Tillage Management Effects on Subsurface Nitrate Transport to Artificial Drain Lines Using Distributed Temperature Sensing

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Dillon Shults

Major Professor: Erin Brooks, Ph.D.

Committee Members: Robert Heinse, Ph.D., C. Kent Keller, Ph.D.

Department Administrator: Robert Heinse, Ph.D.

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Authorization to Submit Thesis

The thesis of Dillon Shults submitted for the degree of Master of Science with a major in Water Resources and titled, "Tillage Management Effects on Subsurface Nitrate Transport to Artificial Drain Lines Using Distributed Temperature Sensing," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ________________________________ Date: _____________

Erin Brooks, Ph.D.

Committee Members: ________________________________ Date: _____________

Robert Heinse, Ph.D.

________________________________ Date: _____________

C. Kent Keller, Ph.D.

Department Administrator: ________________________________ Date: ______________

Robert Heinse, Ph.D.

Abstract

In the Palouse Region, farmers have been adopting no-tillage (NT) management practices over the last 30 years. There is a growing body of evidence that suggests long-term NT practices leads to the establishment of macropore networks through the preservation of earthworm burrows and root channels. These macropores may act as preferential flow paths in the vadose zone. The goal of this study is to quantify and compare the effects of long-term tillage management practices on subsurface preferential flow using distributed temperature sensing technology (DTS) and to assess changes in hydrologic and nitrate transport dynamics and pathways. In this paired watershed study (November 2016 to April 2017) temperature was used as a tracer as snowmelt drained to two artificial drain lines under different tillage management, one draining a conventional tillage (CT) field and the other draining a no-till (NT) field. We found evidence that infiltrated water on the NT field travelled through the vadose zone preferentially as compared to the CT field by observing greater variability of water flow to fiber-optic cables installed in the artificial drain lines (2.2 times the number of temperature decreases greater than 0.35 ^{o}C along each cable), rapid flushing of water through the soil profile (during five early season discharge events the temperature of the drain line reached a minimum temperature 20.9 hours before the CT field), greater relative drops and rapid recovery of EC in NT drainage water during discharge events and early season flushing of nitrate through the soil profile. Major differences were also found in the predominant hydrologic and nitrate transport pathways. Runoff from the CT field (162.8 mm) was much greater than from NT field (0.8 mm) and drain line discharge was 1.4 times greater on the NT field (126.7 mm). On the NT field 100% of nitrate load came through the drain line while on the CT field 55% of the nitrate load came through the drain line and 45% came from surface runoff. Despite these changes in hydrologic flow paths and nitrate transport path ways there was no evidence that tillage management had any effect on the magnitude of total nitrate export to surface water.

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Dedication

I would first like to thank my parents for giving me the opportunity to pursue this degree. Their support, encouragement and love has never wavered. From a child they showed me that through hard work anything is possible. To my fiancé and partner in life Emma, thank you so much for your sacrifices. You mean the world to me.

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Chapter one: Introduction

Nitrogen and agriculture

The rapid modernization and intensification of agriculture systems that began in the 20th Century, commonly referred to as the green revolution, has allowed for greater crop yields and thus the ability to sustain our rapidly growing global population (Galloway et al., 2008). The green revolution was, and continues to be, primarily driven by the use of nitrogen-based fertilizers. Although nitrogen is abundant in our atmosphere, in the form of molecular nitrogen (N_2), photosynthetic organisms require nitrogen in biologically available species for uptake. Prior to anthropogenic nitrogen fixation, the conversion of molecular nitrogen to plant available forms would primarily occur by a small number of nitrogen fixing microbes (Galloway et al., 2003). As a result, plant available nitrogen is a common limiting nutrient for terrestrial photosynthetic organisms (Vitousek and Howarth, 2016).

In the early 20th century the Haber-Bosch process was developed and provided the first economically viable, industrial scale production of plant available nitrogen fertilizers. Since the development of the Haber-Bosh process, and large scale production of nitrogen fertilizers, the productivity of agricultural lands have roughly quadrupled (Smil, 2002), allowing for the global population to increase from roughly 1.6 billion in 1900 to over 7 billion (Smil, 1999). This mass production of reactive nitrogen has perturbed our global nitrogen cycle by increasing the abundance of reactive nitrogen in our environment, given that nitrogen use efficiency is generally less than 50% for agricultural systems (Oenema et al., 2009). Reactive nitrogen refers to biologically, photochemically, and radioactively active nitrogen compounds, including plant available nitrate and ammonium, but also compounds such as nitrogen oxide [NO_x], nitric acid [HNO_3], nitrous oxide [N_2O], ammonia [NH_3] and organic compounds found in proteins and nucleic acids (Galloway et al., 2003).

Excess reactive nitrogen in the environment has been found to contribute to harmful algal blooms, eutrophication and hypoxia in surface water and coastal marine environments (Dodds and Smith, 2016), increased greenhouse gas emissions (Lesschen et al., 2011), and impairment of drinking water resources (Fan and Steinberg, 1996). Nitrogen pollution is widespread and well documented in the United States (United States

Environmental Protection Agency, 2009). For example, the EPA's National River and Streams Assessment 2008-2009, the most recent large survey of the United States surface waters, found the primary cause for the "poor" biologic condition of rivers and streams was nitrogen and phosphorous pollution, with more than 40% of river miles assessed having elevated nutrient concentrations (United States Environmental Protection Agency, 2016).

Nitrogen fertilizers, like other agricultural inputs, will continue to be essential to feed the world's growing population. The global population will add an additional 2 billion people by 2050, increasing the demand for crop-based food by an estimated 100-110% (Tilman et al., 2011). Also, more than 55% of the increase in crop production in developing countries is from the use of nitrogen fertilizers (Li et al., 2009). Therefore, management practices that reduce reactive nitrogen accumulation in the environment, while also feeding our global population, are necessary.

Tillage management, macropores and preferential flow

Since the 1930s growers across the country have been experimenting with reduced tillage farming techniques as a way to reduce runoff and soil erosion (Huggins and Reganold, 2008). One method of reduced tillage, no-till (NT), is a method of seeding crops directly into the previous years' crop residue with a single shank drill. Studies have shown NT management to reduce runoff and erosion from agricultural fields due to several factors such as increased residue cover that reduces the detachment of soil particles (Bradford and Huang, 1994), increased roughness of the soil surface (Mannering and Fenster, 1983) and perhaps most importantly, changes in the soil and pore structure that increase infiltration (Zhang et al., 2007). A significant change in soil structure that occurs in fields under reduced tillage is an increased abundance of macopores (Pagliai et al., 1995; Shipitalo and Protz, 1987; Wuest, 2001).

Macropores are relatively large pores or voids in the soil matrix. Beven and Germann, (1982) determined most studies describe a macropore of having a diameter ranging from 0.03 to 3 mm. Macropores can be formed through abiotic factors (cracks or fissures in the soil) or biotic factors (decayed root channels and pores formed by fauna such as earthworms) (Beven and Germann, 1982). A key driving force behind the increased presence macropores seen on reduced or NT fields are increased densities of earthworms and therefore burrows (Clapperton et al., 1997; Edwards and Lofty, 1982). These burrows, as well as decayed root channels and cracks in the soil, are more likely to stay intact under NT management due to the lack of soil disturbance (Kay and VandenBygaart, 2002).

Macropore networks on agricultural fields create preferential flow paths in the vadose zone, especially in finer, well-structured soils where macropores offer a “path of least resistance” to the denser surrounding soil matrix (Hendrickx and Flury, 2001). The term preferential flow refers to infiltrating water traveling through only a fraction of the total pore space (Hendrickx and Flury, 2001). Preferential flow paths through macropores can rapidly transport water and solutes through the vadose zone because of limited interaction with the surrounding matrix and the low tortuosity of macropores. As such many studies have begun studying how preferential flow through macorpores transport common agricultural chemicals through the vadose zone. Preferential flow is in contrast with uniform flow where a stable wetting front moves relatively uniformly through the soil profile interacting with more of the soil matrix.

Preferential flow and nitrate

When ammonium fertilizer is applied in aerobic drylands soils most of the nitrogen will be transformed into nitrate through nitrification and is the primary form of nitrogen loss from fields (Li et al., 2009). Nitrate is water soluble and nonreactive and therefore acts conservatively in the environment. There is a growing body of research assessing how preferential flow may affect nitrate transport processes and loading on agricultural fields.

In the literature, there is support for rapid transport of nitrate through soil on NT fields with macropore development. For example, Cheng et al. (2014) assessed how preferential flow affected nitrate transport processes in soil cores. In this study two cores (50-cm-high and a 20-cm-diameter) were collected at a field site where previous dye testing indicated preferential flow through macropores was occurring. Another two soil columns were made by filling loosened soil into tubes that were the same size as the cores. In this experiment the two undisturbed cores with macropores were compared to the two disturbed (or repacked) soil columns without macropores. A break through curve was developed for the cores using 1 g/L KNO_3 –N as a tracer. The researchers found the average solute transport time for nitrate-N (when $C/C_0 < 0.05$) for the undisturbed columns with intact macropores to be 12 hours and 28 hours for the disturbed columns. In another study, Shipitalo and Edwards (1993), a two year column lysimeter experiment was conducted on soil columns from a field under 17 years of NT management and conventional tillage (CT) management. During the two years NH_4NO_3 was applied above the columns during the spring and leachate through the columns was collected. The researchers found, similar to Cheng et al. (2014), more rapid transport of nitrate through the columns on the NT columns after fertilization.

There are varying findings in the literature regarding the longer-term (annual) concentrations and loading of nitrate through the leachate of NT fields. Some studies have found a reduction in nitrate concentration following the adoption of NT practices (Angle et al., 1993; Nila Rekha et al., 2011), while other studies documented no change in nitrate concentration on NT fields (Bjorneberg et al., 1996; Shipitalo and Edwards, 1993). In terms of loading, there are studies which have documented increased (Bakhsh et al., 2002), decreased (Syswerda et al., 2012) and no change (Randall and Mulla, 2001) in nitrate loading following the adoption of NT management.

A recent article conducting a meta-analysis of NT vs CT management and its effect on nitrate concentration and loading (Daryanto et al., 2017) found that, generally, loading through surface runoff was roughly equal between the tillage management practices, due to higher nitrate concentration during fewer runoff events on NT fields, but loading through the leachate was more often greater under NT management due to similar concentrations, but increased water flux through the vadose zone. The study also found a significant increase in the percent change of nitrate concentration on dryland farms under NT management. There is agreement amongst the literature that preferential flow occurring on NT fields with macropore development often results in rapid vertical transport, but the effect on leachate concentration and load still remains unclear and seems to vary from place to place due to the variables unique to each site such as soil texture, rainfall variability, topography, crop type and NT duration (changes in soil organic matter and nitrogen cycling) that play a role in nitrate leaching processes (Daryanto et al., 2017).

Regional

The topography of the dryland cropping region of the Palouse in northern Idaho, eastern Washington and eastern Oregon consists of steep rolling hills with varying aspects and slopes, leading to differences in irradiance, soil water content, and soil temperature within a single managed field. Basalts of the Columbia River Group dominate the regional bedrock geology, and overlying soils consist of silt-loam textured loess. The seasonality of precipitation in the region is characterized by a rainy season that occurs from October to April of each year, and a drier season occurring from May to September. The rainy season replenishes soil moisture storage which allows for the growth of wheat and legumes throughout the drier growing season. During the rainy season, precipitation events lead to concerns about the fate and transport of common agricultural chemicals. Throughout the drier growing season, the variability of remaining soil moisture, as well as the depth of soil of bedrock, drives the variability of biological and physical processes on the fields such as nutrient uptake and crop yield.

Excessive tillage on the steep topography over the last 100 years resulted in high soil erosion in the region (Brooks et al., 2010). Due to concerns over erosion and sediment loading there has been widespread adoption of NT management practices over the last 30 years. In the Palouse this shift of management practices has reduced the amount of erosion and sediment loading to receiving waterbodies (Brooks et al., 2010), however little attention has been given to how NT management practices may increase macropore development on agricultural fields and alter local hydrology and nutrient transport processes and total loading.

Similar to other regions in the United States shallow artificial drain lines are present across the Palouse in the lower and flatter landscape positions. By draining water from shallow soil layers, artificial subsurface drainage allows for earlier planting and improved crop productivity on many agricultural fields. These artificial drain lines outflow directly into either drainage ditches or rivers and streams in the region and thus provide a direct pathway from infiltrated water across agricultural fields to nearby surface waters (Keller et al., 2008). Since the lower landscape positions of the Palouse are often artificially drained and there has been a strong push to increase the adoption of NT management, there is concern that the combination of preferential flow on NT fields and the presence of artificial tile lines may be creating flow paths through the vadose zone that rapidly transmit water and agricultural chemicals to receiving surface water bodies with limited interaction with the soil matrix.

Figure 1.1. A soil core taken on a NT field at the Cook Agronomy Farm by Dr. Erin Brooks and his team in 2013 at a depth of approximately five feet showing macropore and preferential pathway development.

Distributed temperature sensing

Distributed Temperature Sensing (DTS) systems measure temperature along the lateral profile of a fiber optic cable rather than at individual sensors and are therefore very useful in hydrologic studies. The DTS sensing unit can be downloaded and provide highly accurate temperature and spatial data with temperature resolution of 0.1 C^{o} or less and spatial resolutions of 1 meter all within a 1 minute or less temporal window (J. S. Selker et al., 2006). A DTS instrument sends laser a pulse down a fiber optic cable and measures the photons scattered back along the fiber. Van de Giesen et al (2012) explains how a DTS system functions:

> “Most backscattered photons have the same frequency as the original laser pulse. Some, however, will show the effect of Raman scattering, with some having a lower frequency (called Stokes) and others a higher frequency (called anti-Stokes). The intensity of the anti-Stokes backscatter is very sensitive to the temperature of the scattering element while the Stokes backscatter is much less sensitive. The ratio of the two then allows for the calculation of the temperature of the fiber. With good calibration, even less expensive DTS systems provide 1–2 m resolutions, with 0.1 K accuracies for integration times of 60s.”

Initial uses for DTS were focused on industrial applications such as fire and oil and gas pipeline monitoring, however in 2006 researchers began using DTS in hydrologic studies (Tyler et al., 2009). Recent research using DTS have studied the interaction of groundwater and surface water in streams (J. Selker et al., 2006), ice shelf melting (Kobs et al., 2014) as well as illicit connections in stormwater (Hoes et al., 2009).

There are three common configurations for DTS deployments, including simple single-ended configuration, duplexed single-ended configuration and double-ended configuration. Each configuration offers certain advantages and disadvantages. In the simple single-ended configuration one end of the cable is attached to the DTS sensor. In this configuration a total of three reference sections are needed for each cable, with two being located near the sensor and one at the end. In the duplexed single-ended configuration, cables that have two fiber-optic cables within one cable sheath are commonly used. The two fibers are spliced at the end, with one end being attached to the sensor and the other being unattached. In this case the two fiber-optic cables follow the same path, both travelling away from the sensor and then back towards the sensor, with only one end of the cable attached to the sensor. The cable thus passes through two reference sections going away from the sensor and then again on the way back towards the sensor.

The double-ended configuration is best suited for harsh environments where stress in the cable such as sharp bends or splices are present. For double-ended measurements the fiber optic cable is attached at both ends to the sensor and lights pulses are sent and recorded from both sides, switching for each temperature trace. Through this process the sensor can get more accurate temperature measurements by monitoring photon backscatter while travelling both directions through the cable. However, since the double ended configuration requires a more complicated deployment, added software computation and increased noise in the signal near the instrument the double-ended configuration is not necessary or even the best suited configuration if the fiber-optic cables are not under excessive stress (van de Giesen et al., 2012).

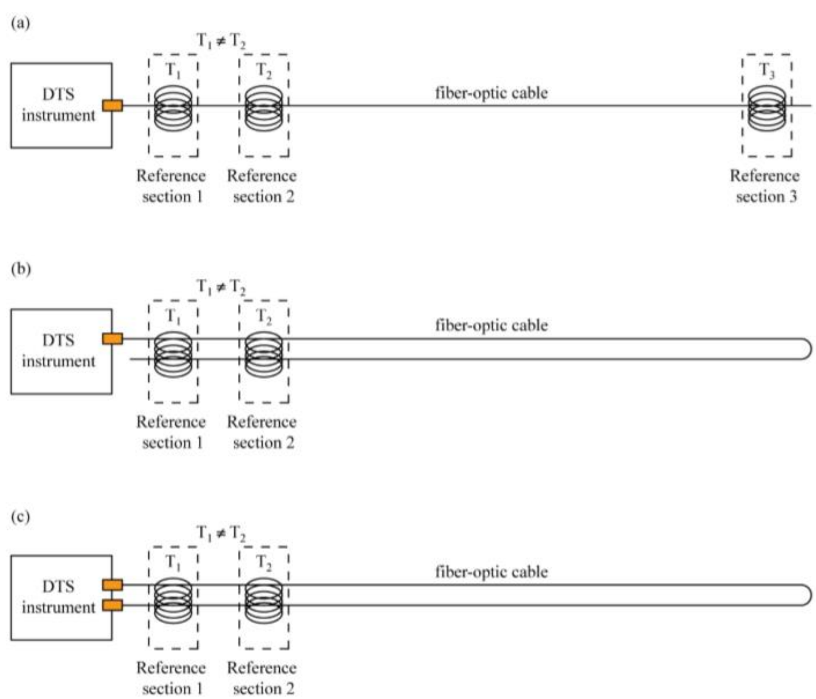


Figure 1.2 Image of the three DTS configurations. Source: Hausner et al. (2011).

Research goal and objectives

The overall goal of this study is to better assess the effects of long-term NT management practices on hydrology and offsite nitrate transport processes. The specific objectives for this study are as follows:

1) Compare high spatial and temporal frequency changes in water temperature within artificial drain lines, during snowmelt events, installed in both NT and CT fields using DTS technology

2) Quantify preferential flow to artificial drain lines using water temperature tracers and hydro-chemical tracers

3) Assess the effects of tillage management on the predominate transport pathway, concentration, timing, and overall export of nitrate nitrogen

This study was conducted at the Washington State University Cook Agronomy Farm (CAF) located in Whitman County, Washington within the Palouse Region. The CAF was formed as a long-term research site by WSU scientist in collaboration with the United State Department of Agriculture Agricultural Research Service (USDA-ARS) and is currently one of the 18 USDA-ARS Long Term Agroecosystem Research Network sites. The CAF is a 57-hectare farm with fields under both CT and NT management. Both the CT and NT fields have been under similar management and planting schedules since 1998, typically consisting of a rotation of winter wheat, spring wheat and spring pulses.

Previous monitoring at the outlet of NT artificial drain line at the CAF has shown a decrease in the temperature of drainage water during discharge events that occur in the winter months, when snowmelt and colder near surface soil water travels to the artificial drain line. Temperature will thus be used as a tracer as snowmelt and colder near surface soil water moves to artificial drainage lines on two fields at the CAF, one under NT management, a previously monitored artificial drain line, and another under CT management. The temperature in each artificial drain line will be collected using DTS technology. This study will use the spatially distributed temperature traces to assess preferential flow to each artificial drain line by identifying changes in thermal energy along each line and quantifying the frequency of preferential contributions. It is our hypothesis that the temperature trace of the drain line under NT management will have greater variability due to more frequent, distinct temperature drops along the drain line occurring during snowmelt events because of the increased presence of preferential flow paths, as compared to the CT field where the dominant flow mechanism is assumed to be matrix flow and therefore snowmelt water is thought to move primarily as a relatively stable wetting front to the drain line. Additionally, we hypothesize that the temperature traces will reach a minimum average temperature more quickly on the NT field as snowmelt is more rapidly transported to the artificial drain lines.

This experiment will be an innovative approach to quantifying preferential flow using recent advances in geophysical sensing technology. There are notable benefits of using DTS data to assess preferential flow as compared to other traditional methods such as dye and salt tracers. Dye tracer experiments are small in scale, often conducted on soils cores, and once conducted the cores are no longer usable so there is no temporal component. Salt tracers are often applied to fields and monitored at one location. Since the monitoring is only conducted at one location, there is limited spatial resolution. DTS data has the advantage of both high spatial, 1.01 meter, and temporal, in this study 15-minute, resolution.

In addition to temperature monitoring, temperature corrected electrical conductivity (EC) will be monitored in drain lines under the NT and CT fields as well. EC also works as a tracer because water increases in dissolved ionic concentrations with a longer contact time and greater interaction with the soil and will this have a higher EC value. Water moving through preferential flow paths in the soil have a characteristically low EC in comparison because of the shorter contact time and limited interaction with the soil matrix. Therefore, we hypothesize that as precipitation travels through the vadose zone to the artificial drain lines during snowmelt or rainfall events, water movement through preferential flow paths should result in be more flashy EC values, decreasing and recovering more quickly, and also reaching a lower relative value than the EC of water moving though the vadose zone as matrix flow.

Finally nitrate concentrations will be monitored in the drainage water from both the NT and CT fields. While nitrate export from artificial drainage systems has been studied in the past (Baker (2001); Gast et al. (1978)), the effects of tillage management on nitrate concentrations and total loading is complex. This study will assess the impacts of tillage management on the timing, magnitude, and overall export of nitrate.

References

Angle, J.S., Gross, C.M., Hill, R.L., McIntosh, M.S., 1993. Soil nitrate concentrations under corn as affected by tillage, manure, and fertilizer applications. J. Environ. Qual. 22, 141–147. https://doi.org/10.2134/jeq1993.00472425002200010018x

Baker, J.L., 2001. Limitations of improved nitrogen management to reduce nitrate leachind and increace use efficiency. Food an Energy Prod. Environ. Prot. 1, 10–16.

Bakhsh, A., Kanwar, R.S., Bailey, T.B., Cambardella, C.A., Karlen, D.L., Colvin, T.S., 2002. Cropping system effects on NO3–N loss with subsurface drainage water. Trans. ASAE 45, 1789–1797.

Beven, K., Germann, P.F., 1982. Macropores and water flows in soils. Wat. Resour. Res. 18, 1311–1325. https://doi.org/10.1029/WR018i005p01311

Bjorneberg, D.L., Melvin, S.W., Kanwar, R.S., 1996. Seasonal changes in flow and nitrate-N loss from subsurface drains. Trans. ASAE 39, 961–967. https://doi.org/10.13031/2013.27582.Rights

Bradford, J.M., Huang, C. hua, 1994. Interrill soil erosion as affected by tillage and residue cover. Soil Tillage Res. 31, 353–361. https://doi.org/10.1016/0167-1987(94)90041-8

Brooks, E.S., Boll, J., Snyder, A.J., Ostrowski, K.M., Kane, S.L., Wulfhorst, J.D., Van Tassell, L.W., Mahler, R., Boylan, R., Minks, K.R., Lowery, B., Madison, F.W., Ruark, M.D., Frame, D., Stuntebeck, T., Komiskey, M., 2010. Long-term sediment loading trends in the Paradise Creek watershed. J. Soil Water Conserv. 67, 237–248. https://doi.org/10.2489/jswc.65.6.331

Cheng, J., Wu, J., Chen, Y., Zhang, H., 2014. Characteristics of preferential flow paths and their effects on soil properties. For. Chron. 90, 192–196.

Clapperton, M.J., Miller, J.J., Larney, F.J., Lindwall, C.W., 1997. Earthworm populations as affected by long-term tillage practices in Southern Alberta, Canada. Soil Biol. Biochem. 29, 631–633. https://doi.org/10.1016/S0038-0717(96)00189-7

Daryanto, S., Wang, L., Jacinthe, P.A., 2017. Impacts of no-tillage management on nitrate loss from corn, soybean and wheat cultivation: A meta-analysis. Sci. Rep. 7, 1–9. https://doi.org/10.1038/s41598-017-12383-7

Dodds, W.K., Smith, V.H., 2016. Nitrogen, phosphorus, and eutrophication in streams. Inl. Waters 6, 155–164. https://doi.org/10.5268/IW-6.2.909

Edwards, C.A., Lofty, J.R., 1982. The Effect of Direct Drilling and Minimal Cultivation on Earthworm Populations. J. Appl. Ecol. 19, 723–734.

Fan, A.M., Steinberg, V.E., 1996. Health implications of nitrate and nitrite in drinking water: An update on methemoglobinemia occurrence and reproductive and developmental toxicity. Regul. Toxicol. Pharmacol. 23, 35–43. https://doi.org/10.1006/rtph.1996.0006

Galloway, J.N., ABER, J.D., ERISMAN, J.W., SEITZINGER, S.P., HOWARTH, R.W., COWLING, E.B., COSBY, B.J., 2003. The nitrogen cascade. Bioscience 53, 341. https://doi.org/10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., Sutton, M.A., 2008. Transformattion of the nitrogen cycle: Recent trends, questions, and potential solutions. Science (80-.). 320, 889–892.

Gast, R.G., Nelson, W.W., Randall, G.W., 1978. Nitrate Accumulation in Soils and Loss in Tile Drainage Following Nitrogen Applications to Continuous Corn. J. Environ. Qual. 7, 258–261. https://doi.org/10.2134/jeq1978.00472425000700020021x

Hausner, M.B., Suárez, F., Glander, K.E., van de Giesen, N., Selker, J.S., Tyler, S.W., 2011. Calibrating single-ended fiber-optic raman spectra distributed temperature sensing data. Sensors 11, 10859–10879. https://doi.org/10.3390/s111110859

Hendrickx, J.M.H., Flury, M., 2001. Uniform and preferential flow mechanisms in the vadose zone, in: Conceptual Models of Flow and Transport in the Fractured Vadose Zone. National Academies Press, Washington, DC, pp. 149–187. https://doi.org/10.17226/10102

Hoes, O.A.C., Schilperoort, R.P.S., Luxemburg, W.M.J., Clemens, F.H.L.R., van de Giesen, N.C., 2009. Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing. Water Res. 43, 5187–5197. https://doi.org/10.1016/j.watres.2009.08.020

Huggins, B.D.R., Reganold, J.P., 2008. No-Till: the Quiet Revolution. Sci. Am.

Kay, B.D., VandenBygaart, A.J., 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Tillage Res. 66, 107–118. https://doi.org/10.1016/S0167-1987(02)00019-3

Keller, C.K., Butcher, C.N., Smith, J.L., Allen-King, R.M., 2008. Nitrate in tile drainage of the semiarid Palouse Basin. J. Environ. Qual. 37, 353–61. https://doi.org/10.2134/jeq2006.0515

Kobs, S., Holland, D.M., Zagorodnov, V., Stern, A., Tyler, S.W., 2014. Novel monitoring of Antarctic ice shelf basal melting using a fiber-optic distributed temperature sensing mooring. Geophys. Res. Lett. 41, 6779–6786. https://doi.org/10.1002/2014GL061155

Lesschen, J.P., Velthof, G.L., De Vries, W., Kros, J., 2011. Differentiation of nitrous oxide emission factors for agricultural soils. Environ. Pollut. 159, 3215–3222. https://doi.org/10.1016/j.envpol.2011.04.001

Li, S.X., Wang, Z.H., Hu, T.T., Gao, Y.J., Stewart, B.A., 2009. Chapter 3: Nitrogen in Dryland Soils of China and Its Management. Adv. Agron. 101, 123–181. https://doi.org/10.1016/S0065-2113(08)00803-1

Mannering, J. V, Fenster, C.R., 1983. What is Conservation Tillage? J. Soil Water Conserv. 38, 140–143.

Nila Rekha, P., Kanwar, R.S., Nayak, A.K., Hoang, C.K., Pederson, C.H., 2011. Nitrate leaching to shallow groundwater systems from agricultural fields with different management practices. J. Environ. Monit. 13, 2550. https://doi.org/10.1039/c1em10120j

Oenema, O., Witzke, H.P., Klimont, Z., Lesschen, J.P., Velthof, G.L., 2009. Agriculture , Ecosystems and Environment Integrated assessment of promising measures to decrease nitrogen losses from agriculture in EU-27. Agric. Ecosyst. Environ. 133, 280–288. https://doi.org/10.1016/j.agee.2009.04.025

Pagliai, M., Raglione, M., Panini, T., Maletta, M., La Marca, M., 1995. The structure of two alluvial soils in Italy after 10 years of conventional and minimum tillage. Soil Tillage Res. 34, 209–223. https://doi.org/10.1016/0167-1987(95)00471-4

Randall, G.W., Mulla, D.J., 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. J. Environ. Qual. 30, 337–344. https://doi.org/10.2134/jeq2001.302337x

Selker, J., van de Giesen, N.C., Westhoff, M., Luxemburg, W., Parlange, M.B., 2006. Fiber optics opens window on stream dynamics. Geophys. Res. Lett. 33, 27–30. https://doi.org/10.1029/2006GL027979

Selker, J.S., Thévenaz, L., Huwald, H., Mallet, A., Luxemburg, W., Van De Giesen, N., Stejskal, M., Zeman, J., Westhoff, M., Parlange, M.B., 2006. Distributed fiber-optic temperature sensing for hydrologic systems. Water Resour. Res. 42, 1–8. https://doi.org/10.1029/2006WR005326

Shipitalo, M.J., Edwards, W.M., 1993. Seasonal patterns of water and chemical movement in tilled and no-till column lysimeters. Soil Sci. Soc. Am. J. 57, 218. https://doi.org/10.2136/sssaj1993.03615995005700010038x

Shipitalo, M.J., Protz, R., 1987. Comparison of Morphology and Porosity of a Soil Under Conventional and Zero Tillage. Can. J. Soil Sci. 67, 445–456.

Smil, V., 2002. Nitrogen and Food Production : Proteins for Human Diets. Ambio 31, 126–131.

