IMPACTS OF CONTROLLED DRAINAGE AND SUBIRRIGATION IN THE RED RIVER VALLEY

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Drainage water management via controlled drainage (CD) and subirrigation (SI) has shown positive effects on water quality. To determine the impact of CD and SI in the Red River Valley (RRV), data from two fields, each with CD and SI, were analyzed. Water samples taken during SI from a North Dakota field during 2012-2018 were significantly different from those taken during CD and free drainage (FD). This was likely due to the SI water source of marginal quality, which also impacted soil quality near the drain tile. Three Minnesota fields were compared during 2013-2019, each with differing drainage practices. Results from a rainfall event showed an intermediate water table depth in the CD and SI field, along with a higher phosphate but lower nitrate concentration in surface runoff samples compared to subsurface drainage samples. Despite differences found between these fields, correlation between drainage practice and crop yield was not present.

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Most importantly, I would like to thank my family for their support throughout my life, especially when the path ahead was not clear. I am truly blessed and forever grateful for their presence in my life. Because of them I will do everything I can to let my heart be good soil.

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LIST OF ABBREVIATIONS

CD..Control drained

DWR...Drainage water recycling

FD ....Free drained

RRV ....Red River Valley

SI..Subirrigation

1. GENERAL INTRODUCTION

1.1. Background

A large portion of land within the Red River Valley (RRV) is used for agricultural production, but many areas are not naturally productive because of poorly draining soils and shallow water tables. To enable areas with these attributes to produce crops, subsurface drainage (SSD) has become a popular option among landowners. SSD involves the installation of corrugated plastic pipe, or drain tile, which excess water flows into. The drain tile then empty into an outlet, usually at the lowest point in a field. Free drainage (FD), where drainage outflow is not managed in anyway is the typical form of SSD, though other options exist for those interested in restricting drainage outflow. Controlled drainage (CD), where drainage outflow is inhibited for portions of the year, reduces the amount of nutrient loss from a field with SSD. In areas with enough of a change in elevation to allow for a gravity outlet, a control structure with internal stop logs can be used to perform CD. Because of how flat the RRV is, sump pump outlets are often necessary to remove water from the SSD system. For fields with a sump pump outlet, CD can be performed simply by turning off the sump pump when desired. The combination of CD and SI provides the potential for an optimization of the soil water content along with a reduced environmental risk caused by agricultural drainage outflow.

1.2. Objectives

The overall objective of this study is to describe the impact of CD and SI on water quality, soil quality, and crop yield. The specific objectives were to 1) analyze water samples taken during FD, CD, and SI, 2) assess the impact of SI with water of marginal quality on soil quality, 3) compare changes in water table depth between fields with differing drainage practices, 4) determine differences between surface and subsurface water samples, and 5) evaluate differences in crop yield between fields with varying drainage practices.

2. LITERATURE REVIEW

2.1. Red River Valley

Contained within the RRV are portions of eastern North Dakota, west central Minnesota, and southern Manitoba. Some of the defining characteristics of this region are a flat topography and clayey soils, which contribute to frequent spring flooding events. These attributes create conditions favorable for agricultural production, as evidenced by the widespread planting of corn (*Zea mays*), soybeans (*Glycine max*), and sugarbeets (*Beta vulgaris*) throughout the area. Despite the prevalence of agricultural fields in the area, growing conditions could be improved in areas impacted by poorly draining soil and high water tables through the installation of subsurface drainage.

2.2. Drainage

Drainage is defined as the, “process of removing surface or subsurface water from a soil profile or area” (ASABE, 2015). Surface drainage involves the construction of channels and reshaping of land to facilitate the flow of water. SSD involves the installation of drain tile, which is a, “subsurface conduit used primarily to remove subsurface water from soil” (ASABE, 2015). The size, spacing, and depth below the soil at which drain tile is installed have to be determined to design a SSD system layout. Many factors, such as topography and soil type, are used to determine the most effective SSD system layout for an area. The design has to facilitate the movement of water into the drain tile, but also the flow of water out of the field, which occurs at the outlet. If there is enough of a change in elevation to allow water to freely flow out of the outlet, it is considered a gravity outlet. Many fields do not have this drop in elevation, so a sump pump outlet is required. Despite the costs associated with the installation of SSD, it can prove to be profitable very quickly because of its benefits.

Soil with excessive moisture is more susceptible to compaction, limits availability of oxygen to crop roots, and prevents equipment traffic. These issues illustrate the importance of subsurface drainage, where excess water is removed from the soil and shallow water tables are lowered. Examples of the impact of SSD on these issues can be found in the literature. Research has shown an increase in soil penetration resistance in soils with SSD (Kandel et al., 2013). Similarly, SSD was shown to increase the number of workable days, based on soil moisture, compared to undrained fields (Mante et al., 2018). Soil moisture and water table depth have also been shown to influence corn and soybean yields. Corn yields were shown to be more consistent and on average higher when grown where there was an intermediate water table depth compared to corn grown on a shallow water table, which was shown to benefit in dry years from contributions from the water table but was negatively impacted in wet years (Zipper et al., 2015). Soybean yields were found to be higher in SSD fields compared to undrained fields in the north central United States, which was attributed to earlier planting dates in the drained fields and the location of the fields in wet areas (Mourtzinis et al., 2021).

Surface runoff and SSD outflow differ in terms of water quality. SSD can reduce phosphorus, sediment, and pesticide concentrations, but nitrate-nitrogen loads in SSD are greater than those from surface drainage systems (Blann et al., 2009). The amount of nitrate-nitrogen lost from a SSD system is heavily influenced by the depth and spacing of drain tile (Sands et al., 2008). The alteration of drain tile depth and spacing may reduce the ability of the system to remove water effectively and efficiently. Another possible consequence of this design is that the weight of equipment can cause drain tile to collapse when installed at too shallow of a depth. Fortunately, other methods of lessening the environmental impact of SSD exist.

2.2.1. Controlled drainage

Intervention at the outlet of a SSD system can reduce the amount of drainage outflow and is known as controlled drainage (CD). Control structures can be installed at a gravity outlet to facilitate the CD. Within a control structure are stop logs, which can be added or removed to block outflow or allow free drainage (FD). Sump pump outlets can be turned off during periods of the year to practice CD. Drainage is usually allowed prior to planting and harvesting in CD systems to dry the soil enough for equipment traffic and provide optimal growing conditions for young crops. Shortly after germination, drainage is prevented in a CD system. Only draining when needed reduced the environmental impact associated with subsurface drainage.

Though the concentrations of nutrients such as nitrate and phosphate are not decreased in CD systems compared to FD systems, the reduction in drainage outflow can reduce the nutrient loads (Wesström et al., 2001). Surface water issues such as harmful algal blooms are thought to be caused at least in part by contributions of nitrate and phosphate from agricultural drainage water (Anderson et al., 2002). Harmful algal blooms can have a variety of impacts on an area, including fatalities of wildlife and humans (Moore et al., 2008). The variability of yearly precipitation coupled with increasing food demands make the need for productive agricultural land in the United States greater than ever before. SSD may be necessary to allow for crop growth in some areas impacted by poorly draining soils or a high water table, but CD can help reduce the potential consequences of nutrient loss from those fields. Because of this, CD has been suggested as part of a, "sustainable intensification of agricultural drainage" (Castellano et al., 2019).

2.2.2. Subirrigation

The application of water back through a SSD system is known as subirrigation (SI). To convert a SSD field for SI, additional drain tiles will likely be installed. A closer drain tile spacing is required to deliver adequate amounts of water to the field and effectively practice SI. A pump will have to be added to facilitate the movement of water back through the SSD system. The source water for SI can be from groundwater, or water that is drained from the same or nearby field, which is known as drainage water recycling (DWR). This reduces water use and reduces the amount of surface water impacted by drainage water. The adoption of SI may appeal to landowners in areas that experience periods of both drought and waterlogging. Both CD and SI require a flat topography to keep the water table nearly level, which reduces the applicability of both practices to certain areas (Yu et al., 2020). In areas where this criteria is met, the same benefits of CD can occur along with the opportunity for supplemental irrigation during dry periods.

The combination of CD and SI gives a landowner the option of draining the field in periods of excess moisture, and applying irrigation in times of drought. Like CD, the combination of CD and SI have been shown to reduce drainage outflow and nutrient losses for both nitrate (Ng et al., 2002), and phosphorus (Tan et al., 2011). Soil moisture and water table depths have been shown to stabilize during years of abnormal moisture conditions in a field with CD and SI (Niaghi et al., 2019). This further illustrates the ability of CD and SI fields to adapt to levels of low, high, or average yearly precipitation.

3. ORGANIZATION

This thesis is made up of two manuscripts, one based on a site near Fairmount, North Dakota, and one based on a site in Clay County, Minnesota. Both sites practice CD and SI, but the source of SI water and type of outlet differ. The first manuscript dealing with the Fairmount site will focus on changes in water quality during the various management practice periods. The impact of SI with groundwater of marginal quality on soil quality will also be discussed in this section. The Clay County section will compare water table depth, drainage outflow, runoff water quality, and crop yield between an UD, FD, and CD and SI field. The inclusion of both manuscripts will give a broad overview of the impacts of CD and SI.

4. OBJECTIVES

The following paper determined the impact of CD and SI on the movement and quality of water, soil quality, and crop yield. The specific objectives were to 1) analyze the quality of water drained from a field during periods of FD, CD, and SI, 2) assess the impact of SI with water of marginal quality on soil quality, 3) compare the water table response to a rainfall event between fields with differing drainage practices, 4) evaluate differences between surface runoff and subsurface drainage water samples, and 5) determine the impact of drainage practice on crop yield.

5. IMPACT OF CONTROLLED DRAINAGE AND SUBIRRIGATION ON WATER QUALITY IN THE RED RIVER VALLEY

5.1. Abstract

Limiting the amount of water removed from a field with tile drainage can reduce its nutrient loss to surface waters. Control structures or lift stations are utilized to control drainage. Besides the environmental benefits of limiting nutrient loss from agricultural fields, retaining moisture in the field may also be required for adequate crop growth. Subirrigation, where water is applied through drain tiles, can also be implemented into existing tile drainage systems to provide the additional soil moisture. However, the potential impact of controlled drainage and subirrigation on the surface water quality are not well known in this region. In this study, water samples were collected and analyzed for chemical concentrations from a tile drained field that also has the controlled drainage and subirrigation modes in the Red River Valley, southeastern North Dakota in 2012-2018. With the drainage and subirrigation flow measurements and other meteorological parameters, a decreasing trend in overall nutrient load loss was observed because of reduced tile drain flow, though some chemical concentrations were found to be above the recommended surface water quality standards in this region, like sulfate, which was recommended to be below 750 mg/L, but was reported at a mean value of 1,971 mg/L during spring free drainage. The chemical composition of the subirrigation water was shown to have an impact on drainage water and the soil, and the impact varied between years. This variation largely depended on the amount of subirrigation applied, soil moisture, and the soil properties. Overall, the results of this study show the benefits of controlled drainage on nutrient loss reduction from agricultural fields.

