY	10/27/2023	10:44 AM	10/27/2023	11:58 PM	0.75	0	13.17	13:10:00	1.367	0.057
2	Open	WET	10/28/2023	1:08 PM	10/29/2023	4:03 AM	0.75	0	14.85	14:51:00	1.212	0.051
3	Open	WET	10/29/2023	12:47 PM	10/30/2023	4:15 AM	0.75	0	15.47	15:28:00	1.164	0.048
4	Open	WET	10/30/2023	2:49 PM	10/31/2024	7:15 AM	0.75	0	16.43	16:26:00	1.095	0.046
5	Open	WET	10/31/2023	10:15 AM	11/1/2023	7:30 AM	0.75	0	21.23	21:14:00	0.848	0.035
6	Open	WET	11/1/2023	12:07 PM	11/2/2023	7:32 AM	0.75	0	19.40	19:24:00	0.928	0.039
7	Open	WET	11/2/2023	4:16 PM	11/3/2023	2:02 PM	0.75	0	21.75	21:45:00	0.828	0.034
8	Open	DRY	11/16/2023	1:35 PM	11/17/2023	3:08 AM	0.75	0	13.55	13:33:00	1.328	0.055
9	Open	DRY	1/15/2024	12:01 PM	1/15/2024	10:20 PM	0.75	0	10.32	10:19:00	1.745	0.073
10	Open	WET	1/16/2024	2:01 PM	1/17/2024	4:34 AM	0.75	0	14.53	14:32:00	1.239	0.052
11	Open	DRY	1/22/2024	12:41 PM	1/22/2024	8:55 PM	0.75	0	8.25	8:15:00	2.182	0.091
12	Open	WET	1/23/2024	2:31 PM	1/24/2024	11:55 AM	0.75	0	21.40	21:24:00	0.841	0.035
13	Open	WET	1/27/2024	7:01 PM	1/28/2024	7:03 AM	0.75	0	12.03	12:02:00	1.496	0.062
14	Open	DRY	1/29/2024	2:09 PM	1/30/2024	2:08 AM	0.75	0	11.98	11:59:00	1.502	0.063
15	Open	WET	1/30/2024	3:26 PM	1/31/2024	3:49 AM	0.75	0	12.37	12:22:00	1.456	0.061
16	Open	WET	1/31/2024	2:34 PM	2/1/2024	3:00 AM	0.75	0	12.43	12:26:00	1.448	0.060
17	Open	WET	2/1/2024	2:19 PM	2/2/2024	3:25 AM	0.75	0	13.1	13:06:00	1.374	0.057
18	Open	WET	2/2/2024	2:34 PM	2/3/2024	3:25 AM	0.75	0	12.15	12:09:00	1.481	0.062
19	Open	DRY	2/6/2024	12:28 PM	2/7/2024	12:46 AM	0.75	0	12.30	12:18:00	1.463	0.061
20	Open	WET	2/7/2024	12:02 PM	2/8/2024	1:19 AM	0.75	0	13.27	13:16:00	1.357	0.057
21	Open	WET	2/8/2024	2:05 PM	2/9/2024	2:48 AM	0.75	0	12.72	12:43:00	1.415	0.059
22	Open	DRY	3/20/2024	1:35 PM	3/20/2024	7:31 PM	0.73	0	5.93	5:56:00	2.953	0.123
23	Open	DRY	3/27/2024	2:42 PM	3/27/2024	10:27 PM	0.64	0	7.73	7:44:00	1.986	0.083
24	Open	WET	3/28/2024	9:23 AM	3/28/2024	6:08 PM	0.63	0	8.73	8:43:48	1.732	0.072
25	Open	DRY	3/31/2024	11:33 AM	3/31/2024	6:46 AM	0.73	0	7.22	7:13:12	2.427	0.101
26	Open	DRY	4/3/2024	1:32 PM	4/3/2024	8:53 PM	0.64	0	7.35	7:21:00	2.090	0.087
27	Open	DRY	4/6/2024	2:38 PM	4/6/2024	9:05 PM	0.68	0	6.43	6:25:48	2.538	0.106
28	Open	DRY	4/9/2024	3:14 PM	4/9/2024	9:30 PM	0.68	0	6.26	6:15:36	2.607	0.109
29	Closed	DRY	4/15/2024	12:49 PM	4/15/2024	6:06 PM	0.71	0	5.28	5:17:00	3.225	0.134
30	Closed	WET	4/16/2024	1:19 PM	4/16/2024	7:45 PM	0.72	0	6.43	6:26:00	2.686	0.112
31	Closed	WET	4/17/2024	3:35 PM	4/17/2024	11:26 PM	0.62	0	7.83	7:50:00	1.900	0.079
32	Closed	WET	4/18/2024	3:28 PM	4/18/2024	10:07 PM	0.71	0	6.63	6:38:00	2.569	0.107
33	Closed	DRY	6/7/2024	9:51 AM	6/7/2024	3:46 PM	0.7	0	5.92	5:55:12	2.838	0.118
34	Closed	WET	6/8/2024	9:59 AM	6/8/2024	5:18 PM	0.7	0	7.32	7:19:12	2.295	0.096
35	Closed	WET	6/9/2024	5:37 PM	6/10/2024	1:04 AM	0.7	0	7.43	7:25:48	2.261	0.094
36	Closed	WET	6/10/2024	1:11 PM	6/10/2024	10:09 PM	0.7	0	8.97	8:58:12	1.873	0.078
37	Open	WET	6/13/2024	3:43 PM	6/11/2024	10:43 PM	0.7	0	7.00	7:00:00	2.400	0.100
38	Open	WET	6/14/2024	10:11 AM	6/14/2024	7:11 PM	0.7	0	9.00	9:00:00	1.867	0.078
39	Open	WET	6/15/2024	1:23 PM	6/15/2024	9:29 PM	0.7	0	8.08	8:05:00	2.078	0.087
40	Open	WET	6/16/2024	12:14 PM	6/16/2024	8:39 PM	0.7	0	8.42	8:25:00	1.996	0.083

