Evaluation of Controlled Tile Drainage on Limiting Edge of Field Phosphorus Losses in a Clay Soil in a Cold Agricultural Region

by

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Author’s Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This section acknowledges the contributions provided by individuals other than the primary author to this thesis that are not otherwise referenced.

Research presented in Chapter 3:

Soil characteristics (i.e. organic matter (OM %), Olsen-P and pH) for the study site were collected in 2016 and originally reported by Plach et al. (2018a).

Staff at the Essex Region Conservation Authority assisted with site selection, ongoing landowner liaison, sample collection and the reporting of field activities.

Mazda Kompanizare performed event delineations for runoff data used in the study using the HydRun tool in MATLAB software.

Will Pluer supported the calculation of event flow-weighted mean concentrations and the production of figures used in this thesis in the R software environment.

Staff with the Ontario Ministry of Agriculture, Food and Rural Affairs contributed to the design and installation of the drainage system modifications at the site, as well as the delineation of contributing areas.

Abstract

This study examined edge of field (EOF) discharge and phosphorus (P) losses from a Brookston clay soil in a cold agricultural region over four years and quantified the influence of controlled tile drainage (CD) on seasonal and annual P exports in tile drainage. Annual EOF P losses ranged from 0.38 to 2.15 kg/ha for total phosphorus (TP), and 0.07 to 0.54 kg/ha for soluble reactive phosphorus (SRP) at the freely drained site. The majority of EOF discharge from the freely drained site was through subsurface drainage (66 to 98% annually), but P losses were evenly divided between surface and subsurface losses. At the CD site, CD is only used during the growing season (GS; May to September) at the site. Given the small volumes of flow during the GS, CD reduced subsurface discharge by 3.9% and P losses by 4.4% over the study period. Water table dynamics and subsurface runoff chemistry were not significantly impacted by the practice. The majority of discharge (90.1%), SRP (96.8%) and TP (94.2%) losses occurred outside of the GS, limiting the overall impact of CD at the site. In order to reduce EOF P losses in tile drainage, it is essential that CD is used throughout the year. Understanding the relative contributions of seasonal drainage control on overall annual losses is important to understanding the overall benefit of the practice and improving its application to reduce EOF P losses.

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List of Abbreviations

Abbreviation	Full Meaning
BMP	Best management practice
CD	Controlled drainage
CDSI	Controlled drainage sub-irrigation
DWM	Drainage water management
EOF	Edge of field
FWMC	Flow-weighted mean concentration
FD	Free drainage
GS	Growing season
MASL	Meters above sea level
N	Nitrogen
NGS	Non-growing season
P	Phosphorus
STP	Soil test phosphorus
SRP	Soluble reactive phosphorus
TP	Total phosphorus

Chapter 1 - Introduction and Problem Statement

Phosphorus (P) is a limiting nutrient in freshwater ecosystems, and when added, can increase productivity of the ecosystem (Schindler, 1977). Eutrophication of a freshwater system can result in algal blooms which can be toxic to humans and animals, as well as hypoxic zones that can result in fish mortality. In North America, Lake Erie has historically had water quality issues that were improved through reductions in point sources (Kane et al., 2014); however, it is now undergoing a period of 're-eutrophication' in the 21st century (Pennuto et al., 2014). Eutrophication has significant environmental, health, and economic consequences as it can cause fish kills and impact recreation, the fishing industry, tourism and threaten municipal drinking water sources (Sharpley et al., 2001; Kronvang et al., 2009; Withers et al., 2009).

Across the Lake Erie basin, agriculture is the dominant land use and has been found to be a significant source of nonpoint source P runoff (IJC, 2014). Adding P to the soil to supply the nutrient requirements of crops is a standard practice in the watershed. Historically, P losses from agriculture were thought to be dominantly through overland runoff pathways and the subsequent movement of soil-bound P in erosion. However, our understanding of P transport has advanced to recognize that subsurface drains are a significant source of P losses to watercourses (Macrae et al., 2007b; King et al., 2015a), particularly in clay soils (e.g. Plach et al., 2019). Tile drainage is critical to modern farming in most regions of Ontario, especially in southwest Ontario where fine textured poorly drained soils are common (Macrae et al., 2021). Tile drainage provides many benefits to farming and water quality, however in order to meet P reduction targets, P losses through subsurface drainage must be addressed.

The practice of controlled drainage (CD), more broadly known as drainage water management (DWM), is an emerging agricultural Best Management Practice (BMP) in the Lake Erie watershed that shows potential for reducing P losses. With CD, the user has the ability to control water table levels in the soil by restricting or partially restricting flow from the subsurface drainage network. This management system allows for drainage at critical times of the year, while increasing the soil's water content at other times to increase water availability to the crop. By reducing drainage volumes from tile drainage, this practice also has the potential to reduce nutrient losses from agriculture. However, many producers employ it during the GS only to avoid tile damage caused by freezing in winter. An improved understanding of the efficacy of this practice on edge of field (EOF) losses of P and water is needed.

Chapter 2 – Literature Review

2.1 Eutrophication and Agricultural Pollution

Eutrophication of Lake Erie is a result of excess nutrients flowing into the lake from the surrounding streams and rivers (Pennuto et al., 2014). Eutrophication is apparent by the growth of algal blooms during the warmer summer months. In addition to causing hypoxic zones due to oxygen depletion, algal blooms can also lead to the production and accumulation of harmful toxins in the water, reducing the water quality for both aquatic and terrestrial use, including humans (Michalak et al, 2013). As the warmest and shallowest of the Great Lakes, Lake Erie is naturally highly productive (Dolan & Chapra, 2012). However, elevated P inputs from its contributing watershed are increasing its productivity (IJC, 2014). Phosphorus has repeatedly been found to be the limiting nutrient in freshwater lakes and can even drive a shift towards the growth of more harmful forms of algae (Schindler, 1977). Although the fate of P in the lake is complex (Pennuto et al., 2014), additions of P are correlated strongly to increases in lake productivity (Schindler et al., 2008), and thus P reductions in contributing tributaries within the Lake Erie basin have been targeted to reduce algal growth (IJC, 2014).

In the late 1970's, actions under the Great Lakes Water Quality Agreement were able to address point-source P pollution and reduce the symptoms of eutrophication in the western and central basins of Lake Erie (DePinto et al., 1986). However, by the early 1990's this trend was reversed, and we now see frequent harmful and nuisance algal blooms (Kane et al., 2014). Point sources of P, mostly from municipal sources, are on a decreasing trend while non-point sources of P are becoming more important contributors of both total phosphorus (TP) (71%) and soluble reactive phosphorus (SRP) (49%) to overall lake loads (IJC, 2014; Maccoux et al., 2016; Wilson et al., 2019). The total P loads to Lake Erie are also increasingly composed of SRP, which is more strongly correlated with algal growth than TP (Richards et al., 2010; Baker et al., 2014; Kane et al., 2014; IJC, 2014; Scavia et al., 2014), although a fraction of TP is also bioavailable (Baker et al., 2014). Thus, attention must be given to both the total loads and the forms of P losses to the Lake in order to meet objectives for the ecosystem (Kane et al., 2014). Phosphorus transport to Lake Erie is tied to hydrology, with higher loading occurring in wet years (Dolan & Chapra, 2012). Thus, loading to Lake Erie is greatest during the spring period, making it a focal point for reductions under the binational targets (USEPA, 2015; Maccoux et al., 2016). Although extremely variable from year-to-year, there is a general trend of upwards precipitation in the Great Lakes region, resulting in increased discharge and P loads in tributaries to the lake (Maccoux et al., 2016). Thus, there is concern that the current water quality issues faced by Lake Erie will worsen in future due to climate change.

Phosphorus is applied to cropland as either fertilizer, manure, or biosolids, to supply nutrients for optimum crop yields. However, runoff water from agricultural land can be enriched with P if sources and applications are not managed judiciously, or if erosion is not managed (Sharpley et al., 1994). Runoff in agricultural landscapes contains P in both dissolved and particulate forms to some extent (Jarvie et al., 2002). Currently, non-point sources from agriculture are responsible for the majority of P losses to the Lake from the Lake Erie watershed. The majority of P inputs (84% TP and 82% SRP) are from the United States, mainly the Maumee and Sandusky Rivers; however, the Ontario tributaries to the Western Basin of Lake Erie are also included in binational targets (USEPA, 2015; Maccoux et al., 2016). Conservation practices (or BMPs) are needed to address the P loss issue (Michalak et al., 2013; Dagnew et al., 2019; Macrae et al., 2021). However, the efficacy of various BMPs can vary both spatially and temporally (Macrae et al., 2021).

2.2 Pathways for Phosphorus Losses at the Edge of Field

Tile drainage is commonplace across much of the Erie basin and provides great benefits to crops. Historically, P losses from agriculture were thought to be dominantly through overland runoff pathways and the subsequent movement of soil-bound P in erosion. Our understanding of P transport has advanced to recognize that subsurface drains are a significant source of losses to watercourses (Macrae et al., 2007b; King et al., 2015a). Subsurface drains are networks of perforated pipes installed beneath agricultural fields to lower the water table, increase the length of the GS, increase the soil temperature at planting and facilitate farm practices (Urban, 2005; Madramootoo et al., 2007).

Tile drainage area and intensity are increasing in the Lake Erie basin (King et al., 2015b). Tiles have been found to increase total water yield from fields and often decrease the amount of runoff through the surface pathway (King et al., 2015b). Thus, the importance of addressing subsurface P pathways is increasing, and will likely continue to do so. The partitioning of P losses between surface and subsurface drainage is dependent upon many factors including the spacing and depth of tile drainage system, topography, soil texture and precipitation event characteristics. Tile drainage consistently contributes less to P loads than it does to total discharge (Eastman et al., 2010; Tan & Zhang, 2011; Pease et al., 2018; Plach et al., 2019). This is driven by the more frequent baseflow in tiles and the frequently elevated flow-weighted mean concentrations (FWMCs) observed in surface runoff (Sharpley, 1995; Tan & Zhang, 2011; Pease et al., 2018). However, tiles can be a significant pathway for overall discharge and P losses, especially for fine-textured soils (King et al., 2015a; Plach et al., 2019).

Best Management Practices exist in Ontario for managing P losses through surface and subsurface pathways by addressing P sources on the landscape (e.g. managing soil test phosphorus (STP) levels, 4R nutrient management; where the right nutrient source is applied at the right rate, at the right time and in the right place (Bruulsema, 2018)). Certain practices may also limit the transport of P through surface runoff, either by slowing surface flow or by protecting surface flow pathways from erosion (e.g. water and sediment control basins, grassed waterways, rock chute spillways, conservation tillage). However, very few options exist for controlling the transport of P once it has entered subsurface drainage. Some options exist in open channel drains for slowing water flow and sediment transport (e.g. two-stage ditches), but within fields, tile drains generally provide a direct conduit of drainage water to a nearby outlet. In areas where tile drainage represents a significant portion of annual EOF P losses, this pathway must be addressed in order to reach Lake Erie targets. Consequently, some producers are investigating the potential of CD or DWM to reduce EOF P losses.

2.3 Seasonality in Phosphorus Losses

In the same way that Lake Erie P inputs are dependent on hydrology, so are agricultural P losses at the EOF scale. Phosphorus losses have been shown to be more prominent in the wetter and cooler winter months. Precipitation is consistent throughout the year in Ontario, however during the non-growing season (NGS; October to April) there is less evapotranspiration, resulting in increased runoff and P losses (Macrae et al., 2007b). The NGS and spring snowmelt period are large contributors to annual loads in Ontario (Plach et al., 2019). Tan & Zhang (2011) also reported that P losses followed the same seasonal trends as both surface and subsurface runoff, where the majority of runoff occurred during the NGS (November to April). This reiterates how EOF P losses are driven by discharge patterns, with the exception of incidental losses from large runoff events following P application (Van Esbroeck et al., 2016; Plach et al., 2018b). For most events, the discharge volumes from large precipitation events drive P loadings, independent of FWMCs (Kleinman et al., 2006).

This highlights the importance of year-round monitoring in the Lake Erie basin in order to understand the impacts of practices on annual discharge and nutrient loads. Multi-year studies are also critical to cover the range of runoff conditions experienced at a site, which are tied so closely to nutrient exports. Due to the difficulty of monitoring runoff through the freezing temperatures of the NGS, EOF losses are not always reported on a year-round basis, giving a narrow perspective on the annual P loss.

2.4 Controlled Tile Drainage

The practice of CD has been proposed for addressing nitrogen (N) and P losses from agricultural land with subsurface drainage, while also improving crop performance. With CD, the water table in a field is managed using a stop-log system in an in-line control structure on the tile drainage system. The effective outlet elevation of the tile system is set by adding or removing stop-logs (gates) in the control structure, however, the tiles are not completely closed, as water can flow over the gates if the water table within the field has reached the target level.

Typical for the region, gates are removed prior to spring and fall field work to increase trafficability and reduce the negative impacts associated with wet soils. After crops are planted in spring, gates are re-deployed to actively retain water in the system through the GS. In some cases, sub-irrigation is also used during the GS by pumping water into the tile system upstream of the stop-logs to supplement water in the soil profile. Although DWM can be used during the NGS to control nutrient losses, this is less common and the focus of the system on working farms is typically to control drainage during the GS when it may boost crop yields.

Controlled drainage is proposed to reduce N and P losses, but through different and possibly opposing modes of action. Under CD, soils may become saturated and water has a prolonged residency time (Gilliam & Skaggs, 1986). Under these anoxic conditions, nitrate metabolization by microbes is amplified, resulting in increased denitrification from the soil (Mejia & Madramootoo, 1998). This process leads to lower nitrate concentrations available for export through subsurface drainage, and by this process, loads can be reduced with DWM. Unfortunately, these same anoxic conditions in saturated soils can result in the conversion of iron (III) oxyhydroxides to iron (II) hydroxide, which binds orthophosphate much more loosely than its oxidized counterpart (Patrick & Khalid, 1974). Under saturated and reduced conditions, the P that was strongly bound to soil particles may be desorbed into the water within the soil matrix, increasing P concentrations in subsurface drainage water. Regardless of concentration changes in the tile effluent, CD has the potential to reduce losses of both nutrients by reducing total discharge from the landscape. Likewise, vertical seepage of water beyond the bounds of the tile system will inherently reduce the measured discharge of the drainage system and reduce losses of both N and P from the tile outlet.

Although not unanimous (Gilliam & Skaggs, 1986; Stampfli & Madramootoo, 2006; Valero et al., 2007), many studies have shown a net reduction of annual N and/or P loads by using DWM (Lalonde et al., 1996; Wesstrom et al., 2001; Drury et al., 2009; Tan & Zhang, 2011; Sunohara et al., 2015; Williams et al., 2015a; Zhang et al., 2015; Sunohara et al., 2016; Saadat et al., 2018; Carstensen et al., 2019). There is little evidence that CD alone (without the use of sub-irrigation) results in an impact on concentrations of N and P. Many studies report no significant change in N and P concentrations in tile drainage water with the use of controlled drainage without sub-irrigation (Lalonde et al., 1996; Wesstrom et al., 2001; Williams et al., 2015a; Sunohara et al., 2015; Saadat et al., 2018; Carstensen et al., 2019). Indeed, a literature review by Skaggs et al. (2012) confirmed that CD does not typically show an impact on nitrate concentrations in drain effluent across varying management strategies, climates and soil types. Williams et al. (2015a) offers an explanation for why concentration impacts are rarely seen with CD studies, noting that denitrification will be highest in the upper portion of soil profile where organic carbon levels are higher. Likewise, P solubility will be highest in shallow P-rich soils under anaerobic conditions where Fe and Al oxides are reduced. However, the bulk soil does not become saturated and reduced for long enough to have an effect with CD to significantly impact concentrations. Thus, the use of CD is expected to reduce nutrient loading primarily through reductions in drainage volume, and not by geochemical changes due to increased water in the soil profile. Agriculture producers and environmental managers share the common goal of desiring to both decrease P losses from agriculture, while increasing profitability of farms (IJC, 2014; Wilson et al., 2019). As such, the practice of CD is a promising solution to non-point source P pollution because it also offers potential yield benefits.

In Southern Ontario, subsurface tile drainage can make crop production possible where it would otherwise not be, or it can increase crop yields in areas already suitable for crop production (Tan & Zhang, 2011; Skaggs et al., 2012; King et al., 2015b). Drainage is especially needed in spring to remove excess soil moisture and allow crops to be planted (King et al., 2015b), however during the dry period of the GS, crops can become moisture-limited and yields can be reduced (Tan et al., 2007). By retaining moisture during the GS, DWM can increase water availability to crops, thus improving yields (Skaggs et al., 2012). Skaggs et al. (2012) explains that in very wet or very dry years, the DWM will not likely have an impact on yields. DWM will more likely have the greatest benefit in years where wet and dry periods alternate through the GS, providing sufficient water that can be stored in the soil profile. With sub-irrigation in place, yield benefits could be sustained through longer dry periods, provided there is sufficient water availability to supply the tile drainage system.

Skaggs et al. (2012) reported that CD (without sub-irrigation) does not generally affect crop yields. On the other hand, very few studies have reported negative yield effects of CD (Elmi et al., 2002; Helmers et al., 2012). As expected, studies in the literature have found that the yield effect of CD is variable year-to-year based on precipitation patterns (Elmi et al., 2002; Tan et al., 2007; Drury et al., 2009). Studies in Eastern Ontario with CD have shown average yield benefits of 4 ± 6% in corn and 3 ±

3% in soybeans with CD (Sunohara et al., 2014), but studies in southwest Ontario that have shown yield boosts from CD have also utilized sub-irrigation and are difficult to compare to the practice of simple controlled tile drainage (Tan et al., 1993; Drury et al., 1997; Tan et al., 2007).

A report by Hunter and Associates (2008) examined the suitability of CD as a practice in Ontario, based on soils and topography. Soils that have an impermeable layer at depth will have low vertical leakage rates and can retain moisture in the field. These soil classes were set as a criterion for assessing the suitability of Ontario farmland for controlled drainage sub-irrigation (CDSI) (Hunter and Associates, 2008). The practice also requires a flat landscape to attain even water table control. Drained farmland with uniform slopes < 0.5% and < 0.1% has been deemed suitable in the Midwest states (Skaggs et al., 2012) and Ontario (Tan & Zhang, 2011), respectively. Greater slopes can be used with DWM, but additional control structures are needed. Hunter and Associates (2008) suggests that slopes of < 0.25% are preferable to minimize the number of structures required. Hunter and Associates (2008) also recommend that closer spacing with shallow depths (60cm) be used for fine textured soils in southwest Ontario for better control of water table zones.

In Ontario, most of the land that is suitable for CDSI is in southwestern Ontario, within Essex, Chatham-Kent and Lambton Counties. In this region, 60 to 84% of land is classified as either good or fair potential for CDSI (Hunter and Associates, 2008). Based on the soil and topography criteria used, CDSI was shown to have extensive potential within this region but is limited across the remainder of the province. Yet, uptake of DWM on commercial farms is limited within the region. Plot-scale research in the area has been successful but may need to be translated to field scale to gain confidence in results for more widespread public uptake. It is also worth noting that extensive tile drainage has been completed in the area, meaning that existing drainage systems would need to be retrofitted to utilize CD, which can be more challenging and costly than designing a CD system at the outset.

The practice of CD may fulfill an important function of reducing P losses through subsurface drains. In regions where tile drainage represents the majority of EOF P losses (Plach et al 2019) and the soils and topography are suitable, CD may offer a solution where there are few other methods for controlling transport of P from subsoils.

2.5 Study Rationale and Thesis Objectives

Past experiments in the region have examined the use of CD in combination with sub-irrigation and have been studied at the plot-scale (Tan et al., 2002; Tan & Zhang, 2011; Zhang et al., 2015). Given the greater investments and site limitations associated with sub-irrigation, there is rationale for the use of simple CD during the GS for the possible yield benefit. However, there is also interest in using CD to reduce P losses in tile drainage.