5.2. Introduction

Agricultural drainage is often required to bring moisture levels in a field to a point where crop growth and equipment traffic is possible. Despite the many benefits of drainage, issues related to surface water contamination are often associated with the practice. Subsurface drainage (SSD) is a specific type of drainage drawing criticism because of the amount of nitrate and phosphate that may leave a field through SSD outlets (Jaynes et al., 2001; Gentry et al., 2007). SSD has become a popular management practice in the Red River Valley (RRV) due to recent wet years, fields with little variation in topography, and soil impacted by salinity. For example, the number of hectares approved for SSD permits by the North Dakota State Water Commission in Richland County, North Dakota rose from 536 in 2005 to 3141 in 2015, an increase of approximately 586% (Finocchiaro, 2016). The introduction of SSD into a field improves trafficability for equipment by lowering the amount of moisture in the soil, which increases soil penetration resistance (Kandel et al., 2013).

Controlled drainage (CD) has been presented as a management practice that limits the nutrient loss out of SSD outlets through a reduction in drain flow. CD is defined as a “regulation of the soil water table by means of pumps, control dams, or check drains, or a combination of these, for maintaining the water table at a depth favorable to crop growth and/or for minimizing the effects of drainage during the fallow season to prevent nutrient loss” (ASABE, 2015).

For a CD field with a pump station outlet, the pump station is turned on prior to planting and harvest to remove moisture from the field, increasing trafficability, or the ability of equipment to maneuver through the field, which saves time for farmers and decreases rutting in the field. During the growing season, the CD status is recommended to be manipulated to best provide optimal soil conditions in terms of aeration and water content (ASABE, 2013). When paired with SI, the CD controls the water table depth that can improve crop yields (Madramootoo et al., 1993; Niaghi et al., 2019).

Along with the positive impact on crop yield, CD has also been shown to reduce nutrient losses from agricultural fields in a variety of studies. Wesström et al. (2001) found a correlation between reduction in drainage outflow and reduction in nitrate and phosphate loss because the highest nitrate concentrations were found during the periods of highest drainage outflow. A 25% reduction in nitrate concentration was reported by Drury et al. (1996) between conventional drainage and CD, with most nutrient losses from the CD field occurring during the non-cropping period. Research from Feser et al. (2010) also concluded that the reduction in nitrate-nitrogen was due to a reduction in drainage outflow.

Subirrigation (SI) is defined as an, “application of irrigation water below the ground surface by raising the water table to within or near the root zone” (ASABE, 2015), and can increase the amount of moisture in a field when desired while still implementing SSD. Despite the benefits of additional moisture through the application of SI, the use of a water source with marginal quality can have deleterious impacts on the surrounding soils. Much of the research published on the use of sodic water for irrigation has taken place in arid environments with sandy soils (Choudhary et al., 2006; Jalali and Ranjbar, 2009). Because of their tendency to swell and disperse during drying and wetting, smectitic soils may be more prone to permeability issues caused by irrigation water quality compared to soils with different minerology (Bauder, 2009). Irrigation water guidelines indicate the potential for a severe reduction in infiltration with a sodium adsorption ratio (SAR) value between 3-6 and an electrical conductivity (EC) below 0.3 dS/m, though a slight risk is possible at as high as 1.2

dS/m (Ayers and Westcot, 1985). Site characteristics such as soil minerology are encouraged to be taken into consideration when using these values to interpret data, however.

CD and SI practices are gaining popularity, but little research has been done in the RRV to determine the impact of CD and SI on surface water and soil quality. This study will use the water quality data from a field with CD and SI to analyze the impacts of these management practices on the surrounding environment. The impact of SI with water of marginal quality on soil quality was also assessed. The resulting data will provide insight into the applicability and environmental benefit of these practices in the RRV. The objectives are to analyze the rainfall and drainage outflow patterns throughout the study period, evaluate if the drainage water from the field meets ND surface water quality standards, estimate the daily chemical loads during the different water management periods, and assess the CD and SI impact on surface water as well as the impact of SI with a marginal water source on soil quality.

5.3. Materials and Methods

5.3.1. Experimental site

The field site is located approximately 4.2 km south of Fairmount in Richland County, ND. The geographic location is 46°00′45″ N and 96°35′47″ W, with an elevation of 296 m above sea level. The area of the field is about 44 ha, with 802 m in the west-east and 548 in the north-south directions. The original field layout was half undrained (north half) and half drained (south half), with 18.2 m spacing (Jia et al, 2012, Rijal et al, 2012). In 2011, the entire field was converted to subirrigation with 9.1 m spacing. The depth of tile varies from 1.0 to 1.5 m below the soil surface. Soil series within the project area are Clearwater-Reis silty clay (Clearwater series, Fine, smectitic, frigid Typic Epiaquerts; Reis series, Fine, smectitic, frigid Typic Calciaquerts), Antler-Mustinka silty clay loam (Mustinka series, fine, smectitic, frigid

Typic Argiaquolls), Antler silty clay loam (Fine-loamy, mixed, superactive, frigid Aeric Calciaquolls), and Doran clay loam (Doran series, Fine, smectitic, frigid Aquertic Argiudolls) (USDA, 2020). Other than 2012, when sugarbeets (*Beta vulgaris*) were planted, a corn (*Zea mays*) and soybean (*Glycine max*) rotation has been used with tillage after harvest each year.

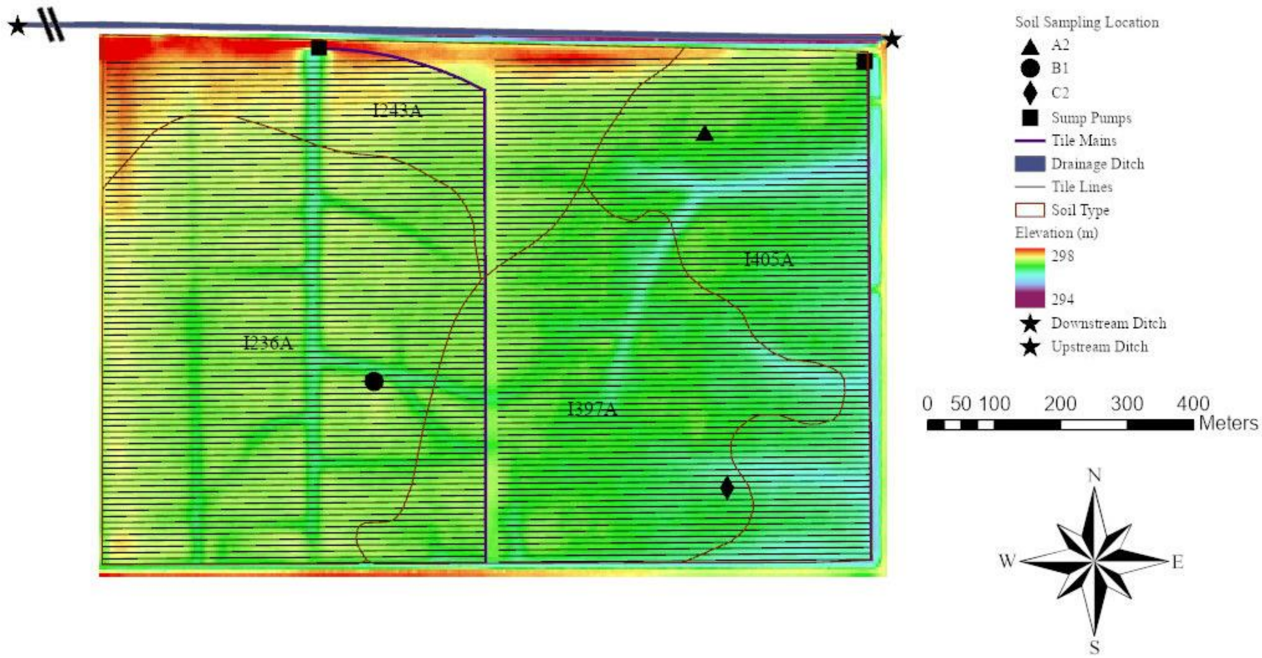

Figure 5.1. Experimental layout, where A2, B1, and C2 are soil sampling locations, and the curved lines identify the soil map units, with I236A for Clearwater-Reis silty clays, I243A for Doran clay loam, I405A for Antler clay loam, and I397A for Antler-Mustinka complex, respectively.

Southeastern North Dakota has a humid continental climate with an average temperature of 6.5°C. According to weather data at the Wahpeton North Dakota Agricultural Weather Network (NDAWN) station, approximately 26 km north of the field site, the average maximum temperature of 28.8°C occurs in July while the average minimum temperature of –17.9°C occurs in January. Average annual precipitation is 567 mm. During the study period of this project (2012-2018), the driest year was in 2012 with only 336 mm of rainfall. The wetter years were in 2013 and 2016 with approximately 521 mm of rainfall (NDAWN, 2020).

5.3.2. Instrumentation

A transducer (Water Level Loggers U20L-04, Onset HOBO, Bourne, MA) and a conductance sensor (Conductivity Loggers U24-002-C, Onset HOBO, Bourne, MA) were installed in the two sump structures in order to monitor the water level and flow rate changes. The drainage flow was monitored by a current switch sensor (CSV-A8, Onset, Bourne, MA) and recorded by a state datalogger (UX90-001, Onset, Bourne, MA). The current sensor was installed on the electrical board of the sump pump.

Near each of the sump pump stations, a paired manual and automatic rain gauge was installed at about 1.5 m above the ground without any obstacles. The manual rain gauges were read every two weeks during field visits. The automatic rain gauges (Stratus RG202, Stratus, Fergus Falls, MN) used a datalogger (WatchDog data Logger Model 115 Spectrum Technologies, Inc, Aurora, IL) to record the data every 10 minutes.

5.3.3. Water sampling

Water samples were taken from the sump structures using a bailer every other week from approximately May to October every year since 2008 (excluding 2011), or when water was not frozen. The water samples were preserved according to the instruction by the North Dakota Department of Environmental Quality (DEQ) Chemistry Laboratory. Each water sample was immediately filtrated with a filter (0.45 micron High-Capacity dispos-a-filters™, Geotech Environmental Equipment, Inc., Denver, CO). For nutrient analysis, 2 mL of sulfuric acid was added to the filtered water in a 500 mL plastic bottle. For trace metal analysis, 2 mL of nitric acid was added to the filtered water in a 250 mL plastic bottle (Pang, 2012). Samples were later grouped by management practice period for comparison purposes. Free drainage (FD) will be defined as when the sump pump was turned on, CD was when the sump pump is turned off, and SI was when water was pumped back into the field.

