Impact of Controlled Drainage on Reaction Factor and Corn Yield

By

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DECLARATION

I declare that this thesis and the work within it are my own as well as the analysis involved with each of the manuscript chapters. I have acknowledged all sources used as reference to previous work or topics. The last two chapters of this work have been submitted in manuscript style as they have been submitted to the Canadian Biosystems Engineering Journal and are both co-authored by Dr. Sri Ranjan. As part of my thesis work, I completed the analysis, interpretation of data analysis and initial draft of Section 3 and 4. Dr. Sri Ranjan provided editorial comments and interpretations, final draft was corrected together.

ABSTRACT

Water table management systems can improve the agricultural landscape under right management conditions. Controlled drainage as a best management practice can be used to decrease drainage outflows, which will thereby decrease the nutrient export from a field when compared to free drainage. The objectives of the study was to determine the impact of water table depth during different stages of corn growth on corn yield and quality, as well as to compare the impact of controlled drainage versus free drainage on reaction factors under different recharge events. A significant difference ($P < 0.05$) was observed in the corn yield between the different depths to the water table, with the corn harvested over the tile having a 6% higher yield over the quarter-way, and 7% higher yield over the half-way location. Average difference in water table depths between the tile and the quarter-way point ranged between 8.5 and 11.0 cm during different stages of growth. Results from this study show that water table management using drainage control structures have the potential to impact corn yield. The Sum of Excess Water within the top 70 cm depth of the root zone (SEW70) index was found to be significantly different ($p < 0.05$) between the three different locations within the tile transect, and found to have a negative correlation to the total corn yield. Piezometers located at the mid-spacing between tiles were used to determine the reaction factor within a controlled and free drained field during the 2017 growing season. The reaction factor in the controlled drainage field was found to be 71% significantly ($p << 0.01$) greater than the free drained field during the spring soon after the gates in the drainage control structure were opened in preparation for field operations prior to planting.

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ACRONYMS

BMP	Best Management Practice
CD	Controlled Drainage
CHU-M1	Crop Heat Units based on a May 1 start date
DCS	Drainage Control Structure
ECCC	Environment and Climate Change Canada
ET	Evapotranspiration
FD	Free Drainage
IR	Irrigated
N	Nitrogen
NI	Non-Irrigated
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
P	Phosphorus
PVC	Polyvinyl Chloride
SEW_{30}	Sum of Excess Water within the top 30 cm
SEW_{50}	Sum of Excess Water within the top 50 cm
SEW_{70}	Sum of Excess Water within the top 70 cm
T_{max}	Maximum Temperature
T_{min}	Minimum Temperature
WT	Water Table
WTM	Water Table Management

1. INTRODUCTION

1.1 Overview

Through the use of controlled drainage (CD) as a best management practice (BMP), it has been found to have the potential to reduce nutrient loading such as nitrogen (N) and phosphorus (P) arising from tile drainage. It has also been found that CD has the potential to increase crop yields (Sunohara et al., 2010; Tan and Zhang, 2011). Little is known on how the CD impacts the rate at which water table rise/fall caused by the addition of precipitation. This rate is also known as the reaction factor (α) (Martinez Beltran, 1999).

Gilliam et al., (1979) examined the application of raising the water table through the use of CD and found that this application caused de-nitrification within the soil profile, which converted nitrate (NO^{3-}) to N_2 gas. The findings from this study indicated that CD technology could increase yields and reduce nitrate loading from tile drainage runoff. Other studies such as Tan et al., (1993), Lalonde et al., (1996); and Drury et al., (2001) were also successful in demonstrating this under different climate and soil conditions. Little is known on how the application of CD versus free tile drainage will impact the reaction factor (α).

Research has been conducted on the impact of the application of CD with other BMPs, such as fertilizer application rate (Drury et al., 2009, 1997; Elmi et al., 2000); cover crops (Drury et al., 2014); tillage (Tan et al., 1993) and optimal water table depths (Mejia et al., 2000). Research has also been done to examine the impact of CD on phosphorus removal (Sunohara et al., 2016; Tan and Zhang, 2011; Valero et al., 2007). However, no research studies have been reported in the literature on the influence of control drainage and tile drainage on the reaction factor.

Despite the research that has been done on controlled drainage, the uptake of this application continues to be slow. Controlled tile drainage has the potential to provide yield benefits to producers, as well as reduce nutrient export to surface water. Is there enough known of the influences of controlled tile drainage versus free tile drainage?

1.2 Scope

Water management systems such as tile drainage have the ability to remove excess water from a field, but controlled drainage has the ability to artificially raise the water table depth to retain excess water within the soil profile in the field for longer periods of time. Although controlled drainage has been found to decrease drainage outflows, the impact it has on the reaction factor has not been thoroughly investigated. No research papers could be found discussing the topic of reaction factor through the use of controlled tile drainage. There is a knowledge gap in regards to this topic looking at the impact that raising the water table through the application of controlled tile drainage will have on the rate at which a field will drain in comparison to a field under free tile drainage. This thesis contains two manuscript-styled chapters, chapters 2 and 3, where each chapter answers a main objective listed in the general objectives.

1.3 General Objectives

The objective of this study was to evaluate two different water table management systems to determine their impact on corn yield and quality and reaction factor under southern Ontario conditions.

Specific topics that will be discussed include:

- To determine the impact of water table depth during different stages of corn growth on corn yield and quality,
- To measure drainage discharge rates as well as water table heads at the half way point between tiles to calculate the reaction factors for a controlled drainage versus a free drainage system after different recharge events.

2. Literature Review

2.1 Introduction

Agricultural drainage systems have an important function in the agricultural landscape. The application of an agricultural drainage system can reduce the risk of excess moisture through drier soil conditions and discharging water. This can further lead to increased oxygen levels, which can improve soil health through stabilized soil structure and more availability of nitrogen in the soil. Surface runoff and soil erosion can also be decreased with a more stable soil structure. Drier soil conditions also increase the ability to get in the field sooner for earlier planting and workability. Another benefit of drainage systems is an increase in crop yields (Ritzma, 2006). Although the application of agricultural drainage systems have a number of benefits, subsurface tile drainage continues to be viewed as a contributing source of nutrient export to surface water in the Great Lakes-St. Lawrence River basin (Chambers et al., 2001).

Since subsurface tile drainage, or free tile drainage, removes excess water from the field, it can also remove any remaining nutrients from the field. Although free tile drainage has many benefits, it can also have a negative impact on the environment through the export of nutrients in the drainage effluent. Certain Canadian ecosystems are at risk due to the excess phosphorus found in Canadian agricultural regions from crop and animal production (Chambers et al., 2001). Studies have found that the adoption of controlled tile drainage as a best management practice has the potential to reduce nitrogen and phosphorus export from tile drains and increase producer profit margins through increased yields (Drury et al., 2009; Tan and Zhang, 2011).

The application of controlled tile drainage systems has been found to have both economic and environmental benefits (Madramootoo et al., 1993; Drury et al., 2009). Controlled tile drainage has not had a significant uptake since its conception (Dring et al., 2016). Since controlled tile drainage is still a relatively new concept, there are no design criteria or management methods available when considering the economic or environmental benefits of this practice (Bahçeci et al., 2008).

2.2 Controlled Drainage with Sub-Irrigation under Canadian Climate

A small number of studies have been found that look at phosphorus export under different drainage conditions. Of these studies, only a small number have been found to be conducted within Canada. Tan and Zhang (2011) looked at phosphorus losses under both surface and sub-surface run-off with free tile drainage and controlled tile drainage under sub-irrigation conditions. This study looked at large scale plots of 0.33 hectares in southwestern Ontario, where the surface and sub-surface flows were measured using tipping buckets. Samples were collected using ISCO auto-samplers which were tripped on a volume interval. For the purpose of this study, the controlled tile drained field had sub-irrigation initiated when the water table level dropped below the control structure gate level of 40 cm below ground level. The results of this five (5) year study indicated that the average flow weighted mean of most forms of phosphorus were reduced through the use of a controlled tile drainage system with sub-irrigation when compared with free tile drainage (Tan and Zhang, 2011).

The results of the study by Tan and Zhang (2011) would agree with the initial results of my project, that phosphorus export from a controlled tile drained system would be lowered when compared with the export from a free tile drained system. The study done by Tan and Zhang (2011) was conducted with the addition of sub-irrigation within the controlled tile drainage field. It is possible that this addition could impact the phosphorus exported, as the field with controlled tile drainage has artificial precipitation added to it, which could impact the comparison to a free tile drainage field that has not had the same addition. By maintaining the water level at 40 cm below the ground surface, more water will be discharged from the field during precipitation events, as the water table is already at the desired height and any excess water will be removed from the field, as it would be removed from the free tile drained field. By having the water table maintained at 40 cm below the surface, this field will now act as a free tile drained field, since any additional precipitation will be free to leave to field, rather than fill any available soil moisture capacity in a field that is operated only under controlled tile drainage conditions. Based on this, I would consider the results for the controlled tile drainage field with sub-irrigation to have potentially higher phosphorus exports than that of a controlled tile drainage field without sub-irrigation. With this assumption, the results of the study done by Tan and Zhang (2011) would indicate that if a controlled tile drainage field with sub-irrigation can have a lower phosphorus export than that of a free tile drainage field, then a controlled tile drainage field without sub-irrigation should have an even lower phosphorus export, when compared with a free tile drainage field.

A similar study was conducted by Valero et al. (2007), which looked at phosphorus export in free tile drainage versus controlled tile drainage with sub-irrigation. This study was conducted on a 4.2-hectare plot in eastern Canada over the 2005 growing season. One of the differences between this study and the study conducted by Tan and Zhang (2011), is that the water table depth was maintained at 60 cm below the ground surface, rather than 40 cm. Well water was used for the purpose of sub-irrigation for maintaining the water table level below the surface. The water table levels were measured using observation wells constructed from PVC; the tile discharge rates were measured using pre-calibrated tipping buckets, and water samples were taken based on a flow proportional pattern. Since this study was using well water for the purpose of sub-irrigation, the water being applied was also tested to measure how much phosphorus was being added into the system. In addition to the field trial, Valero et al. (2007) conducted a soil column test to determine the impact of different water table management levels on phosphorus export. For the soil column test, the water used for the sub-irrigation did not have any phosphorus in it. The purpose of using the phosphorus free water for sub-irrigation was to see if the results of the soil column test would be similar to the field study where the sub-irrigated water did have phosphorus in it. The results of the field trial indicated that the use of controlled tile drainage with sub-irrigation will increase the phosphorus export over that of a free tile drained field. The results of the soil column trial provided the same findings as the field study, where controlled tile drainage with sub-irrigation increased the phosphorus export of the free tile drained field (Valero et al., 2007).

Although the study by Valero et al. (2007) is similar to the study conducted by Tan and Zhang (2011), in that the use of sub-irrigation was used in combination with a controlled tile drained system, the results were found to be opposite of each other. Unfortunately, the studies were not done during the same growing season, so it can-not be determined if this difference is climate related. It should also be noted that the study conducted by Tan and Zhang (2011) did not provide water sample results of the water used for sub-irrigation purposes. Based on the results of the soil column test done by Valero et al. (2007), the water quality of the sub-irrigation water did not impact the results of the study. Since this was done in the lab, it is possible that a field study trial done with similar parameters could result in different findings. In comparing these two studies, one could conclude that it is possible that a field study could result in reduced phosphorus export as indicated by Tan and Zhang (2011).

Another study conducted by Cordeiro et al. (2014) looked at the application of controlled tile drainage with sub-irrigation in comparison to a free tile drainage field with overhead irrigation. For the purpose of this study, the water table was maintained at 75 cm below the ground surface with the use of sub-irrigation between 2010 and 2011. This study was conducted over the growing season only, and the stop-gates were removed in October. The results of this study indicated a reduction in phosphorus export of 69%.

The table below provides a summary of the results found in the Canadian studies described in Section 2.2.1 for the application of controlled tile drainage with sub-irrigation.

Table 2-1: Summary Results for Controlled Drainage with Sub-Irrigation

Study	% Reduction of Total Phosphorus
Tan and Zhang (2011)	12%
Valero et al. (2007)	-131%
Cordeiro et al. (2014)	69%

2.3 Controlled Drainage

Studies have found that the adoption of controlled tile drainage as a best management practice has the potential to reduce nitrogen and phosphorus export from tile drains and increase producer profit margins through increased yields (Drury et al., 2009; Tan and Zhang, 2011).

2.3.1 Canadian Climate

Although the study conducted by Tan and Zhang (2011) used sub-irrigation in the controlled tile drained field, which is different from the proposed study, it was conducted on a year-round basis. Another study by Sunohara et al. (2016) was done only during the growing season, from May to October, over nine (9) years (2005 – 2013) in the eastern portion of southern Ontario. This study looked at a number of factors, including phosphorus export, in uncontrolled tile drainage fields against a paired field with controlled tile drainage. The study looked at seven (7) paired fields ranging from two (2) to 10 hectares. An ISCO auto-sampler was used to collect the water samples twice weekly and an ISCO bubbler was used to measure the flowrate. The results of this nine (9) year study indicated that the mean phosphorus exported in the uncontrolled tile drainage field was 66% higher than that of the controlled tile drainage field (Sunohara et al., 2016).

Based on the results of the study by Sunohara et al. (2016), it would agree with my hypothesis that phosphorus export from a controlled tile drained system would be lower than the export from a free tile drained system. The study done by Sunohara et al. (2016) was conducted during the months of May to October of the growing season. The results from this study only cover half the year, additional phosphorus loss can occur during the off season during the spring melt and fall storm events. Control structures can be used during this time to minimize the phosphorus exported in the tile discharge during any fall storm or spring melt events. Although the study conducted by Sunohara et al. (2016) does confirm the reduction of phosphorus export when comparing a controlled tile drained field with a free tile drained field, it does not consider the entire year.

2.3.2 North American Climate

Studies that have been conducted in the United States, but the study area was limited to North Carolina. Reviews by Evans et al. (1996, 1995) and Skaggs et al. (1994) have summarized water-quality studies with agricultural drainage, looking at both national and international work. The results of these studies found that the use of controlled tile drainage was able to reduce phosphorus loading in surface run-off, but similar results were not found in the sub-surface drainage systems.

One of these studies was a report by Evans et al. (1989), which looked at different water table management practices on seven (7) different sites between 1983 and 1984 for demonstrative purposes. These sites included the comparison of surface runoff and subsurface drainage and drainage laterals set at different spacings. The sizes of these sites ranged from 15 to 73 hectares. Of the seven (7) sites studied, one (1) site compared free tile drainage and controlled tile drainage, which was located on a 15-hectare field. This field was set-up with continuous water table and drainage volume measuring equipment. Autosamplers were also set up on the site to collect samples twice daily at the outlet, where nutrient concentration was measured. The results of this study indicate that the free tile drainage resulted in more frequent flow events of longer durations, but had a lower peak daily discharge rate than the controlled tile drainage system. The results of the phosphorus export indicated that variation between systems and events was believed to be based on the proportion of flow during the event. The authors did state that the experimental setup used could not quantify this result. The results also found an increase in phosphorus during the growing season, which could have been attributed to surface runoff. Unfortunately, the experimental set-up did not allow for a comparison between surface and sub-surface runoff. This study only looked at water table management during the growing season and did not apply any stop-gates during the winter months.

Other studies have been conducted within North America looking at nutrient export. One such study looked at nutrient export within a forested area using controlled tile drainage (Amatya et al., 1998). This study looked at three different watersheds and the impact of three different controlled tile drainage scenarios. The results of this study did not indicate that the use of controlled tile drainage would reduce phosphorus export during different parts of the year, although for the yearly average it was found to reduce total phosphorus export (Amatya et al., 1998). This study did indicate that spring resulted in higher phosphorus export in the controlled tile drainage field over the free tile drainage field. This study was not conducted on a rotational crop, but rather pine trees that had been present for 17 to 20 years.

Another review was conducted by King et al. (2015), which found that controlled tile drainage could reduce the discharge volume from 20 to 95%. Using the findings in Evans et al. (1995), this reduction in discharge volume can often result in a reduction in phosphorus export.