Local studies have observed that the NGS contributes significantly to annual discharge and P losses (Tan et al., 2002; Lam et al., 2016; Van Esbroeck et al., 2016; Plach et al., 2019). Thus, to understand the impact of conservation practices to overall nutrient losses, year-round monitoring is important. Similarly, monitoring over multiple years will further our understanding of how BMPs perform over a range of climatic conditions.

The interaction of soil type, microclimate and field management are significant drivers of agricultural runoff and nutrient losses (Macrae et al., 2021). Thus, regional research is crucial in determining the impacts of CD under unique local conditions. In Eastern Ontario and Southern Quebec, the use of CD through the NGS is not recommended because of the colder winter climate, risking damage to crops and drainage systems under frozen conditions (Stampfli & Madramootoo, 2006; Sunohara et al., 2015). Because of this, CD monitoring in these regions has been mostly limited to the GS. Controlled drainage use through the NGS has been recommended at the lower latitudes of southwestern Ontario and studies have emphasized year-round monitoring (Tan et al., 2002; Tan & Zhang, 2011; Zhang et al., 2015). Results from past studies in Essex County provide strong context for the impacts of EOF losses on an annual basis. However, many producers are reluctant to deploy DWM during the NGS due to fear of frost damage to tile drain systems. Thus, an understanding of the annual reduction in EOF P loss when CD is only used during the GS is necessary.

This study explores the use of CD to regulate soil water through the GS, examining the impacts on water quality and loads within the context of annual losses.

The objectives of this thesis are:

(1) To quantify differences in drainage water volumes, P concentrations and loads between tiles under free and controlled drainage in a clay soil in Ontario, Canada over a four-year period;

(2) To determine if and how runoff, P concentrations and loads vary within and among seasons and years, and if these differ between controlled and free drainage;
(3) And to characterize mechanisms driving variability in flow and P chemistry between controlled and freely drained fields.

Results from this study will benefit farmers who are interested in the potential impacts of CD on water quality and crop performance. Findings may also inform conservation professionals and policy-advisors who are tasked with identifying and supporting practices that will improve water quality by reducing nonpoint source P pollution.

Chapter 3 - Site Description and Methods

The Essex study site was chosen based on the interested landowner, the limited extent of controlled tile drainage in SW Ontario at the time of installation, and the collaborative relationship between the Essex Region Conservation Authority and the landowner. The site is representative of soils in the area and has two fields that offer a controlled experimental design. The study site is located within the Canard River subwatershed, which drains into the Detroit River south of Windsor, ON. This area is part of the Huron-Erie corridor watershed which flows into the western basin of Lake Erie and is thus a priority area for P load reductions in Ontario.

3.1 Study Site Description

The study site is located in Essex County, Ontario, Canada (Fig. 3.1). The climate of the region is described as humid continental, with freezing temperatures in winter, hot summers and precipitation distributed evenly through the year (*Dfa* on the Köppen Classification System). Average daily temperatures fall below 0 ^{o}C from December to February and are above 20 ^{o}C from June through August. Mean annual precipitation is 952 mm, of which 129 mm comes as snow (ECCC, 2020). Soil in the region and at the study site are lacustrine clays, classified as Brookston clay (Richards et al., 1949). This soil type consists of a dark clay topsoil over layers of mottled clay with blue-grey compact gritty clay with few stones and poor natural drainage. Consequently, artificial tile drainage is widespread in agricultural fields throughout the region.

The study site is located on a farm with 15.1 ha of cropland, which is flat (0.03% average slope) and is cropped annually. The farm is split into two fields, each with hydrologically isolated tile drainage systems. The west field is 7.7 ha in size and the east field is 7.4 ha (Fig. 3.1). The system consists of 0.1 m (4” nominal) diameter clay tiles at a depth of 0.7 m. Tile spacing is 9.2 m on the west field and 10.7 m on the east field. A control structure was installed in 2013 on the main header tile of the west field and the east side of the farm remains under normal free drainage (FD). Surface runoff from the farm (6.7 ha in contributing area) is collected into a catch basin from a drainage swale running the length of the farm between the two fields (Fig. 3.2), but this swale predominantly captures flow from the FD field (Fig. 3.1). Most of the CD field surface runoff drains to the west boundary of the farm into a separate outlet but was not monitored during this study. The FD and CD tiles, as well as the surface runoff catchbasin pipe all run in parallel and eventually flow into one common larger outlet that drains into a drainage ditch at the edge of the field (Fig. 3.1). Each of the three pipes have two riser pipes through which flow rates and water chemistry are monitored (Fig. 3.3). All of the riser pipes are enclosed in a shed to protect equipment

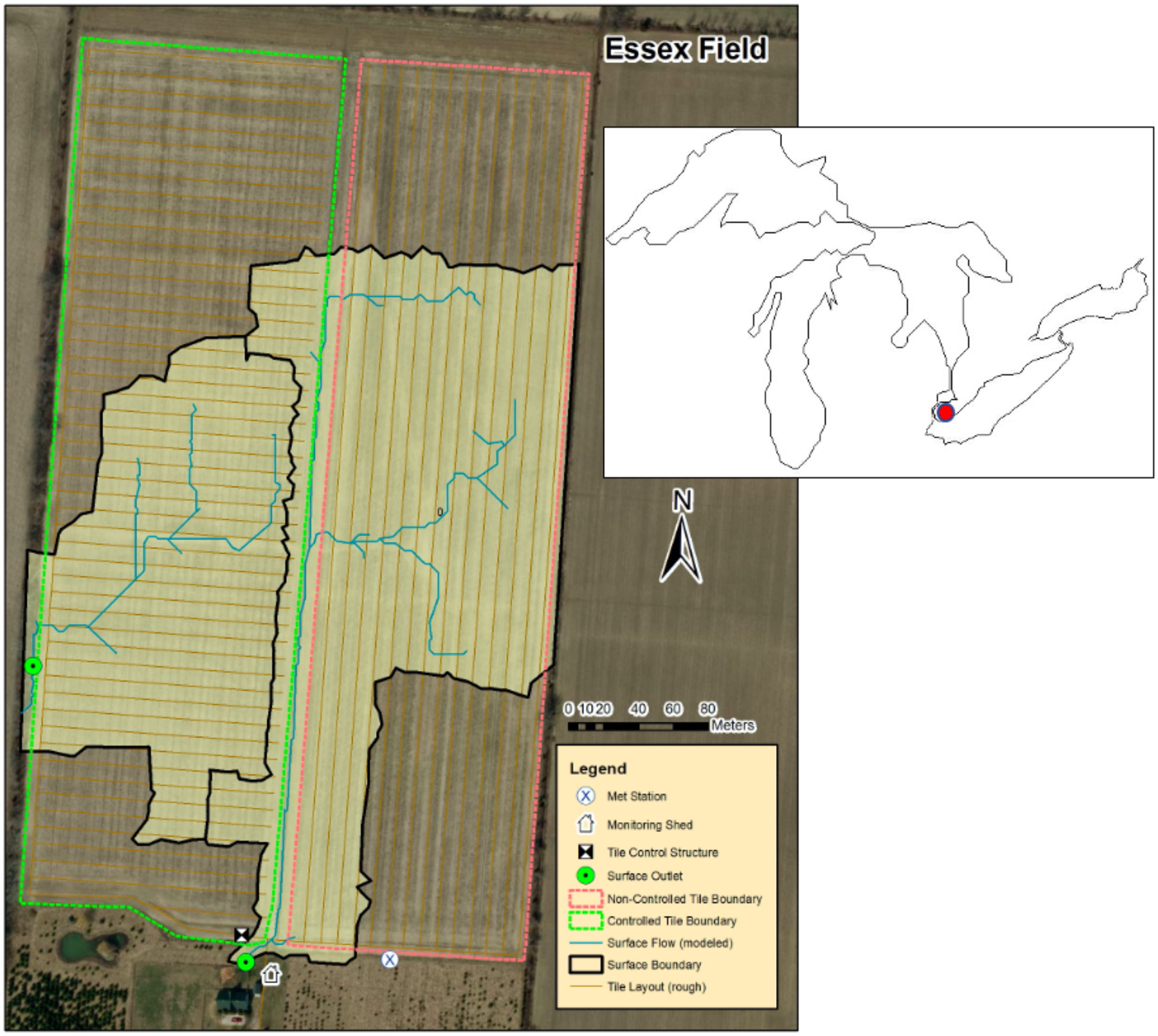

Figure 3.1. Site map and location of the study site within the Great Lakes region (inset).

Soil samples collected in replicate (5 cores per field) from both the CD and FD fields in 2013 and another 3 cores from the FD field in 2016 are described in Table 3.1. Mean STP levels over the study period were similar between the two fields, with 15.1 mg/kg Olsen-P in the CD field and 12.4 mg/kg Olsen-P in the FD field (Table 3.1) The fields fall within the recommended levels for cash crops (12 to 18 ppm) and below the level of 30 mg/kg Olsen-P where additional P fertilizer is not recommended (OMAFRA, 2017). Soil test P concentrations decreased between the 2013 and 2016 sampling periods (Table 3.1), suggesting that crop removal rates and runoff losses exceed fertilizer rates. Although STP was only measured in the FD field in 2016, it is assumed to be similar between both the FD and CD fields as there were no differences in fertilizer management. Some stratification is apparent, with soil P decreasing between 0 and 40 cm; however, this does not differ between the CD and FD fields (Table 3.1).

Figure 3.2. Surface runoff drainage swale is located between the two fields at the study site.

Figure 3.3. In-line monitoring units were installed to allow monitoring of the field tiles and surface drain.

Soil textures are also similar between the two fields, with clay loam at the surface (0 to 15 cm) (33% sand, 28% silt, 39% clay) and clay below this (29% sand, 26% silt, 45% clay) (Plach et al., 2018a).

Field Management		2013				2014	2015		2016		2017
Controlled Drainage Gates in Use		May 7 - Jul. 2 (prior to study period)				Jun. 16 - Sep. 15 Dec. 16 - Dec. 31	Jan. 1 - Jan. 8 May 23 - May 30 Jun. 10 - Jun. 26 Jul. 2 - Sep. 21		May 24 - Oct. 3		Jun. 16 - Nov. 3
Crop	Type	Winter Wheat				Soybeans	Soybeans		Corn		Soybeans
	Planting Date	N/A				Jun. 10	May 23		May 24		Jun. 3
	Harvest Date	Aug. 5				Oct. 26	Oct. 12		Nov. 11		Oct. 17
Yield	CD (kg/ha)	N/A				4,443	3,624		10,748		2,953
	FD (kg/ha)	N/A				4,020	3,678		10,928		2,819
Crop Removal	CD (kg P_2O_5/ha)	N/A				62.3	50.8		77.6		41.4
	FD (kg P_2O_5/ha)	N/A				56.4	51.6		79.0		39.5
Soil Samples	Field	CD		FD		-	-		FD		-
	Depth	0 - 15 cm	15 - 30 cm	0 - 15 cm	15 - 30 cm	-	-		0 - 15 cm	15 - 30 cm	-
	OM (%)	2.9 ± 0.3	2.2 ± 0.1	3.1 ± 0.3	2.3 ± 0.4	-	-		6.1 ± 0.5	5.4 ± 0.8	-
	Olsen-P (mg/kg)	15.1 ± 3.4	7.2 ± 2.3	12.4 ± 4.0	5.8 ± 2.2	-	-		10.3 ± 4.5	2.8 ± 0.8	-
	pH	5.7 ± 0.3	5.9 ± 0.2	6.0 ± 0.4	6.2 ± 0.3	-	-		5.5 ± 0.5	5.6 ± 0.3	-
Tillage		Post-Harvest Oct. 16 Chisel Plow				Pre-Plant May 25 Disced & Cultivated	Post-Harvest Oct. 13 Chisel Plow	Post-Harvest Oct. 20 Disced & Cultivated	Pre-Plant May 24 Cultivated		None
Phosphorus Applications		Post-Harvest Oct. 15 Broadcast 224.2 kg/ha Granular 5.5-26-30 (58.3 kg P_2O_5/ha)				None	Pre-Plant May 3 Broadcast 157.3 kg/ha Granular 6.5-30.7-24.6 (48.3 kg P_2O_5/ha)		At Planting May 24 Subsurface Placement 157.9 l/ha Liquid 15-15-3 (30.8 kg P_2O_5/ha) & 54.1 l/ha Liquid 6-24-6 (17.2 kg P_2O_5/ha)		At Planting Jun. 3 Subsurface Placement 46.8 l/ha Liquid 15-15-3 (9.1 kg P_2O_5/ha)

Table 3.1. Field management, cropping practices and soil characteristics over the study period. Crop removal rate estimates (0.84 lbs P_2O_5/bu for soybeans; 0.405 lbs P_2O_5/bu for corn) taken from the Soil Fertility Handbook, Publication 611 (OMAFRA, 2018).

The study site is a working farm and all management decisions were made by the farmer and owner. The fields are under a corn-soybean rotation and both the FD and CD fields follow the same cropping, tillage and P application management (Table 3.1). Commercial fertilizer was applied for each crop during the study period, either after harvest of the previous crop or before planting in the spring. Fertilizers were often but not always incorporated with tillage.

As this study was on a working farm, the management of the control structure was discussed with project partners, but ultimately the decision on how to operate it was made by the landowner/farmer. Generally, the gates were installed immediately after planting and removed two to six weeks before harvest to ensure trafficability of the soils for harvest equipment (Table 3.1). Gates were installed at a depth of 0.51 m below ground level in years 1 and 2, and 0.33 m below ground level for years 3 and 4. This pattern of gate management held true for the four study years, with the following two exceptions:

A. In late 2014, the control structure gates were installed for approximately three weeks. The landowner expected that the saturated tiles and surrounding soils would cause damage to the clay tiles if cold temperatures arrived. The gates were removed in order to drain the tile system before frozen temperatures reached the depth of the tiles. After this trial, the gates were not used during the winter in the study period again.
B. Following soybean planting in spring 2015, the gates were installed and removed twice before being left in for the GS due to some significant rain events in May and June. The decision was made in order to lessen the risk of crop damage from saturated soils.

3.2 Methodology

3.2.1 Field Monitoring Equipment and Water Quality Sampling

Meteorological conditions were measured using a HOBO Weather Station (Onset Ltd) and recorded at a 15-minute frequency with a HOBO U30 GSM data logger. The station measured rainfall with a tipping bucket rain gauge (0.2 mm Rainfall Smart Sensor - S-RGB-M002), air temperature and relative humidity at 1 m elevation (12-bit Temperature/RH Smart Sensor - S-THB-M002), and soil temperature (12-Bit Temp Smart Sensor - S-TMB-M0002) and moisture (EC-5 Soil Moisture Smart Sensor) were monitored at 10, 30 and 50 cm depths adjacent to the weather station. Snowfall data was obtained from the nearby WindsorA Environment Canada station (ECCC, 2020). Water table depth was monitored in a screened PVC pipe (50 mm ID) installed to a depth of 2 m at one location near the weather station from 2013 to 2015, and then at an additional four locations (two in each field) from 2015 to 2017. Water depths were measured using barometrically corrected pressure transducers (HOBO U20, Onset Ltd) at 15-minute intervals.

Flow rates in the two tiles and in the surface runoff pipe were measured at 15-minute intervals using depth-velocity sensors (Hach Flo-Tote3) installed in the risers of each of the monitoring pipes and recorded on Hach FL900 data loggers. Onset HOBO U20 water level loggers were also installed in each pipe to provide a backup data source and to calculate flow during low-flow conditions (water depths < 50 mm in the pipe) using cipoletti weirs installed in each pipe.

Water samples were collected using Teledyne ISCO 6712 autosamplers, installed downgradient from the flow sensors to avoid disturbing the flow sensors when autosamplers were activated. Water samples were collected during flow events at 2 to 8-hour intervals in tile drainage and at 30-minutes to 3-hour intervals in surface runoff from the FD field. Frequencies were adjusted seasonally based on local knowledge of the sites. Water sampling spanned the entire event hydrograph, including the rising and falling limbs, plus baseflow samples at the beginning and end of an event to capture representative chemistry analyses under varying flow conditions. Samples were collected within 48 hours of collection (24 hours in summer) by staff of the Essex Region Conservation Authority, frozen and then shipped to the University of Waterloo for processing and analysis. A total of 104 runoff events were observed over the four-year study, between October 1, 2013 and September 30, 2017, and a total of 1689 water samples were analyzed from 42 runoff events.

3.2.2 Laboratory Analyses

Soil samples collected in 2013 were analyzed for a standard suite of agronomic parameters (Basic S1B test package), including STP (Olsen-P), by A & L Canada Laboratories Inc. in London, Ontario, Canada. Soil samples collected in 2016 from the FD field were analyzed for texture, Olsen-P, organic matter and pH in the Biogeochemistry Lab at the University of Waterloo (Plach et al., 2018a).

Upon arrival at the lab, water samples were thawed and a subsample was immediately filtered (< 0.45 um cellulose acetate filters). Samples were analyzed for P colorimetrically (ammonium molybdate-ascorbin acid) using an Autoanalyzer III (Seal Analytical, Seattle, USA). Filtered samples were analyzed for SRP (Seal Analytical Method No. G-175-96 Rev. 13). Unfiltered samples were first acidified with H_2SO_4 to 0.2% (v/v) for preservation, then acid digested by total Kjeldahl P and subsequently analyzed for TP (Seal Analytical Method No. G-189-97 Rev. 1 TP). The detection limit of this analysis was 1 ug/L and 10 ug/L for SRP and TP, respectively.

3.2.3 Data Analysis

Individual event responses were delineated with the HydRun toolbox in MATLAB using the methods of Tang & Carey (2017). Events were deemed to have commenced when a flow response above baseflow was observed and was deemed to have ended when flow returned to baseflow conditions or flow ceased altogether if there was no baseflow prior to the event. A peak flow threshold of 0.5 l/s was used to avoid 'noise' in baseflow. For each event, water chemistry samples were combined with monitored flow data to calculate FWMCs (after Williams et al., 2015b) and loads of nutrients:

$$Event\ FWMC = \frac{\sum_1^n (c_i * t_i * q_i)}{\sum_1^n (t_i * q_i)}$$

where q_i = flow in the i^{th} sample

Event FWMCs were then multiplied by event discharge volumes to calculate event loads. Event loads were summed and reported at various time scales (i.e. monthly, seasonal and annual). Although loads were not calculated for time periods outside of the delineated events (i.e. baseflow), discharge was reported for these periods for CD, FD and surface runoff. Given the low concentrations and discharge volumes experienced during baseflow, these periods are expected to have had a minimal impact on total loads from the site.

Occasionally events were missed due to equipment failure or human error. In such cases, event FWMCs were interpolated using relationships developed from measured events. For all events with monitored chemistry data, a discharge-load relationship was developed for each tile (Fig. 3.4). This was then applied to events without chemistry data in order to estimate loading based on the total event discharge. Certain outliers on the discharge-load relationships were considered incidental events, with a known reason for higher than normal SRP and TP losses (e.g. runoff immediately following surface fertilizer application). These were omitted from the discharge-load relationships so as not to skew the underlying relationships. Ratios in SRP and TP loads between the CD and FD tiles were also compared. During events in which data were available for one tile and not the other, if the observed load deviated substantially from the predicted discharge-load relationship, the ratio of the CD:FD tiles was applied instead. Or, if one species of P data (SRP or TP) was not available due to lost samples, a ratio of SRP:TP was applied for that event.

