EVALUATION OF HYDROLOGICAL PROCESSES AND ENVIRONMENTAL IMPACTS OF FREE AND CONTROLLED SUBSURFACE DRAINAGE

by

Samaneh Saadat

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Jane Frankenberger, Chair

Department of Agricultural and Biological Engineering

Dr. Laura Bowling, Chair

Department of Agronomy

Dr. Margaret Gitau

Department of Agricultural and Biological Engineering

Dr. Srinivasulu Ale

Department of Biological and Agricultural Engineering, Texas A&M University

Approved by:

Dr. Nathan S. Mosier

Head of the Graduate Program

To my Mom and Dad, for their endless support

and

To all students and families who are affected by the Travel Ban

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LIST OF ABBREVIATIONS

AD	Average Deviation
ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
ARMA	Autoregressive Moving Average Model
ASABE	Transactions of the American Society of Agricultural and Biological Engineers
CD	Controlled Drainage
DPAC	Davis Purdue Agricultural Center
ET	Evapotranspiration
FD	Free Draining
HL	Higher-level control
K	Hydraulic Conductivity
LL	Lower-level control
N	Nitrogen
NE	North East
NSE	Nash-Sutcliffe Efficiency
NW	North West
P	Phosphorus
PE	Percent error
PET	Potential Evapotranspiration
SE	South East
SFC	Soil Freezing Characteristic
SRP	Soluble Reactive Phosphorus
SW	South West
TP	Total Phosphorus
WTD	Water table Depth

ABSTRACT

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Institution: Purdue University
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Controlled drainage is a management strategy designed to mitigate water quality issues caused by subsurface drainage. To improve controlled drainage system management and better understand its hydrological and environmental effects, this study analyzed water table recession rate, as well as drain flow, nitrate and phosphorus loads of both free and controlled drainage systems, and simulated the hydrology of a free drainage system to evaluate surface runoff and ponding at the Davis Purdue Agricultural Center located in Eastern Indiana.

Statistical analyses, including paired watershed approach and paired t-test, indicated that controlled drainage had a statistically significant effect (p-value <0.01) on the rate of water table fall and reduced the water table recession rate by 29% to 62%. The slower recession rate caused by controlled drainage can have negative impacts on crop growth and trafficability by causing the water table to remain at a detrimental level for longer. This finding can be used by farmers and other decision-makers to improve the management of controlled drainage systems by actively managing the system during storm events.

A method was developed to estimate drain flow during missing periods using the Hooghoudt equation and continuous water table observations. Estimated drain flow was combined with nutrient concentrations to show that controlled drainage decreased annual nitrate loads significantly ($p<0.05$) by 25% and 39% in two paired plots, while annual soluble reactive phosphorus (SRP) and total phosphorus (TP) loads were not significantly different. These results underscore the potential of controlled drainage to reduce nitrate losses from drained landscapes with the higher level of outlet control during the non-growing season (winter) providing about 70% of annual water quality benefits and the lower level used during the growing season (summer) providing about 30%.

Three different methods including monitored water table depth, a digital photo time series and the DRAINMOD model simulations were used to determine the generation process of surface

ponding and runoff and the frequency of incidence. The estimated annual water balance indicated that only 7% of annual precipitation contributed to surface runoff. Results from both simulations and observations indicated that all of the ponding events were generated as a result of saturation excess process rather than infiltration excess.

Overall, nitrate transport through controlled drainage was lower than free drainage, indicating the drainage water quality benefits of controlled drainage, but water table remained at a higher level for longer when drainage was controlled. This can have negative impacts on crop yields, when water table is above a detrimental level, and can also increase the potential of nutrient transport through surface runoff since the saturation excess was the main reason for generating runoff at this field.

CHAPTER 1. INTRODUCTION

1.1 Subsurface drainage and water quality impairments

Subsurface drainage is a necessary water management practice for agricultural production in fields with poorly drained soil, however it contributes to water quality issues. Nitrate transport through subsurface drainage is the main source of nitrate in the Mississippi River and tributaries in the upper Mississippi Basin and a primary cause for hypoxia in the northern Gulf of Mexico (Goolsby et al., 1999 and Rabalais et al., 2001). Phosphorus (P) can also be transported through drainage systems in dissolved and particulate or solid forms (King et al., 2015). Total phosphorus (TP) is a measure of all forms of phosphorus, dissolved or particulate and soluble reactive phosphorus (SRP) is a measure of soluble and inorganic fraction of phosphorus.

Phosphorus loads through subsurface drains are much lower than nitrate loads. Results from a 3-year study in an agricultural field in Indiana indicated a range of 18 to 70 kg ha^{-1} for annual nitrate losses but only an average of 0.04 kg ha^{-1} for annual SRP losses through subsurface drains (Kladivko et al., 1991). Gentry et al. (2007) found that SRP losses in subsurface drainage ranged between 0.05 to 1.0 kg ha^{-1} and total P losses ranged between 0.1 to 1.3 kg ha^{-1} in an agricultural field in Illinois. However, recent studies have shown the importance of P lost through subsurface drainage (King et al., 2015; Kleinman et al., 2015; Lam et al., 2016; Van Esbroeck et al., 2017). For example, Smith et al. (2015) reported that 49% of SRP and 48% of total P losses from fields in the St. Joseph River Watershed in northeastern Indiana occurred via subsurface discharge.

1.2 Controlled drainage- a water management practice to mitigate water quality impairments

Controlled drainage (CD), also known as drainage water management, is a practice used to hold water back in the field, reducing nitrate load and granting farmers control over subsurface water levels in the field during planting and potentially in the growing seasons. A water control structure in the drain allows management of the outlet elevation at different times of the year (Frankenberger et al., 2006) (Fig. 1.1). Along with providing a better growing environment for plants, removing excess water improves trafficability of the soil and mobility of agricultural machinery and facilitates timely farm operations (Fisher et al., 1999; Jaynes 2012). By draining water only when needed to improve trafficability and root growth, crops may take advantage of increased water availability later in the growing season, and raising the outlet and holding water back in the field during this period can decrease nitrate loads to surface waters (Evans et al., 1995; Fausey 2004; Singh, et al., 2007; Adeuya et al., 2012; Gunn et al., 2015; Williams et al., 2015).

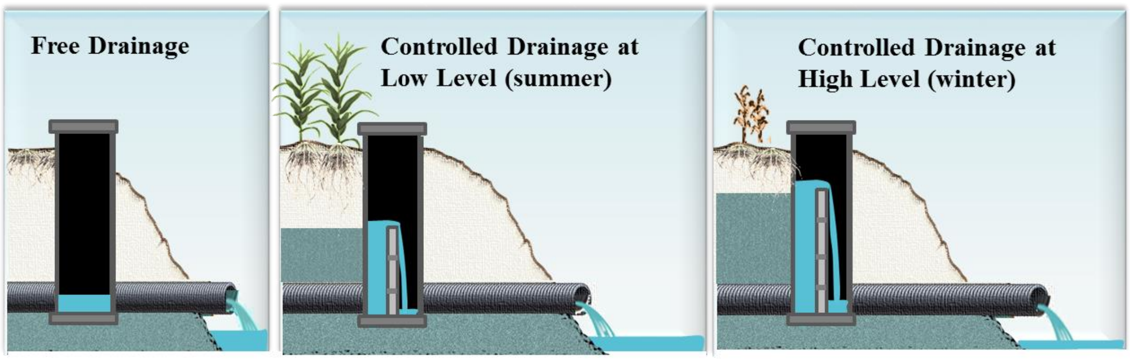

Figure 1-1. Schematic of free drainage and controlled drainage at lower level (summer/growing season) and higher level (winter/non-growing season).

Field studies from multiple locations have found decreases in both average annual drain flow and annual nitrate load due to CD between 18 to 85% and 18 to 79%, respectively (Skaggs et al. 2012, Ross et al. 2016). Skaggs et al. (2012) compared results from 13 experimental field studies at 7 different locations (USA: North Carolina, Ohio, Iowa, Indiana, Illinois; Canada: Ontario; and Sweden) and found a broad range of reductions from 18 to over 85% in average annual drain flow and from 18 to 79% in annual nitrate loss through subsurface drainage under CD. Similarly, Ross et al. (2016) synthesize results from both field studies (17) and model experiments (11), and found 46% reduction in annual drain flow and 48% reduction in annual nitrate loads with CD. In most of these studies, most of the decrease in annual nitrate load is attributed to reductions in annual drain flow (e.g., Wesström and Messing, 2007; Adeuya et al., 2012; Williams et al., 2015 Lavaire et al., 2017). However, in some cases, denitrification has been found to lower the nitrate-N concentrations in the drain flow when drainage was controlled (Kliewer and Gilliam, 1995 and Tan et al., 1998).

Although not as well studied, decreases in the load of both soluble P have been found in some field studies due to CD ranging from 40 to 80% (Williams et al., 2015; Ross et al., 2016; Nash et al. 2015). Ross et al. (2016) synthesized a few field studies and found, on average, a 57% reduction in SRP loads and a 55% reduction in total P loads with CD. Results from a field study in Ohio showed that CD significantly decreased annual SRP loads between 40 to 68% (Williams et al., 2015). CD also decreased SRP load in the drain flow by 80% in a claypan soil in Missouri (Nash et al. 2015). Nash et al. (2015) additionally reported a significant lower SRP concentration in drain flow with CD (0.09 mg L^{-1}) compared with free drainage (0.15 mg L^{-1}), therefore, the reduction in SRP load was due to both a decrease in soluble P concentration and reduced drain flow.

Although the effect of CD on nitrate transport through subsurface drainage has been studied for many locations, the impacts of CD on nitrate and P loss in eastern Indiana have not yet been studied. Additionally, most previous studies have been conducted for a period of less than 5 years. Additional field studies, over longer periods of time, may help to improve understanding of the factors that contribute to the wide variability in the performance of CD reported in the literature from different experimental sites.

1.3 Potential improvement in controlled drainage performance with active management

Even with improved understanding of the environmental impacts of CD, the question remains regarding whether CD can be improved with active management to mitigate the potential negative impacts. Although yield benefits due to CD have been found in some studies (Wesstrom and Messing, 2007; Ghane et al., 2012; Jaynes 2012; Delbecq et al., 2012; Poole et al., 2013, Sunohara et al., 2015), CD has also been reported to decrease the average crop yields of one agricultural field (Helmers et al, 2012) and to not have a significant impact on other fields (Tan et al., 1998; Fausey 2004; Drury et al., 2009). However, on a site-year basis, CD has been reported to have a negative impact (significant or non-significant) on yields of many fields in various years (Cooke and Verma, 2012; Ghane et al., 2012; Jaynes 2012, Crabbé et al., 2012). Year-to-year differences in yield are dependent on weather conditions such as the amount and timing of precipitation and management strategies (Skaggs 2012a).

Yield decreases could potentially be avoided by more active management of the outlet depth. Lowering the outlet prior to or directly after large rainfall events during the growing season may reduce the amount of time that the water table is at a level that is detrimental to either trafficability or crop yield. Belcher and Gleim (2003) addressed this question with a simulation study, estimating the time needed for the water table to recede to the before-rain level after a rainfall event raises the water level to the soil surface, with and without water table control by a weir. They found that removing the weir after rainfall events reduced the required time for the water table to recede. In another simulation study, Fouss et al. (1987) compared conventional drainage with a fixed weir control level and a two-stage weir control, in which the weir was moved between high and low positions during rainfall events. Their results also indicated that the water table was lowered faster with two-stage weir control. However, the benefits of such an active management strategy have not been evaluated with field data.

1.4 Relationship between water table and drain flow

The relationship between midpoint water table height above drain and drain flow has been investigated by laboratory or field experiments since the 1950s (Luthin and Worstell, 1957, Goins and Taylor, 1959, Hoffman and Schwab, 1964). Luthin and Worstell (1957) reported some of the field data collected by other researchers and showed that the relationship between midpoint water table height and drain flow was approximately linear for homogenous soils. Goins and Taylor (1959) also reported that under field conditions when the water table is falling continuously, the relationship between midpoint water table height and drain flow was approximately linear. In contrast to the results for homogeneous soils, Hoffman and Schwab (1964) found that for an anisotropic soil the relationship between midpoint water table height and drain flow was not linear.

Several theoretical equations have been developed for subsurface drainage design that use the relationship between midpoint water table level and drain flow. Hooghoudt (1940) derived an equation based on an assumed elliptical water table profile between two drains in which drain flow varies with the squared water table height above drain. A theoretical drain-spacing equation for a falling water table in homogeneous soils was proposed by Van Schilfgaarde (1963). Although the goal of these equations was to facilitate drainage design, the Hooghoudt equation has been used to estimate drain flow based on water table position in DRAINMOD (Skaggs 1978) and also to determine the effective hydraulic conductivity of wetland soils (Skaggs et al. 2008).

According to Goins and Taylor (1959), tile flow is more related to the position of the water table in the soil profile than to the height of the water table above the drain (m), because of the strong influence of the hydraulic conductivity profile in drainage. The Hooghoudt equation assumes a saturated hydraulic conductivity (K) that is constant with depth, which can be unrealistic under most field conditions. Hydrologic models have assumed various hydraulic conductivity profiles. For example, TOPMODEL assumes that K declines exponentially with depth (Beven and Kirkby, 1979), while Ambroise et al. (1996) generalized the TOPMODEL concepts by incorporating different K profiles within the original TOPMODEL. They introduced two alternative forms of K profiles including linear and parabolic, and showed how the different K profiles can lead to different streamflow recession curves. In the DRAINMOD model, a layered soil profile is assumed with each layer having a different K (Skaggs et al., 2012b). Depending on the water table position, a K_e is calculated as a weighted average of the saturated layers. Although the strong influence of conductivity in soil profile on the drain flow has been stated half a century ago (Goins and Taylor, 1959), the impact of the various representations of K in layered soils to the relationship between midpoint water table height above drain and drain flow has not been fully recognized and this study attempts to address this research gap.

1.5 Surface ponding and runoff generation in a drained agricultural field

In agricultural drained fields, nutrients, pesticides and associated pollutants can be transported through both subsurface drainage and surface runoff and deposited into surface waters such as lakes, rivers, wetlands, etc. Therefore, understanding and quantifying both pathways is critical for implementing appropriate management practices to reduce sediments and associated pollutants. Controlled drainage mitigates water quality issues caused by subsurface drainage however it has the potential to decrease water quality through increasing surface runoff that is difficult to quantify because of the large uncertainty in surface runoff and ponding. Quantifying surface runoff is also important to acquire the precise water balance and understand the hydrological connectivity of surface and subsurface flow. This understanding allows identification of runoff and subsurface flow contribution in nitrate and phosphorus loss through agricultural fields, which has been a major concern for decades (e.g. Thomas et al., 1992; Turner and Rabalais, 1994; Sharpley et al., 2015).

The generation process of surface ponding and runoff and the frequency of incidence in subsurface drained agricultural fields are poorly understood. Although quantifying phosphorus loss through surface runoff in drained agricultural fields has been a research focus for many years

(Sharpley et al., 1994), the conditions under which surface ponding and runoff can occur as well as the distinctions between ponding and runoff have not received enough attention in the literature.

Surface ponding and runoff may occur due to infiltration excess (Horton, 1933), when the rainfall intensity exceeds the infiltration capacity of the soil, or it may occur due to saturation, when the water table level rises to the ground surface (Van Te Chow et al., 1988). Both types can happen in an agricultural watershed throughout the year depending on the climate conditions and infiltration capacity of the soil. Additionally, in regions with cold climate, frozen ground during winter can reduce infiltration rates, and as a result, surface ponding and runoff from rainfall or snowmelt can increase (Shanley and Chalmers, 1999; Cade-Menun et al., 2013). In many studies the non-growing season was found to be a critical time for phosphorus loss through surface runoff in regions with cold climates, particularly where significant snow cover and winter thaws are experienced (e.g. Van Esbroeck et al., 2016; Coelho et al., 2012; Goulet et al., 2006). Therefore, it is important to have an estimation of surface ponding and runoff in all seasons. However, monitoring surface ponding and runoff is challenging, especially during the cold season. Among the studies that included winter observations of surface runoff, many have experienced data gaps due to freezing and equipment malfunction (e.g. Goulet et al., 2006; Jamieson et al., 2003). Thus hydrological models are often used to simulate surface runoff.

Among a few available models for simulating the hydrology of a drained field, DRAINMOD (Skaggs, 1978) is one of the most widely used models developed for drainage applications (Wang et al. 2006a; Zhao et al., 2000). DRAINMOD is a field-scale, process-based hydrologic model that simulates the performance of agricultural drainage and related water management systems. The basic relationship in the model is a water balance for a thin section of soil of unit surface area which extends from the impermeable layer to the surface and is located midway between lateral drains. DRAINMOD was modified in 2000 to reflect the freeze and thaw processes, supporting its use in cold climate conditions (Luo et al., 2000).

The present study focuses on evaluating ponding and runoff frequency and generation processes using both field observations and the DRAINMOD model simulations.

1.6 Objectives and research questions

The goal of this study was to understand the hydrological and environmental effects of controlled drainage (CD) at the field scale including the impacts on water table recession rate, nitrate and phosphorus loads in order to potentially improve the management of the CD system; as well as understanding the generation process of surface ponding and runoff in a drained agricultural field with seasonally cold climate. Specific objective were to:

1. Evaluate the effect of CD on the water table movement and recession rate.

Research questions: How does CD affect the time of water table fall from the surface to a critical level to inform the possible improvement in the management of CD and reducing the potential negative impacts of CD on the yield?

2. Estimate and evaluate drain flow to assess the impact of CD on subsurface drain flow.

Research questions: What does the water table vs. drain flow relationship look like and how different hydraulic conductivity profiles impact the relationship between water table and drain flow in the Hooghoudt equation? How well the Hooghoudt equation is able to predict drain flow using the observed water table depth measurements? How much was the difference in drain flow volume between free and CD sites?

3. Quantify the average concentration and loss of nitrate and phosphorus (P) in subsurface drain water and determine whether CD reduces nitrate and P loss through subsurface drainage compared with free subsurface drainage at the field scale.

Research questions: What are nitrate and P concentrations in the subsurface drain flow? What is the effect of CD on drain flow, nutrient concentrations and loads during periods of low outlet level control (summer) and high outlet level control (winter)?

4. Examine the generation of ponding and runoff using field observations and DRAINMOD model simulations.

Research questions: How can alternative datasets (photo time series and water table depth) be used to better evaluate the frequency and generation process of surface ponding and runoff at the field scale? What is the frequency of occurrence of ponding and surface runoff? How much ponded water actually leaves the field as surface runoff? What are the processes that generate surface ponding and runoff? What is the influence of freeze/thaw processes on simulated surface ponding and runoff in DRAINMOD?

1.7 Organization of Dissertation

The dissertation consists of 6 chapters. Four chapters (chapters 2 through 5) are written in journal article format. Chapter 1 consists of a general introduction, the objectives, and research questions. Chapter 2 addresses the research questions from Objective 1. It determines how much controlled drainage (CD) lengthens the time needed for the water table to fall after a rainfall event to inform the possible improvement in the management of CD system and therefore, mitigate the potential negative impacts on yield. This chapter has been published as an article in the Transactions of the American Society of Agricultural and Biological Engineers (ASABE) in 2016 with the title “Effects of Controlled Drainage on Water Table Recession Rate”. Chapter 3 addresses the research questions from Objective 2. It demonstrates that drain flow can be estimated from the Hooghoudt equation using water table depth measurements. This chapter was published as an article in Journal of Hydrology in 2018 with the title “Estimating Drain Flow from Measured Water Table Depth in Layered Soils under Free and Controlled Drainage”. Chapter 4 addresses the research questions from Objective 3. This chapter evaluates the potential of CD to improve water quality for two different seasons and levels of outlet control, using ten years of field measurements with two different statistical methods. This chapter was published as an article in Water Research in 2018 with the title “Nitrate and phosphorus transport through subsurface drains under free and controlled drainage”. Chapter 5 addresses the research questions from Objective 4. It determines the frequency of occurrence and the extent of surface ponding and runoff, as well as the generation process using field observations and model simulations. Chapter 6 provides the conclusions of this study and recommendations for future work.

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CHAPTER 2. EFFECTS OF CONTROLLED DRAINAGE ON WATER TABLE RECESSION RATE

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2.1 Abstract

Controlled drainage is a best management practice being promoted to decrease nitrate loads from subsurface drainage, but questions remain about optimal operation strategies. One unanswered question is whether the outlet should be lowered prior to or directly after a rainfall event to reduce the amount of time that the water table is at a level that would be detrimental to either trafficability or crop yield. The objective of this study was to determine how much controlled drainage lengthens the time needed for the water table to fall after a rainfall event, to inform the possible improvement in the management of controlled drainage system. This objective was addressed using water table recession rates from two pairs of controlled and free-draining fields located at the Davis Purdue Agricultural Center in Indiana over a period of 9 years from 2006 to 2014. At each pair, comparison of mean recession rate from the two fields indicated that controlled drainage reduced recession rate. The significance of the relationship between paired observations and the effect of controlled drainage was determined by paired watershed approach using the analysis of variance (ANOVA) and covariance (ANCOVA). Raising the outlet of the subsurface drainage system decreased the mean rate of water table recession by 29% to 62%, increasing the time needed for the water table level to fall from the surface to 30 cm and 60 cm depth by approximately 12 to 26 and 24 to 53 hours, respectively. Based on these results, it can be concluded that lowering the outlet before storm events would reduce the amount of time that the water table is at a detrimental level for either crop growth or trafficability. However, the trade-off between costs and benefits of active management depends on the sensitivity of the crop and probability of a severe storm.

2.2 Introduction

Controlled drainage, also known as drainage water management, is a practice used to allow water to be held back in the field, reducing nitrate loss and granting farmers control over subsurface water table levels in the field during planting and growing seasons. A water control structure in the drain allows management of the outlet elevation at different times of the year (Frankenberger et al., 2006). Crop growth conditions vary directly with height and duration of the water table in the root zone (Carter et al., 1988; Allred et al., 2003; Zipper et al., 2015). Along with providing a better growing environment for plant growth, removing excess water improves trafficability of the soil and mobility of agricultural machinery and facilitates timely farm operations (Fisher et al., 1999; Jaynes 2012). By draining water only when needed to improve trafficability and root growth, crops may take advantage of increased water availability later in the growing season, and raising the outlet and holding water back in the field during this period can decrease nitrate loads to surface waters (Evans et al., 1995; Fausey 2004; Singh, et al., 2007; Adeuya et al., 2012; Gunn et al., 2015; Williams et al., 2015).

Although yield benefits due to controlled drainage have been found in some studies (Wesstrom and Messing, 2007; Ghane et al., 2012; Jaynes 2012; Delbecq et al., 2012; Poole et al., 2013, Sunohara et al., 2014), controlled drainage has also been reported to decrease the average crop yields of one agricultural field (Helmers et al, 2012), and to not have a significant impact on other fields (Tan et al., 1998; Fausey 2005; Drury et al., 2009). However, on a site-year basis, controlled drainage has been reported to have a negative impact (significant or non-significant) on yields of many fields in various years (Cooke and Verma, 2012; Ghane et al., 2012; Jaynes 2012, Crabbé et al., 2012). Year-to-year differences in yield are dependent on weather conditions such as the amount and timing of precipitation and management strategies (Skaggs 2012).

Yield decreases could potentially be avoided by more active management of the outlet depth. Lowering the outlet prior to or directly after large rainfall events during the growing season would reduce the amount of time that the water table is at a level that is detrimental to either trafficability or crop yield. The benefits of such an active management strategy have not been evaluated with field data. Belcher and Gleim (2003) addressed this question with a simulation study, estimating the time needed for the water table to recede to the before-rain level after a rainfall event raises the water level to the soil surface, with and without water table control by a weir. They found that removing the weir after rainfall events would reduce the required time for the water table to recede. In another simulation study, Fouss et al. (1987) compared conventional drainage with a fixed weir control level and a two-stage weir control, in which the weir was moved between high and low positions during rainfall events. Their results also indicated that the water table was lowered faster with two-stage weir control.

Only a few studies have examined the effect of various outlet management strategies on yield, and those were based on a fixed management operational strategy and did not examine active or event-based management. Ale et al. (2009) used the DRAINMOD model to determine the effect of raising the outlet on relative yield considering dry and wet stress and identified preferable dates of raising and lowering the outlet during the growing season as 10 days after planting and about 4 to 6 weeks before crop maturity and the height of control as 50 cm above the drain. In another simulation study, Ale et al. (2010) examined the sensitivity of controlled drainage operational strategies for different drain spacing, various control height above the drain and several dates of raising the outlet after planting. However, no studies have evaluated the potential changes during the growing season using event-based management strategies.

A raised outlet in the control structure is likely to decrease the difference in elevation head between the field and the outlet, thus reducing flow rate to the drain, under most conditions. If the water table is at the same height in the controlled and free-drainage plots, the controlled plot will have a lower gradient and therefore lower flow rate, as Belcher and Gleim (2003) showed for the case of subirrigation. However, since the water table itself is usually higher when the outlet is raised, the gradient may or may not decrease. The reduced flow rate could lengthen the time required for the water table to be lowered to a level where it is no longer detrimental for crops. Although lowering the outlet either before or during a rainfall event would speed the water table recession, there are costs in terms of labor for doing it manually, or an automated structure. The overall objective of this study was to determine how much controlled drainage lengthens the time needed for the water table to fall after a rainfall event to inform the possible improvement in the management of controlled drainage system and therefore, mitigate the potential negative impacts on yield.

2.3 Material and methods

2.3.1 Experimental site and water table measurement

The Davis Purdue Agricultural Center (DPAC), a research farm in eastern Indiana located at 40.266°N, 85.160°W, was used for this study (Fig. 2.1). The 0.16 km^2 (39-acre) field (field W) is split into four quadrants of 3.5 to 3.7 ha each. The elevation change in this field is approximately 3 m (< 1% slope). The site consists of Blount (silty clay loam, somewhat poorly drained), Condit (silty loam, very poorly drained), Pewamo (clay loam, very poorly drained) and Glynwood (silt loam, moderately well drained) soils. The drainage system was installed in September 2004 with 10 cm (4 inch) laterals having an approximate depth of 1 m and spacing of 14 m (Utt, 2010). Each of the quadrants has its own 15 cm (6 inch) sub-main that connects to the outlet and empties into the 20 cm (8 inch) main outlet at the northwest corner of the field. The southeast and northwest quadrants had the water table controlled during some periods while the southwest and northeast were allowed to drain conventionally at all times, as illustrated in Figure 2.1. Flow was measured by Electromagnetic flow meters (Krohne Waterflux 3070) which can accurately measure forward and backward flow at very low flow levels as well as high flow levels (Brooks, 2013). A Campbell data logger records the hourly flow data for all four quadrants.