A study was conducted by Williams et al. (2015), which looked at the application of drainage water management, or controlled tile drainage, on drainage discharge rates and nutrient exports in subsurface drainage. This study was conducted in Ohio, USA over a seven (7) year period between 2006 and 2012. The site had two tile outlets that were measured; one had a control structure installed to increase the water table to 45 cm below the ground surface. The control structure was raised between spring and fall. The tile discharge rate was measured using a weir and an ISCO bubbler recording every 10 minutes. An ISCO Autosampler was used to collect water samples every 6 hours for daily water samples. Weekly composite samples were analyzed for total phosphorus concentrations. The results of this study indicated an 8 to 34% reduction in drainage discharge water. The results also indicated that the phosphorus concentration was not impacted by the application of controlled tile drainage, but did result in a 40 to 68% reduction in phosphorus load.

The table below provides a summary of the results found in the studies described in Section 2.2.2 for the application of controlled tile drainage in comparison to free tile drainage for phosphorus export.

Table 2-2: Summary Results for Controlled Drainage

Study	% Reduction of Total Phosphorus
Sunohara et al. (2016)	66%
Amatya et al. (1998)	62%
Williams et al. (2015)	40 – 68%

2.4 Reaction Factor under Controlled Drainage and Free Drainage

Through the use of controlled tile drainage (CD) as a best management practice (BMP), it has been found that this application has the potential to reduce nutrient loading such as nitrogen (N) and phosphorus (P) from tile drainage. It has also been found that CD has the potential to increase crop yields (Sunohara et al., 2010; Tan and Zhang, 2011). Little is known on how the application of CD impacts the rate at which the field drains with a rise in the water table caused by the addition of precipitation. This rate is also known as the reaction factor (α) (Martinez Beltran, 1999).

Gilliam et al., (1979) examined the application of raising the water table through the use of CD and found that this application caused de-nitrification within the soil profile, which converted nitrate (NO^{3-}) to N_2 gas. The findings from this study indicated that CD technology could increase yields and reduce nitrate loading from tile drainage runoff. Other studies such as Tan et al., (1993), Lalonde et al., (1996); and Drury et al., (2001) were also successful in demonstrating this under different climate and soil conditions. Little is known on how the application of CD versus free tile drainage will impact the reaction factor (α).

Research has been conducted on the impact of the application of CD with other BMPs, such as fertilizer application rate (Drury et al., 2009, 1997; Elmi et al., 2000); cover crops (Drury et al., 2014); tillage (Tan et al., 1993) and optimal water table depths (Mejia et al., 2000). Research has also been done to examine the impact of CD on phosphorus removal (Sunohara et al., 2016; Tan and Zhang, 2011; Valero et al., 2007). However, no research studies have been found on the influence of control drainage and tile drainage on the reaction factor.

The impact that control drainage can have on the reaction factor of a field has not been thoroughly investigated. There is a knowledge gap in regards to this topic looking at the impact that raising the water table through the application of controlled tile drainage will have on the rate at which a field will drain in comparison to a field under free tile drainage. A recent study by Saadat et al. (2017) considered optimal management strategies for control drainage to reduce the water table level around a rainfall event to prevent any negative impact on field trafficability or crop yield. This was done by considering the impact controlled drainage had on the time it took for the water table to fall to a desired level following a rainfall event. For this study, two paired sites of controlled drainage and free drainage were compared in Indiana over a nine (9) year period by lowering the outlet of the DCS either before or after a rain event. The results of this study found that lowering the water level at tile outlet by removing the number of gates in the DCS just prior to a rain event would reduce the amount of time it took for the water table to drop in the CD fields.

Through the use of drainage control structures, the water table can be raised artificially to retain excess water within the soil profile in the field for longer periods of time. By raising the water table, the soil profile will be more saturated than a field under free drainage. Since controlled drainage increases the depth to the impervious layer, it is expected that the drainage intensity would be greater when the gates in the controlled drainage structures are opened compared to free drainage systems. The results from Saadat et al. (2017) indicated that by removing the gates prior to a rain event the water table depth would drop faster in the CD fields.

2.5 Factors Impacting Corn Yield

2.5.1 Impact of Water Stress on Corn Yield

Corn yield can be influenced by soil moisture stress during different growth stages, impacting the quality and the quantity of the corn (Abbas and Sri Ranjan, 2017; Cakir, 2004; Kanwar et al., 1998; Mi et al., 2018). A number of studies looked at the impact that water stress can have at different stages of corn growth that could influence corn yield or quality. Corn can be split into two growth stages: the vegetative stages and the reproductive stage. Each of these growth stages can be further subdivided into the tasseling and cob formation stages found at the end of the vegetative stage; silking and flowering, found at the beginning of the reproductive stage, and dough in the middle of the reproductive stage (Ransom, 2013).

Abbas and Sri Ranjan, (2017) completed a study on the effects of overhead irrigation on corn yield in southern Manitoba with a shallow water table. This study was done at two different sites in southern Manitoba where no irrigation and over-head irrigation were considered at each site during the 2014 growing season. The water table and soil water content was measured at the centre of each plot to measure water table movement under the different irrigation treatments. A hand harvest of the corn was completed to complete a corn yield and quality analysis under the different irrigation treatments. The results of this study found that the over-head irrigation treatment resulted in a significantly higher yield at both sites. The results also indicated that the quality of the corn was significantly higher in the over-head irrigated fields as well.

Cakir, (2004) completed a study looking at the impact that water stress can have on corn yield at different stages of corn growth. This study was done by applying 16 different irrigation treatments on a corn crop over a three year period between 1995 and 1997 in Kirklareli, Turkey. The different irrigation treatments had three replicates, and four different growth stages were considered for the purpose of water stress. A number of parameters were considered to evaluate irrigation stress at each of these four growth stages including plant height, leaf area index, grain yield per hectare, as well as number of ears per plant, grain yield per cob and 1000 kernels weight. The results of this study found that water stress during the tasseling and cob formation stages resulted in a reduction in yield.

Kanwar et al., (1998) completed a study looking at the impact that excessive soil water at different stages of corn growth can have on crop yield. This study was done by observing the water table depth in fifty plots over a three year period between 1984 and 1986 to determine the impact that the water table had at five different growth stages. The Sum of Excess Water within the top 30 cm depth of the rootzone (SEW_{30}) was determined within each plot over the three year study to determine the impact on corn yield at different stages of corn growth. The SEW_{30} index is defined as the number of days times the water table height in cm within the top 30 cm depth from the soil surface (Sieben, 1964a; as referenced in Wesseling, 1974). The results of this study found that when the SEW_{30} index was observed at values as low as 40 cm-days during the early growing season the corn yield could be significantly reduced. The study also found that as the SEW_{30} index increased the corn yield decreased.

Mi et al., (2018) completed a study looking at the impact of drought at the vegetative and reproductive stage would have on corn yield. This study was done by applying six different drought conditions during the jointing or tasselling growth stage between 2015 and 2016. Different drought conditions were achieved by not applying irrigation to the crop for different time frames between the different pre-determined growth stages. The results of this study found that drought during either the vegetative or reproductive stages had a significant impact on the yield of the corn, with drought during the reproductive stage having the greatest impact.

The above studies all found that water stress can have an impact on corn yield, where water stress at the end of the vegetative stage and during the reproductive stages have the greatest impact on the corn yield (Cakir, 2004; Mi et al., 2018).

2.5.2 Impact of Water Table Depth on Corn Yield

Corn yield can also be influenced by the water table depth within the field during the growing season. Kanwar et al., (1998) using a three-year study reported that corn yield decreased as the SEW_{30} index increased during two of the three years. This study also indicated that when values were closer to 40 cm-days, corn yield was significantly reduced. During the middle year, which turned out to be the 1985 drought year, the opposite result was found, where an increase in the SEW_{30} also had an increase in corn yield.

Zipper et al., (2015) completed a study looking at the impact that a shallow water table and soil texture can have on corn yield. This study was done between 2012 and 2013 looking at two separate corn fields under a dry and wet growing season respectively. Results from this study indicating that weather conditions during the growing season impacted the yield when shallow groundwater levels were observed. During a dry year, shallow groundwater was found to increase the yield, and decrease the yield during a wet year.

Helmers et al., (2012) completed a study looking at the impact that an undrained field, conventional tile drainage, controlled tile drainage and shallow tile drainage would have on yield. The study was done between 2007 and 2010, and considered four different drainage water management systems on corn and soybeans. The four-year study found that the corn yield was significantly lower in the controlled plots compared to the conventional tile drainage, but not significantly different compared to shallow water table. Under different water management of controlled drainage, the impact on yield could have been different.

Follett et al., (1974) completed a study looking at the impact the irrigation and water table depth had on different crops, including corn. This study was done by applying irrigation at four different application rates each week based on the crops weekly water requirement between 1971 and 1972. Each of the irrigation practices were applied over three different depths of drainage. Results of this study found that the best yield results for corn were on shallow water table, where irrigation was not found to have any impact on the yield. Corn did have a response to the irrigation applied when the drainage were located at the medium and deep depths, but neither of these depths results in yields greater than the shallow depth drainage results. Results from this study also found that that when the water table was below 60 cm from the ground surface there was a decrease in corn yield.

Each of these studies considered the impact that water table depth during the growing season can have on corn yield, in particular shallow water depths. Different results were found when comparing wet and dry years, where shallow water table depths increased yield during a dry year and decreased yield during a wet year (Kanwar et al., 1998; Zipper et al., 2015).

2.5.3 Impact of Irrigation Practices on Corn Yield

Different irrigation practices have also been studied to determine how they impact corn yield (Feng et al., 2018; Kiani and Mosavat, 2016; Kresović et al., 2016). Kiani and Mosavat (2016) evaluated the application of saline and non-saline water under limited and non-limited water supply conditions. Results of this study found that limiting the water supply by 50% reduced the corn yield significantly. In a study where alternate rows were irrigated, using saline water to irrigate the dry rows significantly increased the corn yield. The impact that different irrigation regimes have on grain yield and water use efficiency was investigated by Kresović et al. (2016) in northern Serbia. This study looked at four different irrigation treatments with rain fed as the control. Results indicated that corn yield decreased as the water stress increased, and yield increased linearly as crop evapotranspiration and irrigation increased. The study by Feng et al. (2018) looks at improving crop yield by irrigating at the critical water stress period of corn and wheat crop. The results from this study indicate that the corn yield increased when irrigation was applied during the summer corn sowing stage. All of these studies look at water stress or water use during the growing season, but did not consider the influence that the water table depth might have on corn yield.

2.5.4 Impact of Planting Practices on Corn Yield

Different planting practices have also been investigated to determine their impact on corn yield (Hai-dong et al., 2017; Welde and Gebremariam, 2016). Welde and Gebremariam (2016) evaluated how different furrow and plant spacing could impact corn yield; they also considered water use efficiency under these practices. This study found a significant difference in grain yield and irrigation water use efficiency between these practices, although no significant difference was observed in the corn plants considering plant height and number of cobs per plant. Results indicated that irrigation water use efficiency will change under different plant and furrow spacing. This study shows the importance of agronomic practices on corn yield and water use. The impact of planting date on corn yield was considered by Hai-dong et al. (2017) and how the planting date can influence drought stress, environmental factors and water use efficiency. The results of this study found that earlier planting dates were mainly influenced by soil moisture that affected corn yield, and later planting dates had environmental impacts during the reproductive stage. Results of this study indicated the importance of soil moisture when selecting planting date. These two studies looking at different planting practices show the importance of soil moisture status and water use efficiency affecting corn yield. However, these studies did not consider the water table depth against each of these planting practices.

The tables below provides a summary of the results found in the studies described in Section 2.3, 2.4 and 2.5 covering reaction factor for controlled drainage and free drainage, as well as different factors impacting corn yield.

Table 2-3: Summary Table of Past Work on Reaction Factor for Controlled Drainage and Free Drainage

Author and Year	Place	Plot Information	Crop/Soil	Influencing Factor	Objective	Main Results
Saadat et al. (2017) 2006-14	Davis Purdue Agricultural Center, Indiana	Two pairs of CD and FD fields. Tile info: 4”; 14m spacing; 1 m depth	Corn/ Soybean rotation. Silty loam, silty clay loam, clay loam	Water Table Recession Rate for CD versus FD	Impact of CD on time for WT to drop after rain event over FD for WTM	Lowering DCS outlet before event to reduce time to drop WT

Table 2-4: Summary Table of Past Work on Different Factors Impacting Corn Yield

Author and Year	Place	Plot Information	Crop/Soil	Influencing Factor	Objective	Main Results
Abbas and Sri Ranjan, (2017) 2014	Southern Manitoba	Two sites with 6 equal plots. Irrigated (IR) vs Non-irrigated (NI)	Corn. Sandy loam	IR vs NR for corn yield and quality	Impact of water contribution for shallow WT for IR vs NI	IR fields had significantly higher yield and quality than NI for corn
Cakir, (2004) 1995-97	Kirklareli, Turkey	16 different irrigation treatments with 3 replicates	Corn. Silty loam Entisol soil	Water stress (WS) at different growth stages of corn	Impact of irrigation and WS at different stages of growth on corn yield	WS during tasseling and cob formation stages had reduction in yield
Kanwar et al., (1998) 1984-86	Amex, IA	Fifty plots with no artificial drainage	Corn. Nicollet Soil	SEW Index on corn growth stages	Impact of WT at 5 different corn growth stages on corn yield	SEW_{30} increased as corn yield decreased
Mi et al., (2018) 2015-16	Southwester n NEC	Five plots with 3 replicates	Corn. Cambisol soil	Drought at certain corn growth stages	Impact of drought at different corn growth stages	Drought during reproductive stage greatest impact on corn yield

Author and Year	Place	Plot Information	Crop/Soil	Influencing Factor	Objective	Main Results
Zipper et al., (2015) 2012-13	South-central Wisconsin	Two adjacent fields	Corn. Silt and silt loam	Shallow WT on corn yield in wet and dry year	Impact of shallow WT and soil texture on corn yield	Shallow WT in dry year increased yield, and decreased it in wet year
Helmers et al., (2012) 2007-10	Crawfordsville, Iowa	4 WTM systems, with 2 replicates	Corn/ Soybean. Silty clay loam	Different WTM systems on corn yield	Impact of different WTM systems on corn yield	Corn yield was lower in CD vs. FD, but not different with shallow WT
Follett et al., (1974) 1971-72	Eastern North Dakota	4 irrigation treatments on 3 different drainage depths	Corn, sugarbeets and alfalfa. Sandy soil	Irrigation and WT depth on corn yield	Determine best irrigation drainage combination for crop production	Corn Yield was best on shallow water depths
Kiani and Mosavat (2016) 2012-13	Northern Iran	1 control, 6 irrigation treatments with saline and non-saline water. All with 3 replicates	Corn. Loam and silt loam	Limiting water use with saline and non-saline water	Efficient use of limited water, also replacing saline water with fresh water	Limiting water by 50% significantly reduced corn yield.
Kresović et al. (2016) 2006-08	Northern Serbia	4 irrigation regimes with 4 replicates	Corn. Silty loam texture	Limiting water use through irrigation	Effects of different irrigation levels on corn yield, and water use efficiencies	Corn yield decreased as the WS increased, yield increased as ET and irrigation increased
Feng et al. (2018) 2013-15	Huang-Huai-Hai Plain, China	2 different irrigation strategies. No water applied and 60 mm at sowing	Winter Wheat and Corn. Loam	Critical water requirement point for corn and winter wheat	Improving crop yield by irrigating at critical water requirement point	Corn yield increase when irrigation applied at summer corn seeding stage

Author and Year	Place	Plot Information	Crop/Soil	Influencing Factor	Objective	Main Results
Welde and Gebremariam (2016) 2013	Tigray, Ethiopia	3 furrow spacing combined with 3 plant spacing and 3 replicates. Total of 9 plots	Corn	Plant Spacing on Corn Yield	Evaluated how different furrow and plant spacing could impact corn yield	water use efficiency will change under different plant and furrow spacing
Hai-dong et al. (2017) 2012-14	China	6 planting dates with 4 replicates	Corn. Loess sandy soil	Planting date on corn yield	How the planting date can influence drought stress, environmental factors and water use efficiency	Importance of soil moisture when selecting planting date

2.6 Knowledge Gaps

Based on the research that has already been done on controlled drainage, there are still some knowledge gaps. No studies have been found to report on the influence of control drainage and tile drainage on the reaction factor. Although work has been done to examine the impact that water stress and water table depths can have on corn yield, studies have not examined the impact of water table depth during different stages of corn growth on corn yield and quality under southwestern Ontario conditions. Therefore, the following research question is proposed:

Impact of water table depth on corn yield under tile drainage in southwestern Ontario: The first objective of this study is to determine the impact of water table depth during different stages of corn growth on corn yield and quality under southwestern Ontario conditions.