The FD field data from this site was used in Plach et al. (2019) to compare year-round EOF losses over multiple years from multiple sites in Ontario. The load calculations differ between this thesis and that paper for two main reasons. Firstly, archived surface runoff samples from the May 2015 event were recovered and included in load calculations. This event was a major contributor to overall P losses from the site. Secondly, loads with missing chemistry data were interpolated using different methods. In Plach et al. (2019), FWMCs were linearly interpolated on a daily basis to fill the gaps between events with sample data. In this thesis, gap-filling was done using discharge-load relationships developed for each tile using observed data. The same FD and surface tile discharge data was used in each study.

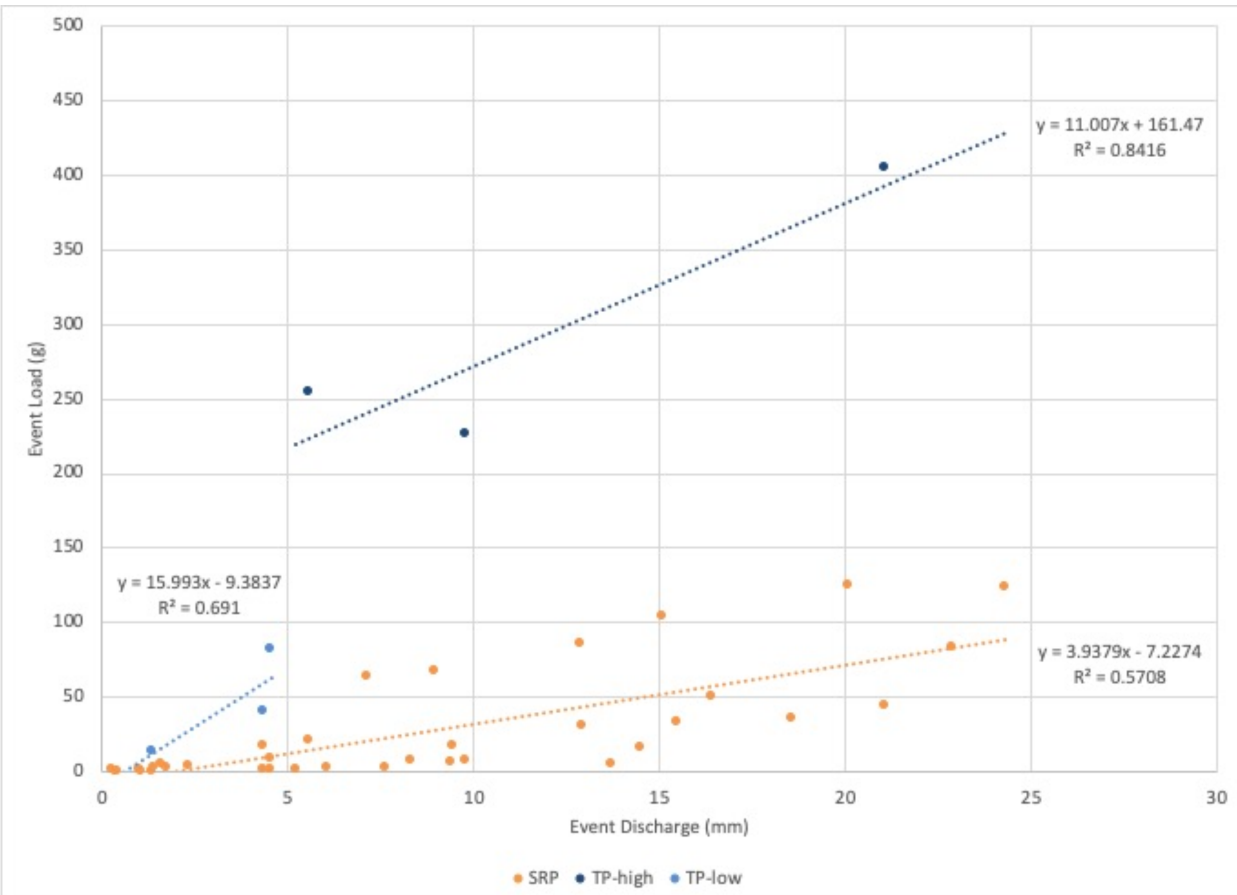

Figure 3.4. Event discharge-load relationship for the CD tile used to estimate SRP and TP loads for events with no chemistry data.

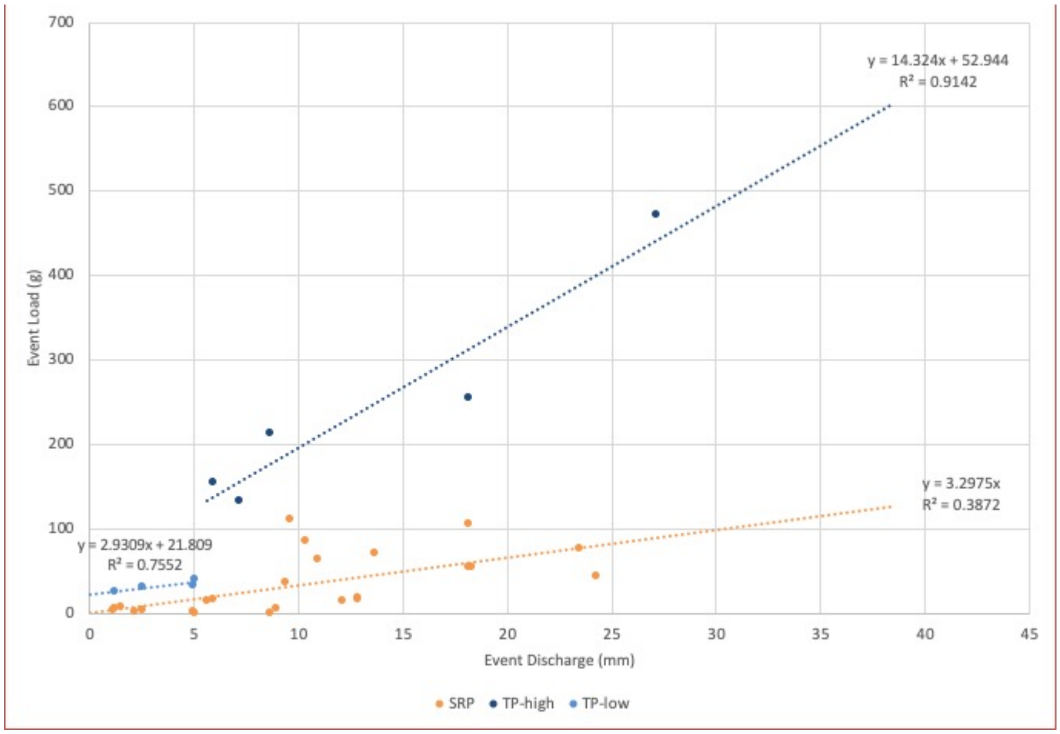

Figure 3.5. Event discharge-load relationship for the FD tile used to estimate SRP and TP loads for events with no chemistry data.

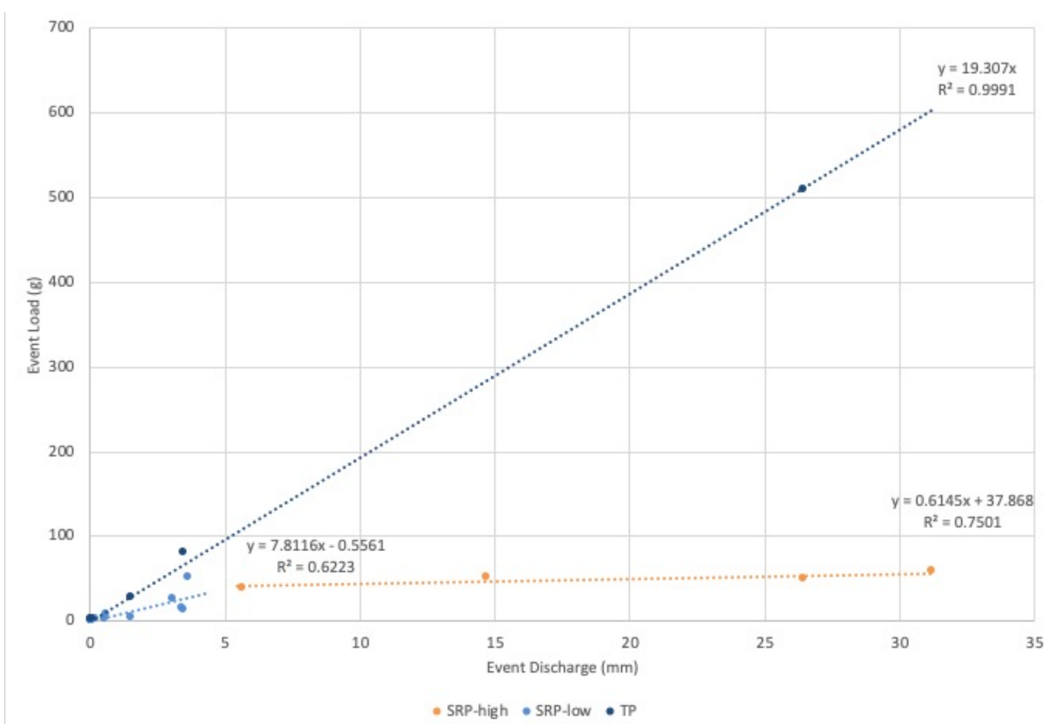

Figure 3.6. Event discharge-load relationship for surface runoff used to estimate SRP and TP loads for events with no chemistry data.

A two-sample t-test with a significance level of 0.05 and assumed unequal variances was used to test for differences in instantaneous samples concentrations over the entire study period, as well as separated by the use of control drainage. T-tests were also used to compare FWMCs between the CD and FD tile when pooled over the study period and when separated by the use of the control structure. Instantaneous soil moisture measurements were also compared between the using this method. A single-factor anova test with a significance level of 0.05 was used to test for differences between instantaneous sample concentrations between seasons for the CD and FD tiles. Statistical comparisons were not performed on interpolated data. All statistical tests were performed in Microsoft Excel.

Chapter 4 – Results

4.1 Hydroclimatic Conditions over the Study Period

Precipitation and air temperatures followed typical seasonal trends for the region with warm temperatures in summer, cold temperatures in winter and intermediate temperatures in spring and summer. However, the four study years experienced contrasting conditions across the seasons (Fig. 4.1).

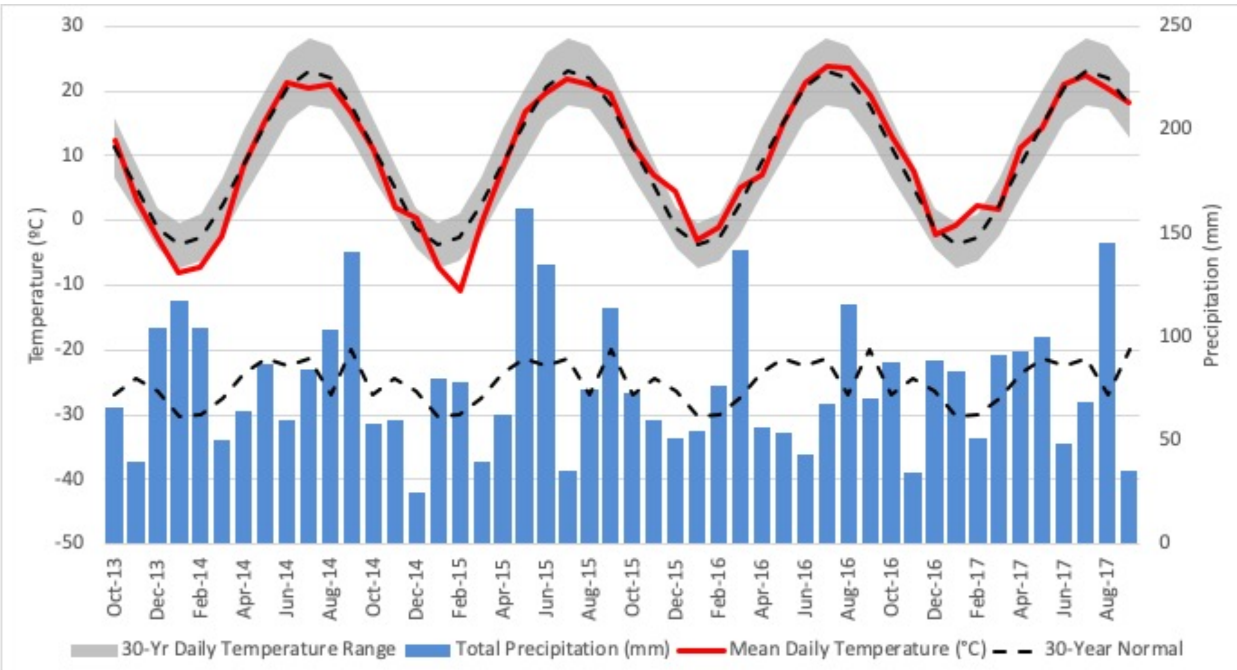

Figure 4.1. Precipitation and temperature over the study period compared to 30-year climate normals from the Windsor A Station (ECCC, 2020).

For example, the winters of 2013 to 2014 and 2014 to 2015 were substantially colder than normal, as the northern hemisphere jetstream meandered southward and parked a cold air mass over Southern Ontario for an extended period of time (a.k.a. polar vortex phenomenon). Coupled with the cold temperatures, precipitation was higher than normal in the 2013 to 2014 winter (year 1), as were the 2014 summer (year 1) and 2015 spring (year 2) seasons. In contrast, the 2015 to 2016 winter (year 3) was warm with more winter precipitation (Fig. 4.1), followed by a very dry spring. The 2016 to 2017 year (year 4) was typical of long term normals. Overall, the most variability in seasonal temperatures was seen in the fall and winter, while spring and summer temperatures fell within the normal range.

4.2 General Patterns and Temporal Variability in Runoff, Drainage and Phosphorus Chemistry

Tile drains responded to rainfall and thaw/snowmelt events, while flow typically ceased between events (Fig. 4.2). Tile discharge occurred year-round, although less frequently during the summer and early fall months. Surface runoff was observed less frequently than tile flow, and typically only in large runoff events.

Total and soluble reactive P concentrations in surface runoff and tile drain effluent generally increased with discharge peaks (Fig. 4.2). Over the study period, observed instantaneous SRP concentrations from the field ranged from < 0.001 to 2.198 mg/L, and TP concentrations ranged from 0.01 to 18.22 mg/L. These ranges include some significant outlier concentrations at the top end of the range (Fig. 4.3). In general, SRP and TP concentrations in both tile and surface runoff were higher during the GS than the NGS. In addition, P concentrations in surface runoff were larger than those in tile drainage, particularly for TP (Fig. 4.3).

Seasonal and annual patterns are evident in cumulative losses (Fig. 4.4). Precipitation occurs year-round, while there are alternating wet and dry periods in EOF runoff. Dry periods align with when the gates were installed in the control structure and wet periods coincide with periods of higher P loads.

Annual EOF runoff at the site ranged from 169.2 to 248.9 mm (mean = 214.0 mm ± 33.6). Annual runoff coefficients were 0.23 ± 0.05, ranging from 0.17 to 0.27. Annual EOF SRP losses ranged from 0.068 to 0.535 kg/ha (mean = 0.211 kg/ha ± 0.22), and TP losses ranged from 0.376 to 2.150 kg/ha (0.925 kg/ha ± 0.824).

Discharge and P losses consistently occurred during the winter months. In contrast, the fall, spring and summer seasons were more storm-dependent and did not consistently contribute discharge and loads. With the exception of summer 2014, which was particularly wet, the contribution of summer to annual discharge and loads is minimal. Likewise, with the exception of fall 2016, the fall season did not contribute nearly as much to discharge and loads as winter. The spring of 2015 was an anomaly, contributing significantly to total discharge and loads.

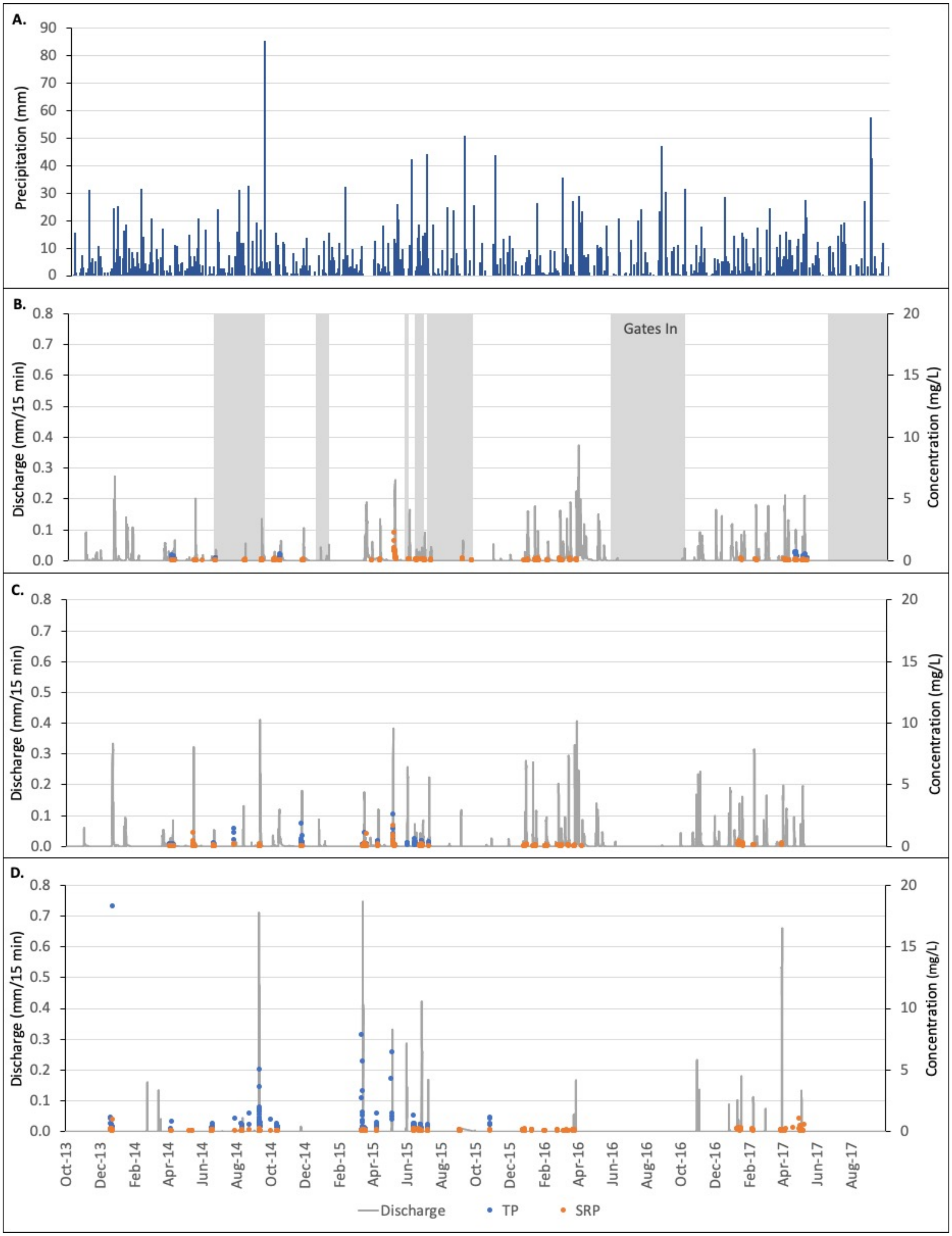

Figure 4.2. (A) Precipitation over the study period, as well as discharge and phosphorus concentrations from the (B) CD tile, (C) FD tile and (D) surface runoff.