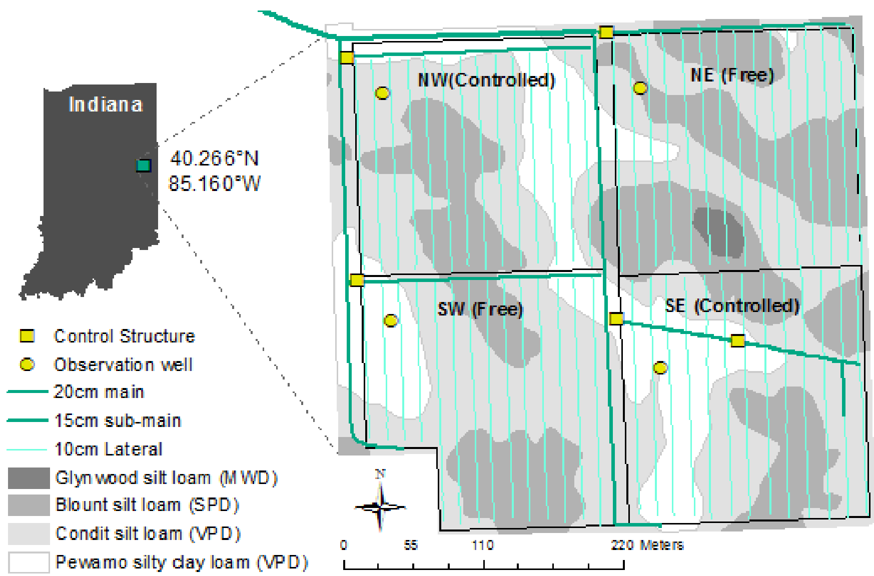

Figure 2-1. Map of field W at DPAC with soil type, tile drain location and observation well and control structure location (MWD: moderately well drained; SPD: somewhat poorly drainaed; VPD:very poorly drained).

In order to measure the movement of the water table in the field, one observation well was installed in each quadrant in 2005 as their locations are shown in Figure 2.1. The observation wells are located at the mid-point between two laterals, within the expected area of influence of controlled drainage based on elevation relative to the outlet. For each of the four quadrants, the relief between the ground surface at the outlet and the observation well ranged from 0.1 to 0.3 m. These wells are perforated two-inch polyvinyl chloride (PVC) pipe installed to a depth of approximately 2 m. Pressure transducers (Global Water WL-16) measured water table level every hour, and data were stored in a data logger fitted inside the top of the pipe. Data from 2006 to 2014 were used in this study. A MATLAB script was written to perform quality control and calculate the water table depth from sensor readings.

Drainage discharge was controlled during both the growing and non-growing seasons. The outlet was lowered a few weeks before planting (late April or early May) and raised to the controlled height of 0.6 m above the outlet (0.4 m below the ground surface) after the spring fieldwork (early June) through the end of September. After harvest the outlet was raised to the height of 0.9 m above the outlet (0.1 m depth from the ground surface) for early January through late March each year. The dates when the boards were raised and lowered and the height to which they were raised in 2014 are shown in Figure 2.2.

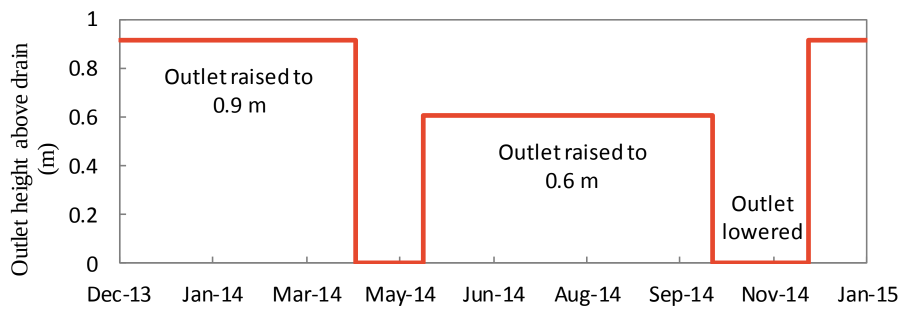

Figure 2-2. Height of outlet above the drain at the control structure during 2014 (when the outlet is raised drainage is controlled).

2.3.2 Drain depth

For this analysis, the water table was referenced to the depth of the subsurface drains, so that all values represent the pressure head at the drain. Drain depths (D_{drain}) at the observation well locations were initially estimated from surveyed elevations at the observation well and the outlet of the sub-main, which was accessible in the sampling culvert (Fig. 2.3). The ground elevation change from the observation well to the outlet (ΔZ_{ground}) was surveyed, and the slope of the drain was found in the contractor's design report. Knowing all these values for each quadrant, the drain depth was estimated using equation 1:

$$D_{drain} = D_{sensor} - \Delta Z_{sensor\text{-}sub} - \Delta Z_{tile} \qquad (1)$$

where D_{drain} is the drain depth below the surface, D_{sensor} is the depth of the water table sensor below the surface, and ΔZ_{tile} is the change in the tile elevation from sub-main to the observation well, calculated by equation 2:

$$\Delta Z_{tile} = L \times \text{Tile slope} \quad (2)$$

where L is the distance between the observation well and the culvert. Finally, $\Delta Z_{sensor\text{-}sub}$ is the elevation difference from the sub-main at the culvert to the bottom of sensor at the observation well, found as follows:

$$\Delta Z_{sensor\text{-}sub} = D_{sensor} - (D_{sub} + \Delta Z_{ground}) \quad (3)$$

where D_{sub} is the depth of sub-main at the culvert, and ΔZ_{ground} is the ground elevation change from observation well to the culvert.

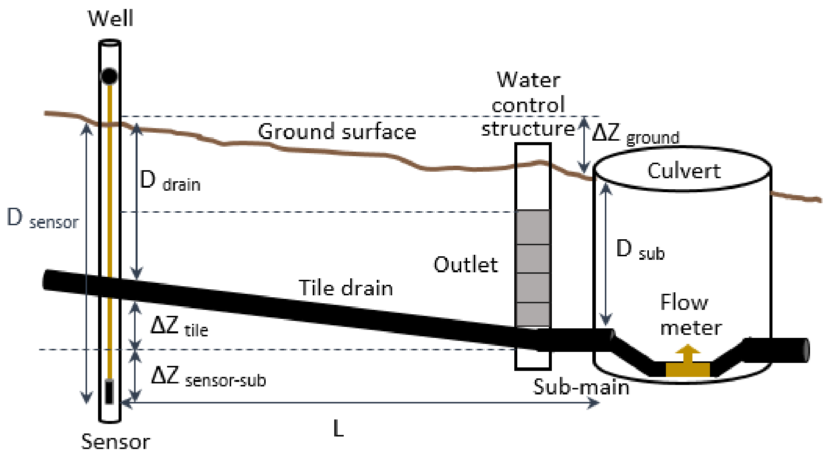

Figure 2-3. Profile view of the well, tile drain, water control structure, sub-main and culvert in the field.

Examination of drain flow measurements provided a hydrological alternative method for estimating drain depth at the observation wells, by assuming that the drains flow only when the water table is above the drains. Based on heterogeneity in water table height, it is possible to observe drain flow at the outlet even when water table at the observation well location is below the drain, but it is more difficult to explain an observed water table level above the drain depth while there is no drain flow observed. Estimation of the drain depth based on physical measurements and the alternative hydrological method both estimated the same drain depth for one of the four quadrants and this confirms the approximate accuracy of both approaches. Given the uncertainty in measurements of drain slope and sensor depth over time, water table heights above the drain were adjusted for all quadrants using the alternative hydrological method. Time periods when the outlet was lowered and drain flow dropped to zero were used to identify an adjustment of the drain depth, so that the depth of water table above the drain was also adjusted to be zero (Fig. 2.4). In one quadrant (SW) the height adjustment was different for two time periods, because the sensor height changed one time during study period.

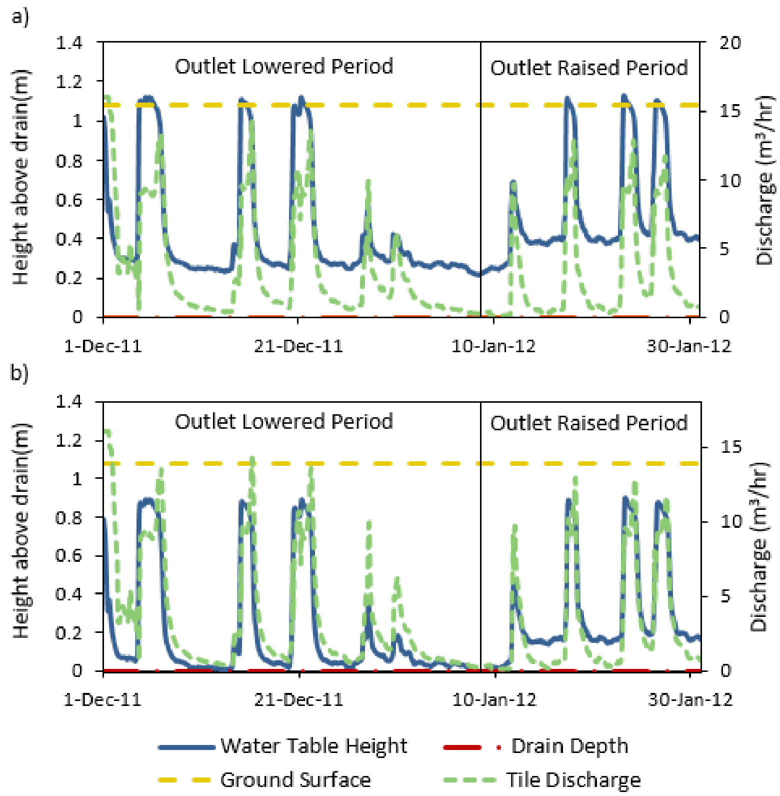

Figure 2-4. Plot of water table height above drain at the observation well location, tile drain flow, drain depth and ground surface to show how the effective drain depth was obtained. a) before adjustment and b) after adjustment.

2.3.3 Identifying events

The beginning and ending of events used in this analysis were identified by the times the water table was above or below a water table reference level. An event started when the water table rose above the reference level and ended when the water table dropped below the same level. Each event for which water table data were available was analyzed to determine the time that the water table stayed above the reference level. The rate of recession was then calculated based on the maximum height of the water table during the event period, and the number of hours from the maximum height of the water table until the end of the event (Fig. 2.5).

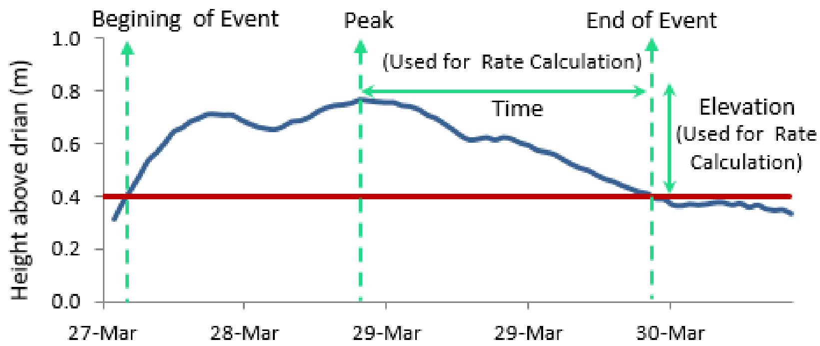

Figure 2-5. Plot of water table elevation relative to the drain to show how the time and elevation change was used to calculate the rate.

The reference level was defined as either the minimum depth at which detrimental effects to plant growth or trafficability could be expected, or the outlet (board) elevation if above that depth. When the outlet was lowered to the drain depth, a water table reference level of 60 cm below the ground surface (40 cm above the drain) was used. The 60 cm limitation was based both on trafficability research by Kornecki and Fouss (2001) and Bornstein and Hedstrom (1982) and considerations of root growth. For a soil to be trafficable, it must have sufficient bearing capacity to prevent the vehicle from sinking too deeply and sufficient traction capacity to propel itself according to Knight and Freitag (1962). The majority of roots for most crops are within 30 to 60 cm of the soil surface (Carter et al., 1988). Since this research was done in fields with rotation of corn and soybean, it was decided that 60 cm below the ground surface would allow enough root growth to not limit yield potential. Selection of a detrimental level is complicated by variations in plant type, soil profile, depth to a change in compaction or horizon, and tillage type.

2.3.4 Paring quadrants

The timing of events in the four quadrants often did not match. In order to compare recession rates across quadrants, events were matched manually across quadrants, and events that occurred in two paired quadrants within twenty-four hours of each other were considered to be the same event. Events were then classified by whether they occurred during a raised outlet period or a lowered outlet (free-draining) period.

In order to find the best-matching pairs among the four quadrants for this analysis, events from 2011 were statistically tested during the lowered outlet period. Paired t-test was used to evaluate the significance of relationship between potential matching pairs. Normal probability plots and autocorrelation plots showed that the model residuals are independent and follow the normal distribution, so the assumptions of the paired t-test were met. Paired t-test results indicated that the rate of water table recession was not significantly different between the two eastern quadrants (NE, SE) and two western quadrants (NW, SW) however showed a significant difference in the rate of recession when the two northern and southern quadrants were paired (i.e. NE, NW pair). This means that the eastern and western pairs had more similar recession characteristics than pairing north and south, despite the difference in topographies and soil types. It appears that other factors controlled the movement of the water table, likely through restriction of the drain flow through the main. However, flow restriction happened less than 1% of the times during the study period. Since water table movement was more similar by pairing the NE with the SE and the NW with the SW, these were used as the pairs for the subsequent analysis.

2.3.5 Statistical analysis

2.3.5.1 Testing representative time periods

After the water table events were paired and recession rate was calculated for each event, recession rate datasets for each quadrant were divided to two groups. One group included the events that occurred when the outlet was raised in the controlled quadrant (raised period) and the other group included those events that occurred when the outlet was lowered in the controlled quadrant (lowered period). The raised period and lowered period data sets from each quadrant pair were tested to ensure that they were equally representative during times with and without treatment of the outlet being raised. The water table recession rates in only the quadrants that were conventionally drained (NE and SW) were compared between the times that the outlet was raised and when it was lowered for each quadrant separately using a paired t-test. There was a concern that since the outlet is often raised in the same season every year, seasonal differences in the water table events could introduce bias into the data. If the differences were seasonal, rather than due to treatment, they should be reflected in the conventionally drained quadrants.

2.3.5.2 Difference in rate of descent using a paired watershed approach

The paired field statistical approach was used to determine the effect of controlled drainage on the rate of descent. In this approach, two watersheds or fields (control and treatment) and two periods of study (calibration and treatment) are required. A detailed description of the paired watershed approach can be found in Clausen and Spooner (1993). Linear regression from the lowered period (free-draining periods) was used to test the significance of the relationship between paired observations using analysis of variance (ANOVA), followed by an analysis of covariance (ANCOVA) of the raised period date (periods with one field controlled) to determine the significance of the difference between the lowered and raised periods. Similar to the studies by Amatya et al. (2000), Adeuya et al. (2012), Sunohara et al., (2015) and Gunn et al. (2015), in this study, events that occurred when the drainage outlets were lowered for field operations were also used for the calibration period, as illustrated in table 2.1.

Table 2-1. Implementation of observation used for paired watershed analysis.

Period	Watershed	
	Control (Free draining)	Treated (Controlled)
Calibration	Lowered outlet	Lowered outlet
Treatment	Lowered outlet	Raised outlet

Analysis of variance and covariance assumes that the regression residuals are independent and normally distributed, however, normal probability plots indicated that the model residuals did not follow a normal distribution, which weakens the power of the statistical analysis. Therefore, all data sets were natural log-transformed to improve the normality based on the Shapiro-Wilk statistic. The datasets were not autocorrelated, indicating that the model residuals are independent.

In the ANCOVA, the significance of the overall regression which combines the outlet lowered and raised period data and the difference in slopes and intercepts for the lowered and raised period regression lines was determined at the α=0.05 level. Statistical tests were accomplished using MATLAB.

2.4 Results and discussion

There were a total of 78 events in the eastern quadrants and 101 events in the western quadrants. For each individual event, the linear regression coefficient of determination (R^2) was calculated. Table 2.2 summarizes the total number of events, minimum, maximum and mean duration of events and minimum, maximum and mean R^2 and average effective hydraulic conductivity of each quadrant. The effective hydraulic conductivity of the profile was calculated from the observed drain flow and height of water table above the drain using the Hooghoudt equation (Bouwer and van Schilfgaarde; Saadat et al., 2016). The average R^2 ranged between 0.84

to 0.91 for each quadrant which justifies the linear relationship assumption that has been made to calculate the recession rate. More events were observed in the outlet raised periods compared to the time that the outlet was lowered in both pairs (Fig. 2.6). The visual inspection of Figure 2.6 shows that the recession rate for the controlled quadrant decreased in both pairs when the outlet was raised and thus the magnitude of the difference in rates increased when the outlet was raised. The difference was found by subtracting the rate of water table descent of the conventionally-drained quadrant from the rate of the controlled quadrant.

Table 2-2. Number and duration of events, coefficient of the linear regression of events and average effective hydraulic conductivity of each quadrant.

Quadrant	# of event	Duration of event (hr)			Linear regression coefficient of determination (R^2)			Avg. effective hydraulic conductivity (m/day)
		Max.	Mean	Min.	Max.	Mean	Min.	
SW	101	389	77	6	0.99	0.91	0.6	0.19
NW	101	378	87	6	0.99	0.91	0.52	0.15
NE	78	156	50	11	0.99	0.93	0.62	0.3
SE	78	81	35	8	1.00	0.84	0.61	0.5

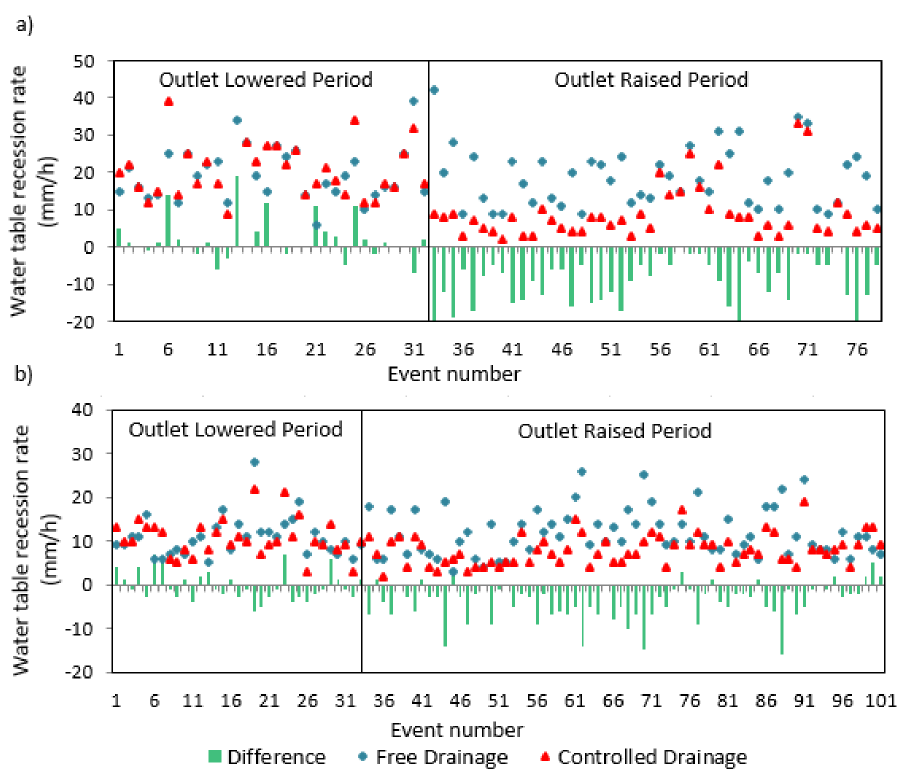

Figure 2-6. The water table event pairs for the a) eastern quadrants and b) western quadrants, grouped by controlled treatment assigned to an arbitrary event number. Bar graph shows the difference (Difference=controlled Drainage-Free Drainage).

For the eastern pair, the outlet lowered period had generally higher rates of recession than the western pair. The lower recession rates in the western pair during the outlet lowered period is likely because the difference in the elevation head between the field and the outlet is lower, even before any management practice had been applied. The higher recession rate in the eastern pair can also be due to the greater average hydraulic conductivity in this pair compared to the western pair (Table 2.2).

Paired t-test results for the free-draining plots (NE and SW) indicated that the mean rate of water table recession was not significantly different between the raised and lowered outlet periods (p-value was 0.67 in the NE and 0.43 in the SW quadrant). This means that the free-draining plots experienced a similar range in events between the outlet raised and lowered time periods and the differences between these two periods were not seasonal.

The relationships between recession rate in the controlled and free-draining plots during calibration and treatment periods is shown in Figure 2.7. The lowered period (calibration) regressions were statistically significant (p-values <0.001) for both pairs meaning that these paired observations can be used for further analysis and a comparison between calibration and treatment periods. The ANCOVA determined that the intercept and overall regressions were significantly different between the calibration and treatment periods in both pairs (Table 2.3) meaning that the controlled drainage had a significant effect on the rate of recession. As stated by Clausen and Spooner (1993), a significant difference in intercepts when slopes are not significantly different, indicates an overall parallel shift in the regression equations which in this case, confirms a significant decrease in the rate of recession when drainage is controlled. But more importantly, it implies that the decrease in rate is independent of the rate itself, meaning that, as the recession rate in the free-draining field decreases, the reduction in rate is not smaller.

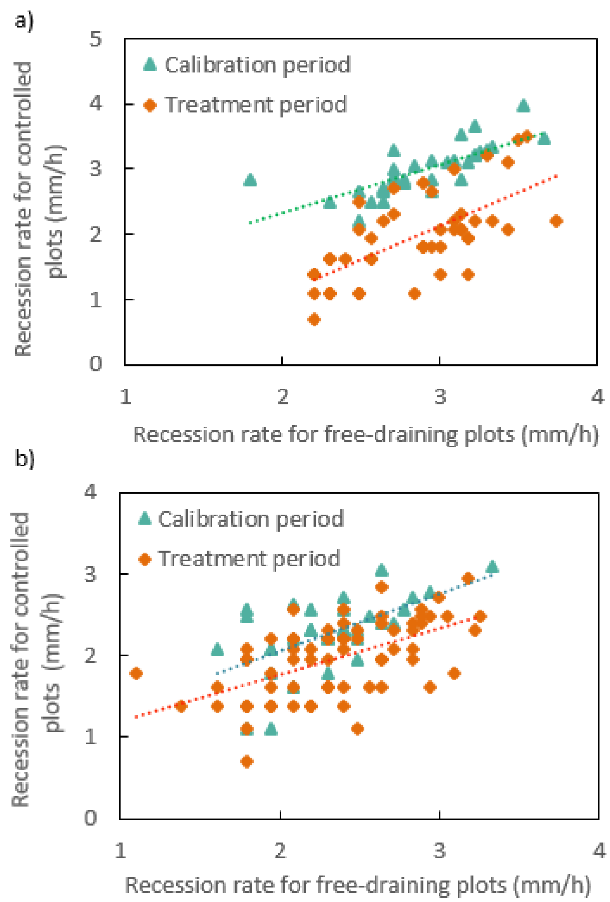

Figure 2-7. Linear regressions between controlled and free-draining plots during the calibration (lowered) and treatment (raised) periods in a) eastern quadrants b) western quadrants.

Table 2-3. Linear model equations for calibration and treatment periods.

	Calibration period			Treatment period				
Pair	Intercept	Slope	R^2	Intercept	*p*-value	Slope	*p*-value	R^2
Eastern	0.825	0.747	0.55	-0.965*	0.014	1.032	0.249	0.45
Western	0.643	0.706	0.35	0.644*	0.009	0.561	0.478	0.32

*Indicates statistically significant difference between calibration and treatment periods at α=0.05.

The effect of controlled drainage on the water table recession rate during the outlet raised period was calculated by comparing the observed values with the values that were predicted by applying the calibration regression equation to the observed rate from free-draining field (Table 2.4). Controlled drainage decreased the mean recession rate of the water table by 29% in the western and 62% in the eastern pair with the range of reduction from 2% to 72% in the west and

7% to 84% in the east. The stronger effect of controlled drainage on the recession rate in the eastern pair may be due to the higher hydraulic gradient in eastern quadrants compare to western quadrants and the fact that in the eastern pair, outlet lowered period had generally higher rates of recession than the western pair (Table 2.2).

Table 2-4. Effect of controlled drainage on mean recession rate of water table during treatment period (outlet raised).

Pair	Predicted[a] (mean ± SD[b]) (mm/h)	Observed (mean ± SD) (mm/h)	Reduction (mm/h)	Percentage reduction (%)
Eastern pair	18.9 ± 6.3	7.1 ± 7.0	11.8	62.4
Western pair	10.1 ± 3.4	7.2 ± 3.5	2.9	28.9

[a]Obtained from the calibration period (free-draining) regression equation by applying the observed values from the treatment period of free-draining field.
[b] Standard deviation

The time of water table fall from the surface to 30 cm and 60 cm depth, which could be examples of critical levels for crops, was also determined using the observed rates and the predicted rates. This increase in the average required time for water table recession from the peak to 60 cm depth when the outlet is raised is illustrated in Figure 2.8 for one pair. Results indicated that raising the outlet increased the time that the water table needs to recede to 30 cm depth by an average of approximately 12 to 24 hours and 24 to 53 hours to recede to 60 cm depth (Table 2.5). The actual range of increase in the hours of recession in the outlet raised period varied between 2 and 250 hours depending on the severity of corresponding rainfall events.