Comparison of reaction factor (α) between controlled and free drained fields: The second objective of this study is to determine if the application of controlled tile drainage versus free tile drainage has any impact on the rate at which excess water is drained from the field.

To answer the proposed research questions above, a field near London, Ontario that has both controlled drainage and free drainage has been set-up with water table, soil moisture and weather measuring equipment.

3. Impact of Water Table Depth on Corn Yield under Tile Drainage in Southwestern Ontario

ABSTRACT: Corn yield and quality can be affected by a number of different factors including water table management. Although tile drainage has been used to remove excess water from the field, controlled drainage using drainage control structures has the ability to retain water within the soil profile during a dry growing season. The objective of this study was to determine the impact of water table depth on corn yield and quality. The water table depth was measured at three different distances along a transect from the tile, i.e. at the tile, at quarter-way as well as at half-way between two tiles. A significant difference ($p < 0.05$) was observed in the corn yield between each of the locations, with the corn harvested over the tile having a 6% higher yield over the quarter-way, and 7% higher yield over the half-way location. Average difference in water table depths between the tile and the quarter-way point was found to range between 8.5 and 11.0 cm during different stages of growth. The Sum of Excess Water within the top 70 cm depth of the rootzone (SEW_{70}) index was found to be significantly different ($p < 0.05$) between the three different locations within the tile transect, and found to have a negative correlation to the total corn yield. Results from this study show that water table management using drainage control structures have the potential to impact corn yield.

3.1 INTRODUCTION

Subsurface drainage is a widely used practice in southern Ontario, where some counties have as much as 85 percent of the agricultural land under tile drainage with the average across southern Ontario of 45 percent (Pearce, 2011). Although subsurface drainage has a number of benefits, drainage discharge continues to be viewed as a source of nutrient loss contributing to the Great Lakes-St. Lawrence River basin (Chambers et al., 2001). When drainage control structures (DCS) are used as a best management practice (BMP) they have the potential to reduce nutrient export from the edge-of-field (Cordeiro et al., 2014; Satchithanantham et al., 2014; Sunohara et al., 2010; Tan and Zhang, 2011). The work of Sunohara et al., (2010) and Tan and Zhang, (2011) has also indicated that the use of DCS has the potential to increase crop yields.

Corn is the second largest field crop grown in Ontario following soybeans, with grain corn covering 0.86 million of the 3.65 million hectares of total crop land in Ontario (OMAFRA, 2018; Statistics Canada, 2016). There are a number of factors that can affect corn yield whether in season influences or influences from previous seasons. These factors include temperature and/or precipitation delaying planting (Drury and Tan, 1994; Nafziger, 2009; Van Roekel and Coulter, 2011); nitrogen fertilization (Drury and Tan, 1994); hybrid selection (Nafziger, 2009), crop rotation (OMAFRA, 2017), plant population (Poncet et al., 2019; Van Roekel and Coulter, 2011), tillage (OMAFRA, 2017), as well as water drainage systems (Ng et al., 2002). Tile drainage has been used as a management practice to increase corn yield, through its ability to remove excess moisture from the field in the spring to allow for early planting (OMAFRA, 2017; Ritzma, 2006). Ng et al., (2002) found that the use of controlled drainage with sub-irrigation increased corn yield by 64% over that of a free drained field.

Corn yield can be influenced by soil moisture stress during different growth stages, impacting the quality and the quantity of the corn (Abbas and Sri Ranjan, 2017; Cakir, 2004; Hall et al., 1981; Kanwar et al., 1998; Mi et al., 2018). Corn can be split into two growth stages: the vegetative stages and the reproductive stage. Each of these growth stages can be further subdivided into the tasseling and cob formation stages found at the end of the vegetative stage;

silking and flowering, found at the beginning of the reproductive stage, and dough in the middle of the reproductive stage (Ransom, 2013). Cakir, (2004) found that water stress during the tasseling and cob formation stages resulted in a reduction in yield. Kanwar et al., (1998) found that corn yield was impacted most by excess moisture during the flowering stage at the beginning of the reproductive stages. Hall et al., (1981) found that water stress during the pre-flowering stage can result in reduced yields due to reduced kernel sizes impacted by insufficient pollination. Mi et al., (2018) found that drought during either the vegetative or reproductive stages had a significant impact on the yield of the corn, with drought during the reproductive stage having the greatest impact.

Corn yield can also be influenced by the water table depth within the field during the growing season. Kanwar et al., (1998) using a three-year study reported that corn yield decreased as the SEW_{30} index increased during two of the three years. The SEW_{30} index is defined as the number of days times the water table height in cm within the top 30 cm depth from the soil surface (Sieben, 1964a; as referenced in Wesseling, 1974). This study also indicated that when values were closer to 40 cm-days, corn yield was significantly reduced. During the middle year, which turned out to be the 1985 drought year, the opposite result was found, where an increase in the SEW_{30} also had an increase in corn yield. A study by Zipper et al., (2015) had similar results indicating that weather conditions during the growing season impacted the yield when shallow groundwater levels were observed. During a dry year, shallow groundwater was found to increase the yield, and decrease the yield during a wet year. Helmers et al., (2012) looked at the impact that an undrained field, conventional tile drainage, controlled tile drainage and shallow tile drainage would have on yield. The four-year study found that the corn yield was significantly lower compared to the shallow water table and conventional tile drainage, but not significantly different compared to controlled drainage. Under different water management of controlled drainage, the impact on yield could have been different. Kemper et al., (2012) measured the water table depth in a field in Wisconsin and found that the average water table depth was 40 cm below the ground surface, which was likely the cause for reduced yield. Similarly, a study by Follett et al., (1974) on corn found that when the water table was below 60 cm from the ground surface resulted in decreased yield.

Different planting practices have also been investigated to determine their impact on corn yield (Hai-dong et al., 2017; Welde and Gebremariam, 2016). Welde and Gebremariam (2016) evaluated how different furrow and plant spacing could impact corn yield; they also considered water use efficiency under these practices. This study found a significant difference in grain yield and irrigation water use efficiency between these practices, although no significant difference was observed in the corn plants considering plant height and number of cobs per plant. Results indicated that irrigation water use efficiency will change under different plant and furrow spacing. This study shows the importance of agronomic practices on corn yield and water use. The impact of planting date on corn yield was considered by Hai-dong et al. (2017) and how the planting date can influence drought stress, environmental factors and water use efficiency. The results of this study found that earlier planting dates were mainly influenced by soil moisture that affected corn yield, and later planting dates had environmental impacts during the reproductive stage. Results of this study indicated the importance of soil moisture when selecting planting date. These two studies looking at different planting practices show the importance of soil moisture status and water use efficiency affecting corn yield. However, these studies did not consider the water table depth against each of these planting practices.

Different irrigation practices have also been studied to determine how they impact corn yield (Feng et al., 2018; Kiani and Mosavat, 2016; Kresović et al., 2016). Kiani and Mosavat (2016) evaluated the application of saline and non-saline water under limited and non-limited water supply conditions. Results of this study found that limiting the water supply by 50% reduced the corn yield significantly. In a study where alternate rows were irrigated, using saline water to irrigate the dry rows significantly increased the corn yield. The impact that different irrigation regimes have on grain yield and water use efficiency was investigated by Kresović et al. (2016) in northern Serbia. This study looked at four different irrigation treatments with rain fed as the control. Results indicated that corn yield decreased as the water stress increased, and yield increased linearly as crop evapotranspiration and irrigation increased. The study by Feng et al. (2018) looks at improving crop yield by irrigating at the critical water stress period of corn and wheat crop. The results from this study indicate that the corn yield increased when irrigation was applied during the summer corn sowing stage. All of these studies look at water stress or water use during the growing season, but did not consider the influence that the water table depth might have on corn yield.

In southwestern Ontario, corn crops rely on precipitation to meet their water demand through-out the growing season. Yield reduction in corn can be attributed to moisture stress during the different growth stages. Through the use of a water table management system, there is potential to retain moisture within the root zone of the crop. A number of studies have looked at different drainage water management practices to determine the impact on corn yield (Helmers et al., 2012; Sunohara et al., 2010; Tan and Zhang, 2011). Although these studies examined different water management practices, they did not look at the impact that the water table depth might have at different locations between the tiles.

Although controlled drainage has environmental benefits, such as decreasing drainage outflows and increasing drainage intensity (Helmers et al., 2012), the impact that water table management has on corn yield has not been thoroughly investigated under southwestern Ontario conditions. The objective of this study was to determine the impact of water table depth during different stages of corn growth on corn yield and quality under southwestern Ontario conditions.

3.2 MATERIALS AND METHODS

3.2.1 Study Site

The experimental site was located near Lucan, Ontario, Canada on an operational farm. For the purpose of this study, data was collected during the 2018 growing season between April and October. The site is planted in a corn-corn-soybean rotation, with the 2018 growing season being in the second consecutive year of corn. The typical growing season for corn in this area is between May and October (OMAFRA, 2018). During the growing season, the average temperature ranges from 13°C to 20°C with an average accumulation of 455 mm of precipitation (ECCC, 2018a). Natural precipitation is relied on to meet the crop water demand through-out the growing season. The study site consists of two different soil types with 60% Brantford-Toledo soil and 40% Brant-Colwood soil both having poor drainage and nearly level slope with a soil texture of silty loam to silty clay loam (Hagerty and Kingston, 1992). Based on a soil type of silty loam, corn has an effective rooting depth of 0.9-1.2 metres (Irmak and Rudnick, 2014). Based on the Ontario crop heat units (CHU-MI) for London, Ontario, the site has a CHU-M1 value greater than 3,000 (OMAFRA, 2018). Using the CHU-M1 value and soil moisture conditions, the optimum planting date is after April 26, once the average soil temperature has reached 10°C (OMAFRA, 2018). For the 2018 growing season, the corn was planted on May 2.

3.2.2 Experimental Design

The site selected is a nine-hectare field that had the drainage tiles installed in May 2014. The entire field network was installed with a systematic tile drainage system, with a tile spacing of 9.1 metres (30 feet) and an average depth of 0.85 metres (2.8 feet). An outlet was installed at the edge of the field in order to measure the flowrate at the outlet. Since the water table depth between the different replicates in the free drained fields were more consistent, the yield analysis was done for the free drained fields. The water table depth was continuously measured during the growing season at nine (9) different locations within the free drained field in order to measure the water table difference at different locations between two tiles. Weather data was also collected at the edge of the field to collect temperature and precipitation data.

3.2.3 Instrumentation and Data Collection:

3.2.3.1 Water Table Depth

Water table depth was measured at nine (9) different locations using observation wells located within the free drained field. The observation wells were installed manually using a 2-inch Dutch auger at depths of 2.5-3.5 metres below ground. A 2-inch outside diameter PVC pipe was used for each well with 3/8-inch holes drilled along four (4) sides. The water table depth was measured in each field using a Solinst levelogger (Solinst Levelogger Model 3001, Solinst Canada, Ltd., Georgetown, ON, Canada) place in each of the observation wells. The levelogger data was calibrated using barometric pressure measured by a Solinst barologger (Solinst Barologger Model 3001, Solinst Canada Ltd., Georgetown, ON, Canada). Each of these loggers were set-up to record the water table head every five (5) minutes. Manual readings were also collected to calibrate the water table depth. The measuring wells were buried with the leveloggers left inside during the growing season and therefore only collected data for 135 days between June 13, 2018 and October 30, 2018. The water table depth was measured at three different distances along a transect from the tile i.e. at the tile, at the quarter-way as well as at the half-way point between adjacent tiles. A total of nine (9) observation wells were located in the field along three different transects.

3.2.3.2 Precipitation Recording

A WatchDog weather station (WatchDog 2000 Series Weather Station Model 2900ET, Spectrum Technologies Inc., Aurora, Il, USA) was utilized to measure the temperature, precipitation, wind direction, wind gust, wind speed, and dew point on a daily basis. Weather data was collected every 15 minutes for the duration of the growing season. The producer was not equipped to apply any irrigation during the growing season, so precipitation is limited to any rainfall collected by the WatchDog weather station.

3.2.4 Agronomic Protocols

Using the data collected from the 2011 Census of Agriculture, 95% of all grain corn produced is grown in some type of a rotation with another field crop, such as hay, soybeans or another cereal (Statistics Canada, 2015). In Ontario, tillage has been found to increase yields by 5-7% for 70% of the time if done after cereals, grain corn or soybeans. Tillage can also improve drainage and has the potential to reduce residue cover as well as loosen the soil to increase soil dry-down before planting (OMAFRA, 2018). For this study site, vertical tillage was completed in November 2017 using a Sunflower Disk. Swine manure was also applied in the fall of 2017. In the spring 2018, the field was cultivated upslope. Using a liquid starter fertilizer, the corn was seeded on May 2, 2018. As part of a yield analysis, hand harvesting was completed on October

22, 2018, the remainder of the field was harvested by the producer the following day. Hand harvesting was carried out on 10 m long strips near each of the nine (9) measuring wells within the field. This method had nine (9) harvest rows in the free drained field; three rows were harvested over the tiles, at the quarter-way between the tiles as well as the half-way point between the tiles. A total of three (3) different sub-samples with three (3) replications were collected for the entire site. Hand harvesting was completed in one day, and stored at the Agriculture and Agri-Food Canada Research and Development Centre in London, Ontario in order to dry before the corn was processed.

3.2.5 Post-Harvest Processing

A corn quality analysis was completed for each of the hand harvested rows. All handling of the corn post-harvest was completed at the Agriculture and Agri-Food Canada Research and Development Centre in London, Ontario. A corn sheller was used to collect the kernels from each harvest section to determine the total weight of the yield. To complete a corn quality analysis, two different sized round-hole grain sieves were used with the 24/64 sieve on top and the 14/64 sieve on the bottom. The sieves were used to separate the kernels into oversized kernels, standard size kernels, and all remaining material that passed through the 14/64 sieve otherwise known as dockage. Once the kernels had been sieved, those kernels that did not pass through the 24/64 sieve were collected and weighed as the over-sized kernels. The kernels that passed through the 24/64 sieve, but remained on the 14/64 sieve were collected and weighed as the standard size kernels, and anything that passed through the 14/64 sieve was collected and weighed as the dockage. The average moisture content for each row was determined using a grain moisture meter. Using the standard size kernel weight, the total yield weight, as well as the average moisture content for each hand harvest row, the yield was corrected to 15% moisture content.

3.2.6 Statistical Analysis

A comparison of means was completed using a T-test (MS Excel, Ver. 2010, Microsoft Corporation) within the free drained field at a significance level of 0.05. This included comparisons between the three different measuring locations along the transect between two tiles; i.e. at the tile, at the quarter-way as well as at the half-way point between two tiles for the corn yield and corn quality. The relationship between the average water table depth within different growth period and the final corn yield was also evaluated. A comparison of means was also completed using a T-Test (MS Excel, Ver. 2010, Microsoft Corporation) for the corn yield between different locations and growth periods, and different SEW_{30} and SEW_{70} index values. The SEW_{70} index was calculated using the top 70 cm of the soil profile.

3.3 RESULTS AND DISCUSSION

3.3.1 Weather Data for Study Site

The precipitation data was collected on-site during the 2018 study year and compared against the 30-year (1981 – 2010) average reported by Environment and Climate Change Canada (ECCC, 2018a). Figure 3-1 illustrates the monthly precipitation difference over the 2018 growing season in millimeters (mm). The 30-year average for total precipitation between May and September is 457 mm. During the 2018 growing season, the average was found to be 489 mm (ECCC, 2018a). Although the 2018 growing season precipitation average is similar to the 30 year average, the monthly totals do not line up. As illustrated in figure 3-1, May, July and August were found to have monthly precipitation greater than the average, with August having more than double the average precipitation. The precipitation totals in June and September were found to be below the average, by less than half. During the 2018 growing season, the total precipitation was found to be 7% greater than the 30-year average.

During the 2018 growing season, the observed average T_{max} and T_{min} were 25°C and 13.9°C respectively. These values were found to be above the 30 year average for T_{max} and T_{min} of 22.6°C and 11.4°C respectively (ECCC, 2018a).