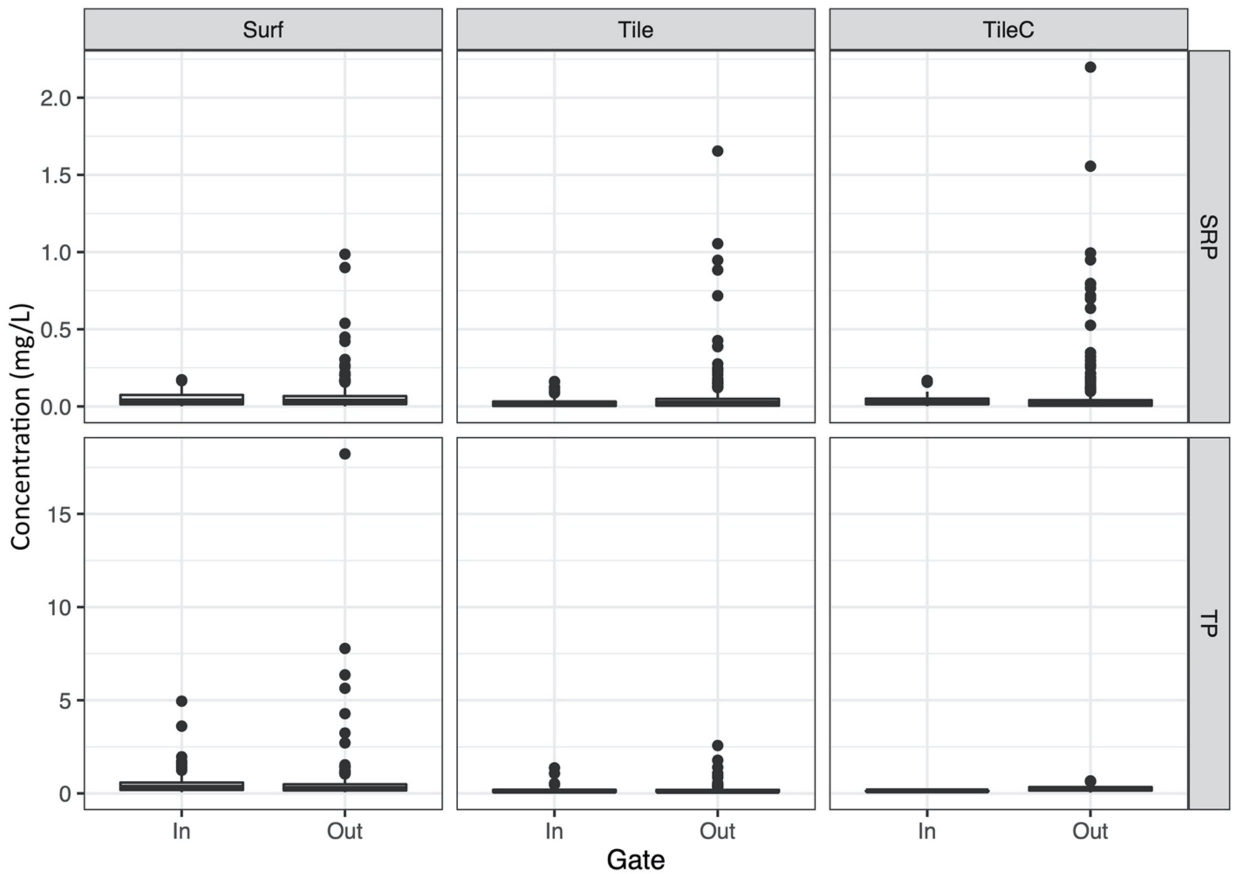

Figure 4.3. Distribution of observed instantaneous phosphorus concentrations over the study period from surface runoff (Surf), the FD tile (Tile) and the CD tile (TileC).

Discharge was highest in winter, and the combination of winter and spring represented the bulk of annual P losses (Fig. 4.5). Over the entire study period, the winter seasons contributed 40.0 ± 22.8% of the total event discharge from the EOF, but accounted for 21.5 ± 16.2% and 50.1 ± 45.6% of the SRP and TP loads, respectively. Spring accounted for 27.5 ± 19.0% of the event runoff, and 65.4 ± 116.3% and 30.5 ± 45.6% of the SRP and TP loads, respectively. Soluble reactive phosphorus contributions in spring are inflated by incidental losses in spring 2015, where 94.3% of the annual SRP load came during the spring season. Summer accounted for 7.6 ± 10.9% of event runoff over the study period, but only accounted for 2.3 ± 3.5% and 4.8 ± 6.5% of the SRP and TP loads, respectively. The fall season accounted for 24.9 ± 12.4% of the event discharge, however it only accounted for 10.9 ± 7.8% and 14.6 ± 7.2% of the SRP and TP loads, respectively. With the exception of one spring season, the losses during the NGS far outweighed those during the GS. Of total EOF losses, 71.3% of discharge, 34.1% of SRP and 67.1% of TP occurred during the NGS.

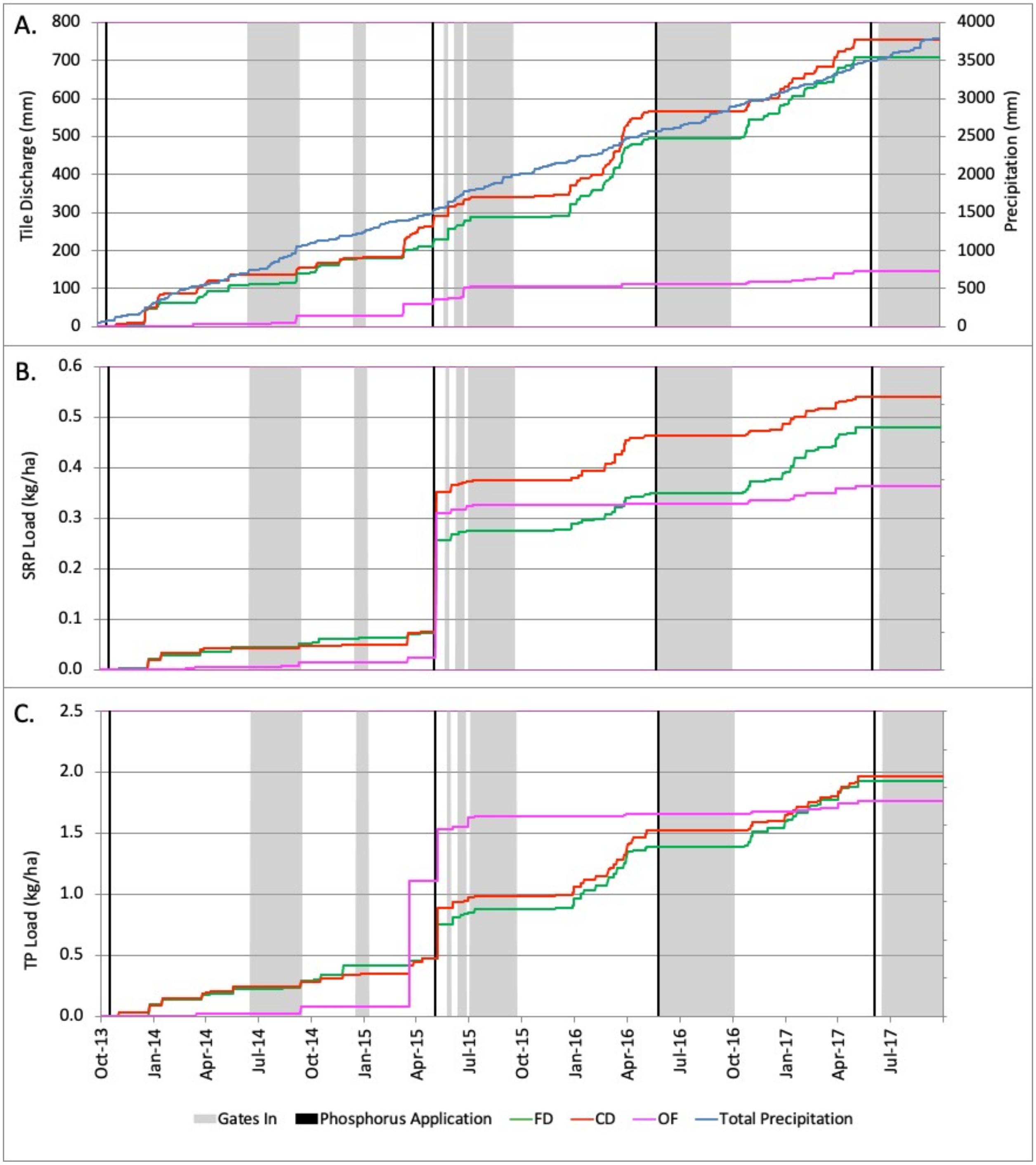

Figure 4.4. Cumulative (A) precipitation and hydrologic losses, (B) SRP loads and (C) TP loads over the study period in surface and subsurface runoff. Shaded bars indicate periods when the gates were installed. Vertical lines show the timing of phosphorus applications.

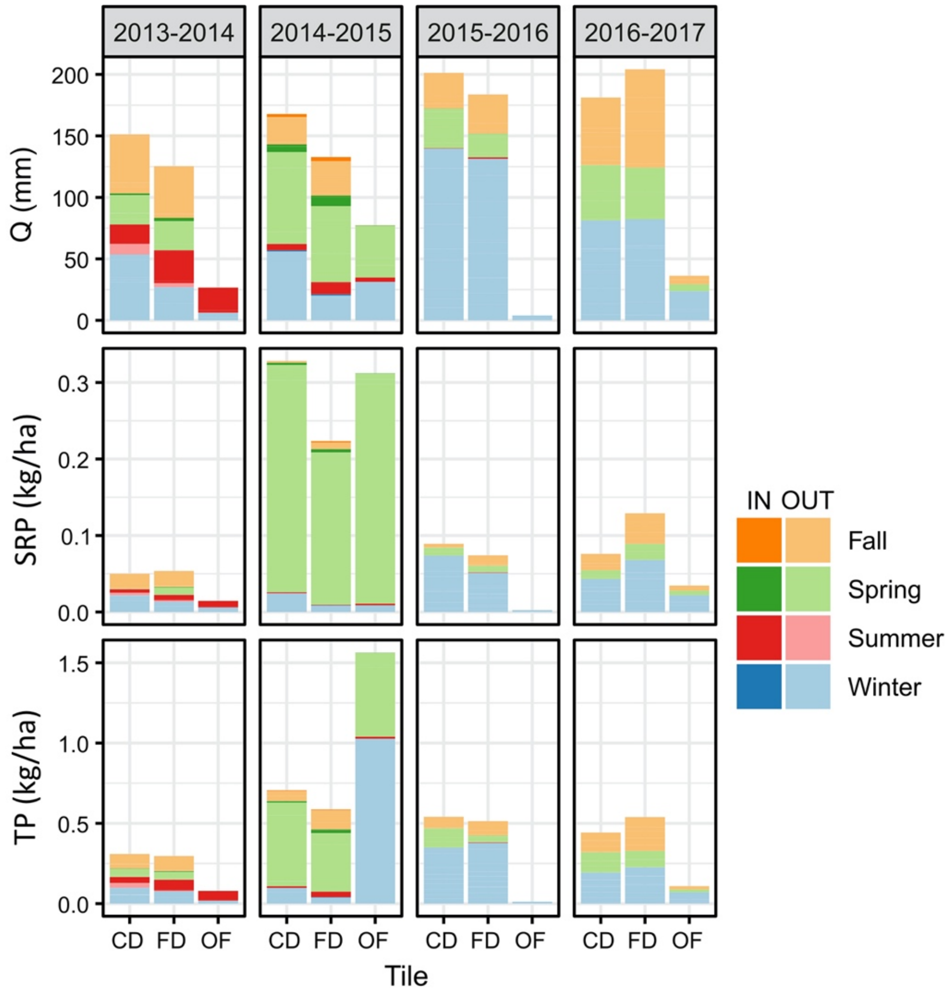

Figure 4.5. Seasonal discharge (Q) and loads from surface (OF) and subsurface runoff (CD and FD) over the study period, with values differentiated based on gate status of the control structure (IN vs. OUT).

Incidental events played an important role in the overall discharge and P losses from the site. Over the study period, there were a total of 85 EOF runoff events, measuring a total of 787.3 mm from event runoff. Of these events, the ten largest events accounted for 337.9 mm (39.5%) of the total runoff, 72.2% of the SRP load and 57.0% of the TP load. More emphatically, single events accounted for 55.6% of the SRP load and 28.7% of the TP load over the study period.

4.2.1 Relative Contributions of Surface and Subsurface Pathways to Runoff and Phosphorus Losses on the Freely Drained Field

Over the four study years, tile drainage accounted for an average of 83 ± 13% (177.2 ± 37.9 mm) of the total EOF runoff annually. This ranged from as low as 66% in 2014 to 2015, to as high as 98% in the 2015 to 2016 water year, which was particularly dry. Tile contributions to runoff also varied seasonally, ranging from 61% in summer to 97% in fall. This varied widely for individual seasons, as 5 of the 16 seasons recorded only tile runoff, and in summer 2017 there was no runoff from either the surface or subsurface tiles. Annually, tile drainage contributed 56.8 ± 23.1% (0.12 ± 0.08 kg/ha) of SRP and 52.3 ± 30.7% (0.48 ± 0.13 kg/ha) of total EOF TP losses. Annual tile contributions to SRP losses ranged from 42% in 2014 to 2015 to 97% in 2015 to 2016, and tile contributions to TP losses ranged from 27% in 2014 to 2015 to 98% in 2015 to 2016. Seasonally, tile contributions to both SRP and TP losses were greatest in the fall (93% and 96%, respectively). Conversely, tile contributions were lowest to SRP losses in spring (44.2%) and to TP losses in winter (39.0%).

Overall runoff partitioning was driven by a few key events where surface runoff was dominant and losses were substantial. However, for most events, tile discharge was the dominant pathway for EOF losses. From a total of 85 events with measured tile and/or surface runoff, discharge was tile-dominant for 80 (94%) of the events and the P losses were tile-dominant for 76 (89%) of those events. Although surface runoff was rarely the dominant pathway, the events that were mainly composed of surface runoff were large and had substantial implications on annual losses.

For instantaneous SRP concentrations measured during the study period, there was no significant difference between the tile (mean = 0.055 mg/l) and surface runoff (mean = 0.058 mg/l, $p = 0.74$). However, TP concentrations in surface runoff (mean = 0.609 mg/L) were significantly higher than in the FD tile samples (mean = 0.204 mg/L, $p < 0.001$). Sample concentrations varied by season in some cases. For surface runoff, SRP concentrations were highest in fall and spring, while summer concentrations were lowest ($p = 0.014$). TP concentrations were not significantly different between seasons in the surface runoff ($p = 0.82$). The opposite was true for tile runoff, where SRP concentrations were not significantly different between seasons ($p = 0.41$), however TP concentrations were significantly higher in winter and spring than in fall and summer ($p < 0.001$).

4.2.2 Differences in Runoff and Phosphorus Losses Between the Freely Drained and Controlled Drain Fields

The CD and FD tile systems responded to the same events, and both had increases in instantaneous P concentrations with discharge peaks (Fig. 4.2). However, the two tile drain systems differed in their event responses. Over the study period, the runoff coefficient for the CD tile was 0.201 and the FD tile was 0.189. Mean annual runoff coefficients were 0.204 ± 0.045 in the CD tile and 0.192 ± 0.050 for FD. Runoff coefficients were highest in winter and lowest in summer for both tiles. For events with the gates out, the CD overall runoff coefficient was 0.427, while FD was 0.381. This aligns with discharge measurements that show the CD field is more hydrologically active than the FD field when the gates are out. For events with the gates installed, CD becomes less hydrologically active with a runoff coefficient of 0.058, compared to the FD tile at 0.095.

Total discharge from the FD tile over the study period was 708.8 mm whereas CD discharge was 754.2 mm, a difference of 45.4 mm (6.4%). In total, the FD tile lost 0.48 kg/ha of SRP, while CD SRP losses were 0.54 kg/ha, a difference of 0.06 kg/ha (12.9%). TP losses were 1.93 kg/ha in the FD tile and 1.97 kg/ha in the CD tile, a difference of 0.04 kg/ha (1.9%) (Fig. 4.5). Tile losses were greater from the CD field overall, however, because the control structure was managed seasonally, it is important to examine the differences between fields separately for when the gates were and were not installed.

The gates were installed for 456 out of 1461 days over the study period (114 ± 18 days per year). Of the total EOF event losses from the site, 9.9% (77.7 mm) of discharge, 3.2% (0.03 kg/ha) of SRP losses and 5.8% (0.21 kg/ha) of TP losses occurred when the gates were installed. For events when the gates were not installed, discharge, SRP losses and TP losses from the FD tile were 589.5 mm, 0.46 kg/ha and 1.79 kg/ha, respectively; compared to 660.5 mm, 0.53 kg/ha and 1.91 kg/ha for the CD tile. This is an increase of 71.0 mm (12.0%) discharge, 0.07 kg/ha (14.7%) SRP losses and 0.12 kg/ha (6.4%) TP losses over the FD tile. For events when the gates were installed, discharge, SRP losses and TP losses were 53.4 mm, 0.02 kg/ha and 0.14 kg/ha for the FD tile; and 32.5 mm, 0.01 kg/ha and 0.06 kg/ha for the CD tile. This is a difference of 20.9 mm (39.2%) discharge, 0.007 kg/ha (42.2%) SRP and 0.078 kg/ha (55.5%) TP. Overall CD losses were greater than FD, but they were less than the FD tile during the time periods when the gates were in.

However, these differences do not simply represent the impact of CD on nutrient losses and runoff at the site. Because of inherent differences in discharge and P losses between the two fields when the gates were not installed, a direct comparison cannot be made to quantify the impact of CD. Instead, a relationship was developed between the two tiles by calculating the ratios of total discharge, SRP and TP during periods of free drainage. These ratios were then applied for periods where drainage was controlled to estimate the discharge and P losses that the CD tile would have produced if the gates had been left uninstalled year-round. The difference between these estimated losses and the measured losses let us estimate the overall impact of CD on discharge and P losses.

Over the study period, it is estimated that the control structure reduced discharge from the west field by 27.3 mm (3.9%), SRP losses by 0.009 kg/ha (1.6%) and TP losses by 0.087 kg/ha (4.4%). It is noteworthy though that estimated reductions were substantially greater in the summer season, reducing discharge by 20.9 mm (49.4%), SRP losses by 0.004 kg/ha (42.1%) and TP losses by 0.065 kg/ha (58.2%) over the four summer seasons in the study period. Estimated reductions for the other seasons were substantially less than the summer season (0.1 to 2.6% for discharge, 0.4 to 3.2% for SRP losses, and 0.3 to 2.1% for TP losses).

Mean annual reductions of discharge, SRP and TP due to CD were estimated to be 4.1 ± 4.7%, 2.7 ± 4.2% and 4.7 ± 5.6%, respectively. However, the annual discharge and P reductions attributed to CD were highly variable. Years 1 and 2 contributed 96.5% of the total discharge reductions over the study period, 92.0% of SRP load reductions and 96.0% of TP load reductions (Fig. 4.6). Year 3 had little impact on overall CD discharge and loads over the study period and year 4 had no net effect.

In comparing FD and CD losses, there are some seasonal and annual patterns to note. Over the study period, annual discharge was greater in the CD tile than the FD tile, with the exception of the 2016 to 2017 year. Seasonally, total discharge was greater in the CD tile for winter and spring, and greater for the FD tile in summer and fall. This pattern held true over the study period, with the exception of three seasons where discharge was nearly equal.

Overall P losses for the study period were greater in the CD tile than the FD tile, however annual variation existed. Phosphorus losses were greater from the CD tile in years 2 and 3 of the study period, while losses were either equal or greater in the FD tile for years 1 and 4. Generally, seasonal SRP and TP loading followed the same pattern as discharge, with CD losses being higher than the FD tile for the winter and spring seasons in most cases, coinciding with the time period when gates were typically not installed.

