ABSTRACT
DEBELL, THOMAS CRAIG. A Novel Approach to High-Resolution Monitoring of Subsurface Water Dynamics in Media Based Treatment Practices (Under the direction of Drs. Chadi Sayde and Barbara Doll).

Innovative, nature-based stormwater control measures have increasingly been used to remedy pollutant loading across the U.S and beyond. However, these measures have demonstrated varying levels of success. While the rate that water moves through the media of such treatment practices is a crucial indicator of their abilities to treat various pollutants, high-resolution measurements of this process are difficult to obtain. Traditional methods and sensors used to monitor water movements lack the resolution needed to effectively quantify the variability thought to impact water treatment in nature-based stormwater control measures. Thus, better instrumentation is required to monitor these water treatment systems' complex and varied dynamics. To address these challenges, this study examines a novel approach to measure water flux at a fine resolution over large distances using actively heated fiber-optic distributed temperature sensing (AHFO-DTS).

To verify the application of AHFO-DTS in this innovative way, a series of laboratory tests were conducted in various media and under different flow conditions in a seepage tank. The results indicate that AHFO-DTS can measure water fluxes ranging from $1.4 \times 10^{-4}$ to $3.4$ cm hr$^{-1}$ in a sandy/wood mulch media collected from a regenerative stormwater conveyance system. In addition, the physical model developed by Perzlmaier et al. (2004) was calibrated by adjusting uncertain media parameters. This calibration improved the estimate of flux through the seepage tank and resulted in an RMSE of 0.21 cm hr$^{-1}$, representing less than 10% measurement error across the range of flows tested.

This AHFO-DTS approach was then used to monitor subsurface water movement in a storm water control measure by installing a 4-meter fiber optic transect at four depths in the media of a regenerative stormwater conveyance structure (RSC) located in Durham, North Carolina. Two intensive monitoring periods took place during storms on February 22 and April 24, 2021. Heated measurements were conducted to inform the spatial and temporal variability of fluxes moving within the media. Water quality samples were taken upstream and downstream of the RSC channel to quantify pollutant reduction. Additionally, hydraulic gradients were monitored, and rainfall totals were collected. The magnitude of water flux was assessed at a spatial
resolution of 0.25 cm, and measurements were obtained from depths of 15.3, 30.5, 45.7, and 76.2 cm across the 4-meter-wide pool at the top of the structure.

The results demonstrate that AHFO-DTS measurements can detect sub-meter scale variations in water flux under various conditions. The maximum and minimum measured flux during monitoring was 2.34 cm hr⁻¹ and 0.32 cm hr⁻¹ respectively. The most substantial variations occurred along the shallowest section of the fiber optic cable installation at a depth of 15.6 cm.

While only a limited number of water quality grab samples were acquired during stormflow monitoring (n=6), they indicate better nitrate concentration reduction performance by the system than a study of the site five years prior. Based on the values of flux obtained over the entire monitoring period, estimates of hydraulic retention time for water in the top pool of the system ranged from 2.2 to 7.0 days, with a mean time of 3.9 days. Changes in temperature caused by localized percolation of water into the RSC media detected by AHFO-DTS also demonstrated it utility to track the propagation of the wetting front during the initial saturation and infiltration above the monitoring transect.

The variations observed are likely not significant enough to warrant immediate maintenance of the site and suggest that the practice's maturation may improve the nitrogen reduction benefit over time. The improvement in nitrate reduction can be attributed to longer retention in the RSC media, providing optimal conditions for denitrification. However, a more comprehensive water quality study is suggested for a more thorough comparison with the earlier study. In addition, fiber optic installation into these media-based practices could offer long-term monitoring benefits and better estimate their efficacy over time.
A Novel Approach to High-Resolution Monitoring of Subsurface Water Dynamics in Media Based Treatment Practices

by

Thomas DeBell

A thesis submitted to the Graduate Faculty of North Carolina State University in partial fulfillment of the requirements for the degree of Master of Science

Biological and Agricultural Engineering

Raleigh, North Carolina 2021

APPROVED BY:

_______________________________
Dr. Chadi Sayde
Committee Co-Chair

_______________________________
Dr. Barbara Doll
Committee Co-Chair

_______________________________
Dr. Joshua Heitman

_______________________________
Dr. William Hunt III
DEDICATION

This thesis is dedicated first to my parents, David, and Teresa DeBell. My educational and personal successes have been largely due to how I was raised and the example you both set for me. Your encouragement, love and faith have helped me in ways impossible to describe in words.

To my entire family and friends, whose support has been paramount in all my efforts.

To Katie Darr, for loving me unconditionally, practicing a great deal of patience with me, and never allowing me to give up.

To my friends, colleagues, professors, advisors and all who lent a kind word or advice.

Finally, to the Lord my God, my refuge and strength.
BIOGRAPHY

Tom DeBell was born on February 3rd, 1996, in Roseburg, Oregon, to David and Teresa DeBell. The first 18 years of his life, he grew up in the small rural town of Glide, Oregon, with a population of fewer than 1,400 people on the North Umpqua River. Some of Tom’s earliest memories revolved around the many pristine waterways of Southern Oregon, blessed with a family that loved to fish, hike, and spend time on the river. These early experiences very well might have influenced his passion to preserve, understand and rehabilitate the natural world. The middle child of three boys, a spirit of healthy competition was always present in the DeBell household. As Tom grew, his parents would be quick to tell that their son’s childlike curiosity of the natural world never ceased.

Tom found his passion for science and the natural world intersect in the Ecological Engineering Department at Oregon State University in Corvallis, just 100 miles North of his hometown. He spent five years studying engineering, minoring in chemistry, publishing independent research, and engaging in several student clubs in “the best college town in the PAC-12.” One of his most fond memories while at OSU was managing a 1,600 square-foot tropical greenhouse as a member of the Ecological Engineering Student Society. During his time at OSU, Tom’s academic and civic performance earned him admittance to the Engineering National Honor Society, Tau Beta Pi, in his junior year, and he served as OSU chapter president his senior year. A year later, Tom found himself 2,900 miles away from his hometown after a serendipitous encounter with an Alumni of his research lab, who recruited him to the BAE Department. Tom was fortunate to be offered a project that intersected his interests allowing him to work with two outstanding researchers and mentors, Dr Chadi Sayde and Dr Barbara Doll. His time at NCSU, while not under the most ideal circumstances, was highlighted by close friendships, excellent instruction, and newfound knowledge of water resources. Upon completion of his degree, Tom is optimistic that the skills he has acquired over his education will serve him, his employers, and the environment well.
ACKNOWLEDGMENTS

There are so many people that I would like to express my deepest gratitude for assisting me during my time at NC State. Co-Chairs Dr. Chadi Sayde and Dr. Doll, I am deeply indebted to you both for the opportunities you provided me and helping me grow as a researcher, engineer and person. Your ability to pivot, given the unusual circumstances we all were placed under, and enable me to produce a study I am proud of, was a monumental task. I am incredibly grateful for the opportunity to work with you both.

This work would not have been possible without my committee members, Dr. William Hunt and Dr. Joshua Heitman, whose insights and instruction were invaluable. Dr. Heitman’s expertise in all things soils was an incredible asset in my endeavors and gave me a much deeper appreciation for the complexities of soil physics. Your class was a pleasure and gave me many of the tools (both figuratively and literally) to perform my research. Bill, your mentorship and friendship has been one of many highlights for me here at NCSU. Your knowledge and passion for Stormwater Control Measures are unparalleled and inspiring. Thank you for showing me that sometimes the best ideas are exchanged over an Old Tuffy at Sammy’s after work.

Mahmoud Shehata, I owe a great deal of this project’s success to your willingness to lend a hand on the many technical aspects of operating a DTS system and splicing incredible small, unbelievable fragile optical fibers. I genuinely appreciate your readiness to help me throughout my time here at NCSU.

Jack Kurki-Fox, thanks for all your CAD help and opportunities to help survey.

Shawn Kennedy, I appreciate you showing me how to use the MPD infiltrometers and helping answer all my questions in the field.

Lance Fontaine of the City of Durham and Terrence Kind of Durham Public Works Maintenance and Operations were instrumental in allowing our field research to take place during such an unusual year. I deeply appreciate their efforts to accommodate us in our work.

Water quality samples were analyzed by the NCSU Center for Applied Aquatic Ecology, thank you to Jenny James and Linda Mackenzie, for your flexibility in organizing schedules and kindness when I came into the lab.

Dan Line, I appreciate your willingness to teach me the ins and out of collecting water samples and borrowing equipment, sometimes with only a moment’s notice.
To the 2020-2021 BAE Graduate Student Association, thank you for helping make a difficult year more tolerable with your friendship and creativity to get together virtually and otherwise. To my roommate, friend, and colleague, Andrew Hillman, I am so thankful for your companionship, especially during this past year. And to my many other friends, colleagues, and professors, I bid you thanks for your part in making this thesis and all my other endeavors possible.
# TABLE OF CONTENTS

List of Tables .................................................................................................................. viii

List of Figures ................................................................................................................... ix

Chapter 1: Review of Literature for Distributed Temperature Sensing in Hydrologic System and Media Based Stormwater Control Measures .............................................. 1

1.1 Introduction .................................................................................................................. 1

1.2 Existing Methods for Monitoring Subsurface Water Dynamics, and Their Limitations ................................................................................................................................. 1

1.3 Distributed Temperature Sensing Background ................................................................ 3

1.3.1 Influence of scale on measurement and DTS Use in Hydrologic Monitoring ............. 3

1.3.2 Extensions of the Heat Up Method to AHFO .................................................................. 4

1.4 Stormwater Control Measures and Regenerative Stormwater Conveyance Background ................................................................................................................................. 5

1.4.1 Bioretention Basins ...................................................................................................... 6

1.4.2 Regenerative Stormwater Conveyance ........................................................................ 7

1.4.3 RSC Design Guidance ................................................................................................ 9

1.4.4 Denitrification in Media Based Treatment Systems ..................................................... 10

1.5 Knowledge Gaps and Relevance of Our Study .............................................................. 13

1.6 Research Objectives ..................................................................................................... 14

1.7 References .................................................................................................................... 16

Chapter 2: Thermal Response of Actively Heated Fiber Optics Under Varied Flow Conditions – A Seepage Tank Study ................................................................. 22

2.1 Abstract ....................................................................................................................... 22

2.2 Introduction .................................................................................................................. 23

2.3 Materials and Methods ............................................................................................... 24

2.3.1 Overview .................................................................................................................... 24

2.3.2 Seepage Tank Design ............................................................................................... 25

2.3.3 Fiber Optic-Cable Orientation and Referencing ....................................................... 26

2.3.4 Media Specifications and Physical Properties ......................................................... 27

2.3.5 Distributed Temperature Sensing and Heat Pulse Methodologies ......................... 28

2.3.6 Glass Bead Media Tests ............................................................................................ 30

2.3.7 Multimedia Validation Tests with RSC Media ......................................................... 31

2.3.8 Calculation of Water Flux and the Perzlmairer Model ........................................................................ 32

2.4 Results ......................................................................................................................... 36

2.4.1 Detection of the Wetting Front .................................................................................... 36
2.4.2 AHFO-DTS Sensitivity to Varied Flows ................................................................. 37
2.4.3 Perzlmaier Model Performance in Glass Media ................................................... 37
2.4.4 Perzlmaier Model Performance in RSC Media ..................................................... 38
2.4.5 Perzlmaier Model Performance in RSC Media ..................................................... 39
2.5 Discussion and Limitations ....................................................................................... 40
2.6 References ............................................................................................................... 43

Chapter 3: Investigation of the Internal Hydraulics of a Regenerative Stormwater
Conveyance Structure Using a Novel Distributed Temperature Sensing Approach .......... 46
3.1 Abstract ...................................................................................................................... 46
3.2 Introduction ................................................................................................................. 47
3.2.1 Site Description ....................................................................................................... 49
3.2.2 Insights from Previous Studies ............................................................................. 51
3.3 Materials and Methods ............................................................................................ 53
3.3.1 Field Installation of Fiber Optic Cable ................................................................ 53
3.3.2 Utility Equipment and DTS Monitoring Trailer ............................................... 57
3.3.3 Pool Water Level Monitoring ............................................................................. 59
3.3.4 Infiltration and Hydraulic Conductivity Measurements ..................................... 59
3.3.5 Water Quality Sampling ...................................................................................... 60
3.3.6 Thermal Property Characterization .................................................................... 61
3.4 Results ...................................................................................................................... 62
3.4.1 Overview ............................................................................................................... 62
3.4.2 Wetting Front Monitoring ................................................................................ 63
3.4.3 Uncertainty in Perzlmaier Flux Estimates ............................................................ 64
3.4.4 Spatially Distributed Flux During Storm Events ................................................. 65
3.4.5 Comparison with Hydraulic Gradients ................................................................. 68
3.4.6 Water Quality Trends ......................................................................................... 70
3.4.7 Variation Across All Flux Measurements ............................................................ 77
3.4.8 Estimation of Hydraulic Retention Time .............................................................. 79
3.5 Discussion .................................................................................................................. 81
3.5.1 Implications of Results ....................................................................................... 81
3.5.2 Future Work and Improvements to Testing Methodology ................................. 83
3.5.3 Design and Maintenance Recommendations ..................................................... 84
3.6 Assumptions and Limitations ................................................................................... 85
3.7 Conclusions .............................................................................................................. 87
3.8 References ............................................................................................................... 87
LIST OF TABLES

Table 1.1         Suggested material specification for RSC construction. Adapted from City of Annapolis, Anne Arundel County, and Duan et al. 2019. ............................. 10
Table 2.1         Summary of select literature on the treatment mechanisms employed by different SCM structures to reduce pollutants. .................................................. 12
Table 3.1         RSC Structure Details .......................................................................................... 51
Table 3.2         Analytical method and detection limit used by the CAAE to quantify each contaminant concentration during sampling. ................................................................. 61
Table 3.3         Summary of Water Quality Analysis for February 22, 2021, bold numbers indicate higher concentration exiting cell 5 then flowing into cell 1. ......................... 72
Table 3.4         Summary of Water Quality Analysis for April 24, bold numbers indicate higher concentration exiting cell 5 then flowing into cell 1. ............................... 74
Table 3.5         Summary of pooled analyte concentrations and reductions from both sampling dates ........................................................................................................ 76
Table 3.6         Darcy flux by depth, calculated from all observations. .......................................... 78
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure 1.1</th>
<th>Typical components of a bioretention system. Adapted from Massachusetts Department of Environmental Protection.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.2</td>
<td>Typical design components of an RSC structure. Adapted from Anne Arundel County, MD 2011.</td>
</tr>
<tr>
<td>Figure 1.3</td>
<td>Major components of an RSC showing variable flow paths. Adapted from Stormwater Solution Engineering.</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Seepage tank partially filled with media, showing the fiber optic cable orientation.</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Fiber optic cable layout attached to fencing mesh with reference points marked in blue tape.</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Ice-filled aluminum chilled cup used to identify reference points on the cable.</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Temperature profile of the fiber optic cable, with the chilled reference point shown relative to its location along the cable.</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>TEMPOS thermal property analyzer measuring the saturated thermal conductivity of a sample glass bead media.</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>Cross-section view of BRUsens cable showing material composition and dimensions. Adapted from Brugg Cables.</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>Temperature profile of fiber optic cable showing calibration baths (blue and red) and sensing section (green).</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>Seepage tank schematic for glass media tests.</td>
</tr>
<tr>
<td>Figure 2.9</td>
<td>Seepage tank schematic for the dual media tests.</td>
</tr>
<tr>
<td>Figure 2.10</td>
<td>Change in cable temperature caused by applying electric current to the stainless steel armoring of the fiber optic cable.</td>
</tr>
<tr>
<td>Figure 2.11</td>
<td>Temperature drop caused by the propagation of the wetting front through the media during fiber optic heating at three points during saturation of the glass bead reference media. The section of cable embedded in media is shown within the blue rectangles.</td>
</tr>
<tr>
<td>Figure 2.12</td>
<td>Change in temperature measured by AHFO-DTS response to varied flow rates in the seepage tank.</td>
</tr>
</tbody>
</table>
Figure 2.13  Volumetric flux measurements compared to Darcy flux calculated from the Perzlmaier model (Eq. 2.9) through glass media in a seepage tank. ................................. 38

Figure 2.14  Observed volumetric flux measurements compared to Darcy flux calculated from the Perzlmaier model (Eq. 2.9) through RSC media in a seepage tank, showing values for glass media (grey) and uncalibrated RSC media (yellow). ................................................................. 39

Figure 2.15  Observed volumetric flux measurements compared to calculated Darcy flux from the Perzlmaier model (Eq. 2.9) in RSC Media, showing calibrated (blue) and uncalibrated (yellow) values .................................................. 40

Figure 2.16  Temperature variability along the center 1 m sensing section of cable during a 20-min heat cycle .................................................................................................................... 41

Figure 3.1  Site map showing RSC watershed and RSC location relative to Southern Boundaries Park, adapted from Koryto et al. 2017 ................................................................. 50

Figure 3.2  RSC plan view showing design features and monitoring equipment deployed, modified from design plans acquired from Jonathan Page. ............... 51

Figure 3.3  Excavated trench along cell 1’s pool width .......................................................................................................................... 54

Figure 3.4  Stainless steel rope between fence posts within the RSC transect (left) and fiber optic cable attachment (right) .................................................................................. 55

Figure 3.5  Schematic showing orientation of the actively heated section of fiber optic cable in the RSC transect ........................................................................................................ 55

Figure 3.6  Electrical splice of fiber optic cable (left) and waterproof enclosure housed above RSC (right) ................................................................................................. 56

Figure 3.7  Non-heated section of cable used to monitor temperature throughout transect passively. .............................................................................................................. 56

Figure 3.8  Temperature profile of the FO cable during initial calibration tests. The x-axis represents the location of the measurement along the FO cable, and the y-axis shows temperature .................................................................................. 57

Figure 3.9  The XT-DTS™ unit and BK 1902 Power supply being controlled via a laptop while housed in the research utility trailer during testing. ................................. 58
Figure 3.10  The research utility trailer (left) housed all sensitive monitoring equipment. Temperature calibration baths were stored outside the trailer near the cable access port (right) .................................................. 59

Figure 3.11  Saturated hydraulic conductivity measurements along monitoring transect. ....... 60

Figure 3.12  Thermal conductivity measurements being made across the monitoring transect before cable installation .................................................. 62

Figure 3.13  Change in temperature as a result of media wetting across depths. ................. 64

Figure 3.14  Flux measurements at 1:26 pm (blue) and 2:05 pm (orange) on April 24, 2021, showing Perzlmaier model output using mean media thermal conductivity (solid line), and ± one standard deviation of thermal conductivity (dashed lines). .................................................. 64

Figure 3.15  Hyetograph showing rainfall intensity, cumulative rainfall, and the time at which flux estimates were made on February 22, 2021 .................................................. 65

Figure 3.16  Distributed flux measurements at four depths on February 22, 2021. The x-axis shows the magnitude of flux (in reverse order to signify the direction of movement), and the y-axis representing the distance of measurement from the left bank .................................................. 66

Figure 3.17  Change in cell 1's pool stage between the first and second heat pulse measurement .................................................. 67

Figure 3.18  Hyetograph showing rainfall intensity, cumulative rainfall, and the time at which flux estimates were made on April 24, 2021 .................................................. 67

Figure 3.19  Distributed flux measurements at four depths on April 24, 2021 with the x-axis showing the magnitude of flux (in reverse order to signify the direction of movement) and the y-axis representing the distance of measurement from the left bank .................................................. 68

Figure 3.20  Darcy flux calculated from the hydraulic gradients between cell 1 and cell 2 through time on April 24th with AHFO-DTS flux measurements represented with red circles .................................................. 69

Figure 3.21  Hyetograph of February 22, 2021 storm event, showing rainfall intensity, cumulative rainfall, and grab water quality sampling times. The green box represents the sampling time for the initial flow, the pink box represents the
sampling time for the peak flow, and the yellow box represents the
sampling time of the falling limb.