5.3.4. Water sample chemical analysis

The water samples were sent to the ND DEQ for chemical analysis. As stated in Jia et al. (2012), flow injection analysis and Environmental Protection Agency (EPA) method 353.2 were used for nitrite and nitrate-nitrogen (NO_x-N) analysis. Method P4500-P B.5 was used for orthophosphate (PO_4-P) analysis. Total dissolved solids and conductivity were determined by Method 1030 E and by Conductivity Method 2510, respectively (Jia et al., 2012). EPA method 200.7 was used for sodium, calcium, magnesium, and potassium ion analysis. EPA method 300.0 was used for chloride and sulfate ion analysis (J. Quarnstrom, personal communication, 3 February 2020). Temperature and electrical conductivity (EC) were measured manually in the field by a transducer (Model 107 TLC Meter, Solinst Canada Ltd., Georgetown, ON). A pH sensor (Low Range pH/Conductivity/TDS Tester, Hanna Instruments, Smithfield, RI) was connected to a data logger and used for pH measurement in the field. These field measurements provided a comparison between the laboratory-analyzed data and the field data.

Since 2016, a duplicated water sample was collected and sent to a laboratory at the North Dakota State University (NDSU) campus for nitrate, ammonium (NH_4-N), PO_4-P, potassium, EC, and pH analysis. This data provided a means for comparison and validation of the North Dakota Department of Health data. At the NDSU laboratory, EPA method 365.1 Revision 2.0 was used for dissolved phosphorus analysis. The Berthelot, or Indophenol Reaction, along with a segmented flow analyzer (SEAL AutoAnalyzer, SEAL Analytical, Mequon, IL), was used for NH_4-N analysis. Nitrate-nitrogen was measured through the trans-nitration of salicylic acid method. An atomic adsorption device (210VGP Atomic Adsorption Spectrophotometer, Buck

Scientific, East Norwalk, CT) was used for potassium analysis (S. Mathews, personal communication, 28 January 2020).

5.3.5. Soil sampling

To observe the impact of SI application with water of marginal quality on soil quality, soil samples were taken around drain tiles within the field and analyzed in 2012, 2014, and 2016. The samples were obtained by excavation of the soil above the drain tiles followed by the collection of soil samples at distances of 0, 20, 41, and 81 cm from the drain tile at three locations, with three replicates. Samples were then sent to the NDSU Soil Testing Lab for analysis. The locations of the soil sampling points are given in Figure 5.1. The ammonium acetate method with an atomic adsorption device (210VGP Atomic Adsorption Spectrophotometer, Buck Scientific, East Norwalk, CT) was used for potassium, calcium, magnesium, and sodium ion analysis. Percent sodium was calculated using Equation 5.1.

$$\%Na = \frac{100Na}{Ca + Mg + K + Na} \tag{5.1}$$

where

units of cations are cmol(+)/kg

To calculate sodium adsorption ratio (SAR) from percent sodium, Equation 5.2 was adapted from DeSutter et al. (2015):

$$\text{SAR} = 1.04\%\text{Na} - 0.35 \tag{5.2}$$

A 1:1 slurry was used for EC measurement along with an electro-chemistry meter (Orion™ Versa Star Pro™, Thermo Fisher Scientific, Waltham, MA). A 1:1 slurry and an electronic pH meter (Accumet AB15 Basic, Fisher Scientific, Hampton, NH) were used for pH measurement (S. Mathews, personal communication, 4 February 2020).

5.3.6. Flow and nutrient load calculations

To determine daily tile flow, the following equation (Equation 5.3) is incorporated from Scherer and Jia (2009):

$$Q_p = \frac{V_s}{T_{on}} + Q_i \tag{5.3}$$

where

Q_p = average pump flow rate over one pump duty cycle

V_s = sump storage volume

T_{on} = time interval when the pump is running

Q_i = average flow rate from the tile into the sump.

Input values for determining daily flow are recorded by the event logger as well as the time of pumping and the dimensions of the sump pump structure (Scherer and Jia, 2009). Daily nutrient loads are calculated from the daily flow rates, nutrient concentrations, and the drainage area.

Since the chemical concentrations were measured every two weeks and drainage flow was measured continuously and calculated daily, the daily chemical load was estimated through linear interpretation of the chemical concentrations.

Due to concerns regarding the quality of the water used for subirrigation, specifically in terms of salinity, the SAR was calculated for the water samples (Equation 5.4).

$$\mathrm{SAR} = \frac{[\mathrm{Na}^+]}{\sqrt{\frac{[\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}]}{2}}} \tag{5.4}$$

where

[] represents the concentration in milliequivalents/liter (meq/L)

Percent sodium was calculated using Equation 5.5 (J. Quarnstrom, personal communication, 3 February 2020):

$$\left(\frac{[\mathrm{Na}^{+}] \div 23.1}{([\mathrm{Na}^{+}] \div 23.1) + ([\mathrm{K}^{+}] \div 39.1) + ([\text{Hardness total}] \div 50)}\right) \times 100 \qquad (5.5)$$

5.3.7. Statistical analysis

To determine if statistically significant differences were present between the chemical concentration data, a two-factor analysis of variance without replications was performed with a Tukey's Honestly significant difference post hoc test. A 95% confidence interval was used. Descriptive statistics were used to summarize the chemical concentration data and simple regression was used to compare chemical load and drainage outflow volume.

5.4. Results and Discussion

5.4.1. Precipitation and drainage outflow

Both the amount of rainfall during the growing season and the snowfall over the winter period have affected the drainage outflow, and vary between each year and season. During the study period from 2012 to 2018, the rainfall amounts were measured in the field, and the snowfall in terms of snow water equivalent (SWE) amounts were obtained from an NDAWN station in Breckenridge, MN, approximately 38 km north of the field. The SWE values were recorded between November and March or April of the current year, depending on precipitation characteristics. Total precipitation was calculated as the sum of SWE and rainfall. The results are listed in Table 5.1.

Table 5.1. Total annual precipitation, snow water equivalent from November to April, rainfall amount from May to October, and subirrigation at the Richland County, ND site.

Year	Total precipitation (mm)	Snow water equivalent (mm)	Rainfall (mm)	Subirrigation (mm)	Drainage outflow (mm)
2012	484	65	418	234	2
2013	747	199	548	173	107
2014	479	94	385	140	56
2015	574	66	508	186	25
2016	614	57	557	154	13
2017	526	117	409	87	12
2018	543	121	421	0	6

With a higher SWE of 199 mm from fall 2012 to spring 2013, the highest drainage flow (107 mm) was found in spring 2013. Similarly, the lowest SWE of 57 mm occurred from fall 2015 to spring 2016, so the least amount of drainage flow was expected to occur in spring of 2016. However, the direct correlation was not found in the results (Table 5.1) due to a higher average daily drainage outflow influenced by SI and rainfall in 2016 (0.5 mm/day) compared to 2017 (0.2 mm/day) and 2018 (0.14 mm/day).

The variation in rainfall and SWE directly affected the drainage outflow. In fact, the drainage outflow in the springtime was affected primarily by the SWE, but the drainage outflow in the summer and the fall season followed with the rainfall distribution (Figure 5.2). Data from 2014-2016 provides an example of how SWE impacted the total drainage outflow. The total precipitation (479 mm) in 2014 was lower than the total precipitation in 2015 and 2016, but more drainage outflow occurred in 2014. This was likely because of the higher SWE in 2014 compared to those in 2015 and 2016. The majority of drainage outflow in 2014 occurred in the spring, when snowmelt contributed more to the drainage flow.

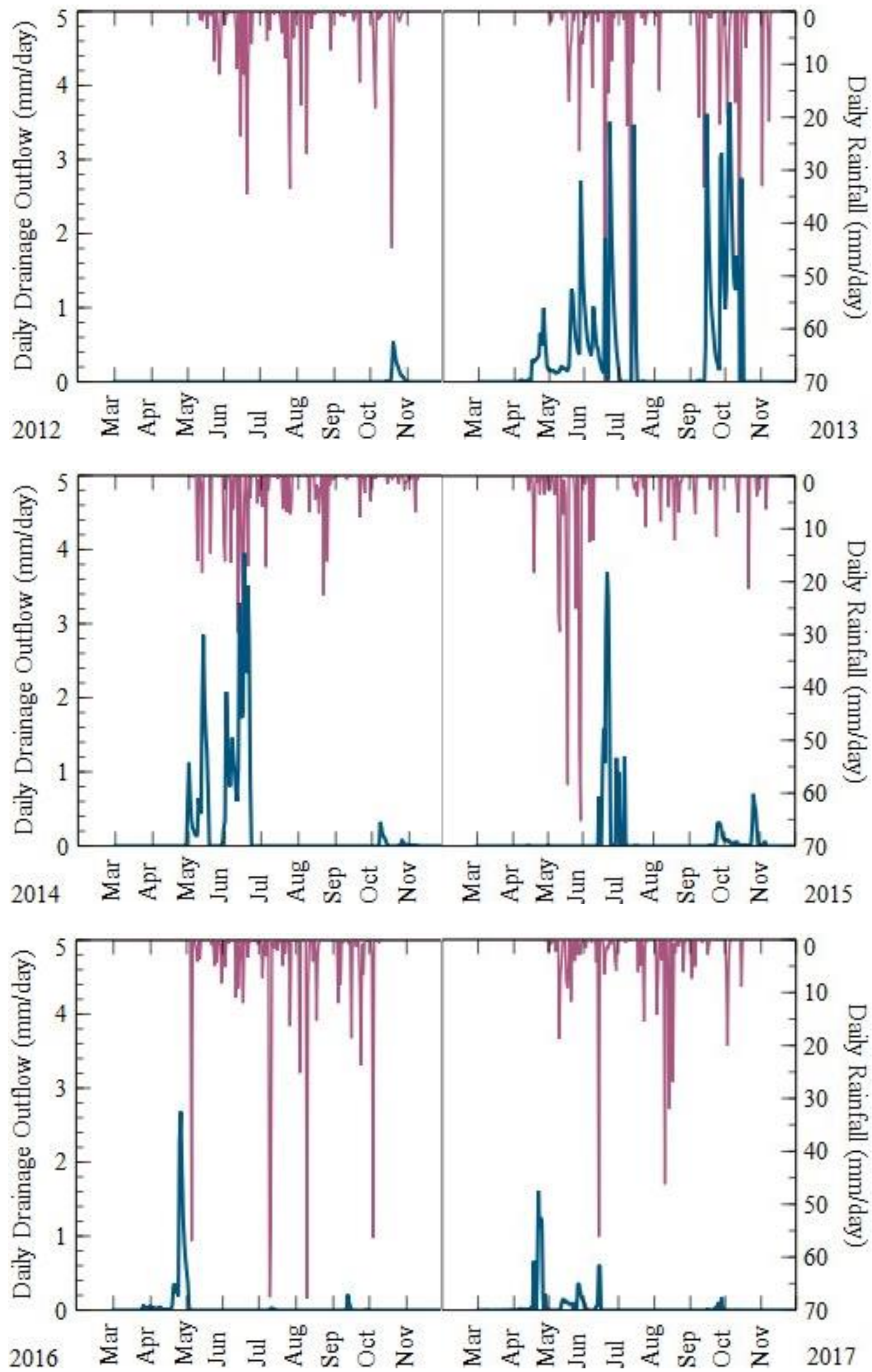

Figure 5.2. Daily rainfall and drainage outflow in 2012-2018 at the east sump of the study site in Richland County, ND.