For the portion of each season when the gates were installed, the CD tile always produced less discharge, less SRP losses (except summer 2015), and less TP losses. Seasonal results were mixed when the gates were out, with discharge, SRP and TP losses from CD not always being greater than FD. This suggests that the seasonal variation in losses between these two tiles is likely dependent on the use of the CD gates. Controlled drainage discharge is lower than FD when the gates are in, however very little flow occurs during these periods (Fig 4.6). Thus, on an annual scale, potential reductions of tile discharge and P losses due to CD are estimated to be quite low at the site.

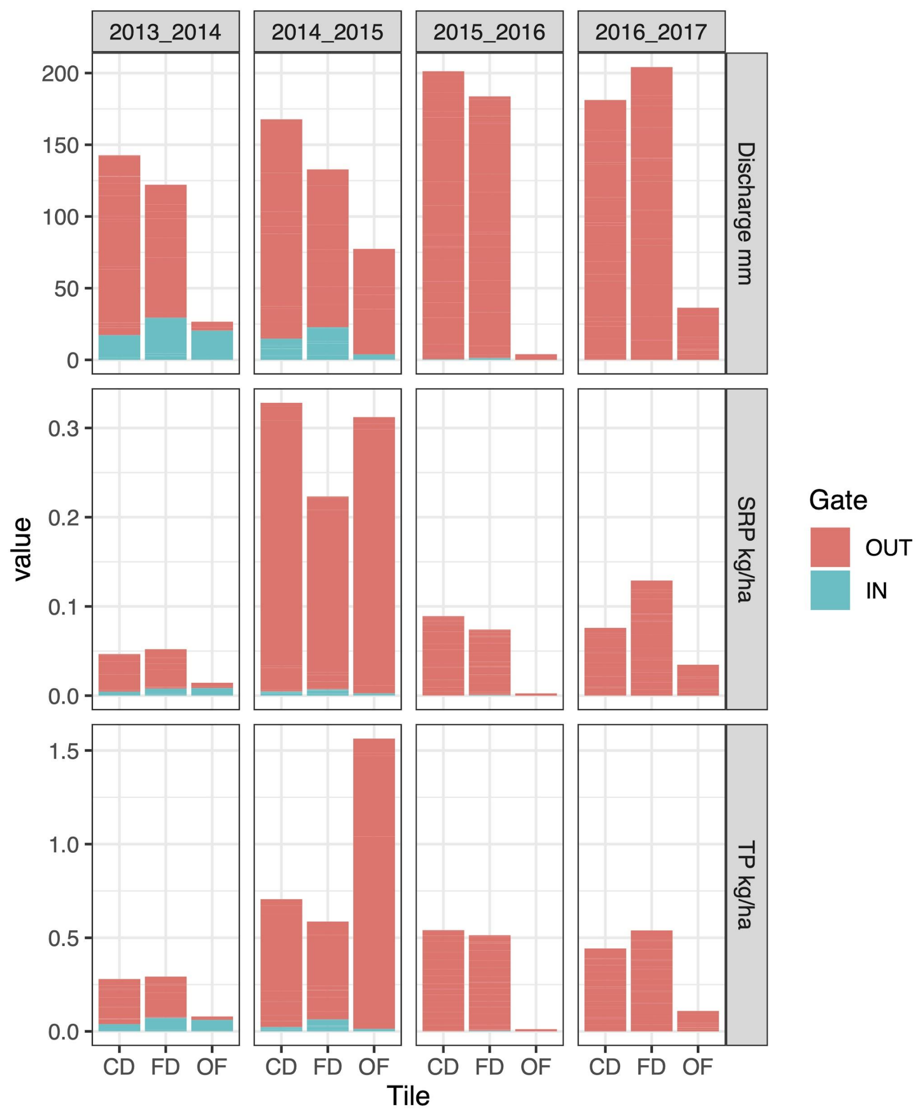

Figure 4.6. Timing of discharge and loads from surface (OF) and subsurface runoff (CD and FD) over the study period in relation to the use of the CD gates.

Edge of field discharge and P losses from the CD tile were generally reduced when the gates were in. Chemistry data can establish whether geochemical processes in the CD field were altered by CD, or whether the observed load reductions were primarily a result of reduced runoff. Instantaneous SRP concentrations in the CD tile (0.056 mg/L ± 0.028) were not significantly different than in the FD tile (0.055 mg/L ± 0.021) ($p = 0.914$) when compared over the entire study period. Likewise, TP concentrations in the CD tile (0.251 mg/L ± 0.027) were not significantly different than in the FD tile (0.204 mg/L ± 0.087) ($p = 0.120$). When the gates are installed, instantaneous SRP concentrations in the CD tile (0.035 mg/L ± 0.001) were generally higher than the FD tile (0.028 mg/L ± 0.001), however this relationship is not statistically significant ($p = 0.179$). Oppositely, TP concentrations in the CD tile (0.129 mg/L ± 0.001) were generally lower than the FD tile (0.194 mg/L ± 0.058) when the gates are in, but this relationship also does not carry statistical significance ($p = 0.074$).

	FD Tile		**CD Tile**		**Surface**	
Year	SRP	TP	SRP	TP	SRP	TP
2013-2014	0.031	0.169	0.018	0.159	0.051	0.281
2014-2015	0.133	0.426	0.289	0.301	0.032	2.027
2015-2016	0.034	-	0.048	-	0.065	-
2016-2017	0.104	-	0.042	0.331	0.094	-
4-Yr Mean	0.065	0.393	0.130	0.271	0.045	1.931

Table 4.1. Annual and total FWMCs (mg/L) for tile and surface runoff.

Over the entire study period, the CD tile had a greater SRP FWMC than the FD tile, but a lower TP FWMC (Table 4.1). The overall surface runoff TP FWMC was greater than both tiles, but the SRP FWMC was lower than for both tiles. These relationships were inconsistent across the four study years and FWMCs were calculated from varying numbers of samples for each discharge source and P form, making interannual comparisons difficult. Event SRP and TP FWMCs were compared between the FD and CD tiles, separated by gate status. Although sample size limits the statistical power of these comparisons, mean event FWMCs for SRP and TP in the CD tile both tend to be lower than in the FD tile, although the difference is not statistically significant (Fig. 4.7).

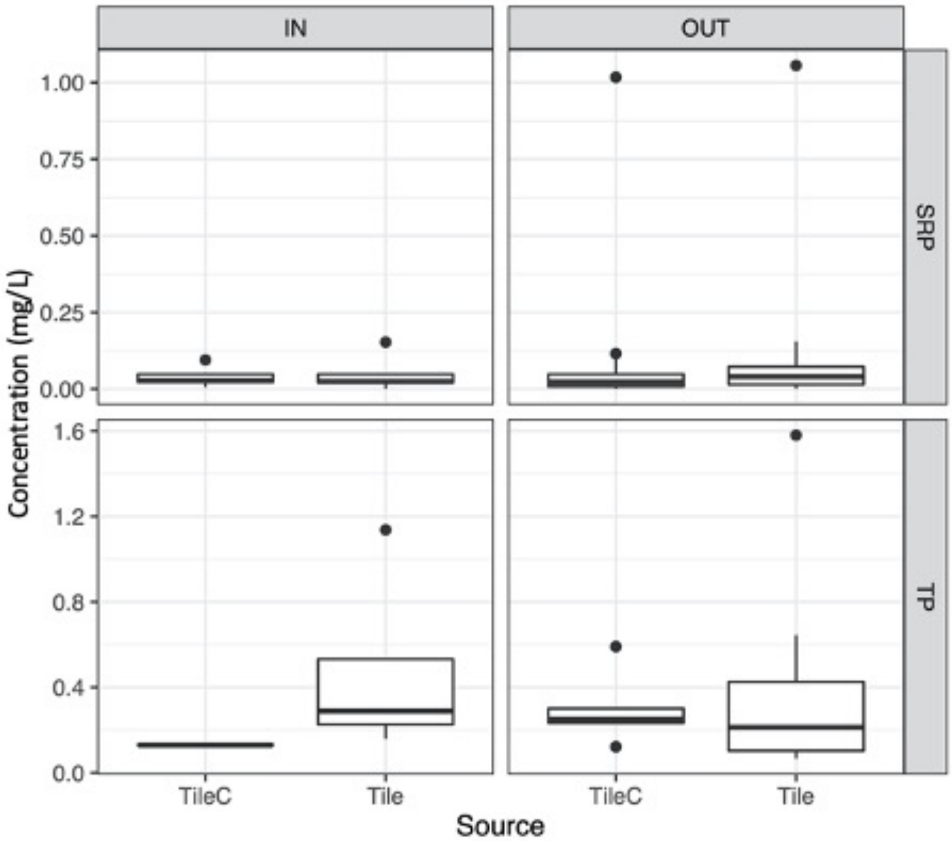

Figure 4.7. Event SRP and TP FWMCs from the FD (Tile) and CD (TileC) tiles in relation to the use of the CD gates. Note that n = 1 for TileC TP FWMCs with gates in.

The relationship of event discharge and FWMCs between the two fields is compared to further determine if geochemistry is altered by the use of CD (Fig. 4.8). There is considerable variation in the relationship between event discharge and FWMC (both SRP and TP), with a scattered distribution (Fig. 4.8). There are no clear differences between the FD and CD tile, or within the CD tile based on gate status. Tile water chemistry does not significantly differ between the CD and FD fields, regardless of gate status or event size. This suggests that loading implications are reliant on runoff quantities and do not hinge significantly on altered geochemistry in soils under CD.

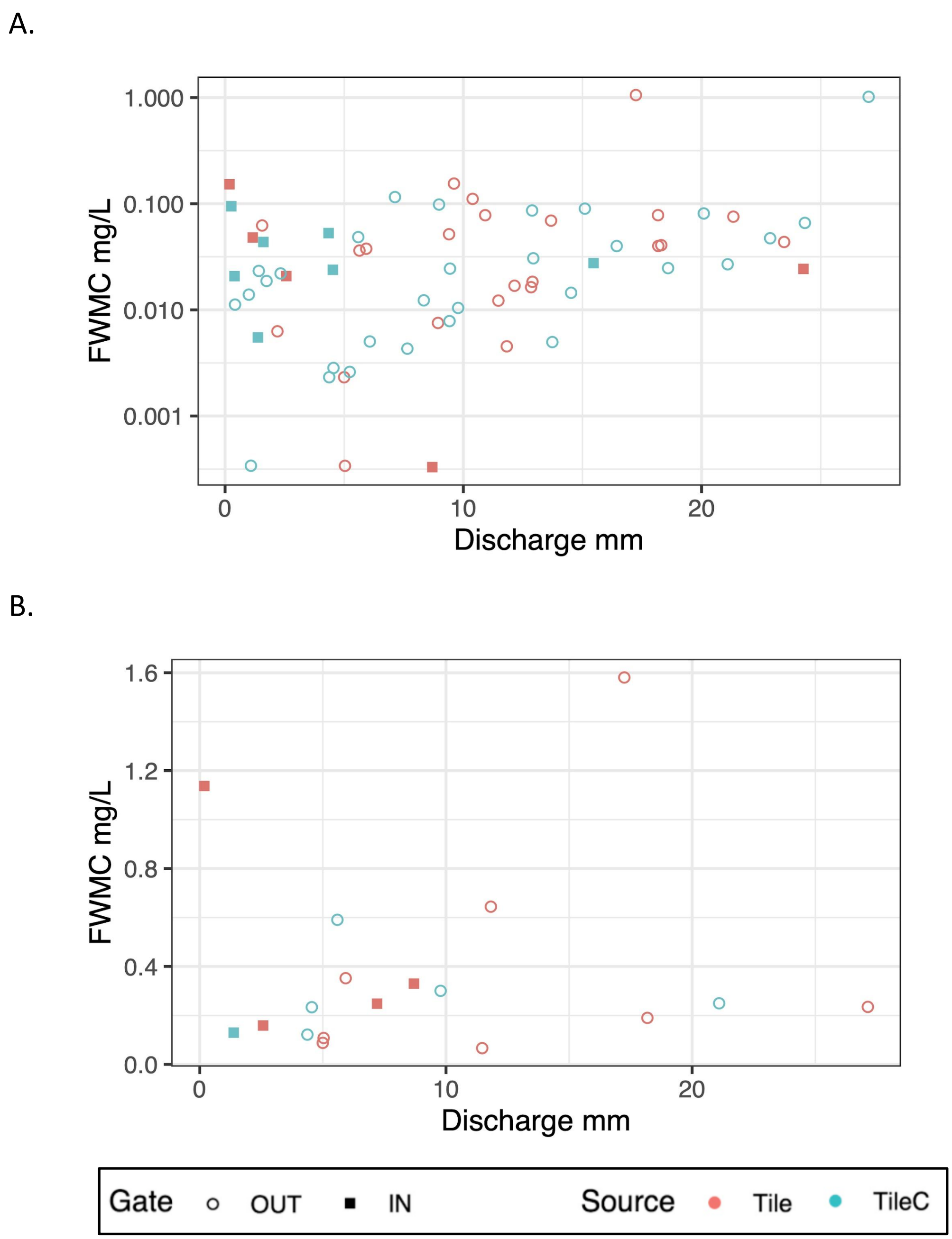

Figure 4.8. Relationship of event discharge volume to (A) SRP and (B) TP FWMCs for the FD (Tile) and CD (TileC) tiles. Note the logarithmic y-axis scale for SRP FWMCs.

4.3 Differences in Field Environmental Conditions between Controlled and Free Drainage

Surface runoff was not monitored on the CD field, and consequently, it is not possible to determine the impacts of CD on total losses at the EOF. However, patterns in both water table and soil moisture conditions can be used as proxies to determine differences in hydrologic storage.

Ground level on the farm is approximately 195 meters above sea level (masl) and the tile system is at 193.6 masl. Over the NGS, the water table generally fluctuated between 194.2 and 194.9 masl with precipitation and melt events (Fig. 4.9). During the GS, water table levels were generally falling until they were at or below the tile depth, with the exception of temporary rises in response to rain events. In summer 2016 the gates were installed for the entire GS, yet water table levels in the CD field generally dropped at the same rate as in the FD field. When CD gates were in place during the two growing seasons shown, the spikes in water table level were more pronounced in the CD field piezometers, however these peaks were temporary and were not sustained (Fig. 4.9). Otherwise when comparing piezometer levels from the fields, there is no discernible difference between the CD and FD fields in water table levels or patterns.

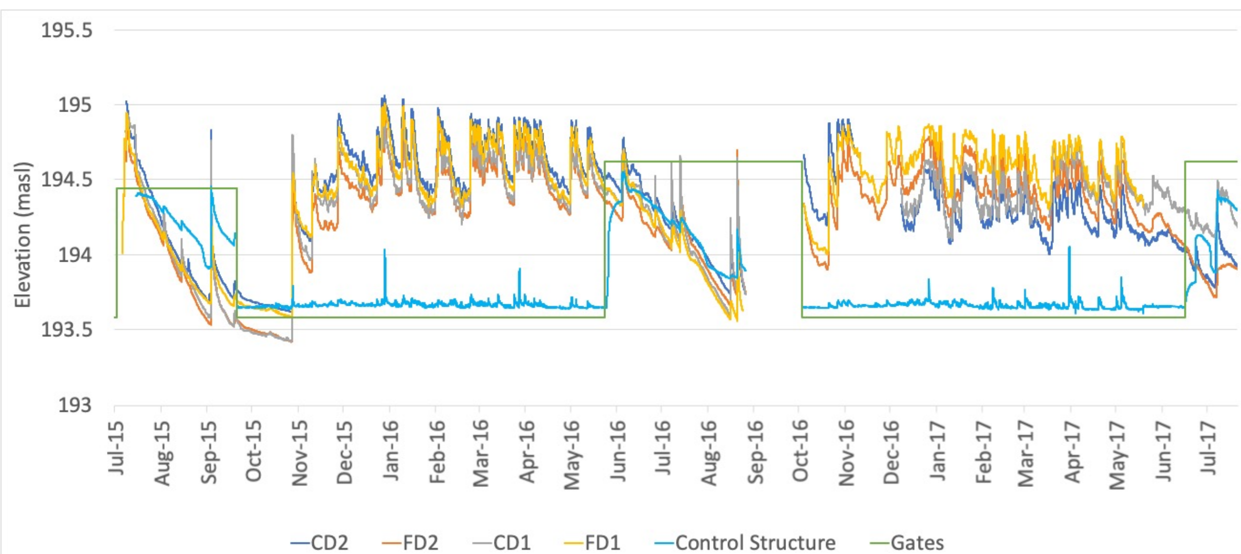

Figure 4.9. Water table position in two locations within each of the fields (e.g. FD1 and FD2) from July 2015 to July 2017. The elevation of the CD stop-log position is shown in green. Ground level ranges between 194.95 and 195.03 masl across the piezometer locations.

In this study, the CD gates were typically only installed during the GS, when water table position across the field is deeper and the likelihood of surface runoff caused by saturation is low. However, even though the NGS represents a greater risk of surface runoff, there was still surface runoff observed during the GS when the gates were installed. Over the study period, only 29% (8 of 28) surface runoff events occurred when the CD gates were in place. These 8 events represent 17% (24.3 mm) of total surface discharge, 3% (0.011 kg/ha) of surface SRP losses and 4% (0.074 kg/ha) of surface TP losses over the study period. The estimated benefits of CD at this site are nearly equivalent to the total measured surface runoff losses over the same time period. This means that an increase in frequency or magnitude of surface runoff caused by CD has the potential to offset any P reductions, leaving us no further ahead.

The four piezometers were located in pairs, with CD2 and FD2 located slightly lower in topography than CD1 and FD1, as the field slopes gently towards the south. There is a mean elevation difference of 28 mm, both within and between location pairs. Although median water table position in the CD field appears to be slightly higher than in the FD field when the gates were activated, this difference is very small and there is no clear, consistent difference in water table position between the fields, (Fig. 4.10), suggesting that the control structure gates had minimal impact on the water table position in the field. Data from the water level logger in the control structure shows that when the gates were in, there was water being held back behind the gates (Fig. 4.9 and 4.10). As with the water table position measured in the field piezometers, the level dropped through the GS, however all available data suggests that water was consistently being held behind the gates. The water retained by CD, however, did not result in a measurable impact on water table position in the field when broken out by season.