Modified Infiltration Swale Infiltration Test

Zone 2: Data Points

Data Point	Valve	WET or DRY	Start Date	Time Start	End Date	Time End	Initial Depth (ft)	Final Depth (ft)	Time Interval (hr)	Time (d:hr:mm:ss)	Rate (ft/dy)	Rate (ft/hr)
1	Open	DRY	1/10/2024	1:15 PM	1/10/2024	4:54 PM	0.66	0	3.65	3:39:00	4.340	0.181
2	Open	DRY	1/22/2024	12:39 PM	1/22/2024	2:25 PM	0.58	0	1.77	1:46:00	7.879	0.328
3	Open	WET	1/23/2024	2:03 PM	1/23/2024	6:07 PM	0.58	0	6.07	6:04:00	2.295	0.096
4	Open	DRY	1/29/2024	1:35 PM	1/29/2024	5:45 PM	0.66	0	4.17	4:10:00	3.802	0.158
5	Open	WET	1/30/2024	2:56 PM	1/30/2024	8:19 PM	0.66	0	5.38	5:23:00	2.942	0.123
6	Open	WET	1/31/2024	2:11 PM	1/31/2024	10:15 PM	0.66	0	8.07	8:04:00	1.964	0.082
7	Open	WET	2/1/2024	1:50 PM	2/2/2024	12:45 AM	0.66	0	10.92	10:55:00	1.451	0.060
8	Open	WET	2/2/2024	2:05 PM	2/3/2024	4:15 AM	0.66	0	14.17	14:10:00	1.118	0.047
9	Open	WET	2/6/2024	12:33 PM	2/6/2024	10:10 PM	0.75	0	9.62	9:37:00	1.872	0.078
10	Open	WET	2/7/2024	11:50 AM	2/8/2024	1:17 AM	0.75	0	13.45	13:27:00	1.338	0.056
11	Open	WET	2/8/2024	2:06 PM	2/9/2024	5:30 AM	0.75	0	15.40	15:24:00	1.169	0.049
12	Open	WET	3/6/2024	2:13 PM	3/6/2024	11:53 PM	0.75	0	9.67	9:40:12	1.861	0.078
13	Open	DRY	3/21/2024	2:15 PM	3/21/2024	4:35 PM	0.67	0	2.32	2:19:00	6.941	0.289
14	Open	DRY	3/28/2024	9:25 AM	3/28/2024	12:41 PM	0.56	0	3.27	3:16:01	4.114	0.171
15	Open	DRY	3/31/2024	11:25 AM	3/31/2024	1:44 PM	0.59	0	2.30	2:18:00	6.157	0.257
16	Open	DRY	4/3/2024	1:33 PM	4/3/2024	5:09 PM	0.62	0	3.60	3:36:00	4.133	0.172
17	Open	DRY	4/6/2024	3:01 PM	4/6/2024	5:16 PM	0.67	0	2.23	2:13:48	7.211	0.300
18	Open	DRY	4/9/2024	3:08 PM	4/9/2024	5:11 PM	0.66	0	2.03	2:01:48	7.803	0.325
19	Closed	DRY	4/15/2024	12:52 PM	4/15/2024	3:28 PM	0.55	0	2.58	2:35:00	5.110	0.213
20	Closed	WET	4/16/2024	1:15 PM	4/16/2024	4:30 PM	0.65	0	3.23	3:14:00	4.825	0.201
21	Closed	WET	4/17/2024	3:46 PM	4/17/2024	7:46 PM	0.47	0	4	4:00:00	2.820	0.118
22	Closed	WET	4/18/2024	3:24 PM	4/18/2024	8:03 PM	0.6	0	4.65	4:39:00	3.097	0.129
23	Open	DRY	5/20/2024	11:04 AM	5/20/2024	12:58 PM	0.51	0	1.9	1:54:00	6.442	0.268
24	Open	WET	5/21/2024	10:54 AM	5/21/2024	1:45 PM	0.51	0	2.85	2:51:00	4.295	0.179
25	Open	WET	5/22/2024	11:25 AM	5/22/2024	3:13 PM	0.51	0	3.80	3:48:00	3.221	0.134
26	Open	WET	5/23/2024	11:15 AM	5/23/2024	1:54 PM	0.51	0	2.65	2:39:00	4.619	0.192
27	Open	WET	5/24/2024	11:04 AM	5/24/2024	1:56 PM	0.51	0	2.85	2:51:00	4.295	0.179
28	Closed	DRY	6/7/2024	9:41 AM	6/7/2024	10:26 AM	0.6	0	0.75	0:45:00	19.200	0.800
29	Closed	WET	6/8/2024	9:42 AM	6/8/2024	10:37 AM	0.63	0	0.92	0:55:12	16.435	0.685
30	Closed	WET	6/9/2024	5:24 PM	6/9/2024	6:26 PM	0.6	0	1.03	1:01:48	13.981	0.583
31	Closed	WET	6/10/2024	12:47 PM	6/10/2024	2:08 PM	0.6	0	1.35	1:21:00	10.667	0.444
32	Open	WET	6/13/2024	3:24 PM	6/13/2024	4:23 PM	0.6	0	0.98	0:59:00	14.644	0.610
33	Open	WET	6/14/2024	9:57 AM	6/14/2024	11:26 AM	0.6	0	1.48	1:29:00	9.708	0.404
34	Open	WET	6/15/2024	1:04 PM	6/15/2024	2:03 PM	0.6	0	0.97	0:58:00	14.897	0.621
35	Open	WET	6/16/2024	11:56 AM	6/16/2024	1:24 PM	0.6	0	1.45	1:27:00	9.931	0.414