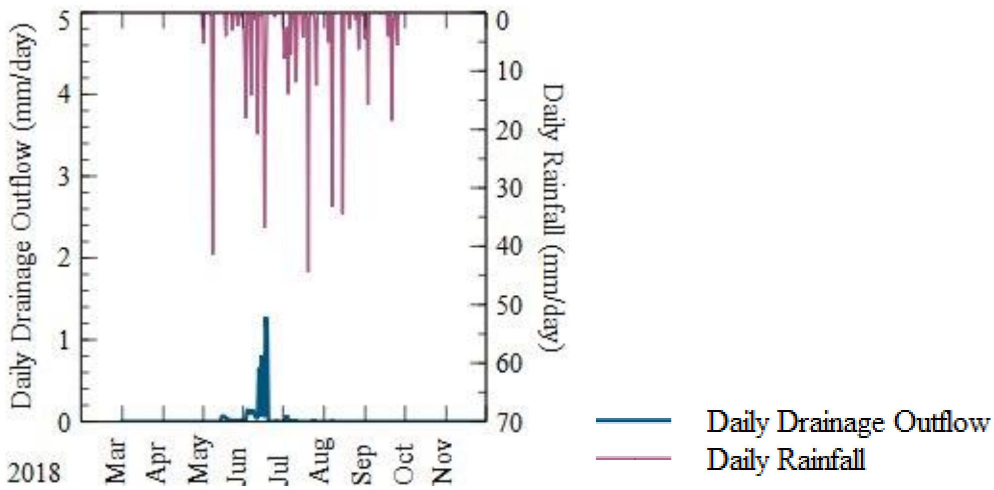

Figure 5.2. Daily rainfall and drainage outflow in 2012-2018 at the east sump of the study site in Richland County, ND (continued).

The predominate trend in Figure 5.2 consisted of two periods of drainage flow, one in the spring and the other one in the fall, which corresponded to the recommended CD practices, where drainage was turned on before planting and harvest in order to allow the soil to dry enough for equipment traffic. The relationship between the total amounts of rainfall and the drainage flow was positive. The highest drainage outflow occurred in the wettest year in 2013. The amount of snowfall in terms of SWE in the previous winter impacted the amount of drainage outflow in the spring. When little flow occurred in the spring or fall, it was likely because there was insufficient rainfall or SWE that could be infiltrated into the field and leached out to generate drainage outflow. This positive relationship was typical, and can be found in other studies (Helmers et al., 2012; Wesström et al., 2001; Carstensen et al., 2019).

5.4.2. Chemical concentrations

To see how different water management practices, including FD, CD, and SI impacted water quality, the chemical concentrations from water samples at the east sump of the site were grouped according to the management practices when the water samples were taken (Table 5.2).

Table 5.2. The mean values for percent sodium, sodium adsorption ratio (SAR), total dissolved solids (TDS), electrical conductivity (EC), and chemical concentrations for sodium, potassium, calcium, magnesium, chloride, sulfate, nitrite + nitrate nitrogen (NO_x-N), and orthophosphate (PO_4-P) in mg/L, from the water samples at the east sump from 2012-2018 during periods of free drainage (FD), controlled drainage (CD), and subirrigation (SI). Significant differences as determined by Tukey's Honestly significant difference post hoc test with an alpha value of 0.05 are shown by different letters.

Parameter	FD-Spring (ab)	CD-Spring (a)	SI (b)	CD-Fall (ab)	FD-Fall (ab)
Percent sodium (%)	21.6	22.6	63.6	47.0	25.8
SAR	2.4	2.6	5.0	3.8	2.7
TDS (mg/L)	2,190	2,310	668	1,130	1,980
EC (dS/m)	3.5	3.7	1.1	1.8	3.2
Sodium (mg/L)	251	273	164	182	244
Potassium (mg/L)	10.0	7.8	3.2	4.4	5.7
Calcium (mg/L)	363	383	43	151	331
Magnesium (mg/L)	274	259	23	84	184
Chloride (mg/L)	59	38	38	38	39
Sulfate (mg/L)	1,971	2,048	162	678	1,643
NO_x-N (mg/L)	17.7	8.5	0.2	2.9	8.2
PO_4-P (mg/L)	0.12	0.22	0.58	0.34	0.20

There were chemical concentration differences during the periods with different management practices, though the only statistically significant difference occurred between the CD-Spring and SI practices. Calcium, magnesium, sulfate, NO_x-N, and PO_4-P were found in much smaller concentrations in the SI samples compared to those in the CD and FD samples, which is mainly due to the difference in water sources. The water in the east sump during CD and FD is mainly influenced by rainfall, horizontal seepage, upward contributions from the water table, and the soil parent materials (Jia et al, 2012; Vidon and Cuadra, 2011). The water source for the SI samples, however, is confined to the irrigation water source. As stated in Jia et al. (2012), the irrigation water is from groundwater, which has a distinct water quality than the drainage water from the cultivated farm field. One distinguishing attribute of the groundwater source is a higher PO_4-P concentration that was reported in Jia et al. (2012), where water samples taken during SI had PO_4-P concentrations an order of magnitude higher than samples taken during the FD and CD. Less significant variances were found in this study compared to what Jia et al. (2012) reported, but PO_4-P concentrations were found to be the highest during the SI application at 0.58 mg/L. Two other parameters found to be higher in the SI samples compared to the samples in CD and FD were percent sodium and the SAR. This was also expected because of the composition of the SI water. A review paper by Evans et al. (1995) indicated that there were no expected differences between NO_x-N and PO_4-P concentrations between the FD and CD samples. However, the results in this study showed greater differences between the FD and CD samples, especially for the NO_x-N and sulfate values. The fall CD results were likely influenced by the residual SI water in the soil, potentially impacting the nutrient concentrations.

Compared to the water quality standard for surface waters, there are five mean concentration values in Table 5.2 that are above the North Dakota Standards of Quality for Waters of the State (North Dakota Century Code, 2019). Among these five parameters, however, only two, NO_x-N and sulfate, impacted the surface water because it occurred during the FD period. The other two parameters, percent sodium in the SI samples and sulfate in every CD and SI sample, had little or no direct effect on the surface water. The only value calculated from the SI samples in violation of the standards is the percent sodium, which is required not to be above 50%, but was found to be 63.6% in this study. This is attributed from the quality of the groundwater used for the SI application. The mean sulfate concentrations in spring FD, fall FD, and spring CD samples were all above the recommended value of 750 mg/L at 1,971 mg/L, 1,643 mg/L, and 2,048 mg/L, respectively. Sulfate is known to predominate in North Dakota soils, so high levels were expected (Keller et al., 1986). However, a sulfate concentration above 1,000 mg/L in drinking water can have a laxative effect on humans, therefore, direct consumption of the surface water is not recommended (USEPA, 2003). The exact value at which negative impacts are experienced by consumers of water high in sulfate has varied between studies, though the United States EPA recommends against consuming water with a sulfate concentration higher than 500 mg/L. The average NO_x-N value during the FD-spring exceeded the recommended value of 10 mg/L at 17.7 mg/L. Samples taken during 2012 increased the mean NO_x-N, which was likely due to a variety of reasons, such as new tile drainage installation in the fall of 2011, spring fertilization, dry weather conditions, etc. Excluding the 2012 samples, the NO_x-N mean concentration in the FD samples was below the 10 mg/L threshold.

5.4.3. Comparison between the surface and subsurface water samples

Along with comparison between management practices, water quality samples from the surface water in the two locations (east and west of the field) along the same ditch were also compared to the subsurface water samples from the east sump. It is assumed that drainage water exiting the field would only influence the ditch samples during the FD period. However, surface runoff and horizontal seepage after substantial rainfall events and during snowmelt might have occurred during the SI and CD periods and may have contributed to the chemistry of the ditch water samples. However, it is unlikely any contribution from the field through these processes would have caused significant changes to the water in the ditch because the volume of water added would have been insignificant. The chemical concentrations at the upstream of the field in the west sampling location, and the downstream of the field in the east sampling location along the same ditch are summarized in Table 5.3 and 5.4, respectively.

Table 5.3. Upstream ditch water mean values for percent sodium in percentage, sodium adsorption ratio (SAR), total dissolved solids (TDS), electrical conductivity (EC), and chemical concentrations for sodium, potassium, calcium, magnesium, chloride, sulfate, nitrite + nitrate nitrogen NO_x-N, and orthophosphate (PO_4-P) in mg/L taken near of the field (west part of the ditch) in 2012-2018 during periods of free drainage (FD), controlled drainage (CD), and subirrigation (SI). Significant differences as determined by Tukey's Honestly significant difference post hoc test with an alpha value of 0.05 are shown by different letters.

Parameter	FD-Spring (ab)	CD-Spring (a)	SI (a)	CD-Fall (ab)	FD-Fall (a)
Percent sodium (%)	20.6	23.9	23.0	20.4	22.2
SAR	2.0	2.6	2.5	2.0	2.4
TDS (mg/L)	1,596	1,950	1,964	1,612	1,990
EC (dS/m)	2.6	3.1	3.2	2.6	3.2
Sodium (mg/L)	180	260	248	181	247
Potassium (mg/L)	8.5	10	10	10	10
Calcium (mg/L)	176	193	189	172	185
Magnesium (mg/L)	227	282	281	226	307
Chloride (mg/L)	32.6	28.6	31.8	22.6	27.2
Sulfate (mg/L)	1,362	1,793	1,856	1,413	1,878
NO_x-N (mg/L)	3.80	2.44	2.03	2.54	1.36
PO_4-P (mg/L)	0.088	0.055	0.13	0.12	0.079

Table 5.4. Downstream ditch water mean values for percent sodium in percentage, sodium adsorption ratio (SAR), total dissolved solids (TDS), electrical conductivity (EC), and chemical concentrations for sodium, potassium, calcium, magnesium, chloride, sulfate, nitrite + nitrate nitrogen NO_x-N, and orthophosphate (PO_4-P) in mg/L taken from the nearby of the field (east part of the ditch) in 2012-2018 during periods of free drainage (FD), controlled drainage (CD), and subirrigation (SI). Significant differences as determined by Tukey's Honestly significant difference post hoc test with an alpha value of 0.05 are shown by different letters.

Parameter	FD-Spring (ab)	CD-Spring (a)	SI (a)	CD-Fall (ab)	FD-Fall (a)
Percent sodium (%)	20.4	22.4	21.5	20.3	24.3
SAR	2.1	2.4	2.4	2.0	2.7
TDS (mg/L)	1,730	1,953	2,087	1,754	2,066
EC (dS/m)	2.8	3.1	3.4	2.8	3.3
Sodium (mg/L)	195	244	249	193	263
Potassium (mg/L)	8.5	11	11	9.9	8.4
Calcium (mg/L)	197	210	229	204	239
Magnesium (mg/L)	253	282	306	244	276
Chloride (mg/L)	31.3	31.1	34.6	26.8	32.9
Sulfate (mg/L)	1,531	1,830	2,014	1,561	1,881
NOx-N (mg/L)	5.11	0.507	0.908	1.87	2.85
PO4-P (mg/L)	0.082	0.035	0.095	0.12	0.12

Flow in this ditch occurs from the west to the east. For the purposes of this study, differences in nutrient concentrations during the FD period will be considered attributed to this field. For most of the parameters measured, chemical concentrations were found to be higher in the downstream samples compared to the upper stream samples during FD-spring and FD-fall. NO_x-N had the largest increase in concentration from the upper stream to downstream at 26% in FD-spring and 52% in FD-fall. These increases in chemical concentrations are indicative of the impact drained water from the field had on nearby surface water, but these increases did not lead to chemical concentrations that exceeded recommended values.