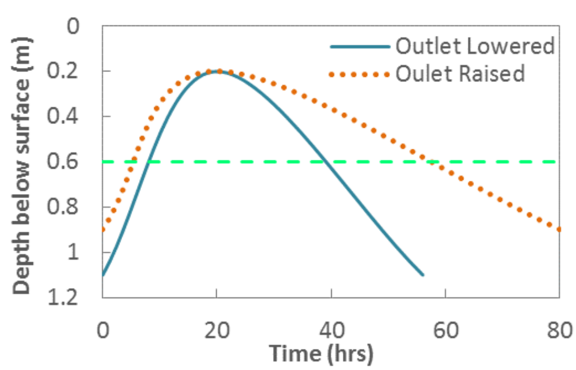

Figure 2-8. Average time required for water table recession from peak to 60 cm depth in the western quadrant.

Table 2-5. Effect of controlled drainage on mean hours of water table recession during treatment period (outlet raised).

	30 cm depth			60 cm depth		
Pair	Predicted[a] (hr)	Observed (hr)	Difference (hr)	Predicted (hr)	Observed (hr)	Difference (hr)
Eastern pair	15.9 ± 5.2 [b]	42.3 ± 30.4	26.4	31.8 ± 10.3	84.5 ± 60.8	52.7
Western pair	29.8 ± 10.7	41.9 ± 23.5	12.1	59.6 ± 21.4	83.8 ± 47.0	24.2

[[a]Obtained from the calibration period (free-draining) regression equation by applying the observed values from the treatment period of free-draining field

[b] Mean ± standard deviation

The time reduction of lowering the outlet discussed here is less than that found by Belcher and Gleim (2003), who conducted a theoretical analysis and found a reduction of 53 to 161 hours in the time needed for the water table to fall from the surface to a depth of 15 cm and 30 cm respectively, by removing the weir. The recession time reduction of removing the weir was influenced by soil properties such as drainable porosity and hydraulic conductivity and drain spacing in their study. Compared to our drain spacing (14 m), drainable porosity (range of 0.14 to 0.06 from surface to 60 cm depth) and hydraulic conductivity (range of 0.15 to 0.5 m/day), Belcher and Gleim (2003) assumed values (15 m drain spacing ,0.1 drainable porosity and 0.4 m/day hydraulic conductivity) in the same range. Therefore, factors other than soil properties may explain the lower observed difference in recession time. Fouss et al. (1987) found a time reduction from lowering the outlet to 40 cm depth with fixed weir control and two-stage weir control in which the weir was moved between high and low positions during rainfall events was 6 and 5 hours respectively, for a different drainable porosity and drain spacing (0.03 and 20m).

Crop yields can be negatively affected by controlled drainage, likely a result of overly wet conditions which could be addressed by event-based management strategies. In a simulation study, Thorp et al. (2008) reported a range of -0.2% to 12% in the yield changes due to fixed controlled management from 48 locations. Field data also show a decrease in the yield on a site-year basis specifically in wet years. Controlled drainage resulted in a lower yield than a conventionally drained site due to the relatively wet weather during the growing season in 2008 (Jaynes, 2012). On a year-to year basis, Cooke and Verma (2012) also found a decrease in the yield in 2005 and 2006 after controlled drainage was installed in the field. Out of 23 site-year yield results reported by Ghane et al. (2012), four of them showed a decrease in yield when drainage was controlled and among those, two cases happened in 2011 which had a higher amount of rainfall during the growing season than other years. In another study, Crabbé et al. (2012) reported a decrease in the corn yield in 2005 and 2009 from a five-year study. These results emphasize the potential negative impacts of rainfall events and wet conditions during growing season and event-based management strategies like lowering the outlet before or just after rainfall events may have mitigated the negative effects of controlled drainage on crop yields in these fields.

2.5 Conclusions

The objective of this study was to determine how much controlled drainage lengthens the time needed for the water table to fall after a rainfall event to inform the possible improvement in the management of controlled drainage system and therefore, mitigate the potential negative impacts on yield. Water table recession rate was used to calculate the amount of time that the water table needs to recede from the surface to a level that could be detrimental to trafficability or crop yield, under both free and controlled drainage conditions. Results indicated that controlled drainage had a statistically significant effect on the rate of water table fall, and that a raised outlet (controlled drainage) increased the time of water table recession from the surface to 30 cm and 60 cm depth by an average of approximately 12 to 26 and 24 to 53 hours, respectively. Based on these results, it can be concluded that lowering the outlet before storm events would reduce the amount of time that the water table is at a detrimental level for either crop growth or trafficability. However, lowering the outlet during rainfall events does have costs in terms of the time required to manage the outlets. Whether the benefits of lowering the outlet outweighs the cost depends on the sensitivity of the crop and probability of a severe storm. Future studies should examine the cost and benefit trade-off of active management of controlled drainage systems.

2.6 Acknowledgment

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CHAPTER 3. ESTIMATING DRAIN FLOW FROM MEASURED WATER TABLE DEPTH IN LAYERED SOILS UNDER FREE AND CONTROLLED DRAINAGE

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3.1 Abstract

Long records of continuous drain flow are important for quantifying annual and seasonal changes in the subsurface drainage flow from drained agricultural land. Missing data due to equipment malfunction and other challenges have limited conclusions that can be made about annual flow and thus nutrient loads from field studies, including assessments of the effect of controlled drainage. Water table depth data may be available during gaps in flow data, providing a basis for filling missing drain flow data, therefore, the overall goal of this study was to examine the potential to estimate drain flow using water table observations. The objectives were to evaluate how the shape of the relationship between drain flow and water table height above drain varies depending on the soil hydraulic conductivity profile, to quantify how well the Hooghoudt equation represented the water table – drain flow relationship in five years of measured data at the Davis Purdue Agricultural Center (DPAC), and to determine the impact of controlled drainage on drain flow using the filled dataset. The shape of the drain flow-water table height relationship was found to depend on the selected hydraulic conductivity profile. Estimated drain flow using the Hooghoudt equation with measured water table height for both free draining and controlled periods compared well to observed flow with Nash-Sutcliffe Efficiency values above 0.7 and 0.8 for calibration and validation periods, respectively. Using this method, together with linear regression for the remaining gaps, a long-term drain flow record for a controlled drainage experiment at the DPAC was used to evaluate the impacts of controlled drainage on drain flow. In the controlled drainage sites, annual flow was 14 - 49% lower than free drainage.

3.2 Introduction

Long records of continuous drain flow are important for quantifying annual and seasonal changes in the subsurface drainage flow from drained agricultural land. This is essential for quantifying load, used for determining the contribution of tile drains to nutrient loads and the impact of practices that have the potential to reduce loads. Yet monitoring drain flow is challenging; equipment malfunction caused by power interruption, lightning strikes, and animals, often causes data corruptions or interruptions.

One practice that requires long-term flow records to properly evaluate is controlled drainage (CD), a practice used to reduce the transport of nitrate through tile drainage to surface waters by using a water control structure to vary the depth of the drainage outlet. Nitrate loss from tile drains with CD systems has been shown to be between 17% to over 80% lower than conventional drainage (Skaggs et al., 2012a). But monitoring challenges have made quantification difficult. Gunn et al. (2015) stated that instrument failure and outlet submergence reduced measured drain flow records in a field in Ohio and limited understanding of the effects of controlled drainage at the field scale. Adeuya et al. (2012) discussed the restriction in drain flow measurements from two drained farms in Indiana because of the submergence conditions of the outlet that required empirical data correction before load calculation. Cooke and Verma (2012) found that uncertainties associated with the flow measurements due to the errors in the low flow measurements and the submergence conditions were the main reasons for uncertainty in annual flow and load estimations. When drain flow data has gaps, other measurements such as water table depth at a monitoring site may provide additional data that can be used in estimating the missing drain flow.

The relationship between midpoint water table height above drain (m) and drain flow (q) has been investigated in the laboratory or with field experiments since the 1950s (Luthin and Worstell, 1957, Goins and Taylor, 1959, Hoffman and Schwab, 1964). Luthin and Worstell (1957) analyzed field data collected by other researchers and showed that the relationship between m and q was approximately linear for homogeneous soils. Goins and Taylor (1959) also found a linear relationship between m and q under field conditions when the water table is falling continuously. However, Hoffman and Schwab (1964) found that for an anisotropic soil the m – q relationship was not linear, in contrast to the results for homogeneous soils.

Several theoretical equations have been developed for subsurface drainage design since 1940 that use the relationship between m and q (Hooghoudt, 1940; Kirkham, 1958; Van Schilfgaarde, 1963; Yousfi, 2014). The Hooghoudt equation assumes an elliptical water table profile below the soil surface, in which q varies with the squared m. Van Schilfgaarde (1963) proposed a theoretical tile-spacing equation for a falling water table in homogeneous soils. Hooghoudt developed the equivalent depth term, and then a correction in the van Schilfgaarde equation was made by substituting the equivalent depth for the thickness of the water-bearing zone (Bouwer and van Schilfgaarde, 1963). Although in these equations the goal was to facilitate drainage design, these equations have been used to estimate q from m in DRAINMOD (Skaggs 1978) and also to determine the effective hydraulic conductivity (K_e) of wetland soils (Skaggs et al. 2008).

According to Goins and Taylor (1959), tile flow is more related to the position of the water table in the soil profile than to the height of the water table above the drain (m), because of the strong influence of the hydraulic conductivity profile in drainage. The saturated hydraulic conductivity (K) is a time-invariant physical parameter that varies with depth in the soil column under most field conditions. The K_e depends on the water table position in the soil profile and therefore varies over time as the water table depth changes. The Hooghoudt equation assumes a K that is constant with depth, which can be unrealistic under most field conditions.

Hydrologic models have assumed various hydraulic conductivity profiles. TOPMODEL assumes that K declines exponentially with depth (Beven and Kirkby, 1979), while Ambroise et al. (1996) generalized the TOPMODEL concepts by incorporating different K (transmissivity) profiles within the original TOPMODEL. They introduced two alternative forms of subsurface K profiles including linear and parabolic, and showed how the different K profiles can lead to different streamflow recession curves. In the DRAINMOD model, a layered soil profile is assumed with each layer having a different K (Skaggs et al., 2012b). Depending on the water table position, a K_e is calculated as a weighted average of the saturated layers. The impact of the various representations of K in layered soils to the relationship between m and q has not been fully recognized, even though the strong influence of conductivity in the soil profile on the drain flow was stated half a century ago (Goins and Taylor, 1959).

Drain flow and water table depth data have been collected at the Davis Purdue Agricultural Center (DPAC) to evaluate the hydrological and environmental effects of CD. However, the drain flow record is not complete due to monitoring challenges, preventing the calculation of annual flow and limiting the conclusions about nutrient loads. The flow measurement limitation provides a motivation to develop a new method for estimating drain flow using measured water table depths.

The objectives of this paper are therefore to (1) explore the m – q relationship using different K profiles in the Hooghoudt equation, (2) evaluate how well drain flow estimated based on the Hooghoudt equation represented the measured flow at this field site, and (3) determine the effect of CD on drain flow by estimating drain flow using water table depth observations with the Hooghoudt equation for the entire monitoring period.

3.3 Materials and method

3.3.1 Experimental site and field measurements

The Davis Purdue Agricultural Center (DPAC) is a research farm in eastern Indiana located at 40.266°N, 85.160°W (Fig. 3.1). The controlled drainage experimental site is the 0.16 km^2 (39-acre) field (field W), split into four quadrants, northwest (NW), southwest (SW), northeast (NE), and southeast (SE) with areas of 3.5 ha, 3.5 ha, 3.6 ha, and 3.7 ha. The elevation change in this field is approximately 3 m (<1% slope). Soils at the site consist of Blount (silty clay loam, somewhat poorly drained), Condit (silty loam, poorly drained), Pewamo (clay loam, very poorly drained) and Glynwood (silt loam, moderately well drained) series, based on an Order 1 soil survey completed in 2001 (Blumhoff et al., 2001). The drainage system was installed in September 2004 with laterals having an approximate depth of 1 m and spacing of 14 m (Utt, 2010). Each of the quadrants has its own 15 cm (6 inch) sub-main that connects to the outlet and empties into the 20 cm (8 inch) main outlet at the northwest corner of the field. Drainage in the SE and NW quadrants was controlled during some periods while the SW and NE were allowed to drain conventionally at all times. A more detailed description of this site can be found in Saadat et al. (2017).

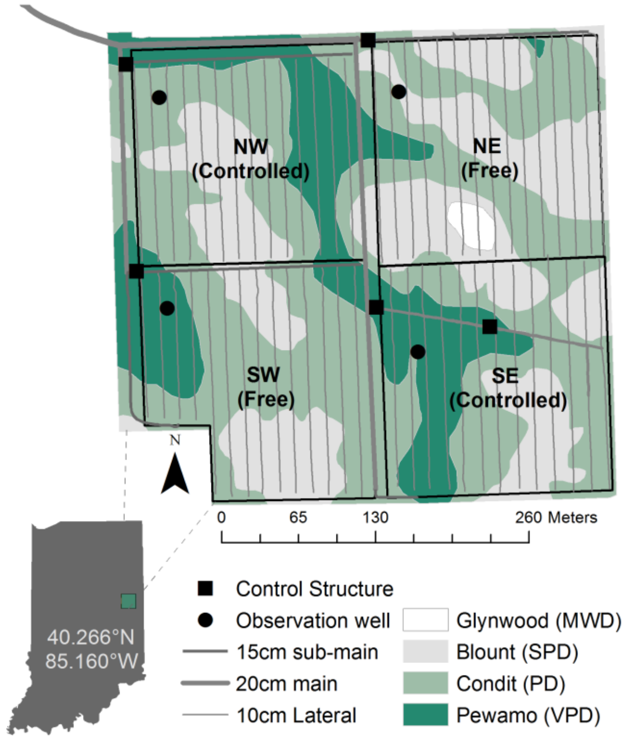

Figure 3-1. Map of Field W at Davis Purdue Agricultural Center with soil type, tile drain location and observation well and control structure location (MWD: moderately well drained; SPD: somewhat poorly drained; VPD: very poorly drained).

The subsurface drain flow was monitored with two different methods throughout the study period. The original method of monitoring drain flow used pressure transducers to measure water level in a circular flume installed in the subsurface drain (Brooks, 2013), but the flow obtained from this method is uncertain because of frequent submergence of the outlet and errors associated with the measurements. Therefore, these measurements were not used in this study. Since 2012, flow has been measured every hour by electromagnetic flow meters (Krohne Waterflux 3070) that are installed downstream of the control structures (Fig. 3.1) and offer the advantage of accurately measuring both forward and backward flow at very low flow as well as high flow levels (Brooks, 2013). Drain flow is often restricted downstream of the field by the subsurface county main with limited capacity, and therefore backward flow can occur at times of high flow, particularly in the lowest (NW) quadrant. Having a measure of backward flow enables the calculation of the net drain flow that exits the field. Electromagnetic flow meters require a signal converter to power the flow meter and provide a user interface to view or change the settings. The signal converters, however, have stopped working many times due to major lightning strikes and for this reason and other sensor malfunctions, drain flow data is often missing in each of the quadrants (Table 3.1).

Table 3-1. Number of missing days in drain flow observations obtained from the electromagnetic flow meters.

Quadrant	2012	2013	2014	2015	2016
NE	119	177	149	172	110
NW	24	18	149	2	59
SE	119	263	178	73	163
SW	24	18	95	180	14

Water table depth was measured throughout the entire 11-year period using observation wells in each quadrant, located at the midpoint between two drains and within the expected area of influence of CD based on an elevation difference relative to the outlet of less than 0.3 m (Bou Lahdou, 2014) (Fig. 3.1). These wells were perforated 5-cm PVC pipe installed to a depth of approximately 2 m. Pressure transducers (Global Water WL-16) measured water table level every hour, and data were stored in a data logger fitted inside the top of the pipe. In one of the quadrants (SW), maintenance that required removing and replacing the water table elevation sensor in the observation well led to uncertainty in the absolute water table elevation. The sensor measures water table relative to the sensor depth, so during periods between maintenance activities the recorded water table elevation was adjusted up or down by a fixed amount relative to the drain elevation, based on the assumption that drains flow only when water table is above the drain. Details of this process are provided in Saadat et al. (2017). Water table depth measurements from June 2006 to December 2016 were used in this study.

3.3.2 Hooghoudt equation

The Hooghoudt equation (Bouwer and van Schilfgaarde, 1963) was used to estimate drain flow based on the measured water table depth. This steady state equation is one of the best known of the theoretical drainage equations, and is widely used for design and research purposes as selected for use in the DRAINMOD model (Skaggs, 1978). Using experimental field data, Ferro (2016) found that the Hooghoudt, Kirkham (1958) and Yousfi (2014) theoretical equations for drainage design under steady-state conditions had similar performance in estimating the ratio of height of water above drain (m) over drain spacing (L), therefore, any of these equations can be used for practical applications. In reality, drainage is a non-steady state process but a good approximation of drain flow can be obtained from the steady state formula presented by Hooghoudt.

$$q = \frac{4K_e\, m(2d_e+m)}{L^2} \qquad (1)$$

where q is the drain flow (cm hr^{-1}), m is the midpoint water table height above the drain (cm) for free drainage and above the drain outlet weir (cm) for controlled drainage, K_e is the effective lateral hydraulic conductivity of the profile (cm hr^{-1}), L is the distance between drains (cm) and d_e is the equivalent depth from the drain to the impermeable layer (cm) and can be obtained from the following equations presented by Moody (1966).

$$d_e = \frac{d}{1+\frac{d}{L}[\frac{8}{\pi}\ln\left(\frac{d}{r}\right)-\alpha} \qquad 0 < d/L < 0.3$$

$$(2)$$

$$d_e = \frac{L\pi}{8[\ln\left(\frac{L}{r}\right)-1.15} \qquad d/L > 0.3$$

where d is the depth of the impermeable layer below drains (cm), and r is the effective drain radius. Alpha can be found by:

$$\alpha = 3.55 - \frac{1.6d}{L} + 2(\frac{2}{L})^2 \qquad (3)$$

The equivalent depth (d_e) was substituted for d in equation 1 in order to correct the resistance due to radial flow, when assuming flow towards the drains is only horizontal. The equivalent depth represents an imaginary thinner soil layer below the drains, shown in Figure 3.2, through which the same amount of water will flow per unit time as in the actual situation with combined radial and horizontal flow (Ritzema, 1994).

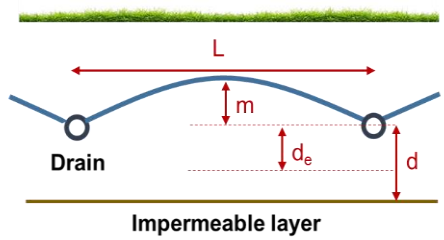

Figure 3-2. Schematic of the Hooghoudt drain flow formula parameters

3.3.3 Hydraulic conductivity profiles

The saturated lateral hydraulic conductivity (K) varies with depth in many soils, and three different theoretical profiles representing the variation in K with depth were compared to explore how the shape of the relationship between q and m varies depending on K profile. The first was a constant profile, based on the assumption of homogeneous soil in the original form of the Hooghoudt equation meaning that the K is constant with depth. The second is a layered profile, calculating an equivalent effective hydraulic conductivity (K_e) for parallel flow through a layered soil profile based on equation 4, similar to what is used in DRAINMOD (Skaggs, 1978):

$$K_e = \frac{\sum_{i=1}^{n} K_i d_i}{\sum_{i=1}^{n} d_i} \tag{4}$$

where K_i is the hydraulic conductivity and d_i is the saturated thickness of soil layer i, as shown in Figure 3.3 and n is the number of layers in the soil profile. K_e is determined in each time step before every flow calculation and it depends on the position of water table because the thickness of the saturated zone in each layer (d_i) varies linearly with the water table position within the layer. If the water table is below the layer, d_i is zero, while if the water table is above the layer, d_i is equal to the layer thickness, D_i.

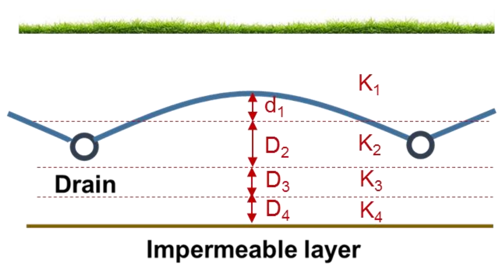

Figure 3-3. Schematic of layered soil with each having a different hydraulic conductivity.

The third profile was an exponential decline in K with depth, which is used for example in TOPMODEL (Beven and Kirkby, 1979) and other models (e.g. DHSVM, Wigmosta et al. 1994). The saturated hydraulic conductivity (K) at each depth is given by (Louis, 1974):

$$K(d) = K_0\, e^{\alpha(d)} \qquad (5)$$

where K_0 is the hydraulic connectivity at the ground surface, α is the decay exponent defining the exponential relationship between K and depth and d is the depth below the ground surface (Fig. 3 4).

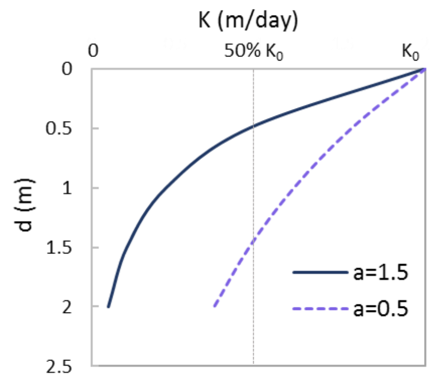

Figure 3-4. The exponential relationship between saturated hydraulic conductivity and depth with two different decay exponents

Hydraulic conductivity (K) is commonly calibrated in models, since it tends to be higher than K values measured in the laboratory or in the field (Chappell et al., 1998; Blain and Milly, 1991). Hoffman and Schwab (1964) also stated that K computed from tile outflow is believed to be a better estimate for tile design than that determined from core and auger-hole measurements.

In the current paper, the Hooghoudt equation was calibrated with respect to observed m and q by adjusting the K and depth of each layer for the constant and layered K profiles. In each time step, the effective lateral hydraulic conductivity of the profile (K_e), which is dependent on the water table position, was calculated using the conductivity and depth values for each layer, before the flow estimation. K values and layer depths were allowed to change in the range reported in the official Soil Survey for these soil series. For each K value and depth, drain flow calculated using the Hooghoudt equation were compared with observations and this process continued until the best efficiency and lowest bias between observed and estimated drain flow were obtained. Because many different combinations of K values provided a high efficiency with low bias, the visual fit between the m- q relationship from the observed data and the Hooghoudt equation was another criteria. K values that resulted in an even distribution of observations around the Hooghoudt equation were retained. A Matlab script was written to automate calibration of the Hooghoudt equation by adjusting K values in the range of 0.1 to 0.8 m/day, and layer depths in the defined range for representative soil series at each quadrant (Soil Survey Staff, 2017). The Pewamo soil series was used to represent the two southern quadrants because it is a very poorly drained soil and will tend to have a higher drain flow compared to other soil series at these plots; in addition, observation wells are located at this soil series. For the two northern quadrants, the Condit was selected, because it was at the well location and compared to the Blount, it is a more poorly drained soil.

Instead of calibrating the Hooghoudt equation for the exponential K profile, the equivalent exponential profile was obtained based on the calibrated K values. The hydraulic conductivity at the ground surface (K_0 in Eq. 5) was assumed to be equal to the calibrated hydraulic conductivity of the first layer in the layered profile (K_1). The decay exponent (α in Eq.5) was then adjusted to yield an equivalent profile to the layered K profile.

3.3.4 Drain flow evaluation

Drain flow was estimated for each hour for which water table depth was available, using calibrated Hooghoudt equation and measured water table depths. Drain flow estimates were calibrated and validated by comparing them with field observations both visually and statistically. Daily flow estimates and measurements from 2012 to 2015 were used for calibration and then estimated and measured drain flow from 2016 were used for validation. The goodness of fit statistics were used for evaluating the drain flow estimation results including the Nash-Sutcliffe efficiency coefficient (NSE), the percent bias or error (PE) and correlation coefficient (R^2):

$$NSE = 1 - \frac{\sum_1^n (O_i - P_i)^2}{\sum_1^n (O_i - \overline{O_i})^2} \quad (6)$$

$$PE = \frac{\sum_1^n P_i - \sum_1^n O_i}{\sum_1^n O_i} \times 100 \quad (7)$$

$$R^2 = \sqrt{\frac{\sum_1^n (O_i P_i - n\bar{O}\bar{P})^2}{(\sum_1^n O_i{}^2 - n(\bar{O})^2)(\sum_1^n P_i{}^2 - n(\bar{P})^2)}} \quad (8)$$

where O_i is the daily measured value, P_i is the daily simulated, $\overline{O}_i$ is the average of measured values, $\bar{P}_i$ is the average of simulated values, and n is the number of observed values. The NSE assesses the predictive power of a hydrological model and the R^2 is a measure of how well trends in the estimated values follow trends in the observed values. The NSE value can vary between minus infinity and 1, with 1 indicating a perfect fit. The value of R^2 can vary from zero to 1, with 1 indicating a perfect linear relationship between the observed and simulated values. The PE value can vary from minus infinity to positive infinity. A negative value indicates under-prediction, and positive value indicates over-prediction.

3.3.5 Filling missing values with regression approach

After gaps in drain flow data were filled using the Hooghoudt equation and water table depth observations, gaps in drain flow estimates remained due to missing values in the water table observations (Table 3.2). These missing values were estimated in order to accurately calculate monthly and annual values of drain flow. The regression approach has been widely used for filling data gaps (Tomer et al., 2003, Haddad et al., 2010) and was selected for this study. Linear regression equations of the daily flow observations from one quadrant against a paired quadrant with the same treatment (free or controlled drainage) were developed and utilized to fill the missing values (Fig. 3.5).

Table 3-2. Number of remaining missing days after drain flow estimates combined with observations.