Smil, V., 1999. Detonator of the population explosion. Nature 400, 415.

Syswerda, S.P., Basso, B., Hamilton, S.K., Tausig, J.B., Robertson, G.P., 2012. Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agric. Ecosyst. Environ. 149, 10–19. https://doi.org/10.1016/j.agee.2011.12.007

Tilman, D., Balzer, C., Hill, J., Befort, B.L., 2011. Global food demand and the sustainable intensification of agriculture. Proc. Natl. Acad. Sci. 108, 20260–20264. https://doi.org/10.1073/pnas.1116437108

Tyler, S.W., Selker, J.S., Hausner, M.B., Hatch, C.E., Torgersen, T., Thodal, C.E., Schladow, S.G., 2009. Environmental temperature sensing using Raman spectra DTS fiber-optic methods. Water Resour. Res. 45, W00D23. https://doi.org/10.1029/2008WR007052

United States Environmental Protection Agency, 2016. National River and Streams Assesment 2008-2009: A collaborative Surey. Washington, D.C.

United States Environmental Protection Agency, 2009. An Urgent Call to Action - Report of the State-EPA Nutrient Innovations Task Group 35.

van de Giesen, N., Steele-Dunne, S.C., Jansen, J., Hoes, O., Hausner, M.B., Tyler, S., Selker, J., 2012.

Double-ended calibration of fiber-optic raman spectra distributed temperature sensing data. Sensors (Switzerland) 12, 5471–5485. https://doi.org/10.3390/s120505471

Vitousek, P.M., Howarth, R.W., 2016. Nitrogen Limitation on Land and in the Sea : How Can It Occur ? Biogeochemistry 13, 87–115.

Wuest, S.B., 2001. Soil biopore estimation: Effects of tillage, nitrogen, and photographic resolution. Soil Tillage Res. 62, 111–116. https://doi.org/10.1016/S0167-1987(01)00218-5

Zhang, G.S., Chan, K.Y., Oates, A., Heenan, D.P., Huang, G.B., 2007. Relationship Between Soil Structure and Runoff/Soil Loss After 24 Years of Conservation Tillage. Soil Tillage Res. 92, 122–128. https://doi.org/10.1016/j.still.2006.01.006

Chapter two: Tillage management effects on subsurface nitrate transport to artificial drain lines using distributed temperature sensing

Introduction

Growers have been practicing reduced tillage farming techniques to reduce runoff and soil erosion for nearly a century (Huggins and Reganold, 2008). No-till (NT) is one method of reduced tillage in which seeds are planted directly in the previous years' crop residue using a single shank drill rather than conventional tillage techniques. Studies have shown NT management reduces runoff and erosion from agricultural fields due to several factors (Bradford and Huang, 1994; Mannering and Fenster, 1983), but perhaps most importantly, an increased abundance of macropores that increase infiltration (Pagliai et al., 1995; Shipitalo and Protz, 1987; Wuest, 2001; Zhang et al., 2007)

A key driving force behind the increased presence of macropores seen on reduced or NT fields are increased densities of earthworms and therefore burrows (Clapperton et al., 1997; Edwards and Lofty, 1982). The increased number of earthworm burrows, as well as decayed root channels and cracks in the soil, are then preserved year to year in NT management due to the lack of soil disturbance (Kay and VandenBygaart, 2002). Macropore networks on agricultural fields have been found to create preferential flow paths in the vadose zone that can rapidly transport water, solutes and particles through the vadose zone (Edwards et al., 1988; Hendrickx and Flury, 2001). Studies that aim to better understand preferential flow commonly use background EC as a tracer because water moving through preferential flow paths in the soil will have a characteristically low EC in comparison because of the shorter contact time and less interaction with the soil matrix (Smith, 2012).

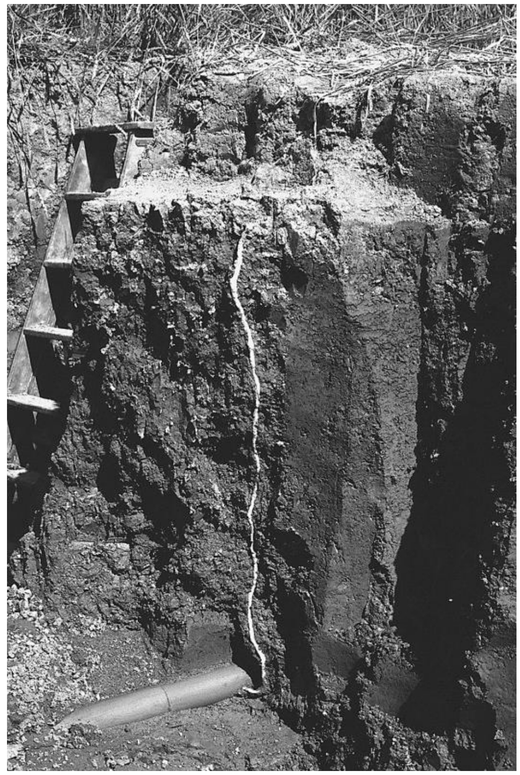


Figure 2.1. Earthworm burrow leading directly to an artificial drain line found in Nuutinen and Butt, 2003.

In the literature, there is support for rapid transport of nitrate through soil on NT fields with macropore development through preferential flow paths (Cheng et al., 2014; Shipitalo and Edwards, 1993). Apart from the agreement of rapid, “early season”, nitrate transport through soil with NT management, and macropore development, there are varying findings in the literature regarding the longer-term (annual) concentrations and loading of nitrate through the leachate of NT fields. In terms of leachate nitrate concentration, some studies have found a reduction (Angle et al., 1993; Nila Rekha et al., 2011) on NT fields, while others have shown no effect (Bjorneberg et al., 1996; Shipitalo and Edwards, 1993). Similarly there is little agreement on the leachate loading (units of mass per time) of nitrate from fields under NT management, where some studies have found NT management has no effects on nitrate loading (Randall and Mulla, 2001), decreased nitrate loading (Syswerda et al., 2012) and increased nitrate loading (Bakhsh et al., 2002).

A recent article conducting a meta-analysis of NT vs CT management and its effect on nitrate concentration and loading (Daryanto et al., 2017) found that, generally, loading through surface runoff was roughly equal between the tillage management practices, due to higher nitrate concentration during fewer runoff events on NT fields, but loading through the leachate was more often greater under NT management due to similar concentrations, but increased water flux through the vadose zone. The study also found leachate concentration and load seems to vary from place to place due to the variables unique to each site such as the duration of NT management that leads to changes in soil organic matter and nitrogen cycling and accumulation, soil texture, rainfall variability, topography and crop type.

Distributed Temperature Sensing (DTS) systems measure temperature along the lateral profile of a fiber optic cable rather than at individual sensors and have great potential for quantifying preferential flow to artificial drain lines. DTS sensing units provide highly accurate temperature and spatial data with temperature resolution of 0.1 °C or less and spatial resolutions of 1 meter all within a 1 minute or less temporal window (J. S. Selker et al., 2006). A DTS instrument sends laser a pulse down a fiber optic cable and measures the two-way travel time of photons scattered back along the fiber. Most backscattered photons have the same frequency of the initial laser pulse, however due to Raman scattering, some backscatter will have a lower frequency (stokes) and some will have a higher frequency (anti-stokes). Since the intensity of anti-stokes is sensitive to temperature and stokes are not, the ratio of the two can be used calculate temperature along the cable by also measuring two-way travel time (van de Giesen et al., 2012).

Initial uses for DTS were focused on industrial applications such as fire and oil and gas pipeline monitoring, however in 2006 researchers began using DTS in hydrologic studies (Tyler et al., 2009). Recent research using DTS have studied the interaction of groundwater and surface water in streams (J.S. Selker et al., 2006), ice shelf melting (Kobs et al., 2014) as well as illicit connections in stormwater (Hoes et al., 2009). Recently, Birkinshaw and Webb, (2010) used temperature as a tracer to better understand flow pathways at the catchment scale. To our knowledge DTS cables have never been used to assess preferential flow to artificial drain lines.

The overall goal of this study is to better assess the effects of long-term NT management practices on hydrology and offsite nitrate transport processes. The specific objectives for this study are as follows:

1) Compare high spatial and temporal frequency changes in water temperature within artificial drain lines installed in both NT and CT fields using DTS technology during snowmelt events using temperature as a tracer

2) Quantify preferential flow to artificial drain lines using water temperature and hydro-chemical tracers

3) Assess the effects of tillage management on the predominate transport pathway, concentration, timing, and overall export of nitrate nitrogen

Site description

This study was conducted at the Washington State University (WSU) Cook Agronomy Farm (CAF) located in Whitman County, Washington. The CAF was formed as a long-term research site by WSU scientist in collaboration with the United State Department of Agriculture Agricultural Research Service (USDA-ARS) and is currently 1 of the 18 USDA-ARS Long Term Agroecosystem Research Network sites. The CAF is a 57-hectare (ha) farm with fields under both CT and NT management. Both the conventional and NT fields have been under similar management and planting schedules since 1998, typically consisting of a rotation of winter wheat, spring wheat and spring pulses. From 2016 to 2018, winter wheat, spring wheat and garbanzo beans were planted respectively.

Figure 2.2. A soil core taken on a NT field at the Cook Agronomy Farm by Dr. Erin Brooks and his team in 2013 at a depth of approximately five feet showing macropore and preferential pathway development.

Precipitation at CAF has been collected with tipping bucket gauges which are not suitable for accurate measurements of precipitation in the form of snow or ice. Therefore, two nearby (within 10 km) NWS-COOP gauges have been used to estimate precipitation at the site. The estimated precipitation is calculated by an elevation weighted average between daily readings at the Palouse Conservation Field Station in Pullman, WA and the University of Idaho station in Moscow, ID. The elevation of the farm is spanned by the difference in elevation between the two precipitation gauges. The precipitation gauges at these sites are manual bucket gauges with windscreens which are manually read every day.

The average annual precipitation at the CAF, from the 2012 water year to the 2017 water year, is 632 mm. Mean annual high and low air temperatures are 27°C in the summer and −7°C in the winter (Geyer et al., 1992). The climate at the CAF is Mediterranean characterized by mild and wet winters and a hot and dry summer. Soils found at the CAF are Palouse, Naff and Thatuna series Mollisols (web soil survey 1/11/18). A restrictive argillic layer is intermittently present across both fields approximately 1-m below the surface, leading to intermittent perched water tables and subsurface lateral flow given the relatively steep topography. The basalt bedrock is thought to be fairly flat, and thus the peaks of the rolling hills are thought to be situated high enough above the basalt bedrock for there to be much effect on hydrology especially when restrictive layers are present. However, in the draws and lower, flatter landscape positions relatively shallow basalt can impede vertical percolation and can lead to shallow local water tables.

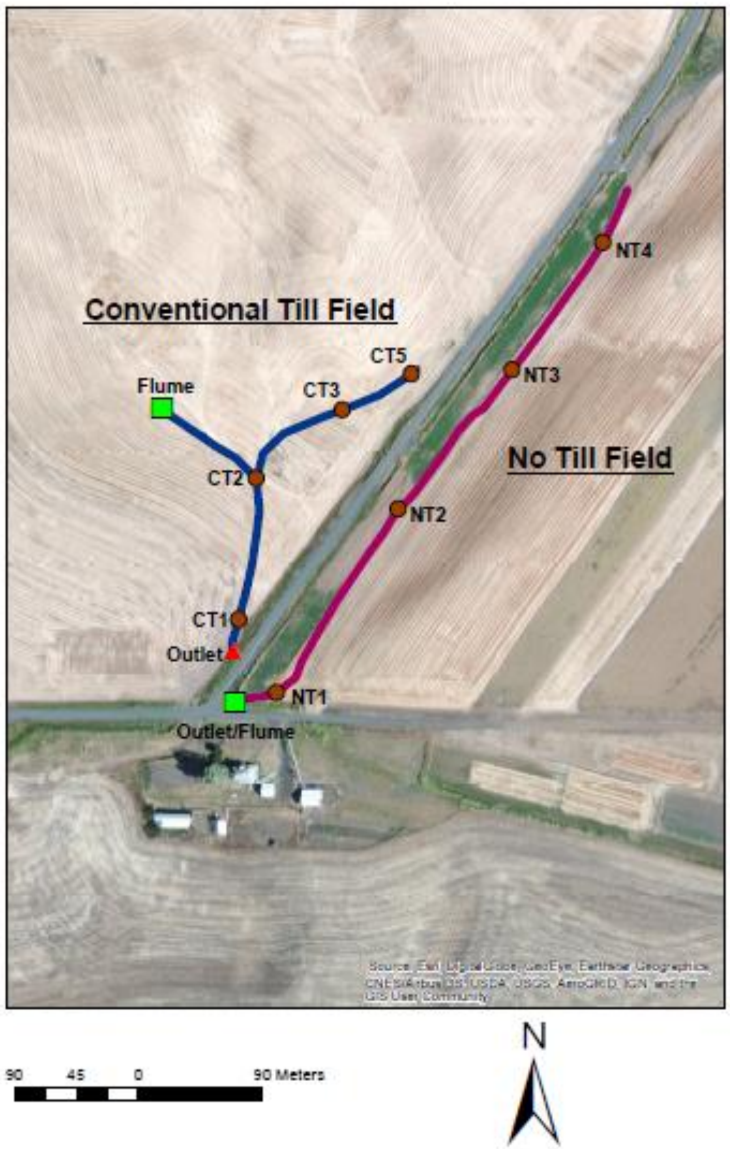


Figure 2.3. Map of study site identifying the location of artificial drain line and drainage flume locations.

Previous CAF research

Recent research at the CAF has focused on better understanding nitrate transport processes from the long-term no-till field site (Kelley et al., 2017; Keller et al., 2008, Kelley et al., 2013). Keller et al. (2008) showed that the seasonality of precipitation at the CAF governs the nitrate losses at the NT drain line outlet. The analysis indicated that it takes approximately 150mm of precipitation each fall for the discharge in the NT artificial drain line to respond to precipitation. Once the soil profile is filled to field capacity moisture content the drain line will flow continuously throughout the rainy season, and each precipitation event will result in an increase in discharge at the drain line outlet. Keller et al (2008) hypothesized that the combination of fall fertilization and nitrification and mineralization during the spring and summer led to a reservoir of nitrate that is held in the soil until the 150 mm precipitation threshold initiates flow in the CAF-NT drain line thus mobilizing this reservoir. Keller et al (2008) suggested that since the first discharge events coincided with high nitrate concentrations, either rapid vertical movement of nitrate from the fertilization zone (15 mm) was occurring or mineralized/nitrified nitrate was distributed throughout the soil profile and was at the depth of the drain line at the time of the first discharge events.

Research conducted by Kelley et al (2013) found that nitrified NH_4^+ fertilizer was the dominant source of nitrate in the drain line at the CAF-NT outlet based on its isotopic composition. These findings provided evidence that rapid vertical transport of nitrate from the fertilization zone to the drain line was occurring via preferential flow, as opposed to the hypotheses that distributed mineralized nitrogen may be the dominant source. Bellmore et al. (2015) assessed dissolved organic (DOM) matter transport at the CAF-NT drain line and also hypothesized that preferential flow was occurring given evidence of litter and topsoil DOM in the drain line leachate during discharge events.

Based on these recent studies conducted at the CAF there is reason to believe that preferential flow is occurring at the CAF-NT, resulting in a high degree of hydrologic connectivity between water, soil surface materials, both dissolved and solid, and the drain tile. With the findings from these recent research projects in mind, this study will attempt to better understanding the preferential flow and nitrate transport processes at the CAF.

Materials and methods

Distributed temperature sensing

This study will use the spatially distributed temperature traces along the DTS cable to assess preferential flow to each artificial drain line by identifying changes in thermal energy along each line and quantifying the frequency of preferential contributions. Previous monitoring at the outlet of the NT artificial drain line at the CAF has shown a decrease in temperature of drainage water during discharge events that occur in the winter months, when snow covers the soil surface. Temperature will thus be used as a tracer as snowmelt moves from the soil surface to artificial drainage lines on two fields at the CAF, one under NT management, a previously monitored outlet, and the other under CT management. It is our hypothesis that the temperature trace along the DTS cable within the artificial drain line under NT management will have greater spatial and temporal variability due to more frequent, distinct temperature drops along the artificial drain line occurring during discharge events under snowmelt conditions than the artificial drain line located in the CT field. The CT field is hypothesized to have less preferential pathway development and the dominant flow mechanism is assumed to be uniform flow and therefore snowmelt is expected to move primarily as a relatively stable wetting front to the drain line. Additionally, we hypothesize that the water temperature in the artificial drain line on NT field will drop more rapidly during discharge events as snowmelt is more rapidly transported as compared to the CT field.

Distributed water temperature within each drain line at the CAF was measured using a Sensornet Oryx DTS (Hertfordshire, England) unit. The DTS unit was configured to simultaneously interrogate two 500 m long AFL flat drop fiber optic cables (Duncan, South Carolina) every 1.01-meter at 15-minute intervals in the duplexed single-ended configuration (Hausner et al., 2011) from November 18th, 2016 to April 22, 2017. The sensor was stored in a waterproof plastic storage container near the outlet of the NT drain line. The sensor was powered by a two 12-volt deep cycle battery, coupled with a 20-watt solar panel. The fiber optic cables were deployed through the CT and NT drain lines using a 150 m long high-pressure water jetting system, similar to what is often used by the stormwater industry to clean storm sewers. Rope was tied to the jetter as it was fed though the drain line starting from each drain line outlet. Every 150 m a backhoe was used to dig down to the drain line, expose the tip of the jetter, grab the rope, relocate the jetter system and push forward another 150 m or until the jetter reached the end of the drain line or was restricted by root wad blockages. After reaching the end of the drain lines the rope was then used to pull the fiber optic cable through each drain line.

At each location where the backhoe was used to dig down to the drain line, 10 cm (4 inch) “T” couplings were put in the drain line to repair the break in the drain line and provide a 10 cm diameter vertical access tube to the drain line from the soil surface. The hole was then filled halfway and bentonite was placed around the vertical pipe to prevent water from flowing vertically down the pipes and into the drain line. These access tubes were put at locations NT1, NT2A, NT2B, NT3 and NT4 on the NT side and CT1, CT2, CT3 and CT5 on the CT side (See figure 2.3). At locations NT2, NT4, CT1, CT3 and CT5 Decagon 5TM soil moisture and temperature sensors were installed 0.3 m and 0.9 m below the soil surface and at the depth of the drain line. At NT1, Decagon 5TM soil moisture and temperature sensors were also installed, but since the depth of the drain line was just over the 0.9m depth, the 5TM sensors were only installed at the 0.3m and the depth of the drain line. All decagon 5TM sensors were used in conjunction with Decagon EM50R data loggers.

In total 428 m of drain line was monitored in the NT field and 237 m of drain line in the CT field. Approximately 12 meters of cable from NT cable and the CT cable were placed in two reference sections near the DTS sensor. The first reference section was an ice bath, inside a cooler, and the second reference section was a coiled section of cable from each cable that was buried approximately 1.5 feet underground and surrounded by sand. Just prior to the splice at the end of each cable an unmonitored reference bath was used allowing for a temperature correction after the splice on both cables. Therefore, starting at the sensor, both duplexed cables passed through an ice bath reference section, a buried reference section, an unmonitored reference bath before and after the splice, and then on its way back to the DTS sensor, the cable again passed through the buried reference section and the ice bath. In this set up, only two reference sections are monitored, but since the cable passes through the sections twice a total of four reference sections are available. Two independent PT100 thermistors recorded by the DTS unit were placed along the two monitored reference sections allowing for the temperature offset and the assessment of the accuracy and precision of temperature readings.

The data were processed using the MatLab® DTS toolbox available from the Center for Transformative Environmental Monitoring Programs (CTEMP). CTEMP's user toolbox provides graphical user interfaces that allows users to completely process and calibrate raw DTS data. To assess the accuracy of the DTS data, the root mean square error (RMSE) was calculated for each of the four reference sections, as the cable left the sensor and then again for when the cable looped back towards the sensor. In each reference section, the temperature of the independent PT100 thermometer is used to set the observed temperature of the bath. Since there are multiple temperature measurements for the sections of cable that are placed in the reference sections, the RMSE is calculated given the observed temperature of each reference section and each temperature reading from the DTS cables in the reference bath (Hausner et al., 2011).

Points along the fiber optic cable which exhibited sharp drops in temperature caused by preferential transport of 0° C snowmelt were identified using post-processing algorithms in MatLab®. Each temperature trace was first de-trended using polynomial regression (polyval and polyfit functions). Residuals around the de-trend line were calculated resulting in a de-trended temperature trace centered around zero, as seen in figure 2.4 below. The temperature trace was then multiplied by negative one and the peaks, or temperature drops, were identified using the Findpeaks function in MatLab® with a minimum peak prominence greater than two times the RMSE of the temperature data and less than 10 meters in width. The minimum length of the peak was set at 10 m to only identify the "small scale," vertical preferential flow contributions to the artificial drain lines. The criteria of two times the RMSE was chosen as it would identify true cooling points rather than temperature drops as a result of the instruments precision. An example of the peak identification can be seen in figure 2.5 below.

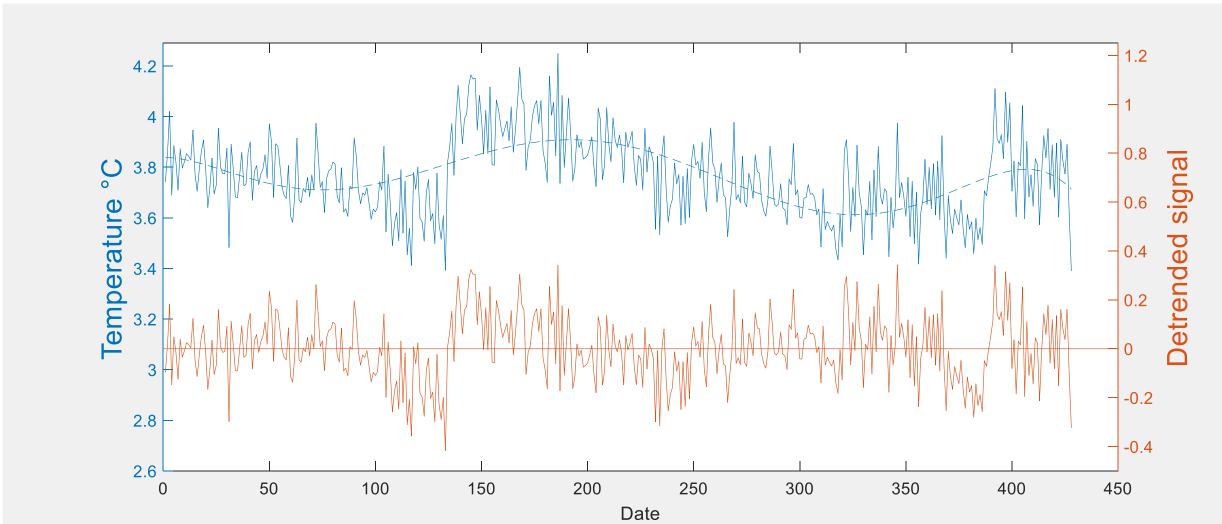


Figure 2.4. Example of the de-trending process.

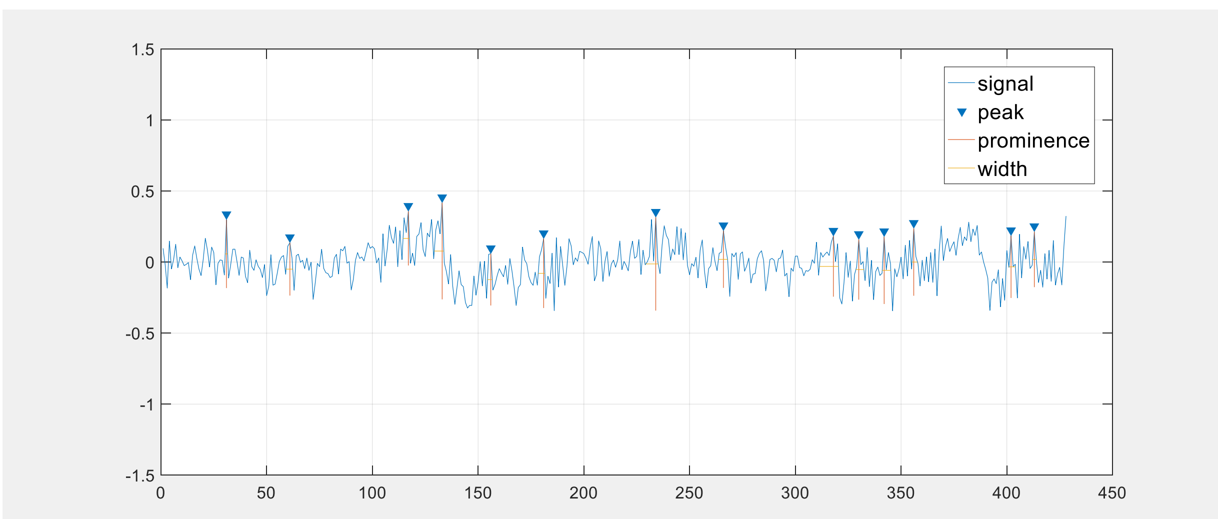


Figure 2.5. Example of peak identification where the de-trended signal is inverted, and the peaks are identified by a prominence greater than 0.35 ° C.

The difference between 4 m and 16 m moving spatial averages was calculated along each temperature trace to identify larger scale regions of bulk snowmelt movement to the artificial drain lines. The average difference in these 4 m and 16 m moving spatial averages were calculated for rising limb periods during critical snowmelt infiltration events. A one sample, one sided T-test was used to determine if the recorded temperature difference at any point along the line was significantly different than zero at alpha = 0.01. Only the first seven discharge events, were analyzed because these events occurred during the time period when discharge events led to decreased temperature of the artificial drain lines and the rising limb was used because it led to the most pronounced differences between the 4 meter and 16 meter moving averages.

Flow and nitrate monitoring

Drain line discharge was measured at both the NT and CT field using 6-inch Parshall flumes during the 2017 and 2018 water year. The NT the Parshall flume was located at the outlet of the drain line just prior to flowing into Missouri Flat Creek. The drain line outlet from the CT field is submerged most of the year in Missouri flat Creek and was therefore unsuitable for measuring discharge. Thus, a Parshall flume was placed farther up the drain line in the CT field. At both flume sites a CS451 pressure transducer (Campbell Scientific Logan, Utah) was used to measure water depth in stilling wells adjacent to each Parshall flume. Pressure transducers were coupled with CR10X data loggers (Campbell Scientific Logan, Utah). Discharge was calculated by using the flume's depth discharge rating curve. Flow monitoring at the NT drain line has been conducted since October 2011. At both flume locations water temperature and the temperature corrected (25°C) electrical conductivity (EC) of the drainage water was measured using a CS547-A probe (Campbell Scientific, Logan, UT). Water depth, temperature and EC were recorded at 15-minute intervals throughout the study. The area contributing to each drainage flume was calculated using a 2 m digital elevation model. Since the extent of the drainage network is unknown the contributing area is an estimate and the drainage network is assumed to collect water from the entire contributing area for both fields.

During the 2018 water year surface runoff was monitored at both the CT and NT fields until June 12, 2018 when all flume locations went dry. The CT surface runoff flume was located adjacent to as the drain line location and collected runoff out of the 5.4-ha bowl. At this location a RF series ramp flume (Global Water, Sacramento, CA) was used in conjunction with a stilling well. The depth of water in the flume was measured and recorded at 15-minute intervals using a CS451 pressure transducer coupled with a CR10X data logger. The NT surface runoff flume collected runoff from a 12.2-ha bowl. At this location a 6-inch Parshall flume was used in conjunction with a stilling well and a TruTrack WT-HR pressure transducer and internal data logger (Intech Instrument Ltd, Riccarton, New Zealand) recording average depth at 15-minute intervals. The area contributing to each surface runoff flume was calculated using a 2m digital elevation model.

Nitrate concentrations were monitored in the drainage water from both the NT and CT fields during the 2017 and 2018 water years using event-based auto-samplers (Teledyne ISCO, Lincoln, Nebraska). Water samples were collected based on water stage thresholds, or weekly in the absence of a change of water height. During the 2018 water year automated water samplers (Teledyne ISCO, Lincoln, Nebraska) were placed at surface runoff flumes to take time weighted samples at 24-hour intervals. Samples were collected once a week throughout the study. The collected water samples were processed at the USDA-ARS lab at Washington State University for nitrate analysis. All nitrate samples were first filtered through 0.45 µm membrane filters. The filtrate was stored frozen and then processed using a Dionex ICS-2100 ion chromatograph with SPEX CertiPrep standards. Annual nitrate load from each flume was determined using discharge and nitrate concentrations with the LOADEST (model 48).

In this study we specifically assess whether there is “early season,” rapid transport of nitrate on the NT field as compared to the CT field and will compare the overall nitrate concentration and export to surface water from each tillage treatment. Having both drainage water and surface runoff flow and concentration measurements in 2018, we will also compare the impact of tillage treatment on the predominate flow path of export.

Results

Precipitation

The 2017 year was a particularly wet year with 752 mm of precipitation, 24% greater than the average annual precipitation of 608 mm for the previous 5 years. As is seen in figure 2.6, the NT drain line reached greater peak flow, on multiple occasions, during the 2017 water year, than at any point during the prior five years. Early in the 2017 water year a majority of precipitation fell as snow and led to a delay in the onset of flow out of the NT drain line.