The water samples from the ditch displayed less variation among the five management practice periods compared to the samples from the subsurface outlet in the east sump. In contrast to samples from the east sump, significant differences were not present between samples from the west end of the ditch (upper stream) and samples from the east side of the ditch (downstream). Major differences were seen for the salts related parameters, including SAR, percent sodium, and EC values between the SI ditch samples and the east sump SI samples. Samples from the east sump during the SI period were found to be statistically different from the samples from the ditch during the same period. This is once again attributed to the different water source for the SI application. Another difference in chemical concentrations between the sampling locations was the seasonality of calcium and magnesium concentration. Samples from the east sump show higher calcium and magnesium concentrations during the spring, while the ditch water samples show fairly consistent concentrations of calcium and magnesium throughout the year. The seasonality of calcium and magnesium concentrations in the east sump may be attributed to the transition to and from the SI water source. The only statistically significant difference between the samples from the east sump and those from both ends of the ditches were samples in the sump during the SI period, and samples in the ditch at both ends during the CD-spring, SI, and FD-fall periods. Since water in the east sump during SI does not contribute to drainage outflow, these differences are not of environmental concern to nearby bodies of water. Because of the overall similarity between the two sampling locations, the results indicated a similar chemical composition of the water in the study field compared to the water drained by nearby fields.

The only nutrient concentrations from the ditch (surface) water samples that were above the recommended values in North Dakota are the mean sulfate concentrations, which are all significantly greater than the recommended 750 mg/L. This is once again expected in this region because of the soil minerology. Sulfate is expected to be found in the soil and water of this field because it is often the anion found in salts in this region, usually in the form of sodium or magnesium sulfate (Keller et al., 1986). To avoid the contribution of sulfate to the surface water in areas impacted by excess sulfate, CD is an effective strategy and may be required to limit negative impacts to surface water.

5.4.4. Chemical loads

The chemical load is a valuable assessment on the impact of the tile drainage water to the surface water system. Three parameters, NO_x-N, PO_4-P, and TDS were selected for the chemical load analysis. NO_x-N and PO_4-P are two of the most criticized nutrients because of their contributions to eutrophication in bodies of water, such as the Gulf of Mexico and their agricultural origin (Turner and Rabalais, 2003). The inclusion of TDS data allowed for the analysis of the amount of dissolved substances present in the water samples. Since the TDS value does not indicate specific components of the water sample, it is more typically assumed as an indicator of the water quality (Jia and Scherer, 2013). Bodies of water with elevated TDS values may have aesthetic issues, such as an abnormal color or taste (Sibanda et al., 2014). The chemical load comparison for the three parameters in 2012 to 2018 is shown in Figure 5.3.

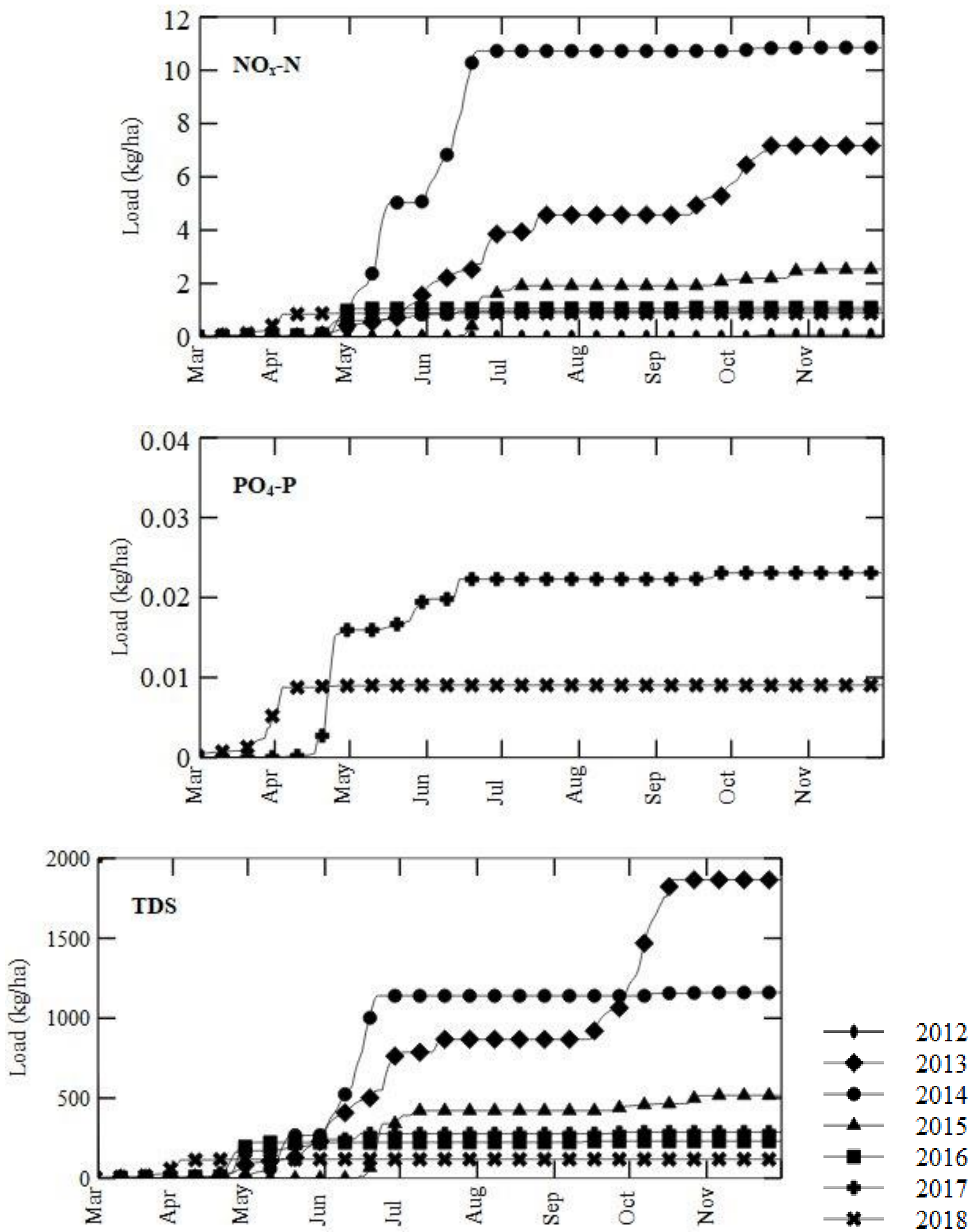

Figure 5.3. Cumulative nitrite + nitrate nitrogen (NO_x-N), orthophosphate (PO_4-P), and total dissolved solids (TDS) loads from the east sump. Orthophosphate concentration data was not collected prior to September of 2016, so only data from 2017 and 2018 are shown.

The largest amounts of load were lost in the spring for all three parameters. The high amounts of NO_x-N load in the spring compared to that in the fall likely corresponds with NO_x-N fertilizer application. Since nitrate is more soluble in water than PO_4-P, a higher proportion of nitrate loss is expected in the spring, when more water is lost through drainage outflow compared to that in the fall. The highest total NO_x-N load was lost in 2014, when the second highest drainage outflow occurred, with a value of 10.9 kg/ha/yr. This correlation provides further evidence that a greater drainage outflow has a greater impact on the loss of nutrient load than the nutrient concentration, similar to what has been previously reported (Bjorneberg et al., 1996). Saadat et al. (2018) reported an average NO_x-N load of 19 kg/ha/yr, which is much greater than the highest load in this study, 10.9 kg/ha/yr in 2014. This difference is likely due to the location difference between Indiana and North Dakota, where there was more precipitation in Indiana. Drainage outflow in their study was also higher in every study period in all years compared to the results of this study, further influencing nutrient load. The lowest NO_x-N load occurred in 2012 and was equal to 0.08 kg/ha/yr. Concentrations of NO_x-N were high in samples during this year, but the extremely low amount of outflow in 2012 did not allow for substantial nutrient loss. Data from nearby Manitoba had a total nitrate load of 10 kg/ha/yr when drainage outflow averaged over three replications was equal to 53 mm (Cordeiro et al., 2014). A similar drainage outflow of 56 mm occurred in 2013, but NO_x-N load was approximately 7 kg/ha/yr, much lower than that found in the Manitoba study.

In 2017, the highest PO_4-P load of 0.023 kg/ha/yr occurred. The lowest PO_4-P load of 0.009 kg/ha/yr occurred in 2018. Data from 2012-2016 was unavailable because PO_4-P concentrations were not measured. An average dissolved reactive phosphorous load of 0.10 kg/ha/yr was reported by Williams et al. (2014), although more drainage outflow occurred in their study. Higher PO_4-P loads may have occurred from 2012-2016 because of more drainage outflow, although exact values are unknown. Since smectite is the dominant clay mineral in the soil in the research field, soil cracking was common, which created multiple macropores during dry periods. Previous research has indicated PO_4-P loss from tile drained fields most commonly occurs through macropores, so relatively high PO_4-P loads were expected in this area, but may be reduced by the small amounts of drainage outflow via CD practice (Vidon and Cuadra, 2011).

The TDS loads appeared to occur more often in the spring compared to that in the fall, similar to the NO_x-N and PO_4-P loads. In 2013, the TDS is different from other years, because TDS increased in October during the fall FD period. The highest load once again occurred in 2013, which was also the wettest year during the study periods. The lowest cumulative TDS load occurred in 2012, the driest year with the least drainage outflow. The coefficient of determination value between cumulative load and cumulative drainage outflow is above 0.95 for PO_4-P and TDS, but only 0.62 for NO_x-N.

5.4.5. Soil quality

Since the water quality for the SI application is marginal, with an EC ranging from 1 to 2 dS/m and an SAR ranging from 4 to 6 (Jia et al., 2012), the impact of the SI water on soil quality has been a concern from the beginning of the project, especially in terms of an increase in soil sodicity. When present in high amounts, soil sodicity can lead to further consequences such as decreased soil permeability (Sumner, 1993) and reduced yield (Rengasamy, 2010). To observe the impact, soil sampling around a tile drainage pipe was planned for every year immediately after harvest. However, this has not been done every year due to weather and funding limitations. The average values and standard deviations for the three replicates at the three locations in the field (Figure 5.1) are described in Table 5.5 according to its distance above the tile.

Table 5.5. Mean pH, electroconductivity (EC) and sodium adsorption ratio (SAR) in relation to the tile position in 2014, 2015, and 2017.