ALDOT Moisture Content Sensors Time Lag Data

Topsoil Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:39	1/29/2024 19:00	0:5:21
2	1/30/2024 15:02	1/30/2024 18:45	0:3:43
3	1/31/2024 14:01	1/31/2024 19:00	0:4:59
4	2/1/2024 13:47	2/1/2024 18:45	0:4:58
5	2/2/2024 14:01	2/2/2024 18:45	0:4:44
Average Time Lag			**0:4:45**

Sand Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:39	1/29/2024 21:00	0:7:21
2	1/30/2024 15:02	1/31/2024 0:30	0:9:28
3	1/31/2024 14:01	1/31/2024 23:15	0:9:14
4	2/1/2024 13:47	2/2/2024 0:30	0:10:43
5	2/2/2024 14:01	2/2/2024 20:15	0:6:14
Average Time Lag			**0:8:36**

Native Side Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:39	1/30/2024 7:15	0:17:36
2	1/30/2024 15:02	1/31/2024 6:30	0:15:28
3	1/31/2024 14:01	2/1/2024 4:15	0:14:14
4	2/1/2024 13:47	2/2/2024 3:45	0:13:58
5	2/2/2024 14:01	2/3/2024 0:45	0:10:44
Average Time Lag			**0:14:24**

57 Stone Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:39	1/30/2024 7:30	0:17:51
2	1/30/2024 15:02	1/31/2024 6:30	0:15:28
3	1/31/2024 14:01	2/1/2024 3:15	0:13:14
4	2/1/2024 13:47	2/2/2024 2:30	0:12:43
5	2/2/2024 14:01	2/3/2024 3:30	0:13:29
Average Time Lag			**0:14:33**

Modified Swale Moisture Content Sensors Time Lag Data

Topsoil Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:34	1/29/2024 13:40	0:0:06
2	1/30/2024 14:56	1/30/2024 15:05	0:0:09
3	1/31/2024 13:55	1/31/2024 14:05	0:0:10
4	2/1/2024 13:42	2/1/2024 14:05	0:0:23
5	2/2/2024 13:57	2/2/2024 14:10	0:0:13
Average Time Lag			**0:0:12**

Sand Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:34	1/29/2024 14:10	0:0:36
2	1/30/2024 14:56	1/30/2024 15:25	0:0:29
3	1/31/2024 13:55	1/31/2024 14:20	0:0:25
4	2/1/2024 13:42	2/1/2024 14:50	0:1:08
5	2/2/2024 13:57	2/2/2024 14:45	0:0:48
Average Time Lag			**0:0:41**