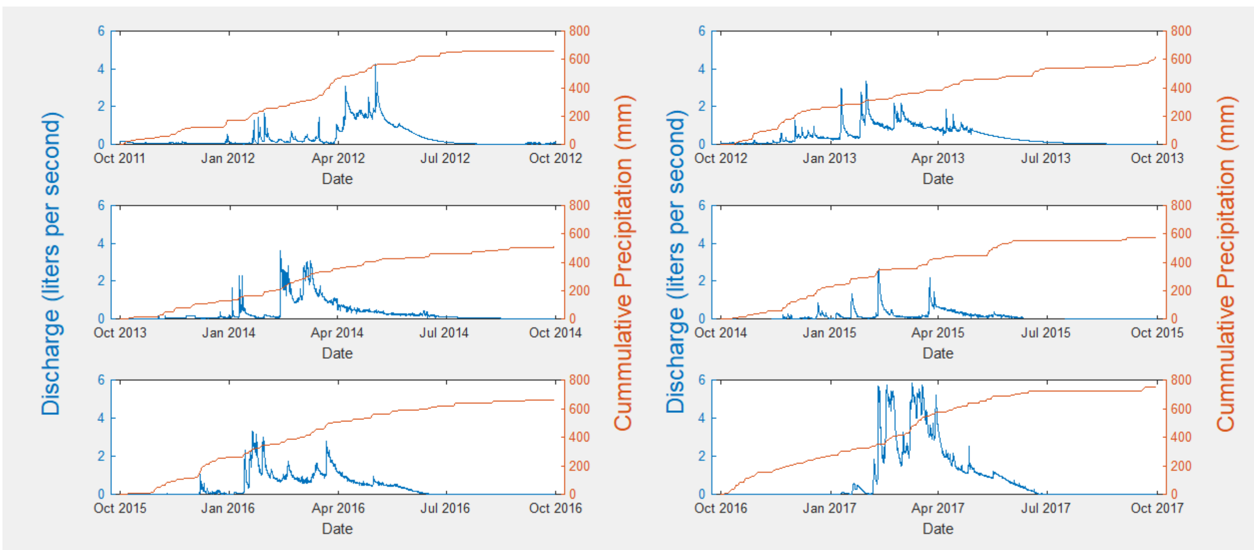


Figure 2.6. Cumulative precipitation and discharge at the NT artificial drainage outlet from October 2011 to September 2017.

Artificial drain line DTS data

The average RMSE in temperature determined from the reference ice baths along the NT and CT cables, was 0.181 ^{o} C and 0.127 ^{o} C, respectively. From the onset of flow in January to mid-March the average temperature of the DTS trace in each drain lines decreased during discharge events with snowmelt, see figures 2.7 - 2.11. This early season time period where the soil profile is filling with snowmelt water will be referred to as the reactive period for the remainder of this paper.

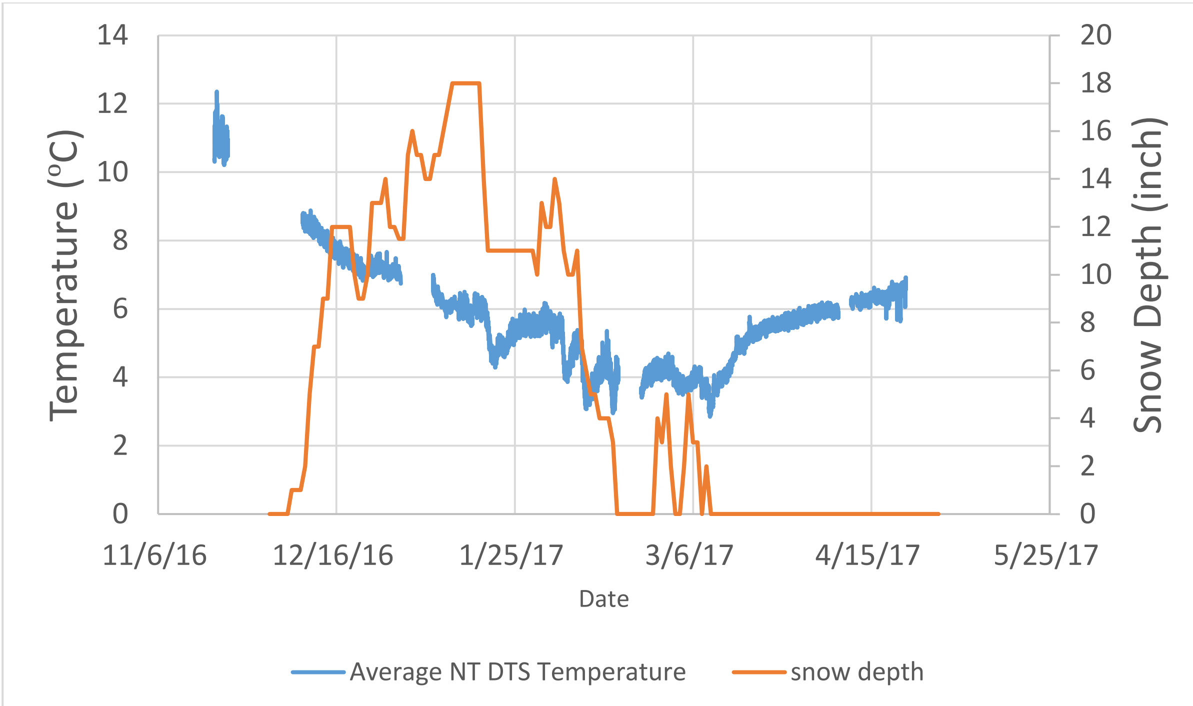


Figure 2.7. Snow Depth and Average DTS Temperature within the artifical drain line on the NT field.

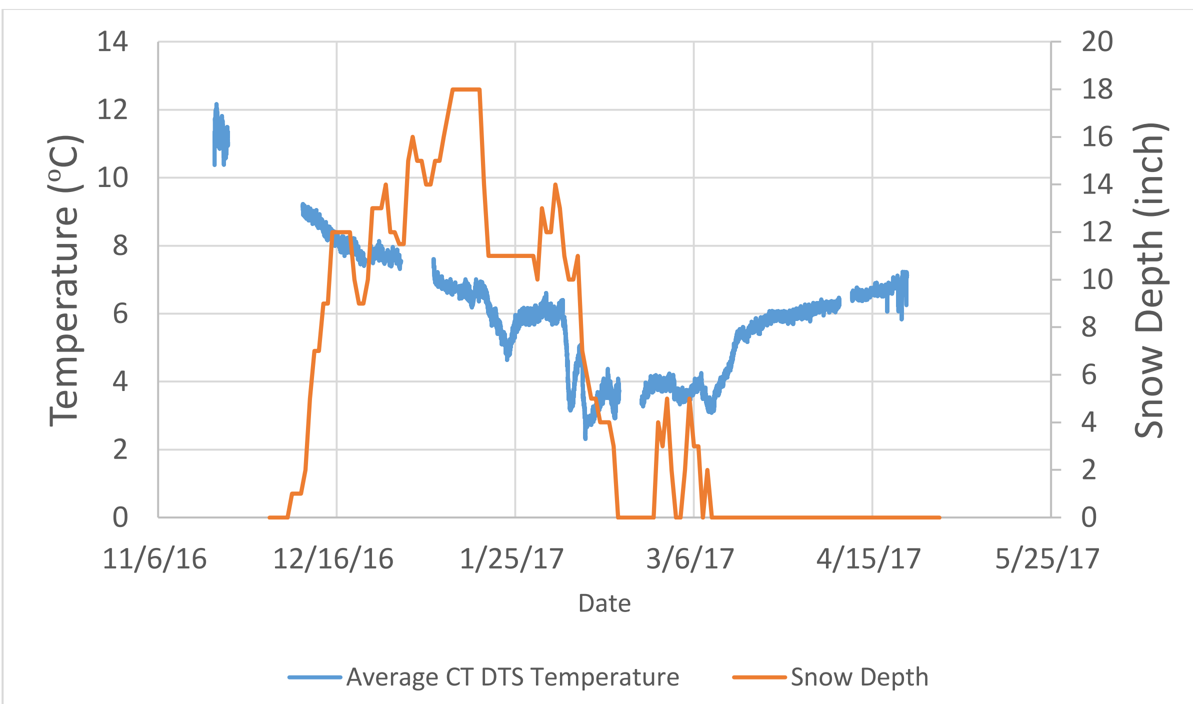


Figure 2.8. Snow Depth and Average DTS Temperature within the artifical drain line on the CT field.

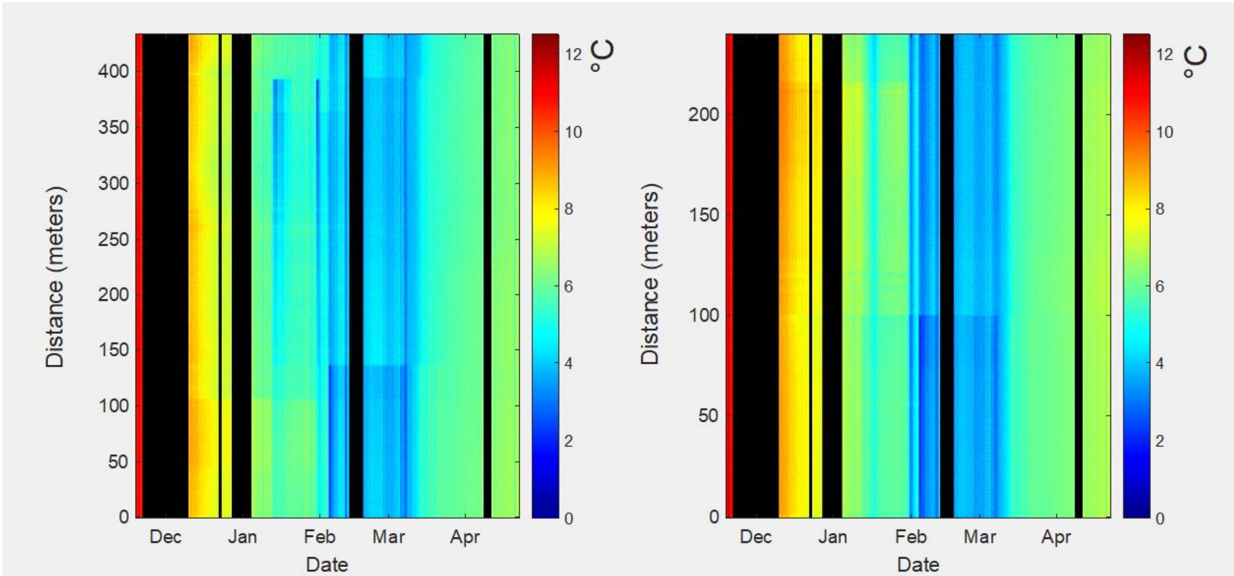


Figure 2.9. Overview of collected distributed temperature sensing data from October 2016 to April 2017. On the y-axis is distance along each fiber optic cable, on the x-axis is the date and the color map is temperature in degrees Celsius.

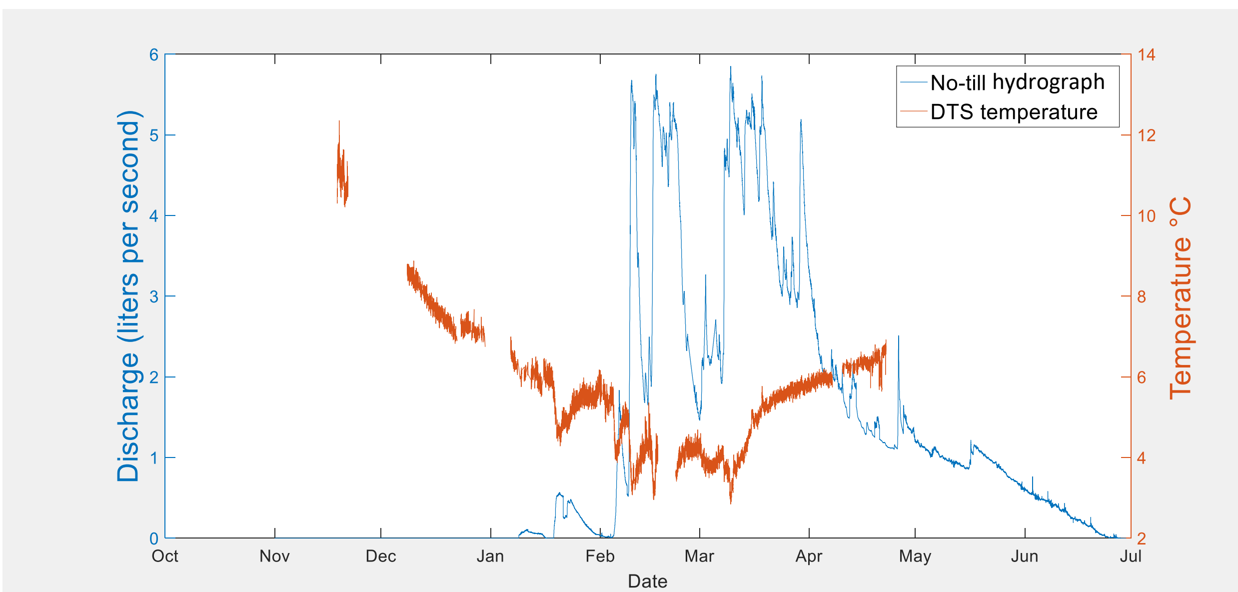


Figure 2.10. Hydrograph of the NT artificial drainage outlet and average temperature of the each DTS trace.

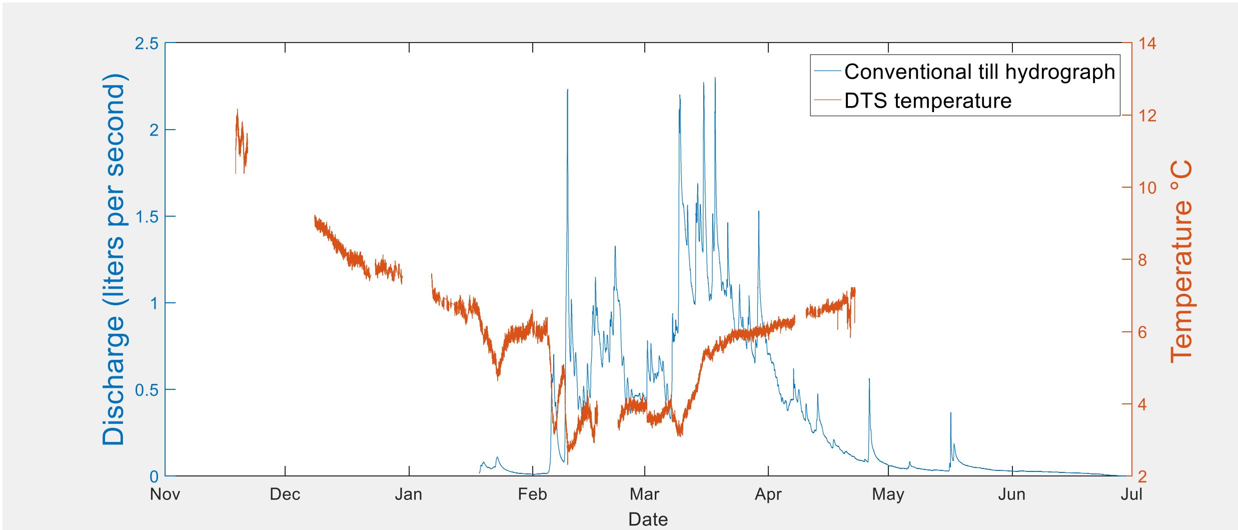


Figure 2.11. Hydrograph of the CT artificial drainage line and average temperature of the each DTS trace. Note the difference in Y-axis scales from the previous graph, this is to better view the discharge and temperature response at each field.

During this reactive period there existed a sharp temperature gradient between the cooler temperature recorded at the 0.3 m soil depth and the warmer soil temperature recorded at the depth of the drain line, see figures 2.12 and 2.13. Additionally, during the first large discharge event in January there was very little water in the drain line resulting in a pronounced response in temperature. Later in the season during this reactive period, the gradient of the soil temperature between the shallow depths (0.3 and 0.9 m) and the depth of the artificial drain line decreased. After mid-March the soil profile was close to isothermal with little temperature gradient within the profile and there was no remaining snow on the soil surface resulting in little to no response in the temperature along the DTS cables during these late season discharge events.

Early in the reactive period, until approximately mid-February, the water temperature along the fiber optic cable would be much cooler than the soil temperature recorded at the depth of the drain line during events but would then recover back to a similar temperature as the soil after the storm event ended. Later in the reactive period, from mid-February to mid-March, the average temperature response recorded by the DTS cable was dampened during discharge events and would no longer recover to the temperature of the soil at the depth of the drain line, see figures 2.10 and 2.11.

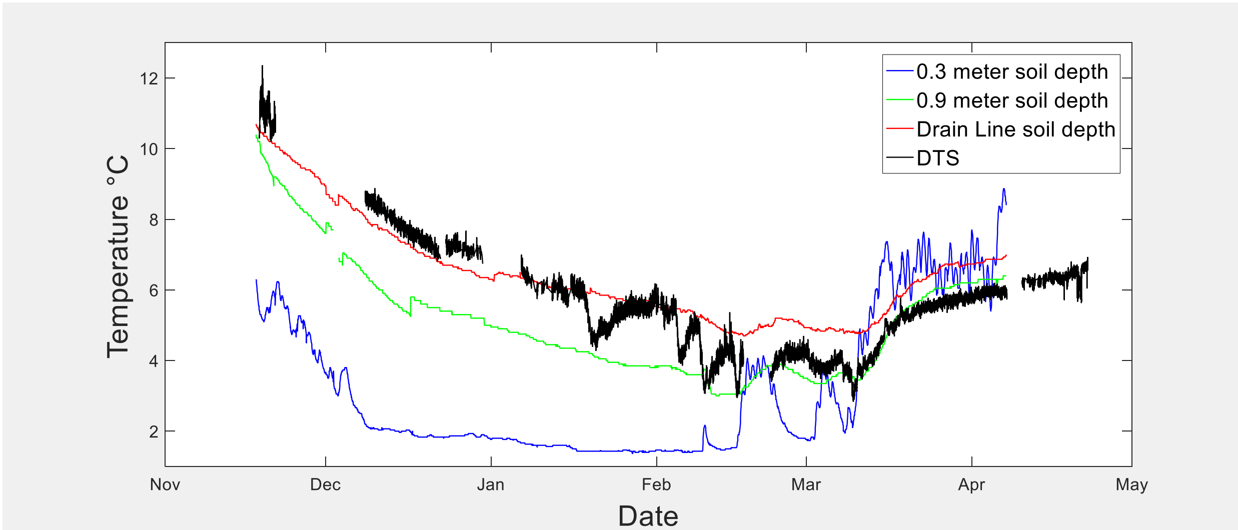


Figure 2.12. Average temperature of the each DTS trace and the average soil temperature at 0.3 meter depth, 0.9 meter depth and the depth of the artificial drainage line on the NT field.

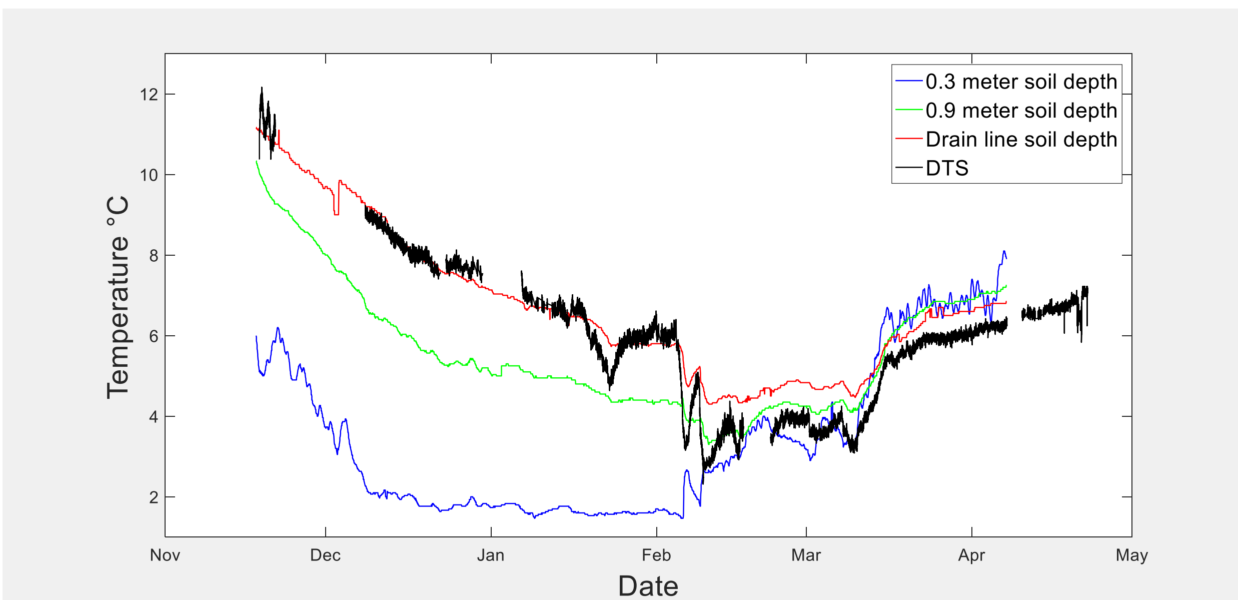


Figure 2.13. Average temperature of the each DTS trace and the average soil temperature at 0.3 meter depth, 0.9 meter depth and the depth of the artificial drainage line on the CT field.

Evidence of preferential flow using distributed temperature sensing

Water temperature along the fiber-optic cable during major discharge events during the reactive period, as specifically identified in figures 2.14-2.17 and Table 2.1, would reach a minimum average temperature more rapidly in the NT field than in the CT field. The one exception was the large discharge event of February 9th and 10th, 2017, where runoff from snowmelt flooded into the manhole housing the CT drain line flume thus rapidly cooling off the temperature trace. Excluding the February 9th and 10th event, the average difference in time between the coolest moment in the NT artificial drain line and the CT drain line was 20.9 hours. The temperature tracer was thus found to move from the soil surface and enter the drain line quicker on the NT field than on the CT field throughout the study. This finding was most pronounced on the first major temperature drop, indicated by the red markers in figures 2.14-2.17, where the minimum temperature was reached on January 20, 2017 14:35 on the NT field and January 23, 2017 3:59 on the CT field. As time went on in in the reactive period the difference in time between the coolest moment in the NT artificial drain line and the CT drain line decreased, see figure 2.18.

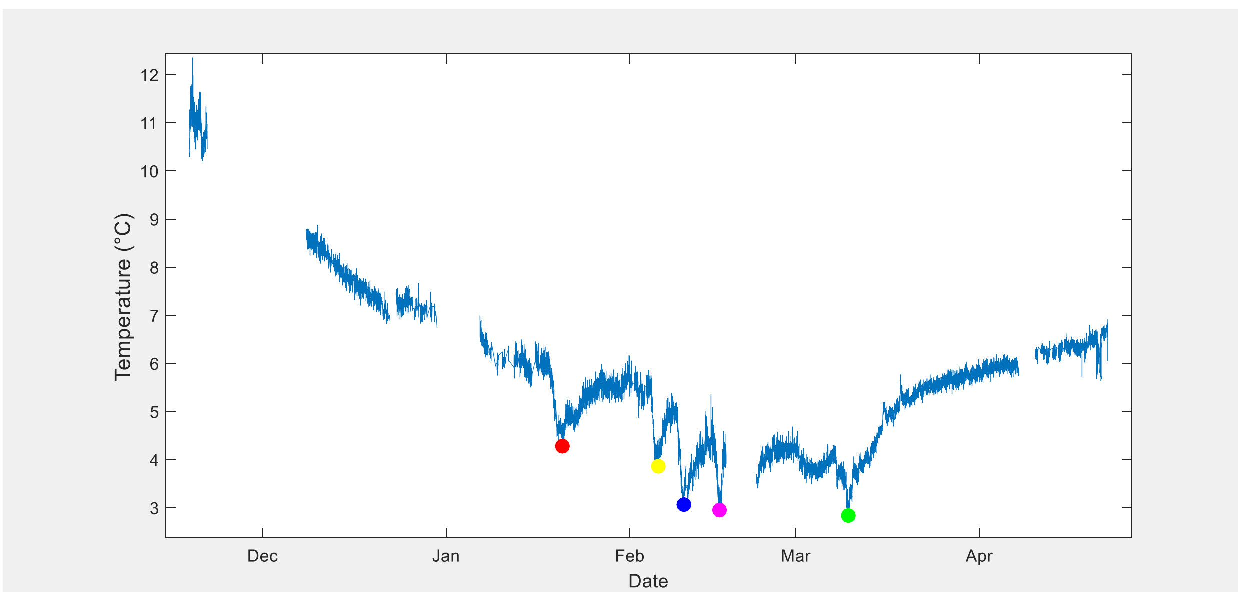


Figure 2.14. Average temperature of DTS trace in NT drain line with markers indicating minimum temperature for each major decrease in temperature during discharge events.

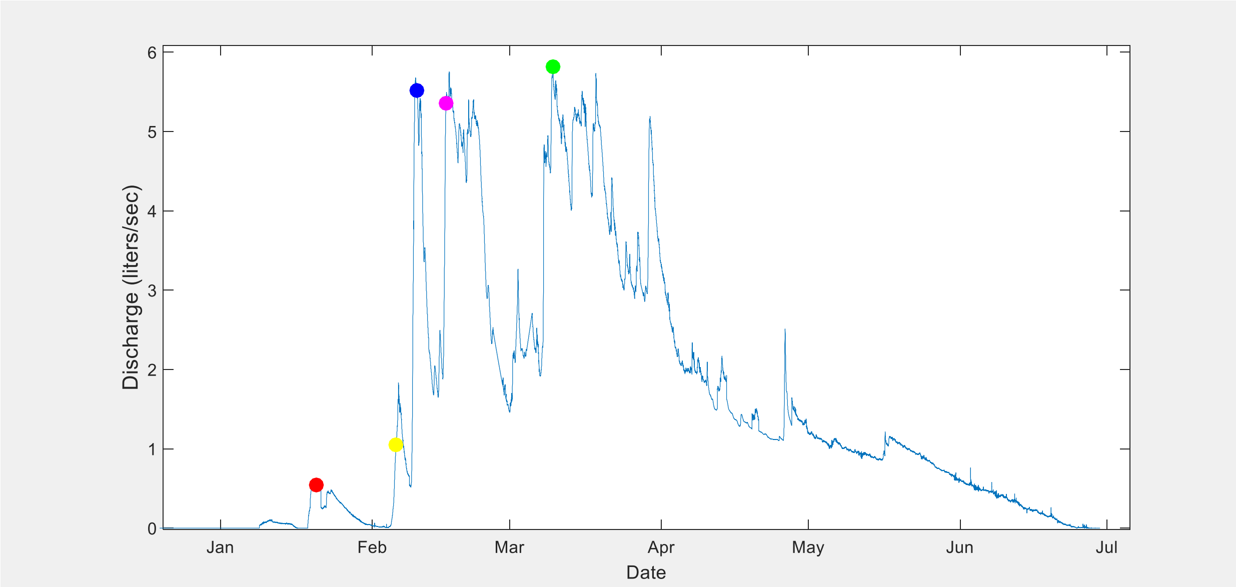


Figure 2.15. Markers indicating the time of minimum temperature for each major decrease in temperature plotted on the NT hydrograph.

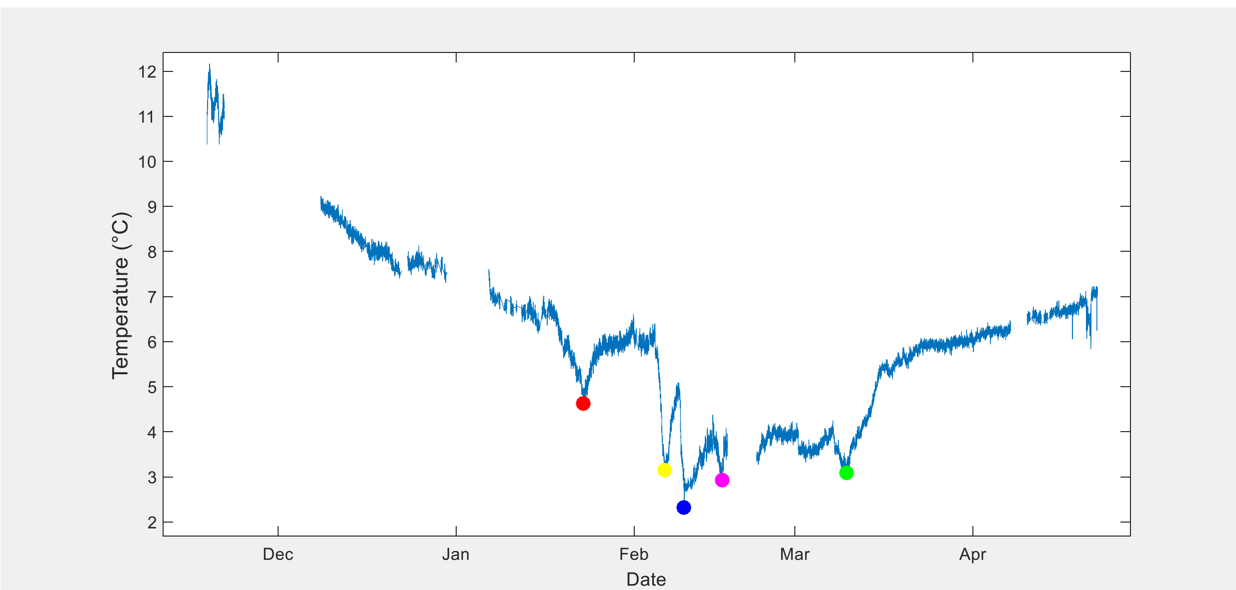


Figure 2.16. Average temperature of DTS trace in CT drain line with markers indicating minimum temperature for each major decrease in temperature during discharge events.