Quadrant	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
NE	20	39	43	4	36	21	0	22	0	0	61
NW	0	88	2	0	148	32	1	2	0	0	1
SE	60	210	52	37	25	38	28	76	0	23	20
SW	0	51	0	7	24	14	0	15	0	23	0

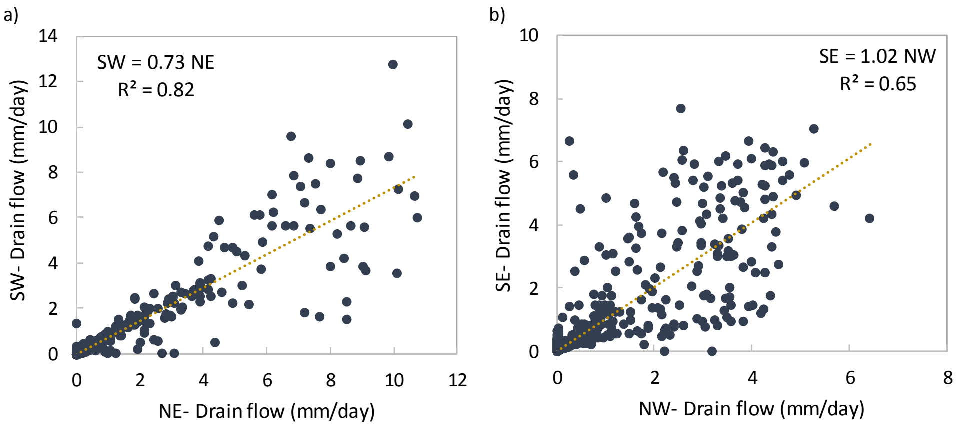

Figure 3-5. Linear regression equations of daily drain flow observations from 2012 to 2016 for a) free quadrants and b) controlled quadrants.

3.4 Results and discussion

3.4.1 Implication of different K profiles on the m – q relationship

The constant, exponential, and layered K profiles are shown in Figure 3.6 for the SW quadrant. For the layered profile, calibrated K values by layer for each quadrant (Table 3.3) were used. The total depth of the soil profile is defined by d_e. The K is higher in the top layer in the NW and SW quadrants, but higher in the bottom layer in the NE and SE quadrants. The soil series at the well location for both SE and SW are the same, however, the proportions and locations of different soils within these quadrants are different and that can affect on the calibrated K values. The reason for having a larger conductivity in the bottom layer of two quadrants is unknown; one possible reason may be a sand layer below the tile drain or other heterogeneity in this glacial landscape. For the constant profile, K was also calibrated while for the exponential profile, an equivalent profile to the layered soil (Table 3.4) was used to maintain the same average conductivity.

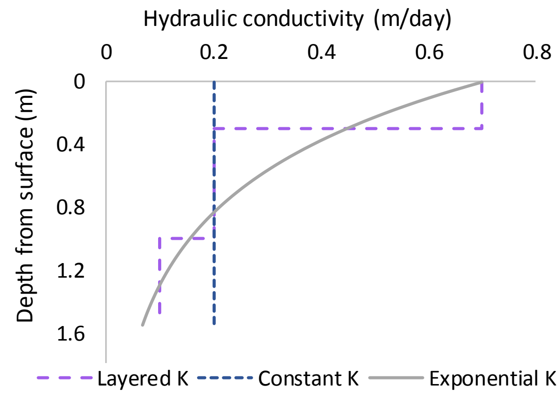

Figure 3-6. Soil profile for the SW quadrant with three different K profiles (layered K, constant K and exponential K)

Table 3-3. Calibrated soil layers and saturated lateral hydraulic conductivity for each individual layer.

NW		SW		NE		SE	
soil layer (cm)	K (m/day)	soil layer (cm)	K (m/day)	soil layer (cm)	K (m/day)	soil layer (cm)	K (m/day)
0-25	0.6	0-30	0.7	0-25	0.25	0-30	0.25
25-160	0.15	30-100	0.2	25-140	0.2	30-100	0.2
160-178	0.1	100-155	0.1	140-164	0.6	100-146	0.6

Table 3-4. The constant and exponential K profiles used in Figures 3.6 and 3.7.

Quadrant	K (m/day)	
	Constant*	Exponential**
NE	0.3	$0.25\ e^{(0.6\ d)}$
SW	0.2	$0.7\ e^{(-1.5\ d)}$
NW	0.15	$0.6\ e^{(-d)}$
SE	0.5	$0.25\ e^{(0.7\ d)}$

*Calibrated
**Equivalent with calibrated K values for each soil layer

Figure 3.7 shows how the Hooghoudt equation can represent the m – q relationship differently from a linear to parabolic relationship depending on the selected conductivity profile. Different K profiles resulted in a different relationship between m and q except for the NW quadrant where both constant and layered K profiles revealed almost the same relationship. In all cases, the constant K profile yields an approximately linear relationship that is consistent with earlier observations (Luthin and Worstell, 1957; Goins and Taylor, 1959). These results indicate that there is not any conflict between the previous observations and the Hooghoudt equation, since

Hooghoudt can appear linear if the constant K profile is used in the equation. However, the relationship between m and q is not always linear for all fields and the correct K profile should be recognized and used in the Hooghoudt equation.

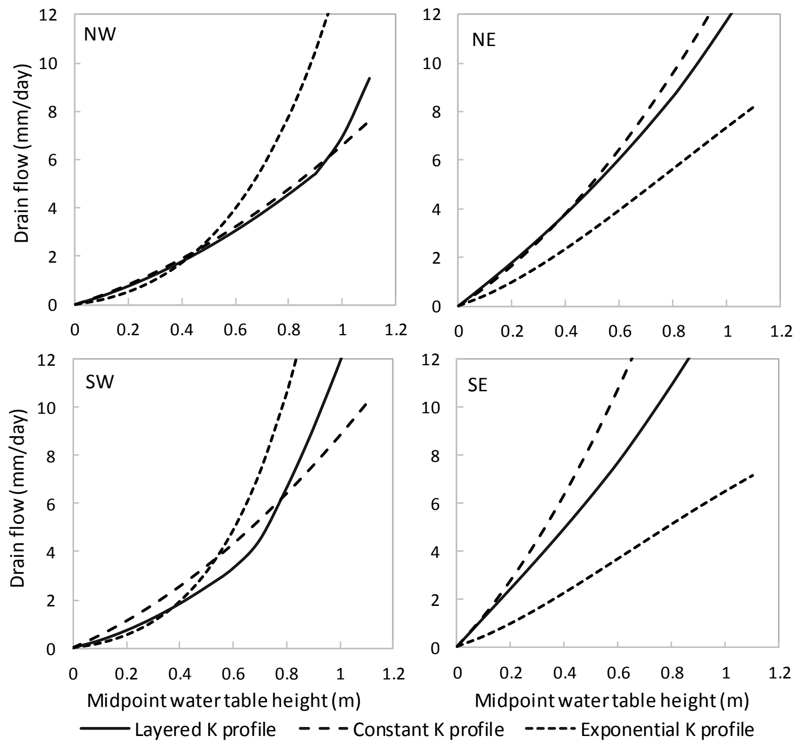

Figure 3-7. The relationship between observed drain flow and midpoint water table height above drain (for free drainage) or above the outlet weir (for controlled drainage) with the application of different K profiles in the Hooghoudt equation.

These relationships are consistent with expected behavior. In homogeneous soils, K is constant with depth, and therefore, when water table drops through the soil profile, drain flow decreases proportionally which results in an approximately linear plot of the m versus q. However, in the layered soils, K_e depends on the water table positon in the soil profile. This could lead to a non-linear relationship between m and q in the layered soils. For example, if the top soil layer has a higher K (e.g SW and NW quadrants), when the water table is near the surface, the higher K is the predominant factor in the K_e as reported by Hoffman (1963). Therefore, when water table is in this layer, drain flow decreases proportionally to a drop in water table. However, when the water table drops below the top layer, the K of other layers are predominant and usually lower than the top layer and this can lead to a decrease in flow while water table has not decreased correspondingly.

3.4.2 Drain flow estimates using layered K profile

Among the three discussed hydraulic conductivity (K) profiles, the layered K profile was chosen for prediction of drain flow because the layered K profile is more physically representative, due to its relation to soil horizons in the soil profile. This allows consideration of an anomalous layer such as a sand layer in between other soil layers while the non-monotonic changes in K with depth is not accurately representable by the exponential profile. The layered K profile is also more physically realistic due to the soil compaction impacts on conductivity. In homogenous soils that K is assumed constant, soil compaction can decrease the K exponentially with depth, while K, which is related to the soil texture, can vary for different soil layers in the layered K profile.

The relationship between observed daily m versus observed q and the observed m versus estimated q from the Hooghoudt equation using layered K profile (Table 3.3) in the calibration period are shown in Figure 3.8. In this figure, rising water table events are separated from falling water table events to examine potential hysteresis in the m versus q relationship for the entire drainage period. However, the difference was found to be small for daily values and since the main goal of this analysis was to estimate drain flow for the entire drainage period, both falling and rising events were considered together in the analysis. Drain flow is also constrained by the hydraulics of the drainage pipes. For the outlet drains of these 3.5 ha quadrants, which consist of corrugated pipes with diameter 15 cm at a slope of 0.1%, the maximum flow is estimated to be 10 mm/day (ASABE Standards, 2015). In the NW quadrant, the hydraulic limit is lower because of an undersized outlet for the field, and was set at 6 mm/day based on observed maximum flow. The SE quadrant also appeared to have a lower flow limit, but the 10 mm value was used since there was no known physical basis for a lower limit and other factors such as errors in the water table depth and drain flow measurements might have contributed to those scattered high water table events in this quadrant.

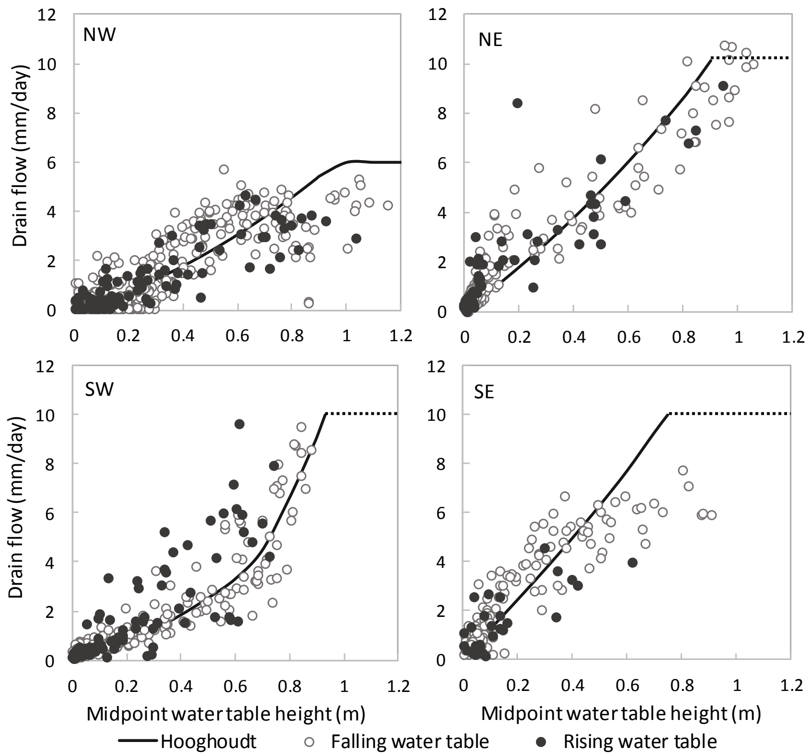

Figure 3-8. The relationship between observed drain flow and midpoint water table height above drain (for free drainage) or above the outlet weir (for controlled drainage) and the Hooghoudt equation using layered K profile with the dashed line showing the constraint on the flow.

Daily estimated and observed drain flow for the four-year calibration period were in good agreement (Table 3.5). Drain flow was under-predicted in the NE and SE quadrants and over-predicted in the SW and NW quadrants, with the lowest PE of 2% and the highest of -15 % in the SW and SE quadrants, respectively. In general, free draining and controlled quadrants performed similarly in predicting drain flow. Although the NW, which is a controlled quadrant, had lower NSE, other factors such as restriction of drain flow through the main may be contributing to the lower performance of this quadrant in predicting flow. In order to better understand the effect of controlled drainage on flow prediction, free drainage and controlled drainage periods were separated and results showed that even in free drainage periods, the NW had lower efficiency than other quadrants (NSE = 0.7).

Table 3-5. Statistical measures of agreement between daily estimated and measured drain flow in the calibration period (percent error (PE) regression coefficient (R^2) and Nash-Sutcliffe Efficiency (NSE))

Quadrant	PE (%)	R^2	NSE
NE (Free)	-10	0.90	0.87
SW (Free)	2	0.82	0.84
NW (Controlled)	11	0.76	0.72
SE (Controlled)	-15	0.87	0.85

Time series of predicted and observed drain flow were plotted and compared visually. An example for 9 months in the SW quadrant is shown in Figure 3.9. Besides the high values obtained for the NSE, visual inspection of this figure also indicates a good agreement between estimated and observed drain flow.

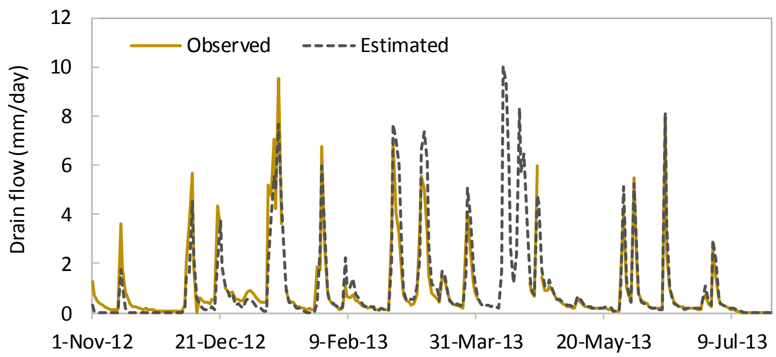

Figure 3-9. Comparison of daily observed and estimated drain flow for the SW quadrant during seven months of study.

Validation of the method using calibrated K_e was conducted by comparing estimated and observed drain flow for 2016 (Fig. 3.10). Values obtained for both R^2 and NSE were above 0.8 for all four quadrants, indicating a good agreement between estimated and observed values. NSE values of 0.91 and 0.84 for estimated drain flow in SW and NW quadrants, respectively, were even higher than that in the calibration period and for the other two quadrants NSE were in a similar range.

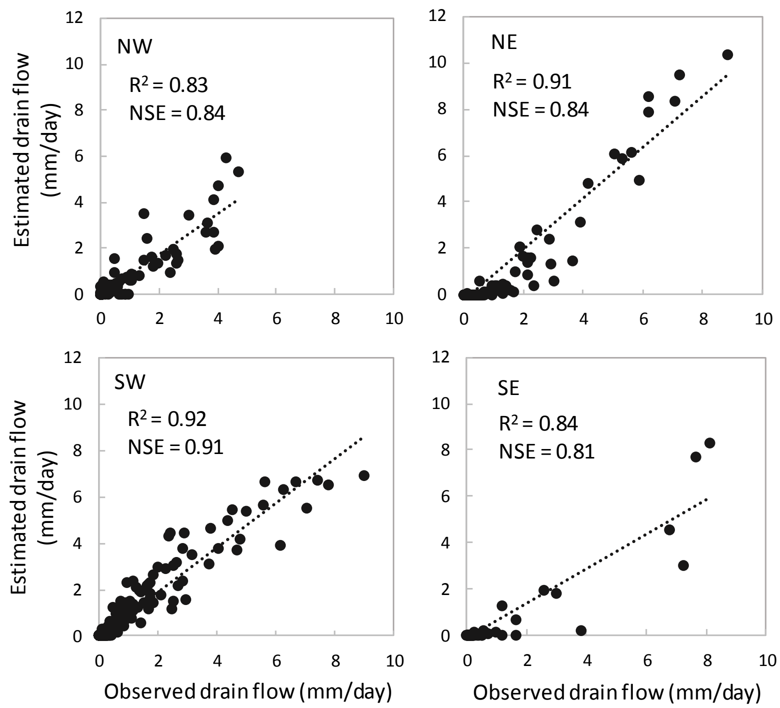

Figure 3-10. Estimated daily drain flow versus observed drain flow and regression coefficient (R^2) and Nash-Sutcliffe Efficiency (NSE) values for each quadrant for the validation year (2016).

Predicted and observed drain flow were also compared on a monthly basis to determine whether the relationship predicts drain flow more accurately in some months than others (Fig. 3.11). This figure indicates the differences between the total monthly values of predicted and observed drain flow including months when both observed and predicted values were available for all days. In some months, there was a complete drain flow dataset at least in one of the years, however, there was not any year with observation data for October in the NE and for December in the SE quadrants. In general, months with higher flow had more disagreement between observed and predicted values specifically in the NW quadrant. Once again, due to the downstream flow restrictions in the outlet, backward flow occurred in this quadrant resulting in observed values that are lower than predictions. The highest difference was in the NW quadrant in June (2015) with around 36 mm over-prediction, which occurred during very high flow. In June 2015, total precipitation was 265 mm/month, while the 10-year mean precipitation for this month is only 135 mm/month. Backward flow occurred in this quadrant more than 5% of the times during this month, and the over-prediction indicates an error in the method when flow is restricted downstream. This could be addressed in future work by considering separately the periods when the pipes are pressurized in flow estimation by looking at the pressure transducers data (which is available only for some periods at this site).

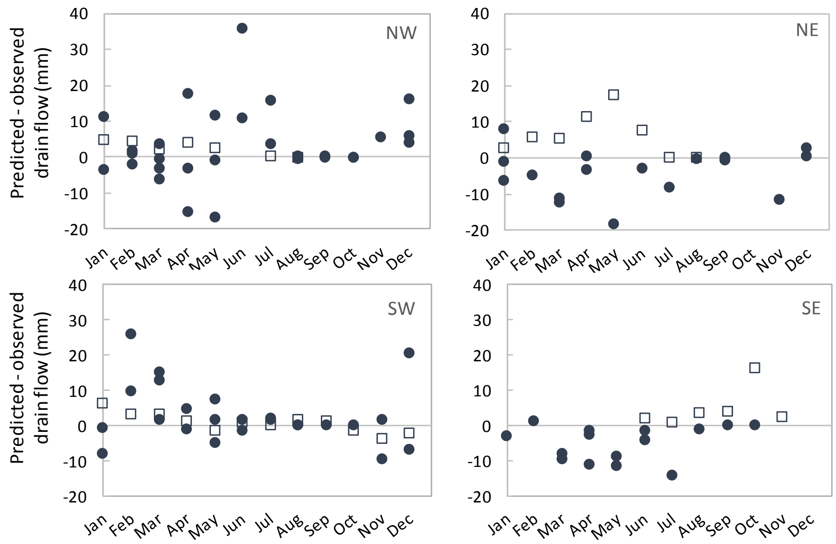

Figure 3-11. Comparison of observed and predicted monthly drain volume (mm) for months with complete drain flow datasets for both calibration and validation periods (Each dot represents a different year in the calibration period and square represents the validation period).

Overall, results indicate that calibrated K_e and the Hooghoudt equation did a good job in predicting daily drain flow from water table depth observations and this method can be used to estimate drain flow for the entire period of study. However, there are uncertainties associated with this method. The Hooghoudt equation is not a perfect representation of the physical system, and the high variability of K over the field limits precision. Measurement uncertainties related to the water table and drain flow values can lead to parameter uncertainty in calibration of the Hooghoudt equation. The flow meter had an accuracy better than ± 2% at all flow levels and ± 0.2% at higher flow (Krohne Waterflux 3070, 2016) and the uncertainty related to the water level sensors was ± 0.2% of the full range (Global Water WL-16, 2016). An additional source of uncertainty for this experimental field could be more due to the limitation caused by the drain outlet and backward flow that sometimes occurred, and the fact that this method is not able to take the backward flow into account.

3.4.3 Effect of controlled drainage on drain flow

Hourly drain flow was estimated for the whole range of water table heights from July 2006 through December 2016 using the calibrated K_e and the Hooghoudt equation. Estimated drain flow was combined with observations for the periods that drain flow were accurately measured at DPAC (2012 to 2016) and only estimates of drain flow were used for the former years of study (2006 to 2011). The remaining gaps in drain flow were then filled using linear regression equations and the filled flow record used to determine the effect of controlled drainage at this site by comparing annual and monthly drain flow in free and controlled quadrants.

Time series of 11-year annual drain flow and total annual precipitation are shown in Figure 3.12. Annual drain flow tended to follow the same trend for all quadrants except for the SE quadrant in 2008 when annual flow decreased while it increased in other quadrants. This could be due to the large number of missing days in this quadrant in the previous year (2007: 210 missing days) that has led to a higher flow value where the paired quadrant regression has been used for filling the gaps. Between the two free quadrants, the NE usually has higher flow compared to the SW quadrant that may be because of a neighboring farm that allowed water to enter towards the northeast section of the experimental field. Overall, annual drain flow followed the annual trends in precipitation; as total precipitation increases, annual flow increases.

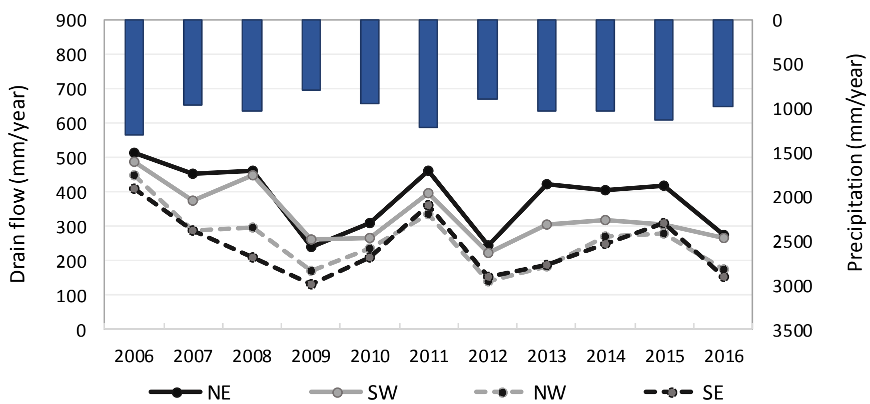

Figure 3-12. Time series of annual drain flow and total precipitation from 2006 to 2016.

Annual drain flow for both free quadrants was greater than controlled quadrants. The overall reduction in drain flow with CD over the 11-year period was 1182 mm. The 11-year averages of annual drain flow and flow rate for each quadrant are given in table 3.6. The average annual drain flow of the two free and the two controlled quadrants was also calculated and compared for each year. The results showed that the average annual drain flow of controlled quadrants was lower than free quadrants in all years between 14% to 49%. This reduction is comparable to other findings reported in the literature as Adeuya et al. (2012) found a 15% to 24%

decrease in annual drain flow with CD from a field in Indiana. Similarly, reductions of 18% to over 85% in the average annual flow with CD have been reported in the review by Skaggs et al. (2012a), which included results from the Illinois, Iowa, North Carolina and Ohio states and also Sweden and Ontario. More recently, Williams et al. (2015) also reported 8 to 34% reduction in the annual flow with CD from a site in Ohio.

Table 3-6. Mean (2006-2016) flow rate and annual drain flow for 11 years.

Quadrant	Average flow rate (mm/day)	Average annual flow (mm/year)
NE	1.07 ± 0.27*	381 ± 97
SW	0.92 ± 0.23	331 ± 84
NW	0.69 ± 0.29	256 ± 89
SE	0.73 ± 0.49	241 ± 90

* Mean ± standard deviation

The 11-year average of monthly drain flow (Fig. 3.13) indicates the seasonal changes in drain flow. As expected, during the months that drainage was controlled, monthly drain flow is greater in free quadrants than controlled. In other months such as May, June, July, October and November the average flow in controlled quadrants is more similar to the free quadrants. In these months, the height to which the outlet was raised in the control structure was lower than other months of control or no management was done at that time and all quadrants were freely drained. This relatively higher flow in controlled quadrants during the months that all quadrants were freely drained or the outlet was not raised as high as other months, again, indicates the effectiveness of the controlled drainage in reducing monthly flow.

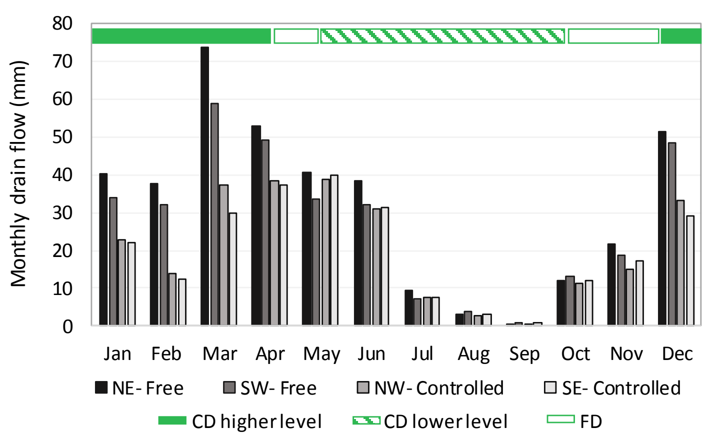

Figure 3-13. The average of complete observations of monthly drain flow for 10 years of study (from 2006 to 2016). CD higher level is when the outlet is raised to 0.9 m and the lower level is when the outlet is raised to 0.6 m above the drain.

3.5 Conclusions

This study explores how variation in hydraulic conductivity (K) with depth within field sites affects the observed relationship between midpoint water table height above drain and drain flow. This clarifies interpretation of field results and demonstrates that the Hooghoudt equation may still be applicable, even when field data does not show the classic parabolic curve. With this understanding, this study demonstrates that drain flow can be estimated from the Hooghoudt equation using water table depth measurements.

Examination of the shape of the water table height above drain (m) – drain flow (q) relationship under various K profiles showed that the Hooghoudt equation can be linear or parabolic depending on the selected K profile. Drain flow estimated from water table height using the layered K profile and the Hooghoudt equation compared well to observed flow in both calibration and validation periods, suggesting that this method could be used to fill in or extend the incomplete drain flow records when water table depth measurements are available. Using this method, together with linear regression for the remaining gaps, a long-term drain flow record for a controlled drainage (CD) experiment at the Davis Purdue Agriculture Center was used to evaluate the impacts of CD on drain flow. In the controlled drainage quadrants, annual flow was 14 - 49% lower than free drainage. The annual flow reductions ranged from 67 mm/year to 200 mm/year over the 11-year study period. In the future, these filled data sets will be used to evaluate the effect of CD on the nutrient losses through subsurface flow. The long record of continuous drain flow will help to better evaluate the effects of CD on water quality and allow for a better understanding of the annual and seasonal changes in both the hydrological and environmental impacts of CD.