	Distance above tile (cm)	pH			EC (dS/m)			SAR		
		2014	2015	2017	2014	2015	2017	2014	2015	2017
Mean	0	8.23	8.13	8.07	0.97	0.81	0.97	1.04	3.67	3.54
	20	8.36	8.19	8.08	1.04	0.77	0.88	1.10	3.96	3.58
	41	8.28	8.12	7.99	1.15	0.83	0.88	1.54	3.26	4.04
	81	8.16	7.82	7.87	1.40	1.10	1.08	1.59	1.62	1.95
Standard deviation	0	0.06	0.06	0.12	0.12	0.10	0.12	1.04	2.48	0.87
	20	0.22	0.18	0.14	0.63	0.13	0.22	0.98	1.98	1.10
	41	0.22	0.23	0.20	0.71	0.19	0.22	0.32	1.83	2.52
	81	0.23	0.21	0.27	0.71	0.39	0.57	2.42	0.82	0.94

The highest EC of 1.40 occurred in 2014 and the highest SAR of 4.04 occurred in 2017. The highest pH value of 8.36 occurred in 2014 while the lowest pH value of 7.82 occurred in 2015. Compared to previously reported soil pH data collected in North Dakota, the range of values between 7.5 and 8 is typical for Richland County (Franzen et al., 2006). Because of the buffering capabilities of calcium carbonate and organic matter, which were very prevalent in the soil, drastic changes in pH were not expected during the study period (Magdoff and Bartlett, 1985). The lowest EC value of 0.77 dS/m was recorded in 2015 and the lowest SAR value of 1.04 was recorded in 2014. Assuming the initial soil conditions are the same at any distance from the tile, changes to pH, EC, and SAR over time are likely attributed to drainage and SI practices in the field.

The four samples taken each year showed no significant patterns of salt reduction. Additional years of extensive drainage may have been needed to produce noticeable salt reduction in the field associated with SSD. As time goes on, the range of EC values in relation to tile position is expected to become lesser due to the leaching of salts from the soil profile through drainage, eventually leading to a homogenous distribution of salts less prevalent than conditions prior to drainage. For this to occur, there needs to be enough precipitation to allow for downward movement of salts.

SAR values in 2015 are the lowest out of the three years of data. 2015 was also the only year to show SAR increase as distance above the tile increases. Results from 2014 and 2017 show significantly higher SAR values near the tile compared to 81 cm from the tile. Despite having a percentage of total precipitation in the form of SI comparable to that of 2015, the cumulative effects of SI with water of marginal quality may not have been evident in 2014, causing much lower SAR values than those in 2015. Considerably less of the total precipitation in 2017 occurred as SI, but the high SAR values may have been a cumulative SI impact from the earlier years. Despite the range of SAR values found in this study, the soil was still well below recommended SAR values. To be classified as a sodic soil, the SAR should be above 13, while the values found in this study fall well below (Richards, 1954). If SI was the main source of water for the field, the SAR may have been negatively impacted, but this scenario has not yet occurred and is unlikely to due to high magnesium and calcium concentrations in the soil.

5.5. Conclusion

Because of the different water source used for the SI application, differences in chemical concentrations were expected between the water samples from the field throughout the growing season. A major factor impacting these differences was the SAR of the SI water, which was higher than that of the CD and FD water source. Along with water samples, soil samples were also taken during the study period. Soil samples above the drain tiles were used to access the impact of drainage and SI on soil quality. Increases in SAR near the drain tiles were possible due to the SAR of the SI water. EC was expected to decrease in relation to tile position through leaching.

Results showed differences related to salinity between the water samples taken during SI compared the water samples taken during other times during the growing season. This is likely attributed to the differences in water sources. Other differences in chemical concentrations, specifically NO_x-N concentration, may be due to other factors such as fertilizer timing and the amount of drainage outflow. Because of the lack of drainage outflow in North Dakota compared to other regions in the United States, nutrient load values found in this study were much lower than those reported in studies elsewhere. Soil sample results showed significant spatial differences in SAR in 2015 and 2017, although these values were well below those found in sodic soils. Because of the marginal quality of the SI water, SAR is expected to be lower in the soil when less of the total precipitation in the field is from SI.

6. WATER TABLE, NUTRIENT CONCENTRATION, AND CROP YIELD RESPONSE TO DIFFERING DRAINAGE PRACTICES IN THE RED RIVER VALLEY

6.1. Abstract

Subsurface drainage (SSD) is a desirable management practice in the Red River Valley (RRV) because of excess moisture within the soil, but further alteration of these systems may provide more benefits to landowners. Only draining prior to planting and harvesting via controlled drainage (CD) is an option to reduce nutrient loss from fields with SSD. Irrigation can be applied through the drain tile via subirrigation (SI). To compare different SSD systems in the RRRV, water table, drainage outflow, and crop yield data were analyzed from an undrained, free drained, and control drained and subirrigated fields. Results showed drastic differences between the movement of water within and out of the fields. The concentrations of phosphate and nitrate also differed between surface and subsurface sources, as evidence by a phosphate concentration of 1.39 mg/L from a surface runoff sample compared to a concentration of 0.04 mg/L from a subsurface drainage sample, both taken at the same time. Despite these differences, a clear relationship between drainage practice and crop yield was not found.

6.2. Introduction

The Red River Valley (RRV) has experienced excess precipitation in the last twenty years, which caused waterlogged conditions in some farmed fields and prevented or delayed planting and harvesting. SSD is often installed with the purpose of lowering a shallow water table, removing excess soil water, and leaching salts from the soil profile. The practice is extremely popular in the eastern Corn Belt of the United States and quickly gaining popularity in the RRV.

Among the benefits of SSD are an improvement in crop growing conditions and easier maneuverability of equipment through fields (Mante et al., 2018). Loss of nutrients such as nitrate (NO_3^- N) in SSD effluent has been widely recognized. Therefore, controlled drainage (CD), "Regulation of the soil water table by means of pumps, control dams, or check drains, or a combination of these, for maintaining the water table at a depth favorable to crop growth and/or for minimizing the effects of drainage during the fallow season to prevent nutrient loss" (ASABE, 2015), is a known method of reducing the volume of drainage outflow, which in turn leads to less nutrient loss (Gilliam and Skaggs, 1986). In areas where irrigation along with drainage is desired, subirrigation (SI) can be used to pump water back through the subsurface drain tile. The same water that is drained from a field can be used for SI, which is known as drainage water recycling.

The impacts of SSD can be made apparent by comparison between drained and undrained fields. SSD has been shown to impact the response to rainfall events in terms of change in water table depth in comparison to undrained fields. A study conducted by Wiersma et al (2010) found subsurface drained fields to have consistently lower water tables and faster returns to typical water table levels after rainfall events compared to an undrained field in northwestern Minnesota. Despite the influence of soil moisture on the movement of water within soil, Schott et al (2017) reported that the shallowest water table depth in their UD treatment, but no difference in volumetric water content between UD and CD soils. Along with the movement of water within a field, SSD also impacts the pathway drained water takes.

Sloan et al (2016) reported a higher amount of subsurface flow compared to surface runoff as the most significant impact on hydrology of subsurface drainage. The change in flow pathway also impacts nutrient loads, specifically in terms of phosphorus and nitrogen through differences in their chemical concentrations. Gilliam and Skaggs (1986) found a NO_3^- N load 10 times greater in SSD compared to surface runoff on poorly draining, North Carolina soils. The concentration of NO_3^- N is thought to be higher in SSD water compared to surface runoff, but phosphorus has shown an opposite trend, which has been attributed to the sorption of phosphorus to soil prior to SSD outflow (Osterholz et al., 2020). Less significant differences between surface and SSD water PO_4-P concentrations have also been reported. Similar concentrations of PO_4-P were found in surface runoff and SSD water samples in a study conducted on a clay soil in Finland (Uusitalo et al., 2001). The amount of SSD can still lead to large PO_4-P loads in certain areas, however. As evidence of this, Smith et al (2015) reported significant PO_4-P losses through SSD rather than surface runoff.

Water table depth is also known to impact crop yield, though the impact of a lowered or controlled water table may depend on seasonal precipitation. Corn (*Zea mays*) grown in Wisconsin was found to benefit from a shallow water table in dry years, but this increase in yield was greater for coarse-grained soil more so than fine-textured soils (Zipper et al., 2015). Matsuo et al (2017) found soybean (*Glycine max*) yields 5% lower when the water table was at 30 cm compared to naturally occurring water table depths (50-60 cm). Differences between CD and FD crop yields have also been reported. A study conducted in eastern Ontario showed soybean and corn yields to be significantly greater when grown with CD rather than FD (Mejia et al., 2000).

A comparison between subsurface drained and undrained fields in the Red River Valley is not present in current literature, though the importance of such work is very clear given the rising popularity of SSD installation in the area. The proximity of a control drained (SI/CD) field, free drained (FD) field, and undrained (UD) field in Clay County, Minnesota allowed for such research to be conducted. This data, which includes changes in water table depth during a rainfall event, water sample nutrient concentrations, and crop yield comparisons, was assessed in this study.

6.3. Materials and Methods

6.3.1. Experimental site

The field with controlled drainage and subirrigation is described previously in Kolars et al. (2019) and Niaghi et al. (2019). The geographic location of the controlled drainage and subirrigation (CD/SI) field site is 46°59'18.5"N 96°41'02.9"W. The soil series are Colvin silty clay loam (Colvin series, Fine-silty, mixed, superactive, frigid Typic Calciaquolls), Overly silty clay loam (Overly series, Fine-silty, mixed, superactive, frigid Pachic Hapludolls), and Bearden silt loam (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls) (USDA, 2020). The tile spacing in the CD/SI portion of the field was 12.2 m with an average drain depth of 1 m below the soil surface. This portion of the field, approximately 17 ha in area, drains into a control structure (AgriDrain, Adair, Iowa). Flashboards within this control structure were periodically removed to allow for free drainage and stacked to control drainage and increase water levels in the field. Crops grown in the field were usually corn (*Zea mays*) or soybean (*Glycine max),* but sugarbeets (*Beta vulgaris*) were planted in 2015.

The undrained (UD) field, which is approximately 16 ha in area, is located just north of the CD/SI field. Soil series present are Colvin silty clay loam (Colvin series, Fine-silty, mixed, superactive, frigid Typic Calciaquolls), Bearden silt loam (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls), and Fargo silty clay (Fine, smectitic, frigid Typic Epiaquerts) (USDA, 2020). Either corn or soybeans was planted each year.

The free drained (FD) field is located northeast of the CD/SI field and east of the UD field. It is approximately 24 ha in area. Soil series present are Colvin silty clay loam (Colvin series, Fine-silty, mixed, superactive, frigid Typic Calciaquolls) and Bearden silt loam (Fine-silty, mixed, superactive, frigid Aeric Calciaquolls) (USDA, 2020). The tile spacing for this field is 18.3 m, with an average drain depth at 1.1 m.