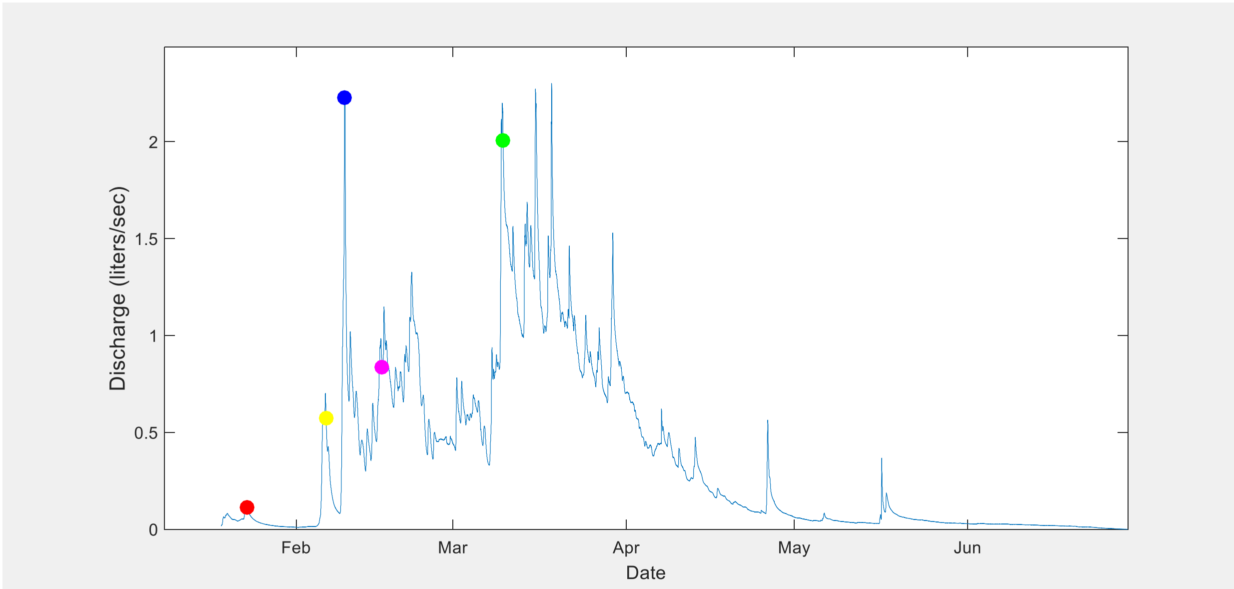


Figure 2.17. Markers indicating the time of minimum temperature for each major decrease in temperature plotted on the CT hydrograph.

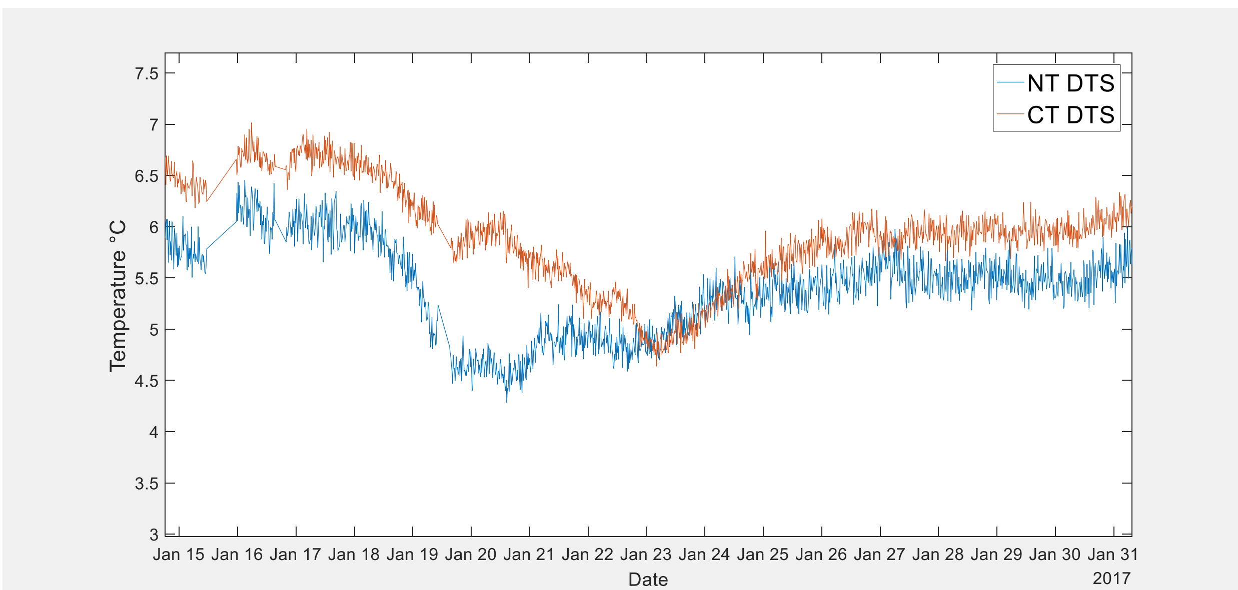


Figure 2.18. The average temperature of the DTS in both the NT and CT fields during the first major discharge event in January, 2017.

Table 2.1. The time at which minimum average temperature of DTS trace occured during the major temperature drops indicated above in figures 2.14-2.17, the difference in hours and the average difference.

	NT field	CT field	Difference (hours)	Average Difference (hours)
Red	1/20/2017 14:35	1/23/2017 3:59	61.4	20.9
Yellow	2/5/2017 19:50	2/6/2017 8:20	12.5	
Magenta	2/16/2017 1:35	2/16/2017 9:20	7.75	
Green	3/9/2017 19:24	3/9/2017 21:24	2	

After detrending and inverting each temperature trace taken from the NT and CT artificial drain line during the study, any decrease in temperature greater than 0.35 ° C and less than 10 meters in length was identified. The criteria of 0.35 ° C was chosen as a threshold that was more than 2 times larger than the RMSE of the DTS temperature measurements and therefore would not be affected by the precision of the instrument and would be a true cooling point. The length of 10 meter was chosen as to only identify small scale, vertical preferential flow paths. The number of temperature drops greater than 0.35 °C per 100 m are plotted in figure 2.19. Early in the season, when the artificial drain line began to flow until February, the number of distinct temperature drops along the drain line increased on the NT cable while the number of peaks on the CT cable remained relatively constant. After February the number of distinct temperature drops along the cable on the NT field then generally declined until the end of the reactive period. The average number of distinct temperature drops per 100 m for the NT and CT lines was 5.6 and 2.5, respectively. In other words, there were 2.2 times more distinct temperature drops per 100 meters along the NT drain line as compared to the CT drain line.

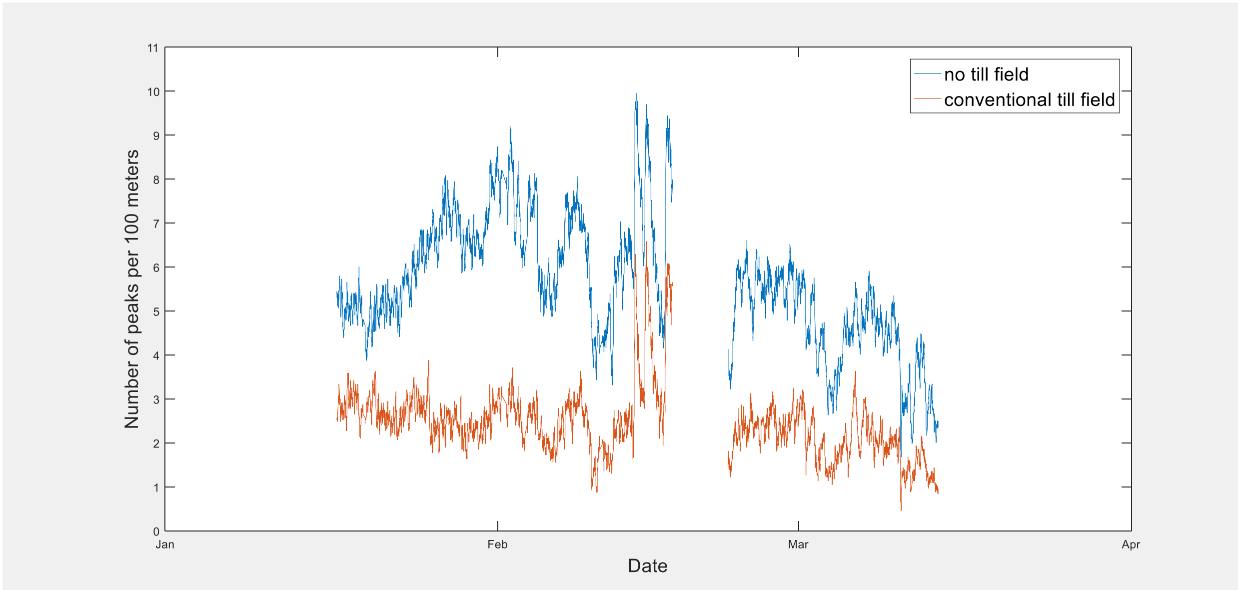


Figure 2.19. The number of peaks greater than 0.35 ° C per 100 meters on both the NT and CT fields for each temperature trace.

Analysis of the DTS data along each line revealed more consistent, large-scale distinct cooling points along the NT line than in the CT line. Figure 2.20 identifies points along each line where the difference between the 4 m move average temperature and the 16 m moving average was significantly different from zero (alpha = 0.01) during the rising limb of the hydrograph for over half the discharge events. In this figure we identify 74 locations on the NT DTS cable and 27 locations on the CT DTS cable. This is equivalent to 17 locations per 100 meters along the NT DTS cable and 11 locations per 100 meters along the CT DTS cable. This suggests that there were 1.5 times more consists preferential cooling points along the NT line than the CT line during these major snowmelt recharge events.

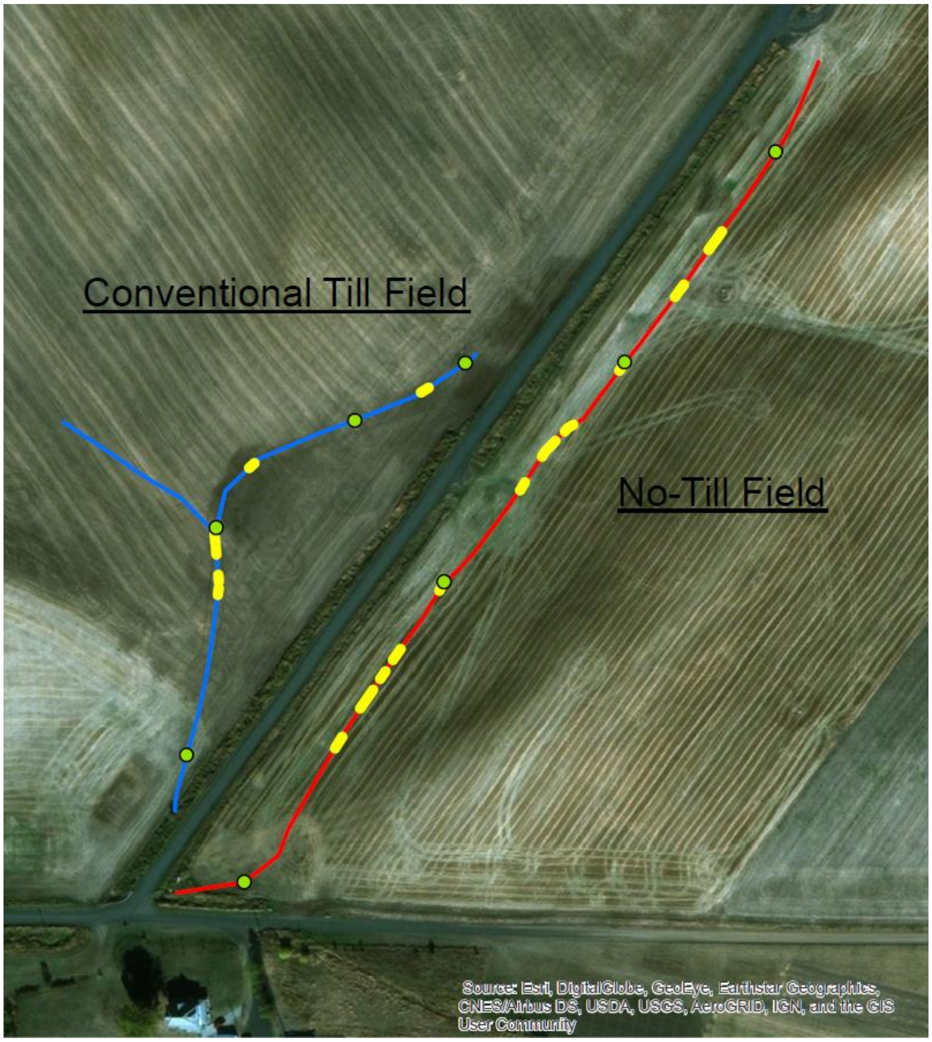


Figure 2.20. Map of differences between 4 meter moving average and 16 meter moving average that were significantly different than 0 (alpha value of 0.01).

Evidence of preferential flow using EC as a tracer

EC in both the NT and CT drainage water at the drain line outlet locations declined during discharge events as precipitation or snowmelt, with lower EC, travelled through the soil profile and entered the drain lines, see figures 2.21 and 2.22. In figure 2.21, the EC in the drainage water from the NT field declined to much lower levels during discharge events in comparison to the EC in the drainage water from the CT field. After dropping during the discharge event, the EC of the drainage water recovered more rapidly after the discharge event had receded from the NT field than from the CT field. The difference in these temporal dynamics between the NT and CT response can be more clearly seen in Figure 2.24 which plots EC in the drainage water from the NT field against EC in the drainage water from the CT field for readings taken at the same and distinguished by monthly time periods. The large discharge events in February and March result in a ‘dog-leg’ pattern indicating disconnected, dissimilar EC response between the NT and CT drainage. Whereas the EC response later in the season in April, May, and June is much more linear indicating synchronized responses from each field. Figure 2.23 shows that the EC in the drainage water from the NT field was also greater than the EC in the drainage water from CT field.

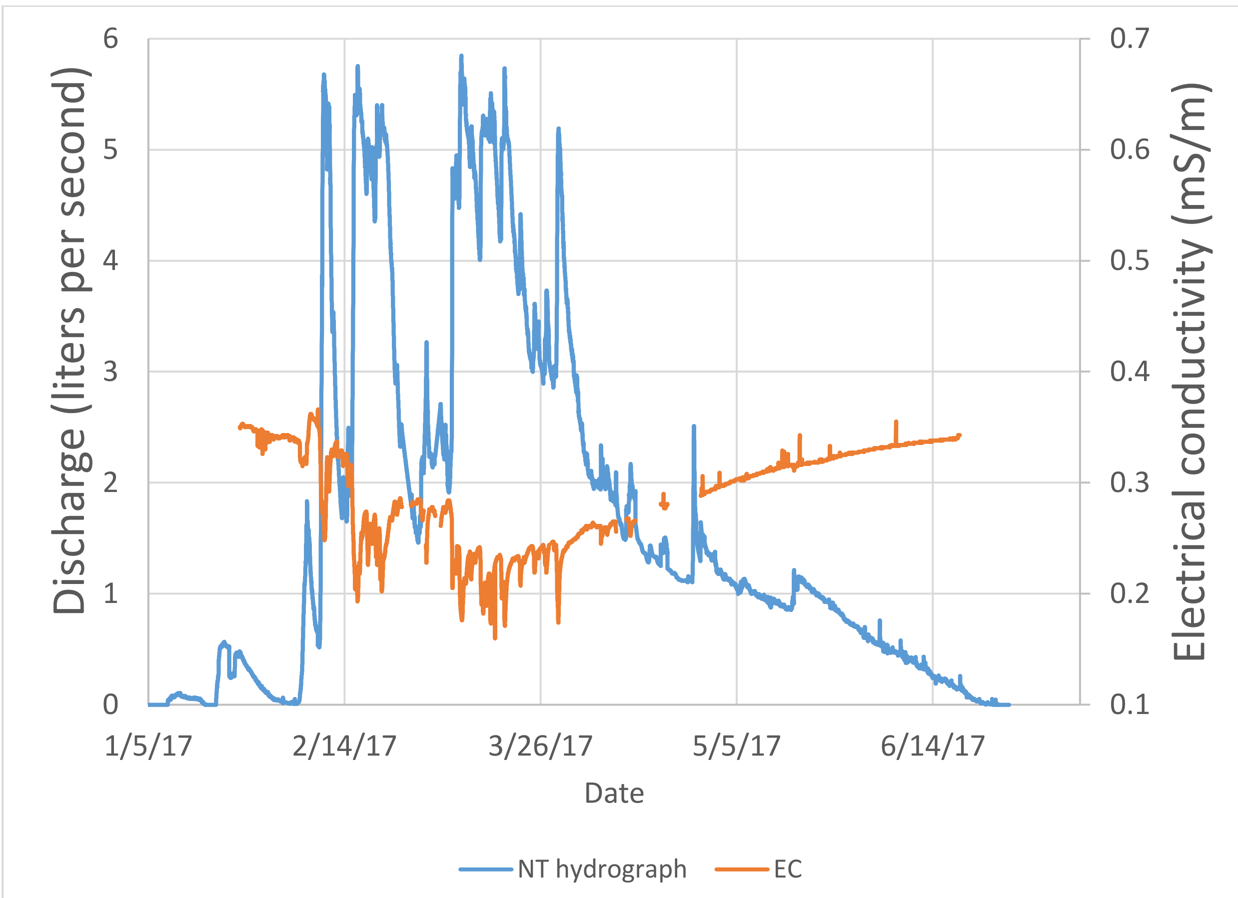


Figure 2.21. Artificial drain line hydrograph and temperature corrected EC of the drainage water at the NT field.

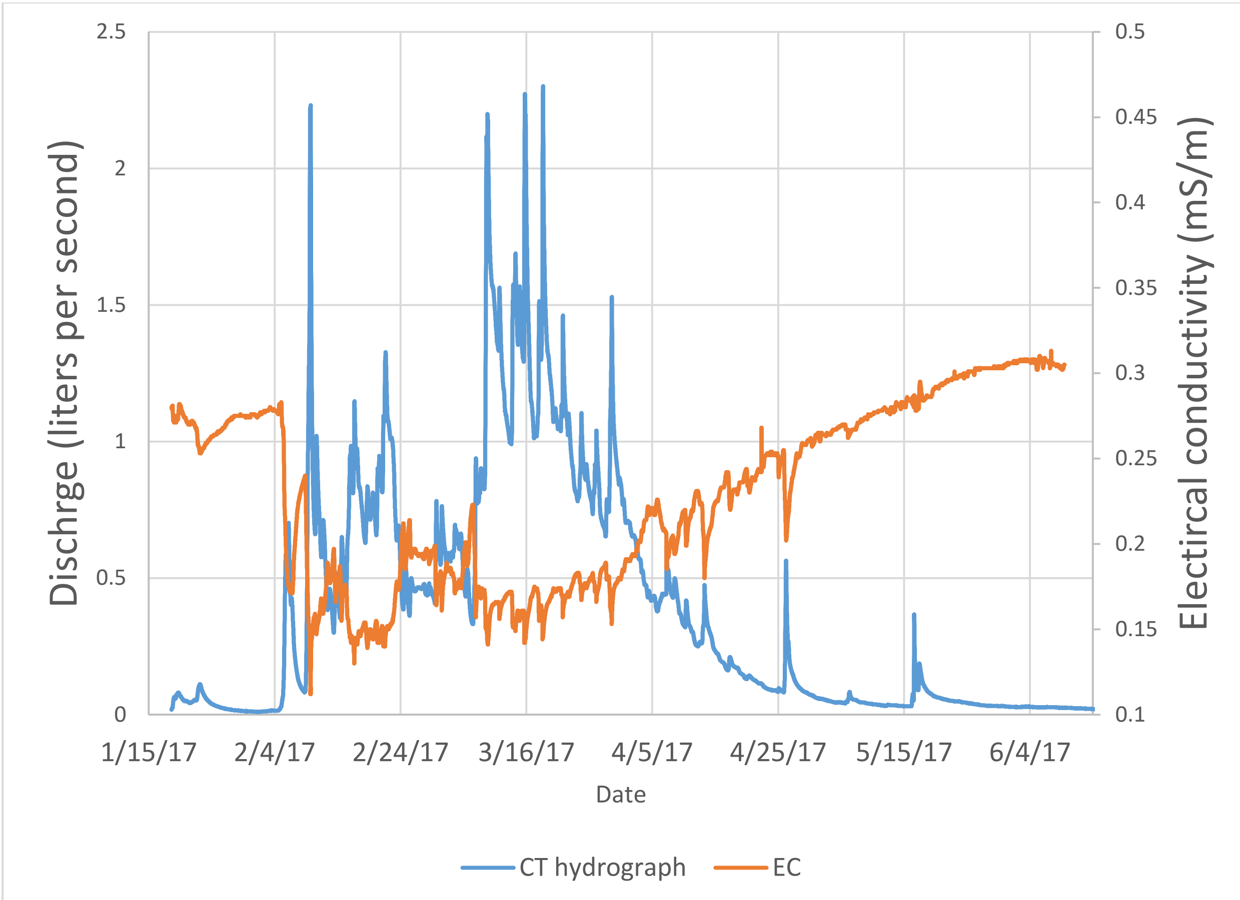


Figure 2.22. Artificial drain line hydrograph and temperature corrected EC of the drainage water at the CT field. Note the difference in Y-axis scales from the previous graph, this is to better view the discharge and EC response at each field.

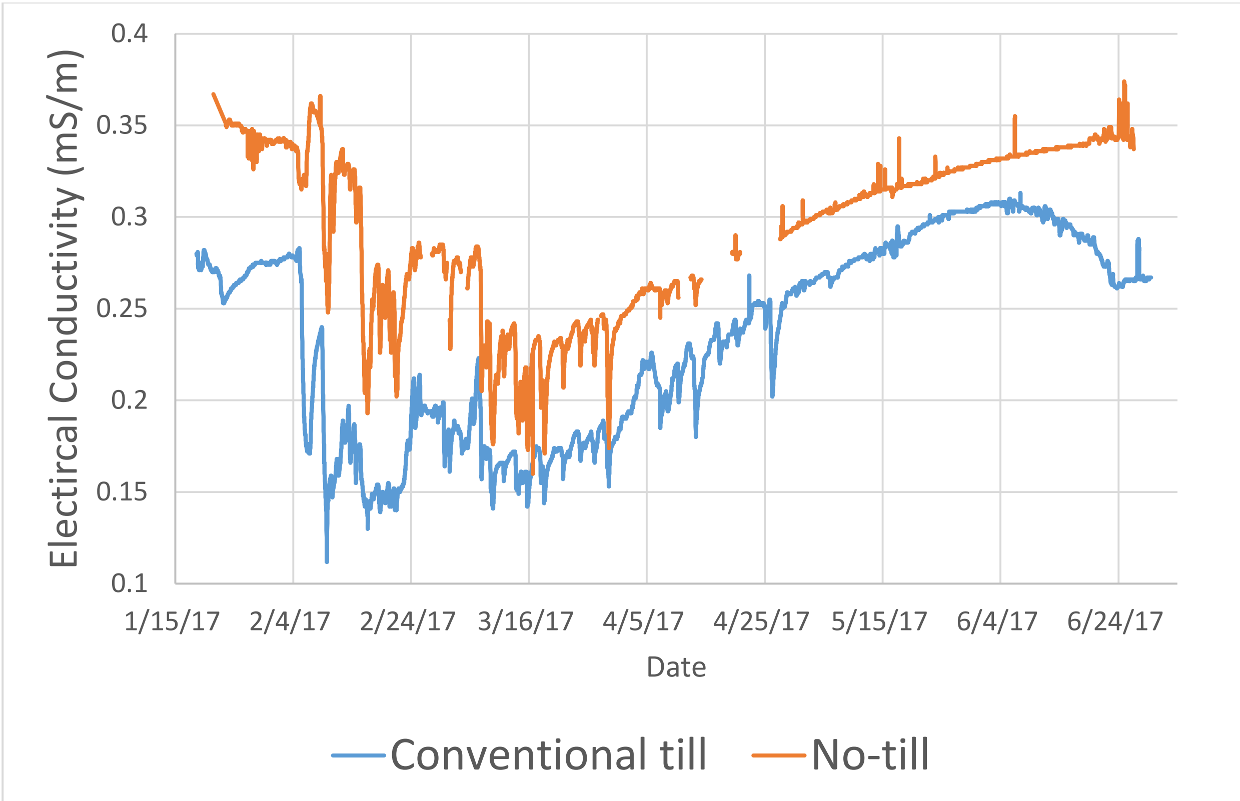


Figure 2.23. EC values of the drainage water of both the NT and CT fields throughout the study.

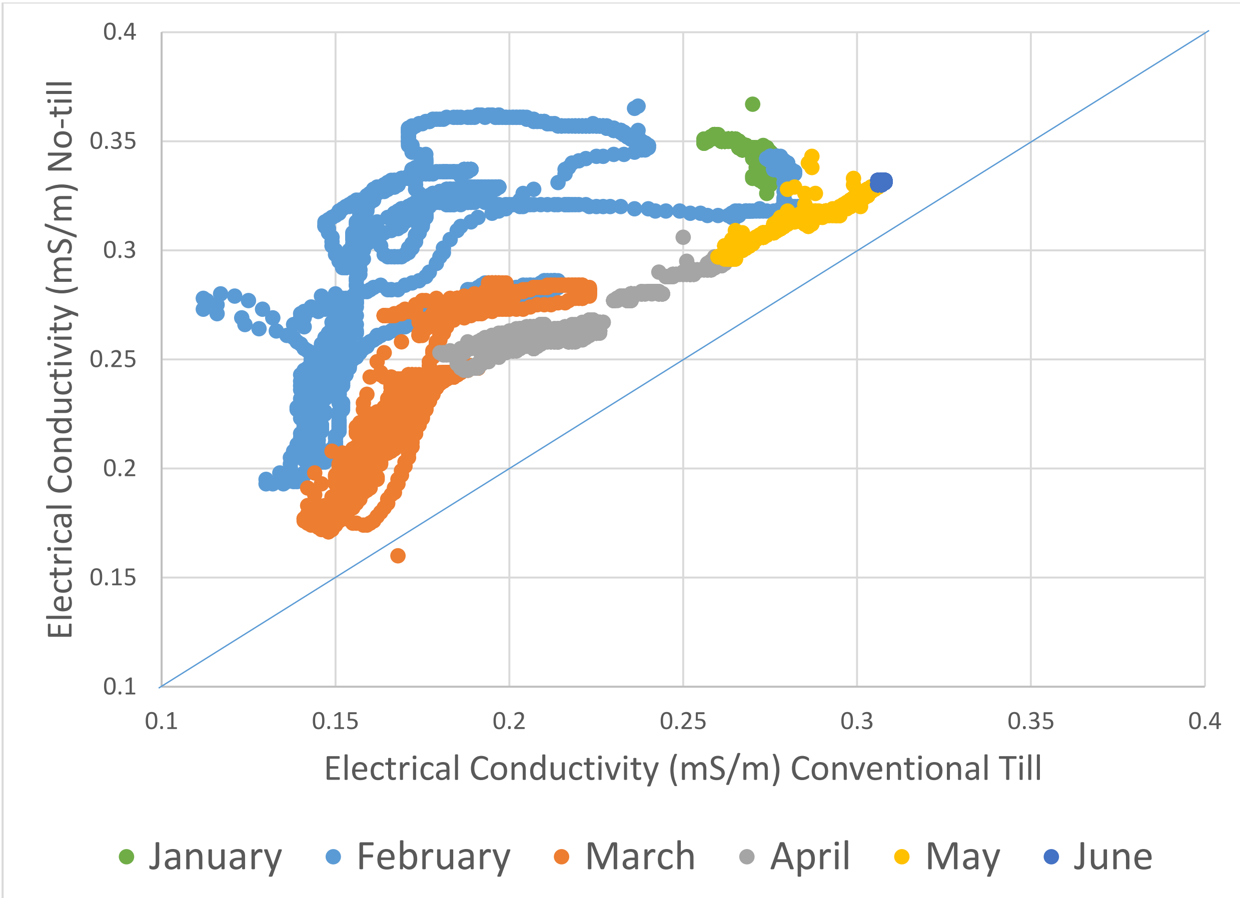


Figure 2.24. EC values of the drainage water of the NT vs CT drainage water recorded at the same time throughout the study.

Nitrate transport dynamics to artificial drain lines

We observed clear differences in the concentration, timing, and magnitude of nitrate transport through the artificial drain lines throughout the study between the NT and CT fields during the 2017 water year (see figures 2.25-2.27). The average nitrate concentration of the NT drainage water was 10.6 ppm nitrate-N and 6.7 ppm nitrate-N for the CT drainage water. There is significant difference between the nitrate concentrations of the two fields at an alpha value of 0.05 when using a two tailed t-test. In addition to the greater nitrate concentrations found in the drainage water from the NT field, the NT field also showed an initial early season flush of nitrate that was not observed in the CT drainage water. This flush can be seen in figure 2.28 as the time period (11/21/16 – 2/6/17) when the discharge from the NT field is directly related to the observed nitrate concentration. Throughout the remainder of the year for the NT field and for the entire year for the CT field nitrate concentrations were inversely related to drain line discharge, see figure 2.29. Additionally, like the EC values, the nitrate values on the NT field are flashier, characterized by rapid drop and recovery of nitrate concentrations during discharge events, than that of the CT field during discharge events after the initial early season flush.