3.6 Acknowledgements

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CHAPTER 4. NITRATE AND PHOSPHORUS TRANSPORT THROUGH SUBSURFACE DRAINS UNDER FREE AND CONTROLLED DRAINAGE

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4.1 Abstract

Controlled drainage (CD) is a structural conservation practice in which the drainage outlet is managed in order to reduce drain flow volume and nutrient loads to water bodies. The goal of this study was to evaluate the potential of CD to improve water quality for two different seasons and levels of outlet control, using ten years of data collected from an agricultural drained field in eastern Indiana with two sets of paired plots. The Rank Sum test was used to quantify the impact of CD on cumulative annual drain flow and nitrate-N and phosphorus loads. CD plots had a statistically significant (at 5% level) lower annual drain flow (eastern pair: 39%; western pair: 25%) and nitrate load (eastern pair: 43%; western pair: 26%) compared to free draining (FD) plots, while annual soluble reactive phosphorus (SRP) and total phosphorus (TP) loads were not significantly different. An ANCOVA model was used to evaluate the impact of CD on daily drain flow, nitrate-N, SRP and TP concentrations and loads during the two different periods of control. The average percent reduction of daily drain flow was 68% in the eastern pair and 58% in the western pair during controlled drainage at the higher outlet level (winter) and 64% and 58% at the lower outlet level (summer) in the eastern and western pairs, respectively. Nitrate load reduction was similar to drain flow reduction, while the effect of CD on SRP and TP loads was not significant except for the increase in SRP in one pair.

These results from a decade-long field monitoring and two different statistical methods enhance our knowledge about water quality impacts of CD system and support this management practice as a reliable system for reducing nitrate loss through subsurface drains, mainly caused by flow reduction.

4.2 Introduction

Subsurface drainage is a necessary water management practice in agricultural fields with naturally poorly drained soil, however, it contributes to water quality issues. Studies suggest that nitrate loss through subsurface drainage is the main source of nitrate in surface water (David et al., 1997; Jaynes and Colvin, 2006) and a leading cause of hypoxia in regions such as the northern Gulf of Mexico (Goolsby et al., 1999 and Rabalais et al., 2001). Phosphorus (P) can also be transported through drainage systems in dissolved and particulate forms (King et al., 2015) and preferential flow appears to be a frequent mechanism of P transport into subsurface drains (Stamm et al., 1998). Phosphorus loads through subsurface drains are much lower than nitrate loads, which has led to less attention to this loss pathway, but recent studies have shown the importance of P lost through subsurface drainage (King et al., 2015; Kleinman et al., 2015; Lam et al., 2016; Van Esbroeck et al., 2017). For example, Smith et al. (2015) reported that 49% of soluble P and 48% of total P losses from fields in the St. Joseph River Watershed in northeastern Indiana occurred via subsurface discharge.

Many approaches have been suggested in the literature to mitigate water quality issues caused by subsurface drainage. Among these, controlled drainage (CD) is a structural conservation practice in which the drainage outlet elevation is managed in order to reduce drain flow volume and nutrient loads to water bodies. (Evans et al., 1995; Fausey 2004; Frankenberger et al., 2006; Singh, et al., 2007; Adeuya et al., 2012; Gunn et al., 2015; Williams et al., 2015a). A comprehensive comparison between controlled and free draining systems from 13 experimental field studies at 7 different locations (USA: North Carolina, Ohio, Iowa, Indiana, Illinois; Canada: Ontario; and Sweden) by Skaggs et al. (2012) indicated a broad range of reductions from 18% to over 85% in average annual drain flow and from 18% to 79% in annual nitrate loss via drainage under CD. In some of these studies, denitrification has been found to lower the nitrate-N concentrations in the subsurface outflow when drainage was controlled (Kliewer and Gilliam, 1995 and Tan et al., 1998). However, in most studies, the significant decrease in nitrate loads has been shown to be a result of reduction in drain flow rather than the reduction in nitrate-N concentrations (e.g., Wesström and Messing, 2007; Adeuya et al., 2012, Lavaire et al., 2017).

From a synthesis analysis based on 17 measured field studies and 11 modeled studies, Ross et al. (2016) found that CD reduced annual drain flow by 46% and annual nitrate loads by 48%. Ross et al. (2016) additionally reported a 57% reduction in soluble P loads and a 55% reduction in total P loads with CD, based on only a few studies available in the literature at that time. Nash et al. (2015) found that CD decreased soluble P load in the subsurface flow by 80% in a claypan soil in Missouri due to both a decrease in soluble P concentration and reduced drain flow.

Although field studies on the effect of CD on drain flow and nitrate loss through subsurface drainage have been ongoing for decades, most have been conducted for a period of less than 5 years. There is also variability in the performance of CD in the literature and a wide range of changes in drain flow and nitrate loads with CD has been reported from different experimental sites. This suggests more studies are still required to provide a complete understanding of nitrate and P transport from agricultural fields to surface water bodies under different weather conditions, soil types, cropping systems and drainage designs over a long-term period. In addition to variability among sites, the design and statistical analysis used to assess CD effects have also varied, which may add to the apparent variability in results.

This paper reports results from a decade-long study in Indiana. Having ten years of drain flow and nitrate-N concentrations and five years of SRP and TP concentrations allows a statistical analysis of the cumulative annual impact of CD, in addition to the common paired field statistical analysis of daily values. This study also includes P transport through subsurface drains. Unlike nitrate, only a few studies have quantified the impacts of CD on P concentrations and loads via subsurface drains. In addition, this study evaluates the water quantity and quality impacts of CD during winter (high outlet level control period) versus summer (low outlet level control period), which has not been emphasized in previous studies. The overall goal of this study was then to evaluate the potential of CD to improve water quality, using ten years of data collected from an agricultural drained field in eastern Indiana. Specific objectives were to:

1- Assess the impact of CD on annual drain flow and nutrient (nitrate-N, SRP and TP) loads;
2- Quantify the relative influence of changes in drain flow versus changes in concentration on reductions in load due to CD;
3- Evaluate the impact of CD during periods of high outlet level control (winter) and low outlet level control (summer).

4.3 Materials and methods

4.3.1 Site description

The controlled drainage experimental site for this study is field W at Davis Purdue Agricultural Center (DPAC) located in eastern Indiana. Field W is relatively flat (slope < 1%), with 0.16 km^2 (39-acre) total area, divided into four plots, northwest (NW), southwest (SW), northeast (NE), and southeast (SE) with areas ranging from 3.5 ha to 3.7 ha (Fig. 4.1). The four soil series at the site range from very poorly to somewhat poorly drained, with a small portion of moderately well drained series. The subsurface drainage system was installed in September 2004, with 10-cm (4 inch) laterals having an approximate depth of 1 m and spacing of 14 m (Utt, 2010), resulting in a drainage intensity of 1.1 cm day^{-1} and drainage coefficient of 1 cm day^{-1}. Drainage in the SE and NW plots was controlled at two different levels during some periods depending on the season (Fig. 4.2), while the SW and NE were allowed to drain freely. This field has been in a corn-soybean rotation since 2011 and in continuous corn before that, and was managed using chisel-plow tillage in the fall and field cultivator tillage in the spring during the study period. Nitrogen (N) and phosphorus (P) fertilizers were applied at different rates prior to and after planting corn (Table 4.1). Phosphorus was also applied prior to soybean planting in two of the three soybean years. The rate and timing of fertilizer applications were uniform for all plots and were based on Purdue Extension recommendations. Further details of the site management and data are available in Abendroth et al. (2017).

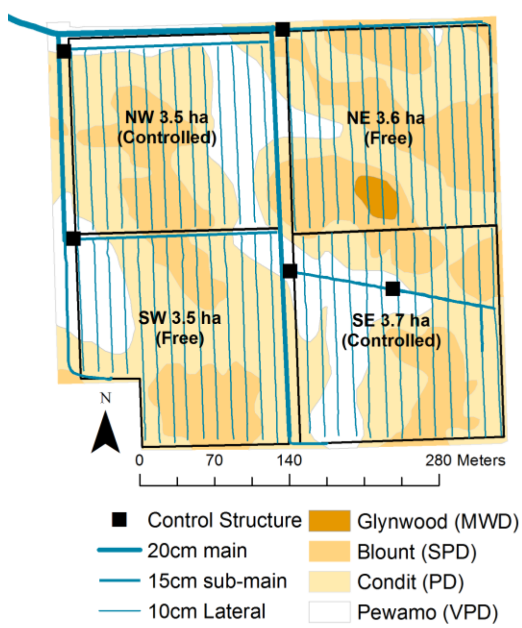

Figure 4-1. Map of Field W at Davis Purdue Agricultural Center with soil type, subsurface drain location and control structure location (MWD: moderately well drained; SPD: somewhat poorly drained; VPD: very poorly drained).

Table 4-1. Cropping sequence and fertilizer application dates and rates for the study period

Year	Crop	Application date (nitrogen or phosphorus rate in kg ha^{-1})								
		N Appl 1	N Appl 2	N Appl 3	N Appl 4	Total N	P Appl 1	P Appl 2	P Appl 3	Total P
2007	Corn	May-3 (41)	May-30 (206)	Oct-10 (26)	…	273	May-3 (16)	Oct-10 (53)	…	69
2008	Corn	Apr-28 (41)	Jun-17 (202)	…	…	243	Apr-28 (16)	…	…	16
2009	Corn	May-22 (34)	Jun-9 (200)	…	…	234	…	…	…	…
2010	Corn	Jan-5 (25)	Apr-19 (35)	Jun-5 (234)	Oct-5 (17)	311	Jan-5 (53)	Apr-19 (15)	Oct-5 (35)	103
2011	Soybean	…	…	…	…	…	…	…	…	…
2012	Corn	Feb-13 (22)	Apr-23 (36)	May-25 (201)	…	259	Feb-13 (46)	Apr-23 (14)	…	60
2013	Soybean	Mar-21 (18)	…	…	…	18	Mar-21 (38)	…	…	38
2014	Corn	Apr-24 (18)	May-8 (36)	Jun-1 (218)	…	272	Apr-24 (37)	May-8 (14)	…	51
2015	Soybean	…	…	…	…	…	…	…	…	…
2016	Corn	Apr-26 (33)	Jun-2 (210)	…	…	243	Apr-26 (13)	…	…	13

4.3.2 Operational strategy of controlled drainage

Drainage was controlled at different levels during winter and summer (non-growing and growing seasons). The drainage outlet was raised to 10 cm below the ground surface after harvest, sometime between November and December, remained at that level through early to mid-April each year (winter, high-level) and was lowered to the drain depth a few weeks before planting. The outlet was raised to 40 cm below the ground surface after spring fieldwork (late May to early June) through the end of September (summer, low-level). This analysis distinguished the effects of CD during higher-level control (HL) and lower-level control (LL). The dates when the outlets were raised and lowered and the height to which they were raised were similar in most years (Fig. 4.2) except for 2012 (drought) and 2015 (management error) when the drainage outlet was never lowered to the drain depth.

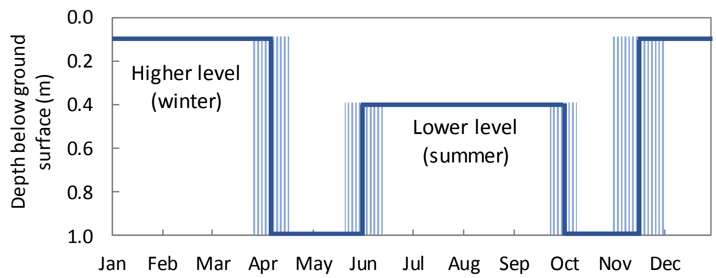

Figure 4-2. Depth of outlet below the ground surface at control structure and the outlet control date ranges.

4.3.3 Drain flow measurements combined with estimations

Drain flow has been measured using electromagnetic flow meters (Krohne Waterflux 3070) since 2012. Prior to that, drain flow monitoring was unreliable but water table was more consistently measured using pressure transducers (Global Water WL-16) installed in observation wells located at the midpoint between two drains in each plot. Therefore, drain flow was estimated using the Hooghoudt equation and water table depth measurements for each hour for which water table measurement was available from January 2007 through December 2016, in a method described in Saadat et al. (2018). Estimated drain flow was combined with observations for the periods that drain flow was measured (2012 to 2016) in order to fill in the gaps. Due to missing values in the water table observations, gaps remained in the drain flow dataset, therefore, linear regression equations of the flow observations from one plot against a paired plot with the same treatment (free or controlled drainage) were used to fill the majority of the missing values (Saadat et al., 2018). After drain flow was filled using the methods explained above, small gaps (54 days over 10 years) still remained in the dataset when there was no measured water table depth or measured flow from the paired plot (Fig. 4.3). These gaps were mostly during the summertime when drain flow was relatively low compared to other times of the year, and days with missing drain flow were not included in the analysis.

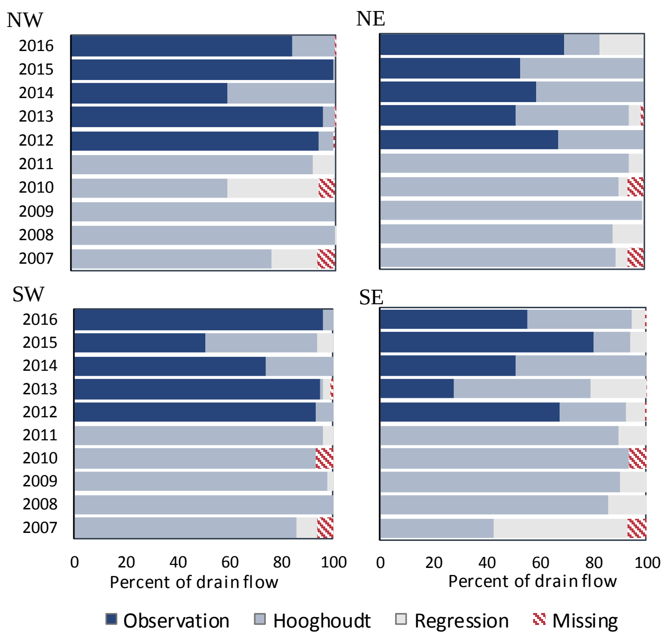

Figure 4-3. The percentage of measured drain flow, estimated drain flow from the Hooghoudt equation, estimated drain flow from the linear regression equation and missing days per year from 2007 to 2016.

4.3.4 Sampling and concentration interpolation method

Automated water samplers (ISCO) were used to draw samples from the drainage outlet flow of each plot, downstream of the control structure. Samples were collected every hour when flow was present except during winter, and combined into weekly composite samples varying in length from twice a week to biweekly. During the winter, water samples were collected manually to avoid freezing problems, approximately every week whenever flow was present. A total of 2130 samples were collected during the study period from which 355 were manually collected grab samples. Samples were kept frozen until analysis and then analyzed on a SEAL Analytical AQ2 auto-analyzer to be tested for nitrate+nitrite-N (referred to subsequently as nitrate-N), soluble reactive phosphorus (SRP) and total phosphorus (TP) according to US EPA methods.

Daily nitrate-N, SRP and TP concentration values needed for the load calculations were estimated using linear interpolation, because water quality samples were collected weekly or less frequently. The composite samples from the automated samplers were considered representative of all days since the previous sample was collected. For manual samples collected in winter, daily concentration was calculated using linear interpolation between data points.

After estimating daily concentrations, daily loads were calculated by multiplying the daily drain flow by estimated daily concentrations.

4.3.5 Statistics and data analysis

In order to evaluate the effect of the CD system statistically, the two eastern and western plots were paired due to their similar water table recession characteristics, as was also done by Saadat et al. (2017). Two separate analyses were conducted with different purposes. The Rank Sum test was used for annual discharge and load, while daily discharge and load and weekly concentration were analyzed using ANCOVA.

4.3.5.1 Annual flow and loads using Rank Sum test

Annual drain flow and nutrient loads were determined by summing the daily flow and loads for each plot for each calendar year from 2007 to 2016 for drain flow and nitrate loads and from 2012 to 2016 for SRP and TP loads. The annual reduction in the CD plots was tested using the non-parametric Rank Sum test (Bradley, 1968). The magnitude of change for the Rank Sum test was estimated with the Hodges-Lehmann estimator (Hodges and Lehmann, 1963), which is the median of all possible paired differences between annual flow/load in the FD plots and CD plots.

4.3.5.2 Daily/weekly values using ANCOVA test

The analysis of covariance (ANCOVA) was used to determine the impacts of CD on daily drain flow, daily nutrient loads and measured nutrient concentrations (approximately weekly). For this model, two fields (control and treated) and two periods (calibration and treatment) are required (Clausen and Spooner, 1993). In this study, the treatment period was further divided into two periods, higher-level (HL) control and lower-level (LL) control periods (Fig. 4.2). Linear regression of the free-draining periods (calibration) was used to test the significance of the relationship between paired observations. If the relationship was significant, the regressions in the treatment period were tested to determine the significance of the difference between the calibration and treatment periods.

The general equation used for the ANCOVA model was:

$$Y = \beta_0 + \beta_1 X + \beta_2 Z_1 + \beta_3 Z_2 + \beta_4 Z_1 X + \beta_5 Z_2 X + e \quad (1)$$

where the dependent variable (Y) is daily drain flow or daily loads or weekly concentrations from the CD site, the independent variable X is daily drain flow or daily loads or weekly concentrations from the FD site, Z is a binary independent variable with Z_1 and Z_2 equal to 1 during HL and LL treatment periods, respectively. $\beta_{0\text{-}5}$ are regression coefficients provided by the model and e indicates the error term.

The standard ANCOVA model assumes that the regression residuals are independent and normally distributed. Due to the high frequency sampling needed to determine drain flow and load, residuals were not independent. The error term in equation 1 was modeled with an autoregressive moving average model (ARMA) to model the autocorrelation in the data. The ARMA error term for the linear regression model can be written as:

$$e_t = \sum_{i=1}^{p} \varphi_i \left(e_{t-i}\right) + \sum_{j=1}^{q} \theta_j \varepsilon_{t-j} + \varepsilon_t \qquad (2)$$

where e_t is the residual (error) from the model at time t, ϕ is the autoregressive parameter, θ is the moving average parameter, p is the order of the autoregressive part, q is the order of the moving average part and ε_t is a normally distributed random error term.

A similar method has been used in other water quality studies, for example to address the correlation in nitrate and TP concentrations data by fitting a linear regression model with an autoregressive (AR) term to the data (Fields et al. 2005; Gassman et al. 2010). However, this is the first study to use the ANCOVA model with ARMA error term to quantify the water quality impacts of CD. Statistical tests were accomplished using R and the maximum likelihood estimator was used to estimate the regression models with ARMA error term. The significance of the slope and intercept for the free draining and controlled period regression lines was tested at the $\alpha = 0.05$ and $\alpha = 0.1$ level to determine the impacts of CD on drain flow, nutrient concentrations and loads in different treatment periods.

4.4 Results and discussion

4.4.1 Drain flow

4.4.1.1 Annual

Drainage volume during free-draining periods was similar in FD (NE and SW) and CD (SE and NW) plots, whereas it was lower in CD plots when drainage was controlled (Fig. 4.4). In all years, total annual drainage volume was lower in the two CD plots compared to the FD plots, including the dry years (2009, 2012, and 2016) when drainage volumes were less than 300 mm y^{-1}, and wet years (2008 and 2011) when total drained water was above 450 mm y^{-1} in the FD plots. The number of days of control varied each year depending on precipitation and field conditions, water table level, planting and harvesting dates, and crop growth stage.

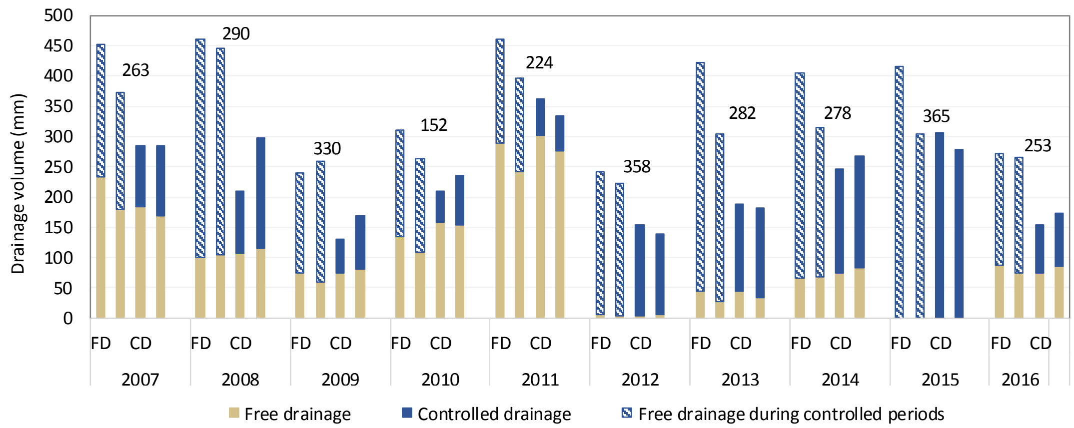

Figure 4-4. Drainage volume in free-draining and controlled periods for FD and CD plots and number of days in each year that drainage was controlled.

The Rank Sum test results for the annual drain flow (Table 4.2) indicated that the difference in drainage volume between the FD and CD sites was statistically significant in both pairs. The median drainage volume was lower in CD sites by 150 mm y^{-1} and 82 mm y^{-1} in the eastern and western pairs, respectively. The range of individual annual differences was between 88-251 mm y^{-1} in the eastern pair and 25-149 mm y^{-1} in the western pair. Also given in table 4.2 is the range of drainage volume for all plots over 10 years of study period (2007 to 2016).

Table 4-2. Ranges of annual drain flow for each plot over 10 years and the rank sum test results on annual flow (difference = FD – CD).

Plot	Range of annual flow (mm y^{-1})	Pair	p-Value	Range of diff. (mm y^{-1})	Median diff. (mm y^{-1})
NE	240 - 462	Eastern	0.007	88 - 251	150*
SE	131 - 362				
SW	224 - 446	Western	0.049	25 - 149	82*
NW	140 - 334				

* Statistically significant difference between FD and CD sites at α=0.05

4.4.1.2 Daily

The ANCOVA analysis showed that the relationship between drain flow in the FD and CD plots for the free-draining period was significant (shown in Fig. 4.5a for the eastern pair). The relationships in treatment periods (LL: Fig. 4.5b; and HL: Fig. 4.5c) were then compared to the free draining period. The modeled relationships for eastern and western pairs (Fig. 4.6) indicate clearly that CD decreased daily flow under LL (summer) treatment, and even more under HL (winter). This figure also indicates that the mass difference between free-draining period and treatment periods was greater at higher drain flow indicating the greater effectiveness of CD in wet conditions. The statistical comparison of these linear regression models with the ARMA residual term (Table 4.3) indicated that both the intercept and slope were significantly different between the free-draining period and the two treatment periods, meaning that drain flow was significantly affected by CD at both levels (summer and winter).

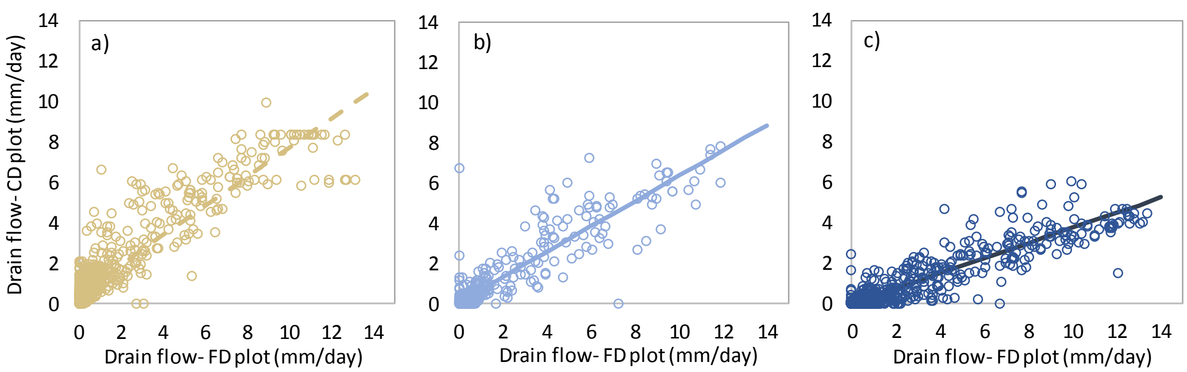

Figure 4-5. Observations and modeled relationships between daily drain flow in the FD and CD plots during three periods: a) free draining, b) LL control, and c) HL control in the eastern pair.

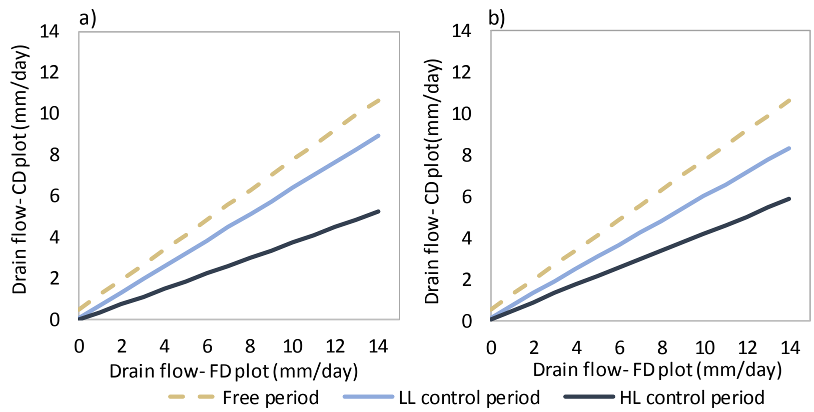

Figure 4-6. Modeled relationships between daily drain flow in the FD and CD plots during three periods: free draining, HL control, and LL control periods in a) eastern and b) western pairs.