Native Side Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:34	1/29/2024 18:50	0:5:16
2	1/30/2024 14:56	1/30/2024 18:50	0:3:54
3	1/31/2024 13:55	1/31/2024 17:55	0:4:00
4	2/1/2024 13:42	2/1/2024 18:30	0:4:48
5	2/2/2024 13:57	2/2/2024 18:05	0:4:08
Average Time Lag			**0:4:25**

57 Stone Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:34	1/29/2024 22:20	0:8:46
2	1/30/2024 14:56	1/30/2024 21:50	0:6:54
3	1/31/2024 13:55	1/31/2024 23:55	0:10:00
4	2/1/2024 13:42	2/1/2024 22:20	0:8:38
5	2/2/2024 13:57	2/3/2024 1:20	0:11:23
Average Time Lag			**0:9:08**

8 Ft Deep Layer

Test #	DD Peak Time	MC Peak Time	Time Lag (hr:mm:ss)
1	1/29/2024 13:34	1/30/2024 8:10	0:18:36
2	1/30/2024 14:56	1/31/2024 7:40	0:16:44
3	1/31/2024 13:55	2/1/2024 7:40	0:17:45
4	2/1/2024 13:42	2/2/2024 7:35	0:17:53
5	2/2/2024 13:57	2/3/2024 7:20	0:17:23
Average Time Lag			**0:17:40**

Initial Moisture Content Time Lag

Modified Swale Moisture Content		
Test 1		
Test Start	1:35 PM	0:05
Increase Start	1:40 PM	

Test 2		
Test Start	2:56 PM	0:09
Increase Start	3:05 PM	

Test 3		
Test Start	2:11 PM	0:04
Increase Start	2:15 PM	

Test 4		
Test Start	1:50 PM	0:10
Increase Start	2:00 PM	

Test 4		
Test Start	2:05 PM	0:10
Increase Start	2:15 PM	

ALDOT Swale Moisture Content		
Test 1		
Test Start	2:09 PM	1:21
Increase Start	3:30 PM	

Test 2		
Test Start	3:26 PM	1:04
Increase Start	4:30 PM	

Test 3		
Test Start	2:34 PM	1:56
Increase Start	4:30 PM	

Test 4		
Test Start	2:19 PM	2:11
Increase Start	4:30 PM	

Test 4		
Test Start	2:34 PM	2:26
Increase Start	5:00 PM	

APPENDIX C

MATERIAL AND PRODUCT SPECIFICATION SHEETS

Get Quote

Levelogger® 5

Model 3001

The Levelogger 5 records highly accurate groundwater and surface water level and temperature measurements. It combines a pressure sensor, temperature detector, 10-year lithium battery, and datalogger, sealed within a 22 mm x 160 mm (7/8" x 6.3") stainless steel housing with a corrosion-resistant coating baked-on using polymerization technology.

The Levelogger 5 measures absolute pressure using a Hastelloy® pressure sensor, offering high resolution and an accuracy of 0.05% FS. Readings are stable in extreme pressure and temperature conditions. The Hastelloy sensor can withstand 2 times over-pressure without permanent damage. Combined with the durable coating inside and out, the Levelogger 5 has high corrosion and abrasion resistance in harsh environments.

The Levelogger 5 uses a Faraday cage design, which protects against power surges or electrical spikes caused by lightning. Its durable maintenance-free design, high accuracy and stability, make the Levelogger 5 the most reliable instrument for long-term, continuous water level recording.

Fast communication and downloading speeds with a high speed Field Reader 5

Levelogger 5 Features

- Highly stable communication: single-eye optical interface—easier to clean, more scratch resistant
- Large memory: 150,000 sets of data
- Strong, robust design: double o-ring seals for increased leakage protection
- High thermistor sensitivity: accurate platinum RTD
- Superior protection in harsh environments: corrosion and abrasion resistant coating—inside and out
- Intuitive Levelogger Software: Diagnostic Utility for more proactive user "self-tests"

Single-eye optical interface

The Levelogger 5 features a smooth, single-eye optical interface, which allows for easy cleaning and more reliable, faster communication. Using a Solinst USB device, including the Field Reader 5 and Levelogger PC Software, programming and data downloading speeds are 57,600 bps.

Applications

- Aquifer characterization: pumping tests, slug tests, etc.
- Watershed, drainage basin and recharge monitoring
- Stream gauging, lake and reservoir management
- Harbour and tidal fluctuation measurement
- Wetlands and stormwater run-off monitoring
- Water supply and tank level measurement
- Mine water and landfill leachate management
- Long-term water level monitoring in wells, surface water bodies and seawater environments

Flexible Communication

Levelogger Software is streamlined, making it easy to program dataloggers, and view and compensate data in the office or the field. Data compensation is made simple; multiple data files can be barometrically compensated at once.