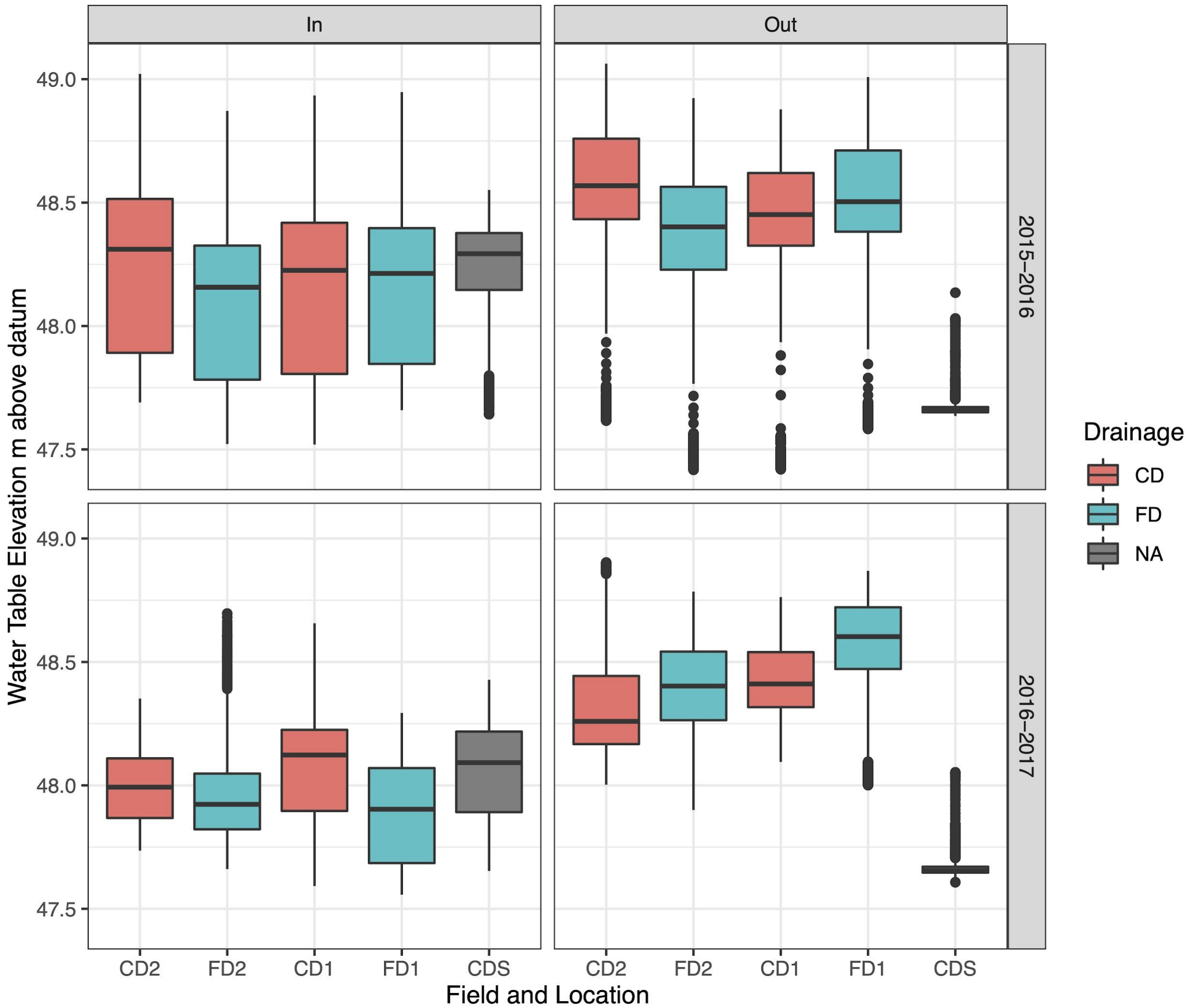

Figure 4.10. Water table position in two locations within each of the two fields (e.g. FD1 and FD2) and within the control structure (CDS) between July 2015 and July 2017.

In addition to water table position, soil moisture levels in the CD and FD fields were collected from July 2015 to July 2017 to see if the CD gates had a measurable impact on water retention. Over two years of data collection, volumetric water content (VWC) at the site ranged from 0.123 to 0.474 m^3/m^3 (Fig. 4.11). Although VWC increased with depth (46 cm, Figure 4.11), there was no difference between the FD and CD fields in either year. At the upper two depths, mean soil moisture levels were lower when the gates were in, aligning with the typically drier summer and fall months, whereas VWC at 46 cm depth was similar between periods when the gates were in and out.

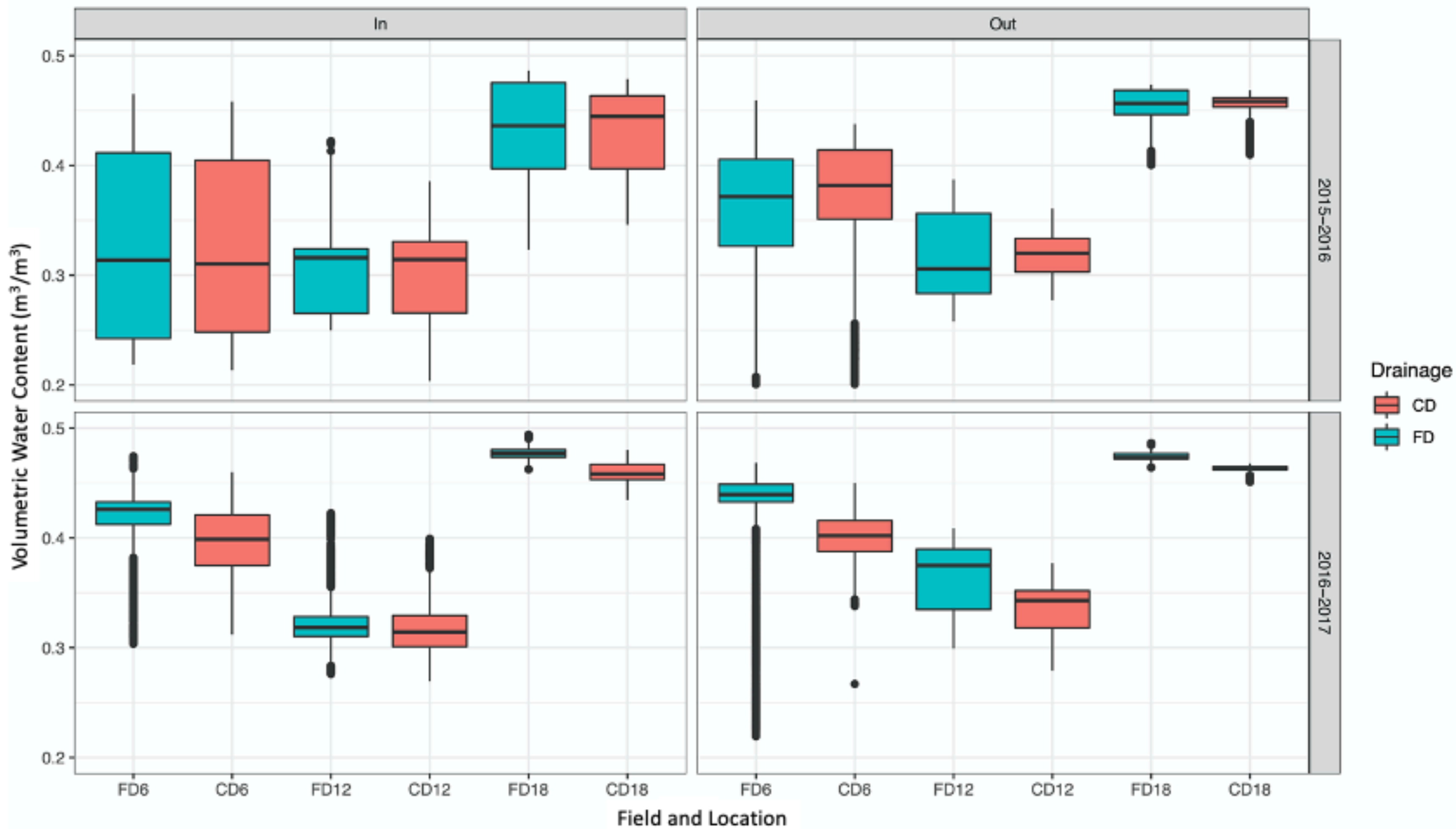

Figure 4.11. Soil moisture at 6” (15 cm), 12” (30 cm) and 18” (46 cm) depths in the CD and FD fields from July 2015 to July 2017 (i.e. “FD6” is soil moisture at 6” (15cm) depth in the FD field).

Chapter 5 - Discussion

5.1 Annual and Seasonal Runoff and Phosphorus Losses in Surface Runoff and Tile Drainage

Weather conditions experienced over this multi-year study were variable, but generally reflected 30-yr climate normals for the region (ECCC, 2020). For example, precipitation received over the study period, deviated by -7.5% to 9.6% of the 30-yr annual normals. Thus, the patterns in EOF runoff amounts and pathways are likely indicative of what is experienced in the study region.

Although weather conditions over the study period were typical for what is experienced in the region, annual runoff losses at the EOF (23 ± 5% of precipitation) were at the low end of what has been reported in other studies in the same region (e.g. 21% in Zhang et al., 2015; 30% in Tan et al., 2002; 34% in Tan & Zhang, 2011). The difference in EOF runoff losses experienced in the current study and other studies within the same region could be explained by differences in tile spacing as tile drain laterals are spaced at 10.7 m in the FD field in the current study but were spaced at 7.5 m at the Zhang et al. (2015) and Tan et al. (2002) studies and 4.6 m in the Tan & Zhang (2011) study.

Runoff received at the EOF in the current study was also smaller than was observed in other studies in Ontario and Quebec. For example, Van Esbroeck et al. (2016) reported tile runoff coefficients of 0.35 to 0.45 and total EOF runoff coefficients of 0.45 to 0.5 in fields in two central western Ontario. Tile spacing is comparable at these sites (9 to 14 m), however the soils are of a lighter texture than those at the current study site. However, in Southern Quebec, tile runoff coefficients were found to be higher in clay loam fields than in sandy loam soils (Eastman et al., 2010). Thus, the difference between the current study and previous studies in Ontario may not be due to soil texture differences alone. Indeed, the sites in Van Esbroeck et al. (2016) are located at a higher latitude than the current study, and farther away from the Great Lakes. Colder winter temperatures at the higher latitude would produce a greater spring freshet than in Essex, and cooler summer temperatures would likely lead to less evapotranspiration from crops. Together, these factors may have led to smaller annual mean runoff coefficients in the current study.

Phosphorus losses at the EOF in the current study (0.211 ± 0.220 kg SRP/ha; 0.925 ± 0.824 kg TP/ha) were greater than those experienced at two Ontario sites (0.09 and 0.21 kg SRP/ha; 0.37 and 0.61 kg TP/ha) in midwestern Ontario over the same time period (Plach et al., 2019). Mean EOF losses in the current study were largely driven by incidental losses in spring 2015 from a snowmelt event and an event immediately following a fertilizer application, which may explain the differences to losses reported by Plach et al. (2019). Excluding year 2, mean annual P losses from the study site were 0.515 ± 0.138 kg TP/ha and 0.102 ± 0.053 kg SRP/ha, which are comparable to those reported by Plach et al. (2019). Although the EOF annual TP losses in three of the four study years were comparable to other studies in Ontario over the same time period, they were lower than other multi-year studies on clay or clay-loam soils in similar geographies, which ranged from 1.6 to 4.2 kg/ha (mean = 1.9 kg/ha) in Quebec (Eastman et al., 2010) and 1.0 to 2.1 kg/ha (mean = 1.1 kg/ha) in southwest Ontario (Tan & Zhang., 2011).

The incidental losses experienced in the second year of the current study largely affected P losses over the entire study period. Spikes in EOF losses have been observed where fertilizer or manure is applied prior to a runoff event (Withers et al., 2003; Van Esbroeck et al., 2016; Plach et al., 2019). Large discharge and P losses have also been observed during the winter snowmelt and spring precipitation events on wet soils in cold temperate regions, both at the EOF scale (Ball Coelho et al., 2012; Van Esbroeck et al., 2016; Plach et al., 2019) and the sub-watershed scale (Macrae et al., 2007a; Irvine et al., 2019).

Aside from the elevated P losses following fertilizer application, the majority of P lost at the EOF in the current study occurred during the NGS when the majority of runoff occurred (> 70% of mean annual discharge). The 2014 to 2015 water year was an exception, where SRP losses in the GS far outweighed those in the NGS, coinciding with incidental losses following fertilizer application. In the remaining three years however, the NGS contributed 57 to 92% of annual discharge, 61 to 90% of annual SRP losses and 54 to 90% of annual TP losses. This finding is slightly smaller than the findings of Van Esbroeck et al. (2016) who reported that 83 to 98% of EOF runoff occurred during the NGS across three Ontario study sites, all of which were located at more northern locations. This is likely due to a combination of smaller snowpack volumes at the more southerly site used in the current study, but also due to greater hydrologic responses in tile drains in summer in the clay soils due to preferential flow pathways (e.g. Macrae et al., 2019).

5.1.1 Contribution of Tile Drains to Overall Runoff and Phosphorus Losses at the Edge of Field

Tiles were the dominant pathway for EOF runoff at this site; however, P losses were contributed almost equally from tile and surface runoff. For most events, tiles were the dominant pathway for P losses, except for a few large incidental events where surface runoff contributed significantly to overall loads. This finding is consistent with other studies conducted in this temperate climate region, where tile drainage is the dominant pathway for EOF discharge, ranging from 73 to 97% of total runoff (Eastman et al., 2010; Tan & Zhang, 2011; Pease et al., 2018; Plach et al., 2019). Sites where tile runoff comprised more than 85% of total runoff were outliers and were likely impacted by either unusually close tile spacing (Tan & Zhang, 2011) or a hummocky landscape with no direct surface drainage pathway (Plach et al., 2019). Tan & Zhang (2011) reported that tiles were the dominant pathway for P losses, contributing 95% of TP. However, this exaggerated subsurface contribution may be partly driven by the narrow tile drain spacing in their study which likely increased subsurface losses and decreased surface losses relative to the current study. Thus, runoff partitioning in this study is consistent with the literature.

The finding that surface runoff accounted for a greater proportion of P losses at the EOF relative to its contribution to runoff is also consistent with the literature (Eastman et al., 2010; Tan & Zhang, 2011; Pease et al., 2018; Plach et al., 2019). This is driven by the more frequent baseflow in tiles and the frequently elevated FWMCs observed in surface runoff (Sharpley, 1995; Tan & Zhang, 2011; Pease et al., 2018). Across many study sites, tiles have been shown to contribute 43 to 90% of SRP losses and 41 to 95% of TP losses (Eastman et al., 2010; Tan & Zhang, 2011; Pease et al., 2018; Plach et al., 2019). Nevertheless, tile drains in the current study contributed a significant proportion of annual SRP (42 to 97%) and TP (27 to 98%) losses at the EOF. This is consistent with other studies on clay soils (King et al., 2015a; Pease et al., 2018).

5.2 Effects of Controlled Drainage on Annual and Seasonal Discharge and Phosphorus losses

This study confirmed that in FD fields, tiles are indeed a significant pathway for P losses (57% of SRP and 52% of TP losses). Thus, CD has the potential to reduce annual P losses at the EOF. It is important to consider, however, that implementing CD may only reduce the EOF P losses delivered through subsurface drainage, and thus, the overall efficacy of CD may be smaller in fields where P losses are divided equally between tile and surface runoff.

In this study, CD did not reduce tile discharge or P losses in comparison to the FD field on an annual basis. In fact, runoff and P losses in tile drainage from the CD field exceeded losses in tile drainage from the FD field. This is likely a result of subtle differences in tile spacing between the two sites, but more importantly, due to the fact that CD was restricted to the GS.

Controlled drainage showed potential for reducing tile discharge and P losses during periods in which drainage was controlled (i.e. post-planting to pre-harvest), as CD discharge was 39% lower than the FD tile for periods when drainage was controlled. However, this period represented very little of the annual tile runoff (8.3%) and P losses (7.2%), limiting the efficacy of CD at this field site. The reduction in tile drainage experienced in the current study *when drainage water was managed* is consistent with what Zhang et al. (2015) observed (~33% reduction in annual runoff coefficients) when drainage was controlled year-round. This demonstrates that using drainage control during the GS and not the NGS is significantly impacting its efficacy as a conservation practice at the study site. The results of the current study demonstrate that it is essential to control drainage on an annual basis if the goal of the practice is to improve water quality.

The CD field was more hydrologically responsive than the FD field during periods in which drainage was not controlled, which was likely related to slight differences in tile spacing between the fields (9.2 m in the CD field, 10.7 m in the FD field). For events with the gates out, which mainly fell within the NGS, the CD tile produced 12% more discharge than the FD tile. Thus, the fact that water yields were greater from the CD field simply reflects these subtle differences in drainage intensity.

Since the two fields were found to behave differently in the control (FD) periods, a discharge relationship between the two tile outlets was developed and then applied to the experimental (CD) periods in order to estimate the impact of CD on discharge. This method has been used in other field-scale CD studies where plots differed under FD and is necessary in large scale field studies where there are inherent differences between the control and experimental fields (Saadat et al., 2018; Carstensen et al., 2019). Using this method, it is estimated that CD reduced tile flow by 27.3 mm (45.7%), SRP by 0.009 kg/ha (50.0%) and TP by 0.087 kg/ha (58.2%) when active over the study period, but this is only 3.9%, 1.6% and 4.4% of total losses, respectively. Across studies, results during the GS generally show that CD has the potential to reduce tile flow by 27 to 95%, with the largest effect seen during years with above-normal precipitation (Lalonde et al., 1996; Sunohara et al., 2015; Williams et al., 2015a). The wide range of results reflect the range of climates, soil types and gate management strategies in the literature. Studies that implemented CDSI during the GS also measured similar runoff reductions when compared to FD (Valero et al., 2007; Zhang et al., 2015). Most studies also found that the use of CD during the GS resulted in lower EOF P loads (Valero et al., 2007; Williams et al., 2015a; Zhang et al., 2015; Sunohara et al., 2015; Sunohara et al., 2016). However, as is found in the current study, hydrological conditions during the GS result in little discharge and associated P losses from FD tile systems as compared to the NGS, so the impact of CD on annual losses is negligible (Stampfli & Madramootoo, 2006). Under local conditions where the NGS represents the majority of annual discharge and P losses (Tan et al., 2002; Eastman et al., 2010; Van Esbroeck et al., 2016; Plach et al., 2019), CD has limited potential to reduce annual budgets if utilized only during the GS, as in the present study. Had CD been implemented over the entire year, and assuming that it did not affect surface runoff and that the reduction rates experienced during the GS are similar to the NGS, it was estimated that CD would reduce SRP by 50% and TP by 58% at this site.

A study by Zhang et al. (2015) is a particularly interesting comparison because it takes place on a Brookston clay soil near the study site with the same crop rotation. Tile plots had a tile depth of 0.6 m with 7.5 m spacing and controlled the water table depth to 0.3 m below ground level. The closer spacing and shallower depth of tile in this study may have increased runoff coefficients, but overall the tile system was comparable to that of the current study. The study examined year-round management of CD, with sub-irrigation during the GS and found that tile discharge, P concentrations and P loads were reduced on an annual basis under normal farming practices (Zhang et al., 2015). This study shows that the year-round use of CD in a similar setting can result in discharge and nutrient abatement. However, the question remains whether the potential benefits of managing CD through the NGS are worth the time investment required to manage the gates, and whether these benefits offset the increased risk of nutrient losses via surface runoff.

5.3 Differences in Subsurface Runoff Chemistry Under Free and Controlled Drain Systems

Nutrient fluxes are typically driven primarily by runoff volumes (e.g. Macrae et al., 2007b; Plach et al., 2019); thus, reducing drainage volumes with drainage control is anticipated to reduce P losses. Many CD field studies have shown that annual nutrient load reductions were tied closely to reductions in EOF discharge, concluding that CD has minimal effect on nutrient concentrations and load reductions were achieved as a result of flow attenuation. This pattern has been observed only for N losses (Wesstrom et al., 2001; Sunohara et al., 2015), only P losses (Tan & Zhang, 2011), or for both N and P in the same study (Williams et al., 2015a; Carstensen et al., 2019). However, CD may have the potential to modify the chemistry of drainage water and either enhance or offset the reduction in P loss through this pathway.

Elevated water tables caused by DWM can lead to reduced oxygen content in the subsurface and thus either anoxic or suboxic conditions (Gilliam & Skaggs, 1986). These conditions can promote denitrification and reduce the nitrate concentrations of tile discharge (Gilliam & Skaggs, 1986); however, such conditions can also enhance the desorption of P from iron oxides (Valero et al., 2007). Consequently, CD has been considered a tradeoff BMP that is beneficial for N losses and unfavourable for P losses. However, this is contested by Williams et al. (2015a), who discuss the impact of CD on water table conditions, concluding that the soil profile does not undergo reduced redox conditions for sufficient time periods to realize the impacts of increased P solubility. This is supported by other CD studies in the literature where it is commonly observed that the water table is not held at the target level for long during the GS, and that the gates need to be raised significantly in order to make a measurable difference in the water table level of the field (Valero et al., 2007; Carstensen et al., 2019). With DWM of 0.3 to 0.5 m below ground surface and given the fluctuating water table position when CD is used without sub-irrigation, reduced soil conditions are not expected to be of great concern to tile P losses. Like many components of CD, the measured impact on P chemistry of runoff water varies across the literature and is likely dependent on a range of factors like climate, gate management, nutrient applications, soil type and STP levels. Results from this study do not support the hypothesis that CD increases P solubility in the soil profile.