Table 4-3. Linear model equations with ARMA errors for free draining and two different treatment periods.

Pair	ARMA errors	Free draining Intercept, β_o	Free draining Slope, β_1	HL-CD Intercept, β_2	HL-CD Slope, β_4	LL-CD Intercept, β_3	LL-CD Slope, β_5
Eastern	(2, 2)	0.47	0.73	-0.05*	0.38*	0.03*	0.63*
Western	(2, 2)	0.52	0.72	0.07*	0.41*	0.15*	0.58*

* Statistically significant difference between FD and CD sites at α=0.05

The effect of CD on daily drain flow during each treatment period was quantified by comparing cumulative observed flow in the CD sites with cumulative flow predicted using the regression equations for each period, (Table 4.4) to take into account the pre-treatment differences in flow between the two FD and CD plots. CD reduced drain flow during HL control (winter) between 58-79% in the eastern and 43-73% in the western pair, with the average reduction of 138 mm and 111 mm per period in the eastern and western pair, respectively. The LL control period (summer) had a similar average reduction compared to HL, with the average reduction of 63 mm in the eastern and 59 mm in the western pair. The reduction was greater during the HL control period (around 2/3rd of the annual reduction) in part because it occurs during the time of the year that drain flow is higher.

Table 4-4. CD impacts on cumulative drain flow during treatment periods

Treatment period	Pair	Avg. control days per year	Predicted [a] (mm)	Observed (mm)	Avg. diff. [b] (mm)	Avg. reduction [b] (%)	Reduction range [c] (%)
HL control	Eastern	142	200	62	138	68	58-79
	Western		190	79	111	58	43-73
LL control	Eastern	128	108	45	63	64	30-85
	Western		115	55	59	58	27-83

[a] Determined from calibration period (free) regression equation by applying observed values from treatment period of control (free-draining) field.

[b] Average of differences or reductions over 10 years.

[c] Range of percent reduction over 10 years.

4.4.2 Nitrate and phosphorus concentrations

Measured nitrate-N concentration ranged from 0.3 mg L^{-1} to 28.3 mg L^{-1} in all plots over 11 years (shown for the eastern pair in Fig. 4.7). Also shown is the daily drain flow for this pair indicating the effect of CD on reducing drain flow.

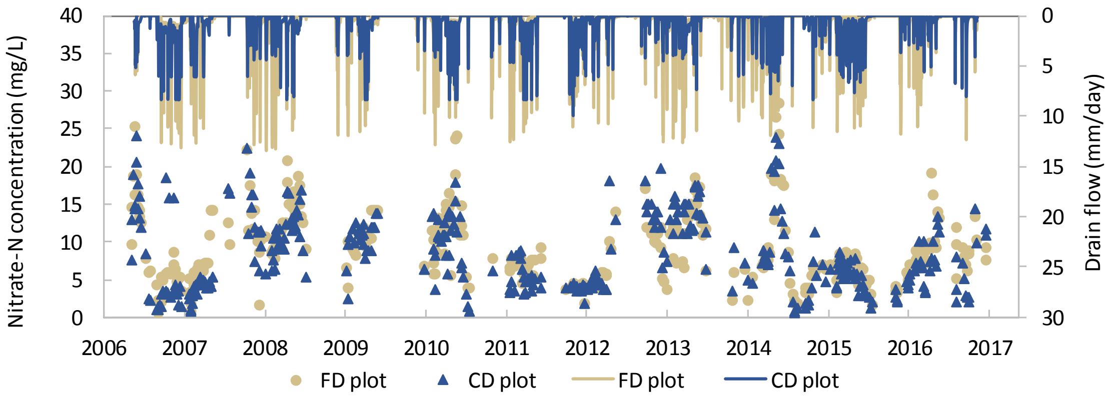

Figure 4-7. Measured nitrate concentrations and daily drain flow at the eastern pair for FD and CD plots.

Measured phosphorus concentrations mostly ranged from 0.002 mg L^{-1} to 0.5 mg L^{-1} for SRP and from 0.004 mg L^{-1} to 1 mg L^{-1} for TP among all sites, shown in Figure 4.8 for the eastern pair. Two high values in both SRP and TP concentrations may have been due to measurement errors or fertilizer application that reached the sampling point. These high values only occurred in the CD fields during the free draining or LL control periods, and for the purpose of interpolation were removed from the dataset.

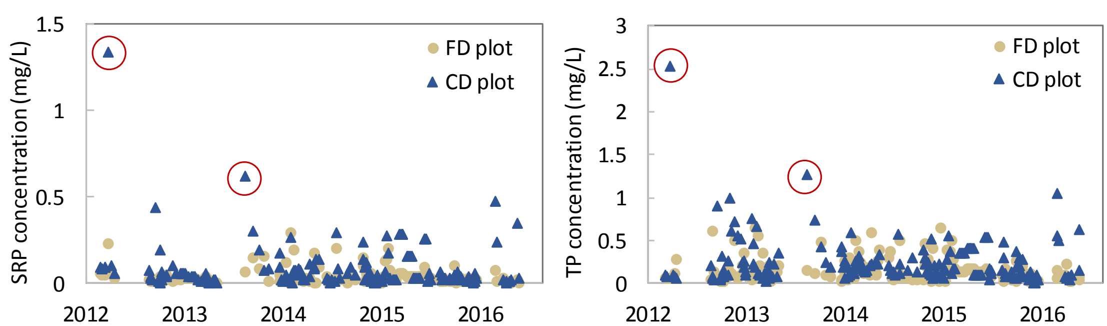

Figure 4-8. Measured SRP and TP concentrations at eastern pair with circles indicating the outliers.

Yearly averages of nitrate-N concentrations over the study period (Fig. 4.9) showed that all four plots had a similar range in the mean yearly nitrate concentrations and there were not considerable differences between the FD and CD sites. The mean concentration was 8.4 mg L^{-1} in FD and 8.5 mg L^{-1} in CD plots. The yearly mean concentrations of SRP and TP in CD plots tends to be higher than in the FD plots as shown in Figure 4.9. SRP had a mean concentration of 0.04 mg L^{-1} in FD plots and 0.06 mg L^{-1} in CD plots and the mean concentration of TP was 0.15 mg L^{-1} and 0.22 mg L^{-1} in FD and CD plots, respectively.

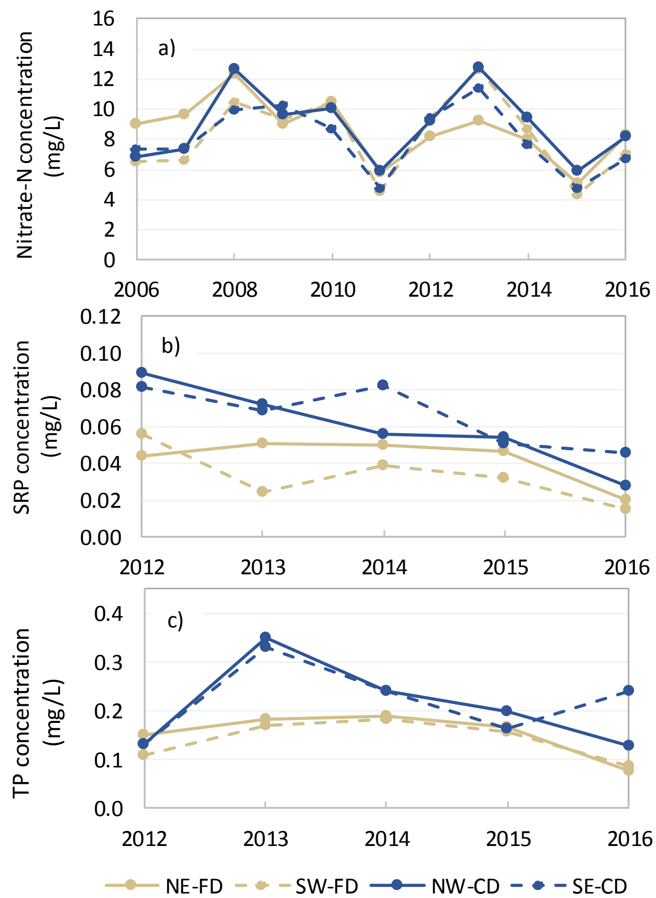

Figure 4-9. Yearly averages of concentrations for 11 years for nitrate-N (a) and for 5 years of SRP (b) and TP (c).

The ANCOVA analysis using linear models with the ARMA residual term was conducted only on each pair in which the relationship between sites was significant in the calibration period (Table 4.5). The calibration period models were statistically significant for nitrate concentration in both pairs, for SRP in the eastern pair, and for TP in the western pair. The linear models for concentrations indicated that there were no significant differences between the slope or the intercept of concentration regressions in any of the treatment levels for nitrate or TP, but the intercepts were significantly different in the SRP concentration regressions for both HL and LL control periods (Table 4.5, Fig. 4.10).

Table 4-5. Linear model equations with ARMA errors for free draining and two different treatment periods.

Variables	Pair	ARMA errors	Free draining		HL-CD		LL-CD	
			Intercept, β_o	Slope, β_1	Intercept, β_2	Slope, β_4	Intercept, β_3	Slope, β_5
Nitrate Conc.	Eastern	(1, 1)	0	0.772	1.398	0.927	0.767	0.82
(mg L^{-1})	Western	(1, 2)	2.185	0.758	3.621	0.626	2.166	0.794
SRP Conc.	Eastern	(1, 0)	0	1.002	0.043**	1.25	0.048**	0.712
(mg L^{-1})	Western	…..	…..	…..	…..	…..	…..	…..
TP Conc.	Eastern	…..	…..	…..	…..	…..	…..	…..
(mg L^{-1})	Western	(1, 0)	0.137	0.18	0.188	0.575	0.143	0.314

** Statistically significant difference between FD and CD sites at α=0.05
* Statistically significant difference between FD and CD sites at α=0.1

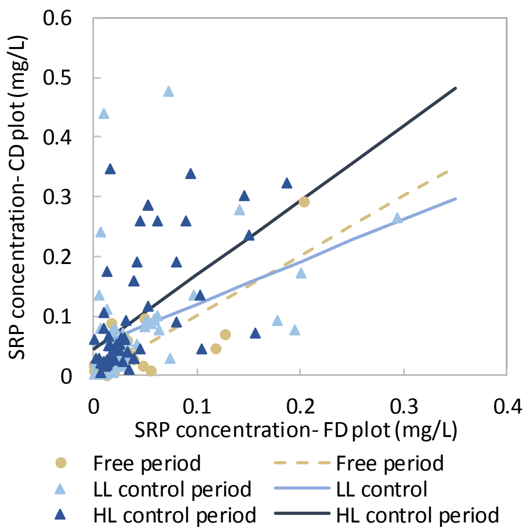

Figure 4-10. Observations and modeled relationships between SRP concentrations in the FD and CD sites during the calibration and treatment periods in the eastern pair.

The effect of CD on nutrient concentrations during each period was determined by comparing the average observed concentration from treatment periods in CD sites with the average predicted concentration using the regression equations (Table 4.6). Nutrient concentrations increased in most years with CD at HL and LL in both pairs, however, as stated above (Table 4.5), only the increase in SRP concentrations were statistically significant.

Table 4-6. CD effects on average nutrient concentration.

Treatment period	Pair	Predicted [a] (mg L^{-1})	Observed (mg L^{-1})	Avg. diff. [b] (mg L^{-1})	Reduction range [c] (mg L^{-1})
Nitrate conc.					
HL control	Eastern	6.68	9.39	-2.71[d]	-5.8 to -0.9
	Western	9.13	9.42	-0.29	-2.7 to 1.6
LL control	Eastern	8.27	8.98	-0.7	-2.9 to 1.9
	Western	9.85	10.62	-0.77	-2.9 to 1.1
SRP conc.					
HL control	Eastern	0.037	0.088	-0.05	-0.032 to -0.072
LL control	Eastern	0.042	0.096	-0.054	-0.161 to -0.004
TP conc.					
HL control	Western	0.172	0.294	-0.122	-0.250 to 0.014
LL control	Western	0.16	0.213	-0.053	-0.233 to 0.043

[a] Determined from calibration period (free) regression equation by applying observed values from treatment period of control (free-draining) field.
[b] Average of differences over 11 years.
[c] Range of reduction over 11 years (2006-2016) for nitrate and 5 years (2012-2016) for phosphorus.
[d] Negative values mean that controlled drainage had higher concentrations than free drainage

4.4.3 Nitrate and phosphorus loads

4.4.3.1 Annual loads

The 10 years of annual nitrate-N loads from this site are among the longer datasets quantifying losses from subsurface-drained fields. The mean annual nitrate-N load in the free draining (FD) fields at this site was 30 kg ha^{-1} y^{-1}. Nitrate-N median loads of 37 kg ha^{-1} y^{-1} for wet years and 14 kg ha^{-1} y^{-1} for dry years were reported by Christianson and Harmel (2015) for sites with conservation tillage in a review of around 1300 subsurface drainage nutrient load site-years of data. The mean TP load measured from FD plots was 0.54 kg ha^{-1} y^{-1}, which is in the range of 0.4 - 1.6 kg ha^{-1} y^{-1} reported by King et al. (2015). This phosphorus load was mainly in particulate form, with only 28% (0.15 kg ha^{-1} y^{-1}) as SRP. These results were consistent with Bottcher et al.

(1981) findings and indicated the significance of preferential flow in P transport through subsurface drains.

Time series of the annual nitrate-N, SRP and TP loads (Fig. 4.11) indicate that throughout the study period, nitrate load was lower in CD plots, while the pattern was not constant for the SRP and TP. The mean annual nitrate-N load was 30 kg ha^{-1} y^{-1} in FD plots and 19 kg ha^{-1} y^{-1} in CD plots. The Rank Sum test results on annual loads (Table 4.7) also indicated that the differences in nitrate-N load between FD and CD sites were statistically significant in both pairs. The median nitrate load was lower in CD sites by 12.8 kg ha^{-1} y^{-1} and 7.1 kg ha^{-1} y^{-1} in the eastern and western pairs, respectively. The differences in SRP and TP loads between FD and CD plots were not statistically significant. The smaller sample size (5 years) for SRP and TP could also weaken the power of the Rank Sum test. The sample size was larger for nitrate (10 years).

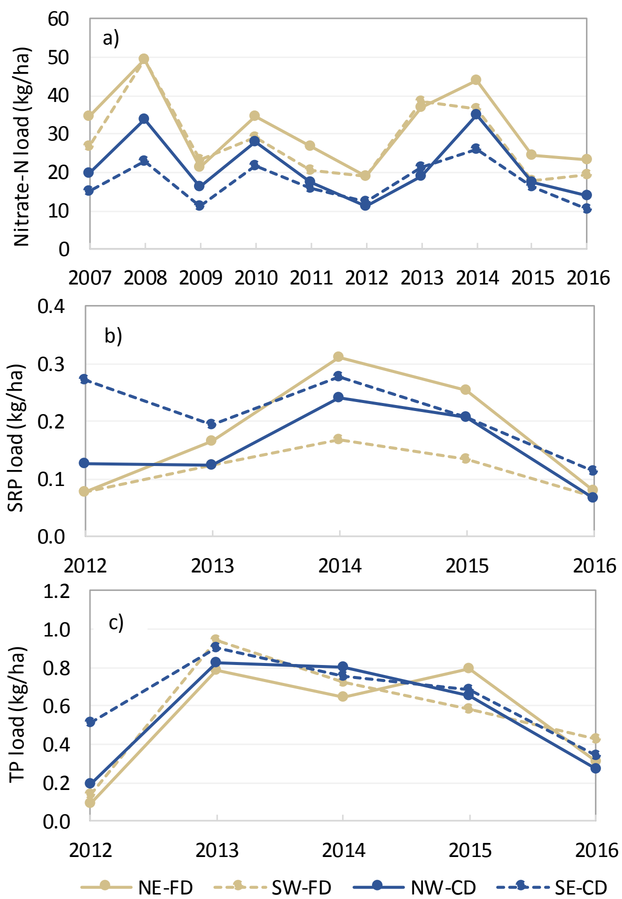

Figure 4-11. Annual load for 10 years of (a), and 5 years of SRP (b) and TP (c).

Table 4-7. Rank Sum test results on annual loads (difference = FD – CD).

Pair	Nitrate-N load		SRP load		TP load	
	p-Value	Median diff. (kg ha^{-1} y^{-1})	p-Value	Median diff. (kg ha^{-1} y^{-1})	p-Value	Median diff. (kg ha^{-1} y^{-1})
Eastern	0.003	12.8*	0.55	-0.033	0.69	-0.11
Western	0.049	7.1*	0.55	-0.047	1	-0.05

* Statistically significant difference between FD and CD sites at α=0.05

4.4.3.2 Daily loads

The linear regression models of nutrient loads in calibration period between the FD and CD plots were significant for both pairs meaning that the relationships between FD and CD sites can be statistically tested during the treatment periods. Results indicated that for nitrate load, both the intercept and slope were significantly different between the free draining period and the two treatment periods (Table 4.8). Visual comparison of these linear models (Fig. 4.12) indicated a reduction in nitrate load with HL-CD (winter), in both pairs, and with LL-CD (summer), in the western pair. The relationships were more complex and not consistent for P loads in both pairs. The linear models on SRP and TP loads also showed a reduction in the slope in the eastern pair but an increase in the western pair, especially at the LL-CD, even though some of these differences were not statistically significant (Table 4.8). Figure 4.12 also indicated that the mass difference between free-draining period and treatment periods was greater at higher loads, which coincide with periods of greater drain flow (Fig. 4.6).

Table 4-8. Linear model equations with ARMA errors for nutrient loads for three periods: free draining, HL control and LL control periods

Variables	Pair	ARMA errors	Free draining		HL-CD		LL-CD	
			Intercept, β_o	Slope, β_1	Intercept, β_2	Slope, β_4	Intercept, β_3	Slope, β_5
Nitrate load (kg/ha)	Eastern	(3, 2)	0.029	0.602	-0.004**	0.377**	0.000**	0.652**
	Western	(1, 2)	0.036	0.789	0.006**	0.419**	0.015**	0.611**
SRP load (kg/ha)	Eastern	(2, 0)	0	0.85	0	0.749	0	0.443**
	Western	(1, 3)	0	0.381	0	0.46	0	0.560*
TP load (kg/ha)	Eastern	(2, 0)	0.002	0.474	0.001	0.334**	0.001	0.436
	Western	(1, 1)	0.001	0.402	0.001	0.425	0.001	0.613**

** Statistically significant difference between FD and CD sites at α=0.05
* Statistically significant difference between FD and CD sites at α=0.1

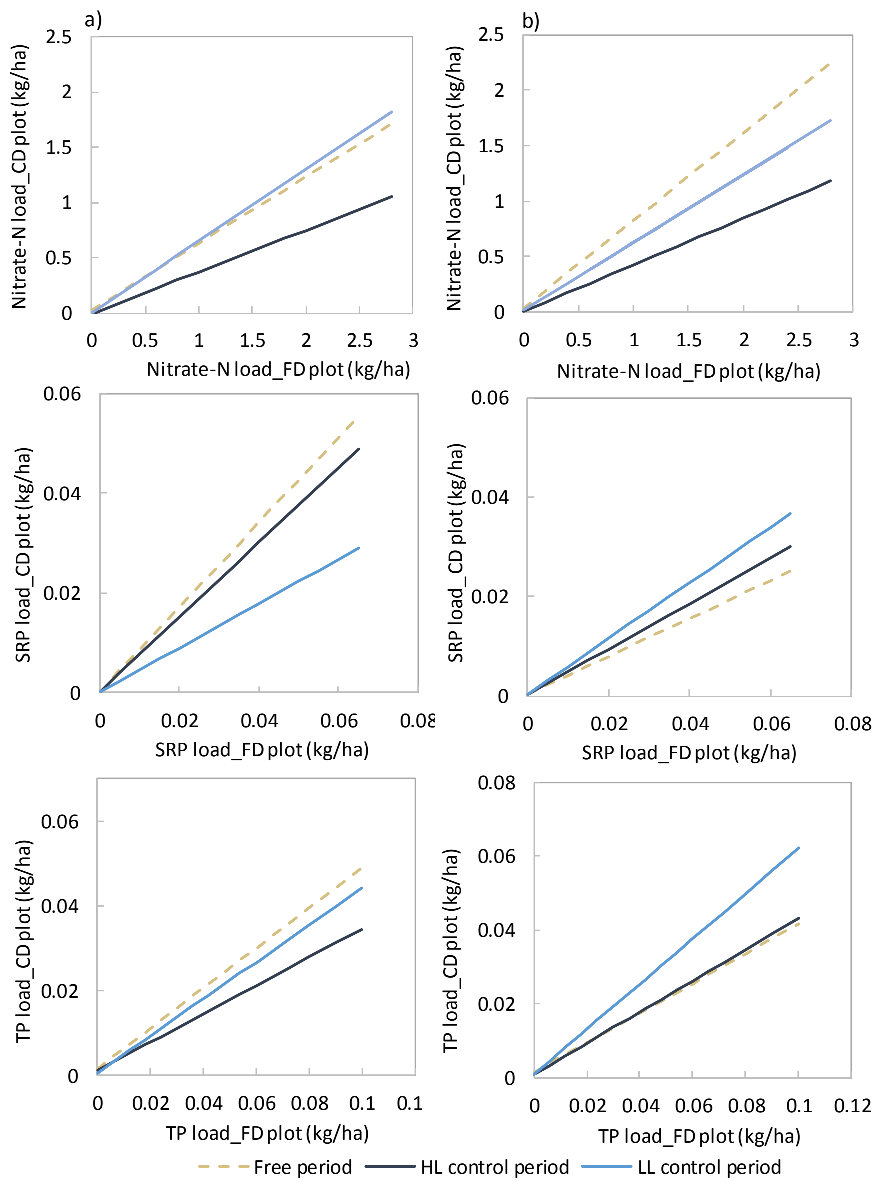

Figure 4-12. Modeled relationship between nitrate-N, SRP and TP loads in the FD and CD sites during the calibration and treatment periods for the a) eastern and b) western pair.

Comparing cumulative observed values from treatment periods in CD sites with cumulative predicted values, obtained from the regression equations, indicated that HL-CD reduced nitrate load between 33% to 74%, during this period, in the eastern pair and between 33% to 60% in the western pair with the average reduction per period of 7.8 kg ha^{-1} and 9.3 kg ha^{-1} in the eastern and western pairs, respectively (Table 4.9). The amount of reduction was lower with LL-CD compared to HL-CD, with the average reduction of 3.5 kg ha^{-1} and 4.3 kg ha^{-1} found in the eastern and western pairs, respectively. The effect of CD on P loads varied more over years compared to nitrate, and the impact of CD during HL vs. LL was not similar between the two pairs (Table 4.9).

Table 4-9. Effects of CD on cumulative nutrient loads during treatment periods.

Treatment period	Pair	Predicted [a] (kg ha^{-1})	Observed (kg ha^{-1})	Avg. diff. [b] (kg ha^{-1})	Avg. reduction [b] (%)	Reduction range [c] (%)
Nitrate-N load						
HL control	Eastern	12.9	5.1	7.8	59	33 to 74
	Western	16.2	6.9	9.3	57	33 to 69
LL control	Eastern	7.8	4.3	3.5	54	-9 to 75
	Western	10.3	6	4.3	48	-3 to 76
SRP load						
HL control	Eastern	0.07	0.085	0.016	18	-39 to 52
	Western	0.065	0.052	0.013	10	-27 to 49
LL control	Eastern	0.092	0.057	0.035	19	-117 to 81
	Western	0.066	0.075	-0.01	0	-84 to 78
TP load						
HL control	Eastern	0.352	0.247	0.105	37	-25 to 75
	Western	0.321	0.244	0.077	27	-23 to 66
LL control	Eastern	0.3	0.149	0.151	49	17 to 87
	Western	0.259	0.204	0.055	29	-52 to 76

[a] Determined from calibration period (free) regression equation by applying observed values from treatment period of control (free-draining) field.
[b] Average of differences or reduction over 10 years.
[c] Range of percent reduction over 10 years (2007 to 2016) for nitrate-N and over 5 years (2012-2016) for SRP and TP loads.

4.5 Discussion

Comparison of cumulative annual subsurface drainage over ten years of study indicated that CD plots resulted in a statistically significant lower drainage volume than FD plots, with the median difference of 150 mm y^{-1} (39%) and 82 mm y^{-1} (25%) in the eastern and western pairs, respectively. During this decade, precipitation ranged from 800 mm y^{-1} to 1213 mm y^{-1}. The cumulative annual analysis method avoids the difficulty of accounting for the transition times immediately after changes in outlet level as well as the potential lateral seepage from CD to neighboring FD fields, but does not account for the pre-treatment differences explicitly. However, cumulative drain flow was 7% and 13% higher in CD plots during free draining periods over the study period in the eastern and western pairs, respectively, confirming that the FD plots were not yielding more drainage than CD in general.

The ANCOVA model results, which take into account the pre-treatment differences between FD and CD fields, indicated an average reduction of 138 mm per period (68%) and 111 mm per period (58%) in the eastern and western pair, respectively, when the outlet was at the higher level (HL-winter) and 63 mm per period (64%) and 59 mm per period (58%) average reduction when the outlet was at the lower level (LL-summer). These results quantify for the first time the greater reduction in drain flow at higher control levels (winter), where there is sufficient drain flow to control. The ANCOVA model indicated an average reduction in annual drain flow of 48% in the eastern and 42% in the western pair when both HL and LL treatment periods, as well as free draining periods were included in the annual reduction calculation.

The higher reductions (48% and 42%) from the ANCOVA statistical method compared to the cumulative annual method (39% and 25%) are likely due to the pre-treatment differences in plot hydrology, which are not taken into account in the cumulative method. Drain flow reductions found through both statistical methods, were higher than the 15-24% reduction found by Adeuya et al. (2012) from two fields in in northwestern Indiana. Differences in control levels, soil characteristics, weather conditions and whether drainage was controlled in the growing seasons or only non-growing seasons can lead to variability in the results from different site studies. In addition to variability among sites, the design and statistical analysis used to assess the CD impacts have also varied among previous studies, which may add to the apparent variability in results. Variations in drain flow reduction with CD obtained from the DPAC site using different statistical methods suggest the need for a method which is applicable to most sites and is reliable for comparing water quality impacts of CD from different site studies.