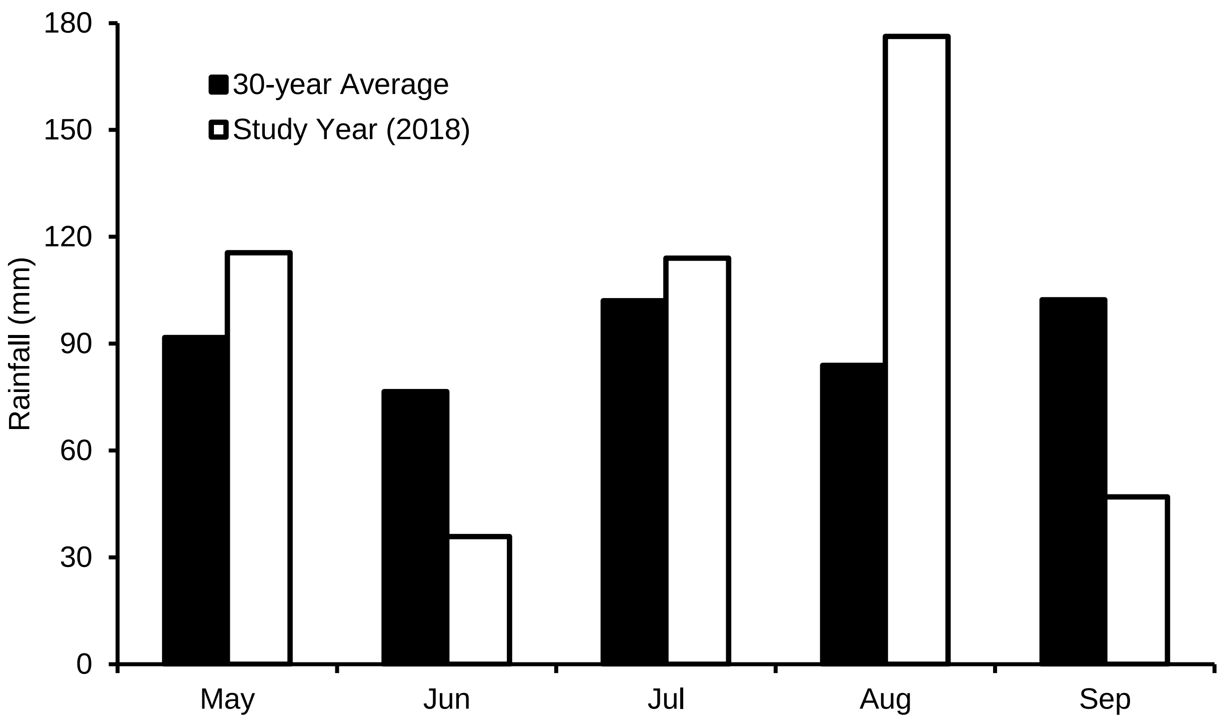

Figure 3-1: Comparison of Precipitation between the 30-year Average and Study Year of 2018

Although May, July and August were found to have a greater depth of precipitation in comparison to the 30-year average, only five events were observed to have precipitation greater than 30 mm. The first two events fell at the beginning of May. The third of these events fell at the end of July, followed by two events at the beginning of August that were two days apart from each other. During June and September, precipitation volume was less than half of the 30-year average, but precipitation fell for 60% of the days during each month. During the 2018 growing season, the maximum precipitation that was observed was 54 mm at the end of July. Almost half of the precipitation that fell during the month of August was during the first week of August during the two events listed above. This field site is flat with very low potential for surface runoff.

3.3.2 Corn Yield and Quality Analysis

The 2018 growing season was a total of 174 days; from May 2, 2018 until October 23, 2018. The yield results between the different locations within the free drained field are illustrated in figure 3-2 for the standard sized kernels, oversized kernels as well as for the total yield on average for all locations. The average 10-year corn yield in Ontario for 2007-2016 was found to be 9.74 Mg ha^{-1} according to data from the Field Crop Reporting Series (OMAFRA, 2018, 2014). The total yields for all of the locations within the free drainage fields were found to be greater than the 10 year average at 15.49 Mg ha^{-1} at the tile, 14.60 Mg ha^{-1} at the quarter-way and 14.40 Mg ha^{-1} at the half-way point between two tiles.

Corn quality analysis was done by first determining the weight of each of the two different kernel sizes. As per the Post-Harvest Processing section, corn kernels were separated using two different sized sieves to obtain oversized kernels greater than the 24/64 sieve, followed by standard size kernels that did not pass through a secondary sieve of a 14/64 size. A corn quality analysis was done for three different locations, each with three replicates. A sample was collected on the tile, at the quarter-way between two tiles, as well as at the half-way point between two tiles in the field. When comparing the corn yield between the different measuring locations and kernel size groups, a significant difference ($p < 0.05$) was found between the tile data, and the quarter-way and half-way measuring locations. For the standard sized corn kernels, a statistical difference ($p < 0.05$) was only observed between the tile data and the data at the quarter-way location. For the oversized yield data, as well as the total yield data, a statistical difference ($p << 0.05$) was found between the tile and the quarter-way location, as well as the tile and the half-way location. The total yield for the tile data was found to be 6% ($p = 0.03$) and 7% ($p << 0.05$) significantly higher in corn yield than the quarter-way and half-way points respectively.

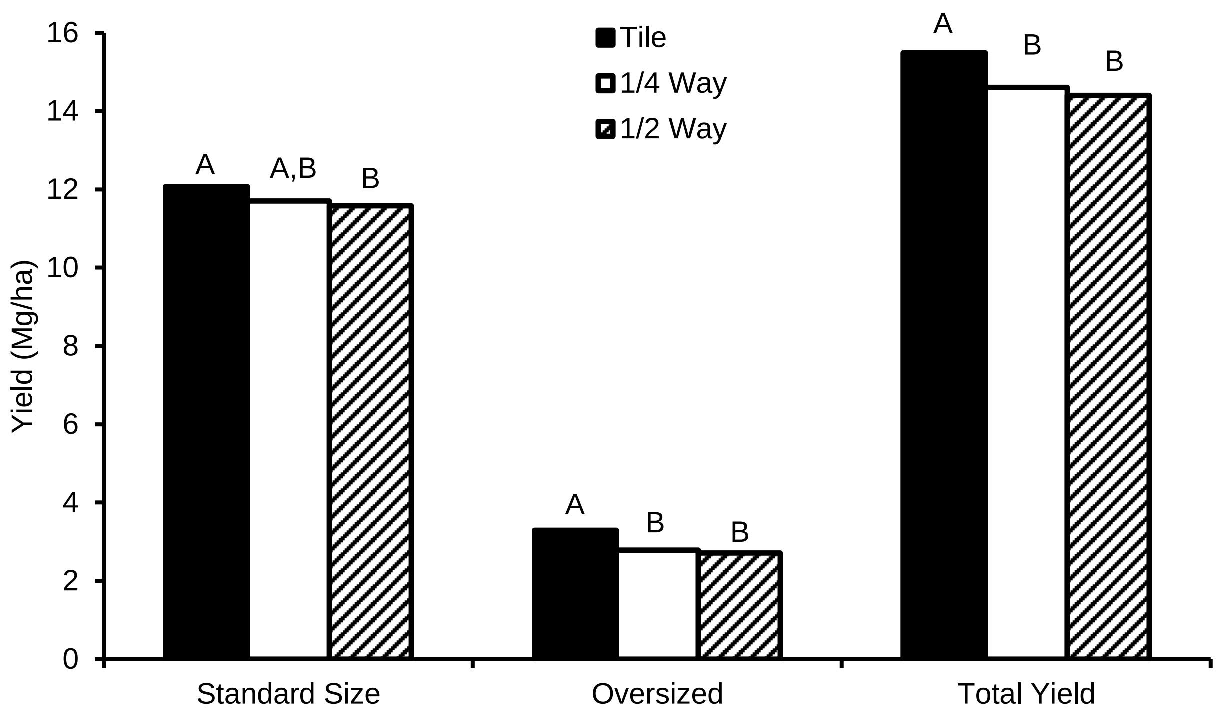

Figure 3-2: Comparison of Corn Yield for Standard Size Kernels, Oversized Kernels and Total Yield during the 2018 Growing Season between the Tile, Quarter-Way (1/4 Way) and Half-Way (1/2 Way) locations between two tiles. Levels not connected by same letter within a size group are significantly different

The corn quality proportion was also compared against the total yield for the standard size kernels and the oversized kernels for each of the locations in the tile transect. The portion of the standard size kernels were found to be significantly ($p < 0.05$) greater in the quarter-way and half-way locations when compared against the tile location. No significant difference was observed between the quarter-way location and the half-way location between two tiles. The portion of the oversized kernels were found to be significantly ($p < 0.05$) greater along the tile compared to either the quarter-way or the half-way location. No significant difference was observed between the quarter-way or the half-way location between two tiles. A larger portion of standard size kernels was observed in the quarter-way and half-way location indicating greater access to moisture at these locations within the tile transect. These locations would have a higher water table and therefore more moisture available within the corn root zone. Results from a study by Abbas and Sri Ranjan (2017) had similar findings when comparing corn yield between irrigated and non-irrigated corn field.

Other factors that were not considered to have an impact on these results include: precipitation and soil as these factors are the same for the study area; crop disease, pest pressure and weed growth were not measured, but incidental observation did not indicate any influence; equipment applied parameters were assumed to be uniform.

3.3.3 Water Table Depth Impact on Corn Yield Analysis

Water table depths were measured at three different locations between tile drains with three replicates in each of the free drained fields. These locations were on the tile, at the quarter-way between two tiles as well as at the half-way point between two tiles. Whenever there was a gap in data due to equipment issues, the water table values from the other sites within the same transect were used to determine the approximate water table depth for the missing value. Total corn yields were used to compare with the average water table depths for each location between the tiles at three different growth stages of the corn. The three stages of growth are comprised of the following: the initial growth period, which consists of the vegetative stages between planting and silking; the mid growth period, which looks at half the reproductive stages between silking and dough; and the final growth period, which looks at the last half of the reproductive stages between dough and maturity of the corn crop. During the entire corn growth cycle, the only precipitation added was by rainfall.

For the experimental site, a scouting camera was used to monitor the corn growth during the growing season. The pictures from this camera were used to assist in determine the approximate point in the growth cycle that indicated a change in the growth period. During the 2018 growing season, the initial period was from May 2 to July 20 at which point the corn reached the silking stage. The mid period was from July 20 to August 15, at which point the corn reached the dough stage. The final period was from August 15 to the end of the growing season. During the initial period of the growth cycle a total of 186 mm of precipitation was recorded at the field site. During the mid period of the growth cycle a total of 164 mm of precipitation was recorded, and 147 mm during the final period of the growth cycle. During the mid period, nearly half of the precipitation fell during two (2) events at the beginning of August that were two (2) days apart, with another event at the end of July that was 54 mm in size. The study by Zipper et al. (2015) found that when the water table depth was between 1-3 metres had a strong yield during a wet and a dry season. Parts of the field that were < 1 m had a negative impact on the yield during a wet year and for parts of the field that had the water table depth > 3 m had poor yield response no matter what that type of growing season. When the water table in the equipment site was below the tile it would result in a strong yield, and when the water table depth was less than a meter below the surface the yield would be negatively impacted during a wet year. Based on the results from the present study, the average water table depth was greater than one metre below the surface during the initial and mid period, and was between 0.7 and 0.9 during the final growth period as per figure 3-3. The total precipitation for the 2018 growing season was similar to the 30-year average, so would not be considered a wet year, which indicates from the Zipper et al. (2015) study that the yield would not be negatively impacted by the water table depth being less than a metre below the surface. The yield for this site was found to be greater than the Ontario average yield. Figure 3-3 illustrates the total corn yield compared with the average water table depth at different growth stages.

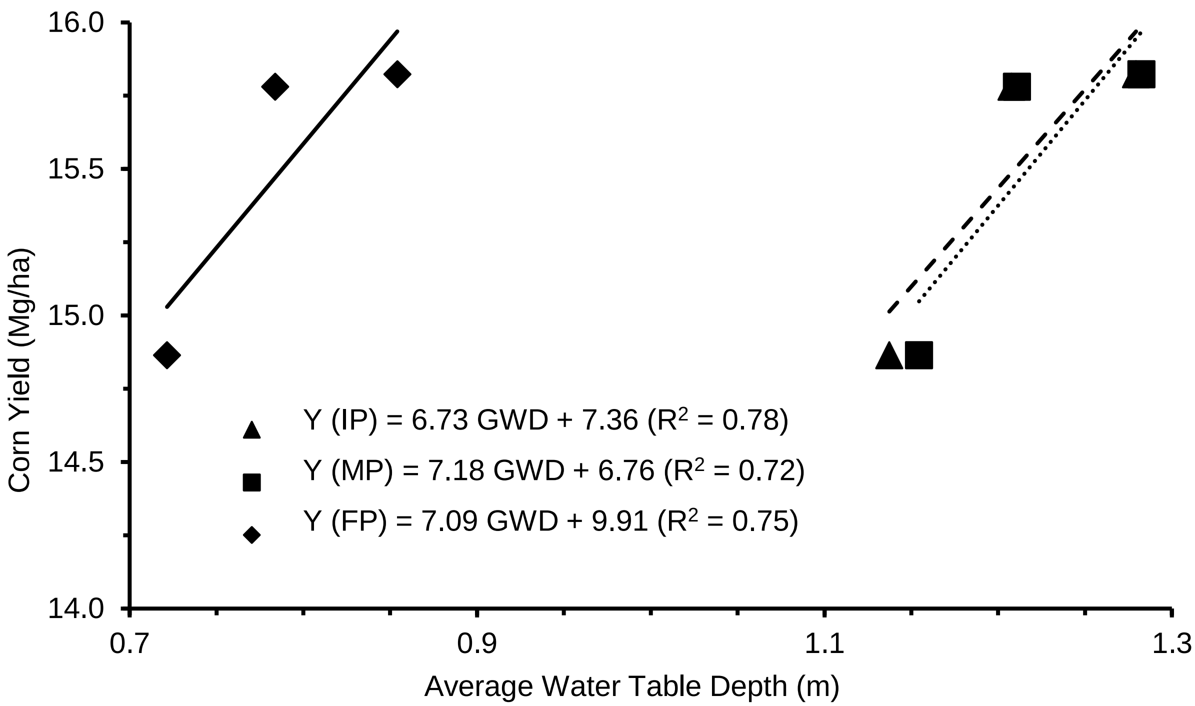

Figure 3-3: Relationship between the average water table depth at the tile, the quarter-way point and half way point between two tiles against corn yield during different stages of growth. Dashed, dotted and continuous lines correspond to the Tile, Quarter-Way and Half-way locations between two tiles respectively. GWD is for ground water depth, IP is for Initial Period, MP is for Mid Period and FP is for Final Period**.**

For each of the water table measuring locations within the free drained field, the results indicated a positive correlation between the water table depths and the total yield during each of the growth stages. The average water table depths during each of these stages were found to have a significant difference ($p < 0.05$) for each location between tiles in the transect, as illustrated in figure 3-4. Based on the average water table depths between the tile transect, a water level difference of as little as 8.5 cm during the final stage and 12 cm during either the initial period or the mid period of the growth cycle resulted in a significant difference in corn yield. This indicates that water table management can have a significant impact on corn yield during the growing season.

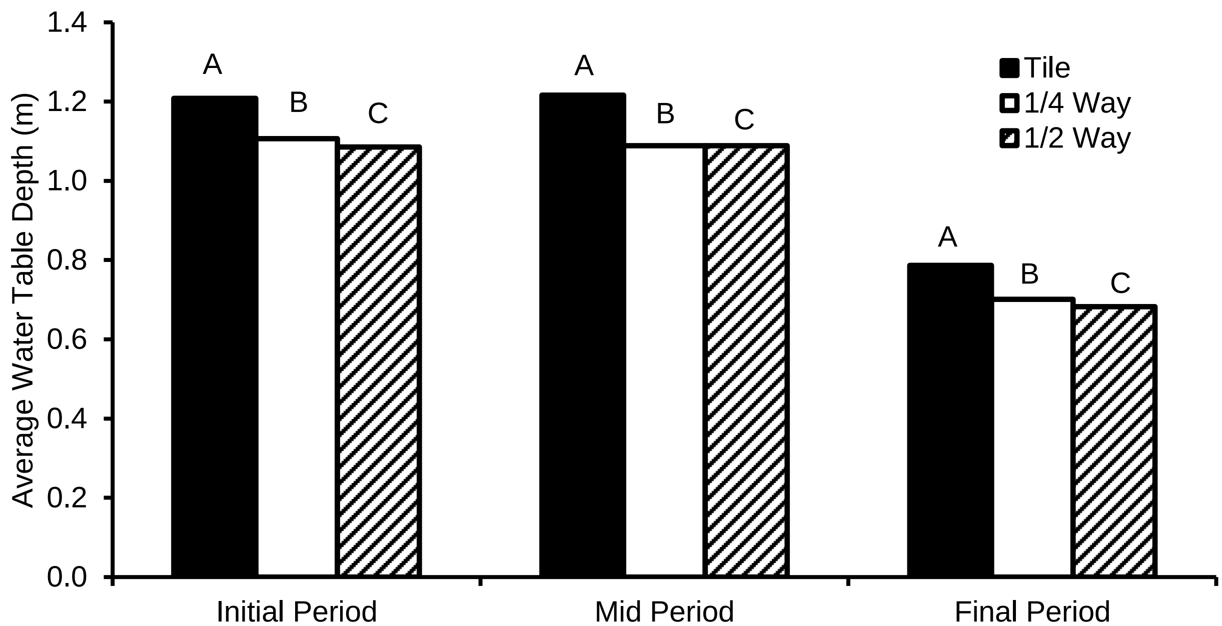

Figure 3-4: Comparison of the Average Water Table Depth at the tile, quarter-way (1/4 Way) and half-way (1/2 Way) points between two tiles during three different growth periods; Initial Period, Mid Period and Final Period. All levels were found to be significantly different within each growth period.