**Figure 3.22** Staked column graph showing the up and downstream concentration of 6 analytes at initial, peak, and falling flows on February 22, 2021. .................................................. 70

**Figure 3.23** Column graph showing the up and downstream concentration of TSS at initial, peak, and falling flows on February 22, 2021. ................................................................. 71

**Figure 3.24** Hyetograph of April 24, 2021, storm, showing rainfall intensity, cumulative rainfall, and sampling times. The green box represents the sampling time for the initial flow, the pink box represents the sampling time for the peak flow, and the yellow box indicates the sampling time for the falling limb of the storm event. ........................................................................................................................................... 72

**Figure 3.25** Staked column graph showing the up and downstream concentration of 6 analytes at initial, peak, and falling flows on April 22. .................................................. 73

**Figure 3.26** Column graph showing the up and downstream concentration of TSS at initial, peak, and falling flows on April 24. ................................................................. 73

**Figure 3.27** Boxplot of upstream analyte concentrations obtained from pooling samples collected from February 22 and April 24, 2021. ................................................................. 75

**Figure 3.28** Boxplot of downstream analyte concentrations obtained from pooling samples collected from February 22 and April 24, 2021. ................................................................. 75

**Figure 3.29** Boxplot comparing upstream and downstream TSS concentrations obtained from pooling samples collected from February 22 and April 24. ................................................................. 76

**Figure 3.30** Darcy flux variations across all measurements and depths, with the orange line representing the overall mean flux acquired over the transect. Measurements made at the same time are shown in the same color. .................................................. 77

**Figure 3.31** Water flux variability (averaged across depths) along the width of the monitoring transect, as a function of the overall mean flux. .................................................. 78

**Figure 3.32** Variation of all flux measurements sorted by depth. .................................................. 79

**Figure 3.33** Cross-section view of Durham RSC, showing the average travel distance water would need to travel in the subsurface before reemerging as surface flow. ........................................................................................................................................... 80
Figure 3.34  Cell’s 3 and 4 partially filled with water above the media, four days after rainfall in March, 2021 ................................................................. 81
Figure 3.35  Pre-Wetting temperature field in the monitoring transect............................................. 85
CHAPTER 1

Chapter 1: Review of Literature for Distributed Temperature Sensing in Hydrologic System and Media Based Stormwater Control Measures

1.1 Introduction

The first chapter of this thesis will provide a review of the relevant literature used to inform this study. A range of topics pertaining to the existing methods to measure water fluxes, how fiber-optic distributed temperature sensing has improved environmental monitoring, and information about media-based stormwater control measures are presented.

1.2 Existing Methods for Monitoring Subsurface Water Dynamics, and Their Limitations

In situ soil water measurements have long been valuable in agronomy, infrastructure monitoring, and, more recently, stormwater research (Eger et al., 2017; Perzlmaier et al., 2006; Reicosky et al., 1977). However, an accurate method for determining soil water flux density continues to be an uncertain but highly sought-after hydrologic measurement (Yang et al., 2013). A commonly used technique to measure soil water flux involves using a heated probe embedded in a saturated porous media and using temperature changes to infer the magnitude of water movement around it (Byrne et al., 1967).

Heated probe techniques have been extensively used to measure soil water behavior in laboratory and field settings (Campbell, 1991; Ren et al., 2005; Vidana Gamage et al., 2018). The origins of the heat-up method trace back to G.F Byrne (1967), who constructed a point source instrument consisting of a resistive heater and thermometer. Byrne argued that the change in the temperature field of the porous media caused by a heat emitter is highly dependent on the media's water content and magnitude of flux (Byrne et al., 1967). However, this early approach required extensive calibration and monitored only a narrow range of flow velocities (Byrne et al., 1967).

In recent years, many variants of Byrne's 1967 heat probe technique have been improved to uncover the physical properties of different porous media and allow more precise measurements of water’s movement through the soil profile. However, these variants of the heat probe technique were constrained to the area of influence around the finite measurement probes (Peng et al., 2019; Ren et al., 2005; Ochsner et al., 2003; Campbell, 1991).

In addition to heat pulse approaches, water fluxes have also been inferred using soil tensiometers by measuring the hydraulic gradient between two depths (Mullins et al., 1986). Using estimates
of the soil's hydraulic conductivity, tensiometers allow water fluxes to be calculated using Darcy's Law (Reicosky et al. 1977). While this measurement approach has been used for over half a century, especially for agricultural applications, it offers only localized flux estimates and depends directly on approximations of the soil’s hydraulic conductivity (Hasegawa et al., 1994). Furthermore, tensiometers operate under a limited range of soil moistures and textures, favoring relatively wet conditions in fine-textured soils (Mullins et al., 1986). Tools such as time-domain reflectometry (Ren et al., 2005), electrical conductivity (Sayde et al., 2010), and impedance dielectric reflectometry (Kaleita et al., 2005) are other widely accepted methods to measure soil water content and estimate fluxes. However, they, too, are inherently limited to measuring the conditions immediately surrounding their point of installation and require media-specific water retention curves to relate moisture content to pressure gradients driving flux (Hasegawa et al., 2012).

Additionally, these sensors’ limited sphere of influence often requires installing a multitude of sensors to capture variability and calibration between sensors to ensure the accuracy of their individual measurements (Bittelli, 2011). While these limitations can typically be overcome for agricultural applications, they are not ideal for measuring water fluxes in other settings, such as infrastructure and stormwater monitoring. Such applications rely on fine-scale measurements over large areas to detect localized zones of high or low water flux, which indicate how the system is functioning (Koryto et al., 2017, Perzlmaier et al., 2006).

Traditional limitations of point measurements have been resolved by implementing fiber-optic distributed temperature sensing (FO-DTS), which allows semi-continuous measurements of soil properties (Sayde et al., 2010). Actively heated fiber-optic distributed temperature sensing (AHFO-DTS) provides further utility by extending localized heat-up methods to dispersed measurements. These novel techniques have been applied successfully to measured soil water content at fine spatial (0.15 m to 0.25 m) and temporal scales (1 second – 5 second), otherwise not practical via conventional approaches (Shehata et al., 2020; Sayde et al., 2014; Benitez-Buelga et al., 2014). Additional applications of the AHFO-DTS methods have allowed for monitoring water movements in cases where traditional approaches would not be feasible, such as seepage around dam embankments and groundwater boreholes (Pouladi et al., 2021; Perzlmaier et al., 2006).
1.3 Distributed Temperature Sensing Background

Distributed temperature sensing systems (DTS) are optoelectronic devices capable of measuring temperatures along lengths of optical fibers using the Raman effect (Hausner et al., 2011; Dakin et al., 1985). The temperature measurements are inferred by the interpretation of Raman scattering caused by emitted light from a high-powered laser within the DTS unit through transparent optical fibers (Selker et al., 2006). This DTS approach enables the collection of semi-continuous temperature measurements, with the optical fibers acting as linear sensors in contrast to traditional discrete point measurements. The arrival time of returning backscatter is recorded by the DTS, while Brillouin and Raman scattering principles are applied to the backscattered photons to calculate fiber temperatures (Dakin et al., 1985). Based on the arrival time data and the speed of light in the optical fiber, the calculated temperatures are associated with precise positions on the optical fiber (Tyler et al., 2009). This form of acquisition allows for both high temporal and spatial resolution temperature measurements at various scales ranging from centimeters to kilometers in space and seconds to hours in time (Selker et al., 2006). Historically FO-DTS use was limited to the oil, gas, and telecommunications industries; however, lower system costs and improved spatial resolution has enabled the use of FO-DTS in a wide variety of hydrologic applications (Simon et al., 2020, Tyler et al., 2009, Selker et al., 2006).

1.3.1 Influence of scale on measurement and DTS Use in Hydrologic Monitoring

The ability to measure temperature over spatial scales ranging from dozens of centimeters to several kilometers using FO-DTS is incredibly enticing for hydrologic monitoring (Simon et al., 2020; Selker et al., 2006). Describing, modeling, and measuring hydrologic processes can be profoundly challenging as they are strongly influenced by interacting forces that span a wide range of spatial scales. Much of the data that researchers and practitioners seek to measure in the field represent a relatively small sphere of influence centered at a point (e.g., stream gauge, soil moisture, rain gauges). These data are scale-dependent and may vary greatly depending on the parameter of interest and the location at which the measurement is made, meaning these data may not represent the conditions beyond the point of acquisition (Selker et al., 2006).

At the field scale, for example (>100m, <1km), soil moisture has been shown to vary widely depending on proximity to landscape features, time in the diurnal cycle at which measurements are made, and soil characteristics (Shehata et al., 2020; Brocca et al., 2010). To capture this
variability across space and time using conventional means of measuring soil moisture (such as capacitance probes, time-domain reflectometry, gravimetric scales, and neutron probes) can be costly and still provide information at only a few selected points (Brocca et al., 2010). This limitation is especially evident in situations where sub-meter data can be critical in detecting design flaws. For instance, the performance of green stormwater infrastructure can be undermined by areas of preferential flow that may only span tens of centimeters and could avoid detection from a point source instrument (Blecken et al., 2017; Koryto et al., 2017).

By allowing semi-continuous measurements at high temporal and spatial resolutions, novel DTS measurement techniques have filled traditional gaps in data collection (Shehata et al., 2020).

1.3.2 Extensions of the Heat Up Method to AHFO

Since their inception, heated probe methods have been used in various configurations to target specific physical properties of soil and quantify water contents, flow paths, and fluxes (Heitman et al., 2003; Ochsner et al., 2003; Campbell, 1991; Byrne et al., 1967). Advances in data analysis have improved the capability of heated probe instruments by accounting for additional background soil properties and conditions (Ochsner et al., 2003; Hopmans et al., 2002; Ren et al., 2000). However, the use cases for these sensors in the field are limited by their small area of influence and variations between sensors (Simon et al., 2020; Vidana Gamage et al., 2018). In addition, any discrete point measurement device cannot measure large-scale process and, therefore, require several sensors to capture the variability of phenomenon throughout space and time (Ochsner et al. 2003).

Fortunately, many of the problems associated with point source devices are resolved by implementing actively heated distributed temperature sensing (AHFO-DTS) to replicate traditional heat pulse methods over much larger scales (Shehata et al., 2020; Sayde et al., 2014; Aufleger et al., 2008). Actively heating the fiber optic cable enables more information to be obtained about the cable’s surrounding environment. By extending the traditional heated probe principles (described by Yang et al., 2013; Heitman et al., 2003; Ochsner et al., 2003; Ren et al., 2000; Campbell, 1991 and others) to DTS acquisition methods, water flux measurements can be acquired in semi-continuous profiles over vast spatial distances while eliminating the need for calibration between sensors (Sayde et al., 2014). This approach has become commonplace in situations where high spatial resolution data is required, such as to track water movement.
through rock fracture networks in boreholes (Read et al., 2014), quantify the extent of saltwater intrusion in aquifers (Folch et al., 2020), or measure the spatial variability of soil moisture across a field (Shehata et al., 2020; Sayde et al., 2014). AHFO-DTS has also been used as a tool to detect fine-scale changes in environmental conditions, like leak detection and regional water fluxes around dams (Perzlmaier et al., 2004 & 2006). These studies show that AHFO-DTS is suitable for a wide range of applications.

AHFO-DTS methods have demonstrated the potential to solve the issue of scale when quantifying water flux behavior beyond a point measurement (Sayde et al. 2014; Perzlmaier et al. 2006). These advances in data acquisition and distributed measurements stand to provide hydrologists, engineers, and soil physicists a more effective tool to understand hydrologic processes at scales and resolutions previously unobtainable.

1.4 Stormwater Control Measures and Regenerative Stormwater Conveyance

Background

Nutrients, sediment, and other pollutant loadings from urban and agricultural areas cause many adverse effects to waterways across the United States and beyond (Oelsner and Stets, 2019). Eutrophication, harmful algal blooms, and unsafe drinking water present widespread damage to ecosystems and human health, driving a need for significant resources and research to find solutions to these problems (Smith, 2003). Nature-based solutions such as stream restoration, riparian buffers, stormwater control measures (SCMs), and pollution best management practices (BMPs) have increasingly been implemented for nutrient retention and removal by utilizing and enhancing ecological processes (T. Brown et al., 2010; Hunt et al., 2008; K. Brown, 2000). To improve the performance of these practices, ecological and environmental engineers have created designs such as bioretention cells, regenerative stormwater conveyances (RSCs), and riparian buffers to improve nutrient and sediment reduction efficiencies using natural materials (Cizek et al., 2018; Davis et al. 2010; Cooper, 1990).

However, SCMs such as RSCs and bioretention cells have shown varying levels of success at reducing nitrogen, phosphorus, and sediments under a range of designs (Cizek et al., 2018; Koryto et al., 2017; Davis et al., 2010; Helmreich et al., 2010).
1.4.1 Bioretention Basins

Bioretention basins are among the most commonly used stormwater control measures (SCMs) and rely on porous media to filter, infiltrate, and detain stormwater (Endreny and Collins, 2009). In bioretention systems, filtration is often the primary treatment mechanism, supported by evapotranspiration, absorption, infiltration, and biotransformation (Davis et al., 2006). Bioretention can also provide stormwater quantity mitigation by attenuating peak runoff and reducing runoff volume through temporary detention and infiltration of water into the native soil below the system (Hunt et al., 2008). These systems typically aim to capture the "first flush" of stormwater caused by rainfall events that would ordinarily end up in waterways. Instead, bioretention allows for the treatment and storage of pollutant-laden stormwater in the system's media (Winston et al., 2016; Davis et al., 2012). Hunt et al. 2008 reported pollutant reductions of 32% for total nitrogen, 60% for TSS, and 31% for total phosphorus in an urban bioretention basin in Charlotte, North Carolina. Davis et al. 2006, reported similar results with reduction ranges of 70-85% of phosphorus and 55-65% of total Kjeldahl nitrogen with high nutrient inputs. Another benefit of these structures is that they can be scaled to suit various situations (Hsieh and Davis, 2005). Bioretention cells have been constructed to treat runoff from parking lots, industrial grounds, and tertiary wastewater effluent showing efficacy at various scales (Austin, 2012). These structures have proven to effectively reduce both nutrient and heavy metal loading (Austin, 2012).

Common influential factors affecting pollutant removal performance found in Mangangka et al., 2016; Austin, 2012; Davis et al., 2010; Endreny and Collins, 2009 studies include:

1. Rainfall characteristics
2. Inflow pollutant concentration
3. Drainage area to system area ratio
4. Total detention time of water through the system
5. Fluctuation in water table elevation relative to the retention basin/cell
6. The basin’s outflow parameters including the diameter of outflow, biofouling potential, and ease of maintenance.
7. The volume of internal water storage
1.4.2 Regenerative Stormwater Conveyance

Regenerative stormwater conveyance (RSC) is an innovative approach to restoring highly degraded incised stream channels that combines stormwater treatment, infiltration, and conveyance within one constructed system. RSC aims to reestablish conditions essential to healthy, natural stream ecosystems by modifying incised channels to reconnect with the floodplain, establish native vegetation, and improve nutrient cycling through the system (T.Brown et al., 2010). RSC systems combine features and treatment benefits of swales, infiltration, filtration, and wetland practices. RSC systems consist of a series of shallow aquatic pools, riffle-weir grade-controls, native vegetation, and underlying sand and wood chip beds to treat, detain, and convey storm flow (Duan et al., 2019). They are often designed to carry extreme flows such as the 10-year or 100-year flow event in a non-erosive manner (T.Brown et al., 2010).

Like bioretention cells, RSCs utilize highly porous media typically composed of woodchips or mulch and sand to promote infiltration and energetically favorable conditions for denitrifying bacteria (Duan et al., 2019). A critical distinction between the two practices is that bioretention cells are typically located in an area that experiences temporary run-on, from a small drainage area with typically one land use condition, such as parking lots or other impervious surfaces in
urban areas (Wardynski et al., 2012). In contrast, RSCs are implemented in ephemeral or intermittent open-channel systems that usually collect runoff from a larger, more diverse drainage area (Cizek et al., 2017 & 2018; Koryto et al., 2017). RSC systems have been extensively applied throughout the mid-Atlantic for nutrient control and as an ecosystem restoration practice for eroded or degraded outfalls and drainage channels (Cizek et al., 2018; Koryto et al., 2017, Anne Arundel County MD, 2012; T.Brown, 2012). It can be used in places where traditional stormwater practices may be challenging to implement (T. Brown et al., 2012). The practice was first widely studied in the state of Maryland, under the name step-pool storm conveyance, where an emphasis on pollutant removal has been placed on the forefront of stream restoration efforts to address degraded stream health across the region (Anne Arundel County, 2012; K. B. Brown, 2000). An illustration of a typical RSC system can be found in Figure 1.2.