A study by Zhang et al. (2015) illustrates how the impact of CD on FWMCs for P may be highly dependent on field management. For example, in their study, different compost additions resulted in varying P concentration results. With the addition of a low-P yard waste compost, the FWMC of SRP was reduced by 14% with CDSI compared to the FD treatment. In contrast, with addition of P-heavy swine manure compost, the FWMC of SRP was increased with CDSI by 56%. For the control plot with no compost added, a smaller reduction in runoff P concentrations (3%) was observed under CDSI. Their study concluded that the input of a high-P source exceeded the saturation threshold of the soil, significantly reducing the soil's capacity for P sorption and making P available for leaching to the tiles with downward water movement (Zhang et al., 2015). With CDSI, there may be more water available in the upper soil profile to transport the soluble P available from the organic amendment that was applied. In contrast, a study by Williams et al. (2015a) took place on fields with high surface soil STP levels (~100 mg/kg), yet found that SRP concentrations in tile runoff were not increased with CD. The difference here may be the use of CD without sub-irrigation, meaning that the soil profile does not experience sustained anaerobic conditions and P desorption like it may have in the CDSI study by Zhang et al. (2015). STP levels at the study site are low and are not likely to exceed the threshold levels of P sorption in the soil (Plach et al., 2019).

Studies in the literature that reported increased P concentrations were limited to those with CDSI during the GS, some of which used a high-P water source for sub-irrigation, plots that received P-rich organic amendments and a study with extremely high water table control during the NGS (Stampfli & Madramootoo, 2006; Valero et al., 2007; Zhang et al., 2015; Saadat et al., 2018). Studies where CD was used without sub-irrigation, regardless of season of use, measured no significant differences in P concentrations in tile discharge (Williams et al., 2015a; Sunohara et al., 2015; Carstensen et al., 2019). These results indicate that the use of CD without sub-irrigation may not sustain a saturated soil profile for long enough to impact redox potential and increase P solubility.

There is a range of P concentrations in tile discharge from CD studies through the literature. The concentrations measured here were about half of those reported in Williams et al. (2015a), and much larger than SRP concentrations reported by Carstensen et al. (2019). This range of P concentrations are thought to be heavily driven by soil type and STP levels. Phosphorus concentrations and chemistry patterns in the current study were similar to those observed nearby in Tan & Zhang (2011), providing a good comparison of climate and soils. In that study, concentrations were highest during the GS and surface runoff concentrations were significantly larger than those observed in tile runoff. They found that the use of CD increased FWMCs of SRP in both surface and tile runoff. The study also reported that CD increased the TP FWMC in surface runoff, but it reduced the TP FWMC in tile discharge which was attributed to the settling of sediments in the reservoir used as a water supply for sub-irrigation. In another nearby study, SRP concentrations in tile runoff were found to be lowered with CDSI under similar farming practices (Zhang et al., 2015). As discussed earlier, both of these studies utilized sub-irrigation during the GS, which may have altered the impact of CD on P concentrations as compared to the current study. Nevertheless, even under comparable climate conditions and soil types, these studies show that the impact of DWM on P runoff concentrations is inconsistent. Although data from the current study shows no significant impact of CD on P FWMCs, over the study period there is an overall increase in SRP FWMC and a reduction in TP FWMC in the CD tile, which follows the same pattern reported by Tan & Zhang (2011).

Although average FWMCs over the entire study period show differences between the CD and FD tile, a comparison of both instantaneous concentrations and event FWMCs show no statistically significant differences between the two tiles. Given the insignificant differences, these results could be attributed to sampling bias. Although sample size was large for many of these comparisons (especially SRP), the timing of sampling was not consistent between the two tiles, nor were samples collected from all of the same events, which could have skewed chemistry results when making comparisons between the two tiles.

5.4 Impacts of Controlled Tile Drainage on Soil-Water Dynamics

One goal of CD is to maintain a desired water table level in the field, maximizing crop health by providing access to adequate soil moisture (Crabbe et al., 2012). Although tile drainage in the CD field was controlled for the entire GS, the dataset in this study does not show a significant increase in either water table position or soil moisture through the GS due to CD.

Although the water was retained *within* the control structure where tile drainage was monitored, this was not reflected in measured water table position within fields. This suggests that the control structure may not necessarily lead to water table control within some fields, likely due to lateral or downward seepage. This has also been observed in other studies (Gilliam et al., 1979; Lalonde et al., 1996; Stampfli & Madramootoo, 2006; Carstensen et al., 2019).

Previous studies have cited various mechanisms for why P concentrations may have been impacted by CD, however, there is little supporting evidence in this study period to suggest an impact from CD. Soils with high clay content like at the current study site have been found to shrink and crack under dry antecedent moisture conditions, resulting in preferential flow (Grant et al., 2019). The presence of macropores that bypass the soil matrix and link the high-P soil surface to the tiles are generally thought to increase subsurface P losses (King et al., 2015b). One hypothesis is that CD could result in a higher water table and prevent desiccation cracks from forming, thereby reducing P concentrations in the tile. Soil moisture data from the site shows no evidence of increased soil moisture in the CD field while the gates were active. Water table data from the piezometers at the site also confirm that water retention in the soil profile of the CD field when the gates were installed was negligible. Although desiccation cracking is experienced at the site (Fig. 5.1), soil moisture in the upper soil profile of the CD field was not higher than in the FD field.

Figure 5.1. Desiccation cracking on Aug. 7, 2015 in the Brookston Clay soil of the study site.

Research in this region that has looked at CDSI has shown an increase in soil moisture (Tan et al., 2002; Tan & Zhang, 2011) and positive crop yield response (Drury et al., 1997; Tan et al., 2007). In this study, the CD field yielded +10.52%, -1.47%, -1.33% and +4.75% compared to the FD field over the 4-year study period. Overall, the soybean yields over three seasons were 4.78% greater in the CD field, and corn yields from one season were 1.33% lower than the FD field.

Based on estimated commodity prices, the CD field generated $192/ha more revenue than the FD field over the four-study period (K. McKague, 2020 unpublished data). This advantage covered the installation costs of the control structure within four years, which aligns with estimates by Crabbe et al. (2012) of a 3 to 4-year payback period. Yields at the site were variable and may have fluctuated in response to precipitation amount and timing, as has been observed in the literature (Elmi et al., 2002; Tan et al., 2007). Given that neither water table position nor soil moisture differed between the FD and CD fields, it is unsurprising that crop yields from the CD field did not consistently exceed the yields from the FD field in this study (Landowner, Pers. Comm.). Inconsistent yield impacts from DWM have been observed in other studies (Skaggs et al., 2012).

5.4.1 Effect of Controlled Drainage on Surface Losses: Avoiding Trade-offs

Although CD has the potential to reduce P losses at the EOF by attenuating flow, it has the potential to increase surface runoff, offsetting the potential benefits. Many CD studies monitor only tile runoff (Wesstrom et al., 2001; Stampfli & Madramootoo, 2006; Valero et al., 2007; Sunohara et al., 2015;

Williams et al., 2015a; Saadat et al., 2018; Carstensen et al., 2019). Similar to the current study, field topography often makes it difficult to collect and measure surface runoff at a single drainage point that is exclusive to the tile drainage area. However, the importance of surface runoff to annual P loads is documented in the region (e.g. Plach et al., 2019) and cannot be ignored. It has been suggested that CD may increase surface runoff from fields by reducing the storage capacity within fields. Gilliam & Skaggs (1986) reported that the use of CD in North Carolina increased surface runoff during the GS. Local studies have also found that CD increased surface runoff in both the GS and NGS over multiple study years, as a tradeoff for reducing annual tile losses (Tan et al., 2002; Drury et al., 2009; Tan & Zhang, 2011). Although this result is not consistent across the entire body of literature, an increase in surface runoff is common enough that it warrants management to minimize. In the current study, annual P losses from surface runoff are greater than the estimated reductions in P loss from CD. This suggests that any increase in surface runoff caused by CD has the potential to turn a net P reduction into a net increase and should be avoided. Multiple approaches are advised to combat the risk of increased surface losses, from actively managing the gates during the NGS (Gilliam & Skaggs, 1986), to utilizing cover crops through the NGS to minimize the nutrient losses associated with surface runoff (Tan et al., 2002) and even avoiding the practice altogether in climates where overland runoff is common during the NGS (Sunohara et al., 2016).

Unfortunately, surface runoff was not measured from the CD field in this study. Consequently, the potential for increased surface runoff was inferred from water table position. Overland flow can occur either as infiltration-excess or saturation-excess (Dingman, 2015). Macrae et al. (2019) employed data from the FD site in the current study to quantify the relative occurrences of these two types of overland flow. They found that saturation-excess overland flow was uncommon in clay soils, and surface runoff was instead typically associated with infiltration-excess overland flow. It is possible that CD could increase the occurrence of saturation-excess overland flow.

Given that CD was utilized exclusively during the GS in this study, it was hypothesized that the water table would not reach the surface because groundwater levels are generally lower during the summer months when CD was utilized. However, data from this study shows that there were instances where the surface runoff was generated during this time period. Under both dry and wet antecedent moisture conditions, higher peak water table levels were observed in the CD field in response to precipitation events.

Although overall water table levels were not impacted by CD, short-term differences in water table reactions during event responses exist between the FD and CD fields. Water table observations suggest that CD increases the likelihood of saturation-excess surface runoff generation during the GS, under both wet and dry antecedent moisture conditions, by temporarily increasing water table level in comparison to the FD field. This study did not have water table data throughout the entire study period, and without separate surface runoff monitoring for the CD and FD fields, the extent to which CD influenced saturation-excess runoff is unknown. Future work should simultaneously monitor both subsurface and surface runoff in comparisons.

5.5 Efficacy of Controlled Drainage as a BMP in Ontario: Importance of Gate Management

Unchangeable factors like soil type and climate may affect the efficacy of CD as a BMP, however the timing and depth of gate management is likely an important driver. Controlled drainage studies in the literature used water table depths ranging from 0.1 to 0.8 m below ground level, with field tile depths ranging from 0.6 to 1.1 m. Selecting a control level that is too low is not likely to have any significant impact on water table depth across the field and the impacts on crops and nutrients losses may be minimal. Conversely, setting the water table depth too high could result in more negative outcomes, both on crop health and on surface runoff losses. Studies in the region have employed a combination of CDSI during the GS and CD during the NGS with a water table control depth of 0.3 to 0.4 m. This strategy has been successful in reducing annual nutrient loads (Tan et al., 2002; Tan & Zhang, 2011; Zhang et al., 2015).

At the study site, a significant portion of annual tile discharge (76%) and TP losses (69%), as well as surface runoff (50%) and TP losses (65%) occurred during the NGS. This means that utilizing CD in the NGS represents a significant opportunity to reduce annual losses, but also represents a risk of increasing surface runoff and subsequent nutrient losses. The current study also shows that the FWMCs of P in surface runoff is notably higher than that of tile runoff. The management of CD over the NGS would need to ensure that the frequency and magnitude of surface losses is not increased.

Although many studies include discussion around the risks of year-round management due to freezing water, trafficability and winter crop damage (Lalonde et al., 1996; Crabbe et al., 2012; Sunohara et al., 2015; Sunohara et al., 2016; Dring et al., 2016), few studies that test this practice have reported deleterious effects of using CD year-round on nutrient losses. In fact, Tan & Zhang (2011) actually suggest that using the CD gates only during the GS would significantly limit the nutrient retention potential of the practice.

Water table control over the NGS has been found to reduce discharge, nitrate and P losses on an annual basis (Wesstrom et al., 2001; Tan & Zhang, 2011; Williams et al., 2015a; Carstensen et al., 2019), however this can result in an increased proportion of EOF runoff coming as surface losses which could be problematic (Tan & Zhang, 2011). Results from Saadat et al. (2018) show that high water table control through the NGS can have the unwanted outcome of increased P concentrations in tile runoff, counteracting the reduced discharge from controlling drainage.

Using CD year-round is expected to increase the efficacy of the practice for reducing nutrient losses, as was done in Zhang et al. (2015). The uptake of year-round CD in this region may be more limited by practical and logistical concerns, rather than the efficacy of the practice in controlling nutrient losses. At more northern sites, the risk of damage to tile systems under frozen conditions is cited as a major concern (Dring et al., 2016), however studies in southern Ontario have not found this to be a problem (Tan et al., 2002; Tan & Zhang, 2011; Zhang et al., 2015). To minimize risks, the use of CD during the NGS would not be recommended in fields where extreme P stratification is present, in order to limit the transport of nutrients from the soil surface via overland runoff.

There is support for using an adaptive gate management during the NGS, whereby gates are managed prior to expected runoff or melt events to increase the capacity for water storage in the soil profile. This strategy would involve gradually drawing down the water table prior to precipitation events to create more storage, maximizing runoff capture in the soil profile during an event and avoiding a rapid flush of discharge water from the system. To our knowledge this has not been studied yet, however it was cited as a management option by Gilliam & Skaggs (1986) to minimize the environmental impacts of runoff. The goal of this strategy would be to achieve runoff retention in the soil profile without increasing surface losses. Widespread uptake of this management strategy may be limited by its labour requirement, which has been cited as a disincentive to DWM (Dring et al., 2016).

Another factor to consider with CD is the flush of water and nutrients that may come when gates are lowered. Carstensen et al. (2019) measured an increase in nitrate, TP and phosphate losses in the first week after opening the CD gates in spring, but these losses were negligible in terms of annual loads. Stampfli & Madramootoo (2006) observed a large discharge volume when the gates were lifted in fall for harvest and measured increased discharge over the following two months. This is a finite event which is not well-monitored or fully understood. To minimize the effect of the flush when gates are removed, a gradual water table drawdown should be considered to allow more opportunity for dissolved P to resorb into the soil profile.

During the GS, CD gates in the literature are most commonly set to 0.4 to 0.6 m below ground level, which generally has positive results in terms of reducing discharge and P losses, and in some cases, maintaining an elevated water table level to promote crop development. Soil column experiments have tested different water control levels and found that discharge increased with higher gate levels (Drury et al., 1997), and that P runoff concentrations also increased (Valero et al., 2007). Drury et al. (1997) concluded that WTC at a depth of 0.6 m was the ideal level to minimize N losses, while providing adequate soil moisture for the corn crop. Soil column experiments eliminate lateral and downward groundwater flow, so the correlation between water table control depth and runoff measurements is strong. In a field setting, more water is able to evade the tile system, resulting in a weaker influence of water table control depths on runoff volumes and concentrations.

5.6 Agronomic Context

The crop rotation and nutrient management on this farm is typical for a grain farm in Essex County, where soybeans and grain corn make up the majority of cropland (OMAFRA, 2021). The Brookston Clay soil series found at the study site is also representative of the region, comprising 42 to 65% of the soils in Essex, Lambton and Kent counties in southwestern Ontario (Evans & Cameron, 1983). Soil test phosphorus at the study site ranged from 12.4 to 15.1 mg/kg Olsen-P in the top 15 cm across the two fields. These levels fall within the range recommended by OMAFRA for grain production (OMAFRA, 2017), and are similar to other Ontario study sites in the literature which fall within reasonable levels of $\leq$ 25 mg/kg (Tan & Zhang, 2011; Plach et al., 2018b). Fertilizer rates either closely matched or underestimated crop removal rates over the study period. Nutrients applied to the field ranged from 9.1 to 58.3 kg P_2O_5/ha for each crop (mean = 40.93 kg P_2O_5/ha). Fertilization rates in this study are considered normal farming practices and are in line with annual mean P application rates reported by Plach et al. (2018b) on working farms (3.4 to 116.8 kg P_2O_5/ha) and by Tan & Zhang (2011) on field plots (76.8 kg P_2O_5/ha). Overall, the field management at the study site is believed to be quite representative of local farming practices and is an excellent site for studying EOF P losses.

5.7 Uncertainty

As with any field experiment of this size, there are areas of uncertainty. This section will discuss those areas and what improvements could be considered for future study of the subject to address these uncertainties. As discussed throughout the paper, the hydrology of the CD and FD fields behaved differently when both were freely drained. The hydrological relationship between the two fields from the NGS was used to predict outcomes in the GS when CD was active. Although this method has been used in previous studies, future study should consider a before-after control-impact approach to achieve greater confidence in the relationship between the two fields being monitored, prior to implementing CD.

There is some uncertainty in the amount of EOF runoff that left the field through the monitored tile drains, versus alternative pathways that were not monitored. Under CD, an elevated water table may have caused lateral groundwater movement to adjacent fields, which is something this study did not set out to quantify. Laboratory or plot studies that are monitoring the effects of CD have often used soil columns or installed in-ground plastic curtains to minimize the influence of lateral seepage on water table level (Drury et al., 1997; Wesstrom et al., 2001; Stampfli & Madramootoo, 2006; Valero et al., 2007; Zhang et al., 2015). The installation of a curtain may not be practical with large-scale field studies; however, lateral and deep seepage are causes for uncertainty when studying the impact of CD on water table levels and nutrient losses (Sunohara et al., 2014; Williams et al., 2015a; Sunohara et al., 2015; Saadat et al., 2018). In future studies, piezometers should be installed across the field site moving outwards from the control structure to show the extent of water table control. Piezometers could also be installed in a transect across the field boundary to monitor flow gradients at the field edge to better understand the role of lateral flow with an isolated CD field (Williams et al., 2015a).

In this study, tile drainage was monitored from two fields, however surface runoff was collected mainly, but not exclusively, from the FD field based on topography limitations. An important component of CD research is to determine the impact on surface runoff. This study used water table data to make inferences about surface runoff from the CD field but could not determine nutrient loads without a distinct surface runoff catchment area. Future research should consider monitoring tile and surface drainage separately for CD and FD plots. This is often difficult to attain on field-scale research, however earthen berms could be considered to create distinct runoff catchments if the landscape lends itself to this method. At the study site, the effect of CD on surface runoff losses could also be achieved by installing a control structure on the east field, capturing a before-after comparison of surface runoff with free and controlled drainage. However, this experimental design still lacks a direct control for comparing both tile and surface runoff.

Event-based sampling was employed in this study, which is key to obtaining more accurate load estimates. Increased sampling frequency is recommended for future study to increase confidence in load estimates (Williams et al., 2015b). During the study period, there were multiple breaks in the FD header tile that were repaired on July 3, 2015. Although unconfirmed, it is possible that this caused contamination of the FD tile with surface water through the broken tile prior to this date.

Data from the FD and surface tile was previously reported in Plach et al. (2019). Discharge values in this thesis closely match those reported by Plach et al. (2019), however there are differences in how the chemistry data was used to calculate loads. Firstly, there were additional archived samples included in the analysis for this study that were not used in Plach et al. (2019). These samples were from an event with large discharge, and thus had a significant impact on overall P loads and relative contributions of transport pathways. Secondly, in this study, events with chemistry gaps were filled using a relationship between discharge and load developed from events with observed data for each tile. Plach et al. (2019) used a daily linear interpolation method to gap-fill between known chemistry values. As an annual average, this study reported that the surface tile contributed 43% of the SRP load and 48% of the TP load. Plach et al. (2019) reported the mean annual surface contribution as 20% and 40% of the SRP and TP loads, respectively. Williams et al. (2015b) reported the uncertainties associated with load estimates from small tile-drained landscapes and noted that load estimation algorithms can be a significant source of uncertainty, which is demonstrated by the difference in results from Plach et al. (2019) to this study. Future study should examine sampling design and interpolation methods as a priority in study design to minimize uncertainty in load estimates.