Although the average water table depths was found to be below the tile drainage level during the initial and mid growth periods, the daily average water table depth did have days above the tile. During the initial growth period, the average daily water table height was observed to be above the tile between June 23 and July 3, 2018 for 11 consecutive days for a total of 15% of the initial growth period. During the mid-growth period, the average daily water table height was observed to be above the tile on July 25, 2018, between August 8-15, 2018 and between August 17-20, 2018 for a total of 36% of the mid growth period. The average daily water table height remained above the tile into the final growth period from August 21 to September 7, 2018, as well as from September 25, 2018 to when the corn was harvested on October 23, 2018 for a total of 73% of the final growth period. Although the number of days that the water table was above the tile was low during the initial and mid growth periods, they have been found to have a significant impact on the corn yield, as they all have similar slopes in fig. 3.

3.3.4 Excess Moisture

Water table depths were measured through-out the growing season to determine the excess soil water conditions as quantified by the SEW_{30} index, which is a sum of the number of days times the height in cm of the water table within the top 30 cm from the ground surface, for each measured location within the tile transect. The average SEW_{30} index observed on the tile, at the quarter-way and the half-way point between the tiles were 1.88 cm-day, 30.42 cm-day and 41.34 cm-day, respectively. Wesseling (1974) found that when the SEW_{30} index was between 100 to 200 cm-days, there was a significant decrease in corn yield. However, even smaller SEW_{30} index seems to have an impact on corn yield. Average SEW_{50} index and SEW_{70} index were also determined at each location to determine a correlation with the total corn yield.

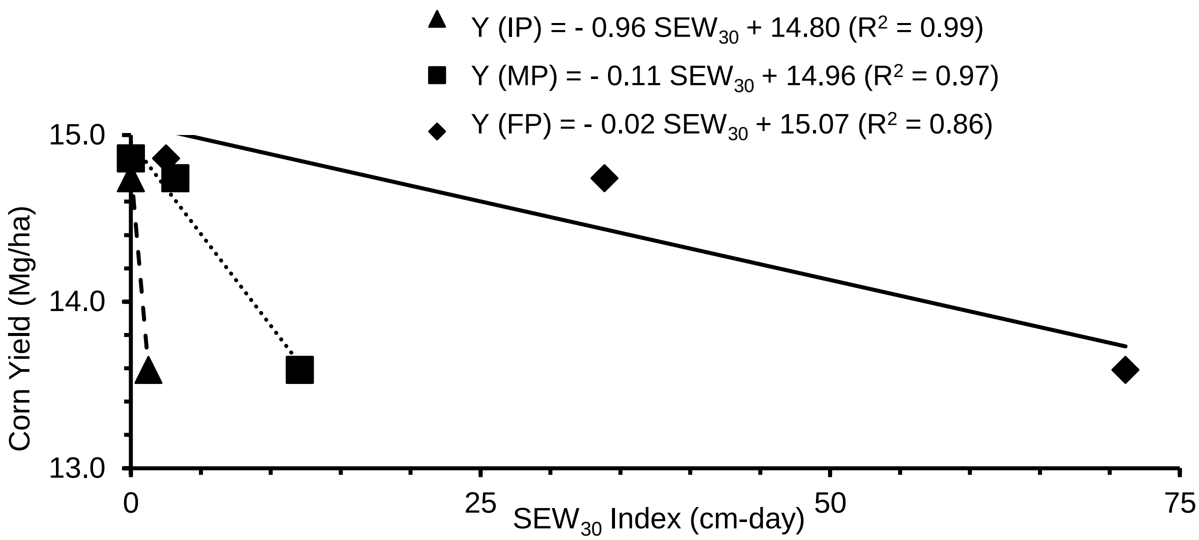

Figure 3-5: Relationship between the SEW_{30} index at the half-way point between two tiles during the three growth periods. Dashed, dotted and continuous lines correspond to the initial growth period, mid-growth period and final growth period, respectively. IP is for Initial Period, MP is for Mid Period and FP is for Final Period.

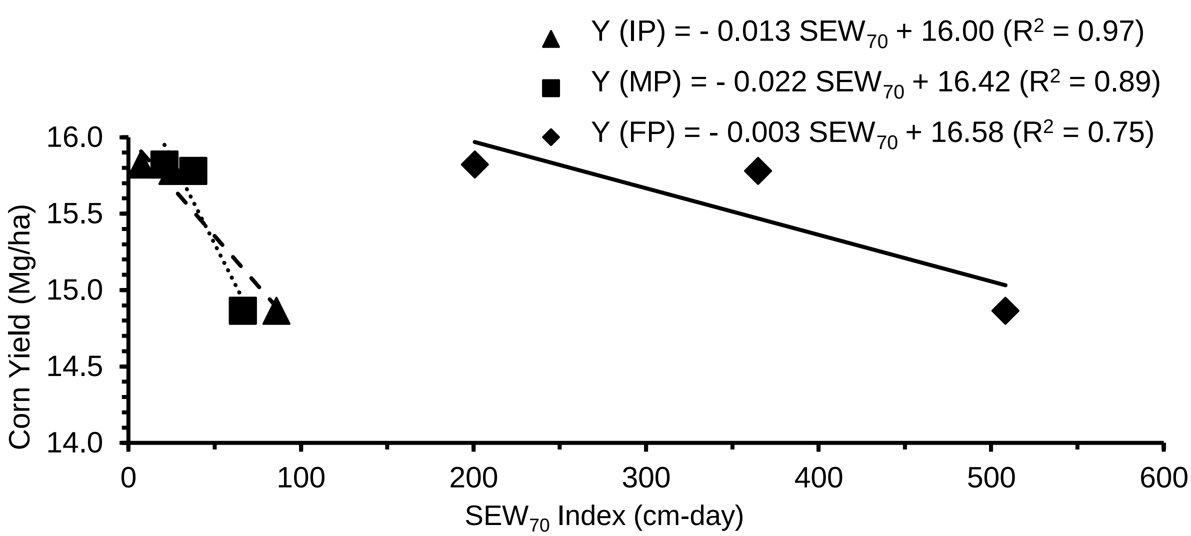

Figure 3-6: Relationship between the SEW_{70} index on the tile during the three growth periods. Dashed, dotted and continuous lines correspond to the initial growth period, mid-growth period and final growth period, respectively.

The SEW indices during each growth period were compared against the total corn yield along the tile transect. Figures 3-5 and 3-6 illustrate the strongest correlation between any of the SEW index values at different locations in the transect between tiles. During the three growth periods, the SEW_{30} index and the SEW_{70} index was found to have a negative correlation to the total corn yield at the half-way point between the tiles and on the tiles, respectively. The SEW_{70} index determined for the entire growing season was found to have a significant difference ($p < 0.05$) for each location between tiles in the transect. This indicates that the water table depth within the root-zone at depths up to 70 cm below the ground surface can have a significant impact on corn yield.

3.4 CONCLUSION

The objective of this study was to determine the impact of water table depth during different stages of corn growth on corn yield and quality under southern Ontario conditions. When comparing the total corn yield within the tile transect, a significant difference ($p < 0.05$) was observed between the row of corn growing just above the tile drain compared to quarter-way and half-way between the tiles. The corn harvested over the tile had a 6% higher yield over the quarter-way location, and a 7% higher yield over the half-way location. The average water table depths during each of the different growth stages were found to have a significant difference ($p < 0.05$) between the three different locations within the tile transect. The difference in average water table depths, within each growth stage, between the tile and the quarter-way point ranged between 8.5 and 11.0 cm. Similarly, the difference in average water table depths, within each growth stage, between the tile and the half-way point ranged between 10.0 and 12.0 cm. These results indicate that even a small difference in water table depth during different stages of growth can have a significant impact on corn yield. The SEW_{70} index was found to be significantly (p <

0.05) different between the three different locations within the tile transect, and was found to have a negative correlation to the total corn yield through-out the growing season. The greater the number of days and depth the water table was found to be within the top 70 cm of the root zone, the lesser the yield. Results from this study show that precise water table management through the use of drainage control structures can have the potential to increase or decrease corn yield within a field. During wetter than normal periods lowering the water table will decrease the SEW_{70} index resulting in corresponding yield increases.

4. Comparison of Reaction Factor (α) between Controlled and Free Drained Fields

ABSTRACT: Controlled drainage as a best management practice can be used to decrease drainage outflows, which will thereby decrease the nutrient export from a field when compared to free drainage. Through the use of drainage control structures, the water table within the field can be raised artificially to retain excess water within the soil profile in the field for longer periods of time. The reaction factor is an indicator of how fast the water table falls after a recharge event. Although controlled drainage has been found to decrease drainage outflows, the impact it has on the reaction factor has not been thoroughly investigated. The objective of this study was to measure drainage discharge rates to calculate the reaction factors for controlled drainage versus free drainage systems due to different recharge events. Water table elevation changes as a function of time at mid-spacing of tiles were used to determine the reaction factor. Since controlled drainage increases the depth to the impervious layer, it is expected that the drainage intensity would be greater soon after the gates in the controlled drainage structures are opened compared to free drainage systems. The reaction factor in the controlled drainage field was found to be 71% significantly ($p << 0.01$) greater than the free drained field during the spring soon after the gates in the drainage control structure were opened in preparation for field operations prior to planting.

4.1 INTRODUCTION

Agricultural drainage systems have an important function in the agricultural landscape, and are widely used across Ontario. Data from 2000 indicate that an average of 27.4 million metres of tile drainage have been installed annually within Ontario with an annual value of $50 million (LICO, 2000). This works out to approximately 43,706 hectares of land per year for a total of 1.2% of the 3.65 million hectares of total crop land in Ontario (Statistics Canada, 2016).

There are a number of benefits using tile drainage, such as removing excess moisture from the field, rapid lowering of the water table, and increased aeration. Tile drainage can also aid in improving soil health by increasing the oxygen levels in the field, which in turn stabilizes the soil structure and can increase nitrogen uptake in the soil (Ritzma, 2006). An additional benefit caused by the improvement of soil health is to reduce surface runoff and soil erosion. By removing excess moisture from the field, access to the field can be sooner due to drier soil conditions (Ritzma, 2006). Since tile drainage removes excess water from the field, it can also remove nutrients from the field through the tile outlets. Using controlled drainage as a best management practice has been found to decrease the loss of nutrients from a tile drained field (Cordeiro et al., 2014; Drury et al., 2009; Madramootoo et al., 1993; Satchithanantham et al., 2014; Tolomio and Borin, 2018; Williams et al., 2015). Although controlled drainage has not been widely implemented across agricultural landscapes, there are a number of benefits to its application. These benefits include the reduction of nitrogen and phosphorus loss, as well as the ability to increase crop yields (Drury et al., 2009; Sunohara et al., 2014; Wesström and Messing, 2007).

Controlled drainage uses the application of a drainage control structure at the drainage outlet to hold back water to raise the water table within the field to the desired depth. This is done by installing adjustable stop-logs or gates to raise the water table height (Irmak and Rudnick, 2014). By increasing the water table height above the drain, the height of water above the impervious layer also increases.

Gilliam et al., (1979) examined the application of raising the water table through the use of controlled drainage (CD) and found that this application caused de-nitrification within the soil profile, which converted nitrate (NO^{3-}) to N_2 gas. The findings from this study indicated that CD technology could increase yields and reduce nitrate loading from tile drainage runoff. Other studies such as Tan et al., (1993), Lalonde et al., (1996); and Drury et al., (2001) were also successful in demonstrating this under different climate and soil conditions. Little is known on how the use of CD will impact the reaction factor (α) compared to free drainage.

Research has been conducted on the impact of the application of CD with other BMPs, such as fertilizer application rate (Drury et al., 2009, 1997; Elmi et al., 2000); cover crops (Drury et al., 2014); tillage (Tan et al., 1993) and optimal water table depths (Mejia et al., 2000). Research has also been conducted to examine the impact of CD on phosphorus removal (Cordeiro et al., 2014; Sunohara et al., 2016; Tan and Zhang, 2011; Valero et al., 2007). However, no research studies have been found on the influence of control drainage and tile drainage on the reaction factor.

The rate at which excess water drains from the field depends on the tile spacing, height of the mid-spacing water table above the drains, installation depth, and soil properties of the field (Smedema et al., 2004; Waller and Yitayew, 2016). If the tile depth and soil properties remain the same within an agricultural field, the drainage rate becomes dependent on tile spacing. The drainage discharge rate can also be described as the reaction factor (α), which is an indicator of the intensity with which the drains respond to a recharge event (Smedema et al., 2004). The reaction factor can be described as either having a slow response or a rapid response, with values ranging from $\alpha = 0.1 – 0.3$ and $\alpha = 2.0 – 5.0$ respectively.

The reaction factor has been described by the following relationship based on the Glover-Dumm drainage formula (Smedema et al., 2004):

$$\alpha = \frac{\pi^2 K d}{\mu L^2} \quad 4.1$$

where, α is the reaction factor in day^{-1}, K is the hydraulic conductivity of the soil (m/day), d is the equivalent depth to the impermeable layer (m), μ is the drainable pore space, which is dimensionless and L is the drain spacing (m).

Since the drainable pore space (μ) is difficult to determine, the reaction factor can be estimated through observations made in the field. The following relationships can be used to determine the reaction factor based on observed values of the water table head at the mid-spacing between tiles as well as the drainage discharge rates (Smedema et al., 2004).

$$\alpha = 2.30 \frac{\log q_{t-1} - \log q_t}{\Delta t} \quad 4.2$$

$$\alpha = 2.30 \frac{\log h_{t-1} - \log h_t}{\Delta t} \quad 4.3$$

where, q is the observed drainage discharge rate at time t and t-1, h is the observed water table height above the drain at time t and t-1, Δt is the difference between time t and t-1. In order to determine the reaction factor, a plot of the log of the drainage discharge rate as a function of time can be used. A plot of the log of the water table height at mid-spacing between the tiles as a function of time can also be use. The reaction factor is the slope of the aforementioned plots, which should follow a straight line through the data points (Smedema et al., 2004).

Saadat et al. (2017) considered optimal management strategies for control drainage to reduce the water table level around a rainfall event to prevent any negative impact on field trafficability or crop yield. This was done by considering the impact controlled drainage had on the time it took for the water table to fall to a desired level following a rainfall event. For this study, two paired sites of controlled drainage and free drainage were compared in Indiana over a nine (9) year period by lowering the outlet of the DCS either before or after a rain event. The results of this study found that lowering the water level at tile outlet by removing the number of gates in the DCS just prior to a rain event would reduce the amount of time it took for the water table to drop in the CD fields.

Through the use of drainage control structures, the water table can be raised artificially to retain excess water within the soil profile in the field for longer periods of time. By raising the water table, the soil profile will be more saturated than a field under free drainage. Since controlled drainage increases the depth to the impervious layer, it is expected that the drainage intensity would be greater when the gates in the controlled drainage structures are opened compared to free drainage systems. The results from Saadat et al. (2017) indicated that by removing the gates prior to a rain event the water table depth would drop faster in the CD fields.

Although controlled drainage has been found to decrease drainage outflows, the impact it has on the reaction factor has not been thoroughly investigated. There has not been much research reported looking at the change in reaction factor under controlled drainage. There is a knowledge gap about the impact that raising the water table by controlled drainage has on the rate at which a field will drain in comparison to a field under free drainage. The objective of this study was to measure drainage discharge rates to calculate the reaction factors for control drained versus free drained fields soon after different recharge events. Water table heights at the mid-spacing between tiles were also used to determine reaction factor. Since controlled drainage increases the depth to the impervious layer, it is expected that the drainage intensity would be greater under these conditions when compared to free drained fields.