![Figure 1.2 Typical design components of an RSC structure. Adapted from Anne Arundel County, MD 2011.](image)

Additionally, these systems have shown promise in reducing heavy metals, creating habitat, and mitigating the flashiness of stormwater flows (Koryto et al., 2017; Cizek et al., 2017 & 2018). Dune et al. 2019 paired study of two RSC systems with two representative controls in Anne Arundel country, Maryland, found that nitrogen removal was impacted by the concentration of nitrate inputs and quality of carbon included in the media of the structure. The Dune study reported a 16-36% reduction of total dissolved nitrogen in the RSC with high nitrate inputs. However, they found that the RSC with lower nitrate inputs (<0.15 mg/L) showed a negligible reduction in concentration, suggesting that influent concentration is an essential factor in performance. Similarly, Koryto et al. 2017 saw only modest reductions in nitrogen during a 14-month observation period of an RSC in Durham North Carolina, reporting only a 4.4% reduction.
in total nitrogen. While more research is needed to understand these systems more comprehensively and under varied conditions, the existing literature shows significant trends and design parameters that provide crucial insight moving forward.

1.4.3 RSC Design Guidance

Documents from the City of Annapolis, Anne Arundel County MD, and Duan et al. 2019 study provide some "best practices" guidance into the design of RSC structures. Additional information about the specifications of the material is included in Table 1.1. These guidelines include:

1. The longitudinal slope should not exceed 5 percent. If the overall slope exceeds 5 percent, then one or more cascades should be designed into the system.
2. The length of the grade control structure should be equal to the length of the pool proceeding it.
3. The depth of the flow over the grade control structures should be a maximum of 10 cm (4 inches).
4. The pool depth should be a minimum of 46 cm (1.5 feet) and a maximum of 92 cm (3 feet).
5. The sand bed should consist of at least 80% medium grain sand and no more than 20% wood chips and run beneath the RSC System's entire length. In addition, a 30 cm (1-foot) layer of type 67 gravel (or similar) should be placed beneath the sand bed and base material to prevent preferential flow and undermining of the sand bed.
6. A 30 cm layer of cobbles (minimum of 15 cm diameter) should be placed over the run separating cells of the structure to minimize scour.
Table 1.1 Suggested material specification for RSC construction. Adapted from City of Annapolis, Anne Arundel County, and Duan et al. 2019.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Riffle Boulders</td>
<td>Class 2 or 3 Rip Rap (Average Diameter of 48.8 cm – 67.1 cm)</td>
</tr>
<tr>
<td>Riffle Cobbles</td>
<td>Equivalent in size to Gabion Stone (minimum diameter of 15.2 cm)</td>
</tr>
<tr>
<td>Sand/Woodchip Bed</td>
<td>The sand component of the sand/wood chip bed should be between 0.5 – 1.0 mm.</td>
</tr>
<tr>
<td></td>
<td>Aged, hardwood chips of uniform size are preferred. The woodchips shall</td>
</tr>
<tr>
<td></td>
<td>be added to the sand mix, approximately 20 percent by volume, to increase</td>
</tr>
<tr>
<td></td>
<td>the organic content, promote plant growth, and provide a carbon source.</td>
</tr>
<tr>
<td>Mulch</td>
<td>The mulch, if used, should be applied as a top dressing over the RSC System.</td>
</tr>
<tr>
<td></td>
<td>It should consist of a 100% organic wood mulch, with a pH of between 6.0 and</td>
</tr>
<tr>
<td></td>
<td>7.0, and moisture content between 30 and 55%</td>
</tr>
</tbody>
</table>

1.4.4 Denitrification in Media Based Treatment Systems

One of the primary methods implemented by designers to reduce nitrate loading in the environment is to optimize the conditions needed for biological denitrification (Bachand & Horne, 1999). Biological denitrification utilizes specialized or indigenous microbial communities to convert nitrate (NO$_3^-$) to gas-phase N$_2$ through the following chemical reaction:

$$[2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O] \quad \text{Eq. 1.1}$$

This process requires an electron donor source and occurs primarily in anaerobic conditions where the lack of oxygen makes the reaction energetically favorable (Kim et al., 2003). Wetlands, bioretention cells, and RSC utilize these principles to optimize this reaction rate by providing ideal conditions for microbial populations while also encouraging stormwater infiltration (Duan et al., 2019; Hunt et al., 2008; Bachand and Horne, 1999). Biological denitrification has been used to treat nitrate successfully in biological systems, including constructed wetlands, woodchip bioreactors, and other stormwater management practices like bioretention and RSC (Duane et al., 2019; Christianson et al., 2013; Davis et al. 2006). Bachand
and Horne reported an average nitrate removal rate of 125mg NO₃⁻/m²/day for 115 monitored wetland locations. Bioretention facilities have recorded a more variable range of nitrate removal efficiencies, attributed partially to influent concentrations and hydraulic residence times (Davis et al., 2006). While Davis et al.'s 2006 study proved bioretention to be effective at reducing total nitrogen, the study also reported low nitrate reductions (>20%), with authors suggesting a lack of anoxic contact time as a factor for its limited performance. To optimize biological denitrification, water must have sufficient residence time in low oxygen conditions, along with a microbial labile carbon source (Law et al., 2018; Schmidt and Clark, 2013; Cameron and Schipper, 2010; Davis et al. 2006).

Designed systems, such as RSCs, implement these conditions via the transfer of stormwater to shallow groundwater by infiltration into the media (Duan et al., 2019). Total residence time in RSCs is further increased by the number of step pools constructed. Duan et al. study found that dissolved oxygen trended between 39%-76% lower in concentration in the pair of RSCs they studied than their representative control reaches without step pools with shorter retention times. These findings by Davis et al. and Duan et al. suggest that short-circuiting or preferential flow paths may be a contributing factor to inadequate performing systems. Furthermore, few studies exist that monitor the long-term performance of these media-based treatment practices. However, a 2014 case study of stormwater wetland offered insight that maturation (or aging) of nature emulating practices can have increased water quality benefits compared to the period shortly after implementation (Merriman & Hunt, 2014). Merriman & Hunt found that a 5-year-old constructed stormwater wetland had Overall nitrogen event mean concentration (EMCs) were reduced as the wetland matured. Wetland maturation appeared to positively impact the treatment processes, especially of inorganic nitrogen. A summary of select literature stating the treatment mechanism, target pollutant, and design structure can be found in Table1.2.
Table 1.2 Summary of select literature on the treatment mechanisms employed by different SCM structures to reduce pollutants.

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Nutrients or Pollutants Treated</th>
<th>Pollution Source</th>
<th>Treatment Mechanisms</th>
<th>Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austin, 2012</td>
<td>Portland, OR</td>
<td>TSS, E.Coli, TN, P, Copper, Pb, Zn</td>
<td>Urban Stormwater</td>
<td>Infiltration, Assimilation, Denitrification</td>
<td>Biorientation Cell</td>
</tr>
<tr>
<td>Endreny et al. 2009</td>
<td>Syracuse, NY</td>
<td>TSS, NO₃ (Indirectly)</td>
<td>Wastewater discharge</td>
<td>Infiltration</td>
<td>Biorientation Cell</td>
</tr>
<tr>
<td>Hunt et al. 2008</td>
<td>Charlotte, NC</td>
<td>TN, TKN, NH₄, NO₃, NO₂, TP, Zn, Pb</td>
<td>Urban stormwater</td>
<td>Infiltration, Filtration, Denitrification</td>
<td>Biorientation Cell</td>
</tr>
<tr>
<td>Mangangka et al. 2016</td>
<td>Multiple</td>
<td>TSS, TP, NO₂, NH₄, NO₃, TN</td>
<td>Ag &amp; Urban Stormwater</td>
<td>Detention, Denitrification, Infiltration</td>
<td>Biorientation Cell</td>
</tr>
<tr>
<td>Brown et al. 2010</td>
<td>Anne County, MD</td>
<td>NO₃, NH₃</td>
<td>Urban Stormwater</td>
<td>Infiltration, Denitrification, Adsorption</td>
<td>RSC</td>
</tr>
<tr>
<td>Cizek et al. 2017</td>
<td>Supply, NC</td>
<td>TSS</td>
<td>Stormwater</td>
<td>Exfiltration</td>
<td>RSC</td>
</tr>
<tr>
<td>Cizek et al. 2018</td>
<td>Multiple in NC</td>
<td>NO₃, TN, TKN, TAN, TP, OP</td>
<td>Stormwater</td>
<td>Denitrification, Plant-uptake, Infiltration</td>
<td>RSC</td>
</tr>
<tr>
<td>Koryto et al. 2017</td>
<td>Durham, NC</td>
<td>TSS, TP, TN, ZN</td>
<td>Urban drainage</td>
<td>Denitrification, Plant-uptake, Infiltration</td>
<td>RSC</td>
</tr>
<tr>
<td>Bachand and Horne, 1999</td>
<td>Riverside, CA</td>
<td>NO₃, NH₃, Organic N, TN</td>
<td>Urban stormwater</td>
<td>Denitrification, Plant-uptake</td>
<td>Macrocosm Wetlands</td>
</tr>
<tr>
<td>Filoso &amp;Palmer, 2009</td>
<td>Cape Charles, MD</td>
<td>TN, TSS</td>
<td>Urban Wastewater</td>
<td>Plant-uptake, Ecosystem Metabolism</td>
<td>Stormwater BMP</td>
</tr>
<tr>
<td>Burford et al. 1978</td>
<td>Ames, IA</td>
<td>NH₃, NO₃</td>
<td>Fertilizer</td>
<td>Denitrification, Adsorption</td>
<td>Mesocosm</td>
</tr>
<tr>
<td>Lyn Dennis, 1987</td>
<td>Ames, IA</td>
<td>NO₃</td>
<td>Fertilizer</td>
<td>Stimulated Denitrification</td>
<td>Woodchip Bioreactor</td>
</tr>
<tr>
<td>Cooper, 1990</td>
<td>New Zealand</td>
<td>NO₃</td>
<td>Sediments</td>
<td>Denitrification, Plant-uptake, Infiltration</td>
<td>Riparian Buffer</td>
</tr>
</tbody>
</table>
1.5 Knowledge Gaps and Relevance of Our Study

While the rate water flows through media-based treatment practices can be a crucial indicator of its effectiveness at treating a variety of pollutants, high-resolution measurements of this process are difficult at present and warrant further investigation (Dune et al., 2019; Cizek et al., 2018; Davis et al., 2006). Additionally, this quantity and rate of water moving through the media is often a highly uncertain term when creating a water balance, causing difficulty tracking where water enters and exits a system (Cizek et al., 2017; Eger et al., 2017). Discrete measurements of water fluxes would be cumbersome and may have significant spatial variability, making DTS monitoring an exciting alternative to traditional in situ methods (Shehata et al., 2020). With RSC rapidly being implemented across the mid-Atlantic region of the United States and beyond, researchers need a better way to evaluate their effectiveness and locate deficiencies (Duan et al., 2019). While water balances have provided some insight into the efficacy of RSC and have been made possible by automated water sampling, weather stations, and flow monitoring, fine-scale water movement remains hidden within the structures subsurface (Koryto et al., 2017). Further, although nutrient transformation, adsorption, and retention have been shown to take place primarily in the RSC subsurface (Figure 1.3), little research has been done to quantify the rate of water passing through the media. Thus, estimates of effective treatment time, the magnitude of flux, and hydraulic variations (and flaws) are difficult to quantify (Duan et al., 2019).

Figure 1.3 Major components of an RSC showing variable flow paths. Adapted from Stormwater Solution Engineering.
To overcome these systems' "black box" effects, better instrumentation is needed to measure the complex and potentially varied rates of water moving through their media. Advances in distributed temperature sensing offer an opportunity to measure semi-continuous data over large scales and at high temporal and spatial resolutions, not previously possible in stormwater control measures. To address these challenges, we will be implementing an AHFO-DTS monitoring approach allowing us, for the first time, to measure the magnitude, variability, and range of water fluxes throughout the media of an RSC system under varied conditions. Methods for monitoring water movements in RSC media will be explored in detail in the remaining chapters of this thesis.

1.6 Research Objectives

Chapter 2 of this thesis will focus on testing, calibrating and validating AHFO-DTS methods during laboratory seepage tank trials to track the wetting front propagation and calculate distributed water fluxes in two kinds of media. Chapter 3 will detail how such methods were applied to monitor water movements in the media of an RSC in the field. It will present results and their implication for RSC, limitations of the study, and conclusions.

Study Objectives addressed in CH 2:

- Verify the application of previously described relationships between distributed temperature measurements and water flow in saturated media using AHFO-DTS.
- Use temperature changes to measure the propagation of the wetting front through two types of media.
- Generate media-specific calibration parameters needed to validate the physical model developed by Perzlmair et al. (2004) to measure dispersed water flux using AHFO-DTS.
- Quantify the accuracy of the Perzlmair model to calculate water flux in 1) uniform media acting as a reference and 2) media collected from an RSC.

Study Objectives addressed in CH 3:

- Quantify the spatial variability of the media’s ability to retain and transport water using a novel AHFO-DTS monitoring approach and in situ hydraulic conductivity measurements.
• Track and measure the propagation of the wetting front from the initial surface run-on to the media using AHFO-DTS.
• Assess the practice’s water quality performance by collecting time distributed upstream and downstream grab samples during storm flow events.
• Estimate the hydraulic retention time of water moving through the media and its variability based on the fluxes calculated during monitoring.
1.7 References


Law, J. Y., Soupir, M. L., Raman, D. R., & Moorman, T. B. (2018). Exploring multiple operating scenarios to identify low-cost, high nitrate removal strategies for electrically-
https://doi.org/10.1016/j.ecoleng.2018.05.001


https://doi.org/10.1111/j.1365-2389.1986.tb00397.x

https://doi.org/10.2136/vzj2003.5720


https://doi.org/10.1016/j.jhydrol.2021.126450


CHAPTER 2
Chapter 2: Thermal Response of Actively Heated Fiber Optics Under Varied Flow
Conditions – A Seepage Tank Study.

2.1 Abstract
Distributed temperature sensing (DTS) has proven to be a viable means of detecting variations in hydrologic phenomenon at the sub-meter scale. Tests conducted by Perzlmaier et al. 2004 & 2006 outlined the utility of actively heated fiber-optic distributed temperature sensing (AHFO-DTS) to measure seepage velocity based on the properties of the media in which it was embedded. The objective of this study is to verify the application of AHFO-DTS to detect the presence of water and estimate water flux in porous media by leveraging previously described relationships between temperature and water flow in saturated media.

The application of AHFO-DTS for these novel purposes was validated in a laboratory setting by conducting a series of tests in a seepage tank containing two different media: (1) uniform glass beads (reference media) and (2) sand/mulch mix collected from a regenerative stormwater conveyance system. Eight meters of fiber optic cable were fixed to plastic fencing and embedded in the media, with five 1-meter sections oriented perpendicular to the flow in the tank. Observations from these seepage tank trials suggest that AHFO-DTS can be used to track the structure and arrival time of the wetting front. The change in temperature caused by the presence of water, by changing the volumetric heat capacity of the media, enabled high temporal (5 seconds) and spatial (15 cm) resolution observations. Additionally, the seepage tank experiments showed that AHFO-DTS could measure changes in temperature, caused by the rate of water flow via convective cooling, through various media. The model proposed by Perzlmaier et al. 2004 performed better in tests conducted in glass bead media (RMSE 0.13 cm hr⁻¹) than in sand/mulch media (RMSE 0.61 cm hr⁻¹), when compared to the flux rate found by monitoring the flow rate into the seepage tank. However, calibration of the model by adjusting uncertain media parameters improved the estimate of flux through the seepage tank to an RMSE of 0.21 cm hr⁻¹, representing less than 10% measurement error across the range of flows tested.

Seepage tank tests indicate that using the methods described by Perzlmaier et al. 2004 & 2006 can enable distributed flux measurements and the propagation of wetting fronts in regenerative stormwater conveyance structures (RSC); thereby allowing subsurface water movements to be
quantified with a spatial resolution that has never previously been attempted in a media-based treatment system.

2.2 Introduction

This chapter outlines a series of seepage tank experiments used to track the propagation of the wetting front and quantify the magnitude of water fluxes using an actively heated fiber-optic distributed temperature sensing system (AHFO-DTS).

Distributed temperature sensing (DTS) has proven to be a viable means of detecting variations in hydrologic conditions at the sub-meter scale, including in soil moisture content, land surface energy exchanges, borehole water circulation, and stream temperature (Tyler et al., 2009; Selker et al., 2006). As the precision and availability of these systems have increased in recent years, the applications for environmental monitoring have become more widespread (Selker et al., 2006). As outlined in the first chapter of this thesis, DTS systems were first developed decades ago and were primarily used in the energy and telecommunications sectors (Tyler et al., 2009). They operate by using optical fibers as temperature sensors, allowing for high temporal and spatial resolution temperature measurements that would otherwise be challenging to acquire (Shehata et al., 2020; Kurashima et al., 1990; Dakin et al., 1985). DTS systems have also been configured such that the fiber optic cables’ metal cladding acts as a resistive heater when electrical current is applied, known as actively heated fiber-optic distributed temperature sensing (AHFO-DTS). This approach allows for more information about the cable’s surrounding environment to be inferred by observing the effects of the environment on the change in temperature caused by the induced heating (Vidana et al., 2018; Sayde et al., 2014).