The Levelogger 5 App Interface on your in-field Leveloggers creates a *Bluetooth*® connection between your dataloggers and the Solinst Levelogger App on your smart device. The Solinst Readout Unit (SRU) connects to your deployed Leveloggers to display and save real-time water level readings that are automatically barometrically compensated. Also an option, the DataGrabber 5 is a field-ready USB data transfer unit.

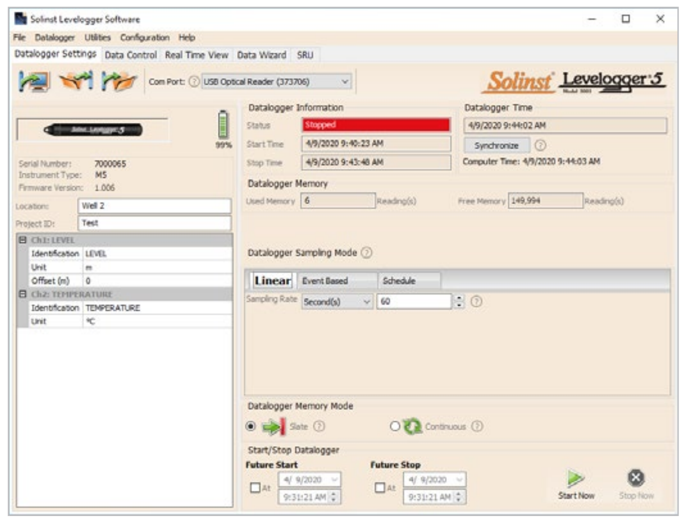
Remote monitoring options include the LevelSender 5, a simple and compact device that fits right in a 2" well, SolSat 5 Satellite Telemetry, STS Telemetry Systems, and the RRL Remote Radio Link. In addition, Levelogger 5 Series dataloggers are SDI-12 compatible.

Levelogger Setup

Programming Leveloggers is extremely intuitive. Simply connect to a PC using an Optical Reader (Desktop Reader 5 or Field Reader 5) or PC Interface Cable. Use a single screen to fill in your project information and sampling regime. Templates of settings can be saved for easy re-use.

The Levelogger time may be synchronized to the computer clock. There are options for immediate start or future start and stop times. The percentage battery life remaining and the amount of free memory are indicated on the settings screen.

Leveloggers can also be programmed with a sampling regime and start/stop times using the Solinst Levelogger App on your smart device.

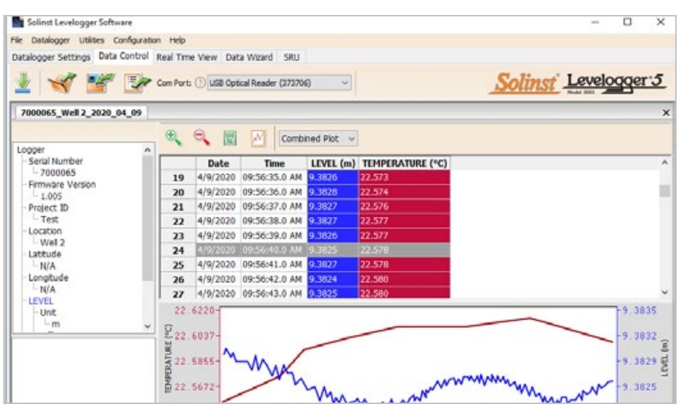


Convenient Sampling Options

Leveloggers can be programmed with linear, event-based, or a user-selectable sampling schedule. Linear sampling can be set from 1/8 second to 99 hours.

Event-based sampling can be set to record when the level changes by a selected threshold. Readings are checked at the selected time interval, but only recorded in memory if the condition has been met. A default reading is taken every 24 hours if no “event” occurs.

The Schedule option allows up to 30 schedule items, each with its own sampling rate and duration. For convenience, there is an option to automatically repeat the schedule.



Data Download, Viewing and Export

Data is downloaded to a PC with the click of a screen icon. There are multiple options for downloading data, including ‘Append Data’ and ‘All Data’. The software also allows immediate viewing of the data in graph or table format using ‘Real Time View’.

Level data is automatically compensated for temperature; the temperature data is also downloaded. Barometric compensation of Levelogger data is performed using the Data Wizard, which can also be used to input manual data adjustments, elevation, offsets, density, and adjust for Barometric efficiency. The Levelogger Software allows easy export of the data into a spreadsheet or database for further processing.

The Solinst Levelogger App also allows you to view and save real-time or logged data right on your smart device, or you can view and save the data using an SRU.

Helpful Utilities

The Diagnostic Utility can be used in case of an unexpected problem. It checks the functioning of the program, calibration, backup and logging memories, the pressure transducer, temperature sensor and battery voltage, as well as enabling a complete Memory Dump, if required. A firmware upgrade will be available from time to time, to allow upgrading of the Levelogger 5, as new features are added.