4.2 MATERIALS AND METHODS

4.2.1 Study Sites

The measuring site was located near Lucan, Ontario, Canada, which is 30 km north-west of London, Ontario, Canada. Data was collected between April 2015 and October 2017 on a field with controlled drainage and free drainage. The field was in a corn-corn-soybean rotation, with a typical growing season falling between May and October (OMAFRA, 2017). The 2015 and the 2017 growing season were in corn, and the 2016 growing season was in soybeans. The soil type in this field ranged from 60% Brantford-Toledo soil to 40% Brant-Colwood soil with poor drainage and nearly level slope with a soil texture of silty loam to silty clay loam (Hagerty and Kingston, 1992). Under silty loam soils, the effective rooting depth of corn and soybeans range from 0.9 – 1.2 metres and 0.6 – 0.9 metres respectively (Irmak and Rudnick, 2014). The average temperature for this location ranged from 13 to 20°C, with an average precipitation accumulation of 455 mm between the months of May and September (ECCC, 2018a). The optimum planting date for corn near London, Ontario is after April 26, when the soil temperature should be above 10°C, since the crop heat unit (CHU) is greater than 3,000 CHU-M1 (OMAFRA, 2017).

4.2.2 Experimental Design

In May of 2014, the 14-hectare field selected for this project was divided into three different fields and a systematic tile drainage system was installed throughout the entire field. 9.2 hectares (22.8 acres) was set-up as a free drained (FD) field. The remaining 5 hectares (12.4 acres) was split into two separate control drained (CD) fields, with CD-1 having 2.3 hectares (5.6 acres) and CD-2 having 2.7 hectares (6.7 acres). Outlets were installed at the edge of each of the three sections. The tiles were installed at 9.1 metre (30 feet) spacing, with an average depth of 0.85 metres (2.8 feet). A drainage control structure (DCS) was installed at the outlet of each of the two CD fields to enable independent water table control in each field. Using the stop logs or gates in the DCS, the water table height was maintained at 50 cm below the ground surface between the end of October and the beginning of April, as well as between the middle of May and the beginning of October. The stop logs were removed just prior to planting and harvest for each growing season, and maintained at 50 cm below the surface during the remainder of the year. During the 2015 & 2017 growing seasons the field was in corn, and during the 2016 growing season the field was in soybeans. In order to determine the reaction factor, the water table head at mid-spacing between the tiles and the tile drainage discharge rate were measured. Soil water content was measured within each field, as well as precipitation and temperature using a weather station at the edge of the field.

4.2.3 Instrumentation and Data Collection

A site map of the equipment layout for this site is illustrated in Figure 4-1, where the equipment used to collect data are outlined in sections 4.2.3.1 to 4.2.3.4.

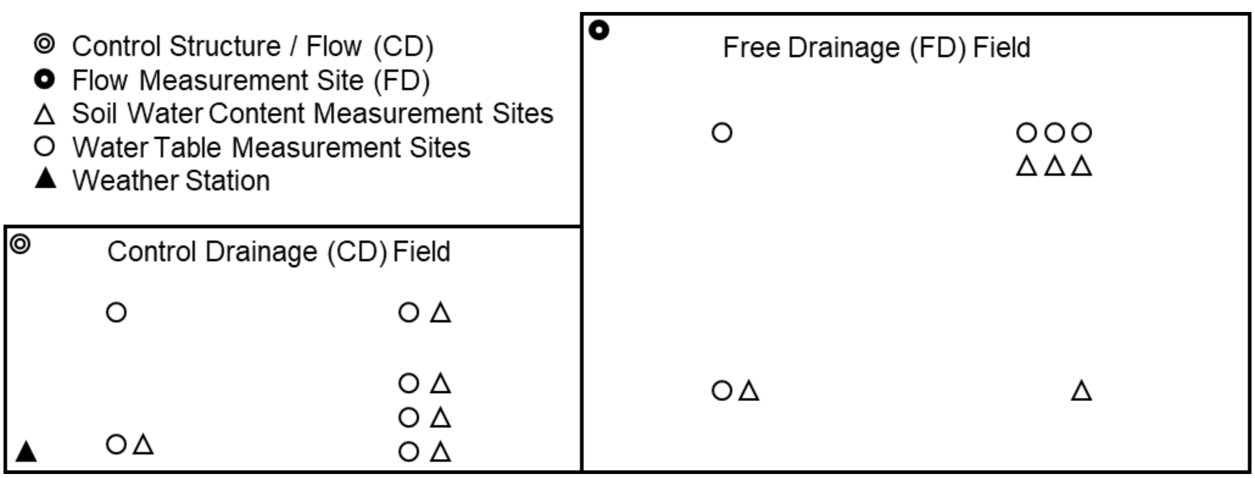

Figure 4-1: Site Map

4.2.3.1 Water Table Depth Measurements

Observation wells were installed using a Dutch auger at 2.5-3.5 m below ground. Each well consisted of 2-inch diameter PVC pipe with 3/8-inch holes drilled along four (4) sides of the pipe. The water table level was measured using a Solinst Levelogger (Solinst Levelogger Model 3001, Solinst Canada, Ltd., Georgetown, ON, Canada), which was installed in each of the water table measuring wells. The Levelogger was programmed to record the water table head every 15 minutes. The barometric pressure was also measured using a Solinst barologger (Solinst Barologger Model 3001, Solinst Canada Ltd., Georgetown, ON, Canada), which was located along the edge of the field as a correction factor for the water table data. Manual readings were taken monthly for the purpose of calibrating the Levelogger readings. In order to determine the reaction factor, water table head values were obtained by installing measuring wells at six (6) different locations within the CD-2 field, as well as five (5) different locations within the FD field all at the mid-spacing point between the tiles. Multiple sites were used for the purpose of replication. Water table depth was measured from June 2016 until October 2017.

4.2.3.2 Soil Water Content Measurements

Soil water content was measured using EC-5 sensors (Decagon Devices, Pullman, WA) connected to an EM-50 datalogger (Decagon Devices, Pullman, WA). The sensors were installed at five different depths; 0.15, 0.30, 0.45, 0.60 and 0.75 m below the ground surface. The top sensor at 0.15 m also measured soil temperature. The EC-5 sensors measured the volumetric soil water content in m^3/m^3. The soil water content measuring sites were located near the piezometers used for measuring the water table depth. The datalogger was programmed to collect data points every 15 minutes when installed in the field. For the purpose of this study there were five (5) different sites instrumented with soil water content measuring equipment in each of the control drained and free drained fields.

4.2.3.3 Tile Discharge Rate Measurements

The tile discharge rate was measured through the use of a Hach datalogger (Hach FL900 Series Flow Logger, Hach, Loveland, CO, USA) and flowmeter sensor (FLO-TOTE 3 AV Sensor, Hach, Loveland, CO, USA). The sensor was located at the drainage outlet at the edge of each field. A tile outlet was constructed to provide the minimum pipe size of 6-inches required for the Hach flow sensor complete with the required smooth pipe with five times the pipe diameter upstream and ten times the diameter downstream. The datalogger was programmed to record the flowrate every 15 minutes. The flowmeters were installed for the duration of the study period.

4.2.3.4 Precipitation Measurements

A weather station was located on the site (WatchDog 2000 Series Weather Station Model 2900ET, Spectrum Technologies Inc., Aurora, Il, USA) to measure the temperature, precipitation, wind direction, wind gust, wind speed, and dew point on a daily basis. No irrigation was applied to the field, so precipitation values are limited to WatchDog precipitation values recorded. Supplementary weather data was used from a weather underground site (Weather Underground, 2018) located 10 km west of the study site, as well as from Environment Canada (ECCC, 2018b) located 22 km south-east of the study site. These data sets were only used to fill gaps in data when the WatchDog weather station failed to record data on site.

4.2.4 Determining the Reaction Factor

The reaction factor can be determined graphically by plotting the observed water table head in metres at mid-spacing between the tiles as a function of time on semi-log paper. A similar plot can be made using the observed discharge flowrate at the tile outlet as a function of time (Smedema et al., 2004). Water table readings were corrected for barometric pressure changes. They were also calibrated using manual readings and plotted to determine the appropriate time durations required to calculate the reaction factor. Water table depths for CD and FD were selected for the same time period for comparison purposes. Flowrate values for both the CD and FD tile outlets from the same time period was used to calculate the reaction factor.

4.2.5 Statistical Analysis

The drainage control structure was managed under two separate settings; the first was to maintain the gates at a height that gave a watertable depth 50 cm below the surface; and the second was immediately after the gates were removed from the DCS. Two separate analyses were completed to compare the means of the reaction factor values in the CD and FD fields. These two scenarios were to compare the mean under gate conditions, and no gate conditions in the CD field. A one-way analysis of variance or a one-way ANOVA (MS Excel, Ver. 2010, Microsoft Corporation) was used to compare the means under these two conditions at a significance level of 0.05. Regression analysis was used to determine if there was a relationship between the reaction factor and the air temperature, precipitation, soil temperature and soil water content values (MS Excel, Ver. 2010, Microsoft Corporation).

4.3 RESULTS AND DISCUSSION

4.3.1 Weather Data for the Study Site

The precipitation data collected between January 2015 and December 2017 has been plotted in Figure 4-2, which illustrates the monthly precipitation (mm) against the 30-year (1981 – 2010) average reported by Environment and Climate Change Canada (ECCC, 2018a). The entire year has been plotted rather than just the growing season since the water table went above the tile level during the non-growing season. During 2015, a total of 1,119 mm was observed which was above the 30-year average of 1,070 mm, with a peak of 404 mm during the month of June. Precipitation was below the 30-year average, with the exception of May and June 2015. During 2016, a total of 797 mm was observed, which was below the 30-year average; precipitation was above average during February, March, June and July. During 2017, a total of 912 mm was observed, which was below the 30-year average; the precipitation was above average from March – June, but below average the remainder of the year.

Using the 30-year average during the growing season, a comparison can be made of the observed average T_{max}, T_{min}, and total precipitation values specific to the growing season of May through September. Table 4-1 illustrates the observed values against the Environment and Climate Change Canada (ECCC, 2018a) 30-year averages. The observed T_{max} and T_{min} values were all found to be above the 30-year average. The precipitation was 60% higher during the 2015 growing season, it was 40% lower during the 2016 growing season and it was 2% higher than the 30-year average during the 2017 growing season.

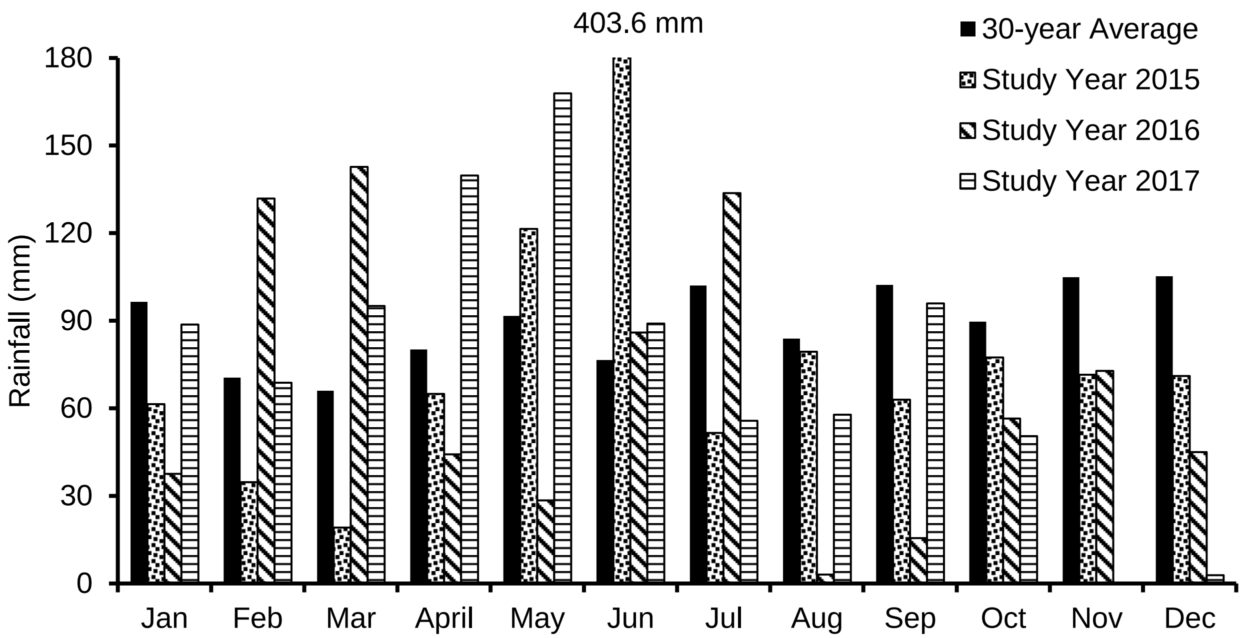

Figure 4-2: Comparison of Precipitation between the 30-year Average and Study Year of 2015 – 2017

Table 4-1: Summary of Weather during Growing Season

	T_{max} (°C)	T_{min} (°C)	Precipitation (mm)
2015 Study Year	24.1	12.7	719
2016 Study Year	25.0	13.0	267
2017 Study Year	23.4	12.2	466
30-Year Average	22.6	11.4	457

During the 2015 growing season, 3 events had precipitation greater than 60 mm with each falling before June 9, 2015. The remainder of the growing season was below average. During the 2016 growing season, only one event had precipitation greater than 60 mm observed on July 28, 2016 which accounted for half the precipitation for that month. May, August and September were below the average precipitation with June having one event near 60 mm to take June over the average precipitation for that month. Although May and June of the 2017 growing season were above average for precipitation there were no events greater than 60 mm. Precipitation events were recorded on 60% of the calendar days during this period, with July through September under the average precipitation.

4.3.2 Reaction Factor

The reaction factor was calculated using the water table recession data as a function of time immediately after a rain fall event. Figure 4-3 illustrates the water table head at two separate measuring sites for a control drained and a free drained field. This graph illustrates that for each rise in the water table, there is a precipitation event observed prior to the water table rise. To determine the reaction factor for one event, a graph was plotted for each decline in water table. A precipitation event with a corresponding drop in the water table head was selected to compare between CD and FD fields. Figure 4-4 illustrates one of these events from May 1, 2017. The period of time was kept the same between the control drained event and the free drained event for comparison purposes. To determine the reaction factor from the event period highlighted in Figure 4-4, a semi-log plot was made for the water table head at mid-spacing of the tiles as a function of time for the control drained and free drained fields. Figures 4-5 and 4-6 illustrate the semi-log plot for the free drained and control drained fields respectively. The reaction factor is the slope of the lines illustrated in Figures 4-5 and 4-6, which was found to be 1.87 day^{-1} for the free drained field and 2.55 day^{-1} for the control drained field. This event resulted in a 26% difference between the CD and FD fields. The time period of figure 4-3 through figure 4-6 fall within a month of removing the gates in the drainage control structures for spring planting. These results are in agreement with the results from Saadat et al. (2017) indicating that the field under control drainage will have the water table depth drop faster due to a rain event soon after the gates are removed.

The reaction factor can also be determined by reviewing the tile discharge rate at each of the field outlets. Figure 4-7 illustrates the tile discharge rates for the control drained and free drained fields between May and July during the 2015 growing season. During this time period, only one drainage event was observed in the controlled drainage field. This event happened between June 9 and June 11, 2015 as illustrated in Figure 4-8. Similar to the results from the water table head, a semi-log plot was done using the tile discharge as a function of time. Since the two fields are not of equal size, the discharge rate was divided by the area of each field in order to compare the two values. The reaction factor is the slope of the lines illustrated in figures 4-9 and 4-10, which was found to be 0.30 day^{-1} for the free drained field and 1.42 day^{-1} for the control drained field. This event resulted in a 79% difference between the CD and FD fields.

During the month of June 2015, a total of 404 mm of precipitation was recorded, as illustrated in figure 4-2, with a large precipitation event on June 9, 2015. Unfortunately, this site did not receive any other large precipitation events for the remainder of the study period when water table measuring sites were installed between June 2016 and October 2017.