Many studies have demonstrated the ability of AHFO-DTS to measure water content and quantify water movements in porous media (Shehata et al., 2020; Vidana Gamage et al., 2018; Sayde et al., 2014; Benitez-Buelga et al., 2014; Perzlmaier et al., 2004 & 2006). Perzlmaier et al.’s 2004 and 2006 studies sought to measure water fluxes directly by using fiber optics to monitor localized seepage in embankment dams and earthen structures. In contrast, Sayde et al.'s 2014 study calculated water flux density indirectly using waterfront travel time between different depths and moisture contents. Both Perzlmaier et al.’s and Sayde et al.’s techniques utilized heated measurements that relied on induced temperature gradients to reveal seepage and, where feasible, quantify flux. These studies showed that AHFO-DTS could be applied to measure a
variety of environmental phenomena. Further, studies have shown the importance of monitoring subsurface water movements to provide a more complete understanding of media-based treatment systems, such as bioretention cells or regenerative stormwater conveyance systems, which rely on their media's ability to infiltrate and store water to reduce pollutant loading into waterways (Duan et al., 2019; Koryto et al., 2017; T. Brown et al., 2010).

This chapter details the laboratory tests conducted to (1) test the capability of AHFO-DTS to measure the propagation of the wetting front through porous media, (2) generate media-specific parameters needed to calibrate the physical model developed by Perzlmaier et al. (2004) and (3) quantify the accuracy of the model to measure water fluxes using AHFO-DTS. These laboratory tests helped inform the deployment of AHFO-DTS in a regenerative stormwater conveyance structure (RSC), which will be discussed in the third chapter of this thesis.

2.3 Materials and Methods

2.3.1 Overview

To implement the Perzlmaier water flux model, a series of seepage tank tests were conducted. The DTS unit selected for testing was an Ultima™ DTS unit made by Silixa. Data were collected using 5-second integration times with a 0.125m sampling resolution (Silixa Ltd, United Kingdom). These temperature measurements were later calibrated using two PT-100 Temperature probes during post-processing with software supplied by the Center of Transformative Environmental Monitoring Programs (CTEMPS, USA). One hundred meters of BRUsens™ 3.8 mm fast response, multimode, fiber optic temperature sensing cable with stainless steel armoring was selected to measure temperature within the tank (Solifos Fiber Optic Systems, USA). This cable was positioned into a serpentine shape within the seepage tank before it was filled with media. This was done to optimize the length of the cable perpendicular to the direction of flow through the tank. The thermal response of water flowing through the media and cable was then measured while heat was applied to the cable, allowing for the inference of water flux. These tests ultimately informed what parameters must be measured and calibrated when applying this technique in the field or heterogeneous media.
2.3.2 Seepage Tank Design

The testing methodology employed by our study required the use of a seepage tank capable of generating various flux rates to test the heated fiber optic cable's response to moving water. An integral part of the tank's design was the ability to continuously and precisely monitor the water’s flow rate into the tank while still being large enough to ensure edge effects were reduced.

An S1 Armfield drainage and seepage tank™ (Armfield, United Kingdom) was modified with a section of perforated PVC cut in half radially to help distribute water flow across the bottom of the tank. The distribution pipe was covered with 10 cm of #8 pea gravel (3.2-9.5 mm) and covered with a mesh fabric designed for piezometer screening. This was done to prevent mobilization of fine particles through the tank and prevent clogging. The media to be tested was then packed on top of this layer, separated by the mesh fabric. The total working volume of the tank had dimensions of 150 cm length, 10 cm width, and 60 cm height. Two drainage orifices were located at the top of the tank to continuously recycle water through the system from a storage reservoir below the working section. The seepage tank is shown in Figure 2.1.

![Seepage tank partially filled with media, showing the fiber optic cable orientation.](image)

The tank was configured with a ½ horsepower sump pump to move water through the bottom of the tank. An E-Series™ solid-state ultrasonic flow meter (15 mm model) from Badger meter was used to monitor flow pumped from the storage reservoir up through the media in the seepage tank (Badger Meter, USA). The manufacture specification for device accuracy at the flow ranges tested was ±1.5%, corresponding to an uncertainty in flows ranging from 0.825 cm$^3$ s$^{-1}$ to 1.8 cm$^3$ s$^{-1}$. The design configuration provided variable flow rates, ranging from 40 cm$^3$ s$^{-1}$ to 120 cm$^3$ s$^{-1}$, through nearly 90 liters (0.09 m$^3$) of media. These flow rates were also used to monitor the
volumetric water flux by dividing the inflow rate by the cross-sectional area of the tank. In addition, two butterfly valves were installed to divert water either through the tank past the flow meter or back into the water reservoir. This was done to regulate the flow rate diverted into the sump pump and prevent unnecessary pressure on the pump while adjusting flow rates.

2.3.3 Fiber Optic-Cable Orientation and Referencing

A 1.5 mm thick, flexible section of 55 cm by 140 cm of polypropylene plastic fencing, with 1 cm by 1 cm linkages, was used to frame the optical fiber cable in a serpentine orientation with 10 cm spacing between sections (see Figure 2.2). This configuration was designed to maximize the length of fiber optic cable perpendicular to the flow direction through the tank without creating sharp turns that create excessive signal losses inside the cable.

![Figure 2.2 Fiber optic cable layout attached to fencing mesh with reference points marked in blue tape.](image)

The fiber optic cable required georeferencing to distinguish the location of measurements along the cable length relative to their position on the frame. Fourteen reference points (marked in blue tape in Figure 2.2) were used to aid in post-processing data parsing. Reference points were located at the start and ends of each bend in the cable and near the electrical splice. This referencing was done so that only straight sections of the cable, perpendicular to flow, would be used in the analysis. Referencing was carried out by running the DTS unit to collect temperature measurements along the FO cable while placing a narrow-chilled aluminum cup on the point of interest on the cable (see Figure 2.3). Once a clear response was observed on the DTS temperature profile (see Figure 2.4), the distance shown on the DTS viewer software was noted with the corresponding location on the fencing. A clear response was observed after
approximately one minute of contact. After referencing, the fencing with the fiber optic cable attached was placed in the center of the seepage tank (Figure 2.1).

Figure 2.3 Ice-filled aluminum chilled cup used to identify reference points on the cable.

Figure 2.4 Temperature profile of the fiber optic cable, with the chilled reference point shown relative to its location along the cable.

2.3.4 Media Specifications and Physical Properties

1 mm soda glass beads supplied by Preciball™ were selected as the initial test media in the seepage tank (Preciball, USA). This allowed us to test the Perzlmaier model under well-characterized conditions with uniform particle size, thermal properties, and hydraulic characteristics. A sieve analysis showed that 79% of the bulk media had a particle size between 0.841 mm to 1.00 mm. All particle sizes outside this range were discarded from testing. Next thermal conductivity measurements were made in six samples of the glass bead media, each contained in a fully saturated 500 cm³ beaker (Figure 2.5). The thermal conductivity of the media was measured under saturated conditions using a METER Group TEMPOS Thermal Properties Analyzer, utilizing the SH-3 dual needle probe after the media was then allowed to settle to its natural bulk density, estimated to be 1.8 g cm⁻³. (METER Group Inc., USA). The mean and
standard deviations of the six measurements were 0.8557 W m\(^{-1}\) K\(^{-1}\) and 0.0065 W m\(^{-1}\) K\(^{-1}\), respectively.

![Figure 2.5 TEMPOS thermal property analyzer measuring the saturated thermal conductivity of a sample glass bead media.](image)

A second media collected from the RSC tested in Chapter 3 was also tested in the seepage tank set-up. This media consisted of 80% medium sand (~0.2 mm) and 20% woodchip/mulch by volume. Due to the significant portion of variable organic material, sieving or hydrometer tests were unreliable, making this media more challenging to classify thoroughly. However, information from the designer of the RSC provided a reference for the particle size of the sand component, estimated to be 0.2 mm.

Like the glass bead media test, six measurements of the RSC material’s saturated thermal conductivity were taken from different media samples collected from the field, with a bulk density of 1.38 g cm\(^{-3}\). The mean value of the six thermal conductivity measurements was 1.0241 W m\(^{-1}\) K\(^{-1}\) and the standard deviation was 0.0142 W m\(^{-1}\) K\(^{-1}\). Note that the standard deviation of the RSC media was more than double the glass beads’ deviation.

2.3.5 Distributed Temperature Sensing and Heat Pulse Methodologies

As mentioned in the first chapter of this thesis, many studies have demonstrated the ability of AHFO-DTS to measure water movements in porous media.

The approach detailed by Perzlmaier et al. (2004 & 2006) and later utilized by Gregory et al. (2009) was employed to quantify water flux spatially throughout a seepage tank. Their methodology used the change in temperature experienced by the fiber optic cable during a
controlled heat pulse event, the geometry of the fiber optic cable, and the thermal properties of media and cable to interpret water flux. The cable selected for testing was 100 meters of BRUsens fiber optic cable, composed of an inner multimode fiber-optic filament capable of measuring temperature and stainless-steel armoring, allowing rigidity and an ability to act as a resistive heater (see Figure 2.6).

![BRUsens cable cross-section](image)

Figure 2.6 Cross-section view of BRUsens cable showing material composition and dimensions. Adapted from Brugg Cables.

Much of the 100 m length was used for post-processing calibration and validation “baths” where the cable is held in stable, known temperatures. Thirty-two meters were submerged in a 60-L cooler with a circulating ice slurry. Similarly, thirty-five meters were held in a separate 60-L “warm” circulating water bath, each equipped with a class-A PT-100 temperature probe connected to the DTS unit that reported temperature inside the baths every 5-seconds with an accuracy of ± 0.06 °C (Figure 2.7).

![Temperature profile](image)

Figure 2.7 Temperature profile of fiber optic cable showing calibration baths (blue and red) and sensing section (green).
A detailed description of the calibration procedure can be found in Hausner et al. (2011). Post-processing calibration to improve the precision of the temperature measurements was achieved using CTEMps MATLAB DTS Toolbox obtained from the Center for Transformative Environmental Monitoring Programs (CTEMPS, 2015). Of the remaining cable not used for calibration and validation, 8 meters were mounted to the plastic fencing material (as shown in Figure 2.2 above). An electrical splice was then made on each end of the 8 m cable run to supply uniform heating throughout the 8-meter section of the cable. The heating of the cable was achieved by splicing two 2.2 m sections of 6-gauge copper wire to the stainless steel armoring of the BRUsens™ cable on each end of the 8-meter section. The copper wire was electrified by a BK Precision 9205 600W DC power supply (B&K Precision Corp., USA). The resistivity of the cable’s stainless steel jacket was determined using a multimeter to be 0.4143 Ω·m⁻¹ for a total resistance of 3.31 Ω for the 8-meter run. Perzlmaier et al. 2006 recommended using a minimum power of 10 W·m⁻¹ to heat the cable. A targeted heat flux of 20 W·m⁻¹ was selected for testing to increase the magnitude of the temperature change generated by the heat pulses. Using Ohms law, the current required to reach the targeted heat flux per unit length of 20 W·m⁻¹ was determined. This required a total of 160 Watts to be applied from the BK Power supply.

2.3.6 Glass Bead Media Tests

The fiber optic cable was placed into the center of the seepage tank. The glass bead media was then placed around the fencing to 2.5 cm below the drainage ports and allowed to settle to its natural dry bulk density approximated to be 1.8 g cm⁻³ (Figure 2.8). No further settling of the media was observed throughout the experiment. An initial heat test was conducted before saturating the tank to ensure uniform heating throughout the 8-meter cable run. Next, the DTS was configured to acquire data every second while supplying continuous heating at 160 watts to the cable in the unsaturated media. Water was then pumped through the tank at 64 cm³ s⁻¹ saturating the media to observe the temperature response of the cable as the wetting front moved through the tank.
Next, eight saturated flow tests were conducted at flows of 57 cm$^3$ s$^{-1}$, 85 cm$^3$ s$^{-1}$, 88 cm$^3$ s$^{-1}$, 95 cm$^3$ s$^{-1}$, 107 cm$^3$ s$^{-1}$, 117 cm$^3$ s$^{-1}$, 139 cm$^3$ s$^{-1}$, and 145 cm$^3$ s$^{-1}$. After reaching stable flow conditions (5 minutes of continuous flow running without variations greater than 3.2 cm$^3$ s$^{-1}$) at a targeted flow rate, DTS measurements were collected at 5-second increments for the entire duration of the test. Noting the start time of current application, a 20-minute heat pulse was generated by continuously applying 160 Watts of power (at 25 volts and 6.4 amps) to the cable using the DC power supply. After heating, water continued flowing through the tank for an additional 30 minutes between flow tests to allow the cable to reach thermal equilibrium with the media. To ensure that relative equilibrium was met, the saturated media temperature was monitored with a PT-100 probe and compared to temperature measured by the DTS unit. Once the DTS system reported that the cable temperature and temperature probe differed by less than 0.1 K, it was assumed the system was in thermal equilibrium.

2.3.7 Multimedia Validation Tests with RSC Media

The second series of seepage tests were conducted using a sand/mulch media mixture collected from an RSC located in Durham, North Carolina. Tests were conducted at six flow rates of 69 cm$^3$ s$^{-1}$, 73 cm$^3$ s$^{-1}$, 82 cm$^3$ s$^{-1}$, 88 cm$^3$ s$^{-1}$, 110 cm$^3$ s$^{-1}$, and 114 cm$^3$ s$^{-1}$ with the upper 15 cm of the tank filled with the RSC material with the remaining 45 cm of the tank filled with the glass bead media from the previous tests as a reference (Figure 2.9).
2.3.8 Calculation of Water Flux and the Perzlmaier Model

The following equation, presented in Perzlmaier et al. (2004), relates the temperature change, $\Delta T$ (K), observed at the center of a coated cylinder, in our case a shielded fiber optic cable, to the heat flux applied to it.

$$\Delta T = \frac{q_L}{2\pi} \left[ \frac{1}{\lambda_m} \ln \left( \frac{r_a}{r_i} \right) + \frac{1}{a r_a} \right]$$  Eq. 2.1

Where:

$q_L$ = heat flux per unit length (W m$^{-1}$)

$\lambda_m$ = Thermal conductivity of cable coating (W m$^{-1}$ K$^{-1}$)

$r_a$ = outer radius of the coating (m)

$r_i$ = inner radius of the coating (m)

$a$ = heat transfer coefficient (W m$^{-2}$ K$^{-1}$)

The thermal conductivity, the outer radius, and the inner radius of the BRUsens cable coating $\lambda_m$ = 0.25 W m$^{-1}$ K$^{-1}$, $r_a = 1.9 \times 10^{-3}$ m and $r_i = 1.7 \times 10^{-3}$ m respectively, were estimated from the manufacturer’s specification.

$\Delta T$ was determined by averaging the temperature measurements during a two-minute period immediately before power was applied to the stainless-steel armoring of the cable and comparing it to the average temperature over the last 5 minutes of the heating period. 20-minute heating
cycles were selected due to the relative stability of the temperature measurement after approximately 12-13 minutes of heating (Figure 2.10).

Figure 2.10 Change in cable temperature caused by applying electric current to the stainless steel armoring of the fiber optic cable.

To calculate the heat transfer coefficient, \( a \), in equation 2.2, the ratio of convective to conductive heat transfer can be represented by the dimensionless Nusselt number, \( Nu_D \). Using the formula given for cylinders, the Nusselt number can be used to express the heat-transfer coefficient, \( a \), as:

\[
Nu_D = a \frac{D}{\lambda_{fl}} \quad \text{Eq. 2.2}
\]

Where:

- \( D \) = diameter of the cylinder (m)
- \( \lambda_{fl} \) = thermal conductivity of the fluid (W m\(^{-1}\)K\(^{-1}\))
- \( a \) = heat-transfer coefficient (W m\(^{-2}\)K\(^{-1}\))

The outer diameter of the cylinder was 3.8*10\(^{-3}\) m (manufacturer specifications and verified using calipers), and the thermal conductivity of water at testing conditions was 0.6 W m\(^{-1}\)K\(^{-1}\).

Solving equation 2.2 by the relationship given in equation 2.1 for the heat transfer coefficient, \( a \), results in:
\[ a = \frac{1}{q_L \cdot \frac{1}{\lambda_m} \cdot \ln\left(\frac{r_d}{r_f}\right)} = \frac{N_{uD} \cdot \lambda_f}{D} \quad \text{Eq. 2.3} \]

From here, the effective Nusselt number for forced convection in a Darcy-flow regime, taken from Perzlmaier et al. (2004) in following the work of Fand et al. (1993), can be used to correct the empirical relationships with Darcy-flow regimes in saturated porous media. Thus, connecting these temperature measurements to fluid movements. The expression can then be written as:

\[ Nu_{eff} = 1.248 \times Re_d^{0.5} \times Pr_{eff}^{0.3534} \times 1.325 \times \left(\arctan\left(\frac{D}{d}\right)^{0.5}\right) \quad \text{Eq. 2.4} \]

Where:

- \( Re_d \) = the dimensionless Reynolds number of a cylinder
- \( Pr_{eff} \) = dimensionless Prandtl number
- \( d \) = diameter of particles (m)

The mean particle diameter used for initial seepage tank tests was 1 mm for soda glass beads and 0.2 mm for the RSC media mixture (which was later adjusted to calibrate the model).

Solving for the Reynolds number gives:

\[ Re_d = \left(\frac{N_{u_{eff}}}{1.248 \times Pr_{eff}^{0.3534} \times 1.325 \times \arctan\left(\frac{D}{d}\right)^{0.5}}\right)^{0.5467} = \frac{vD}{\mu} \quad \text{Eq. 2.5} \]

Where:

- \( v \) = pore velocity of the fluid (m s\(^{-1}\))
- \( D \) = diameter of the cylinder (m)
- \( \mu \) = kinematic viscosity of water at testing temperature (m\(^2\) s\(^{-1}\))

Continuing with the methodology described by Perzlmaier et al. (2004), the effective Prandtl number shown above can be solved by:

\[ Pr_{eff} = \frac{\mu}{k_{eff}} \quad \text{Eq. 2.6} \]
Where \( k_{\text{eff}} \) is the effective thermal diffusivity, which can be solved by:

\[
k_{\text{eff}} = \frac{\lambda_{\text{eff}}}{\rho_{fl} \cdot c_{pfl}} \quad \text{Eq. 2.7}
\]

Where:

\( \lambda_{\text{eff}} \) = effective thermal conductivity of the media (W m\(^{-1}\) K\(^{-1}\))

\( \rho_{fl} \) = density of water (kg m\(^{-3}\))

\( c_{pfl} \) = specific heat capacity of water (J Kg\(^{-1}\) K\(^{-1}\))

The reference value for kinematic viscosity of water during testing was \( 1.002 \times 10^{-6} \) m\(^2\) s\(^{-1}\), the density of water is approximately 1000 kg/m\(^3\), and the specific heat capacity is 4190 J kg\(^{-1}\) K\(^{-1}\).