Levelogger 5 App Interface

The Levelogger 5 App Interface uses *Bluetooth®* technology to connect your Levelogger to your smart device. With the Solinst Levelogger App, you can download data, view real-time data, and program your Leveloggers. Data can be e-mailed from your smart device directly to your office (see Model 3001 Levelogger 5 App Interface data sheets).

Download on the App Store

GET IT ON Google play

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Solinst Readout Unit (SRU)

Connect an SRU to an in-field Levelogger via an L5 Direct Read Cable or L5 Threaded or Slip Fit Adaptor to display instant water level readings, Levelogger status, save a real-time logging session, and download data to the SRU memory.

DataGrabber 5

The DataGrabber 5 is a field-ready data transfer device that allows you to copy data from a Levelogger onto a USB flash key (Dual USB & USB-C key provided).The DataGrabber 5 is compact and very easy to transport. It connects to the top end of a Levelogger's Direct Read Cable, or directly to a Levelogger using an adaptor. One push-button is used to download all of the data in a Levelogger's memory to a USB device.

LS5 LevelSender

LevelSender 5 Telemetry

The LevelSender 5 is a simple, low cost telemetry system designed to send data from Leveloggers in the field, to your smart device and PC database via cellular communication. There is two-way communication between the LevelSender 5 and Home Station, allowing remote updates. LevelSender 5 stations are compact in design, which allows them to be discreetly installed inside a 2" (50 mm) well (see Model 9500 data sheet).

STS Telemetry System

STS Telemetry

STS Telemetry provides an efficient method to send Levelogger data from the field to your desktop. Cellular communication options give the flexibility to suit any project. STS Systems are designed to save costs by enabling the self-management of data. Alarm notification, remote firmware upgrades and diagnostic reporting make system maintenance simple (see Model 9100 data sheet).

SolSat 5 Satellite Telemetry

SolSat 5 Satellite Telemetry

The SolSat 5 Satellite Telemetry uses Iridium satellite technology to provide global connectivity for your remote water monitoring projects. The SolSat 5 is simple to set up with Solinst dataloggers using an intuitive and secure Wi-Fi App on your smart device. The SolSat 5 features a built-in barometer, solar panel and a compact weatherproof enclosure for deployment almost anywhere.

RRL Remote Radio Link

RRL Remote Radio Link

The RRL Remote Radio Link is ideal for closed-loop, short range applications up to 30 km (20 miles). The RRL can be linked to an STS telemetry station to change from a closed-loop telemetry system to one which can be accessed from anywhere through internet connectivity. (see Model 9200 data sheet).

®Kevlar is a registered trademark of DuPont Corp.

Standard Cable Deployment

Leveloggers may be suspended on a stainless steel wireline or Kevlar® cord. This is a very inexpensive method of deployment, and if in a well, allows the Levelogger to be easily locked out of sight and inaccessible. Solinst offers wireline and cord assemblies in a variety of lengths.

Solinst 3001 Well Cap Assembly

The 2" Locking Well Caps are designed for both standard and Direct Read Cable deployment options.

The well cap has a convenient eyelet for suspending Leveloggers using wireline or Kevlar cord. The Well Cap insert has two openings to accommodate direct read cables for both a Levelogger and Barologger. Adaptors are available to fit 4" wells.

The cap is vented to equalize atmospheric pressure in the well. It slips over the casing, and can be secured using a lock with a 9.5 mm (3/8") shackle diameter.

Levelogger 2" Locking Well Cap Installations (see Well Caps data sheet for more details)

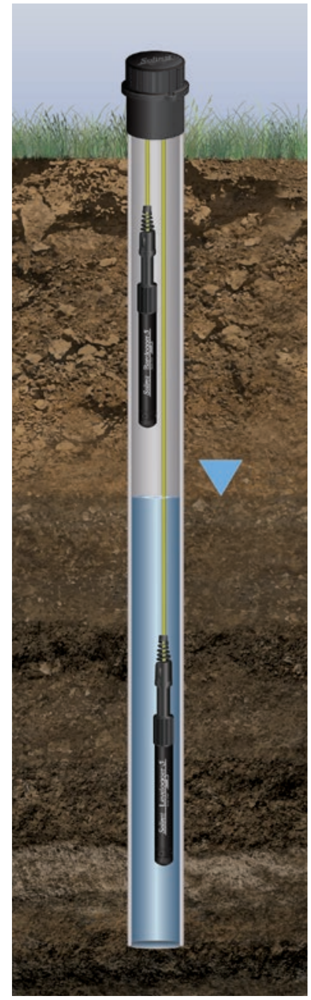
L5 Direct Read Cables

When it is desired to get real-time data and communicate with Leveloggers without removal from the water, they can be deployed using L5 Direct Read Cables. This allows viewing of data, downloading, and programming in the field using a portable PC, or Solinst Levelogger 5 App Interface. You can view and save data to an SRU, or just download data with a DataGrabber 5.