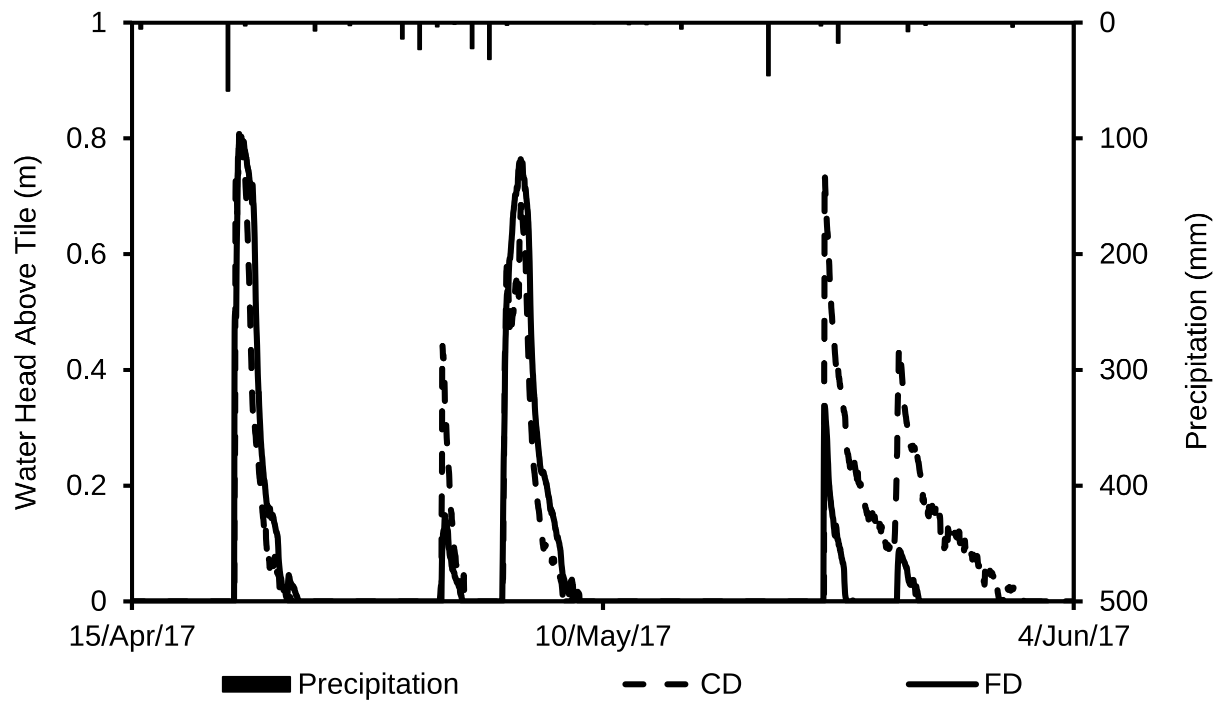

Figure 4-3: Water Table Head at a measuring site for controlled drainage and free drainage during spring 2017

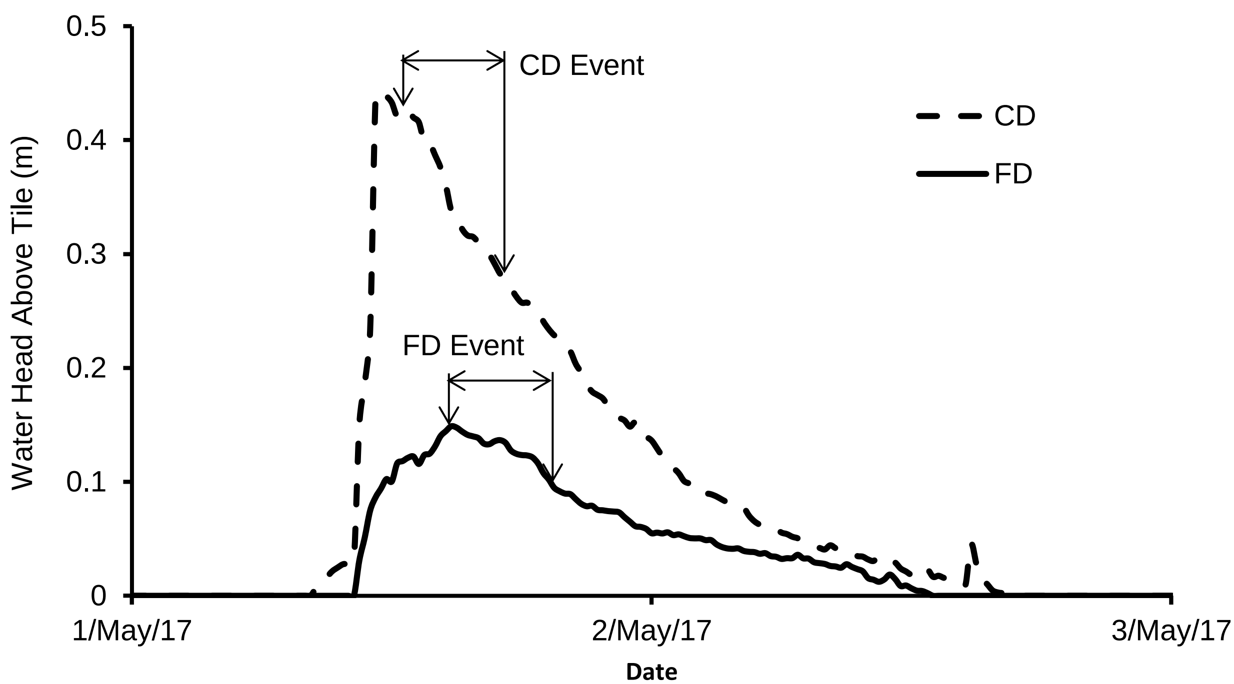

Figure 4-4: Water Table Head for one event starting on May 1, 2017

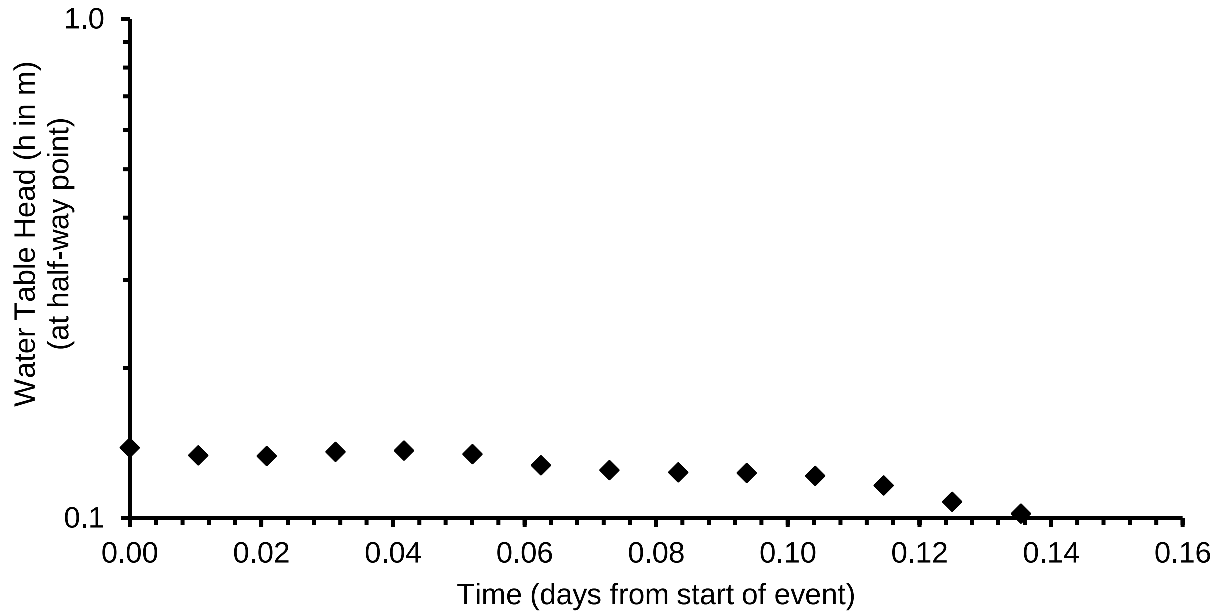

Figure 4-5: Water Table Head versus time for Free Drainage Field to determine Reaction Factor on May 1, 2017

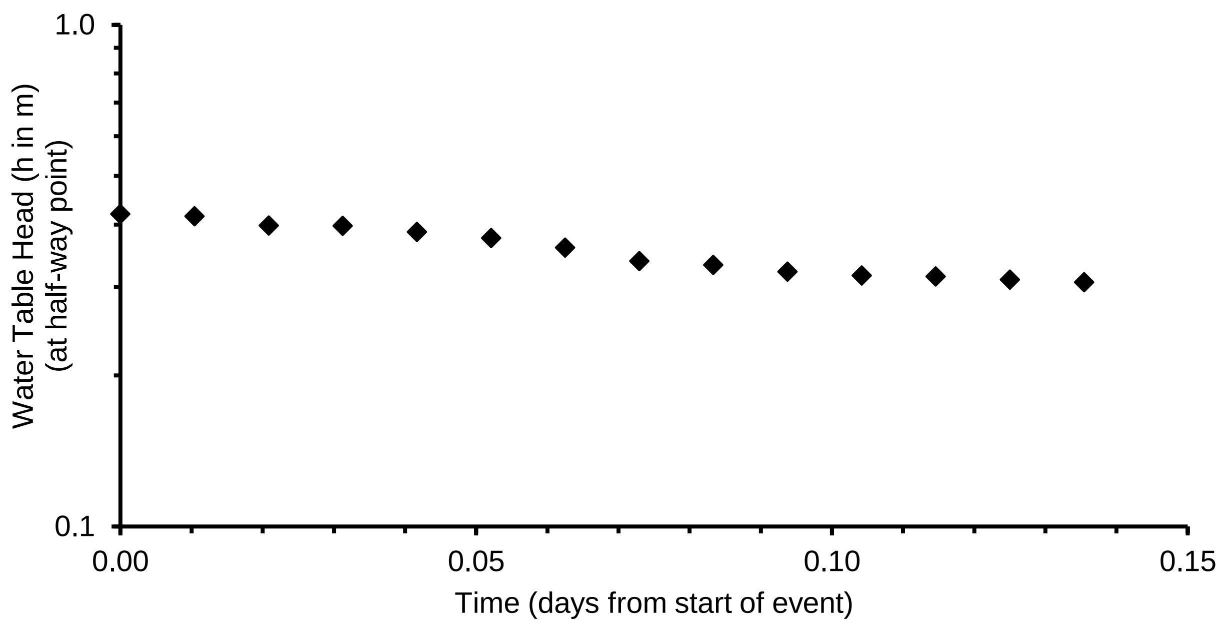

Figure 4-6: Water Table Head versus time for Controlled Drainage Field to determine Reaction Factor on May 1, 2017

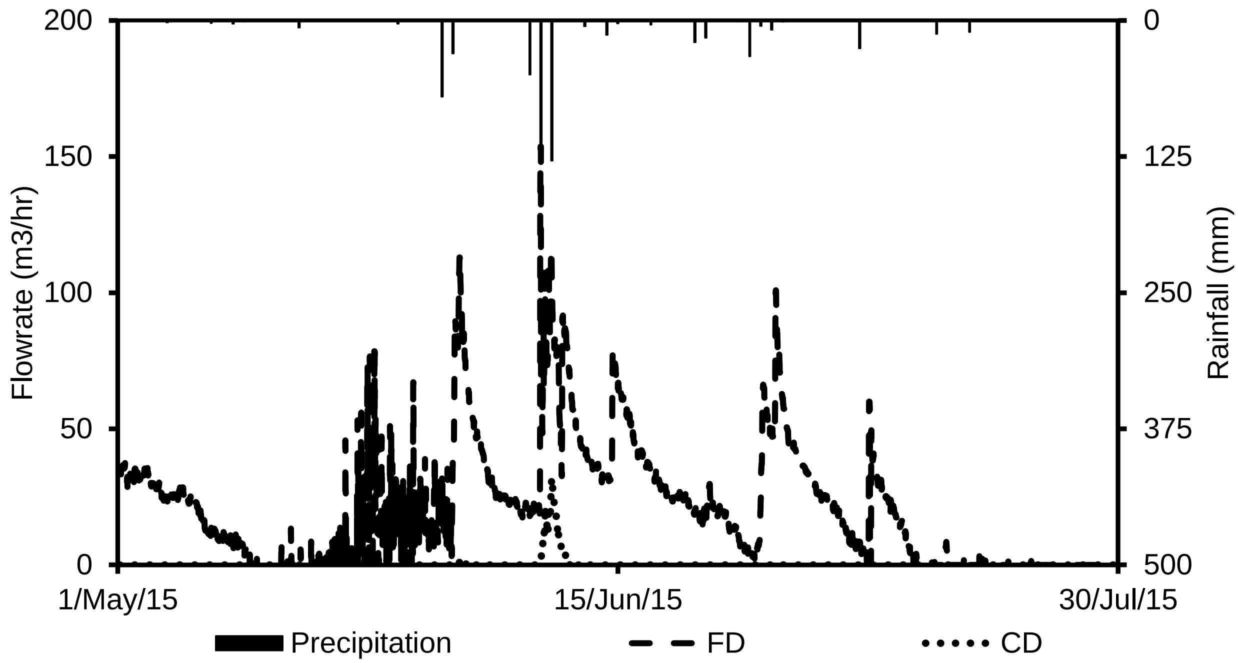

Figure 4-7 Tile Discharge rate at the tile outlet for controlled drainage and free drainage during the growing season of 2015

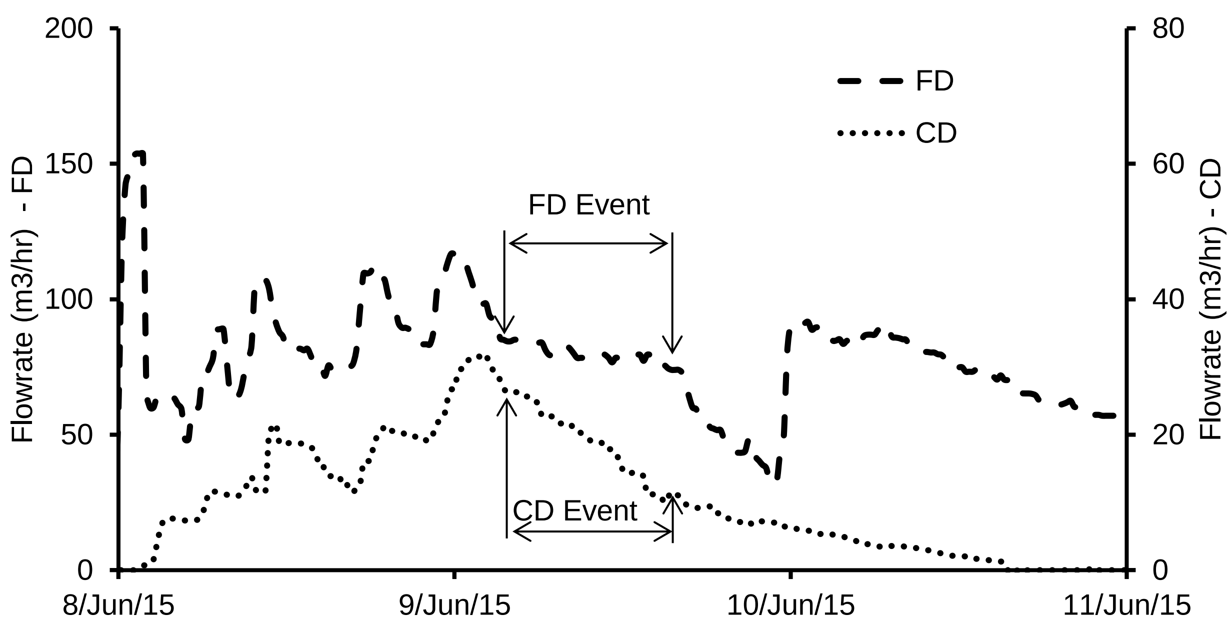

Figure 4-8: Tile Discharge rate at the tile outlet for one event starting on June 9, 2015