Figure 6.1. Experimental layout where the curved lines represent soil map units, with I376A representative of Colvin silty clay loam, I383A representative of Overly silty clay loam, I467A representative of Bearden silt loam, and I641A representative of Fargo silty clay.

The least amount of rainfall during the study period occurred in 2017, with 337.8 mm. The most rainfall occurred in 2019 with 612.1 mm. Data from the National Weather Service reporting station in Georgetown, Minnesota, which is approximately 11 km from the CD/SI field, showed a mean maximum temperature of 28.3°C in July and a mean minimum temperature of -19.5°C in January (MN DNR, 2020).

6.3.2. Water sample analysis

Water samples were collected weekly from the SI/CD control structure and both ends of the drainage ditch north of the SI/CD field and FD outlet and surface ditch of the UD fields.

When drainage outflow was occurring from the FD field, a sample was taken from the outlet. Surface runoff samples were taken from the FD and UD field when water was present. Temperature and electrical conductivity (EC) were measured manually in the field by a transducer (Model 107 TLC Meter, Solinst Canada Ltd., Georgetown, Ontario). The water samples were kept in a cooler with ice coolant in the field until transported to the laboratory for chemical analysis.

Water samples were sent to the NDSU Soil Testing Laboratory for analysis. At the NDSU laboratory, EPA method 365.1 Revision 2.0 was used for dissolved phosphorus (P) analysis. Nitrate-nitrogen was measured through the trans-nitration of salicylic acid method. (S. Mathews, personal communication, 28 January 2020).

6.3.3. Instrumentation

A more detailed discussion of the instrumentation located in the CD/SI field is described previously in Kolars et al. (2019) and Niaghi et al. (2019). The instrumentation used to collect data in this project will be discussed briefly.

6.3.4. Precipitation

Rainfall data was collected from a wireless weather station (Onset® Computer Corporation, HOBO®, Bourne, Massachusetts) located in the SI/CD field. A manual rain gauge placed by the control structures in the SI/CD field was used for data verification and comparison.

A National Oceanic and Atmospheric Administration (NOAA) weather station at Hector International Airport located approximately 7 km from the SI/CD field was used to represent winter precipitation in the form of snow water equivalent.

6.3.5. Water table depth

As described in Kolars et al. (2019) and Niaghi et al. (2019), six piezometers were installed in each of the FD, UD, and SI/CD fields in the fall of 2011. The six observation wells were placed in sets of two at the upper, middle, and bottom part of the fields, where one well was located 1 m to the drain tile and the other in the middle between two tile lines. A barometric pressure compensated transducer (Model U 20-001-01, Onset Computer, Pocasset, Massachusetts) located within each well measured water table depth every hour (Kolars et al., 2019). Barometric pressure data from the Fargo NDAWN station was used for depth calculations. The locations of these wells are shown in Figure 6.1.

6.3.6. Drainage outflow

To determine daily drainage outflow from the SI/CD field, the following equations (6.1-6.3) were incorporated from Kolars et al. (2019).

When flow occurred though the 45° v-notch weir,

$$Q = 0.0242H^{2.0464} \tag{6.1}$$

When flow occurred above the 45° v-notch weir and $H_2 > 0.27W$,

$$Q = 0.0242{H_1}^{2.0464} + 0.021W{H_2}^{1.37} \tag{6.2}$$

When flow occurred above the 45° v-notch weir and $H_2 < 0.27W$,

$$Q = 0.0242{H_1}^{2.0464} + 0.02(W - 0.74H_2){H_2}^{1.48} \tag{6.3}$$

where

Q = drainage flow rate in L/s

H_1 = height of the bottom of the v-notch weir in cm

H_2 = height of water within the control structure in cm

W = width of the weir, 31.27 cm.

Daily drainage outflow from the FD field was monitored with a battery-powered sensor and data logger placed within the outlet pipe (Greyline Stingray 2.0 Portable Level-Velocity Logger, Pulsar Measurement, Largo, Florida). This sensor provided water level, velocity, and temperature data. Drainage outflow was calculated by multiplying the area of flow within the pipe by the measured velocity of water exiting the pipe (Equation 6.4).

$$Q = \frac{1000VR^2(\Theta - \sin(\Theta))}{2} \tag{6.4}$$

where

Q = drainage outflow in L/s

V = velocity in m/s

R = radius of the outlet, 0.2 m

θ = angle from center of pipe to water edge in rad

6.3.7. Crop yield

Yearly crop yields were reported by the landowner responsible for each field. County average corn, soybean, and sugarbeet yield data for Clay County, MN was retrieved from the National Agricultural Statistics Service (NASS) website. Planting and harvest dates were also reported by the landowner and are given in Table 6.1 below.

Table 6.1. Planting and harvest dates for the UD, FD, and SI/CD fields from 2013-2019 reported by the landowners.

Year	SI/CD	FD	UD
2013	May 7/Nov 7 (corn)	May 11/Oct 2 (soybean)	May 13/Oct 2 (soybean)
2014	May 24/Oct 7 (soybean)	May 22/Sep 26 (soybean)	May 24/Oct 23 (corn)
2015	Apr 13/Oct 15 (sugarbeet)	Apr 29/Oct 16 (corn)	May 2/Sep 22 (soybean)
2016	Apr 27/Oct 30 (corn)	May 7/Sep 27 (soybean)	May 9/Sep 21 (soybean)
2017	May 3/Oct 20 (corn)	May 7/Oct 29 (corn)	May 5/Oct 27 (corn)
2018	May 14/Nov 21 (corn)	May 15/Oct 19 (soybean)	May 7/Sep 14 (soybean)
2019	May 16/Oct 24 (soybean)	May 12/Nov 14 (corn)	May 12/Nov 1 (corn)

6.4. Results and Discussion

6.4.1. Precipitation

In general, a positive relationship between total precipitation and drainage outflow is expected for a typical drained field. Because the SI/CD control structure was managed to allow free drainage in the spring prior to planting, snow water equivalent (SWE) was expected to impact the drainage outflow in the SI/CD field more than the drainage outflow in the FD field. The drainage outflow patterns in FD were not expected to closely resemble those from SI/CD since the drainage flow in the FD field was not restricted or managed during the growing season. The flow in the SI/CD field was managed due to the presence of flashboards within the control structure. This is evidenced in Table 6.2, with drainage outflow from both the SI/CD and FD fields, along with SI, SWE, rainfall, and total precipitation during the study period.

Table 6.2. Snow water equivalent, rainfall, subirrigation, drainage outflow from the subirrigated and controlled drainage site, drainage outflow from the free drainage site, and the sum of snow water equivalent and rainfall (total precipitation) along with their average values in millimeters from 2013-2019.

Year	Total precipitation (mm)	Snow water equivalent (mm)	Rainfall (mm)	Subirrigation (mm)	SI/CD drainage outflow (mm)	FD drainage outflow (mm)
2013	699.5	161.0	538.5	0	4.1	39.4
2014	510.8	76.5	434.3	58.4	46.3	80.1
2015	435.4	49.3	386.1	0	5.5	39.0
2016	492.0	57.7	434.3	4.8	<0.1	6.2
2017	426.2	88.4	337.8	20.4	0	2.8
2018	576.6	111.8	464.8	4.6	0	0
2019	792.7	180.6	612.1	0	53.8	101.3
Average	539.0	103.6	458.3	12.6	18.3	38.4

Out of the seven-year study period, 2019 was the wettest year with 792.7 mm of total precipitation. The driest year was in 2017, when only 426.2 mm of total precipitation was recorded. As a result of this, the most drainage outflow occurred in both the CD/SI field (53.8 mm) and the FD field (101.3 mm) in 2019. Other than in 2018, when no drainage outflow was recorded for either field, the volume of drainage outflow in the FD field was always greater than that in the CD/SI field.

6.4.2. Water table depth

Without SSD in the UD field, it was expected that the water table would be the shallowest out of the three fields. The water table depths in the FD field were expected to be the deepest. Because of the functions of the control structure, the water table in the CD/SI field would display intermediate depth values compared to those in the UD and FD field. All three fields had similar soil series (Figure 6.1), but soil moisture was expected to vary because of a multitude of factors including the differing drainage practices. Factors impacting infiltration rates, along with soil moisture, include tillage practices and crops grown. This may be another source of variation between infiltration rates in each field. The responses to a rainfall event in terms of change in water table depth and drainage outflow are compared between the three fields in Figure 6.2.

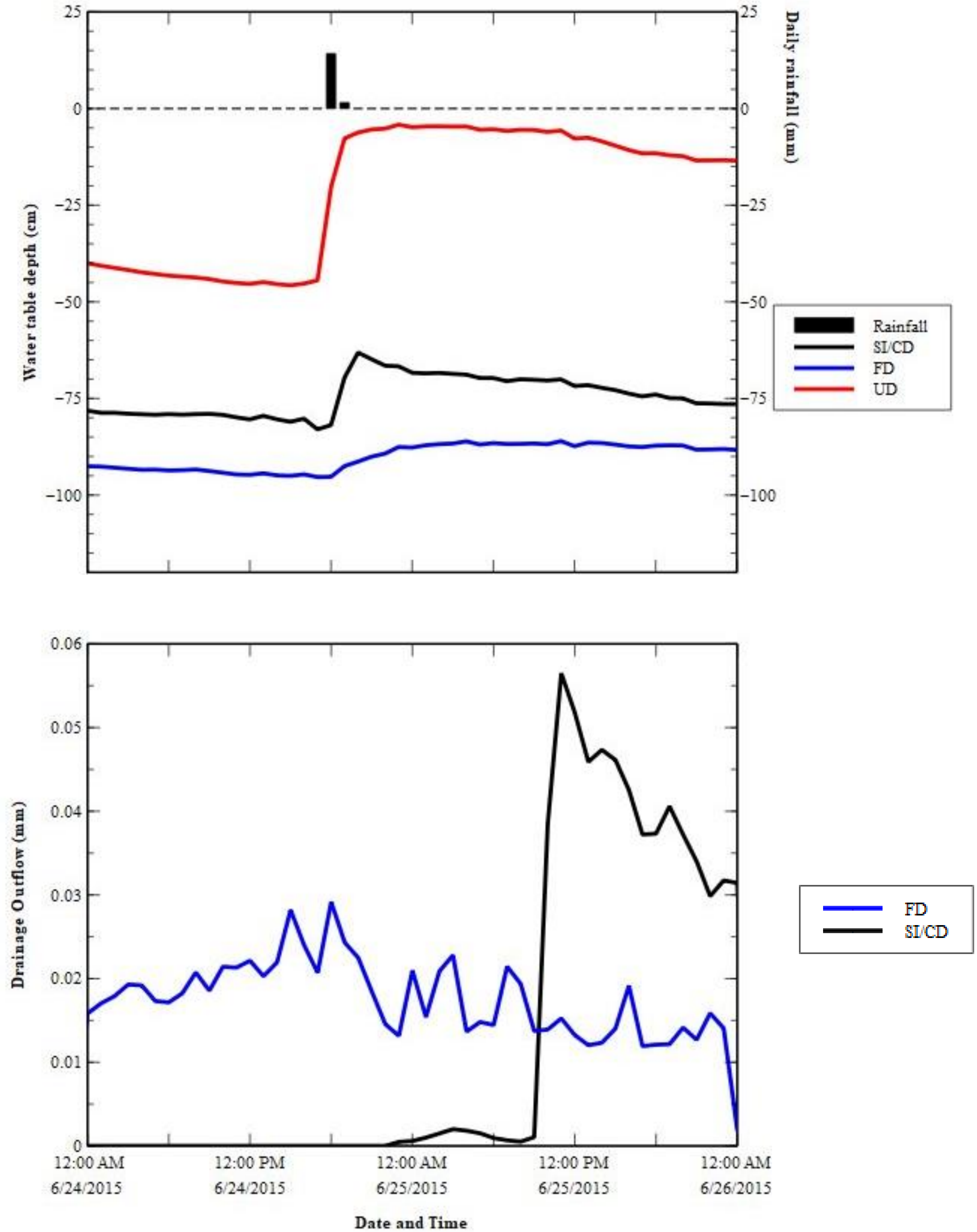

Figure 6.2. Water table depth changes in the observation wells within the three fields, rainfall, and drainage outflow from the SI/CD and FD fields from June 24th 2015 to June 26th 2015.