Leveloggers can be connected to an SDI-12 datalogger using the Solinst SDI-12 Interface Cable attached to a L5 Direct Read Cable.

Cable Specifications

L5 Direct Read Cables are available for attachment to any Levelogger in lengths up to 1500 ft. The 3.175 mm dia. (1/8") coaxial cable has an outer polyurethane jacket for strength and durability. The stranded stainless steel conductor gives non-stretch accuracy.



Barologger 5 and Levelogger 5 installed in Well Using L5 Direct Read Cables

Accurate Barometric Compensation

Leveloggers measure absolute pressure (water pressure + atmospheric pressure) expressed in feet, meters, centimeters, psi, kPa, or bar.

The most accurate method of obtaining changes in water level is to compensate for atmospheric pressure fluctuations using a Barologger 5, avoiding time lag in the compensation.

The Barologger 5 is set above high water level in one location on site. One Barologger can be used to compensate all Leveloggers in a 30 km (20 mile) radius and/or with every 300 m (1000 ft.) change in elevation.

The Levelogger Software Data Compensation Wizard automatically produces compensated data files using the synchronized data files from the Barologger and Leveloggers on site.

The Barologger 5 uses pressure algorithms based on air rather than water pressure, giving superior accuracy.

The recorded barometric information can also be very useful to help determine barometric lag and/or barometric efficiency of the monitored aquifer.

The Barologger 5 records atmospheric pressure in psi, kPa, or mbar. When compensating submerged Levelogger 5, Edge, Gold or Junior data, Levelogger Software can recognize the type of Levelogger and compensate using the same units found in the submerged data file (e.g. feet or meters). This makes the Barologger 5 backwards compatible.

Synchronize and Simplify Barometric Compensation Across Entire Site

Levelogger 5 Specifications

Level Sensor:	Piezoresistive Silicon with Hastelloy Sensor
Accuracy:	± 0.05% FS (Barologger 5: ± 0.05 kPa)
Stability of Readings:	Superior, low noise
Resolution:	0.002% FS to 0.0006% FS
Units of Measure:	m, cm, ft., psi, kPa, bar, ºC. ºF (Barologger 5: psi, kPa, mbar, ºC, ºF)
Normalization:	Automatic Temperature Compensation
Temp. Comp. Range:	0º to 50ºC (Barologger 5: -10 to +50ºC)
Temperature Sensor:	Platinum Resistance Temperature Detector (RTD)
Temp. Sensor Accuracy:	± 0.05ºC
Temp. Sensor Resolution:	0.003°C
Battery Life:	10 Years – based on 1 reading/minute
Clock Accuracy (typical):	± 1 minute/year (-20ºC to 80ºC)
Operating Temperature:	-20ºC to 80ºC
Maximum # Readings:	150,000 sets of readings
Memory Mode:	Slate and Continuous
Communication:	Optical high-speed: USB, SDI-12 57,600 bps with USB
Size:	22 mm x 160 mm (7/8" x 6.3")
Weight:	146 grams (5.2 oz)
Corrosion Resistance:	Baked-on coating using polymerization technology (inside and out)
Other Wetted Materials:	Delrin®, Viton®, 316L stainless steel, Hastelloy, PFAS-free PTFE coating
Sampling Modes:	Linear, Event & User-Selectable with Repeat Mode, Future Start, Future Stop, Real-Time View
Measurement Rates:	1/8 sec to 99 hrs
Barometric Compensation:	Software Wizard and one Barologger 5 in local area (approx. 30 km/20 miles radius)

Models	Full Scale (FS)	Accuracy	Resolution
Barologger	Air only	± 0.05 kPa	0.002% FS
M5	5 m (16.4 ft.)	± 0.3 cm (0.010 ft.)	0.001% FS
M10	10 m (32.8 ft.)	± 0.5 cm (0.016 ft.)	0.0006% FS
M20	20 m (65.6 ft.)	± 1 cm (0.032 ft.)	0.0006% FS
M30	30 m (98.4 ft.)	± 1.5 cm (0.064 ft.)	0.0006% FS
M100	100 m (328.1 ft.)	± 5 cm (0.164 ft.)	0.0006% FS
M200	200 m (656.2 ft.)	± 10 cm (0.328 ft.)	0.0006% FS

Low Cost Datalogging: See Levelogger 5 Junior data sheet.
Vented Dataloggers: See LevelVent 5 & AquaVent 5 data sheets.
Conductivity Datalogging: See Levelogger 5 LTC data sheet.