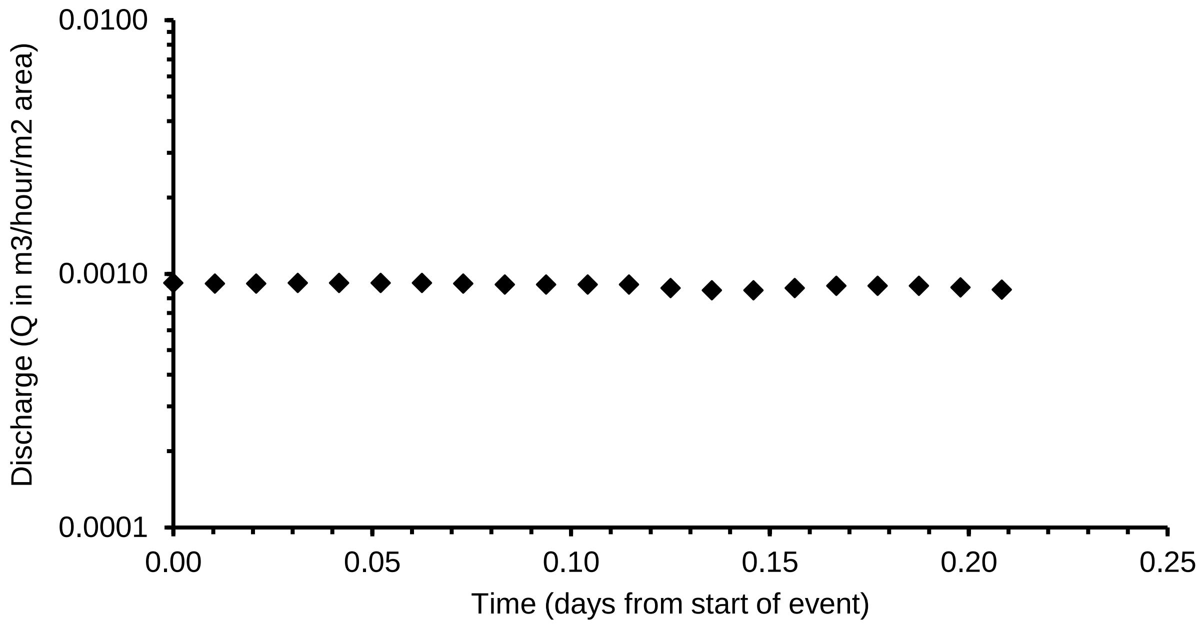

Figure 4-9: Discharge rate versus time for Free Drained Field to determine Reaction Factor on June 9, 2015

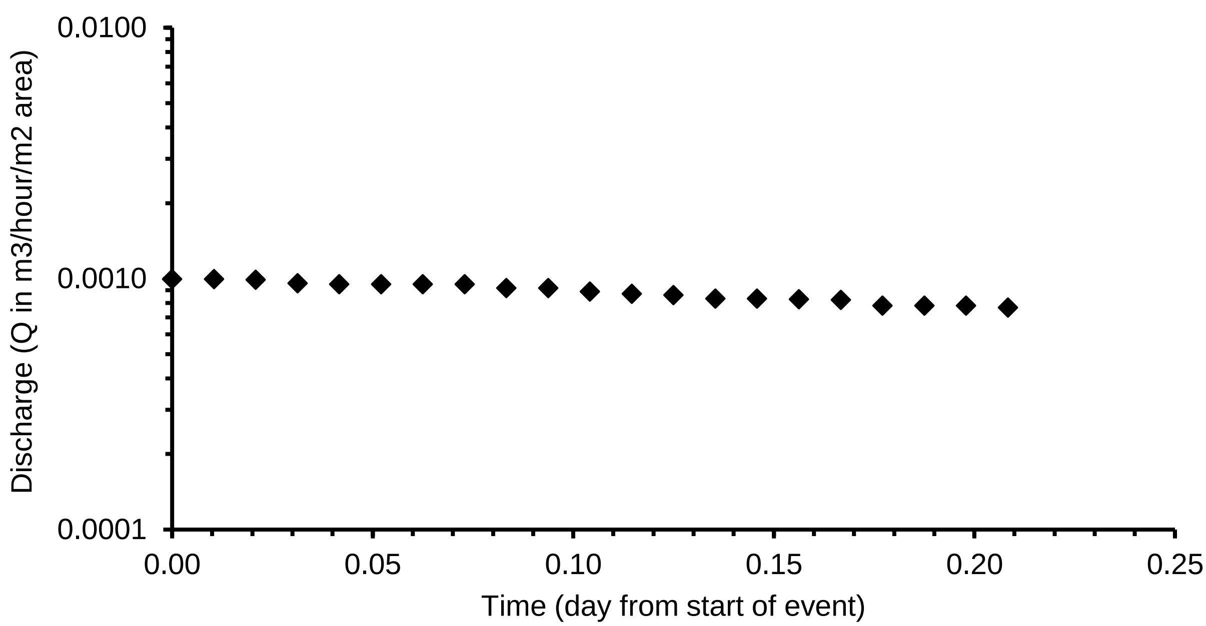

Figure 4-10: Discharge rate versus time for Control Drained Field to determine Reaction Factor on June 9, 2015

4.3.3 Reaction Factor Comparison

During the study period between 2015 to 2017, the gates in the DCS were installed between May and October, as well as between November and April. The gates were not installed during the 2015 study period for 11 days in October, during the 2016 study year for 64 days and during the 2017 study period for 86 days. The period of time when the gates were not installed was dependent on the farmers need to work in the field. Using the 11 different water table measuring sites located at mid-spacing between the tiles, the reaction factor was determined at each drop in water table above the tile drainage in order to determine the rate at which each field drained. During the period that the gates were up within the DCS, a total of 191 reaction factors were calculated from the 11 measuring sites. These values were compared against the 35 observed values between April 7 and May 19, 2017 immediately after gates were removed from the DCS. Figure 4-11 illustrates the reaction factors calculated using the water table depth values, with the section highlighted the time period immediately after the gates were removed from the DCS. The results of the reaction factor from the flowmeter data highlighted in figures 4-7 through 4-10 are not shown here, as they occurred during a different time period when no water table measuring equipment was installed in the study area. The results were also both below 1.5 day^{-1}. During the 2016 growing season the field had below average precipitation, which did not result in an increase in water table above the tile drainage depth. For this reason no reaction factors could be determined during the 2016 growing season. Although the 2017 growing season had above average precipitation amounts, the water table did not go above the tile drains after the beginning of June.

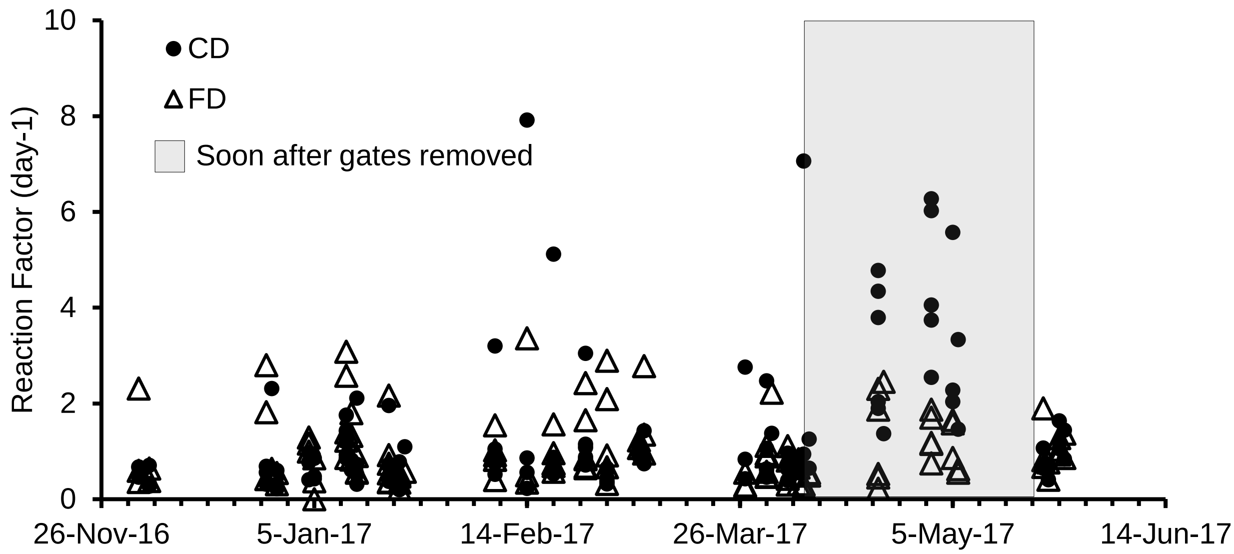

Figure 4-11: Summary of Reaction Factor for Controlled Drainage (CD) versus Free Drainage (FD) applications based on water table head data at mid-spacing between tile drains.

The reaction factor in the controlled drainage field was found to be 71% significantly ($p << 0.01$) greater than the free drained field during the spring period of 2017 immediately after the gates in the drainage control structure were temporarily removed for spring planting. These results are in agreement with the study by Saadat et al. (2017) showing that by removing the gates from the control structure, the field will be able to see a faster decline in the water table height after a precipitation event as shown at this site. The water level within the field had been at the top of the gates in the DCS immediately before the gates were removed at the beginning of April 2017 indicating that the soil in the controlled drained fields remained more saturated compared to the free drained field.

The difference in reaction factor between the free drained and the controlled drained field was not significantly different during 2017 non-growing season when the gates were in place. The results of these comparisons are shown in Figure 4-12. Unfortunately, there was insufficient data to determine if there was any difference between control drained and free drained fields when the gates were installed during the growing season. One event was recorded during June 9, 2015, which showed a 79% difference between the control drained field and the free drained field. This value was calculated using flowmeter readings and found the reaction factor in the control drained field to be higher than that of the free drained field.

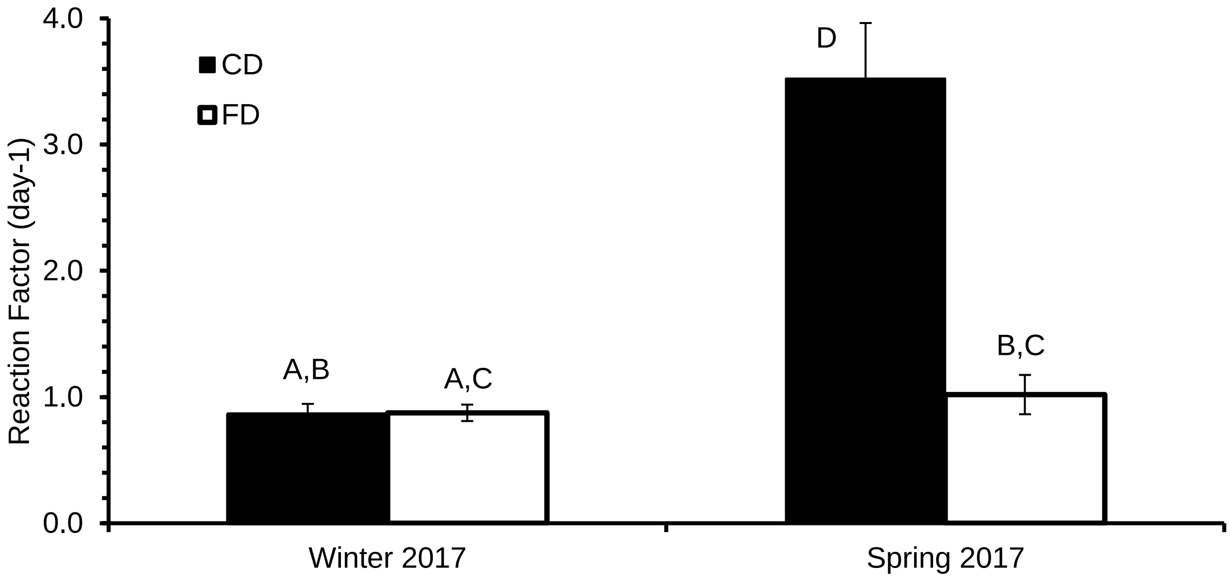

Figure 4-12: Average Reaction Factor for Controlled Drainage (CD) versus Free Drainage (FD) applications during the winter 2017 and spring 2017 immediately after the gates were removed. Levels not connected by the same letter are significantly different ($p > 0.05$).

The reaction factor data was compared against data collected using the weather station. Using regression analysis, no correlation was observed between the reaction factor values for the free drained field and precipitation, or temperature. When the control drained reaction factor values were compared against precipitation, a correlation was found with precipitation that fell the day before the event ($p = 0.003$). A correlation was also found between the CD reaction factor values and the maximum, minimum and mean temperatures ($p = 0.035$, $p = 0.005$, p =

0.008 respectively) which may be the indirect effect of the changes in viscosity of the drainage water.

The reaction factor data was also compared against the soil moisture data collected. Using regression analysis, the free drained reaction factor had no correlation to the soil moisture data collected at 0.15, 0.30 or 0.45 m below the surface; a correlation was observed for the 0.60 and 0.75 m depths ($p = 0.02$, $p = 0.01$ respectively). The control drained reaction factor values were also compared against the soil moisture data collected at five different depths. The results indicated the opposite correlation to that of the free drained reaction factor values. A correlation was observed with soil moisture data at 0.15, 0.30 and 0.45 m below the surface ($p = 0.05$, $p = 0.02$, $p = 0.02$ respectively); no correlation was observed for the 0.60 and 0.75 m depth values. The R^2 value did not exceed 0.23 for any of the above correlations.

Although no statistical difference was observed between the control drained and free drained field when the gates were installed in the field during the non-growing season, the data indicates that soil moisture has an impact on the reaction factor based on the results from June 2015.

4.4 CONCLUSION

This objective of this study was to measure drainage discharge rates as well as water table depth at the mid-spacing of the tiles to calculate the reaction factors for control drained and free drained fields after different recharge events. The reaction factor in the controlled drainage field was found to be 71% significantly ($p << 0.01$) greater than the free drained field during the spring period of 2017 within a month of removing the gates in the drainage control structures for spring planting. The soil in the controlled drained fields remained more saturated compared to the free drained fields due to the gates being in place. Results from the 2015 growing season indicated that the field with controlled drainage had a faster response time of 79% over that of the free drained field, hence greater drainage intensity than compared to the field with free drainage. The drainage control structure holding back the water thereby increasing the unsaturated hydraulic conductivity of the soil contributed to a higher drainage intensity compared to a freely drained field.

5. SUMMARY AND CONCLUSION

Water table management systems were measured during the 2017 and 2018 growing seasons to determine their impact on corn yield and quality, as well as on the reaction factor. The water table head at the mid-spacing was measured during the 2017 growing season to determine the reaction factor, and the corn crop was hand harvested during the 2018 growing season to determine the impact of water table depth on corn yield and quality. The main objectives of this study were to determine the impact of water table depth on corn yield and quality as well as on the impact of controlled drainage and free drainage on reaction factor.

The conclusions are as follows:

1. When comparing the total corn yield within the tile transect, a significant difference ($p < 0.05$) was observed between the row of corn growing just above the tile drain compared to quarter-way and half-way between the tiles. The corn harvested over the tile had a 6% higher yield over the quarter-way location, and a 7% higher yield over the half-way location. The average water table depths during each of the different growth stages were found to have a significant difference ($p < 0.05$) between the three different locations within the tile transect. The difference in average water table depths, within each growth stage, between the tile and the quarter-way point ranged between 8.5 and 11.0 cm. Similarly, the difference in average water table depths, within each growth stage, between the tile and the half-way point ranged between 10.0 and 12.0 cm. These results indicate that even a small difference in water table depth during different stages of growth can have a significant impact on corn yield. The SEW_{70} index was found to be significantly ($p < 0.05$) different between the three different locations within the tile

transect, and was found to have a negative correlation to the total corn yield through-out the growing season. The greater the number of days and depth the water table was found to be within the top 70 cm of the root zone, the lesser the yield. Results from this study show that precise water table management through the use of drainage control structures can have the potential to increase or decrease corn yield within a field. During wetter than normal periods, lowering the water table will decrease the SEW_{70} index resulting in corresponding yield increases.

2. The reaction factor in the controlled drainage field was found to be 71% significantly ($p << 0.01$) greater than the free drained field during the spring period of 2017 within a month of removing the gates in the drainage control structures for spring planting. The soil in the controlled drained fields remained more saturated compared to the free drained fields due to the gates being in place. Results from the 2015 growing season indicated that the field with controlled drainage had a faster response time of 79% over that of the free drained field, hence greater drainage intensity than compared to the field with free drainage. The drainage control structure holding back the water thereby increased the unsaturated hydraulic conductivity of the soil and contributed to a higher drainage intensity compared to a freely drained field.

6. RECOMMENDATIONS

Based on the results of this study, the following recommendations are suggested for future research:

1. The impact that a small difference in water table depth has on yield indicates that artificially raising the water table has the potential to impact corn yield within a field.
2. Further study into the impact of different water table depth management strategies could be proposed to optimize corn yield under control drainage practices.

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