The top 30 cm of soil is known as the infiltration zone. The soil moisture conditions within the infiltration zone directly affect the infiltration rate. All of the fields were tilled after harvest of the previous year, but the crops grown were not the same in each field in 2015. Sugarbeets were grown in the SI/CD field, corn was grown in the FD field, and soybeans were grown in the UD field. Preferential flow along the roots likely varied between the three fields because of the different crops grown, which subsequently impacted infiltration rates.

The changes in water table depth over time among the observation wells in each field were significantly different from each other. The largest increase in water table depth of approximately 40 cm occurred in the UD field. The second largest increase of approximately 15 cm occurred in the SI/CD field. The smallest and most gradual increase in depth of approximately 10 cm occurred in the FD field. As expected, the UD depths were the shallowest, followed by the CD/SI field, then the FD field. The water table nearly reached the soil surface in the UD field, which likely lead to issues for crop growth and made equipment traffic in the field difficult for tasks such as spraying. The optimal water table depth for soybeans, which were planted in the UD field in 2015, has been found to be somewhere between 70 to 90 cm below the soil surface for crop growth and yield (Fidantemiz et al., 2019). The UD field was above this depth throughout the observation period, potentially leading to crop yield reduction if these depths occurred throughout the growing season.

The patterns in drainage outflow varied greatly between the FD and SI/CD fields. An overall decrease in outflow occurred in the FD field, with no visible response to the rainfall event. In contrast to this, the SI/CD field showed a sharp increase in outflow around 9:00 PM June 25th. The difference in antecedent water table depth between the FD and SI/CD fields may partially explain the differences in drainage outflow, though the impact of this is not completely clear. Previous research has indicated that antecedent water table depth does not significantly impact drainage outflow, but rather the amount of rainfall is the most important factor in determining drainage outflow volume from CD and FD fields (Lahdou et al., 2019). Initial soil moisture conditions may also explain some of the discrepancies in both change in water table depth and drainage outflow. It has been previously reported that soils with SSD have a higher infiltration rate than undrained soils due to their higher unsaturated hydraulic conductivity, porosity, and water holding capacity, among other factors (Roy et al., 2015).

6.4.3. Water nutrient concentrations

Along with changes in water table depth, nutrient concentrations in the drainage outflows were measured and analyzed. To compare drainage water quality among the three fields, samples from the CD/SI control structure, FD drainage outlet, and surface runoff from the UD field, along with samples from the ditch of the downstream and upstream of the field were compared on the same date (Table 6.3). The water quality changes in the drainage ditch between the upstream and downstream of the field might be caused by the drainage outflow from the CD/SI field and the surface runoff from the UD field. Drainage outflow from the FD field flows into the ditch prior to the upstream sampling location. This section of the drainage ditch is the last part before joining the Buffalo River. An elevation drop of 2.63 m occurred from the upstream to downstream ditch sites, contributing to a higher gradient in the channel. Because of this, the bank of the ditch has been structurally unstable, so contributions of eroded soil likely occurred throughout the study period. Though the exact number is unknown, multiple fields contribute surface runoff and/or SSD water into this ditch upstream of the upstream sampling site, impacting the water quality.

Table 6.3. Nitrate (NO_3^- N), phosphorus (P), and electrical conductivity (EC) from the water samples taken from the CD/SI control structure, UD surface runoff ditch, FD drainage outlet, downstream ditch, and upstream ditch on June 24th 2015. Values within the CD/SI control structure column are in bold because drainage outflow was not occurring during the time of sampling.

Parameter	CD/SI control structure	UD surface runoff ditch	FD drainage outlet	Downstream ditch	Upstream ditch
NO_3^- N (mg/L)	**16.5**	0.2	11.9	3.7	2.8
P (mg/L)	**0.04**	1.39	0.05	0.15	0.04
EC (dS/m)	**1.4**	0.8	3.6	1.7	1.3

Because of the binding of P to soil particles, it is expected that higher P concentrations in the surface runoff samples compared to those from the control structure and the FD outlet (Turtola and Paajanen, 1995). Conversely, a higher NO_3^- N in the samples from the control structure and the FD outlet were expected compared to those in the surface runoff samples because the ability of NO_3^-N to be present in the dissolved state.

The highest concentration of NO_3^- N of 16.5 mg/L was found in the CD/SI control structure. Even though this value exceeded the recommended NO_3^- N concentration of 10 mg/L, at the time of sampling drainage outflow was not occurring from the control structure, so the water within the structure was not contributing to nearby surface water. The lowest NO_3^- N concentration of 0.2 mg/L was found in the UD surface runoff ditch sample. The NO_3^- N concentration increased by about 24% from the upstream sampling location to the downstream location. Despite this increase, the concentration at the downstream sampling site was still well below the recommended maximum NO_3^- N concentration of 10 mg/L at 3.7 mg/L. The NO_3^- N concentration from the FD field drainage outlet was above the recommended value of 10 mg/L, like the CD/SI control structure sample, at 11.9 mg/L. Previously conducted research shows a reduction in NO_3^- N concentration of 25% in SI/CD SSD water compared to FD outflow (Drury et al., 1996). This relationship may not have been present in this study due to the upper portion of the SI/CD soil not being wet enough to favor denitrification, which would have decreased the NO_3^- N concentration.

As was expected, the UD surface runoff sample contained a significantly higher P concentration than the rest of the samples. The P concentration of 1.39 mg/L at the UD surface runoff ditch was an order of magnitude higher than the next highest sample, which was the downstream ditch at 0.15 mg/L. The lowest P concentration was found within the CD/SI control structure at 0.04 mg/L. The P concentration increased by approximately 275% from the upstream ditch to the downstream ditch, much higher than the increase in NO_3^- concentration. Subsurface runoff samples were found to have a total phosphorus concentration approximately 45% lower than surface runoff samples in a study conducted in Quebec (Jamieson et al., 2003). This difference is much less than that found in this study, but the analysis of multiple subsurface and surface water samples may have produced an average more similar to this reported value.

6.4.4. Crop yield

Yields from the UD, FD, and CD/SI fields were compared to assess the impacts tile drainage on crop yield. We expected yields from the UD field to be the lowest in years with the most moisture, like 2013 and 2019. Years with relatively high SWE were expected to cause later planting dates in the UD field compared to the FD and CD/SI field. Similarly, the UD harvest date was expected to be later in years with higher rainfall totals. To assess the impact factors discussed previously have on crop yield, the reported yields from the CD/SI, UD, and FD fields along with the Clay County average yields are given in Table 6.4.

Table 6.4. Corn, soybean, and sugarbeet yield comparisons between the controlled drainage and subirrigated, free drained, and undrained fields along with average yields reported in Clay County, MN from 2013-2019. The Clay County average sugarbeet yield for 2019 has not been reported.

Year	SI/CD	FD	UD	Clay County average corn	Clay County average soybean	Clay County average sugarbeet
2013	176.6 (corn)	54.0 (soybean)	43.4 (soybean)	138.2	36.1	25.6
2014	54.8 (soybean)	58.2 (soybean)	119.4 (corn)	131.4	35.2	20.8
2015	25.6 (sugarbeet)	180.6 (corn)	46.1 (soybean)	156.6	40.6	27.9
2016	182.4 (corn)	40.1 (soybean)	43.2 (soybean)	181.7	44.0	32.2
2017	176.6 (corn)	196.8 (corn)	186.8 (corn)	165.9	41.1	32.4
2018	175.9 (corn)	55.2 (soybean)	51.5 (soybean)	184.6	45.6	28.9
2019	51.6 (soybean)	193.6 (corn)	167.7 (corn)	165.7	38.8	-

Though the UD field's yields were lower than those of CD/SI and FD in 2013 and 2019, the wettest years out of the study period, they were still higher than the Clay County averages. When the same crop was grown in all three fields (corn in 2017), the SI/CD yield was the highest, followed by FD and UD. Overall, the FD field's yields were the highest, followed by the SI/CD field and the UD field. One must note that other factors, such as fertilizer and pesticide applications, crop varieties, and tillage have not been considered.

Because many factors can impact crop yield, no definitive conclusions can be made from this data, but it can provide a broader description of the impact of agricultural drainage in this region. Previous research on yield differences between drainage practices emphasized the timing of precipitation and management of a CD system as major factors impacting crop yields

(Delbecq et al., 2012). In the future, a more in depth analysis of seed variety, timing of rainfall, and disease presence may be conducted to further explain differences in crop yield between differing drainage practices.

6.5. Conclusion

Three different SSD systems (SI/CD, FD, and UD) were compared in terms of the movement of water within and from the drainage system, the water quality drained from the fields, and the resulting crop yields. The response to a rainfall was assessed by comparing the change in water table depth between the three fields. The volume of drainage outflow between the SI/CD and FD was compared, as was the chemical composition in terms of NO_3- N concentration, P concentration, and EC value for these SSD outflow samples. A surface runoff sample from the UD field was also included in this analysis along with samples taken from the upstream and downstream ditch. Crop yields were compared between the three fields to show the impact of drainage practice on crop growth.

Results showed significant differences in terms of change in water table depth and pattern of drainage outflow. The water table within the UD field rose the most and was the shallowest, followed by the SI/CD water table, which rose the second most and had a depth in between that of the UD and FD water tables. Along with having the deepest water table and most gradual increase in water table depth, drainage outflow in the FD field did not increase in response to the rainfall event, it instead decreased gradually over the observation period. In contrast to this, drainage outflow in the SI/CD field started approximately 15 hours after the rainfall event. Both the SSD samples from the SI/CD field and the FD field showed relatively high NO_3- N concentrations and low P concentrations in relation to the surface runoff sample from the UD field. It is not possible to assess the impact of these nutrient concentrations on nearby surface water since the amount of surface runoff was not measured, however.

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