The impacts of CD on nitrate-N, SRP and TP concentrations were more complex and not consistent across pairs. The averages of nitrate-N, SRP and TP concentrations were slightly higher in controlled periods, however, they were not significantly different from the free-draining periods except for the SRP in the eastern pair. The non-significant difference in nitrate concentrations was similar to what the majority of other studies have reported (Fausey, 2005; Adeuya et al., 2012 and Williams et al., 2015a), although some have observed lower nitrate concentration in CD fields. The increase in SRP was comparable to observations from Valero et al. (2007), Feser et al. (2010), and Tan and Zhang (2011).

Nutrient concentrations in the soil are affected by different factors such as water table level, soil organic matter, and temperature. CD raises the water table levels leading to anaerobic soil conditions, which could be expected to increase denitrification and therefore, lower nitrate concentration in drain flow. Yet, other factors such as cold temperature can reduce the amount of denitrification, especially when high-level control mostly occurs during the wintertime. Stanford et al. (1975) found that denitrification rate decreases almost ten times as the temperature drops from 10 °C to 5°C. During the five years for which soil temperature data were available (2011-2016) 88% of the drain flow during HL controlled periods occurred when the average soil profile temperature was below 10 °C. Therefore, denitrification was unlikely to have significantly reduced the nitrate concentration, and this is reflected in the similarity of concentrations in FD and CD. P concentration in drainage may also increase under CD due to anaerobic soil conditions which facilitate the movement of P in the soil (McDowell et al., 2001). This may explain the higher SRP concentrations during controlled periods in the eastern pair.

Comparing actual annual values of nitrate-N load from FD and CD plots over 10 years showed a median reduction of 12.8 kg ha^{-1} y^{-1} (43%) and 7.1 kg ha^{-1} y^{-1} (26%) in CD plots in the eastern and western pairs, respectively. The ANCOVA results also indicated that CD at HL decreased nitrate-N load by 7.8 kg ha^{-1} (59%) in the eastern and by 9.3 kg ha^{-1} (57%) in the western pair. The average reduction with CD at LL was 3.5 kg ha^{-1} (54%) in the eastern and 4.3 kg ha^{-1} (48%) in the western pairs. The average reductions in nitrate load were comparable to the flow reductions found in this study (HL control: 68% in the eastern pair and 58% in the western pair; LL control: 64% in the eastern pair and 58% in the western pair) indicating that the main factor contributing to nutrient load reductions in CD sites was still the reduction in drain flow, as concentrations were slightly higher (not significant) in CD fields.

The effects of CD on phosphorus (P) load varied more over years compared to nitrate, because there were more variations in the P concentrations than nitrate. The annual SRP and TP loads were greater in CD plots than FD plots in some years and were lower in other years, but based on the Rank Sum test results, the differences were not statistically significant. Similar to the Rank Sum test results, the ANCOVA model also indicated inconsistent results over years and across plots. Changes in SRP and TP loads were not proportional to the flow reduction, implying the importance of P concentration that is affected by many factors other than the water table level set by CD. CD impact on SRP and TP loads quantified in the current study were not similar to the values reported in the literature, such as the 80% reduction in soluble P loads observed by Nash et al. (2015), and the 40% to 68% reduction in soluble P found by Williams et al. (2015a). P concentration and load are spatially and temporally variable and dependent on a combination of factors, including soil characteristics, drainage design, management practices, and climate variables (King et al., 2015). Additionally, in the studies conducted by Nash et al. (2015) and Williams et al. (2015a), the statistical approach was different than the current study and may contribute to the variability in the results.

An uncertainty analysis on annual nitrate-N and SRP load estimates at field scale indicated that estimated annual SRP loads tended to be less precise and more biased than nitrate-N loads estimates (Williams et al., 2015b). In order to be able to make any conclusion about the effects of CD on P load, more frequent concentration measurements are required, especially during storm events, since storm discharge can significantly affect the P transport (McDowell et al., 2001; Schelde et al., 2006; Zimmer et al., 2016). Williams et al. (2015b) recommended a higher sampling frequency for SRP compared to nitrate-N to yield the same accuracy in annual SRP and nitrate-N loads estimates. In addition to the uncertainties acknowledged in the literature related to the sampling frequency and type (e.g., Birgand et al., 2010; Jiang et al., 2014; Williams et al., 2015b), there are some uncertainties related to drain flow dataset for the DPAC site due to combining measured drain flow with estimated values. Detailed explanation of uncertainties associated with measured and estimated drain flow for this site is given in Saadat et al. (2018). Beside the measurement methods, load estimation using interpolation can introduce uncertainty into the annual load estimates. However, Williams et al. (2015b) found that linearly interpolating the concentration combined with continuous flow (used in the current study) resulted in the best balance between accuracy and precision for annual nutrient load estimates.

In general, the difference between HL-winter and LL-summer control emphasizes the impacts of control level and season on drain flow and therefore, water quality benefits of CD systems. The HL-winter control during the non-growing season provided about 70% of annual water quality benefits and the other 30% was obtained by LL-summer control during the growing season. Furthermore, variation over years at one control level can be due to the different duration that drainage was controlled in each year, and whether it was a wet or dry year.

Despite the reduction found in drain flow with CD in this and other studies, the question of the fate of the retained water, and whether the nitrate reduction at the outlet of the subsurface drainage system extends to the watershed scale, remains unresolved. For example in Illinois, Lavaire et al. (2017) found only a 10% reduction in drain flow and nitrate loads with CD when two neighboring fields were both controlled, to avoid lateral seepage to the FD neighboring field. Future research that quantifies the effect of CD on other potential flow paths such as surface runoff and lateral seepage, denitrification occurring in these pathways and the potential for increasing nitrous oxide emissions, would enable a more complete characterization of the impact of CD.

4.6 Conclusions

This study evaluated the potential of controlled drainage (CD) to improve water quality using ten years of field measurements with two different statistical methods. The first method was a cumulative annual analysis that avoids the difficulty of accounting for the transition times as well as the potential lateral seepage between the neighboring fields, and the second was a rigorous statistical method that accounts for the pre-treatment relationship between the CD and FD fields, and explicitly models dependence in the data, allowing daily data to be used in the analysis.

- Results using two separate statistical methods indicate that CD significantly decreased drain flow and nitrate load through subsurface drainage in both eastern and western pairs. Nitrate concentrations were not significantly affected by CD, indicating that load reduction was mainly due to drain flow reduction.
- The CD impacts on phosphorus (P) loads were more complex and inconsistent over years and across plots but overall during 5 years, CD decreased P loads. P concentrations were not significantly different, except for a significant increase in SRP concentration with CD in the eastern pair.
- The higher level of outlet control during the non-growing season (winter) provided about 70% of annual water quality benefits while the lower level used during the growing season (summer) provided about 30%. By quantifying the magnitude of the increased impact, this study clarifies the added water quality benefit of controlling drainage at a higher level, especially during the non-growing season.
- At both control levels, the effectiveness of CD was greater when more drain flow or load was present in the field. These results support the CD system as a reliable management practice for reducing nitrate loads from subsurface drains, mainly due to the reduction in flow.

Future research should investigate phosphorus impacts through event-based sampling, and the effect of CD on other flow paths such as surface runoff and lateral seepage to fully characterize the impact on nutrient loads at the watershed scale.

4.7 Acknowledgements

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CHAPTER 5. SURFACE PONDING AND RUNOFF GENERATION IN A SEASONALLY FROZEN DRAINED AGRICULTURAL FIELD

5.1 Abstract

Surface runoff is an important component of pollutant transport in poorly-drained agricultural fields that is often very poorly quantified. The overall goal of this study was to determine the frequency and extent of occurrence, as well as understanding the generation process of ponding and runoff using the observation and simulation results. Three different methods were used to determine the generation process of surface ponding and runoff and the frequency of incidence in a seasonally frozen subsurface drained agricultural field in eastern Indiana. Surface ponding was monitored with a timelapse camera at the edge of the field for three years. Using photo evidence of ponding together with the water table depth measurements, the potential of predicting surface ponding from water table depth measurements was examined. A 10-year simulation was conducted using DRAINMOD to predict surface ponding and runoff. The model was calibrated and validated by comparing model predictions of subsurface drainage and water table depth with field observations.

The simulation results indicated that surface runoff only contributed 1-10% of annual water export from the field whereas subsurface drainage contributed between 26 to 45%, annually. On average, 45% of simulated ponding occurred during the cold season (December-March) indicating the importance of soil freeze/thaw condition and snow accumulation. However, DRAINMOD was not able to predict the snow accumulation and melt accurately during parts of the cold season, resulting in drain flow under-prediction and runoff over-prediction. Results from both simulations and observations indicated that all of the ponding events were generated as a result of a saturation excess process rather than an infiltration excess. The generation of ponding at this field was only observed above a water table threshold of 35 cm. Therefore, in the absence of direct evidence of ponding, water table depth measurements above the defined threshold provided a simple alternate for saturation excess ponding events.

5.2 Introduction

Surface runoff from agricultural fields is a pathway by which sediments, nutrients, pesticides and associated pollutants are carried away and deposited into surface waters such as lakes, rivers, wetlands, etc. Therefore, understanding and quantifying this pathway is critical for implementing appropriate management practices to reduce sediments and associated pollutants. Conservation practices are used in agricultural fields to reduce non-point source pollutants entering surface waters. However, they might have unintended consequences. One suggested practice for mitigating water quality issues caused by subsurface drainage in agricultural fields is controlled drainage. Controlled drainage is a water management practice that manages the drainage outlet elevation in order to reduce drain flow and nitrate loss through subsurface drainage, however it has the potential to worsen water quality through increasing surface runoff that is difficult to quantify because of the large uncertainty in surface runoff and ponding. Quantifying surface runoff is also important to acquire the precise water balance and understand the hydrological connectivity of surface and subsurface flow. This understanding allows identification of runoff and subsurface flow contribution to nitrate and phosphorus loss through agricultural fields, which has been a major concern for decades (e.g. Thomas et al., 1992; Turner and Rabalais, 1994; Sharpley et al., 2015).

Processes generating surface ponding and runoff and their frequency of incidence in subsurface drained agricultural fields are poorly understood. Although quantifying phosphorus loss through surface runoff in drained agricultural fields has been a research focus for many years (Sharpley et al., 1994), the conditions under which surface ponding and runoff can occur as well as the distinctions between ponding and runoff have not received enough attention in the literature. Not every ponding event leads to surface runoff leaving the field, particularly in depressional topography or with high surface roughness. Accumulated water can infiltrate back into the soil before leaving the field and contribute to the subsurface flow or get lost through evaporation. Therefore these processes need to be studied separately, although generated by similar processes.

Surface ponding and runoff may occur due to infiltration excess (Horton, 1933), when the rainfall intensity exceeds the infiltration capacity of the soil, or it may occur due to saturation excess, when the water table level rises to the ground surface (Van Te Chow et al., 1988). Both types can occur in an agricultural watershed throughout the year, depending on climate conditions and infiltration capacity of the soil. For instance, in poorly drained soils in the Netherlands saturation excess runoff appeared to be more common in winter while infiltration excess predominated in summer (Kwaad, 1991; Ritsema et al., 1996). Additionally, during wintertime, frozen ground can reduce infiltration rates, and as a result, surface ponding and runoff from rainfall or snowmelt can increase (Shanley and Chalmers, 1999; Cade-Menun et al., 2013).

In many field studies of subsurface drained fields, the non-growing season was found to be a critical time for phosphorus loss through surface runoff in regions with cold climates, particularly where significant snow cover and winter thaws are experienced (e.g. Van Esbroeck et al., 2016; Coelho et al., 2012; Goulet et al., 2006). Therefore, it is important to have an estimation of surface ponding and runoff in all seasons. However, monitoring surface ponding and runoff is challenging, especially in cold season. Among the studies that included winter observations of surface runoff, many have experienced data gaps due to freezing and equipment malfunction (e.g. Goulet et al., 2006; Jamieson et al., 2003). Thus hydrological models are often used to simulate surface runoff.

DRAINMOD (Skaggs, 1978) is one of the most widely used models developed for simulating the hydrology of a subsurface drained field. DRAINMOD is a field-scale, process-based hydrologic model which simulates the performance of agricultural drainage and related water management systems. It has been extensively tested and widely applied in many parts of the world for a wide range of agronomic and climatic conditions (e.g. Skaggs et. al., 1981; Fouss et. al., 1987; Cox et. al., 1994; Borin et al., 2000; Luo et al., 2001; Wang et al. 2006a; Ale e al., 2009).

DRAINMOD was modified in 2000 to reflect freeze and thaw processes, supporting its use in cold climates (Luo et al., 2000). In the modified version, soil temperature is predicted by numerically solving the heat flow equation. The infiltration rate is limited by the ice content in the soil profile when simulated soil temperatures are less than or equal to 0 °C. Snow melt is calculated using the degree-day method. Many researchers have used the modified version of the model in cold regions. For example, Wang et al. (2006b) found that the modified version performed better in winter months in Canada than the original model. Morrison et al. (2014) simulated the hydrology of an agricultural drained land in Canada using DRAINMOD and reported that during the snowmelt period, the model performed slightly better in predicting surface runoff than drain flow.

In this study, a 10-year simulation was conducted using DRAINMOD to predict surface runoff in a relatively flat and seasonally frozen subsurface drained agricultural field in eastern Indiana, and the results were compared with evidence of surface ponding and runoff from three years of field monitoring with a timelapse camera and ten years of measured water table depths at this field. This study explores the generation of ponding and runoff using field observations and model simulations with the following objectives:

1. Determine the frequency and the extent of surface ponding and runoff using three methods.
2. Understand the processes that generate surface ponding and runoff: infiltration excess or saturation.
3. Understand when and how the freeze/thaw processes influence on simulated surface ponding and runoff in DRAINMOD.

5.3 Methods

5.3.1 Site description

The southwest (SW) quadrant of Field W at Davis Purdue Agricultural Center (DPAC), a research farm in eastern Indiana (Fig. 5.1) was used for this study. The mean annual precipitation at this site was 990 mm over 10 years (2007-2016) with approximately 6% of the precipitation falling as snow. The mean monthly precipitation was highest in May and June and the mean snow fall was highest in January and February (Fig. 5.2). The 10-year mean temperature ranged from - 4.4°C in January to 22.6°C in June. The SW site is relatively flat (slope < 1%) with 3.5 ha area. The site consists of very poorly drained to somewhat poorly drained soil series. The subsurface drainage system at this site was installed in 2004 in an experiment to assess the impacts of controlled drainage on ground water recession rate (Saadat et al., 2017) and water and nutrient loss through subsurface drains (Saadat et al., 2018b). A more detailed description of this field can be found in these studies.

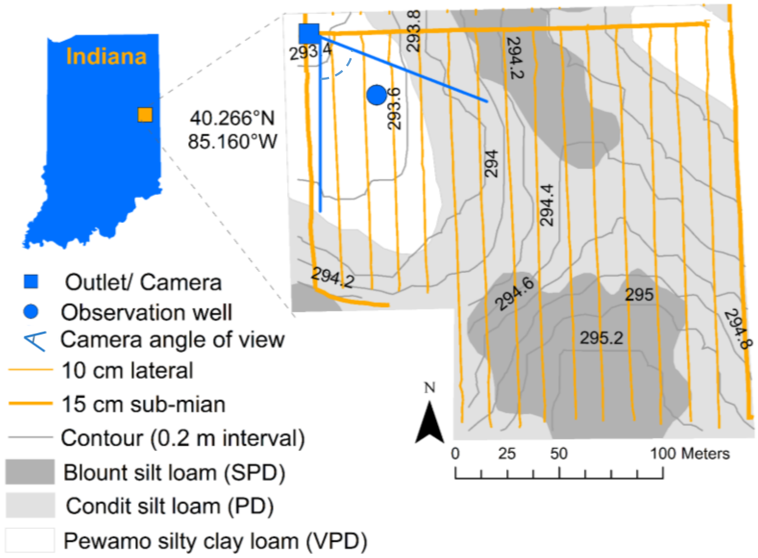

Figure 5-1. Map of SW quadrant of field W at DPAC (PD: poorly drained; SPD: somewhat poorly drained; VPD: very poorly drained).

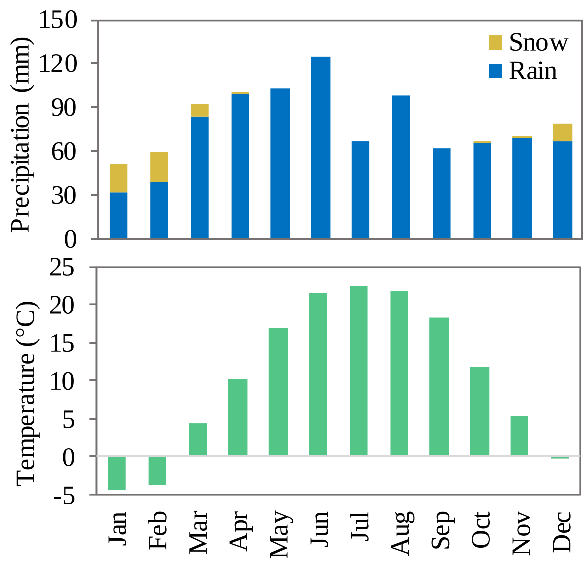

Figure 5-2. The mean monthly precipitation and temperature at DPAC over 10 years (2007-2016).

5.3.2 Field observations

Water table depth was measured throughout the study period (2007-2016) using an observation well located at the midpoint between two drains, 25 m from the outlet and 0.2 m higher in elevation (Fig. 5.1). The observation well was installed to a depth of approximately 2 m. A pressure transducer (Global Water WL-16) was used to measure water table level every hour. There were some uncertainties associated with the absolute water table elevation caused by water table sensor replacement during maintenance. Therefore, the recorded water table elevation was adjusted up or down by a fixed amount relative to the drain elevation during periods between maintenance activities based on the assumption that drains flow only when water table is above the drain. Details of this process are provided in Saadat et al. (2017). There were also some small gaps in water table depth measurements (Fig. 5.3), mainly during the summertime when water table level was often below the drain that were excluded from the analysis. The end-of-day water table depth was used as daily measurement.

Hourly drain flow was measured using an electromagnetic flow meter (Krohne Waterflux 3070) since 2012. Prior to flow meter installation, and during the missing periods, drain flow was estimated using a theoretical drainage equation (Hooghoudt) and water table depth measurements. A daily drain flow record was then constructed from drain flow measurements combined with drain flow estimated using the Hooghoudt equation, together with linear regression equations as described fully in Saadat et al. (2018a). Small gaps still remained in drain flow records, mainly during the summertime when drain flow was relatively low compared to other times of the year (Fig. 5.3) and were excluded from the analysis.

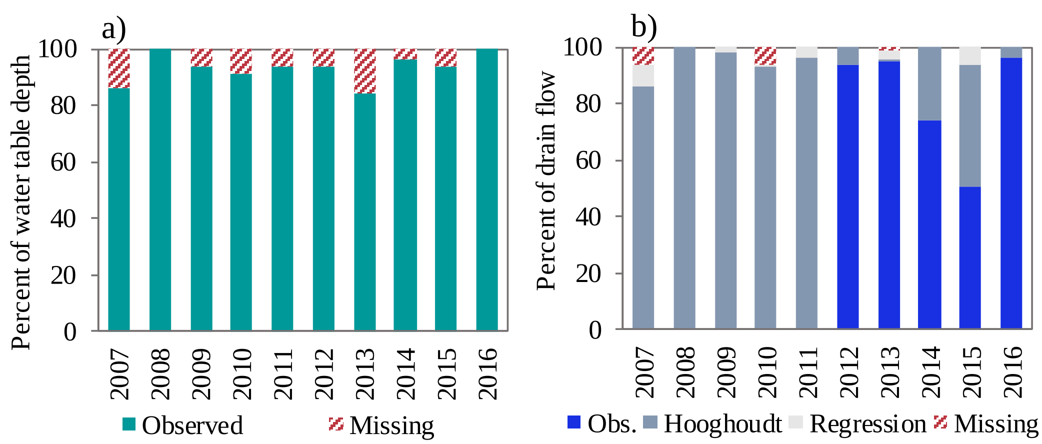

Figure 5-3. The percentage of a) observed and missing water table depth; b) observed, estimated and missing drain flow.

Soil temperature was measured at depths of 10, 20, 40, 60, and 100 cm using soil moisture and temperature sensors (Decagon 5TE (10 cm), 5TM (others)) beginning in June of 2011. Sensors were installed near the observation well (Fig. 5.1) in actively farmed areas, requiring that the 10 and 20 cm sensors being removed during tillage operations and replaced following planting.

Hourly wind speed and precipitation were measured at the on-farm weather station that was located on the western side of the field, close to the outlet (Fig. 5.1). A tipping bucket was used to measure liquid precipitation only, because it was not modified to measure solid precipitation. Daily precipitation (liquid and solid) as well as daily maximum and minimum air temperatures were measured at the National Climatic Data Center Coop Station (COOP: 122825, Farmland 5 NNW) located at DPAC. Precipitation data from the COOP station was used to supplement the on-farm measurements. Missing or erroneous data were supplemented by 30-minute wind speed, precipitation, solar radiation and air temperature from the Purdue automated station (https://iclimate.org/30min-purdue_automated/), located at DPAC.

In order to collect evidence of surface ponding and runoff, a timelapse camera was installed in December 2014 near the outlet to take photos from the field every hour during the daytime. The approximate angle of view and the location of the camera is shown in Figure 5.1. Two staff gages were made manually from 5-cm PVC pipes covered by colored tape, with each color representing 5 cm depth. These staff gages were installed in the field in the camera angle of view for a few months before planting and provided an indicator of ponding depth captured in the photos (Fig. 5.4).

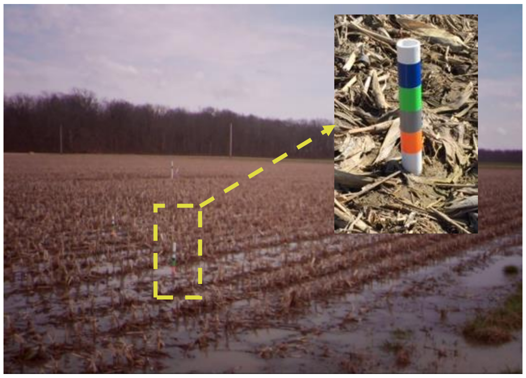

Figure 5-4. Staff gage installed in the camera angle of view for estimating ponding depth.

5.3.3 Surface ponding and runoff

Three different methods, two based on observations and one based on model simulations, were used to determine the frequency and extent of surface ponding and runoff. The first method was based on the hourly timelapse photos, the second used water table depth measurements along with photos; and simulation of surface ponding and runoff with the DRAINMOD model was the third method.

5.3.3.1 Timelapse photo processing strategies

A total of 13,000 hourly photos were collected from December 2014 to October 2017. Due to the camera angle being changed by strong winds, the field was not completely visible in photos from July to November 2016 and mid-January to early March 2017, therefore these photos were excluded from the analysis. Photos were then classified into five different categories based on the ponding depth and extent (Table 5.1, Fig. 5.5). The ponding classification was based on visual inspection of photos in addition to the approximate measurements obtained from the staff gauges that were installed in the field for part of the year (Fig. 5.4). In the cold season, the snowmelt ponding was identified if accumulated snow was melted and ponded on the ground. The classification of ponding for snowmelt events were similar to rain events. Using the ponding categories, a photo time series was generated for all times when photos were available for the field.

Table 5-1. Surface ponding categories and descriptions.

Category	Description
0	No ponding
1	Minor ponding, water visible but not connected
2	Moderate ponding, water connected up to height of furrows
3	Major ponding, water connected across furrows
4	Extreme ponding continues to the edge of the field, water connected across the field

Figure 5-5. Photo ponding classification.

5.3.3.2 Water table depth method

Water table depth (WTD) above the ground surface could be an indication of surface ponding in the field. However, the measurements only represented the water table level at the well location, and since this field is not completely flat, the water table level can vary across the field. Therefore, the photo time series was used to find a threshold for WTD above which there was evidence of ponding in the field. A threshold of 35 cm was then obtained (Fig. 5.6) and was used to indicate the timing, duration and frequency of ponding events in years in which photo evidence of ponding was not available.

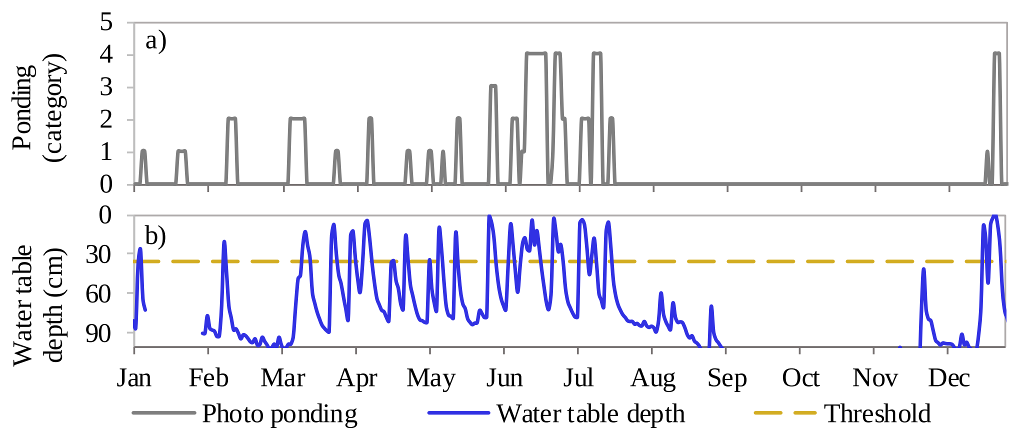

Figure 5-6. Surface ponding from photos (a) and water table depth measurements (b) in 2015.