Finally, the previous equations can be rearranged to solve for pore velocity resulting (which has also been demonstrated by Gregory, 2009) by the following:

\[
v = \mu \cdot \left( \frac{D}{\sqrt{\frac{\Delta T \cdot 2\pi}{q_{L} \cdot \lambda_{m} \cdot \ln\left(\frac{r_{a}}{r_{l}}\right)}}} \right)^2 \cdot \frac{\lambda_{fl}}{1248 \cdot Pr_{\text{eff}}^{0.3534} \cdot 1.325 \cdot \arctan\left( (D/d)^{0.5} \right)^{0.5467}} \quad \text{Eq. 2.8}
\]

Perzlmaier et al.’s 2006 evaluation of this methodology found the measurement range using this approach extended from pore velocities of \( 1 \times 10^{-6} \) to \( 1 \times 10^{-3} \) m s\(^{-1}\) (0.36 cm hr\(^{-1}\) to 360 cm hr\(^{-1}\)).

Finally, the pore velocity, found by Eq. 2.8 can be converted to the more commonly used Darcy (volumetric) flux by multiplying by the effective porosity fraction of the media.

\[
J_{\text{darcy}} = v \cdot f \quad \text{Eq. 2.9}
\]

Where:

\( v \) is the pore velocity given by Eq. 2.8 (L T\(^{-1}\))

\( f \) is the effective porosity of the media expressed in a decimal form (unitless)

The porosity of each media was determined by measuring the dry mass of media in a 2-inch ring and solving for the bulk density given by equations 2.10 and 2.11:

\[
\rho_{\text{bulk}} = \frac{\text{Mass}_{\text{media}}}{\text{Volume}_{\text{media}}} \quad \text{Eq. 2.10}
\]
\[ f = 1 - \frac{\rho_{\text{bulk}}}{\rho_{\text{particle}}} \quad \text{Eq. 2.11} \]

The manufacture stated particle density of the soda glass beads was given to be 2.65 g cm\(^{-3}\), and the particle density of RSC media was estimated to be 2.42 g cm\(^{-3}\) by taking the weighted average of the particle density of quartz sand (80% at 2.65 g cm\(^{-3}\)) and organic material (20% at 1.5 g cm\(^{-3}\)).

2.4 Results

2.4.1 Detection of the Wetting Front

The presence of water was precisely detected by the fiber optic cable embedded in the media during actively heated tests. Figure 2.11 shows the rapid temperature change caused by saturation of the glass media as the wetting front moved up the seepage tank past the heated fiber optic cable. Perzlmaier et al. 2004 showed similar results, noting that the rise and fall of the water table could be monitored reliably using AHFO-DTS.

![Figure 2.11](image)

Figure 2.11 Temperature drop caused by the propagation of the wetting front through the media during fiber optic heating at three points during saturation of the glass bead reference media. The section of cable embedded in media is shown within the blue rectangles.

Under dry conditions, a temperature drop, ranging between 21 and 45 kelvin, was observed when the wetting front arrived at a location monitored by the heated fiber optic cable. However, under higher moisture conditions (~ field capacity of the media), a smaller temperature drop, ranging between 3 and 12 kelvin, was measured when the wetting front saturated media around the cable. Using the same process to detect the wetting front for RSC media, dry conditions resulted in
temperature drops ranging from 6 and 18 kelvin and 0.25 and 3 kelvin under higher moisture conditions.

2.4.2 **AHFO-DTS Sensitivity to Varied Flows**

The change of temperature measured by the AHFO-DTS showed sensitivity to the rate of water moving through the seepage tank. Applying a uniform power of 20 W m\(^{-1}\), Figure 2.12 displays this relationship, with the change of temperature decreasing as flow rate increases. The temperature change was calculated using the methodology described in 2.3.7 and represented in Figure 2.12.

![Figure 2.12 Change in temperature measured by AHFO-DTS response to varied flow rates in the seepage tank.](image)

2.4.3 **Perzlmaier Model Performance in Glass Media**

Following the procedure outlined in section 2.3.8, the average Darcy flux was calculated using the Perzlmaier model for the eight trials conducted in the glass media. This flux was then compared to the volumetric flux found by dividing the volumetric flow rate recorded by the ultrasonic flow meter by the cross-sectional area of the seepage tank. This comparison is shown in Figure 2.13, with the 1:1 line representing a perfect fit between the observed volumetric flux and the calculated Darcy flux.
Figure 2.13 Volumetric flux measurements compared to Darcy flux calculated from the Perzlmaier model (Eq. 2.9) through glass media in a seepage tank.

The fit between the observed volumetric flux and the calculated Darcy flux indicates the Perzlmaier model performed well across the range of flows tested, with an RMSE of $0.13 \text{ cm/hr}$. This result suggests less than a 4% relative error, on average, when estimating fluxes using the Perzlmaier approach across the range of fluxes tested.

### 2.4.4 Perzlmaier Model Performance in RSC Media

Like the analysis conducted on the glass bead media, the average Darcy flux was calculated for the six trials conducted in the dual media set-up (Figure 2.9). For these tests, fluxes were calculated in the upper 15 cm of the tank containing the RSC media and in the lower section containing the glass media as a control. Similarly, fluxes were then compared to the flux rate found by dividing the volumetric flow rate recorded by the ultrasonic flow meter by the cross-sectional area of the seepage tank. This comparison is shown in Figure 2.14, with the 1 to 1 line representing a perfect fit.
Figure 2.14 Observed volumetric flux measurements compared to Darcy flux calculated from the Perzlmaier model (Eq. 2.9) through RSC media in a seepage tank, showing values for glass media (grey) and uncalibrated RSC media (yellow).

The results suggest that the Darcy flux calculated from the Perzlmaier model estimated volumetric water flux more accurately in the glass media than the RSC media with RMSE values of 0.14 and 0.61 cm hr⁻¹, respectively. However, estimates made in the RSC media were improved by calibrating uncertain and more variable media properties in the model.

2.4.5 Perzlmaier Model Performance in RSC Media

Calibration of the model presented by Perzlmaier et al. (2004) was necessary for the RSC media due to uncertainty in physical properties compared to the glass bead media. The media particle size and thermal conductivity were adjusted due to uncertainty and variability in estimating their physical properties. By comparing the output of Eq 2.9 to the observed fluxes in the seepage tank, these parameters were manually adjusted to improve the model's estimate of the known flux across the range of flows tested. The initial sand size specification approximation of 0.2 mm was adjusted to 0.8 mm, better representing the bulk media’s particle size, influenced by its wood-mulch composition. Additionally, the thermal conductivity of the media was adjusted from the mean value of 1.024 W m⁻¹ K to a value of 1.01 W m⁻¹ K, which is within the standard deviation of the six measurements measured by the TEMPOs probe. By applying these calibrated
parameters to the Perzlmaier model, the RMSE improved from 0.61 cm hr\(^{-1}\) to 0.21 cm hr\(^{-1}\) across the range of flows tested in the seepage tank (Figure 2.15).

![Figure 2.15 Observed volumetric flux measurements compared to calculated Darcy flux from the Perzlmaier model (Eq. 2.9) in RSC Media, showing calibrated (blue) and uncalibrated (yellow) values.](image)

This improved RMSE suggests that less than a 10% relative error, on average, is expected when estimating fluxes in the RSC media when using the Perzlmaier approach.

### 2.5 Discussion and Limitations

Results from the flux trials through the RSC media suggest that the model began to lose precision at velocities exceeding 3 cm hr\(^{-1}\). A possible explanation for this behavior may be the inherently lower permeability of the RSC material relative to the larger and more uniform glass bead media. By inducing flow through the tank at rates possibly exceeding the natural permeability of the RSC media, it is possible that water began to bypass the media along preferential flow paths along the sides of the tank. This would result in an under prediction of flux calculated by the Perzlmaier method due to a diminished thermal response caused by less water passing by the heated cable. However, fluxes at this range are likely beyond what is anticipated to occur under field conditions and should not affect this approach’s efficacy in the field. Based on estimates of the RSC media’s hydraulic conductivity (mean value of 12.8 cm hr\(^{-1}\)), an relatively high hydraulic gradient of over 0.30 cm cm\(^{-1}\) would be needed to drive flux rates
to the level at the upper end of our testing. Additionally, while the design of the seepage tank proved adequate at applying and monitoring flows ranging from 57 cm$^3$ s$^{-1}$ to 145 cm$^3$ s$^{-1}$ (corresponding to volumetric fluxes between 1.4 to 3.4$\times$10$^{-4}$ cm hr$^{-1}$), future work to test a more expansive range may prove valuable especially regarding very low flows when examining low permeability media. Additionally, uncertainty in the effective particle density of the RSC media, limits the precision that porosity can be calculated by, and may require further calibration. Tests performed in both media showed little temperature variability during stable flow conditions, with a standard deviation of 0.63 K during heat pulses along the width of each cable run, perpendicular to flow. Figure 2.16 shows the temperature variability of a 1 m sensing section of the cable located at the middle of the seepage tank (see Figures 2.7 and 2.8) during a heating cycle. This suggests stable flow conditions and uniform water flux during testing, and uniform heating over the length of the cable.

![Temperature variability along the center 1 m sensing section of cable during a 20-min heat cycle.](image)

Additionally, while using temperature variations as means of detecting the absence or presence of water has been explored, distributed temperature sensing appears to enable insights into the shape of the wetting front, which may prove helpful in describing fluid flow behavior through media (Sayde et al., 2014; Perzlmaier et al., 2006). These insights could help quantify the instability of the wetting front in non-homogeneous porous media and identify preferential columns of infiltration during percolation. Such a phenomenon allows for water to penetrate
more deeply than would be possible under stable wetting fronts (Hill et al., 1972), which would impact treatment potential in RSC. However, due to the uniformity of tests conducted in our seepage tank tests, the robustness of detecting subtle changes in wetting has yet to be seen.

Another limitation of this method is the uncertainty associated with the RSC media's background thermal properties and effective particle size. Unlike mineral soils, RSC media is heavily influenced by the fraction of sizeable organic matter dispersed throughout its profile. The calibration of these parameters allows for higher accuracy measurements than otherwise would have been possible by our limited ability to quantify the physical properties of heterogeneous media. Directly measuring physical and thermal parameters and estimating their variability but making replicate measurements of different samples, aided in applying this model. Measuring the variation in background thermal properties, especially when this method is applied under more variable field conditions in chapter three, is essential. For parameters that are difficult to measure, such as the diameter and porosity of mixed material, a calibration procedure similar to the one described in this chapter can be employed to estimate an effective value of these parameters.
2.6 References


CHAPTER 3


3.1 Abstract

While stormwater control measures (SCMs) are increasingly being implemented for their pollutant mitigation potential, conventional methods to evaluate the hydraulic performance of SCMs are lacking and do not measure fine-scale changes. Advances in fiber-optic distributed temperature sensing (FO-DTS) offer the opportunity to measure changes in soil-water dynamics at fine temporal and spatial scales.

This study seeks to quantify the spatial variability of the media’s ability to retain and transport water using a novel actively heated fiber-optic distributed temperature sensing approach (AHFO-DTS). This AHFO-DTS approach was used to monitor subsurface water movement in a storm water control measure by installing a 4-meter fiber optic transect in the media of a regenerative stormwater conveyance structure (RSC) located in Durham, North Carolina. Two intensive monitoring periods took place during storm events. Heated measurements were conducted to inform the spatial and temporal variability of fluxes moving within the media. Water quality samples were taken upstream and downstream of the RSC channel to quantify pollutant reduction.

The results demonstrate that AHFO-DTS measurements can detect sub-meter scale variations in water flux under various conditions. The maximum and minimum measured flux during monitoring was 2.34 cm hr\(^{-1}\) and 0.32 cm hr\(^{-1}\), respectively. The most substantial variations occurred along the shallowest section of the fiber optic cable installation at a depth of 15.3 cm. While only a limited number of water quality grab samples were acquired during stormflow monitoring (n=6), they indicate better nitrate concentration reduction performance by the system, when compared to a study of the site five years prior. The use of AHFO-DTS as a long-term monitoring strategy in conjunction with water quality sampling in RSC systems and other media-based treatment practices can provide a broader understanding of complex system dynamics that impact water quality goals.
3.2 Introduction
Reliable treatment of stormwater runoff is of the utmost importance to preserve and restore degraded waterways across the country and beyond. Urban development and expanded agricultural practices have had devastating impacts on water quality and downstream ecosystems due to pollutant-laden stormwater runoff (Oelsner & Stets, 2019). These effects have become increasingly evident in North Carolina, with freshwater and marine ecosystems suffering from excess sediment and nutrient loading (Manuel, 2014; Lenat & Crawford, 1994). Eutrophication, habitat degradation, and negative impacts on human health are all consequences of excess pollutant loading in waterways (Davis et al., 2006; Smith, 2003). For example, a 2012 report estimated over 16 tons (14,500 kg) of total nitrogen, 1.8 tons (1,600 kg) of total phosphorus, and 397 tons (360,000 kg) of sediment were entering Jordan Lake - a major drinking water reservoir - from the Third Fork Creek Watershed, per year (Durham Stormwater, 2012). Jordan Lake, in turn, has a long history of algal blooms and cyanotoxins (Wiltsie et al., 2018).

Fortunately, mitigation strategies to reduce pollutant loading, including the use of stormwater control measures (SCMs), have increasingly been implemented to meet regulatory targets (Sadeghi et al., 2018; Davis et al., 2010). For example, in Raleigh, NC, there are more than 2,200 privately-owned SCMs and an additional 75 practices operated by the city (City of Raleigh, 2020). In addition, advancements in the design and construction of green SCMs such as swales, wet ponds, and stormwater wetlands have demonstrated their ability to improve water quality and mitigate high peak flows caused by impervious land uses (Sadeghi et al., 2018; Davis et al. 2010). However, more recent media-based treatment practices, such as regenerative stormwater conveyance (RSC) and bioretention, and their treatment mechanisms have not yet thoroughly been evaluated (Duan et al., 2019; Koryto et al. 2017). Media-based SCM’s utilize a mix of sand and organic material in their construction, allowing for multiple pollutant removal processes, including sorption, physical straining, sedimentation, biological denitrification, desiccation, and heat exchange (Blecken et al. 2017; Hunt et al., 2008). However, few tools exist that allow for in situ monitoring of water flow through the media; therefore, hydraulic deficiencies such as preferential flow, short retention times, or clogged media can go undetected. Instead, single-point measurements taken with tools like infiltrometers are used to verify a design. This lack of fine-scale evaluation can lead to undetected deficiencies that reduce SCM’s water quality benefits and lead to a shorter design life (Davis et al., 2012; Hsieh & Davis, 2005). Furthermore, few long-
term or follow-up studies have monitored media-based SCMs, beyond what is required by regulators, offering a limited understanding of their efficacy over time (Johnson & Hunt, 2019).

RSCs, in particular, are of growing interest to designers because they collect runoff from a larger, more diverse drainage area than many SCMs and include aspects of stream restoration. They also provide stabilization of erosive head cuts and are designed to withstand large stormflows. However, even across a diversity of designs, this practice has shown varying levels of success at removing pollutants and reducing peak flows (Duan et al., 2019; Cizek et al., 2018; Cizek et al., 2017; Koryto et al., 2017). The State of Maryland has accepted RSCs as an acceptable practice to meet total maximum daily load requirements (Anne Arundel County). However, North Carolina has not yet accepted RSC as a means for meeting nutrient and sediment reduction requirements and has not yet set minimum design criteria for the practice (NC DEQ, 2018). This study aims to provide more evidence of RSCs’ utility, a framework for future monitoring endeavors, and to discuss how this practice and RSC monitoring can be improved.

Challenges in measuring subsurface flow in media-based treatment systems have limited researchers’ ability to relate how flow through the media impacts pollutant reduction on fine scales (Duan et al., 2019; Davis et al., 2010). Approaches such as long-duration water balances to account for subsurface flow have been implemented but offer limited insights into how water moves through the media (Cizek et al., 2018; Cizek et al., 2017; Koryto et al., 2017). However, these subsurface dynamics are critical in RSC’s treatment mechanisms, such as filtration, sorption, and biological denitrification (Duan et al., 2019; Blecken et al., 2017; Davis et al., 2010; Hunt et al., 2008).

This research seeks to test the ability of a novel fiber-optic distributed temperature sensing (FO-DTS) approach to uncover the internal hydraulics of RSC media-based water quality treatment systems. Specifically, FO-DTS was used to measure in situ water fluxes at numerous locations across the width and depths of an RSC system located in Durham, NC. The FO-DTS approach applied is detailed extensively in Chapter 2. This approach can offer fine-scale spatial (25 cm) and temporal (as low as 5 seconds) measurements not previously possible in the field. The ability to measure in situ water fluxes offers insights into the spatial variability of water moving through the media, the average residence time of water in the treatment media, and preferential flow
paths during percolation. These findings provide greater understandings of how the system has matured in the five years since it was last monitored and test the utility of the FO-DTS system for SCM monitoring. While FO-DTS has been used to monitor water fluxes in groundwater wells (Pouladi et al., 2021), wetlands (Gregory, 2009), and around dam embankments (Perzlmaier et al., 2005), this study is the first time such a technology has been applied to a SCM.

In addition to AHFO-DTS, the model applied to measure fluxes within the RSC media in this study was validated using monitoring wells, in-situ hydraulic conductivity, and thermal conductivity measurements. Water quality grab samples were also taken to compare with prior measurements at the site and investigate short-duration analyte trends at different periods during stormflow.