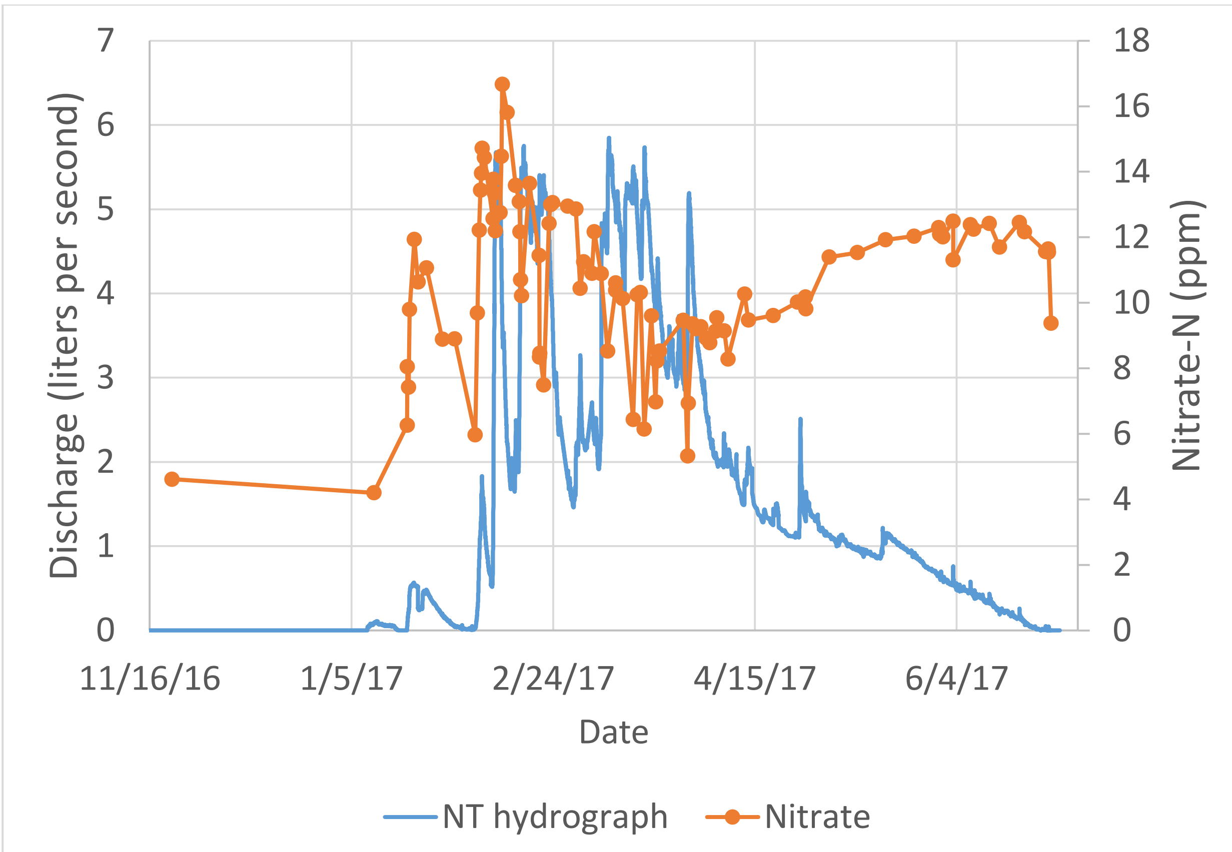


Figure 2.25. The NT artificial drain line hydrograph and nitrate concentration of event-based water samples. Note that early discharge events are correlated with increased nitrate concentrations and then later discharge events are inversely correlated.

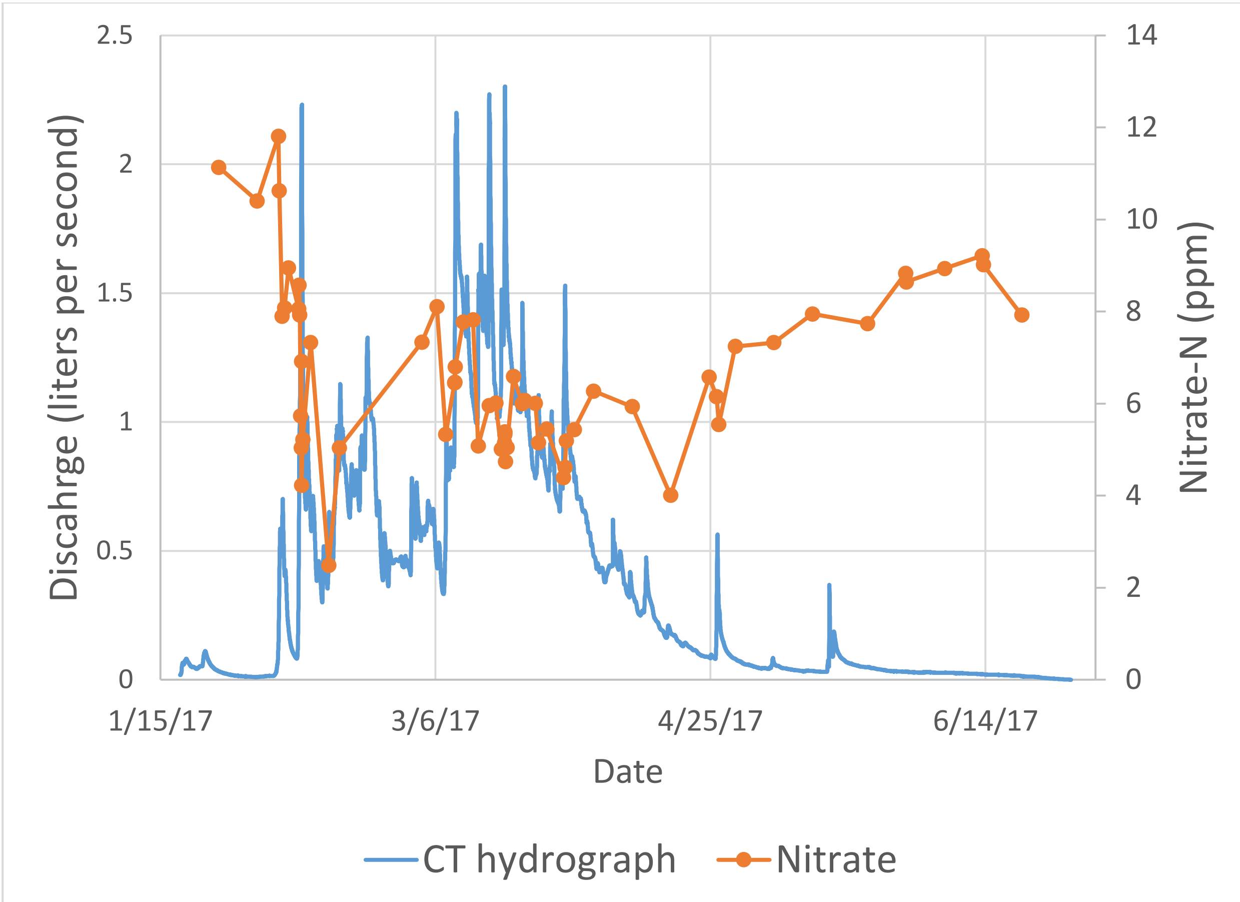


Figure 2.26. CT artificial drain line hydrograph and nitrate concentration of event-based water samples. Note the difference in Y-axis scales from the previous graph, this is to better view the discharge and nitrate-N response at each field.

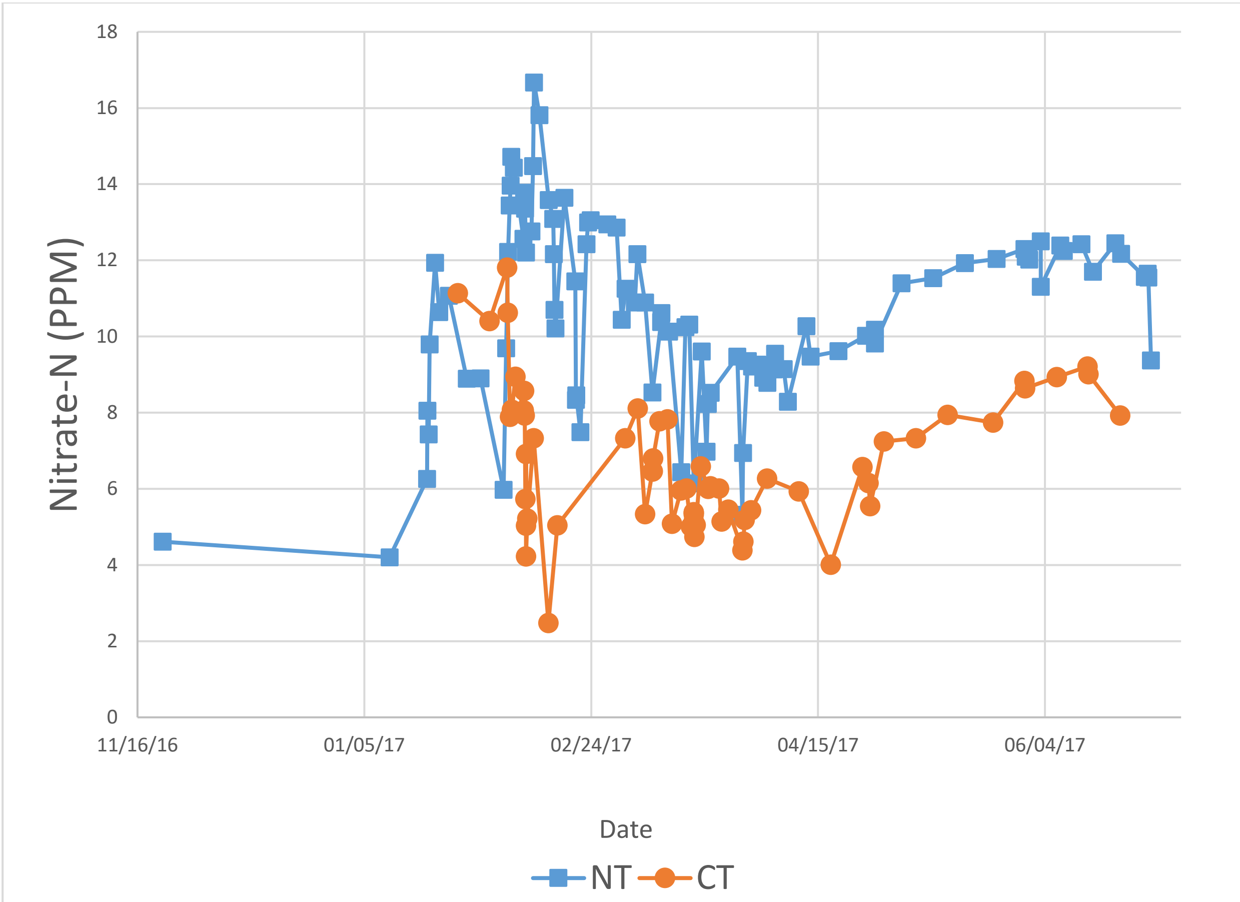


Figure 2.27. Nitrate concentrations of the drainage water from the NT and CT fields.

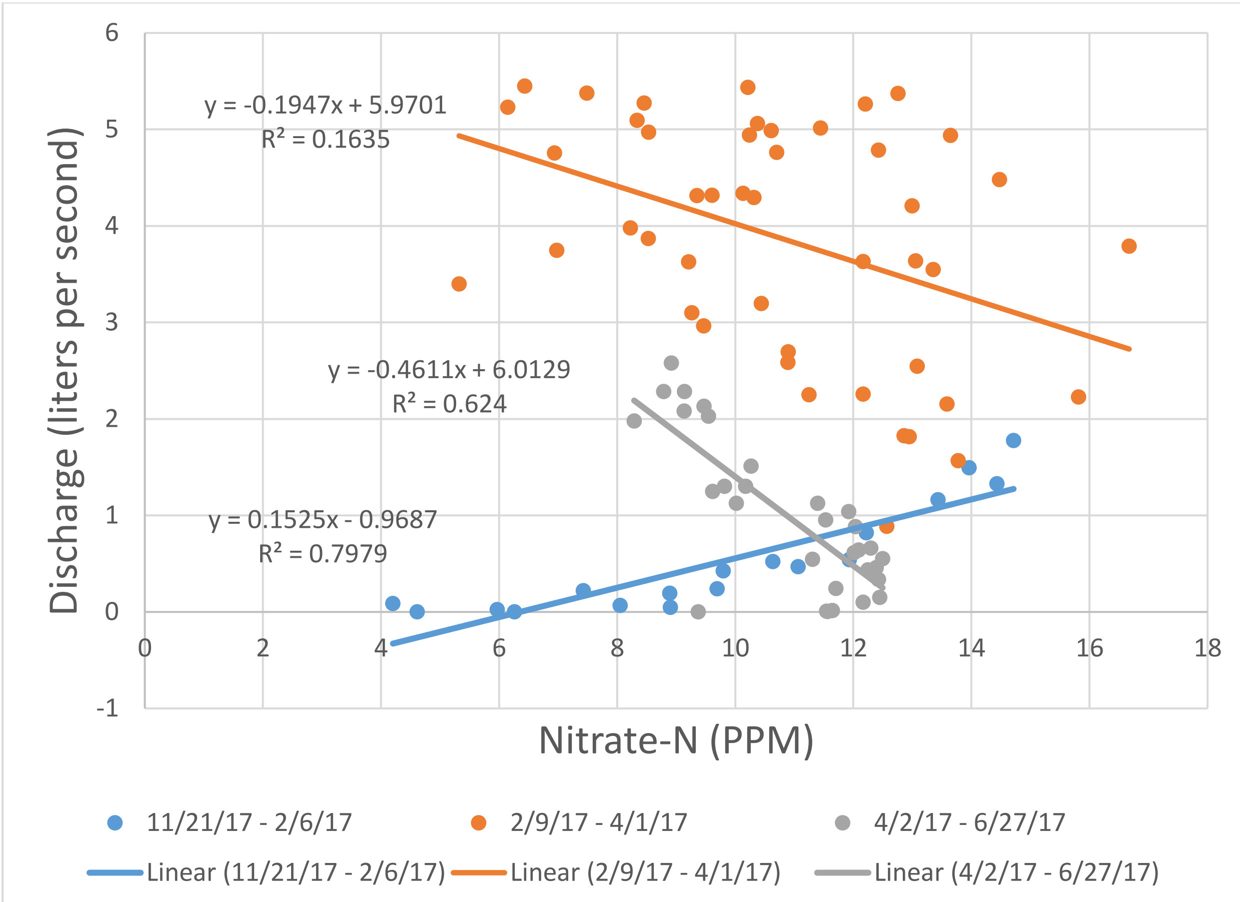


Figure 2.28. Discharge of the NT artificial drain line vs. nitrate concentrations broken up by time.

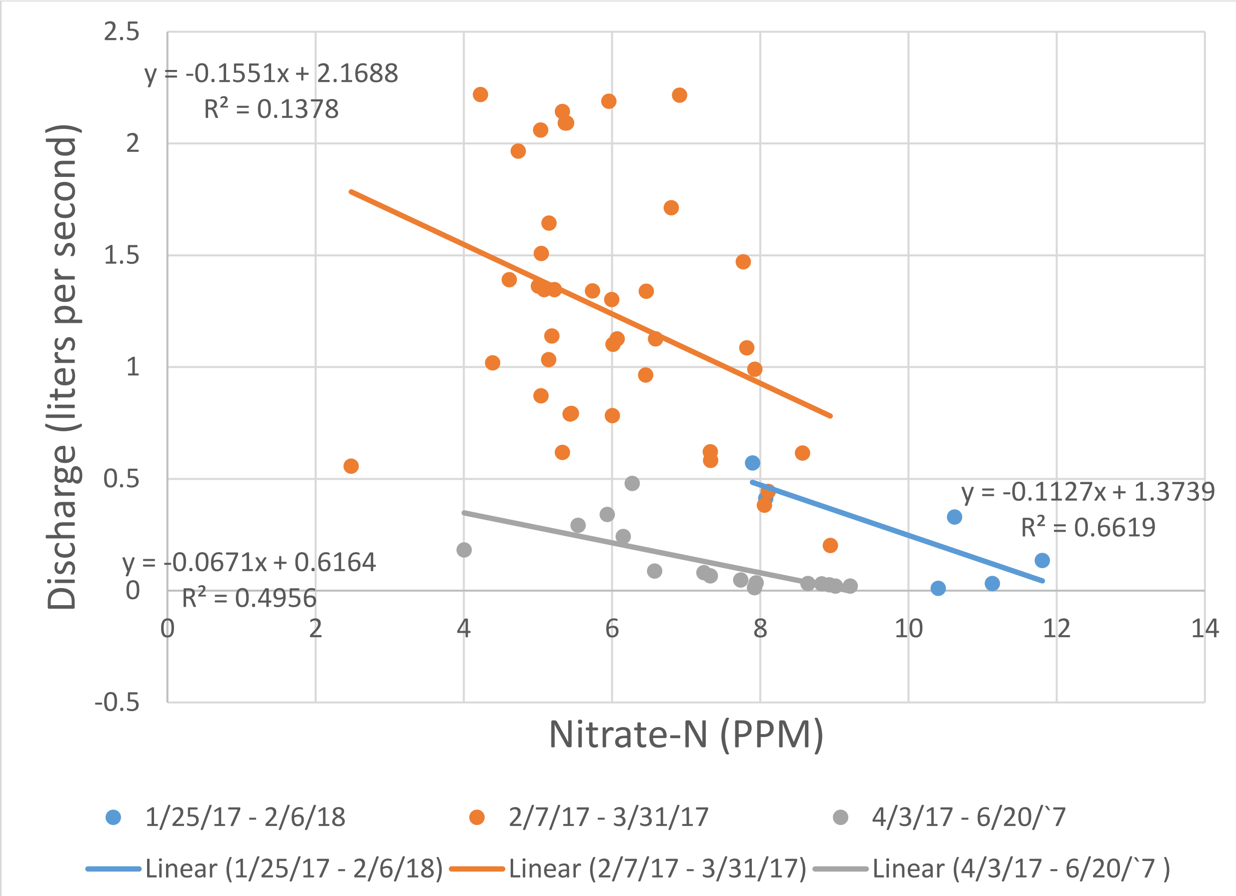


Figure 2.29. Discharge of the CT artificial drain line vs. nitrate concentrations broken up by time.

Flow paths and nitrate transport pathways

Dramatic changes in flow paths were observed between the NT and CT fields during the 2018 water year, see table 2.2. Surface runoff from the CT field (162.8 mm) was much greater than from NT field (0.8 mm) during the 2018 water year. Drain line discharge was 1.4 times greater on the NT field (126.7 mm) than on the CT field (90.4mm). A total of 127.5 mm and 252.7 mm of water left through the surface runoff flume and drain line flumes at the NT and CT field respectively. This corresponds to 2 times the amount of excess water at the CT field. On the NT field 99% of water leaving the field came as drain line discharge, while on the CT field 36% of water left through the drain line and 64% percent of water left through surface runoff.

The nitrate transport pathways were also drastically different between the two fields. On the NT field 100% of nitrate load came through the drain line while on the CT field 55% of the nitrate load came through the drain line and 45% came from surface runoff. Although there was nearly twice the amount of excess water leaving the CT field, and predominate pathways were different, the total load per hectare per year of both drainage water and surface runoff was nearly identical between the NT field (19.97 kg/ha/year) and the CT field (19.80 kg/ha/year).

Table 2.2. Table showing 2018 water year data for the surface runoff flume and drain line flume on both fields. The presented data includes water budget data and nitrate concentration and loading data.

Description	Discharge (m^3/yr)	Discharge (mm/yr)	Discharge % of total	Total Nitrate Export (kg/yr)	Total Nitrate Export (kg/ha/yr)	Total Nitrate % of total	Average Nitrate Concentration
NT drain line	15,452.9	126.7	99%	242	19.90	100%	15.7
NT surface runoff	99.6	0.8	1%	0.80	0.07	0%	8.0
NT total	15,552.5	127.5		243	19.97		
CT drain line	4,881.0	90.4	36%	59	11.0	55%	12.2
CT surface runoff	8,765.9	162.3	64%	48	8.80	45%	5.4
CT total	13,646.9	252.7		107	19.80		

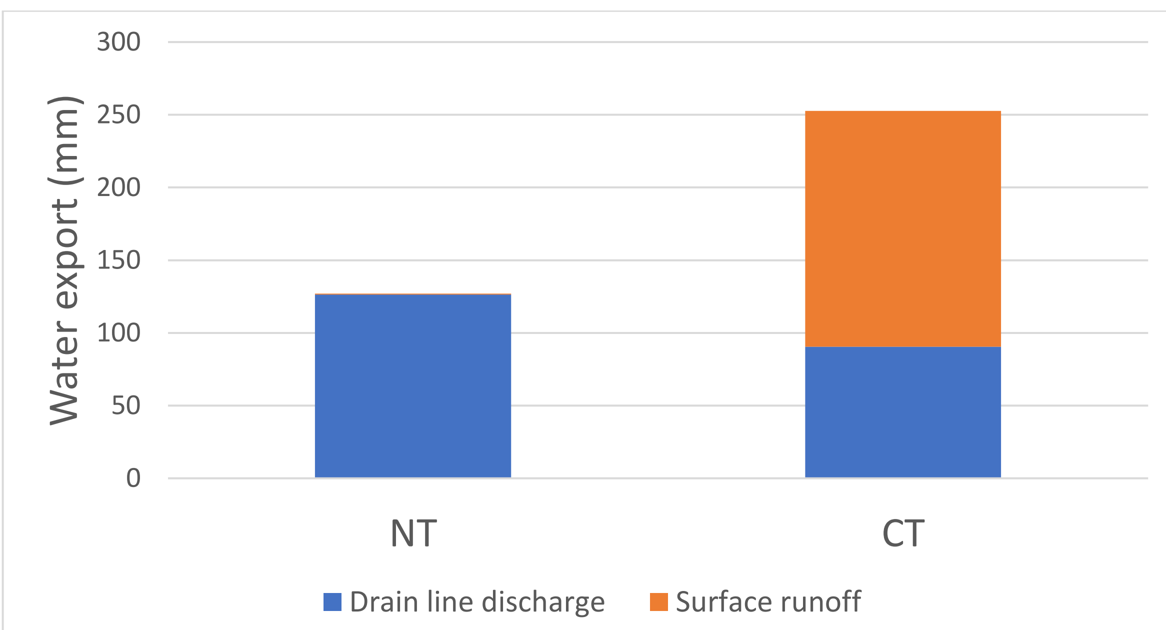


Figure 2.30. Total water export to surface water at the NT and CT fields separated by flow paths.

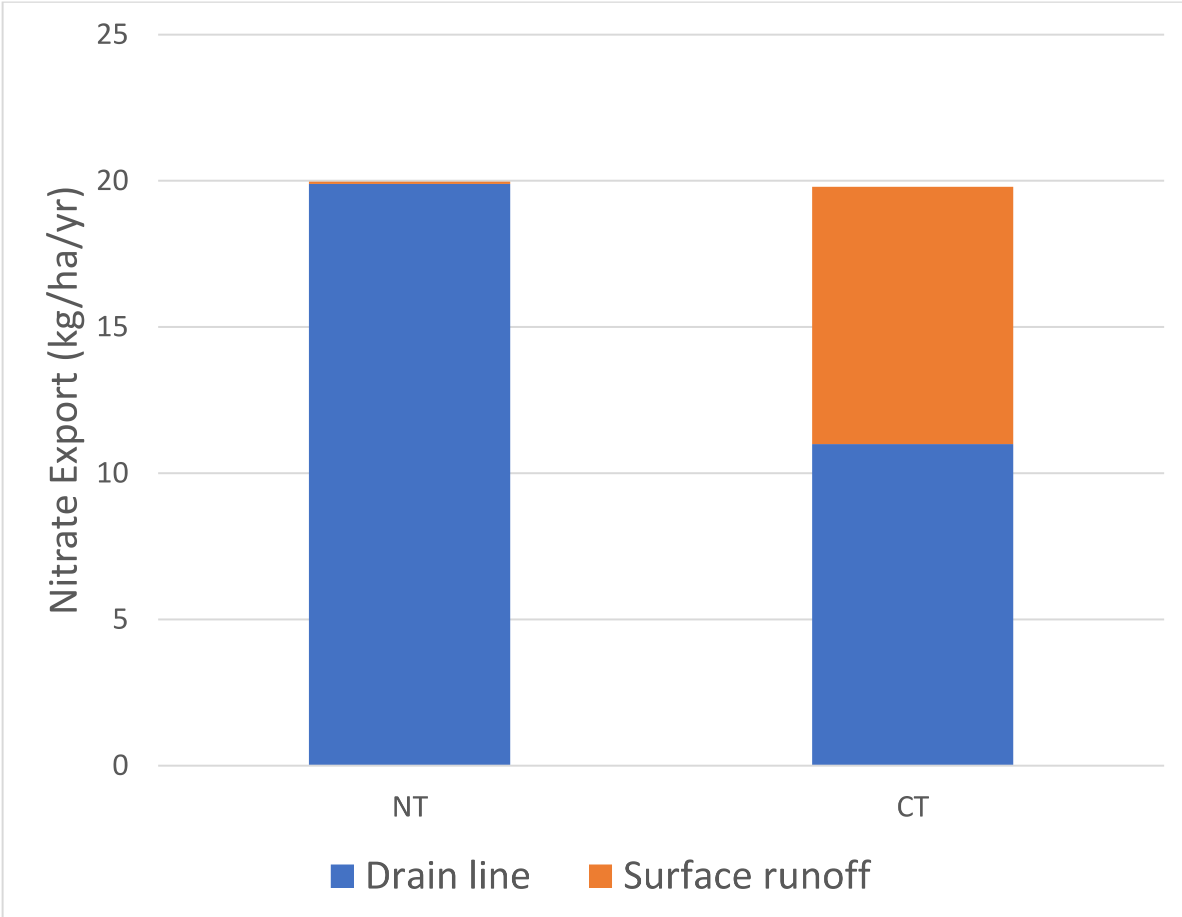


Figure 2.31. Total nitrate export (kg/ha/yr) from the NT and CT fields separated by transport pathways.

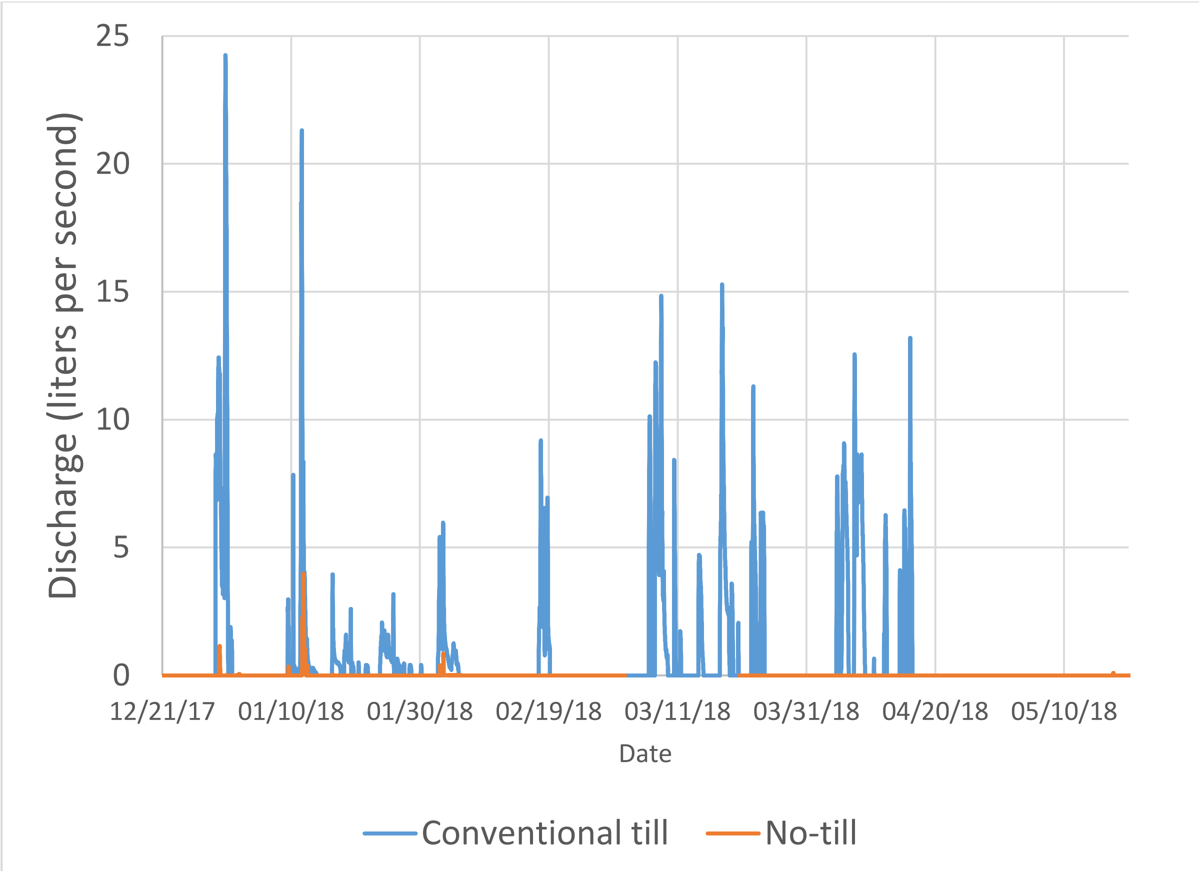


Figure 2.32. Surface runoff hydrographs for the NT and CT fields collected during the 2018 water year.