Chapter 6 - Summary and Conclusions

This thesis studied the impact of CD on EOF discharge and P losses on a working farm in Essex County, Ontario with clay soil. Soil moisture and water table level in the field were also monitored to better understand the effects of CD on soil-water interactions. Literature on the subject suggests that CD is an effective tool for limiting nitrate tile losses by reducing discharge and by promoting denitrification in the soil profile where water is retained (Gilliam & Skaggs, 1986; Wesstrom et al., 2001; Tan & Zhang, 2011; Williams et al., 2015a; Carstensen et al., 2019). This study set out to determine how the practice of CD affects EOF P losses while utilizing a conservative gate management approach. The study site was situated in an area of Ontario where soils and topography are naturally suitable for CD (Hunter and Associates, 2008). Hence extensive plot-scale research has been conducted on DWM in the region, which provides a good comparison to this study. However, the current study uses a unique gate management strategy, as the practice was scaled up to a working farm where management decisions were ultimately made by the field manager. The study included year-round monitoring of tile and surface runoff over a four-year period, which provides data across a range of climatic temperature and precipitation conditions. This study provides an important link between existing research in the literature to understand how CD may impact EOF losses across a range of climates, soils and gate management strategies.

Edge of field monitoring at this site demonstrated that P losses from a clay soil in Southern Ontario are largely driven by NGS runoff, and that incidental losses can be a major contributor to annual loading. The findings of this study are important to understanding the potential benefits of utilizing CD exclusively during the GS. Most of the benefit of CD reducing tile discharge and P losses was observed in years 1 and 2 of the study, which experienced wet conditions during the late spring or summer season. In years with normal or low precipitation, CD had very little impact on tile discharge and P losses. During the GS when CD was active, reduced discharge and loads were observed. The GS period represented a small portion of annual losses, and thus, CD has limited ability to reduce annual P losses if not employed during the NGS.

The study also observed that tile discharge was the dominant pathway for EOF runoff for most of the year, with exception of incidental events where surface losses were significant. Although runoff occurred largely in the subsurface, P losses were split evenly between the surface and subsurface, demonstrating that surface runoff contributed disproportionately more P (relative to its runoff contribution). The implications of this are that if CD increases surface runoff, it may have a net negative effect on P loss. Although surface runoff was not monitored from the CD field in this study, water table measurements suggest that CD could increase the likelihood of overland flow. Thus, further study is needed. Given that drainage only contributes half of the EOF P loss at the study site, and the fact that CD only has the potential to reduce P losses through the subsurface pathway, it has limited capacity to reduce P losses. This demonstrates that CD is not a singular solution for reducing EOF nutrient losses. Controlled drainage must be combined with other strategies for reducing P losses at the field scale and reducing available P in near surface soils remains a critical method for minimizing EOF P losses.

Controlled drainage can be a BMP for water quality or crop yields (or both). This study found no conclusive impacts of CD on crop yields, with significant year-to-year variation. Future research should examine the spatial impact of CD on crop yields on a finer scale to determine if there are any impacts observed within the field, either closer to the control structure, or perhaps over the tile runs where soil moisture may have been increased.

As used in this study, CD is a relatively inexpensive practice to adopt and shows potential for reducing P losses during wet years. Future research should examine the use of sub-irrigation and NGS gate management on a field-scale to determine if the results from the literature are scalable, and if this form of DWM has increased economic/yield advantage while achieving greater EOF P reductions.

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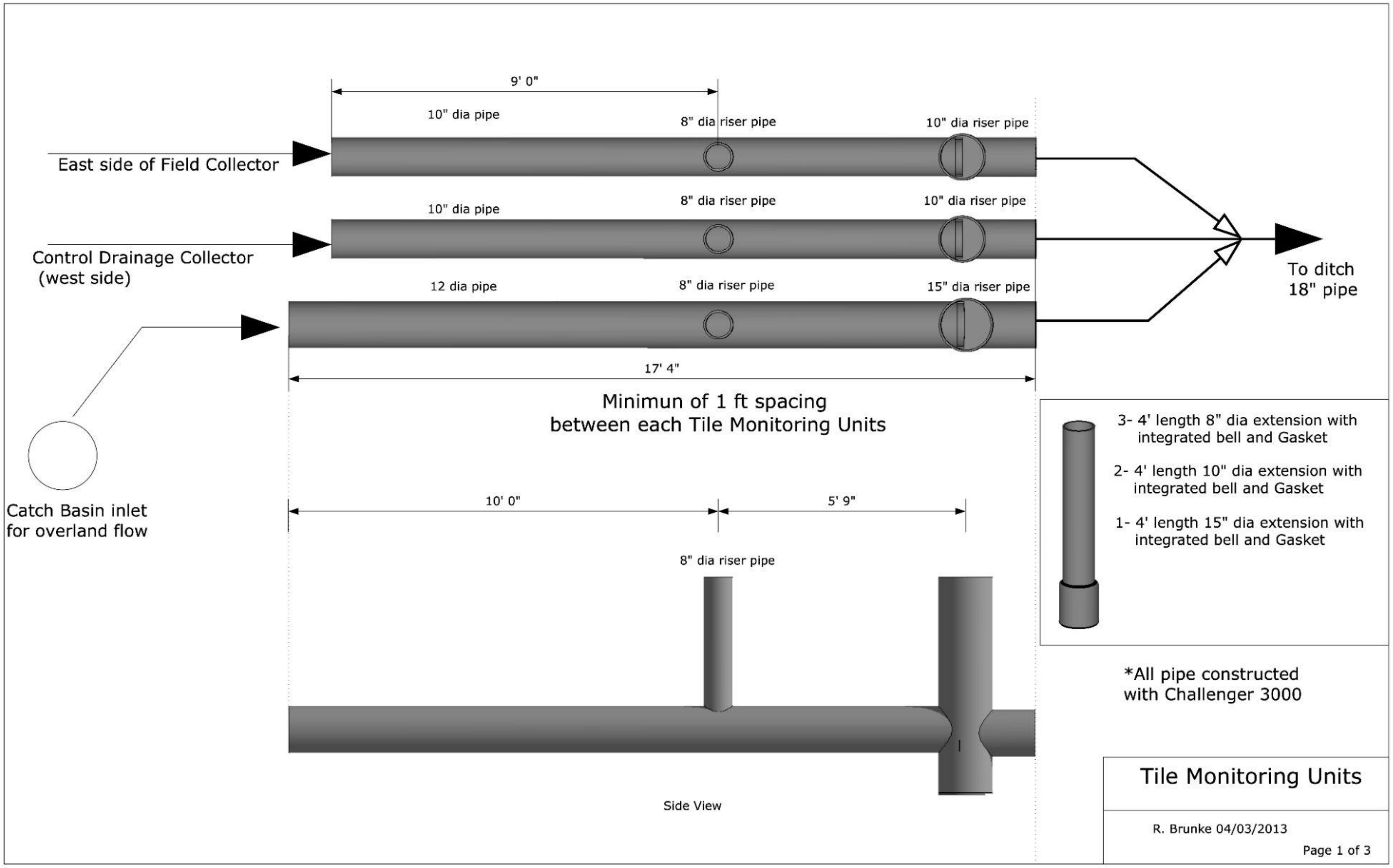
Appendix A

	Free Drain Tile				Controlled Tile				Surface Runoff				
	Discharge (mm)	Runoff Coefficient	SRP (kg/ha)	TP (kg/ha)	Discharge (mm)	Runoff Coefficient	SRP (kg/ha)	TP (kg/ha)	Discharge (mm)	Runoff Coefficient	SRP (kg/ha)	TP (kg/ha)	Precipitation (mm)
Fall	47.02	0.22	0.02	0.09	50.13	0.24	0.02	0.09	0.00	0.00	0.00	0.00	210.6
Winter	32.20	0.12	0.01	0.08	57.62	0.21	0.02	0.10	6.22	0.02	0.01	0.02	272.4
Spring	33.42	0.16	0.01	0.05	30.12	0.14	0.00	0.05	0.61	0.00	0.00	0.00	211.4
Summer	27.57	0.08	0.01	0.07	16.04	0.05	0.00	0.04	22.14	0.07	0.01	0.06	329.6
2013-2014 Subtotal	140.21	0.14	0.05	0.29	153.92	0.15	0.05	0.28	28.96	0.03	0.01	0.08	1024
Fall	39.61	0.28	0.01	0.12	27.31	0.19	0.00	0.07	0.37	0.00	0.00	0.00	143.8
Winter	23.22	0.12	0.01	0.04	63.01	0.32	0.02	0.10	31.34	0.16	0.01	1.03	198.1
Spring	75.67	0.21	0.20	0.39	91.77	0.26	0.30	0.53	42.33	0.12	0.30	0.52	359
Summer	10.52	0.05	0.00	0.03	5.53	0.02	0.00	0.01	3.50	0.02	0.00	0.01	224.8
2014-2015 Subtotal	149.02	0.16	0.22	0.59	187.63	0.20	0.33	0.71	77.54	0.08	0.31	1.56	925.7
Fall	33.77	0.18	0.01	0.09	30.84	0.17	0.01	0.07	0.00	0.00	0.00	0.00	184.2
Winter	141.60	0.52	0.05	0.38	145.15	0.53	0.07	0.35	3.99	0.01	0.00	0.01	272.7
Spring	30.66	0.20	0.01	0.04	48.85	0.32	0.01	0.12	0.00	0.00	0.00	0.00	153.6
Summer	1.15	0.00	0.00	0.00	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	254
2015-2016 Subtotal	207.18	0.24	0.07	0.51	225.07	0.26	0.09	0.54	3.99	0.00	0.00	0.01	864.5
Fall	85.33	0.41	0.04	0.21	58.60	0.28	0.02	0.12	7.03	0.03	0.01	0.02	210.6
Winter	80.34	0.35	0.07	0.23	78.86	0.35	0.04	0.19	23.78	0.10	0.02	0.07	226.5
Spring	46.77	0.19	0.02	0.10	50.16	0.21	0.01	0.13	5.64	0.02	0.01	0.02	242.6
Summer	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	249.6
2016-2017 Subtotal	212.44	0.23	0.13	0.54	187.62	0.20	0.08	0.44	36.45	0.04	0.03	0.11	929.3
Annual Mean	177.21	0.19	0.12	0.48	188.56	0.20	0.14	0.49	36.73	0.04	0.09	0.44	935.9
4-Year Total	708.84	3.09	0.48	1.93	754.24	3.28	0.54	1.97	146.94	0.56	0.36	1.76	3743.5

Table A-1. Summary of discharge, phosphorus loads and precipitation at the site over the study period.


9' 0"
10" dia pipe
8" dia riser pipe
10" dia riser pipe
East side of Field Collector
10" dia pipe
8" dia riser pipe
10" dia riser pipe
Control Drainage Collector
(west side)
12 dia pipe
8" dia riser pipe
15" dia riser pipe
To ditch
18" pipe
17' 4"
Minimun of 1 ft spacing
between each Tile Monitoring Units
Catch Basin inlet
for overland flow
3- 4' length 8" dia extension with
integrated bell and Gasket
2- 4' length 10" dia extension with
integrated bell and Gasket
1- 4' length 15" dia extension with
integrated bell and Gasket
10' 0"
5' 9"
8" dia riser pipe
*All pipe constructed
with Challenger 3000
Side View
Tile Monitoring Units
R. Brunke 04/03/2013
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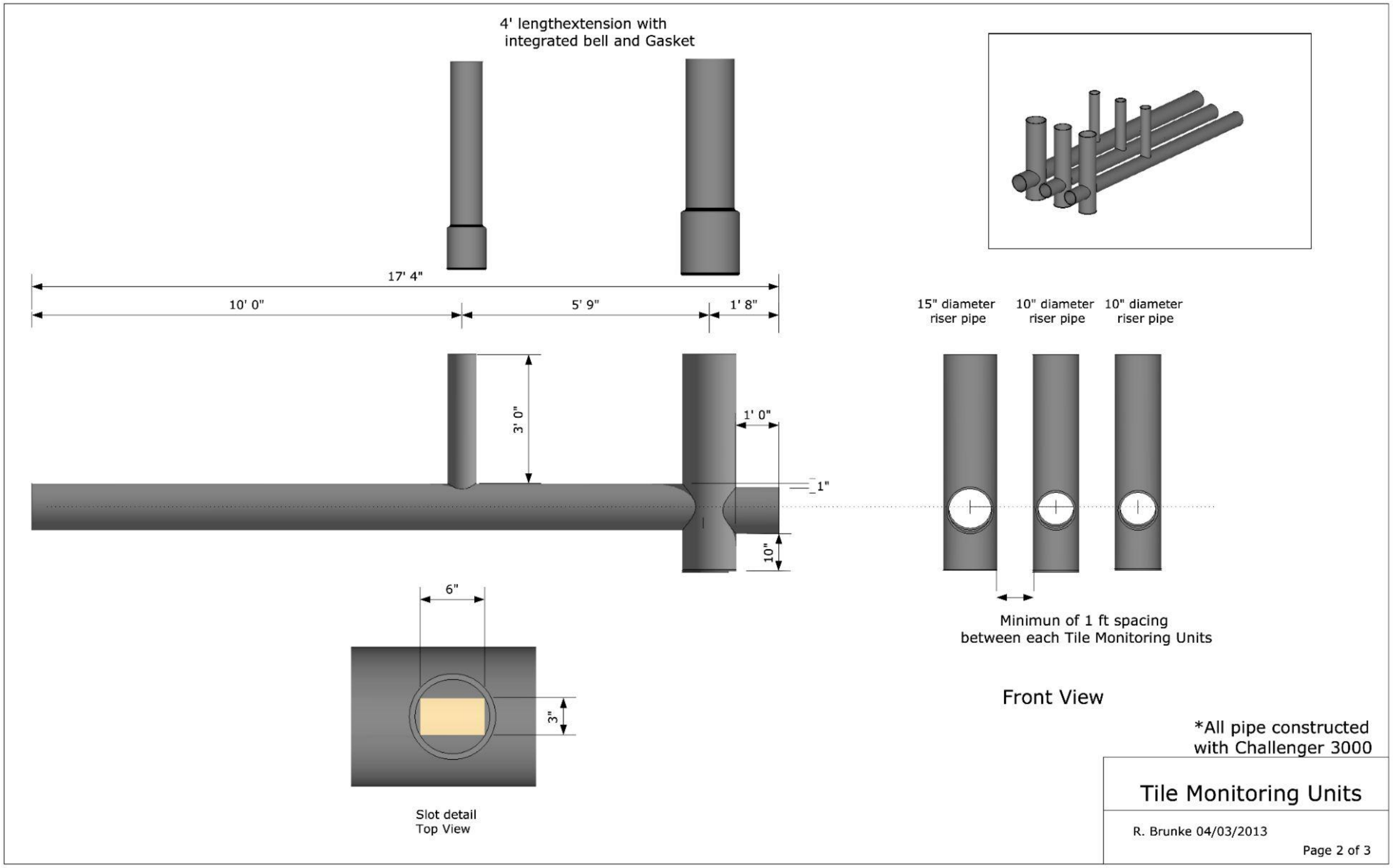
4' lengthextension with
integrated bell and Gasket
17' 4"
10' 0"
5' 9"
1' 8"
3' 0"
1' 0"
1"
10"
6"
3"
Slot detail
Top View
15" diameter
riser pipe
10" diameter
riser pipe
10" diameter
riser pipe
Minimun of 1 ft spacing
between each Tile Monitoring Units
Front View
*All pipe constructed
with Challenger 3000
Tile Monitoring Units
R. Brunke 04/03/2013
Page 2 of 3

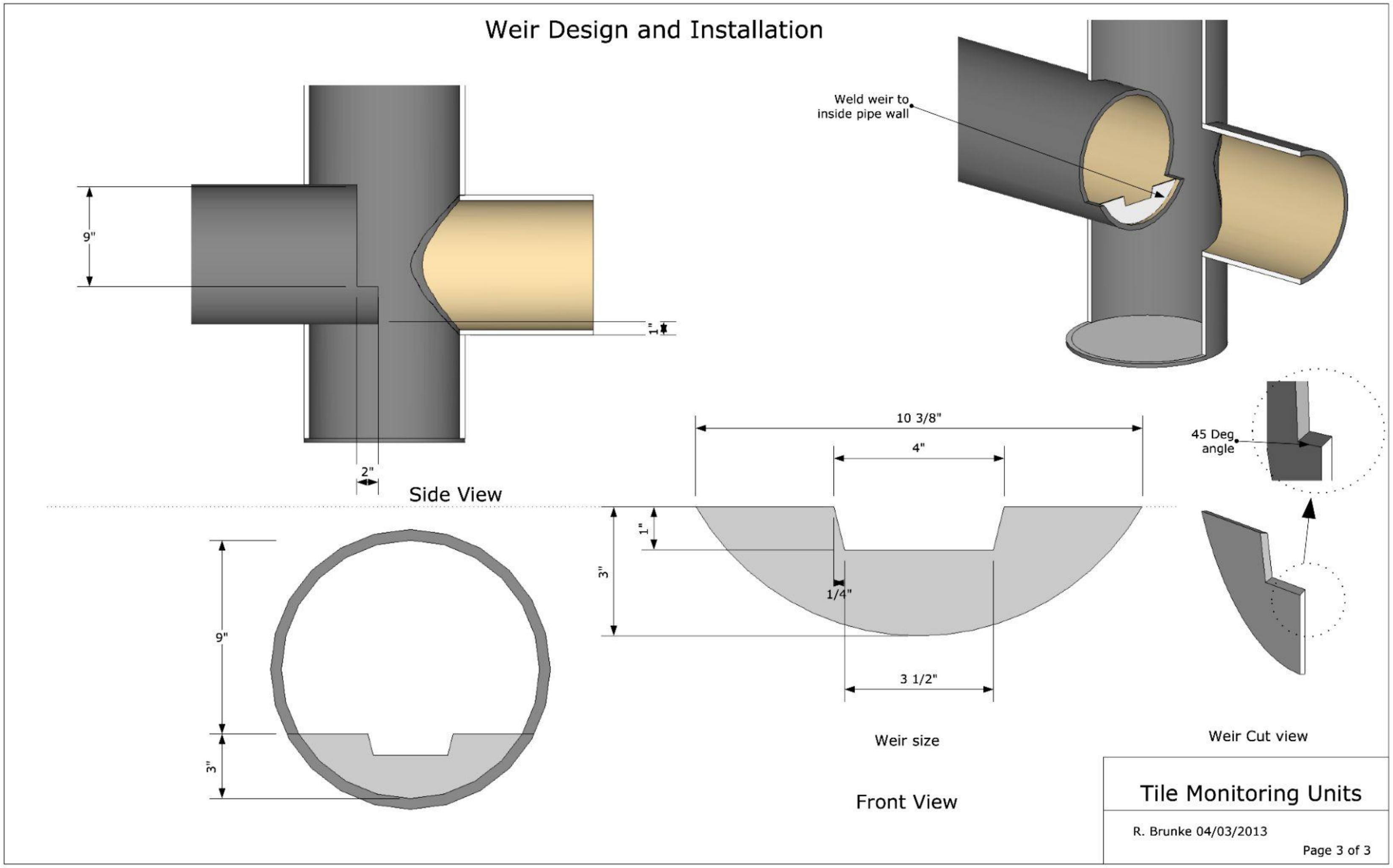

Figure A-1. Design of the tile monitoring riser units used at the site (R. Brunke, unpublished).