The RSC channel in Durham, NC, was monitored and evaluated with the following study objectives:

1. Quantify the spatial variability of the media’s ability to retain and transport water using a novel AHFO-DTS monitoring approach and in situ hydraulic conductivity measurements.
2. Track and measure the propagation of the wetting front from the initial surface run-on to the media using AHFO-DTS.
3. Estimate hydraulic retention time of water in the media and its variability based on the fluxes calculated during monitoring.
4. Assess the practice’s water quality performance by collecting time distributed upstream and downstream grab samples during storm flow events.

3.2.1 Site Description
The RSC monitored for this project is located southwest of Southern Boundaries Park (35.956°N, 78.928°W) in Durham, NC, located within Third Fork Creek Watershed. Third Fork Creek drains to Jordan Lake and is within the larger Cape Fear River Basin. The Third Fork Creek Watershed was listed for exceeding turbidity standards by 12.2% in 2005 (NC DEQ, 2005). The most recent evaluation of Third Fork Creek’s Water Quality Index in 2019 was graded 79/100 due to poor bacteria levels and elevated nutrients and sediments (City of Durham, 2019). However, this was an improvement from the previously reported water quality evaluations, with an index of 75/100
in 2016, due to poor turbidity levels (caused by sediments) and fair nutrient levels (City of Durham, 2016).

The RSC channel was designed to transport and treat stormwater runoff from a 2.83-ha watershed consisting of athletic facilities, parking lots, and forested areas around Southern Boundaries Park (Figure 3.1).

![Figure 3.1 Site map showing RSC watershed and RSC location relative to Southern Boundaries Park, adapted from Koryto et al. 2017](image)

The watershed is estimated to be 38% impervious with NRCS hydrologic soil group D soils. The site's underlying soil (White Store Urban Complex) has a restrictive clay layer at a depth of 15–90 cm, common for the area, with a low estimated infiltration rate of 0–1.5 mm/h (NRCS Soil Survey, 2020). An additional 0.23-ha of the forested area was estimated to contribute to the watershed along the length of the practice by a previous study of the site conducted by Koryto et al. (2017). The regenerative stormwater conveyance structure serves as both a grade-control and treatment structure consisting of a 5-cell cascading system with a 10% average longitudinal slope. A summary of design details can be found in Table 3.1. The impetus for the construction of the Durham RSC was the need to stabilize a rapidly eroding head cut in the tributary that
threatened to undermine 3rd Fork Road. A post-construction monitoring period was conducted at this site from February 1st, 2015, to March 31st, 2016 (Koryto et al., 2017)

Table 3.1 RSC Structure Details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>RSC Location</td>
<td>Southern Boundaries Park, Durham NC</td>
</tr>
<tr>
<td>Latitude and Longitude</td>
<td>35.956°N, 78.928°W</td>
</tr>
<tr>
<td>Number of Cells</td>
<td>5</td>
</tr>
<tr>
<td>Watershed Area (ha)</td>
<td>2.82</td>
</tr>
<tr>
<td>Watershed CN</td>
<td>88</td>
</tr>
<tr>
<td>Design Rainfall event (mm)</td>
<td>6</td>
</tr>
<tr>
<td>Cell 1 Media Depth (Designed) (cm)</td>
<td>83</td>
</tr>
<tr>
<td>Cell 1 Media Depth (Measured) (cm)</td>
<td>93</td>
</tr>
<tr>
<td>Cell 1 Media Storage (Designed) (m³)</td>
<td>2.6</td>
</tr>
</tbody>
</table>

This study primarily focused on water movement between cell 1 and cell 2, shown in Figure 3.2 below.

![RSC plan view showing design features and monitoring equipment deployed, modified from design plans acquired from Jonathan Page.](image)

Figure 3.2 RSC plan view showing design features and monitoring equipment deployed, modified from design plans acquired from Jonathan Page.

3.2.2 Insights from Previous Studies

This study benefited from previous monitoring of the RSC, which provided a baseline to compare our results and further investigate factors thought to impact its performance. Koryto et al.’s 2017 study sought to quantify pollutant reductions and hydraulic mitigation performance shortly after the RSC construction in 2015.
Koryto et al. (2017) were able to calculate discharge volumes in each pool using a series of specially designed weirs that restricted surface flow and monitoring the stage height of water. They then implemented flow-proportional composite water quality sampling and discharge monitoring using a series of ISCO™ automated water samplers in three of the five cells of the practice. Their study reported reductions in event load and event mean concentration between where water entered the RSC and each cells’ pool. By monitoring the volume of water entering and leaving each cell, pollutant loading was found by multiplying the median pollutant concentration by the volume of water. Event load reductions were found by taking the difference between influent and effluent load in three of the five cells. Similarly, reductions in event mean concentration was calculated between the influent into the RSC system and the effluent of each of the cells.

Notable results from Koryto et al. (2017) study include:

1. Most of the water treatment took place between cell 1 and cell 2.
2. Hydraulic conductivity of the RSC media varied widely, ranging from 1 to 55 cm hr\(^{-1}\) with a median value of 18 cm hr\(^{-1}\).
3. Small but statistically significant reductions in event mean concentrations occurred: 17% total suspended sediment (TSS), 17% total phosphorus (TP), and 3% total nitrogen (TN) during the monitoring period.
4. A 14-month water balance suggested cell 2 received an estimated 49% of its water via media flow from cell 1, possibly explaining disproportionate treatment.
5. Cells 3, 4, and 5 frequently did not dewater after storms due to elevated groundwater table.

Koryto et al. (2017) also offered several factors that may have contributed to the modest pollutant removal at the Durham RSC. Including:

1. Transport of particulate-bound pollutants by high-intensity flows, bypassing the sand layer (Helmreich et al., 2010; Miguntanna et al., 2013).
2. Lack of residence time within the sand layer, limiting sorption and microbial transformation mechanisms (Davis et al., 2010).
3. Sand wash out, scour, and bank slumping, resulting in additional sediment loading.
4. Flushing of nitrogen leached during inter-event periods.
3.3 Materials and Methods

Following the laboratory tests described in chapter 2, the same method of using AHFO-DTS to measure water fluxes was applied to the media of an RSC located in Durham, NC. These measurements were supplemented with water level measurements using monitoring wells, water quality grab sampling, and in situ measurements of the media hydraulic and thermal properties. A water level monitoring well was installed in the first cell of the RSC structure on August 14, 2020, and a second monitoring well was installed in cell 2 on March 21, 2021 (see Figure 3.2). On October 1, 2020, excavation of the monitoring transect of cell 1 of the RSC was completed, and thermal property measurements were conducted. The fiber optic cable was installed in the transect on October 8, 2020. AHFO-DTS monitoring of the RSC media occurred on eight days between January 14 and April 24, 2021, during saturated conditions. Coincident with AHFO-DTS monitoring, water quality samples were acquired during two storm events on February 22, 2021 (7.6 mm rain event) and on April 24, 2021 (5.3 mm rain event). These storms would be considered relatively small for the area using the threshold of 12.7 mm set by Koryto et al. (2017). Estimates from the North Carolina State Climate Office (NCSCO), estimate storms of this size would occur between 36.9 and 47.9 times respectively, in a given calendar year. These storms were optimal for monitoring due to the estimated design storm of the system being a 6 mm rainfall depth. In situ hydraulic conductivity measurements were made on April 22, 2021.

3.3.1 Field Installation of Fiber Optic Cable

The uppermost pool of cell 1 (shown in Figure 3.2) was determined to be the most suitable location for installing the fiber optic cable into the media of the RSC due to persistent standing water above the media surface in the lower pools. A 2.54-cm diameter soil push probe was used across the length of the RSC to determine the average depth of media. The average depth was estimated to be 90 cm from the surface. This media depth occupied an additional 10-15 cm of pool storage compared to a 2015 as-built survey, suggesting substantial aggregation of upstream sediments on top of the designed media.

A narrow trench was dug across the channel approximately two meters behind the top of the rockfall structure separating the pools. Media was removed to a depth of 90 cm and approximate width of 20 cm (see Figure 3.3). After reaching a depth of approximately 50 cm into the media,
we encountered saturated conditions, requiring the installation of a well and pump to dewater the remaining media.

After reaching the bottom of the RSC media at the targeted excavation depth of 90 cm, four 150-cm fence posts were installed in the trench spaced 115-cm apart along the 4-m transect. 19-gauge stainless steel rope was fixed between each fence post at various depths along the posts across the transect. Two fence posts along the banks were used as anchors, allowing the wire to be secured under tension. A total of 7 sections of stainless steel wires were stretched along the cross-section at depths of 15.3, 20.5, 30.5, 40.7, 45.7, 60.9, and 76.2 cm below the media surface. These wires acted as a frame to attach the fiber optic cable, ensuring it was held taut at a known depth (see Figure 3.4). A total of 41.2 m of the same BRUsense FO cable used in the tests described in Chapter 2 was then affixed to the stainless-steel wire in a meandering configuration.
Of the 41.2 m of cable installed in the media, 20.25 m of the cable length was used to make AHFO-DTS measurements, at depths of 15.3, 30.5, 45.7, and 76.2 cm (see Figure 3.5). These sections were used to apply the heat up model presented in Chapter 2 to measure distributed water fluxes.

The cable was electrified via an electrical splice with 6-gauge copper wire on each end of the cable run contained in a waterproof junction box (Figure 3.6). This cable was then run approximately 30 m to the research utility trailer, where electricity was supplied by a BK 1902 B DC power supply (B&K Precision Corp, USA).
The remaining 21 m of fiber optic cable were not heated. Instead, this cable was used to monitor the temperature throughout the transect and served as a reference during heating. This section of cable was attached to the wires at depths of 20.5, 40.7, and 60.9 cm in a similar meandering configuration to the heated cable, shown in Figure 3.7.

Georeferencing of the cable was conducted using the method described in Chapter 2.3.3, but instead of using ice, heat was applied to the cable at areas of interest. The reference points were located at the loops where sections would change depths and near the electrical splice, which separated the heated and non-heated sections of cable. This referencing allowed for above-ground control points (fence posts) to identify where in the media measurements were being made and allowed for comparisons of measurements at different depths. Only straight sections of the cable that were perpendicular to flow were used in our analysis, resulting in 3.75 m of the 4
57 m transect having active monitoring. The measurement points were all referenced in their position in relation to the left bank (looking upstream) anchor post.

In total, 244 m of FO cable was used, with 92 m housed in temperature control baths, 41 m embedded in the RSC media, and 111 m used to traverse the distance between the RSC and the DTS unit with additional length to accommodate any unforeseen issues. A plot showing the temperature along the 244-m length of fiber optic cable with different locations of interest labeled is shown in Figure 3.8.

![Temperature profile of the FO cable during initial calibration tests. The x-axis represents the location of the measurement along the FO cable, and the y-axis shows temperature.](image)

Following installation and preliminary georeferencing of the cable, media was refilled into the trench by hand. Care was taken to minimize compaction and match the existing bulk density when replacing the media around the fiber optic cable. Further, a three-month recovery period after installation allowed settling and remediation of the cell before additional measurements were made.

### 3.3.2 Utility Equipment and DTS Monitoring Trailer

A utility research trailer was stationed approximately 30 meters from the RSC transect near an access road adjacent to Southern Boundaries Park. The two 6-gauge copper electrical lines and the BRUsense fiber-optic cable were run this distance from the RSC transect into the research trailer via an access port. A Craftsmen 3500-Watt portable generator supplied power to the
Additionally, two 12v 250-amp-hour deep-cycle batteries were used to supplement power draw with a 3,000-Watt pure sine wave inverter (Craftsmen, USA; Renogy, USA). The DTS unit selected for monitoring was an XT-DTS™ (Silixa Ltd, United Kingdom) (Figure 3.9). This model was more appropriate for field-testing than the Ultima™ unit used in laboratory tests, with an expanded operating temperature range (-40 to 65 °C), battery-enabled operation (11 W draw at 12v), and laptop connectivity. Data were collected using 5-second integration times with a 0.25 m sampling resolution. These temperature measurements were later calibrated using two PT-100 Temperature probes during post-processing using software supplied by the Center of Transformative Environmental Monitoring Programs as mentioned in Chapter 2 (CTEMPS, USA).

Figure 3.9 The XT-DTS™ unit and BK 1902 Power supply being controlled via a laptop while housed in the research utility trailer during testing.

Similar to previous laboratory tests, two 60-L coolers were used as temperature calibration baths located outside the trailer shown in Figure 3.10. Each bath contained a PT-100 temperature probe connected to the DTS unit that reported temperature inside the baths every 5-seconds with an accuracy of ± 0.06 °C. Each cooler had recirculating pumps to maintain stable temperature conditions during measurements. 20-minute heat pulses at 427 watts were applied to generate the change in temperature required by the Perzlmaier model to estimate water flux along the length of fiber optic cable.
3.3.3  **Pool Water Level Monitoring**

A water level monitoring well was installed in the cell 1 of the RSC structure to a depth of 92 cm below the media surface with a 61-cm casting extending above the media surface. Two Onset HOBO™ Water Level Data Loggers (U20L-04) were installed, one submerged at the bottom of the well and one held at the top of the casing to monitor atmospheric pressure (Onset Computer Corporation, 2020). The difference between the two pressures allowed for monitoring of the water level in the cell at 15-minute increments. This monitoring allowed us to verify saturated conditions throughout the media profile before AHFO-DTS measurements were made.

A second well was installed 7.62 m downstream, just below the boulder cascade separating cell 1 and cell 2 (see Figure 3.2). A single HOBO Water Level Data Logger was installed to monitor the water level in the lower elevation pool. Using the geometry of these two wells relative to each other, the installation allowed for monitoring the hydraulic gradient between the two pools.

3.3.4  **Infiltration and Hydraulic Conductivity Measurements**

A Modified Phillip Dunne Infilrometer (MPD) (ASTM D8152, 2018) and a Compact Constant Head Permeameter (CCHP, also known as an Amoozemeter) (NRCS, 2014) were used to estimate saturated hydraulic conductivity (Ksat) along the transect of the cell pool near the fiber optic installation. These measurements were made to identify localized regions where preferential flow may take place and quantify the spatial variability of the media. Seven measurements were made using the Upstream Technologies Proprietary MPD System in approximately 60-cm increments along the fiber optic transect (Upstream Technologies, 2021). After individual Ksat values were measured, the method used by the MPD software to determine
the “best site average saturated hydraulic conductivity” as described by Weiss and Gulliver (2015) was determined to be 12.8 cm hr\(^{-1}\). The individual saturated hydraulic conductivity values measured by MPD infiltrometer ranged widely from 2.7 cm hr\(^{-1}\) to 82.7 cm hr\(^{-1}\). These values were comparable with lower K\(_{\text{sat}}\) values found from the three measurements using the CCHP, which uses the Glover equation to solve for the saturated hydraulic conductivity by measuring the volume of water infiltrating into a shallow bore hole of known geometry (NRCS, 2014). The CCHP measurements resulted in a mean value of 9.2 cm hr\(^{-1}\). Figure 3.11 shows where these individual measurements were made and their values.

![Figure 3.11 Saturated hydraulic conductivity measurements along monitoring transect.](image)

Koryto et al. (2017) also found a wide range of hydraulic conductivities in the media ranging from 1-55 cm hr\(^{-1}\) with a median value of 18 cm hr\(^{-1}\). Koryto proposed variations in K\(_{\text{sat}}\) were attributed to the heterogeneity of the media and lack of uniformity in the mulch component, which this study also found.

### 3.3.5 Water Quality Sampling

While previous studies of the site have explored a more thorough and continuous evaluation of water quality (see Koryto et al., 2017), this study sought to explore the water quality response within single storms during periods of intensive observations. Samples were collected at two locations, (1) a culvert that conveys water to the RSC structure from the watershed and (2) a boulder step located at the downstream end of the system (see Figure 3.2). This was done to
measure changes in sediment and nutrient concentrations entering and leaving the system, similar to the Koryto et al. (2017) study. Samples were collected during the initial run-on, approximate peak flow, and falling limb of the storm at both locations. The samples were then transported on ice to the North Carolina Center for Applied Aquatic Ecology Lab (CAAE), where they were analyzed for total suspended solids (TSS), total phosphorus (TP), total ammoniacal nitrogen (NH3-N or TAN), nitrate/nitrite nitrogen (NO3+NO2) and total Kjeldahl nitrogen (TKN) (see Table 3.2).

Table 3.2 Analytical method and detection limit used by the CAAE to quantify each contaminant concentration during sampling.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Pollutant Name</th>
<th>Analytical Method Standard</th>
<th>Detection Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKN</td>
<td>Total Kjeldahl Nitrogen</td>
<td>SM 4500 N Org D</td>
<td>280 µg/L</td>
</tr>
<tr>
<td>NO2,3-N</td>
<td>Nitrate/Nitrite Nitrogen</td>
<td>SM 4500 NO3-F</td>
<td>11.2 µg/L</td>
</tr>
<tr>
<td>TAN</td>
<td>Total Ammoniacal Nitrogen</td>
<td>SM 4500 NH3 G</td>
<td>17.5 µg/L</td>
</tr>
<tr>
<td>ON</td>
<td>Organic Nitrogen</td>
<td>TKN- TAN</td>
<td>-</td>
</tr>
<tr>
<td>TN</td>
<td>Total Nitrogen</td>
<td>TKN+NO2,3-N</td>
<td>-</td>
</tr>
<tr>
<td>TP</td>
<td>Total Phosphorus</td>
<td>SM 4500 P F</td>
<td>10 µg/L</td>
</tr>
<tr>
<td>TSS</td>
<td>Total Suspended Solids</td>
<td>SM 2540 D</td>
<td>2.5 mg/L</td>
</tr>
</tbody>
</table>

3.3.6 Thermal Property Characterization

After excavation of the RSC and prior to installing the fiber optic cable, measurements of the media thermal properties were made using the same METER Group TEMPOs Thermal Properties Analyzer described in Chapter 2 (METER Group Inc., USA) (Figure 3.12). Measurements were made along the transect at approximately 90-cm increments at depths of 15 cm, 30 cm, 60 cm. This was done to estimate the error of the Perzlmaier model associated with the variations in background thermal properties. However, the three measurements from the 15-cm depth were discarded from the analysis because the media at that depth was not fully saturated during acquisition. The nine remaining thermal conductivity measurements had a mean value of 1.014 W m$^{-1}$ K$^{-1}$ with a standard deviation of 0.077 W m$^{-1}$ K$^{-1}$. While the standard deviation of these measurements is larger than those tested by media samples analyzed in the lab in Chapter 2 (0.014 W m$^{-1}$ K$^{-1}$), the mean value of 1.014 W m$^{-1}$ K$^{-1}$ is very comparable to both the
calibrated value used in laboratory tests (1.01 W m$^{-1}$ K$^{-1}$) and the mean of the six laboratory measurements (1.024 W m$^{-1}$ K$^{-1}$).