Summary

The extensive set of hydro-chemical measurements of both the surface runoff and subsurface drainage provides a unique opportunity to comprehensively examine the impacts of from a long-term NT on multiple aspects of water flow and nitrate transport. In particular the DTS approach for capturing high temporal temperature fluctuations within a drain line provided a unique and novel data set to use water temperature as an indicator of preferential flow. The following list below summarizes the key observational differences in hydrologic and nitrate transport between the two fields.

- Water flow was much more rapid in NT than in CT
  - During early season storm events the water temperature would respond on average 20.9 hours sooner in the NT drain line than the CT drain line.

- The NT field had a higher density of localized small-scale preferential flow contributions
  - There were over twice (2.2) as many distinct locations where the temperature dropped more than 0.35 ^{o}C within a 10 m distance along the NT drain line than the CT drain line
- The NT field had greater large-scale variability in preferential flow
  - There were 1.5 more locations along the NT drain line where there was a significant difference between the 4 m moving average and the 16 m moving average temperature than along the CT drain line.
- NT drain lines showed greater evidence of preferential pipe flow than matrix flow
  - The EC of the drainage water in the NT drain line was much more dynamic and responsive to storm events than the CT drain line.
- Major differences in hydrologic flow paths and magnitude of water export in the NT field
  - Nearly all (99%) the excess water leaving the NT field was through subsurface flow through the drain line whereas the majority (64%) of the excess water leaving the CT field was through surface runoff
  - The total drainage water from the NT field (127 mm) was 1.4 times the total drainage water from the CT field (90 mm)
  - The total excess water (runoff + drainage water) from the CT field (252 mm) was nearly twice the excess water from the NT field (128 mm)
- Major differences in nitrate transport pathways, average nitrate concentration and magnitude of export in the NT field
  - 100% of nitrate left the NT through the drain line as compared to 55% leaving through the CT artificial drain line (the remaining 45% left through surface runoff)
  - NT drain line had a distinct early seasonal flush of nitrate which was not observed in the CT field
  - The nitrate concentration in the NT drain line was significantly greater than the nitrate concentration in the CT artificial drain line in both 2017 and 2018

Discussion

This study suggests the adoption of NT in this region will result in a dramatic increase in infiltration and reduction of runoff, like what previous studies have found (Edwards et al., 1988; Shipitalo et al., 2000; Zhang et al., 2007). As suggested by these cited studies and supported by the DTS response data in this study, the decreased runoff found on NT fields can be attributed to increased preferential flow likely due to the preservation of macropores, especially worm burrows, that connect surface soil layers with the subsoil. The DTS system deployed during snowmelt conditions provided the unique ability to see not only the temporal transport dynamics at the outlet but the spatial dynamics through the entire artificial drainage system. The preferential transport of water indicated by the temperature signal was corroborated with the EC dynamics and nitrate signal recorded at the drainage outlets. The relative reduction in EC during storm events is a good indicator of the degree of interaction and mixing that occurs within the soil profile before leaving the field through the artificial drainage networks. A distinct drop in EC during a storm event and rapid recovery of EC after the event suggests an increase in the proportion of rain or snowmelt water through preferential flow (Smith and Capel, 2018; Verseveld et al., 2008). Other studies have used bromide (Frey et al., 2012) and nitrate (Cheng et al., 2014; Shipitalo and Edwards, 1993) as tracers to better understand preferential flow and the transport of conservative chemicals and have found similar results where preferential flow through macropores result in rapid transport through soil matrix.

The preferential flow and nitrogen dynamics, the early season flushing and late season dilution, in this study align well with surface mixing layer concepts described by Steenhuis et al., (1994). This paper presents a mathematical model for estimating preferential flow solute concentrations. The model suggests that there is a mixing zone near the soil surface where rain water and snowmelt mix with solutes present. Once this mixing layer becomes saturated, solutes travel vertically to the subsoil as a combination of both preferential and matrix flow. The concentration of solutes traveling as preferential flow is considered to be relatively unchanged as it passes through the soil profile and is thus representative of water found in the mixing layer.

As suggested by Steenhuis et al. (1994) it is possible that early in the season there is a reservoir of nitrate close to the soil surface in this mixing layer as a result of the nitrification of fall applied fertilizer. As precipitation and snowmelt infiltrate and saturate this mixing layer nitrate moves preferentially through macropores that extend into this mixing layer. These macropores then facilitate rapid transport of water, nitrate, and other dissolved inorganic and organic substances to the drain line as observed by Bellmore et al., (2015). Particularly in the NT field we observed rapid vertically movement through the soil profile resulting in an early season flush of nutrients. This can best be seen in figure 2.28, where early in the water year, November to early February, discharge is correlated with nitrate concentration at the NT drain line. Steenhuis and Andreini (1990) documented similar processes during column experiments where the bulk of the soil profile was bypassed by preferential flow as macropores extended to the soil surface. After this initial reservoir of nitrate in the mixing zone is depleted and nitrate is transported deeper into the soil profile or exported through the drainage system, there is a dilution effect where nitrate concentrations decline in the drainage water as precipitation and snowmelt infiltrates and moves through macropores, see figure 2.28.

This idea of fall fertilization priming the soil with a reservoir of nitrate is similar to concepts proposed by Kelley et al., (2013) to describe the transport of nitrate to the drain line at the Cook Agronomy Farm. It was proposed that following fall fertilization and precipitation events in the early fall, nitrate is distributed throughout the soil profile and precipitation throughout the water year continues to transport additional nitrified fertilizer. The rapid early season flush and subsequent dilution of nitrate observed in the NT field as well as the predominance of preferential macropore flow as indicated by dynamic EC and temperature response observed in this study suggests that this reservoir of nitrate may be closer to the soil surface than as a reservoir near the drain line.

Through tillage operations in the CT field there are likely fewer macropores, due to fewer worm burrows, see Clapperton et al. (1997), and since the existing macropores do not reach the soil surface nitrate this rapid transport of nitrate early in the season does not occur. Steenhuis and Andreini (1990) found similar results where column infiltrations experiments indicated that on tilled soils the infiltration was uniform until water infiltrated past the depth of tillage and reached structured soil where macropores were present. Since nitrate isn't rapidly transported vertically through macopores early in the season and there is much greater surface runoff, see figure 2.32 and table 2.2, nitrate leaves the field through a combination of surface runoff and drain line discharge. On the CT field, discharge and nitrate were found to be inversely correlated throughout the year, see figure 2.29. Figures 2.33 and 2.34 present these conceptual differences between nitrate transport processes in both the NT and CT fields.

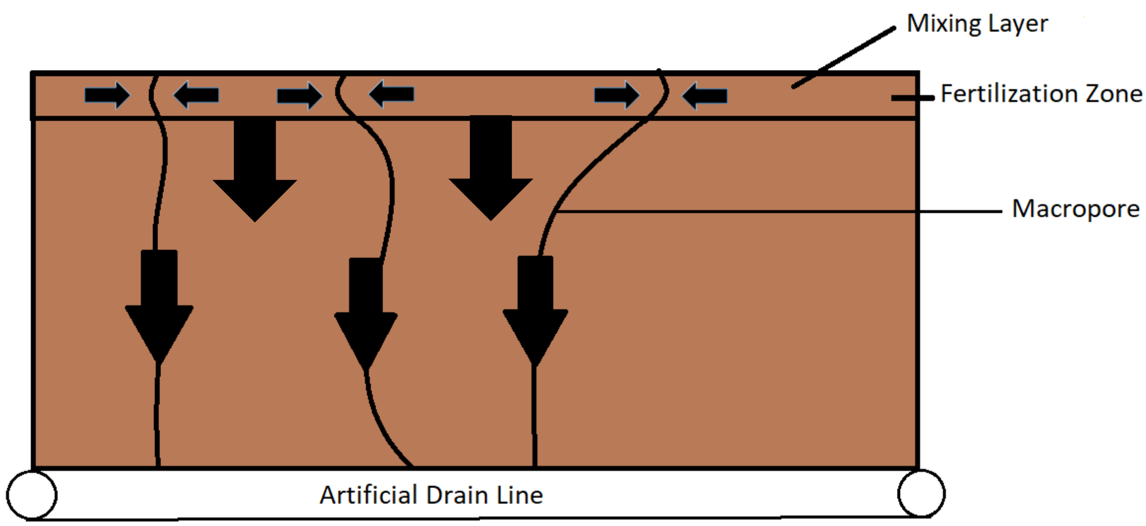


Figure 2.33. Conceptual model of flow path and transport mechanism for nitrate leaving the NT field.

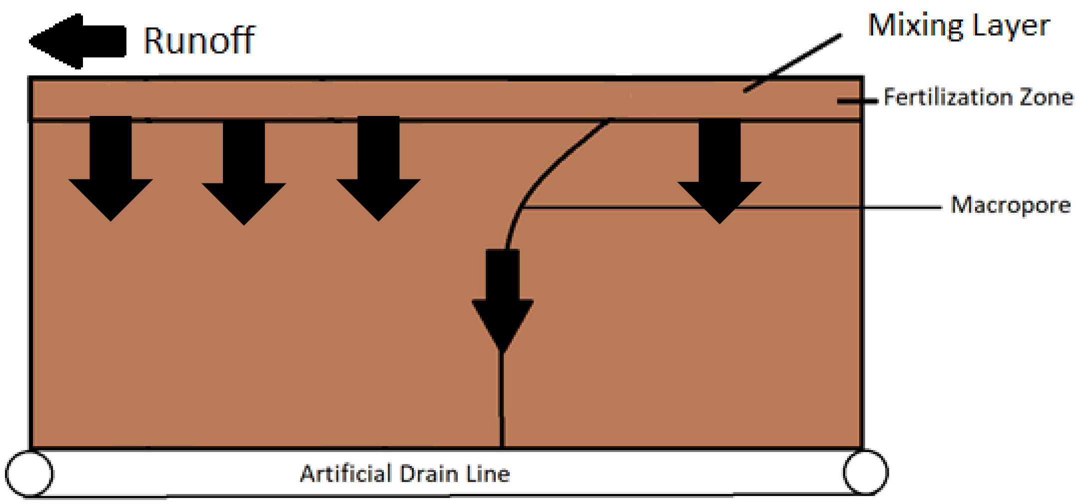


Figure 2.34. Conceptual model for the CT field. There are fewer macropores present and macorpores do not extent to the soil surface.

The dramatic reduction in surface runoff and associated increase in subsurface drainage from the adoption on NT has profound implications on sediment, particulate bound and soluble agrichemical transport in the region. Across the Palouse Region the adoption of reduced tillage management has resulted in significant reductions in sediment loading (Brooks et al., 2010). Since there is so little runoff and sediment transport on NT fields, particulate bound chemical loading to local streams is likely dramatically decreased or eliminated on NT fields in the region.

Although water quality in local streams is improved by reducing sediment and particulate bound chemicals transported in surface runoff, the decrease in runoff is leading to an increase in drainage discharge and likely perched water tables and subsurface lateral flow as more water is infiltrated into the soil profile under NT management (Brooks et al., 2012). It is our hypothesis that the non-uniform flow to drain lines on the NT field demonstrates greater abundance of vertical preferential flow paths and increased lateral flow as a result of greater infiltration. This suggests that the 'trade-off' with NT may be a decrease in particulate bound pollutants be an increase in soluble pollutant. The increased infiltration and saturation of convergence points on field is also likely leading to greater potential for gullies to form in these saturated regions (Mcdaniel et al., 2008).

Interestingly, the 2018 data suggest that adoption of NT may be leading to increased soil water storage and/or plant uptake. The decline in surface runoff with NT did not lead to an equivalent increase in magnitude of subsurface drainage. The fact that there was nearly twice as much overall drainage (drainage + runoff) from the CT than the NT suggests that either the excess water is being stored and used by plants or could possibly be recharging through the underlying basalt layer. Other studies have documented greater soil water content of fields under reduced tillage practices as compared to paired conventionally tilled fields (Copec et al., 2015; Gozubuyuk et al., 2014). In water limited regions, such as the Palouse, increased field capacity/soil water content will likely lead to higher yields.

Despite differences in major hydrologic flow paths and overall magnitude of excess water between the NT and CT fields it was interesting that the total nitrate losses were nearly identical between the NT and CT fields during the 2018 water year. The nitrate concentration leaving the NT field as drainage and runoff were both much greater than the CT field. Both fields were in the same crop and received the same amount of fertilizer therefore either the NT field was not able to retain fertilizer as well as the CT field or there was more nitrogen mineralization from the NT field. Unger and Huggins (2014), conducted research at the CAF in 2008 and found the conversion lead to an increase in soil profile nitrogen, from 0-5 feet, by 35 pounds per acre annually which would suggest increased mineralization could be a possible explanation. Although NT management has effectively eliminated surface runoff as a transport pathway for nitrate, the greater concentration and drainage discharge led to equal total nitrate loss with the CT field.

Conclusion

Although NT management strategies have been widely advocated by soil conservation planners throughout the nation over the last 30 years, as the impacts of this adoption on the reduction in soil erosion are widely known, this study provided further evidence that adoption of no-tillage management strategies can also have profound implications on the timing, magnitude, and flow paths of water and nitrate. This study tied together a number of processes that are affected by changes in tillage management.

Primarily we found evidence that infiltrated water on the NT field showed signs of preferential flow as compared to the CT field by identifying increased frequency of temperature decreases along fiber optic cables as compared to the CT field (2.2 times the number of temperature decreases greater than 0.35 ^{o}C), rapid flushing of water through the soil profile (during five early season discharge events the temperature of the drain line reached a minimum temperature 20.9 hours before the CT field), greater relative drops and rapid recovery of EC in NT drainage water during discharge events and early season flushing of nitrate. We infer increased preferential flow led to increased infiltration and reduced infiltration excess runoff as there was 1.4 times more drainage discharge on the NT field. The data suggests that NT management may reduce runoff and erosion but will likely lead to increased transport of and export of soluble pollutants through subsurface pathways due to increase preferential flow and infiltration.

This experiment was an innovative approach to quantifying preferential flow using recent advances in distributed temperature sensing (DTS). This may be the first application of DTS to study water and agrichemical transport to artificial drain lines. DTS allowed us to assess water transport to artificial drains for approximately 5 months at high spatial and temporal frequency. In the short history of hydrologic applications of DTS, this is one more application that shows incredible potential to better understand complex spatial processes in ways that are otherwise not measurable

References

Angle, J.S., Gross, C.M., Hill, R.L., McIntosh, M.S., 1993. Soil nitrate concentrations under corn as affected by tillage, manure, and fertilizer applications. J. Environ. Qual. 22, 141–147. https://doi.org/10.2134/jeq1993.00472425002200010018x

Bakhsh, A., Kanwar, R.S., Bailey, T.B., Cambardella, C.A., Karlen, D.L., Colvin, T.S., 2002. Cropping system effects on NO3–N loss with subsurface drainage water. Trans. ASAE 45, 1789–1797.

Bellmore, R.A., Harrison, J.A., Needoba, J.A., Brooks, E.S., Keller, K.C., 2015. Hydrologic control of dissolved organicmatter concentration and quality in a semiarid artificially drained agricultural catchment Rebecca. Water Resour. Res. 51, 9127–9140. https://doi.org/10.1002/2014WR016259

Birkinshaw, S.J., Webb, B., 2010. Flow pathways in the Slapton Wood catchment using temperature as a tracer. J. Hydrol. 383, 269–279. https://doi.org/10.1016/j.jhydrol.2009.12.042

Bjorneberg, D.L., Melvin, S.W., Kanwar, R.S., 1996. Seasonal changes in flow and nitrate-N loss from subsurface drains. Trans. ASAE 39, 961–967. https://doi.org/10.13031/2013.27582.Rights

Bradford, J.M., Huang, C. hua, 1994. Interrill soil erosion as affected by tillage and residue cover. Soil Tillage Res. 31, 353–361. https://doi.org/10.1016/0167-1987(94)90041-8

Brooks, E.S., Boll, J., McDaniel, P.A., 2012. Hydropedology in Seasonally Dry Landscapes : The Palouse Region of the Pacific Northwest, in: Hydropedology:Synegistic Integratoion of Soil Science and Hydrology. Academic Press, pp. 329–350. https://doi.org/10.1016/B978-0-12-386941-8.00010-1

Cheng, J., Wu, J., Chen, Y., Zhang, H., 2014. Characteristics of preferential flow paths and their effects on soil properties. For. Chron. 90, 192–196.

Clapperton, M.J., Miller, J.J., Larney, F.J., Lindwall, C.W., 1997. Earthworm populations as affected by long-term tillage practices in Southern Alberta, Canada. Soil Biol. Biochem. 29, 631–633. https://doi.org/10.1016/S0038-0717(96)00189-7

Copec, K., Filipovic, D., Husnjak, S., Kovacev, I., Kosutic, S., 2015. Effects of tillage systems on soil water content and yield in maize and winter wheat production. Plant, Soil Environ. 61, 213–219. https://doi.org/10.17221/156/2015-PSE

Daryanto, S., Wang, L., Jacinthe, P.A., 2017. Impacts of no-tillage management on nitrate loss from corn, soybean and wheat cultivation: A meta-analysis. Sci. Rep. 7, 1–9. https://doi.org/10.1038/s41598-017-12383-7

Edwards, C.A., Lofty, J.R., 1982. The Effect of Direct Drilling and Minimal Cultivation on Earthworm Populations. J. Appl. Ecol. 19, 723–734.

Edwards, W.M., Norton, L.D., Redmond, C.E., 1988. Characterizing Macropores that Affect Infiltration into Nontilled Soil. Soil Sci. Soc. Am. J. 52, 483. https://doi.org/10.2136/sssaj1988.03615995005200020033x

Geyer, D.J., C.K. Keller, J.L. Smith, and D.L. Johnstone. 1992. Subsurface fate of nitrate as a function of depth and landscape position in Missouri Flat Creek Watershed, U.S.A. J. Contam. Hydrol. 11:127–147.

Gozubuyuk, Z., Sahin, U., Ozturk, I., Celik, A., Cemal, M., 2014. Tillage effects on certain physical and hydraulic properties of a loamy soil under a crop rotation in a semi-arid region with a cool climate. Catena 118, 195–205. https://doi.org/10.1016/j.catena.2014.01.006

Hendrickx, J.M.H., Flury, M., 2001. Uniform and preferential flow mechanisms in the vadose zone, in: Conceptual Models of Flow and Transport in the Fractured Vadose Zone. National Academies Press, Washington, DC, pp. 149–187. https://doi.org/10.17226/10102

Hoes, O.A.C., Schilperoort, R.P.S., Luxemburg, W.M.J., Clemens, F.H.L.R., van de Giesen, N.C., 2009. Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing. Water Res. 43, 5187–5197. https://doi.org/10.1016/j.watres.2009.08.020

Huggins, B.D.R., Reganold, J.P., 2008. No-Till: the Quiet Revolution. Sci. Am.

Kay, B.D., VandenBygaart, A.J., 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Tillage Res. 66, 107–118. https://doi.org/10.1016/S0167-1987(02)00019-3

Kelley, C.J., Keller, C.K., Evans, R.D., Orr, C.H., Smith, J.L., Harlow, B.A., 2013. Nitrate-nitrogen and oxygen isotope ratios for identification of nitrate sources and dominant nitrogen cycle processes in a tile-drained dryland agricultural field. Soil Biol. Biochem. 57, 731–738. https://doi.org/10.1016/j.soilbio.2012.10.017

Kobs, S., Holland, D.M., Zagorodnov, V., Stern, A., Tyler, S.W., 2014. Novel monitoring of Antarctic ice shelf basal melting using a fiber-optic distributed temperature sensing mooring. Geophys. Res. Lett. 41, 6779–6786. https://doi.org/10.1002/2014GL061155

Mannering, J. V, Fenster, C.R., 1983. What is Conservation Tillage? J. Soil Water Conserv. 38, 140–143.

Mcdaniel, P.A., Regan, M.P., Brooks, E., Boll, J., Barndt, S., 2008. Linking fragipans, perched water tables, and catchment-scale hydrological processes. Catena 73, 166–173. https://doi.org/10.1016/j.catena.2007.05.011

Nila Rekha, P., Kanwar, R.S., Nayak, A.K., Hoang, C.K., Pederson, C.H., 2011. Nitrate leaching to shallow groundwater systems from agricultural fields with different management practices. J. Environ. Monit. 13, 2550. https://doi.org/10.1039/c1em10120j

Nuutinen, V., Butt, K.R., 2003. Interaction of Lumbricus terrestris L. burrows with field subdrains. Pedobiologia (Jena). 47, 578–581. https://doi.org/10.1078/0031-4056-00232

Pagliai, M., Raglione, M., Panini, T., Maletta, M., La Marca, M., 1995. The structure of two alluvial soils in Italy after 10 years of conventional and minimum tillage. Soil Tillage Res. 34, 209–223. https://doi.org/10.1016/0167-1987(95)00471-4

Randall, G.W., Mulla, D.J., 2001. Nitrate nitrogen in surface waters as influenced by climatic conditions and agricultural practices. J. Environ. Qual. 30, 337–344. https://doi.org/10.2134/jeq2001.302337x

Selker, J., van de Giesen, N.C., Westhoff, M., Luxemburg, W., Parlange, M.B., 2006. Fiber optics opens window on stream dynamics. Geophys. Res. Lett. 33, 27–30. https://doi.org/10.1029/2006GL027979

Selker, J.S., Thévenaz, L., Huwald, H., Mallet, A., Luxemburg, W., Van De Giesen, N., Stejskal, M., Zeman, J., Westhoff, M., Parlange, M.B., 2006. Distributed fiber-optic temperature sensing for hydrologic systems. Water Resour. Res. 42, 1–8. https://doi.org/10.1029/2006WR005326

Shipitalo, M.J., Edwards, W.M., 1993. Seasonal patterns of water and chemical movement in tilled and no-till column lysimeters. Soil Sci. Soc. Am. J. 57, 218. https://doi.org/10.2136/sssaj1993.03615995005700010038x

Shipitalo, M.J., Protz, R., 1987. Comparison of Morphology and Porosity of a Soil Under Conventional and Zero Tillage. Can. J. Soil Sci. 67, 445–456.

Smith, E.A., 2012. Spatial and Temporal Variability of Preferential Flow in a Subsurface- Drained Landscape in North-Central Iowa. University of Minnesota.

Steenhuis, T.S., Andreini, M.S., 1990. Preferential Paths of Flow under Conventional and Conservation Tillage. Geoderma 46, 85–102.

Steenhuis, T.S., Boll, J., Shalit, G., Selker, J.S., Merwin, I.A., 1994. A Simple Model for Predicting

Preferential Flow Solute Concentrations. J. Environ. Qual. 1058–1064.

Syswerda, S.P., Basso, B., Hamilton, S.K., Tausig, J.B., Robertson, G.P., 2012. Long-term nitrate loss along an agricultural intensity gradient in the Upper Midwest USA. Agric. Ecosyst. Environ. 149, 10–19. https://doi.org/10.1016/j.agee.2011.12.007

Tyler, S.W., Selker, J.S., Hausner, M.B., Hatch, C.E., Torgersen, T., Thodal, C.E., Schladow, S.G., 2009. Environmental temperature sensing using Raman spectra DTS fiber-optic methods. Water Resour. Res. 45, W00D23. https://doi.org/10.1029/2008WR007052

Unger, R., Huggins, D., 2014. Cropping system nitrogen use efficiency after 10 years of no-tillage. Reg. Approaches to Clim. Chang. Pacific Northwest Agric. 62–63.

van de Giesen, N., Steele-Dunne, S.C., Jansen, J., Hoes, O., Hausner, M.B., Tyler, S., Selker, J., 2012. Double-ended calibration of fiber-optic raman spectra distributed temperature sensing data. Sensors (Switzerland) 12, 5471–5485. https://doi.org/10.3390/s120505471

Wuest, S.B., 2001. Soil biopore estimation: Effects of tillage, nitrogen, and photographic resolution. Soil Tillage Res. 62, 111–116. https://doi.org/10.1016/S0167-1987(01)00218-5

Zhang, G.S., Chan, K.Y., Oates, A., Heenan, D.P., Huang, G.B., 2007. Relationship Between Soil Structure and Runoff/Soil Loss After 24 Years of Conservation Tillage. Soil Tillage Res. 92, 122–128. https://doi.org/10.1016/j.still.2006.01.006

Chapter three: Synthesis

No tillage (NT) management practices have reduced erosion and sediment loading to receiving waterbodies in the Palouse Region, however little attention has been given to how NT management practices are affecting biophysical, hydrologic and chemical processes in the soil that are ultimately impacting regional water quality. The motivation of this study was to fill this gap, specifically, to better understand the effects of NT management on hydrologic flow paths and nitrate nitrogen transport pathways, concentration, timing, and magnitude of overall export. Using distributed temperature sensing technology within artificial drain lines we were able to use water temperature as a tracer for preferential water flow at the field scale during snowmelt conditions. These high temporal and spatial frequency data sets as well as continuous surface runoff and subsurface drainage with event-based water sampling provided a comprehensive look at the impacts of long-term tillage management on nitrate transport. This paired study which documented and compared the hydrologic and nitrogen response from a conventional till and a long-term NT field indicated that adoption of NT management led to greater preferential flow through the soil matrix, increased infiltration, and almost the complete elimination of surface runoff. However, the water which infiltrated lead to increased subsurface drainage and nitrate losses. The nitrate transport in the NT field was distinct from the CT with more pronounced early season nitrate flushing events.

The study suggests that despite a pronounced influence on the dominant water and nitrate transport pathways, adoption of tillage management may have little net effect on total nitrate export to surface water. From a long term, annual, water quality perspective, this suggests that further reduction of nitrate loading to water bodies will require adoption of other practices (e.g., cover crops, variable rate N application, split N application). Overall NT is a beneficial management practice in the region for reducing erosion and sediment bound pollutant loading as well as the elimination of pollutant transport through surface runoff. The reduction in surface nitrate losses and a decline in overall water export from the NT field was countered by an increase in nitrate concentration in the drainage water which lead to no change in the net overall nitrate loss from the field. This suggests that NT fields are much more susceptible to leaching processes and therefore growers should consider reducing fall application of fertilizer before the winter season and relying more on spring application of fertilizer.

From a grower's standpoint the most interesting finding is NT may lead to increased field capacity and increase in plant available N in the soil. In water limited regions, such as the Palouse, increased field capacity/soil water content will likely lead to higher yields. An increase in plant available nitrogen suggests growers may be able to cut fertilizer rates. The combined effect of increased water storage and reduced reliance on fertilizer also suggests that adoption of no-till practices will lead to more resilient, sustainable agricultural systems.

There are several critical knowledge gaps and opportunities to extend this work. Bromide or other N15 tracers could be applied to the NT and CT soils to confirm the extent to which preferential flow from a surface mixing layer drives nutrient transport during early season wetting events. Also drain gauge lysimeters could be installed on both the NT and CT fields to monitor water and nitrate transport to groundwater. This would determine if NT management is resulting in more groundwater recharge and assess whether there is greater nitrate loading to groundwater, as would be expected given greater infiltration, reduced water export to surface waters and greater nitrate concentrations in the drainage leachate as compared to the CT field in this study. Greater nitrate loading to groundwater resources could lead to the impairment of drinking water resources in the region. And finally, given the clear evidence for preferential flow on the NT field in this study it is critical to assess phosphorous or herbicide/pesticide export and transport dynamics.

Chapter four: Feasibility of detecting illicit connections to storm drains using distributed temperature sensing technology

Introduction

Impervious surface cover leads to increased runoff during precipitation and snowmelt events in urban regions. To prevent flooding, urban runoff is rapidly diverted away from homes and businesses through efficient stormwater conveyance systems and channelized stream channels. If runoff is discharged directly to receiving water bodies, the combination of high runoff generation and rapid diversion away from developed regions leads to a "flashy" hydrograph characterized by rapidly rising and falling limbs and greater runoff volume (Leopold, 1968). This increases the potential for instream scouring events, bank destabilization and sediment loading. As such urban river channels are often wider, deeper and lacking the in-stream complexity needed to support healthy aquatic ecosystems (Hammer, 1972; Leopold, 1973).

These urban landscapes are also a significant source of pollution to receiving surface water bodies. Common pollutants found in stormwater includes nutrients, pesticides, sediments, heavy metals, hydrocarbons and pathogenic microorganisms. Sources of these pollutants come from a variety of anthropogenic activities such as, but not limited to, lawn fertilization application, improper disposal of household and industrial chemicals, illicit and cross connections with sanitary sewers, automobiles leaking hydrocarbons on to road surfaces and so on. Urban stormwater also tends to increase sediment loading allowing for transportation of sediment bound pollutants that would otherwise be less prone to transport. The combination of hydrologic alteration and increased pollution loading leads to the degradation of aquatic habitat, ecosystem functionality, and beneficial uses of the nation's waterways.

To address the environmental impacts of stormwater discharges congress established a two-phase approach to stormwater control using the NPDES program. In 1990 EPA issued the Phase I Stormwater Rule requiring NPDES permits for operators MS4s serving populations over 100,000 and for runoff associated with industrial activity, including runoff from construction sites five acres and larger. In 1999 EPA issued the Phase

II Stormwater Rule which expanded the requirements to small MS4s in urban areas and to construction sites between one and five acres in size.