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TEROS 10
Tech Specs

TECHNICAL SPECIFICATIONS

Volumetric Water Content

Range

Mineral Soil Calibration: 0.0000 – 0.6400 m^3/m^3

Soilless Media Calibration: 0.0000 – 0.7000 m^3/m^3

Apparent Dielectric Permittivity (εa): 1 (air) to 80 (water)

NOTE: The VWC range is dependent on the media the sensor is calibrated to. A custom calibration will accommodate the necessary ranges for most substrates.

Resolution

0.0010 m^3/m^3

Accuracy

Mineral Soil Calibration: ±0.03 m^3/m^3 typical in mineral soils that have solution EC <8 dS/m

Soilless Media Calibration: ±0.05 m^3/m^3 typical in media that has a solution EC <8 dS/m

Medium Specific Calibration: ±0.01–0.02 m^3/m^3 in any porous medium

Apparent Dielectric Permittivity (εa): 1–40 (soil range) , ±1 εa (unitless) 40–80, 15% of measurement

Measurement Specifications

Dielectric Measurement Frequency	70 MHz
Measurement Volume	See comparison article

Communication Specifications

Output	1,000 – 2,500 mV
Data Logger Compatibility	Data acquisition systems capable of switched 3.0–15 VDC excitation and single-ended voltage measurement at greater than or equal to 12-bit resolution. See compatibility chart

Physical Specifications

Dimensions	**Length:** 5.1 cm (2.02 in) **Width:** 2.4 cm (0.95 in) **Height:** 7.5 cm (2.95 in)
Needle Length	5.4 cm (2.11 in)
Operating Temperature Range	**Minimum:** -40.00 °C **Typical:** NA **Maximum:** 60.00 °C

	NOTE: Sensors may be used at higher temperatures under certain conditions; Contact Customer Support for assistance.
Cable Length	5 m (standard) 40 m (maximum custom cable length) **NOTE: Contact Customer Support if a nonstandard cable length is needed.**
Cable Diameter	0.165 ± .004 (4.20 ± .10 mm) with min. jacket of .030 (.76 mm)
Connector Types	3.5-mm stereo plug connector or stripped and tinned wires
Stereo Plug Connector Diameter	3.5 mm
Conductor Gauge	22 AWG/24 AWG drain wire

Electrical and Timing Characteristics

Supply Voltage (VIN to GND)	**Minimum:** 3.0 VDC **Typical:** NA **Maximum:** 15.0 VDC
Measurement Duration	**Minimum:** 10 ms **Typical:** NA **Maximum:** NA

ZL6 Data Logger Tech Specs

ZL6 Pro Tech Specs

TECHNICAL SPECIFICATIONS

Measurement Specifications

Sensor Logging Interval	5 min to 12 h (average or accumulation of 1-min sensor reading)
Logger Reporting Interval	Hourly with the ability to enable more frequent reporting
Time Keeping	Synchronize automatically and on-demand; GPS, cellular, or ZENTRA Utility software

Communication Specifications

Computer Communication	Standard USB cable, USB A to micro-USB B
Internet Downloads	SSL/TLS encrypted
Cellular Communication	**3G Specifications:** UMTS 3G 5-band cellular module with 2G fallback **3G Coverage:** AT&T® and T-Mobile® in USA, 550+ global partner carriers. Cellular and data hosting service provided by METER

4G Specifications: 4G LTE-M and NB-IoT cellular

4G Coverage: AT&T® and Sprint® or Verizon® in USA. Cellular and data hosting service provided by METER

Mobile Communication	Bluetooth 5.2 supporting Bluetooth Low Energy protocol
GPS Communication	**Type:** Integrated 56-channel GPS/QZSS receiver **Update:** Daily (automatic) and on-demand (manual) **Accuracy:** ±3 m, with good sky view

Physical Specifications

Dimensions	**Length:** 14.9 cm (5.9 in) **Width:** 6.3 cm (2.5 in) **Height:** 25.0 cm (9.9 in)
Enclosure Material	Weather-, impact-, and UV-resistant polymer
Enclosure Rating	IP56, NEMA 3R
Enclosure Access	Hinged door with latches and eyelets for lock or zip tie
Sensor Input Ports	6 (supports METER analog, digital, or pulse sensors)
Sensor Port Type	3.5-mm stereo plug connector
Memory Type	Nonvolatile flash, full data retention with loss of power

Data Storage	8 MB (40,000 to 80,000+ records depending on configuration)
Battery Capacity	6 AA NiMH or alkaline batteries
Battery Life	**Alkaline:** 3–12 months depending on configuration **NiMH:** 3+ years with unobstructed view of sun. Charging through solar energy harvesting or USB
Operating Temperature Range	**Minimum:** –40 °C **Maximum:** +60 °C

Other

Compatibility	See compatibility chart
Compliance	EM ISO/IEC 17050:2010 (CE Mark)
GSA	View GSA details

Request a quote