![Figure 3.12](image)

Figure 3.12 Thermal conductivity measurements being made across the monitoring transect before cable installation.

### 3.4 Results

#### 3.4.1 Overview

Applying the Perzlmair model presented in Chapter 2, estimates of the average linear velocity and Darcy flux were made throughout the media of the RSC during heat pulses generated by applying 20 W m$^{-1}$ to the heated sections of FO cable. AHFO-DTS measurements at four depths allowed investigation of variations of flux across the 4-meter width of the RSC and at different depths. Each heat pulse allowed fluxes to be calculated at 66 points in the RSC media. Additional heated measurements also allowed for tracking water moving through the RSC media profile during the initial wetting of the media, offering insights to preferential flow paths during percolation. Additionally, throughout storm events, estimations of Darcy flux were made based on changes in hydraulic gradient recorded by the monitoring wells and saturated conductivity values. This enabling comparison between AHFO-DTS estimates of flux to values calculated using Darcy’s law. Pollutant removal trends found throughout two storm events are also presented.

Water flux in the RSC media was monitored on eight days between January 14 and April 24, 2021, using AHFO-DTS measurements during saturated conditions. Of these dates, water quality
grab samples were taken during storm events on February 22\textsuperscript{nd} and April 24\textsuperscript{th}. Rainfall data for the site was retrieved from a USGS Weather station (ID # 0209725960) located approximately 500 m south of the project site on Martin Luther King Jr Parkway (USGS, 2021).

\textbf{3.4.2 Wetting Front Monitoring}

Sub-freezing early morning temperatures on February 22, 2021, provided an optimal opportunity to detect the infiltration of water much colder than the ambient subsurface conditions in the RSC. Before stormwater run-on occurred in cell 1 of the RSC, continuous heating was applied to the fiber optic cable to detect temperature changes caused by the infiltration of near-freezing water. The stable temperature profile was disrupted, and a thermal response by the heated fiber optic cable was observed as water percolated into the media. The drop in cable temperature shown in Figure 3.13 corresponds to the arrival of water saturating the media around the heated cable. While the observed drops in temperature were smaller than observed during lab testing, it provided insight into how water traveled through the media profile during the initial run-on. At the 15.3 cm depth nearest the surface, the greatest initial drop in temperature was observed at 1.25 and 2.25 m from the left bank. These points roughly correspond to the areas where high surface infiltration rates were measured (Figure 3.11). Looking deeper into the monitoring transect, we see this trend continue with larger temperature drops associated with water infiltrating between 2.5 and 3.5 meters from the left bank (see Figure 3.13). However, the temperature drop at 1.25 m is diminished, and temperature drops begin to trend further to the right. This suggests that water did not penetrate the media and percolate entirely vertically but found preferential paths. It is also notable that a drop in temperature was not observed everywhere along the transect initially, suggesting instability of the wetting front and preferential infiltration of water into the RSC media as theorized by Hill (1972).
3.4.3 Uncertainty in Perzlmaier Flux Estimates

The larger standard deviation observed during field measurements of the media’s thermal conductivity, compared to observations in the lab, necessitated quantifying its effect on the model. The dashed lines in Figure 3.14 represent the uncertainty in the flux measurements at different times in the April 24, 2021, storm due to the variations in thermal conductivity.

Figure 3.13 Change in temperature as a result of media wetting across depths.

Figure 3.14 Flux measurements at 1:26 pm (blue) and 2:05 pm (orange) on April 24, 2021, showing Perzlmaier model output using mean media thermal conductivity (solid line), and ± one standard deviation of thermal conductivity (dashed lines).
The upper and lower bounds (surrounding each of the solid lines) represent the result of the Perzlmaier model ± one standard deviation of thermal conductivity (0.077 W m\(^{-1}\) K\(^{-1}\)), with the middle line showing the calculated flux using the mean value of thermal conductivity (1.014 W m\(^{-1}\) K\(^{-1}\)). This uncertainty corresponds to an estimated relative error of 7.6% for any given estimate.

### 3.4.4 Spatially Distributed Flux During Storm Events

Three heat pulses were applied to the FO cable installation during a 7.1-mm rainfall event on February 22, 2021. Measurements were made at 1:26 pm, 2:05 pm, and 2:45 pm, corresponding to the initial saturated flow through cell 1, peak flow, and falling limb of the storm (see Figure 3.15).

![Figure 3.15](image)

Figure 3.15 *Hyetograph showing rainfall intensity, cumulative rainfall, and the time at which flux estimates were made on February 22, 2021.*

Comparing these measurements between each depth, some notable trends emerge. The results show that the area with the highest magnitude of fluxes was between 1.5 and 2.5 meters from the left bank at a depth of 15.3 cm, near where temperature drops were measured earlier. Moreover, this corresponds to roughly the location of the highest saturated conductivity shown in Figure 3.11. However, these measurements conflict with a zone of lower-than-average flux at the same distance from the bank at the 30.5 cm depth (Figure 3.16). Additionally, measurements across all four depths suggest a zone of higher-than-average flux between 2.75 m and 3.5 meters from the left bank.
Comparing the results through time, an increase in flux was observed across the transect and at each depth between 1:26 and 2:05 pm. The rising hydraulic gradient caused this increase in flux due to a build-up of hydraulic head in the pool as it filled with water (Figure 3.17). It is notable that while flux increased at all 66 measurement points during this period, that the flux did not increase by the same magnitude. For example, between 3 and 3.5 meters from the left bank at the 45.7 cm depth, flux disproportionately increased by 7.2% compared to flux measurements at the 30.5 cm depth, where flux increased by less than 2% across the width of the transect (Figure 3.16). In addition, disproportionate flux rates were most pronounced under peak hydraulic gradients during storm flows.
Another intensive monitoring period on April 24, 2021, allowed six heat pulses to be administered during a 5.25-mm rainfall event (Figure 3.18). This storm took place over a longer period, allowing for more measurements to be made and finer-scale changes to be detected compared to February 22, 2021, storm.

Several trends emerged while looking at the flux values. First, similarly to the February results, the greatest change in flux occurred early in the storm event after relatively intense between 2:00 pm and 2:35 pm (represented by dark blue and orange lines, respectively) (see Figure 3.19). This interval corresponds to the initial period of water filling cell 1 prior to over topping and conveying water into cell 2, where a rapid change in hydraulic gradient would be present.
Figure 3.19 Distributed flux measurements at four depths on April 24, 2021, with the x-axis showing the magnitude of flux (in reverse order to signify the direction of movement) and the y-axis representing the distance of measurement from the left bank.

Figure 3.19 shows how water flux varied along the RSC transect at four depths, at six different points in time on April 24, 2021. The overall highest magnitude of flux during the monitoring period was observed at 5:00 pm after an hour and half of sustained rainfall, preceded by a brief duration of intense rain (see Figure 3.18). The increase in flux after periods of rainfall and decrease after periods of no rain can be observed throughout the six measurement intervals.

3.4.5 Comparison with Hydraulic Gradients

The two wells, installed in cell 1 and cell 2, allowed monitoring of the hydraulic gradient at 15-minute intervals. Using these gradients, estimates of Darcy flux were calculated using the distance between the two wells (7.62 m) and the estimates of saturated hydraulic conductivity using Equation 3.1.
\[ J_{\text{Darcy}} = -K \frac{\Delta H}{L} \quad \text{Eq. 3.1} \]

Where:

\( J_{\text{Darcy}} \) is the Darcy flux (cm hr\(^{-1}\))

\( K \) is the saturated hydraulic conductivity (cm hr\(^{-1}\))

\( \Delta H \) is the change in pressure head between the two wells (cm)

\( L \) is the distance between the two wells (cm)

The estimates of Darcy flux, given by Eq. 3.1, were compared to the flux measurements calculated from the FO temperature data during the duration of a storm on April 24 (Figure 3.20).

Figure 3.20 shows how the overall average of six FO flux measurements (represented by red circles) compares to flux calculated from Darcy law through time during a storm on April 24. Hydraulic conductivities of 18 cm hr\(^{-1}\) (red line) reported by Koryto et al. (2017), 12.8 cm hr\(^{-1}\) found by MPD method (blue line), and 9.2 cm hr\(^{-1}\) found by the CCHP method (green line) were used to generate the different fluxes using the hydraulic gradient and distance between wells.

The dashed blue line shows a theoretical saturated conductivity value of 9.8 cm hr\(^{-1}\), representing
the best fit value for the fluxes found using the Perzlmaier model. The error bars on the fiber-optic cable flux represent the variability of flux along the width and depth of the transect at the time of the heat pulse.

3.4.6 Water Quality Trends

Eighteen water quality samples were acquired on February 22 and April 24, 2021, during the intensive monitoring period mentioned above (see Figure 3.21).

A comparison of upstream and downstream concentrations of each analyte at different points in the February 22nd storm is represented in the figures and summary tables (Figure 3.22, Figure 3.23, Table 3.3). The majority of measurements indicate a reduction in concentrations of each analyte sampled. Notable exceptions were ammoniacal nitrogen (NH₃-N) which showed slightly higher concentrations at the outlet throughout the three flow conditions. Additionally, after a 92.6% reduction in TSS during initial run-on sampling, the system exported higher TSS loads than it received during peak flow and falling limb measurements. Sampling also revealed a reduction of nitrate/nitrate concentration during initial flow and peak flow sampling but a modest increase in concentration during falling limb sampling.
Figure 3.22 Stacked column graph showing the up and downstream concentration of 6 analytes at initial, peak, and falling flows on February 22, 2021.

Figure 3.23 Column graph showing the up and downstream concentration of TSS at initial, peak, and falling flows on February 22, 2021.
Table 3.3 Summary of Water Quality Analysis for February 22, 2021, bold numbers indicate higher concentration exiting cell 5 then flowing into cell 1.

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Sample Location</th>
<th>Initial Flow Concentration (mg/L)</th>
<th>Percent Reduction</th>
<th>Peak Flow Concentration (mg/L)</th>
<th>Percent Reduction</th>
<th>Falling Limb Concentration (mg/L)</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>Inflow</td>
<td>293.67</td>
<td>92.62</td>
<td>81.68</td>
<td>-5.02</td>
<td>7.82</td>
<td>-45.95</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>21.68</td>
<td></td>
<td>86.00</td>
<td></td>
<td>17.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inflow</td>
<td>0.88</td>
<td></td>
<td>0.25</td>
<td></td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>Outflow</td>
<td>0.06</td>
<td></td>
<td>0.22</td>
<td></td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inflow</td>
<td>2.03</td>
<td></td>
<td>0.86</td>
<td></td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>ON</td>
<td>Outflow</td>
<td>0.37</td>
<td>81.53</td>
<td>0.67</td>
<td>22.09</td>
<td>0.39</td>
<td>10.90</td>
</tr>
<tr>
<td></td>
<td>Inflow</td>
<td>0.17</td>
<td></td>
<td>0.10</td>
<td></td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>NH3-N</td>
<td>Outflow</td>
<td>0.18</td>
<td>-10.98</td>
<td>0.13</td>
<td>-30</td>
<td>0.03</td>
<td>-55.55</td>
</tr>
<tr>
<td>TN</td>
<td>Inflow</td>
<td>2.54</td>
<td>76.61</td>
<td>1.21</td>
<td>17.36</td>
<td>0.53</td>
<td>3.73</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.59</td>
<td></td>
<td>1.00</td>
<td></td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>NO3+NO2</td>
<td>Inflow</td>
<td>0.34</td>
<td>89.83</td>
<td>0.24</td>
<td>16.67</td>
<td>0.08</td>
<td>-16.59</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.03</td>
<td></td>
<td>0.20</td>
<td></td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>TKN</td>
<td>Inflow</td>
<td>2.20</td>
<td>74.54</td>
<td>0.96</td>
<td>16.67</td>
<td>0.45</td>
<td>7.77</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.56</td>
<td></td>
<td>0.80</td>
<td></td>
<td>0.42</td>
<td></td>
</tr>
</tbody>
</table>

The same analysis was conducted on water quality samples obtained on April 24, 2021, during a 5.2-mm storm (Figure 3.24).

Figure 3.24 Hyetograph of April 24, 2021, storm, showing rainfall intensity, cumulative rainfall, and sampling times. The green box represents the sampling time for the initial flow, the pink box represents the sampling time for the peak flow, and the yellow box indicates the sampling time for the falling limb of the storm event.
More considerable reductions in pollutant concentration were found in samples collected from April 24 compared to February 22. Reductions in analyte concentration were found at all points in the storm for all analytes except for a slight increase in TSS during falling limb sampling (Figure 25 and 26).

Figure 3.25 *Staked column graph showing the up and downstream concentration of 6 analytes at initial, peak, and falling flows on April 22.*

Figure 3.26 *Column graph showing the up and downstream concentration of TSS at initial, peak, and falling flows on April 24.*

Compared to February 22 water quality samples, initial influent concentrations were considerably higher for all analytes except for TP, ranging between a 62.4% increase in TSS, 69.7% increase in ON, 89.5% increase NH3-N, 72.5% increase in TN, 61.8% increase in NO3+NO2, and a 73.6% increase in TKN concentration. This increase in influent water
concentration is suspected to be caused by a nutrient-rich pollen “super bloom,” which occurred in the days leading up to the storm. TP initial influent concentration was 22.7% lower compared to February 22nd initial upstream concentration value. A summary of these results can be found in Table 3.4.

Table 3.4 Summary of Water Quality Analysis for April 24, bold numbers indicate higher concentration exiting cell 5 then flowing into cell 1.

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Sample Location</th>
<th>Initial Flow Concentration (mg/L)</th>
<th>Percent Reduction</th>
<th>Peak Flow Concentration (mg/L)</th>
<th>Percent Reduction</th>
<th>Falling Limb Concentration (mg/L)</th>
<th>Percent Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>Inflow</td>
<td>780.71</td>
<td>96.24</td>
<td>1067.67</td>
<td>97.68</td>
<td>16.77</td>
<td>-16.02</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>29.35</td>
<td></td>
<td>24.71</td>
<td></td>
<td>19.97</td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>Inflow</td>
<td>0.68</td>
<td>92.65</td>
<td>0.72</td>
<td>93.06</td>
<td>0.19</td>
<td>63.16</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.05</td>
<td></td>
<td>0.05</td>
<td></td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>ON</td>
<td>Inflow</td>
<td>6.72</td>
<td>93.15</td>
<td>4.08</td>
<td>90.93</td>
<td>1.15</td>
<td>57.39</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.46</td>
<td></td>
<td>0.37</td>
<td></td>
<td>0.49</td>
<td></td>
</tr>
<tr>
<td>NH3-N</td>
<td>Inflow</td>
<td>1.62</td>
<td>70.37</td>
<td>1.02</td>
<td>52.94</td>
<td>0.62</td>
<td>27.42</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.48</td>
<td></td>
<td>0.48</td>
<td></td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>TN</td>
<td>Inflow</td>
<td>9.23</td>
<td>89.34</td>
<td>5.80</td>
<td>.84.66</td>
<td>1.99</td>
<td>50.25</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.98</td>
<td></td>
<td>0.89</td>
<td></td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>NO3+NO2</td>
<td>Inflow</td>
<td>0.89</td>
<td>95.51</td>
<td>0.69</td>
<td>94.2</td>
<td>0.21</td>
<td>76.19</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.04</td>
<td></td>
<td>0.04</td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>TKN</td>
<td>Inflow</td>
<td>8.34</td>
<td>88.73</td>
<td>5.10</td>
<td>83.33</td>
<td>1.78</td>
<td>47.19</td>
</tr>
<tr>
<td></td>
<td>Outflow</td>
<td>0.94</td>
<td></td>
<td>0.85</td>
<td></td>
<td>0.94</td>
<td></td>
</tr>
</tbody>
</table>

Pooling the samples from both dates monitored, mean upstream and downstream concentrations for each analyte were calculated and visualized by Figures 3.27-3.29. A summary can be found in Table 3.5.
Figure 3.27 Boxplot of upstream analyte concentrations obtained from pooling samples collected from February 22 and April 24, 2021.

Figure 3.28 Boxplot of downstream analyte concentrations obtained from pooling samples collected from February 22 and April 24, 2021.
Figure 3.29 Boxplot comparing upstream and downstream TSS concentrations obtained from pooling samples collected from February 22 and April 24.

Table 3.5 Summary of pooled analyte concentrations and reductions from both sampling dates.