Discharges of sanitary sewage from illicit connections, cross connections or combined sewer overflows are also an environmental and public health concern as they increase the risk of human illness. In older cities in the United States, especially in the Northeast, Great Lakes and Pacific Northwest Regions, a combined sewer system (CSS) may be in place. A CSS combines both raw sewage and stormwater into the same piping network which is then sent to a treatment facility prior to being discharged. A CSS offers certain tradeoffs for urban regions. For example, by combining stormwater runoff and sewage the stormwater is at least treated, but precipitation and/or snowmelt events can cause combined sewer treatment facilities to exceed capacity leading to combined sewer overflows where urban runoff and raw sewage is discharged directly to waterbodies. Due to the environmental concerns associated with CSS overflows, they are no longer constructed in the United States. In fact, some cities, such as St Paul, Minnesota have undergone construction efforts to separate their combined sewer system into a separate storm sewer system (US EPA, 1999). Most communities in the United States are thus served by a municipal separate storm sewer system (MS4) where the stormwater and sanitary sewers are separate systems.

It is difficult to find the source of illicit and cross connections to MS4s. However, recent work by Hoes et al. (2009) demonstrated that illicit connections to a stormwater sewer can be identified using Distribute Temperature Sensing (DTS) technology. Illicit connections are identifiable due to the difference in temperature between storm water and warmer sanitary sewer water. Distributed Temperature Sensing (DTS) systems measure temperature along the lateral profile of a fiber optic cable rather than at individual sensors and are therefore very useful in hydrologic studies. The DTS sensing unit can be downloaded and provide highly accurate temperature and spatial data with temperature resolution of 0.1 C^{o} or less and spatial resolutions of 1m all within a 1-minute or less temporal window (J. S. Selker et al., 2006).

The objectives of this study are as follows:

1) Evaluate the collected data from a long-term deployment in a storm drain to determine the likelihood of identifying illicit connections or cross connections
    - Can illicit connections be identified by finding warm sections of a DTS cable place in storm drains?
2) Determine the feasibility of rapid deployment of DTS across the city to identify illicit connections

Site Description

In August of 2008 the City of Moscow, Idaho received a letter indicating that the EPA would list the City as one of the entities that would fall under the requirements of the Phase II NPDES stormwater permit. In September 2009, the City made an application for an NPDES Permit for stormwater discharge. Following this application, Jessica Balbiani, a University of Idaho Graduate Student and employees of the City of Moscow, conducted dry weather sampling of stormwater outfalls to identify potential illicit discharges from illicit connections or cross connections to the City of Moscow's MS4 for future NDPDES stormwater permitting.

Balbiani identified 12 outfalls within the Moscow City limit discharging water with E. coli concentrations greater than the Idaho State Standard for E. coli in secondary recreation waters, like Paradise Creek, of ≤576 MPN/100ml. Given the high concentrations of E. coli found, it is likely that direct illicit connections to household wastewater, cross connections to the septic system or indirect connections to septic system were occurring.

Materials and methods

From August 18th to August 23rd an Oryx DTS (Sensornet, Hertfordshire, England) unit was used to collect temperature data in a storm drain adjacent to Sweet Avenue in the City of Moscow, see figure 4.1. The DTS unit was set to collect temperature traces at a 1.01-meter spatial resolution at 3-minute intervals. The sensor was stored in a waterproof plastic storage container near the near a manhole, see figures 3.2 and 3.3 below. The sensor was powered by a 12-volt deep cycle battery. Additionally, Hoboware (UA-002-08) temperature sensor/data loggers were installed to collect air temperature measurements in the monitored storm drain and in a sanitary sewage line directly next to the storm drain.

The DTS unit was configured in the duplexed single-ended configuration. The fiber optic cables that were deployed were AFL flat drop cable (Duncan, South Carolina). The cables were deployed using a high-pressure water jetting system. A fiber-optic cable of approximately 500m (distance to splice) in length was attached to channel 1. A fiber-optic cable of approximately 500m (distance to splice) was attached to channel 2. Approximately 12 meters of both cables were placed in two reference sections near the DTS sensor. The first reference section was an ice bath, inside a cooler, and the second reference section was also in a cooler of water but was ambient temperature. Just prior to the splice at the end of each cable an unmonitored reference bath was used allowing for a temperature correction after the splice on both cables. Therefore, starting at the sensor, both duplexed cables passed through an ice bath reference section, an ambient temperature bath, an unmonitored reference bath before and after the splice, and then on its way back to the DTS sensor, the cable again passed through the ambient temperature bath and the ice bath. In this set up, only two reference sections are monitored, but since the cable passes through the sections twice a total of four reference sections are available. Two independent PT100 thermometers on the DTS were placed along the two monitored reference sections allowing for the temperature offset and the assessment of the accuracy of temperature readings.

The data was processed using the MatLab® DTS toolbox available from the Center for Transformative Environmental Monitoring Programs (CTEMP). CTEMP's user toolbox provides graphical user interfaces (GUIs) that allows users to completely process and calibrate raw DTS data. The two monitored reference sections were used to calibrate and validate the data, and the unmonitored bath at the end of each cable was used as a point to correct temperature before and after the splice.

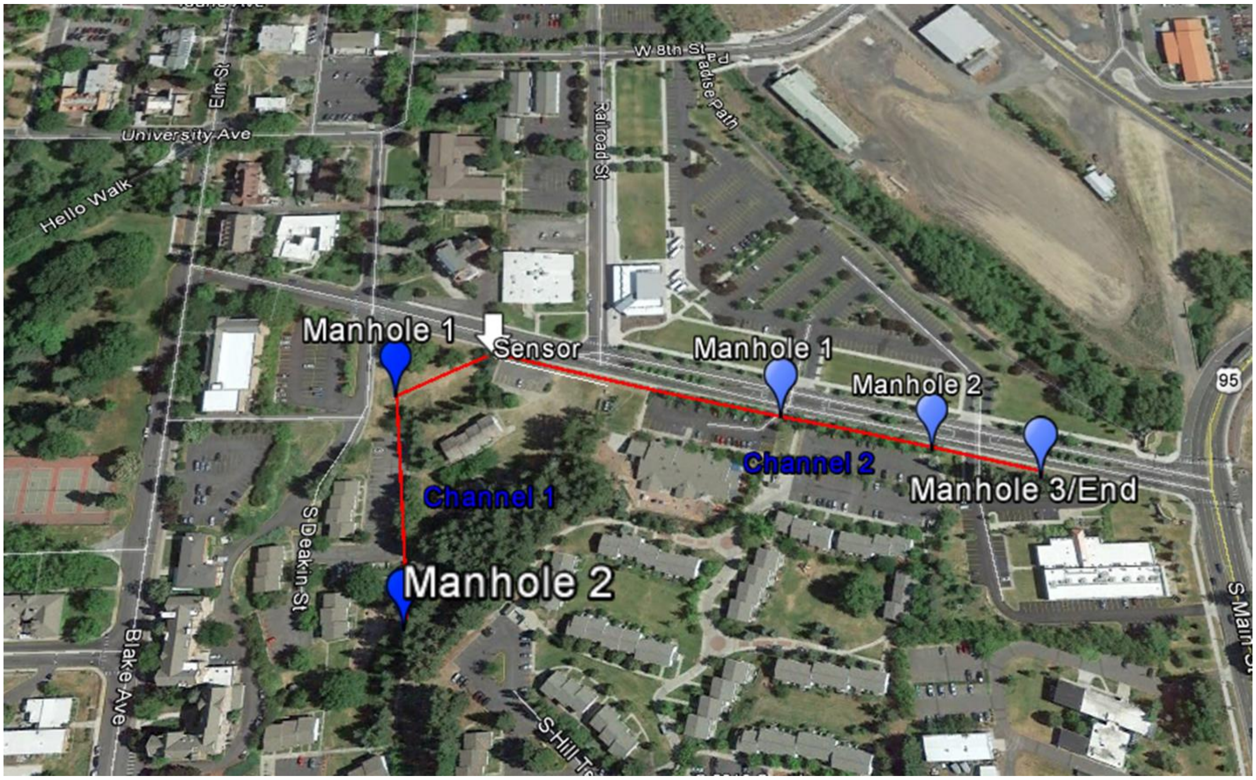


Figure 4.1. Map of study site. Note the location of the sensor and, in blue, the labels for channel 1 and channel 2 corresponding to the two fiber-optic cables in the storm drain.

Results and discussion

The biggest difficulty encountered in the of deployment of the DTS equipment was the rope that was pulled through the storm drain, to then pull the fiber-optic cable, would often break on the sharp edges of the drain lines when going around bends. For certain sectons of the drain a thin metal cable was used instead of the rope.

Prior to the deployment the cables were spliced on the ends and encased in a plastic data logger box, but the deployment broke then boxes and the splice. The enclosed box also made it difficult to pull the cable through the drains. It was determiend that splicing would be necessary for each deployment and would have to be done in the field. Another challenge included finding manholes that were hidden to conceal the asspciated equipment. One thought was to purcahse a small trailer for deployments across the city. This would make it easier to conceal the sensor and associated equipment. The estimated time to set up a deployment was 2-5 days depending on site conditions, as pulling the jetter and cable through the stormwater drains was the most time intensive activity and is site specific.

Figure 4.2. Phototgraph of deployment site and associated equipment.

Figure 4.3. Photograph of fiber-optic cables entering the storm drain and the coolers used for calibration baths.

Figure 4.4. Photograph of equipment needed for splicing the fiber-optic cable.

The calculated average root mean square error for Channel 1 was 0.139 ^{o}C and 0.180 ^{o}C for channel 2. An overview of the collected data, for both channels, from the deployment is shown below in figures 4.5 and 4.6. These heatmaps were used to identify warm sections of the cable. The warm sections were then plotted against against the collected air temperature in the stormwater drains. Some warmer sections of the cable would trend with air temperature of the drain line indicating the cable was sticking out of the water and was abnormally warm because it was exposed to the air in the drain. See figure 4.7 below for an example.

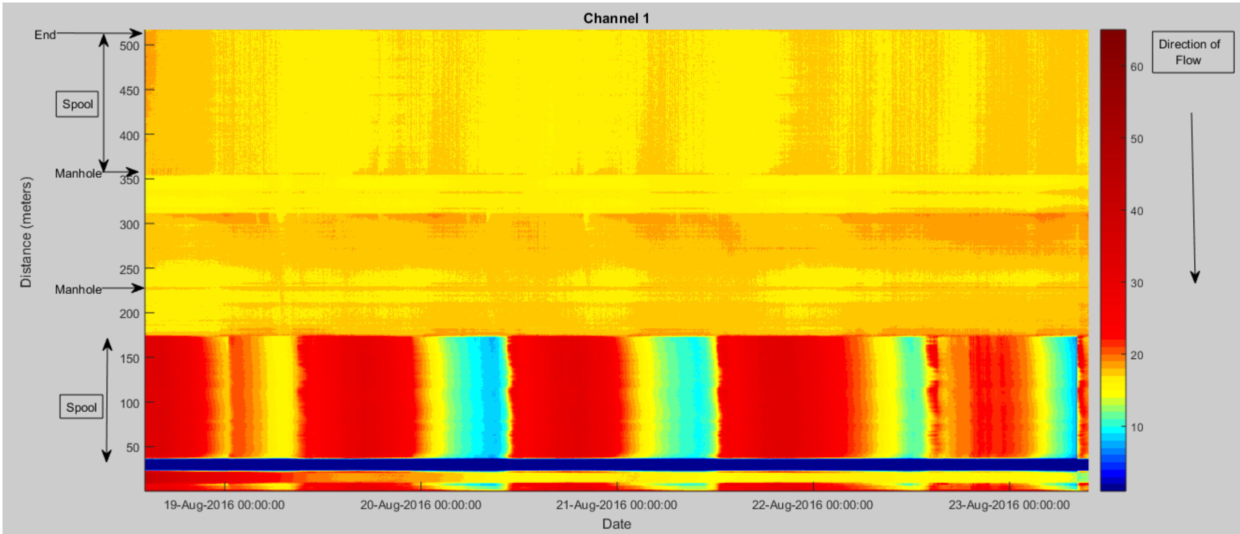


Figure 4.5. Heat map of the deployment on Channel 1.

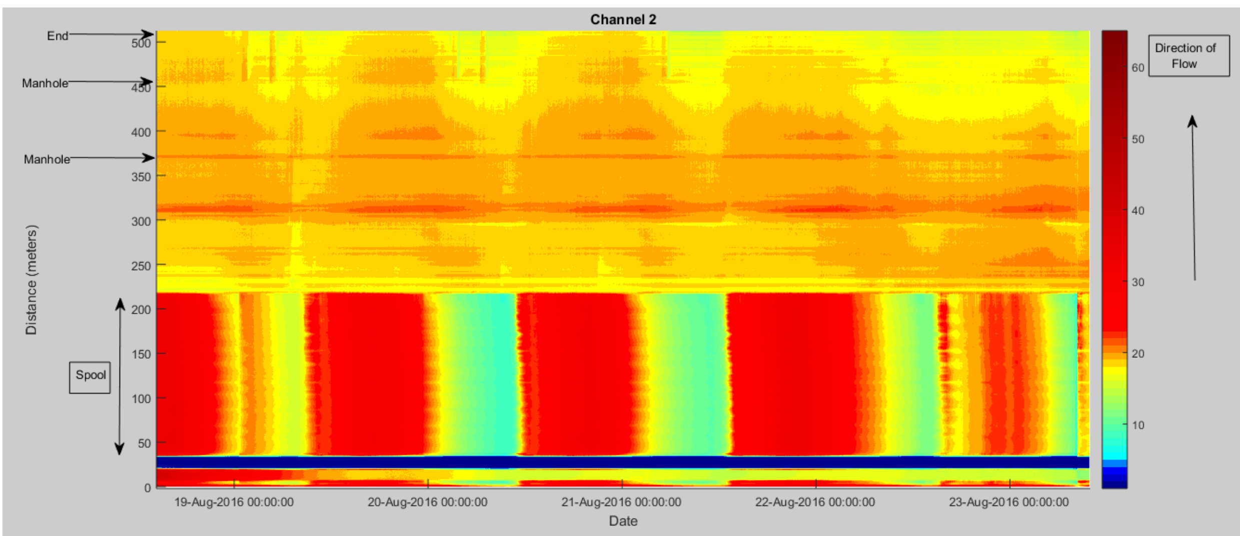


Figure 4.6. Heat map of the deployment on Channel 2.

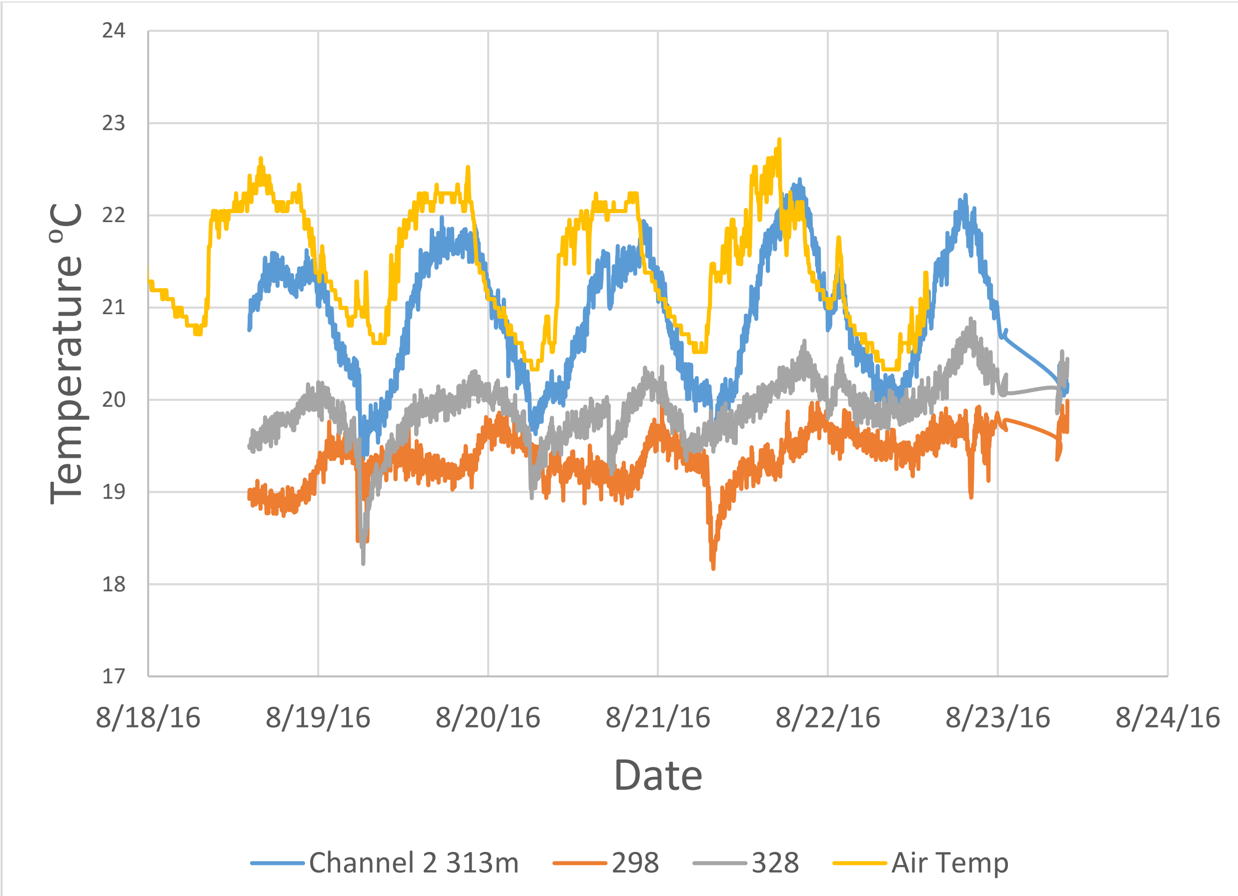


Figure 4.7. Graph of temperature collected at meter 313 on channel 2, a warm section of the cable, from 8/18/16 to 8/23/16. Also plotted is the air temperature in the drain line and the temperature of the DTS cable 15 meters above and below the warm section at 313 meters. Note how the warm section of cable trends with the air temepratue.

One section, however would rapidly heat up and cool down and did not trend with the collected air temperature within the drain line. This point was meter 460 on Channel 2. This point was idetified on the heatmap. Below, figure 4.8 and 4.9, is the plotted temperature at meter 460 on channel 2 as well as the air temperature in the drain line. In this graph the temperature at meter 460 would rapidly heat up and cool down while the air temperature does not. Figures 4.10 and 4.11 are graphs of the entire temperature trace taken at the spike in tempeature at meter 460 and subsequent time intervals after the temeprature spike. The temeparture at this location would rapidly heat and cool, therefore it was likely that the source of heating and cooling was not air temprature, but rather an input of warm and then cold water

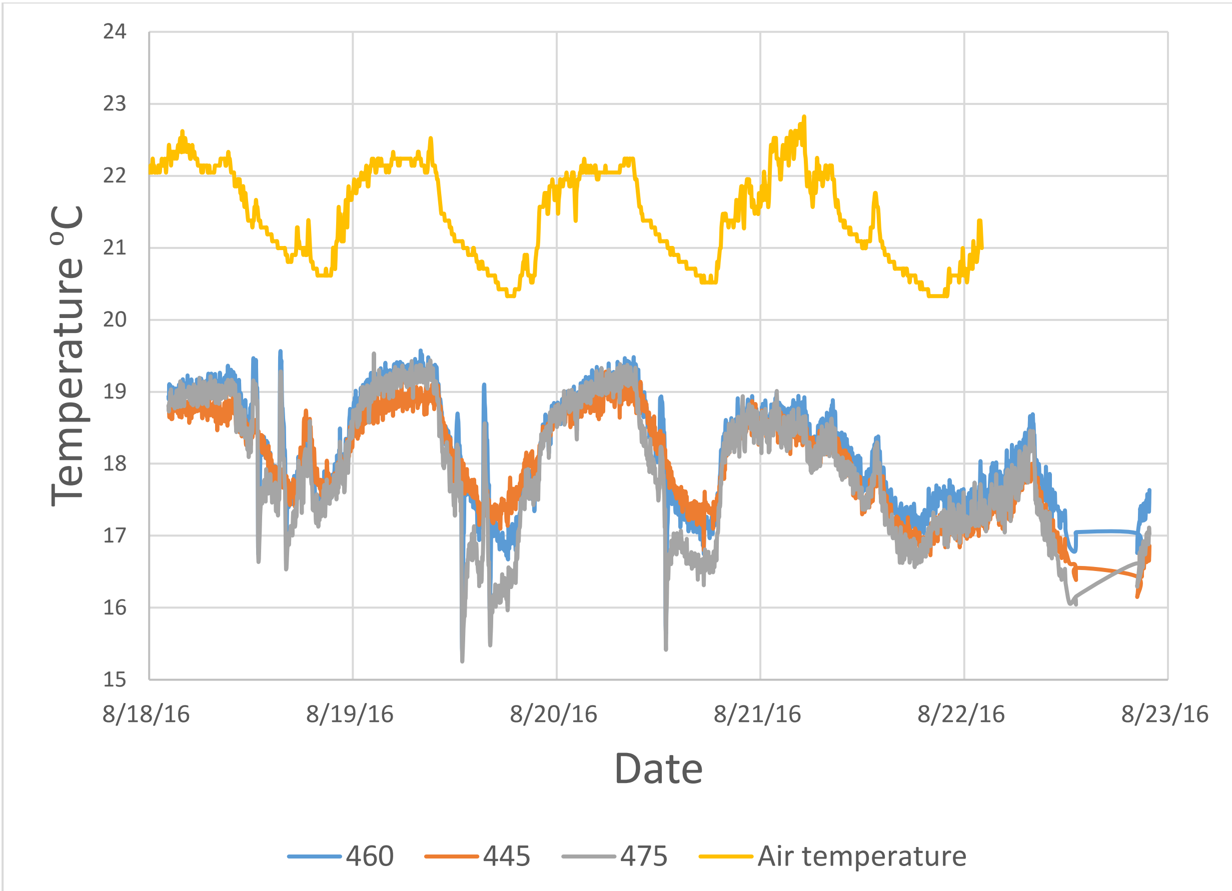


Figure 4.8. Graph of air temperature in the drain line and temperature at meter 460 on channel 2, and 15 meters above and below meter 460 from 8/18/16 through 8/23/16.

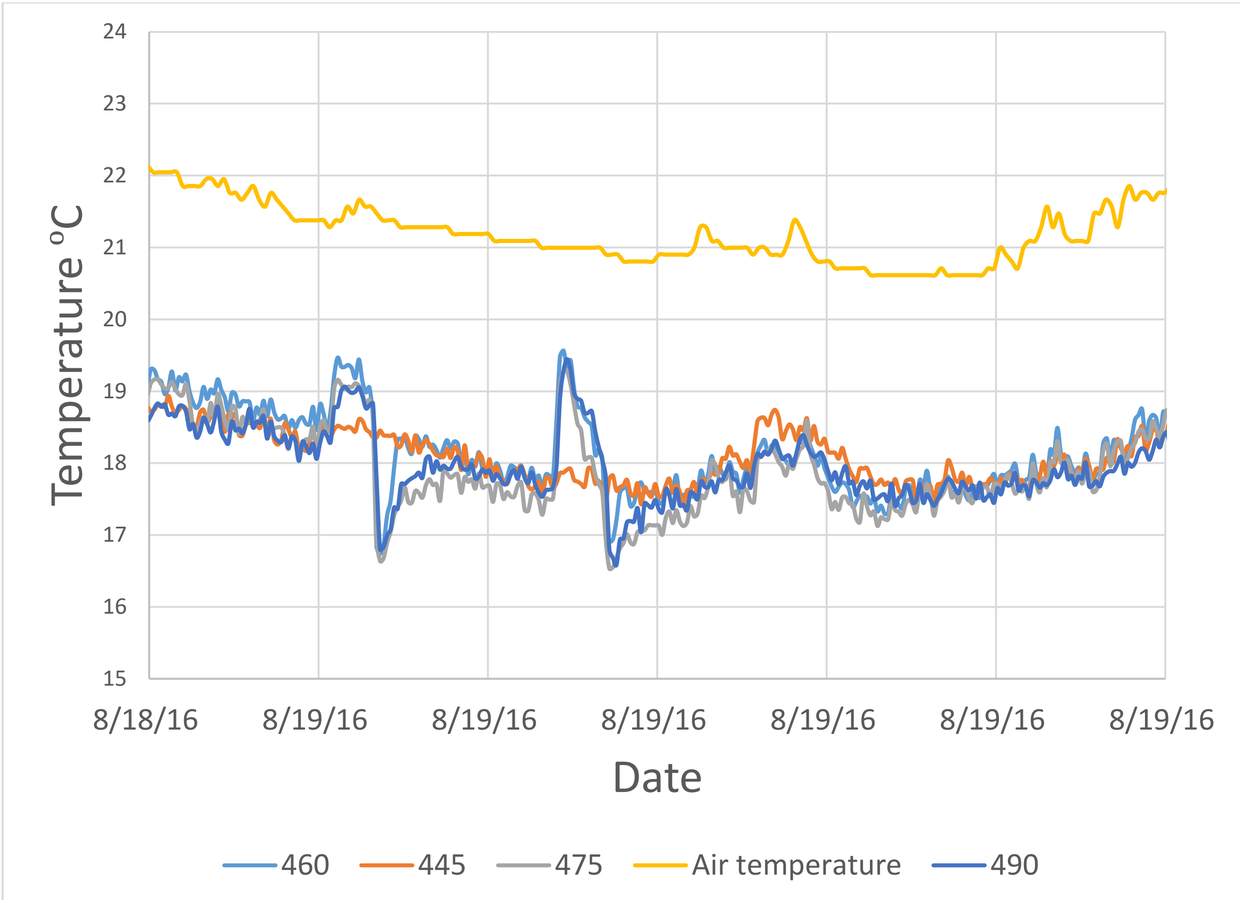


Figure 4.9. Graph of air temperature in the drain line and temperature at meter 460 on channel 2, and 15 meters above and below meter 460 from 8/18/16 through 8/19/16. This graph is an enhanced from the previous figure to show more detail during one of the observed rapid heating and cooling events.

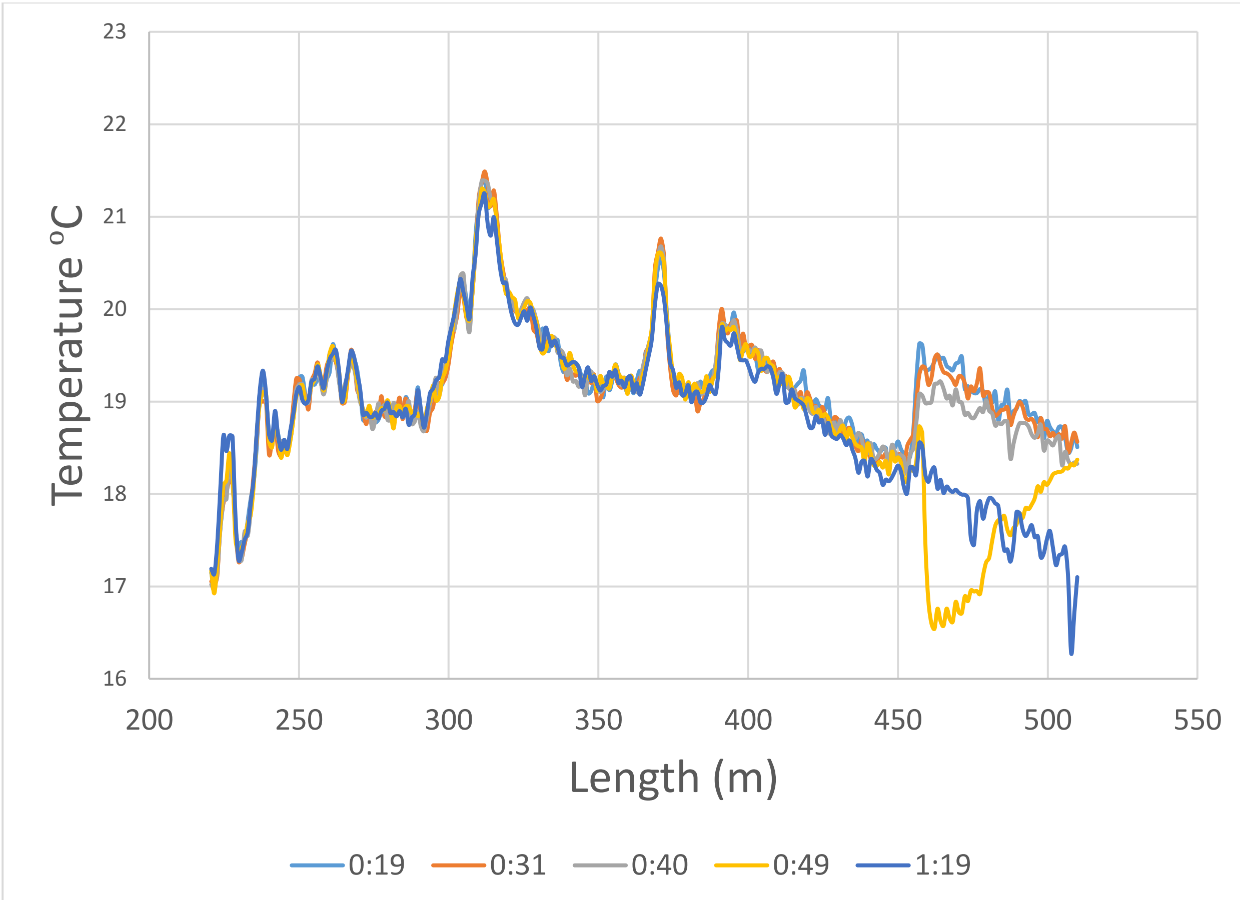


Figure 4.10. Graph of entire temperature trace of fiber-optic cable taken at the peak of the rapid spike (at 0:19) on Channel 2 at meter 460 on March 19th, and full temperature traces following the rapid spike in temperature.

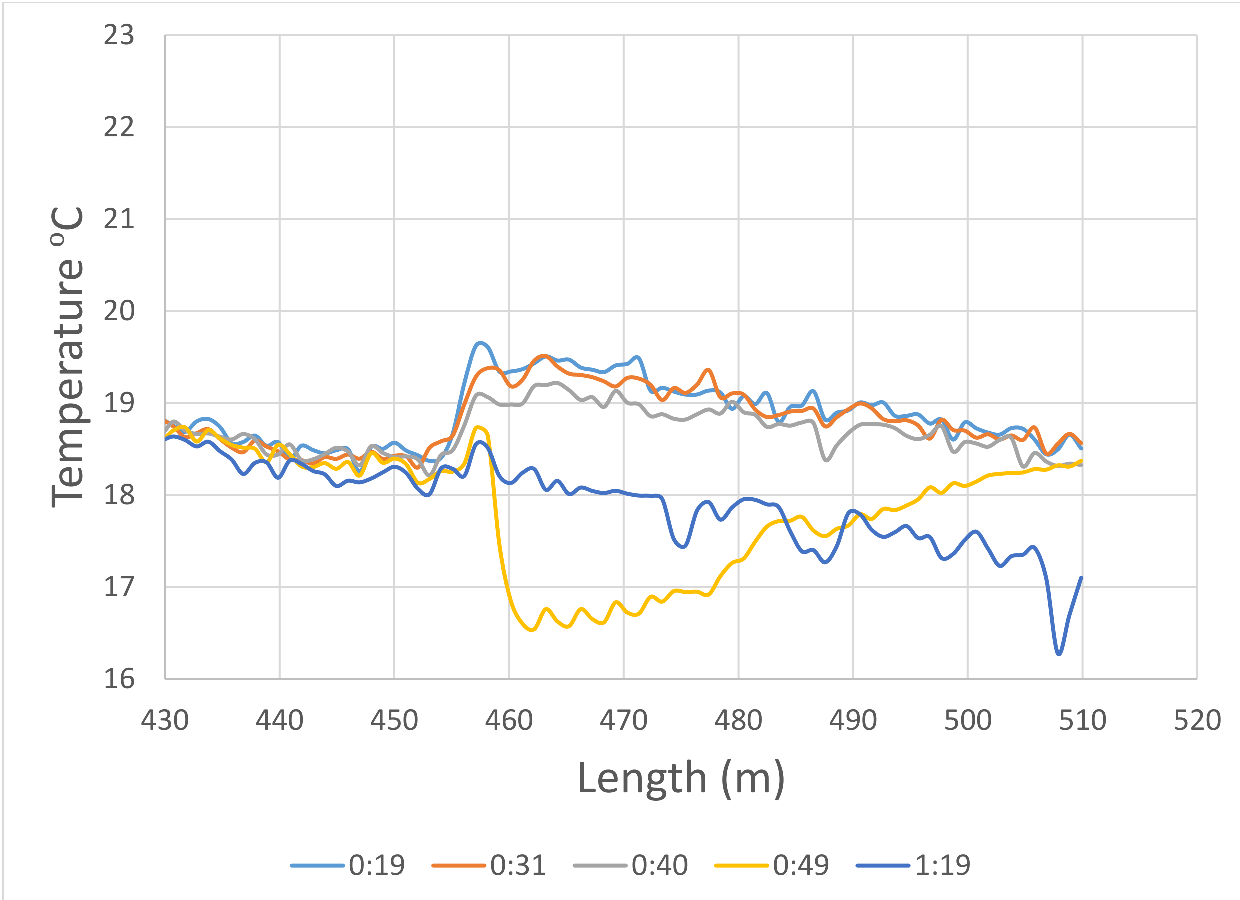


Figure 4.11. Enhanced graph of previous figure. Note how at roughly meter 460 the temperature rapidly spikes and then at the following time intervals the temperature decreases.

When the distance above the drain line was measured, meter 460 corresponded to a catch basin collecting runoff from a parking lot on the University of Idaho campus, see figure 4.12. The data was presented to engineering staff at the University of Idaho. The engineering staff hypothesized that the sprinkler systems were the cause of the rapid heat up and cool down at that location. It was hypothesized that the water in the hose line would heat up during the day and when sprayed at night this would at first release warm water followed by cooler water that was not in the hose during the day. This would explain the rapid warming and then cooling at meter 460.

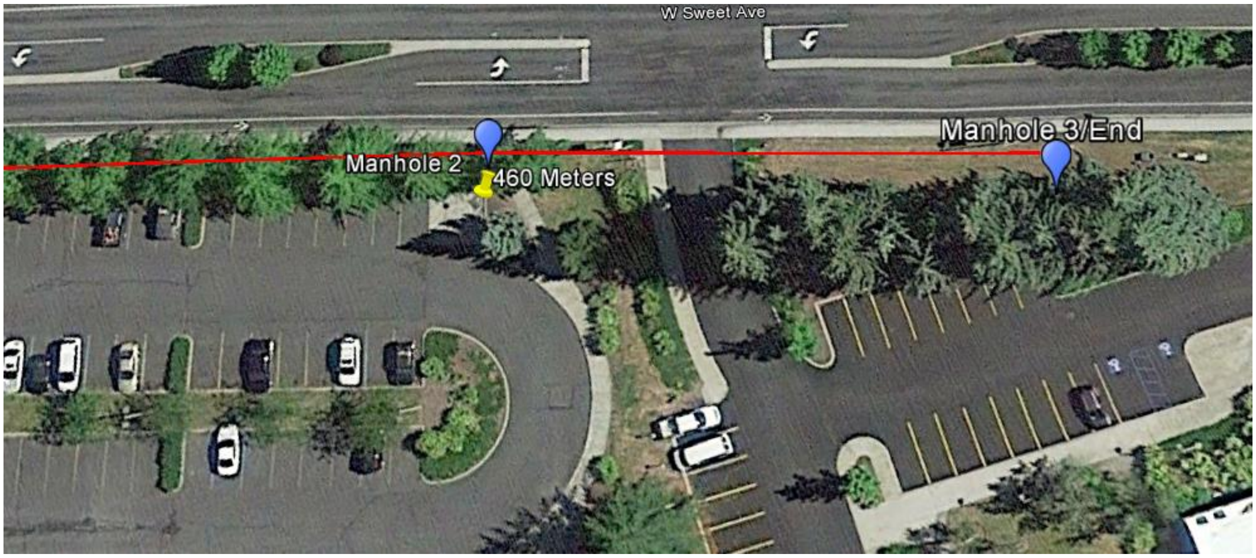


Figure 4.12. Photograph of location meter 460 on channel 2. This location lines up with a catch basin that collects water from a paring lot.

Conclusion

Given the increasingly rigorous permitting process facing many MS4 operators, inexpensive and time efficient methods are needed to remain within compliance. This study found that DTS could detect an illicit connection the monitored storm drain. The study also found the DTS could likely be deployed in 2-5 days in storm drains across the city, and that a small trailer would be helpful to conceal equipment. The biggest challenge in terms of evaluating a deployment was identifying warm areas that were due to a possible illicit connection rather than sections of the cable sticking out of the water within the storm drain. Monitoring the air temperature with in the drain helped identify sections that would trend with air temperature. It seems that areas that slowly warm and cool, in a diurnal pattern, were likely sections of the cable out of water and that illicit connections would likely be identified by rapid changes in temperature. Overall, the study showed DTS technology an efficient and cost-effective way to identify illicit connections to storm drains.

References

Hammer, T.R., 1972. Stream channel enlargement due to urbanization. Water Resour. Res. 8, 1530–1540. https://doi.org/10.1029/WR008i006p01530

Hoes, O.A.C., Schilperoort, R.P.S., Luxemburg, W.M.J., Clemens, F.H.L.R., van de Giesen, N.C., 2009. Locating illicit connections in storm water sewers using fiber-optic distributed temperature sensing. Water Res. 43, 5187–5197. https://doi.org/10.1016/j.watres.2009.08.020

Leopold, L., 1968. Hydrology for Urban Land Planning - A Guidebook on the Hydrologic Effects of Urban Land Use. Geol. Surv. Circ. 554, 1–21.

Selker, J.S., Thévenaz, L., Huwald, H., Mallet, A., Luxemburg, W., Van De Giesen, N., Stejskal, M., Zeman, J., Westhoff, M., Parlange, M.B., 2006. Distributed fiber-optic temperature sensing for hydrologic systems. Water Resour. Res. 42, 1–8. https://doi.org/10.1029/2006WR005326

United States Environemntal Protection Agency, 1999. Combined Sewer Overflow Technology Fact Sheet. Washignton, D.C. https://doi.org/EPA 832-F-99-041

Appendix

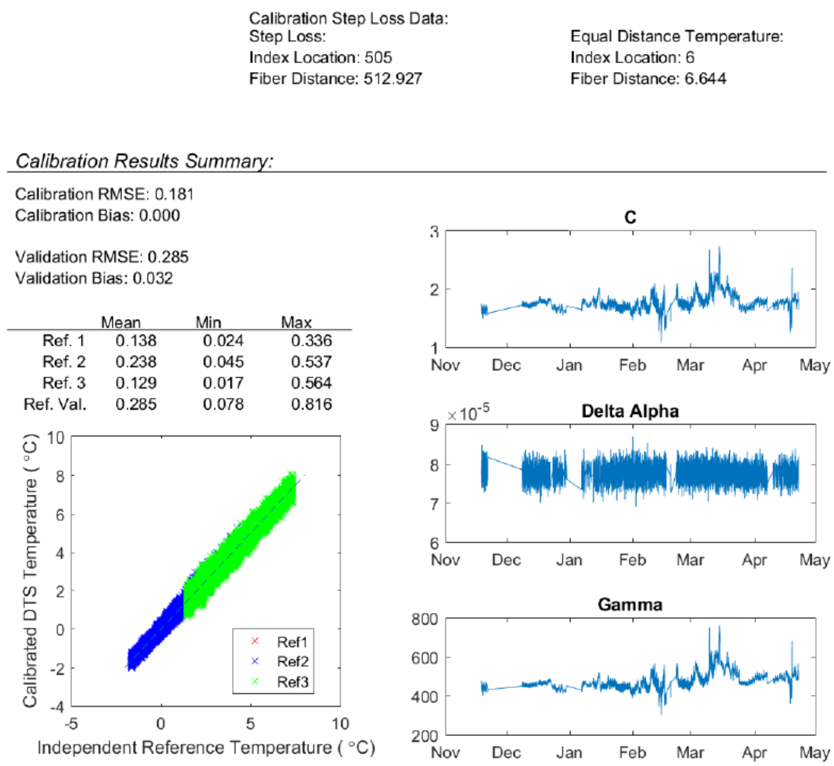


Figure A.1. Calibration result summary from Channel 1 that was placed in the no-till field artificial drain line.

Calibration Step Loss Data:
Step Loss:
Index Location: 496
Fiber Distance: 503.795

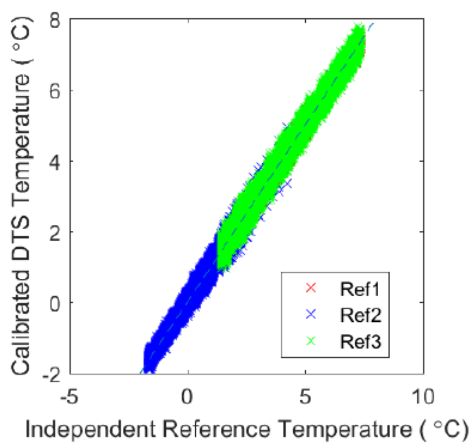
Equal Distance Temperature:
Index Location: 5
Fiber Distance: 5.629

Calibration Results Summary:

Calibration RMSE: 0.127
Calibration Bias: 0.000

Validation RMSE: 0.183
Validation Bias: 0.045

	Mean	Min	Max
Ref. 1	0.110	0.018	0.240
Ref. 2	0.150	0.035	0.337
Ref. 3	0.099	0.015	0.462
Ref. Val.	0.183	0.033	0.644



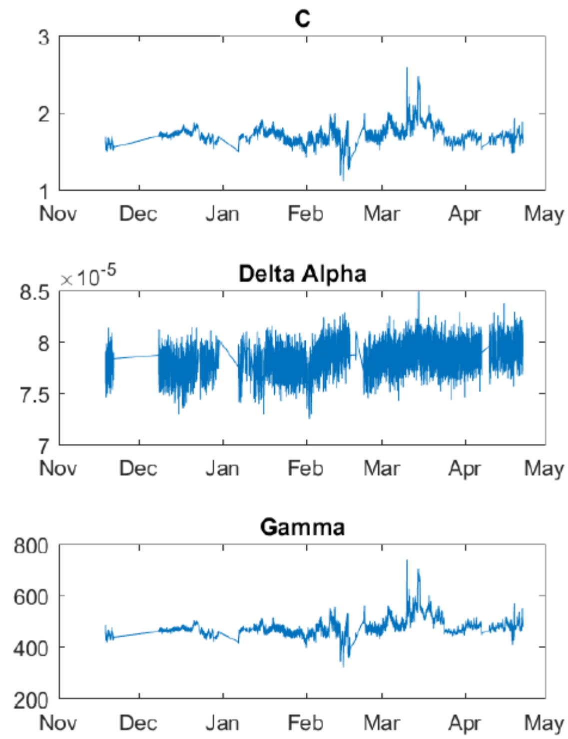


Figure A.2. Calibration result summary from Channel 2 that was placed in the conventional till field artificial drain line.

Figure A.3. Photograph of where a backhoe was used to dig down to the artificial drain line while pulling rope to then pull the fiber optic cable.

Figure A.4. Photograph of where “T-junctions” were put into the artificial drain lines.

Figure A.5. A photograph of the no-till field at the cook agronomy farm taken on January 20, 2017.

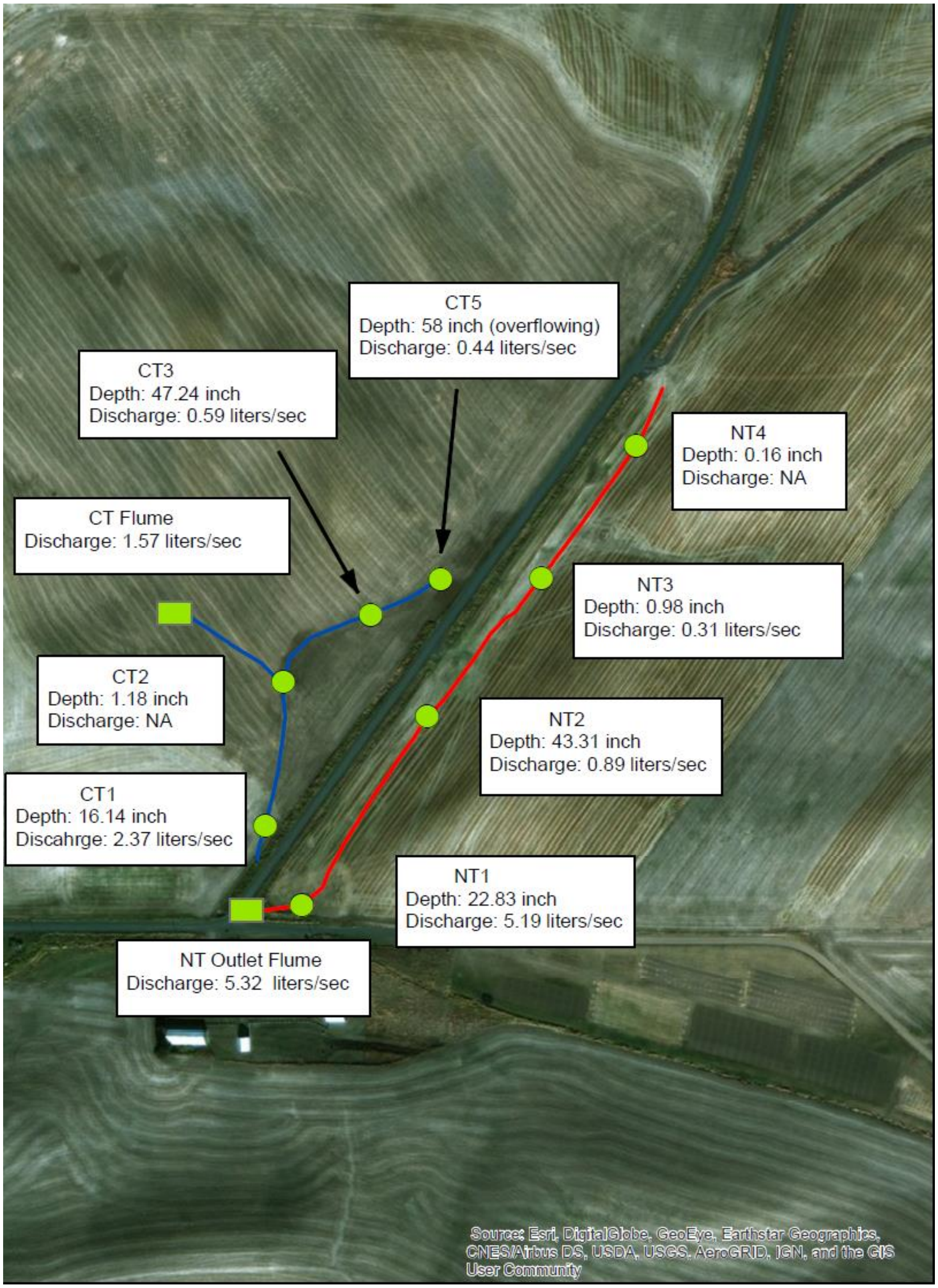


Figure A.6. Map showing discharge and depth of water along the artificial drain line on March 10, 2017.

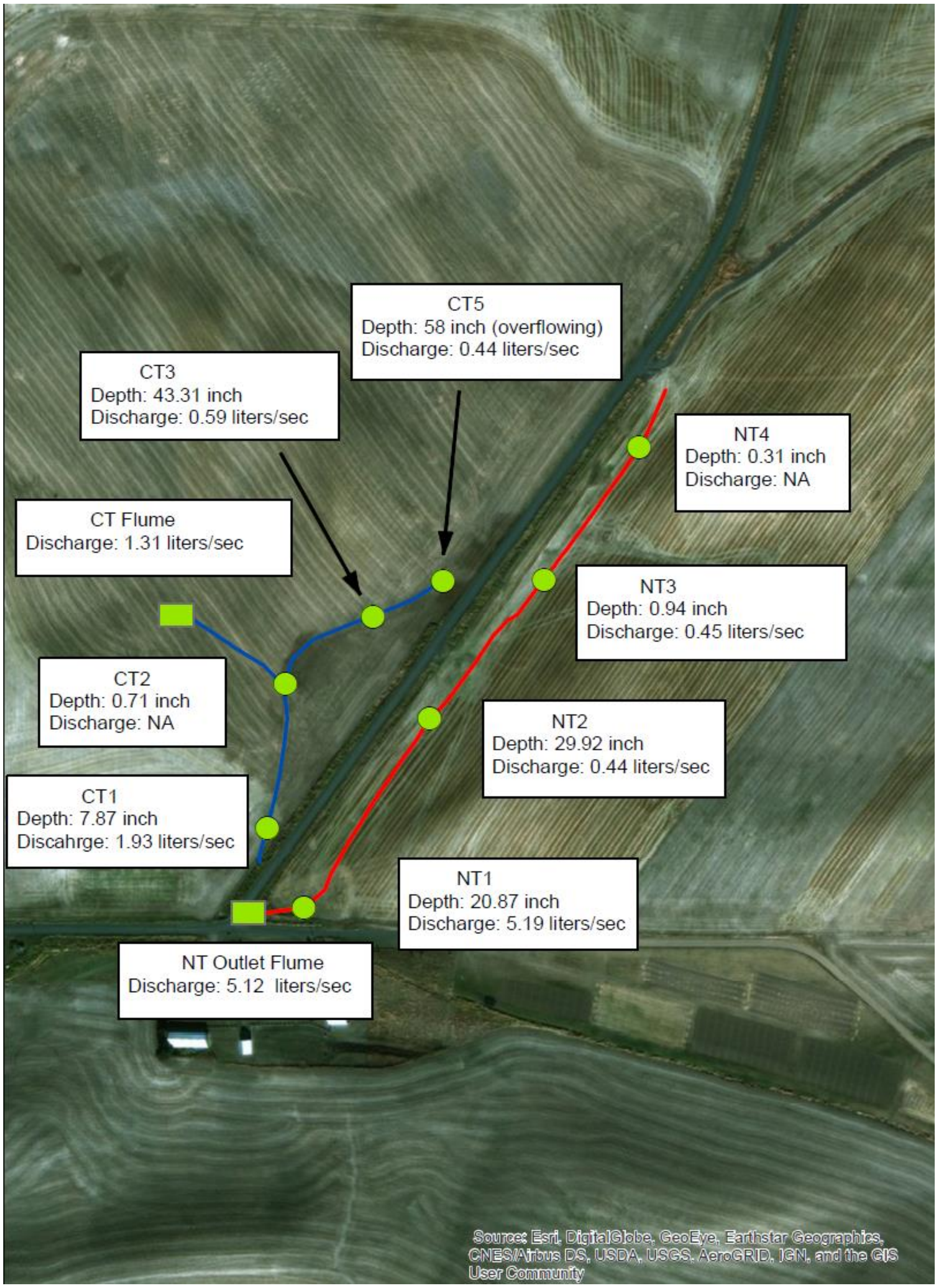


Figure A.7. Map showing discharge and depth of water along the artificial drain line on March 16, 2017.

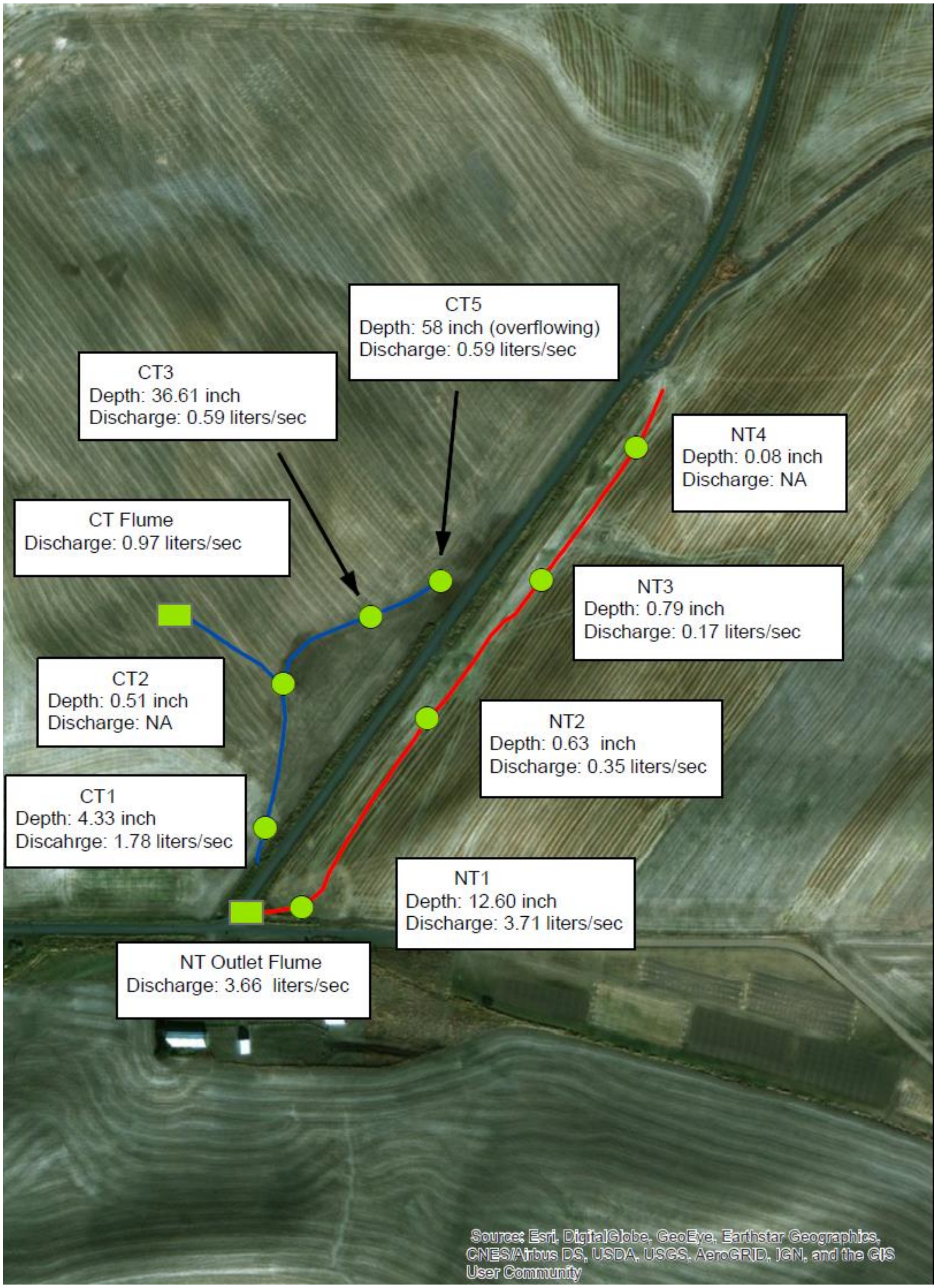


Figure A.8. Map showing discharge and depth of water along the artificial drain line on March 22, 2017.

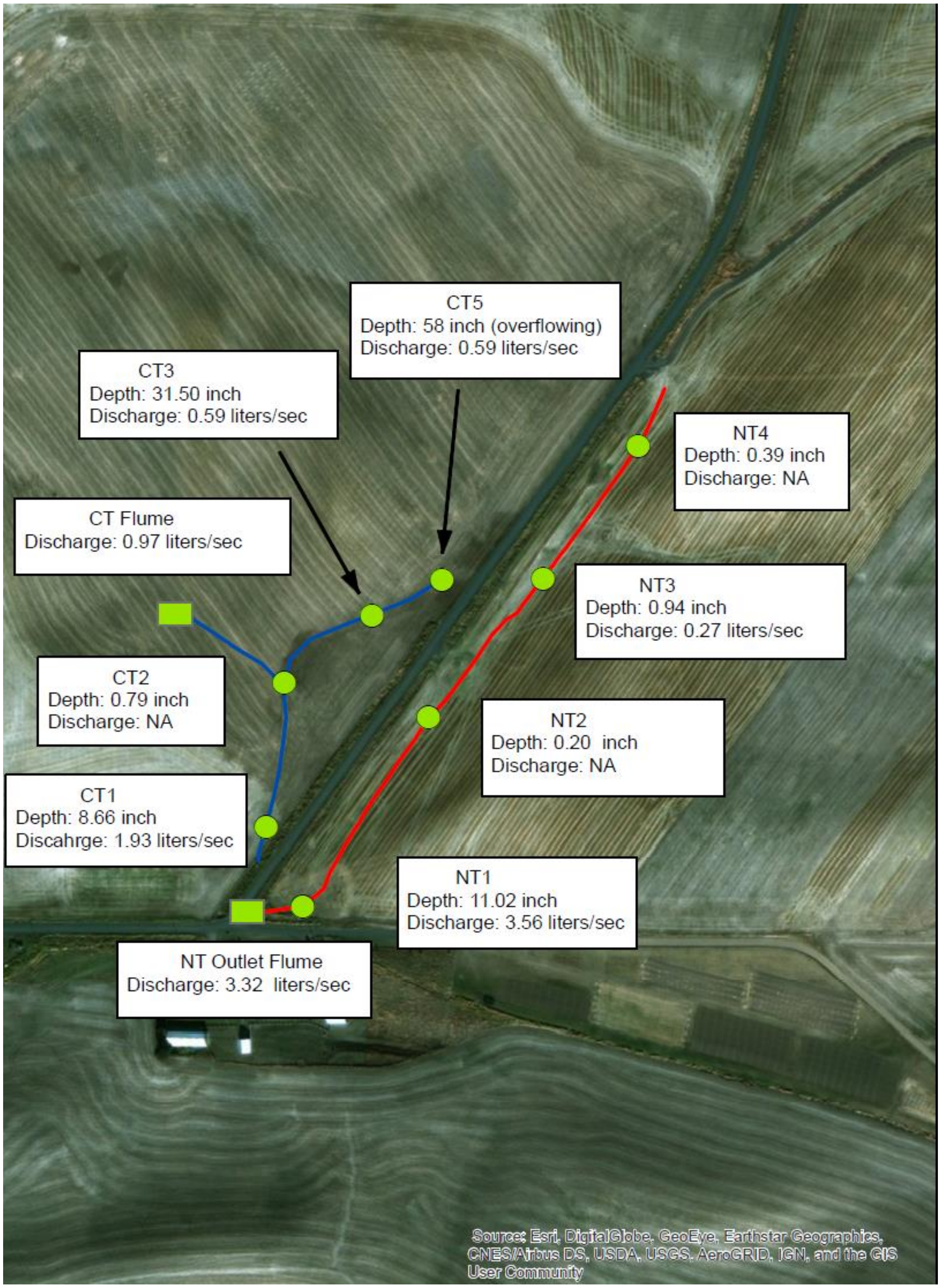


Figure A.9. Map showing discharge and depth of water along the artificial drain line on March 29, 2017.