<table>
<thead>
<tr>
<th>Analyte</th>
<th>Mean Upstream Concentration (mg/L)</th>
<th>Mean Downstream Concentration (mg/L)</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>TKN</td>
<td>3.14</td>
<td>0.75</td>
<td>76.07</td>
</tr>
<tr>
<td>NO\textsubscript{3}+NO\textsubscript{2}</td>
<td>0.41</td>
<td>0.08</td>
<td>81.16</td>
</tr>
<tr>
<td>TN</td>
<td>3.55</td>
<td>0.83</td>
<td>76.66</td>
</tr>
<tr>
<td>NH\textsubscript{3}-N</td>
<td>0.59</td>
<td>0.29</td>
<td>50.36</td>
</tr>
<tr>
<td>ON</td>
<td>2.55</td>
<td>0.46</td>
<td>82.04</td>
</tr>
<tr>
<td>TP</td>
<td>0.47</td>
<td>0.09</td>
<td>80.82</td>
</tr>
<tr>
<td>TSS</td>
<td>374.72</td>
<td>33.12</td>
<td>91.16</td>
</tr>
</tbody>
</table>

Pooled samples from above cell 1 and below cell 5 collected on February 22, 2021, and April 24, 2021, show substantial reductions in mean concentration of the six analytes investigated (Table 3.5). However, due to relatively small sample sizes (n=6), and relatively small storms investigated (5.3 mm and 7.6 mm rainfall depths), these results do not reflect a comprehensive view of the systems performance. However, these results do suggest that pollutant removal mechanisms such as denitrification (81.1% reduction in nitrate/nitrite), sorption (80.8% reduction in total phosphorus), and filtration/sedimentation (91.1% reduction in total suspended solids).
3.4.7 Variation Across All Flux Measurements

In total, 22 heat pulse measurements were made under various conditions ranging from heavy rainfall and storm flows through the RSC to slow dewatering of the pool in cell 1 following a storm event. From each heat pulse, flux estimates were made following the Perzlmaier et al. (2006) and Gregory (2009) approach outlined in Chapter 2. To visualize the magnitude of water flux variability under these different conditions, Figure 3.30 shows every flux value measured, across all depths, sorted by their location along the monitoring transect (from the left bank).

![Figure 3.30 Darcy flux variations across all measurements and depths, with the orange line representing the overall mean flux acquired over the transect. Measurements made at the same time are shown in the same color.](image)

Across all measurements, the greatest average difference in water flux is observed between the 2.75 m and 3.75 m from the left bank. On average, water fluxes occurring at 2.75 m from the left bank were 24.4 % faster than a meter further to the right at 3.75 m. The overall water flux variability is illustrated in Figure 3.31.
Figure 3.31 Water flux variability (averaged across depths) along the width of the monitoring transect, as a function of the overall mean flux.

Table 3.6 shows a summary of the 1,320 flux measurements acquired during heat pulses, sorted by depth.

Table 3.6 Darcy flux by depth, calculated from all observations.

<table>
<thead>
<tr>
<th>Depth</th>
<th>Mean Darcy Flux (cm/hr)</th>
<th>Median Darcy Flux (cm/hr)</th>
<th>Min (cm/hr)</th>
<th>Max (cm/hr)</th>
<th>Standard Deviation (cm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.3</td>
<td>1.478</td>
<td>1.498</td>
<td>0.328</td>
<td>2.341</td>
<td>0.397</td>
</tr>
<tr>
<td>30.5</td>
<td>1.339</td>
<td>1.339</td>
<td>0.714</td>
<td>1.948</td>
<td>0.293</td>
</tr>
<tr>
<td>45.7</td>
<td>1.325</td>
<td>1.313</td>
<td>0.417</td>
<td>2.122</td>
<td>0.366</td>
</tr>
<tr>
<td>76.2</td>
<td>1.516</td>
<td>1.528</td>
<td>0.732</td>
<td>2.297</td>
<td>0.353</td>
</tr>
</tbody>
</table>

Note: 330 measurements were taken at each depth for a total of 1,320

The minimum flux observed was 0.33 cm hr\(^{-1}\) at a depth of 15.3 cm near the right bank. The maximum overall flux (2.34 cm hr\(^{-1}\)) was also observed at this shallow depth, 1.5 meters from the left bank (Figure 3.32). Notably, this location corresponds with the location of the highest hydraulic conductivity measurement, which was taken at the surface using the MPD infiltrometer. The fastest mean Darcy velocity occurred at the 76.2 cm depth.
3.4.8 Estimation of Hydraulic Retention Time

Hydraulic retention time through the media was calculated assuming that horizontal flux dominated the movement of water downstream during fully saturated conditions (Fetter, 2018). This time was found using the average linear velocity of water, calculated from the Perzlmaier et al. (2004) model; over the average distance, water would have to travel from the middle of cell 1 to the boulder cascade where water entered cell 2 (Figure 3.33).
Figure 3.33 Cross-section view of Durham RSC, showing the average travel distance water would need to travel in the subsurface before reemerging as surface flow.

This relationship is given by equation 3.2.

$$\tau_{\text{media}} = \frac{L_{\text{media}}}{J_{\text{linear}}} \quad \text{Eq. 3.2}$$

Where:

$\tau_{\text{media}}$ is the amount of time water is traveling through the media (days)

$L_{\text{media}}$ is the average estimated length water has to travel from Cell 1 to Cell 2 (m)

$J_{\text{linear}}$ is the average linear subsurface water velocity (m day$^{-1}$)

The shortest possible retention time based on the time it would take water to flow from cell 1 to cell 2 via the path shown in Figure 3.33 was found to be 2.2 days. This value corresponds to a hypothetical case where a high hydraulic gradient was present during the entirety of the water particles' travel path, and water moved through the area of highest flux. The longest retention time would be 7.0 days under the same conditions if a water particle were to travel through the region of the lowest observed flux. By using the mean value for water flux observed from all measurements at all locations, an average retention time of 3.9 days was found. These retention estimates align well with visual observations made at the site following storm events. Visual observations indicated it would take several days for cell 1 to completely dewater during winter when evaporation and transpiration losses were low (see Figure 3.34).
Figure 3.34 Cell’s 3 and 4 partially filled with water above the media, four days after rainfall in March, 2021

3.5 Discussion

3.5.1 Implications of Results

The observed variability in water flux throughout the profile demonstrates that a disproportionate volume of water moves through select areas of media, driven via flow accumulation during storm events. While the mean water flux between depths did not vary by more than 13% over the observations made (Table 3.6), there were substantial variations across the width of the transect (Figures 3.29 and 3.30).

The high flux rates observed between 1.5 and 2.0 meters at the top depth of the monitoring transect conflict with the lower-than-average values observed at the lower three depths at the same horizontal location (see Figures 3.16 and 3.19). A possible explanation for this conflicting observation is the development of preferential flow paths near the surface due to clogging deeper in the profile between 15.3 cm and 30.5 cm, which has restricted the flux rate. Figure 3.30 illustrates this best, showing the 32.6% reduction in flux rate, between 15.3 and 30.5 cm depths 1.5 m from the left bank. These differences in velocity may be due to aggregation of fine materials from upstream or from mass wasting of the streambank (Helmreich et al., 2010), localized regions of high hydraulic conductivity due to the heterogeneity of bioretention material (especially fibrous mulch) (Koryto et al., 2017), or compaction of media (Blecken et al., 2014). Darcy’s Law states there is a proportionate relationship between saturated hydraulic conductivity and water flux. However, the differences between the saturated hydraulic conductivity
measurements showed much greater variability (see Figure 3.11), then was observed by the
AHFO-DTS measurements of water flux. Figure 3.20 highlights the importance of finer scale
monitoring offered by AHFO-DTS as opposed to simply using Darcy Law and monitoring wells
with an estimated site hydraulic conductivity to determine flux. Figure 3.20 also illustrates, how
the estimate of $K_{\text{sat}}$ directly impacts the magnitude of flux estimated by Darcy’s law, even within
a relatively narrow range of averaged saturated hydraulic conductivity values. Further, if
saturated hydraulic conductivity values were to continue to drop overtime, monitoring wells
would not demonstrate where clogging or hydraulic deficiencies are located, making
maintenance and remediation of the site difficult.

Large variations in mulch particle sizes in bioretention media have been known to cause
clogging as smaller fragments disperse into the pores of larger particles (Hsieh and Davis, 2005;
Arias et al., 2001). The RSC media was constructed with a shredded wood mulch as opposed to
the currently recommended hardwood chip mix, which has a more uniform particle size (Koryto
et al., 2017). This shredded mulch contained intertwined fibers, likely contributing to low
hydraulic conductivity zones. The drop in saturated hydraulic conductivity found by this study
compared to those reported by Korto et al. (2017) further indicates that there has been a change
to the media’s hydraulic properties overtime. Regions of slower infiltration likely impact the
practice’s ability to mitigate peak flow, but they also allow longer retention in anoxic
environments, which is needed for denitrification. While such variability in hydraulic properties
is anticipated in natural and constructed systems, understanding how these variations occur and
their effect on treatment warrant further investigation. Our results offer some insights having
observed that the variability of flux rate throughout the media increases during relatively high
intensity rainfall events, that cause heightened hydraulic gradients to form between cells.
Further, increased reductions in analyte concentration on April 24, 2021, compared to February
22, 2021, are likely the result of higher influent concentrations, warmer weather promoting
increased biological activity, and longer duration of the storm events (Duan et al. 2019).

Although we did not conduct a comprehensive water quality study, by pooling the analyte
concentrations found on February 22 and April 24, a mean concentration removal efficiency of
81.2% for nitrate/nitrite and 76.6% for total nitrogen suggest improved denitrification was
taking place in the media compared to previous work done at this site. These results contrast
Koryto et al. (2017) study, which found concentration reductions of 9% for organic nitrogen and
10% for nitrate/nitrite nitrogen obtained from composite sampling conducted during stormflows (>2.5 mm of rainfall). However, it also important to note that 44% of the storms sampled in Koryto et al. (2017) study had rainfall depths larger than 12.7-mm, more than double the average of the two storms presented in this study. Since RSC water quality improvements would be reduced during larger rainfall depths, it is likely that the results presented in this study are skewed towards better performance because of the relatively small storms sampled.

Nevertheless, the observed increase in performance of nitrate reduction is likely attributed, in part, to the 27% reduction in hydraulic conductivity between 2016 and 2021 and increased average hydraulic retention time of water in the media as the RSC matured in the years since construction. Merriman & Hunt (2014) study conducted on an aging stormwater wetland found similar trends, reporting that the overall reductions of nitrogen event mean concentrations were improved as the wetland matured compared to the years immediately following its construction. This concept of maturation of SCMs and increased water quality improvement over time is an increasing area of interest to practitioners seeking to gain additional mitigation credit. It is also notable that mean TSS reduction of 91% during stormflow would currently exceed the requirement for this RSC to be considered a Primary Practice set by the North Carolina Stormwater Control Measure Credit document (NC DEQ, 2015).

Our estimates of hydraulic retention time ranged from 2.2 to 7.0 days, suggesting sufficient time for denitrification to occur according to studies conducted on nature and media-based treatment systems. Toet et al. (2005) study found 45% annual nitrate reduction after four days of retention time in treatment wetland, and Cameron et al. (2010) showed hydraulic retention times as short as 1.7 days could achieve a moderate degree of denitrification in saturated organic media beds. However, more work is required to find the optimal hydraulic retention time to achieve denitrification in these complex systems.

3.5.2 Future Work and Improvements to Testing Methodology

This study indicates that AHFO-DTS would provide valuable insights during long-term deployments. This would allow monitoring changes in hydraulic residence time, identify areas in need of maintenance, and help estimate the SCM’ effective design life. Such an installation would allow periodic monitoring during the maturation of practice. It could be used to detect significant (greater than an order of magnitude) differences in water flux that could affect the
system’s performance. For example, monitoring for years could reveal preferential flow paths evolving into restrictive flow regions due to clogging from the addition of fines and organic material delivered over time by flow events.

Installation of the fiber-optic cable into the media of cell 1 was cumbersome due to the need to excavate media. Ideally, the fiber-optic installation would occur during or shortly after the construction of the structure to ensure any disturbance to the media is mitigated before monitoring occurs. Additionally, testing the pre and post installation bulk density would help account for disturbances caused by the installation, and is suggested for future deployments. Our initial monitoring plan called for this; however, construction of the intended RSC monitoring site was delayed due to agency review of mitigation plans, environmental permitting, and Covid-19. Allowing a settling period of 2-3 months between installation and monitoring is also recommended.

Combining AHFO-DTS monitoring in conjunction with other monitoring techniques and protocols may help to further explain water flow dynamics in media-based treatment systems. For example, automated rhodamine dye tracer tests injected into the saturated media may offer further insights into the variability of retention times and verify the estimates presented by this study. In addition, automated water sampling during monitoring would allow a more comprehensive view of water quality in the RSC channel and give further insights into event loading and load reductions. This study confirms that further monitoring is needed to fully identify the impact that subsurface water movements have on overall water quality performance.

3.5.3 Design and Maintenance Recommendations

The design of media-based stormwater control measures requires considering what functional treatment mechanisms are most important at the site. This requires designers to balance mechanisms over different time scales; for example, RSCs should promote long-duration treatment processes such as denitrification while maintaining short-term mitigation of flashy stormflows and physical straining of suspended solids.

For example, the modest reduction in infiltration rate between our study and that conducted by Koryto et al. (2017) from 18 cm hr⁻¹ and 12.8 cm hr⁻¹ offers greater denitrification potential than previously observed. However, this comes with the potential tradeoff of less water infiltrating the media during stormflows. Blecken et al. (2014) expressed the importance of preserving the
surface infiltration rates of media-based SCM’s to maximize media filtration. Therefore, designers are encouraged to balance the needs of stakeholders and determine whether greater denitrification potential is worth a potential decrease in peak flow mitigation and volume of run-on subjected to filtration.

Additionally, it is recommended that careful consideration of the media particle size, especially wood components, be made to reduce the formation of preferential flow paths. Further, the accumulation of non-construction material in cell 1 suggests that either a forebay be included in future designs, or regular servicing of the top pool takes place to preserve uniformity of the pool surface material. This suggestion, reaffirms Koryto et al. (2017) previous call for the inclusion of a forebay.

Finally, this study recommends that longer-term monitoring of these practices is conducted to quantify an effective baseline for their performance.

3.6 Assumptions and Limitations
Differences in background water content, soil density and material composition could all contribute to additional variations in the temperature field observed during the wetting front monitoring. This is likely the cause of the 2 degrees C variations in pre-wetting temperature along the monitoring transect in the initial temperature field shown in Figure 3.35.

![Graph showing pre-wetting temperature field in the monitoring transect.](image)

Figure 3.35 Pre-Wetting temperature field in the monitoring transect.

While the initial media samples used in laboratory testing were considered to be representative of cell 1’s media properties, it is possible that additional uncertainty due to the non-uniformity of
the overall media mixture could result in additional error. Furthermore, it was assumed that the variability in the media physical properties, such as saturated hydraulic conductivity, thermal conductivity and porosity were representative of the cell. However, it is possible that additional variability in these properties exist that were not accounted for in our measurements and samples.

The assumption that horizontal flux is dominant through the monitoring transect is only valid in periods where the RSC media has reached saturation, and vertical infiltration is limited near the outlet of the cell. Such conditions were present during all measurements presented in this study. Development of a system capable of discerning the direction of flux would be helpful in the future. However, the vertical component of flux is likely more significant near the upstream portion of cell 1 where water enters the system, and vertical pressure gradients could potentially form. Additionally, infiltration below the RSC media into the native soil is assumed to be negligible over the time scales presented in this study due to the restrictive clay composition and low hydraulic conductivity values (0-1.5 mm hr) of the subsoil material (NRCS, 2020).

The water quality grab samples acquired in this study do not provide a comprehensive view of the long-duration benefits of this system but rather a snapshot into its treatment potential during different points within ideal storms. Nevertheless, the reported reductions in analyte are concentration are promising and offer insight into the immediate conditions in the RSC channel during two storm events. A more robust analysis capable of calculating the total load and total load reduction by continuously monitoring flow rate and acquiring flow-weighted composite samples would allow further comparisons to Koryto et al. (2017) and confirm the improved water quality performance suggested by this study.

While efforts were made to quantify the variability of background thermal properties within the media profile, it is possible that regions of higher variability exist, which could produce additional errors in the flux estimate. Furthermore, disturbance caused by the installation may also have introduced differences in media condition caused by compaction or destruction of macropores. Additionally, Zhang et al. (2014) documented that soil physical properties can be affected by climate conditions and reduce the accuracy of heat-pulse probes, such as the Meter Group Thermal Properties Analyzer, which was used to obtain estimates of media’ thermal
conductivity. This effect may explain why a greater increase in the standard deviation for the media’s thermal conductivity was observed.

Finally, while this study only thoroughly investigated 1 of 5 RSC cells, it offers a limited but valuable understanding of the complexities of these systems overall.

3.7 Conclusions
This study verified the innovative use of AHFO-DTS to detect submeter scale variations in water flux under a range of conditions, as shown by its installation in an RSC located in Durham, NC. Variability of flux was most evident at the 15.3-cm depth of the monitoring transect with maximum and minimum observed fluxes ranging from 2.34 cm hr$^{-1}$ and 0.33 cm hr$^{-1}$, respectively. Looking across all measurements and depths, the most substantial difference in water flux was observed between the 2.75 m and 3.75 m from the bank, recording 24.4 % faster water fluxes at 2.75 m from the left bank than a meter further to the right at 3.75 m.

Changes in temperature caused by localized percolation into the RSC media also suggest the utility of AHFO-DTS to detect and track the propagation of the wetting front during initial run on when there was convective cooling cause by sufficient differences in water temperature and the heated cable. This newfound ability to monitor preferential flows of unstable wetting fronts could have profound impacts on pollutant monitoring in the future, especially if background conditions such as water content, soil density and material composition can be accounted for.

The hydraulic variations observed in this study compare well to work done previously at the site. The variations observed are likely not substantial enough to warrant immediate maintenance of the system and even suggest that the maturation of the practice may improve the nitrogen reduction benefit over time. Overall, reductions in analyte concentrations appear to correspond with the magnitude of fluxes observed during stormflows and increased average residence time of water in the media compared to prior monitoring. This highlights the importance of conducting follow-up studies to monitor a system’s evolution and efficacy to understand if it is meeting its objectives or requires repair. Additionally, a more comprehensive sampling effort should be explored to estimate load reductions for better comparison to the previous study results of Koryto et al. (2017).

Long-term AHFO-DTS monitoring in RSC systems and other media-based treatment practices would offer sustained high-resolution monitoring and may give better estimates of their useful
life. In addition, pairing novel AHFO-DTS monitoring with robust water quality sampling efforts would support a comprehensive understanding of the subsurface dynamics of these systems that ultimately impact our environment, economy, and communities.
3.8 References


Onset Computer Corporation. HOBO U20L-04 Data Logger.