5.3.3.3 DRAINMOD

DRAINMOD is a process-based model that can predict hydrologic variables including infiltration, subsurface drainage, surface runoff, evapotranspiration, vertical and lateral seepage, and water table depth in the soil profile on a daily, monthly or yearly basis (Skaggs et al., 2012). The basic relationship in the model is a water balance for a thin section of soil of unit surface area which extends from the impermeable layer to the surface and is located midway between lateral drains.

The Green-Ampt equation is used to predict infiltration and surface runoff is characterized by the depth of depression storage that must be filled before runoff can begin. In DRAINMOD, if the ponded water on the ground surface exceeds the maximum surface storage, surface runoff begins, otherwise the surface storage indicates the ponding depth that does not lead to runoff leaving the field.

When the profile is saturated and water is ponded on the surface, the drainage rate is calculated by equations developed by Kirkham (1957), otherwise, the steady-state Hooghoudt equation (Bouwer and van Schilfgaarde, 1963) is used to calculate drainage rate. Vertical and lateral seepage are simulated using Darcy's Law. A detailed description of the model can be found in Skaggs (1978).

5.3.3.3.1 Model inputs

Model inputs include weather, soil properties, site characteristics, drainage system parameters, inputs related to crop or other vegetation, and management factors such as timing and manipulation of drainage outlets, described in the following paragraphs.

Weather data inputs to DRAINMOD are hourly precipitation, maximum and minimum daily air temperatures and daily potential evapotranspiration (PET) values. The continuous hourly precipitation and daily maximum and minimum air temperature records (2007-2016) were generated for the DPAC site using measurements from the three different weather stations described in the weather data measurements. The daily PET was calculated with the Penman-Monteith equation using the on-site measured weather parameters such as short wave radiation and wind speed (Chiu C.M., 2013).

The drain depth, drain spacing, and drainage coefficient were based on knowledge of the drainage system. Soil survey and additional soil property measurements were used to estimate the depth and thickness of the restrictive layer as well as Piezometric head of aquifer. The equivalent depth from drain to impermeable layer and the Kirkham's coefficient were calculated based on the distance between drains and effective drain radius as well as distance between the drain and impermeable layer by an internal DRAINMOD subroutine (Table 5.2).

Table 5-2. Drainage system design parameters (surface and subsurface).

Drainage system design	Value
Drain depth from soil surface (cm)	97
Spacing between drains (cm)	1400
Drainage coefficient (cm/d)	1
Actual distance from surface to impermeable layer (cm)	200
Thickness of the restricting layer (cm)	200
Piezometric head of aquifer (cm)	200
Effective radius of drains (cm	0.51
Equivalent depth from drain to impermeable layer (cm)	59.16
Kirkham's coefficient	12.32

DRAINMOD requires the effective rooting depth over time that defines the zone from which water can be removed to supply ET. The corn effective rooting depths were estimated from a minimum of 3 cm to a maximum of 45 cm (Ale et al., 2009) based on a typical planting and harvest date at the SW field over the study period (Table 5.3). Although in three years during the study period soybean was planted (2011, 2013 and 2015), it was decided to parametrize the model based on the corn rooting depth. In DRAINMOD, crop growth in individual years does not affect simulated ET. The limiting water table depth was set to 30 cm and the lower limit of water content in root zone (0.27 cm^3/cm^3) was taken from the volumetric water content of the topsoil layer at 15000 cm tension (wilting point).

Table 5-3. Corn effective rooting depth distribution.

Month	Day	Root depth (cm)
1	1	3
6	5	9
6	19	18
7	25	31.5
8	15	40.5
9	8	45
9	28	40.5
10	12	35
10	19	27
10	20	3

Required soil property inputs to DRAINMOD are lateral saturated hydraulic conductivity and the volumetric water contents of the soil profile at tension values from 0 to 15000 cm (Table 5.4). The lateral saturated hydraulic conductivity was estimated for 3 soil layers using the Hooghoudt equation and the measured water table depth and drain flow, as described in Saadat et al. (2018a). On-site soil volumetric water contents measurements were available at 0, 3, 50, 100, 330, and 15000 cm tensions. These measurements were obtained from 648 soil samples which were collected in 2011, 2013 and 2015 at 4 depths from 3 different sub-plots with 3 replicates (Kladivko et al., 2014). For the top soil layer (0-50 cm), the averages of measured volumetric water contents of 0-10, 10-20, and 20-40 cm layers were used, while for the second layer (50-100 cm) the actual measured values from the 40-60 cm layer were used. For the third layer (below the drain), the volumetric water content values were estimated in the calibration process.

Table 5-4. Soil properties input.

Depth	Lateral K_s	Volumetric water content (cm^3/cm^3) at a given tension (cm)					
(cm)	(cm/h)	0	3	50	100	330	15000
0-50	2.9	0.43	0.43	0.38	0.37	0.36	0.27
50-100	0.8	0.42	0.42	0.41	0.40	0.39	0.26
100-300	0.4	0.46	0.45	0.42	0.40	0.39	0.26

These soil properties were also used in the DRAINMOD soil utility program to estimate unsaturated hydraulic conductivities, volume drained, upward flux, and Green-Ampt infiltration parameters versus water table depth.

DRAINMOD requires additional inputs in order to reflect the freeze/ thaw processes (Luo et al., 2000). The two soil thermal conductivity constants (TKA and TKB), which are used to calculate soil thermal conductivity as a function of soil water content, were obtained from an empirical model with three input parameters including saturated water content of 0.5 (cm^3/cm^3), volume fraction of organic matter content of 0.05, and thermal conductivity of soil solids (10 cal/cm.s.°C). The coefficients of computational depth function (a_z, b_z) were estimated using equation 1 (Luo. et al., 2000) by assuming a thermal damping depth of 4 m, where annual fluctuation of temperatures are damped out and the soil temperature is assumed constant below this depth (Table 5.5).

$$Z_{n+1} = Z_n + a_z \times b_z^{n-1} \qquad \text{(n=1, 2… 20)} \qquad (1)$$

where Z_n is the nodal depth from the soil surface (e.g. Z_1=0 at the soil surface). The constants a_z and b_z were calculated by trial and error in order to reach the Z_{21} of 4 m.

The soil temperature at the bottom of the profile was assumed to be equal to the long-term average air temperature (Penrod et al., 1958). The snow melt coefficient and the critical ice content above which infiltration stops were adjusted during the calibration process. Other soil temperature parameters were taken from Luo et al. (2000) (Table 5.5).

Table 5-5. Soil temperature input parameters.

Soil temperature parameters	Value
Soil thermal conductivity function- TKA	0.35
Soil thermal conductivity function- TKB	1.58
Computational depth function- a_z	2.42
Computational depth function- b_z	1.19
Soil temp at the bottom of the profile (ºC)	9
Snow melt coefficient (mm/d ºC)	3
Critical ice content above which infiltration stops (cm^3/cm^3)	0.4
Snow melt base temperature (ºC)	1
Snow/rain dividing temperature (ºC)	0
Phase lag for daily air temperature sine wave (h)	8
Snow density (kg/m^3)	100

The soil freezing characteristic curve (SFC), describing the relationship between unfrozen water content and soil temperature, was derived from equation 2 as described in Luo et al. (2000):

$$T = \frac{h}{122} \quad (2)$$

where T is the below-zero temperature (°C) and h is the pressure head at a given T (m). However, since 150 m (15 bar) was the highest pressure head for which soil water content was measured, the only part of the SFC curve obtained from equation 2 and the measured soil water characteristic curve, was 0 to -1.2 °C. Therefore, the values given in Luo et al. (2000) were used as initial values for the rest of the curve and were then adjusted in the calibration process (Table 5.6) as explained later in the results.

Table 5-6. The soil freezing characteristic curve.

Unfrozen water content (cm3/cm3)	Soil temperature (°C)										
	0	-1	-2	-3	-4	-5	-6	-7	-10	-20	-30
Before adjustment	0.45	0.29	0.14	0.111	0.08	0.053	0.023	0.023	0.023	----	---
After adjustment	0.45	0.42	0.4	0.38	0.35	0.3	0.2	0.1	0.05	0.001	0

5.3.3.3.2 Surface roughness and infiltration parameters

In DRAINMOD surface runoff is characterized by the maximum depth of depression storage that must be filled before runoff occurs. If the ponded water on the ground surface exceeds the maximum surface storage (S_m), surface runoff begins, otherwise the surface storage indicates the ponding depth which does not lead to runoff. The maximum surface storage and the minor surface depressional storage (S_l), representing storage in small depressions, were taken from the literature and were adjusted during the calibration process (Table 5.4).

Although there are many equations to predict infiltration, the Green-Ampt equation is used to characterize the infiltration in DRAINMOD (Skaggs, 1990). For a specific soil with a known initial water content, the infiltration rate is:

$$f = \frac{A}{F} + B \tag{3}$$

where f is the infiltration rate (cm/h), F is cumulative infiltration (cm), A (cm^2/h) and B (cm/h) are parameters that depend on soil properties and crop parameters such as soil water content and depth of root zone. The Green-Ampt parameters were calculated by an internal DRAINMOD subroutine as a function of water table depth using these equations:

$$A = K_s \times M \times S_{av} \tag{4}$$

$$B = K_s \tag{5}$$

where K_s is the saturated hydraulic conductivity (cm/h), M (fillable porosity) is the water content at saturation minus the water content at a given water table depth (cm^3/cm^3) based on the input soil water characteristic curve, and S_{av} is the suction at the wetting front (cm). During cold season, the infiltration may be limited by soil ice content. When ice is formed in the soil, soil hydraulic conductivities and fillable porosity are modified based on the volumetric content of ice and unfrozen water in the soil (Luo et al., 2000). When the ice content exceeds the critical ice content (given as model input), infiltration stops and water leaves the field as surface runoff.

When the rainfall rate exceeds the infiltration capacity, calculated by Equation 3, the excess water is accumulated as surface storage (ponding) and when the surface storage exceeds the maximum surface storage depth, the additional excess is surface runoff (Skaggs 1978).

5.3.3.3.3 Calibration and validation strategy

The DRAINMOD model was calibrated by adjusting the sensitive parameter inputs that were not available from direct measurements (Table 5.7). The range was based on a guideline provided by Skaggs et al. (2012) and the values reported by other researchers, especially for soil temperature parameters (Luo et al., 2000; Sands et al., 2003; Wang et al., 2006b; Singh et al., 2006 Yang et al., 2007; Ale et al 2009; Morrison et al., 2014; Garmdareh et al., 2018). Daily observed and predicted water table depths and drainage volumes from 2007 to 2016 were plotted and compared visually with respect to both the timing of occurrence and the magnitude of response. Observations from 2010 to 2014 were used for validation and other years were used for calibration of the model. Calibration and validation periods were specified in a way that each period contains both wet and dry years as well as measured drain flow. Additionally, the surface ponding time series created from timelapse photos from 2015 and 2016 were visually compared to the DRAINMOD ponding and runoff predictions for qualitative calibration of surface storage parameters. The maximum surface storage parameter in DRAINMOD was adjusted to find the best agreement between the photo time series and DRAINMOD estimates of surface ponding and runoff.

The agreements between monthly predicted and measured drain flow and daily water table depth were quantified by statistics, including the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe, 1970) and percent bias (PE), which are relative error measures, as well as the Average Deviation (AD), which is an absolute error measure. These error measures can be calculated from the following equations:

$$NSE = 1 - \frac{\sum_1^n (O_i - P_i)^2}{\sum_1^n (O_i - \overline{O_i})^2} \tag{6}$$

$$PE = \frac{\sum_1^n P_i - \sum_1^n O_i}{\sum_1^n O_i} \times 100 \tag{7}$$

$$AD = \frac{1}{n} \sum_{i=1}^{n} |O_i - P_i| \tag{8}$$

where O_i is the daily measured value, P_i is the daily simulated, $\overline{O_i}$ is the average of measured values, and n is the number of observed values. The NSE assesses the predictive power of a hydrological model and it can vary between minus infinity and 1, with 1 indicating a perfect fit. The PE value can vary from minus infinity to positive infinity. A negative value indicates under-prediction, and positive value indicates over-prediction.

The adjusted sensitive parameters for the SW site and the range in which they were adjusted are given in Table 5.7.

Table 5-7. Adjusted parameters and values and the range of change in calibration process.

Calibrated parameters	Adjusted values	Range of change
Kirkham's depth for flow to drains, S_1 (cm)	0.5	0.25 - 1
Maximum surface storage, S_m (cm)	1	0.25 - 2
Snow melt coefficient (mm/d ºC)	3	1 - 5
Critical ice content above which infiltration stops (cm^3/cm^3)	0.4	0.1 - 0.5
Vertical conductivity of restricting layer (cm/h)	0.0017	0 - 0.1
Soil water characteristic curve of the bottom soil layer	Table 5.4	……
Soil freezing characteristic curve	Table 5.6	……

5.4 Results and discussion

5.4.1 Model calibration and validation

Visual comparison of daily observed and simulated water table depths (end-of-day values) and drain flow, in general, indicated agreement in both calibration and validation periods (Fig. 5.7). However, the water table was often predicted deeper than observed in summer and was predicted shallower in October and November in some years, especially in 2008 and 2009.

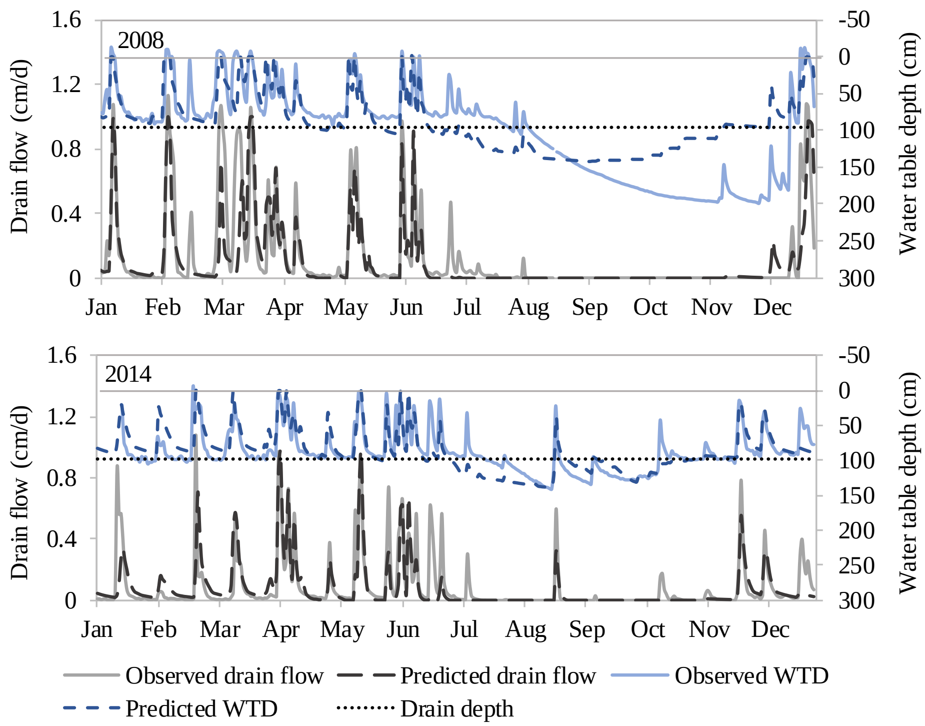

Figure 5-7. Observed and simulated water table depth and drain flow for 2008 (calibration period) and 2014 (validation period).

Comparing DRAINMOD simulations of ponding and runoff with photo estimates of ponding indicated that the model accurately simulated the timing of some of the major and extreme ponding events (category 3 & 4) observed in the field (shown in Fig. 5.8 for 2015). However, photo time series indicated more minor and moderate (category 1 & 2) ponding events than DRAINMOD predicted.

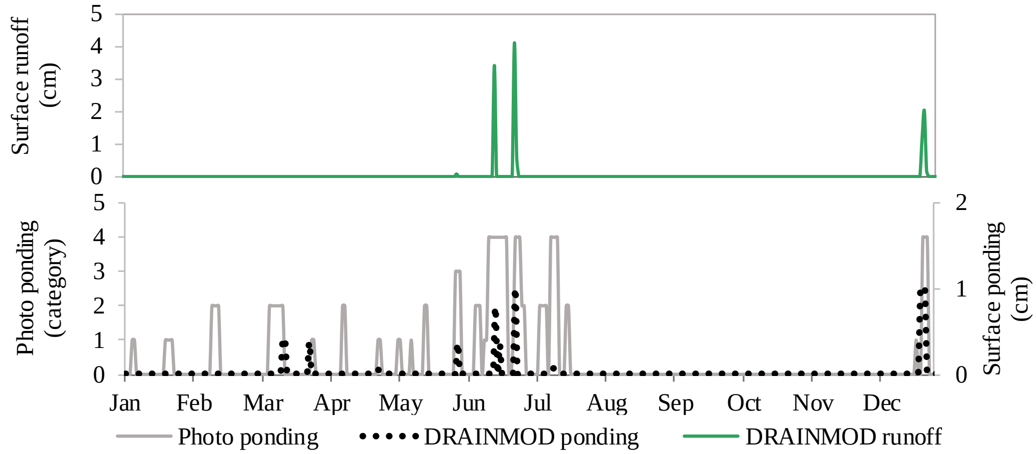

Figure 5-8. Simulated surface ponding and runoff along with photo time series in 2015.

The statistical results also indicated that DRAINMOD performed well in predicting water table depth in the calibration period and even better during the validation period (Table 5.8). The NSE value of 0.24 in 2009 was the lowest and mainly due to discrepancy in model simulations and observations during the summertime when surface runoff rarely happens at DPAC. In most years, the PE was positive indicating that over a year, DRAINMOD tended to predict deeper water table depth than observed values. One possible reason for lower NSE in some years could be the end-of-day value that is used for comparison instead of hourly water table depth since DRAINMOD outputs the end-of-day value. Youssef et al. (2006) showed that due to rapid fluctuations of water table in a day, the difference between observed and simulated water table depth can get as high as 100 cm if there is a few hours lag time between observed and simulated values.

Table 5-8. Agreement between observed and simulated daily water table depths for the calibration and validation periods.

		Daily statistics		
		NSE	PE (%)	AD (cm)
Calibration	Overall	0.50	2.9	23.5
	2007	0.74	16.3	15.0
	2008	0.47	-8.9	32.5
	2009	0.24	-9.0	32.4
	2015	0.57	14.8	20.4
	2016	0.64	8.7	16.0
Validation	Overall	0.61	9.2	18.8
	2010	0.63	16.7	15.8
	2011	0.42	24.0	22.8
	2012	0.51	-7.4	23.1
	2013	0.77	15.0	19.4
	2014	0.61	3.2	13.5

Annual drain flow was under-predicted in some years and over-predicted in other years with the highest over-prediction in 2011, mainly due to over-prediction of flow in November and December (Table 5.9).

Table 5-9. Comparison of annual observed and simulated drain flow and statistical agreements between monthly observed and estimated drain flow.

		drainage (cm/yr)		Monthly statistics		
		Observed	Predicted	NSE	PE	AD (cm)
Calibration	Overall	170.60	167.95	0.79	-1.6	1.0
	2007	42.82	40.64	0.85	-2.4	1.0
	2008	44.63	36.41	0.90	-18.4	0.8
	2009	26.17	27.9	0.75	6.7	1.3
	2015*	30.31	35.88	0.74	18.4	0.8
	2016*	26.68	27.12	0.35	-3.4	1.2
Validation	Overall	151.35	155.81	0.60	3.0	1.0
	2010	26.88	24.46	0.80	-9.0	0.8
	2011	39.58	52.51	0.30	32.6	1.7
	2012*	22.35	25.99	0.31	16.6	0.9
	2013*	31.88	25.1	0.86	-21.2	0.7
	2014*	30.66	27.75	0.68	-9.5	0.9

* Drain flow measurements were available in these years (Fig. 5.3).

5.4.2 Surface ponding and runoff

5.4.2.1 Photo estimate of ponding

The majority of ponding events observed with cameras were classified in categories 1 and 2. In each year, there were only a few severe and extreme ponding events (category 3 & 4) that were expected to cause runoff (Table 5.10 and Fig. 5.8), indicating ponding does not always lead to runoff. The field was also buffered by grass at the edges for most of the time (Fig. 5.9), therefore, accumulated water often infiltrated into the soil or evaporated before it could run off the field.

Between 30 to 58% of photo ponding events occurred during the cold season (Dec. – Mar.), indicating that cold season processes may also affect the ponding and runoff generation at this field (Table 5.10). However, the photo time series was not available for the entire year due to the camera angle being changed by strong winds.

Table 5-10. Direct evidence of frequency and extent of ponding events from timelapse photos.

Year	Number of events			Ponding events
	Total	Category 1 & 2 (ponding)	Category 3 & 4 (runoff)	during cold season** (%)
2015	23	18	5	30
2016*	12	9	3	58
2017*	13	9	4	31

* Data is missing from late Jul. to late Oct. 2015, Jul. to late Dec. 2016, and mid-Jan. to early Mar. 2017

**Cold season was from Dec. through Mar. of each year.

Figure 5-9. Water accumulated in the field, showing that ponding may not lead to runoff.

Snowmelt ponding was not very frequent in the SW field. During the period in which photo evidence of ponding was available (Dec. 2014 to Oct. 2017), only three events were observed that were generated by snowmelt or snowmelt combined with rain events (shown in Fig. 5.10). Similar to other seasons, saturation excess was the main reason for ponding in the cold season, according to water table depth measurements which were below the threshold (35 cm) for every ponding event observed in the photos. In the cold season, soil temperature at 10 cm depth was less than or equal to 0°C about 6% of the time. However, none of the cold season ponding events occurred during these periods, therefore, the partially frozen soil was unlikely to contribute to the ponding generation process.

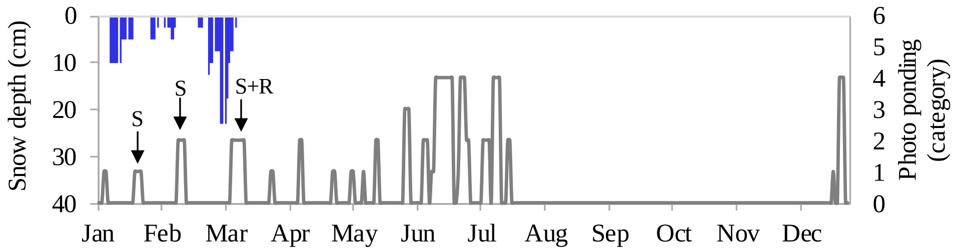

Figure 5-10. Photo estimates of ponding and snow depth in 2015. Arrows indicate the snowmelt ponding (S) or snowmelt combined with rain event (S+R).

5.4.2.2 Water table depth estimate of ponding

When photo and water table depth (WTD) observations were available, there were 32 ponding events captured by both methods. For every photo evidence of ponding, the WTD was always below the specified threshold (35 cm). There was only one ponding event estimated with the WTD method that was not captured by photos mainly because it occurred during the night when the camera was turned off. The 100% correspondence between water table estimate of ponding and photo estimate of ponding (Fig. 5.11), suggests that the saturation excess was the driving force for all of the ponding events observed in the SW field.

The ponding frequency and duration varied over years (Table 5.11). Ponding frequency ranged from 8 to 24 events per year and the total duration of ponding in a year ranged from 15 to 43 days. However there was not a correlation between the frequency and duration of ponding. For instance, ponding duration in 2009 with 8 ponding events was similar to that in 2010 and 2014 with 22 events. Shown in Table 5.11 is also the percentage of occurrence of ponding events during cold season that ranged from 14% in 2014 to 92% in 2012.

Table 5-11. Water table estimates of frequency and duration of ponding events (WTD < 35 cm).

Year	No. of ponding events	Days of ponding	Ponding events in cold season* (%)
2007	17	27	53
2008	22	43	50
2009	8	31	38
2010	22	30	36
2011	24	42	42
2012	12	15	83
2013	12	27	42
2014	22	30	23
2015	20	27	30
2016	21	28	52

* Cold season: December-March

With the WTD method, unlike the photo method, the ponding events were not classified into different categories, however, the inverse correlation between photo category and the minimum measured water table depth during a WTD ponding event provides indirect information on the extent of ponding (Fig. 5.11). At the SW field, when WTD was close to the ground surface, there was photo evidence of runoff (photo category 3 & 4). All of the ponding events that were expected to cause runoff, according to photos, occurred when WTD was below 8 cm. Therefore, runoff was not expected at WTD greater than 8 cm, however, not all of the ponding events with WTD < 8cm led to runoff.

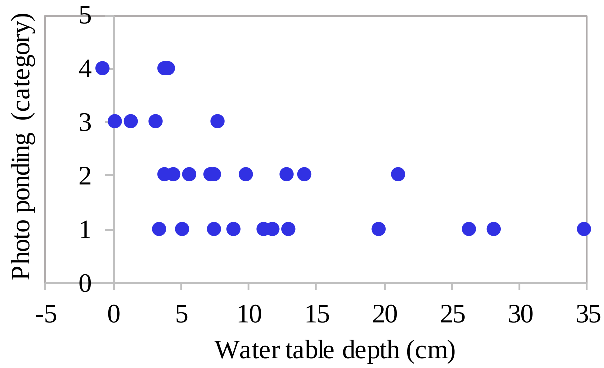

Figure 5-11. The inverse correlation between minimum WTD during each ponding event and ponding category.

5.4.2.3 DRAINMOD estimate of ponding and runoff

The simulated annual water balance indicated that on average, ET and drain flow accounted for 51% and 34 % of the annual precipitation, respectively, while surface runoff only accounted for 7% (Fig. 5.12). The range of change was from 24 to 53 cm yr^{-1} and 1 to 12 cm yr^{-1} for annual drain flow and runoff, respectively. The low percentage of generated runoff was comparable to what others have found in agricultural drained fields. For example, in a simulation study in Iowa, Singh et al. (2007) reported that only 5% of annual precipitation contributed to surface runoff. From an experimental study conducted in three agricultural fields in Ontario, Canada, Van Esbroeck et al. (2016) also concluded that only 5-10 % of precipitation contributed to surface runoff.

The simulated monthly water balance indicated that 61% of total water loss through surface runoff occurred in the cold seasons (Dec. to Mar.). On average over 10 years, water loss through drain flow and runoff was the highest in March and the lowest in September (Fig. 5.12).

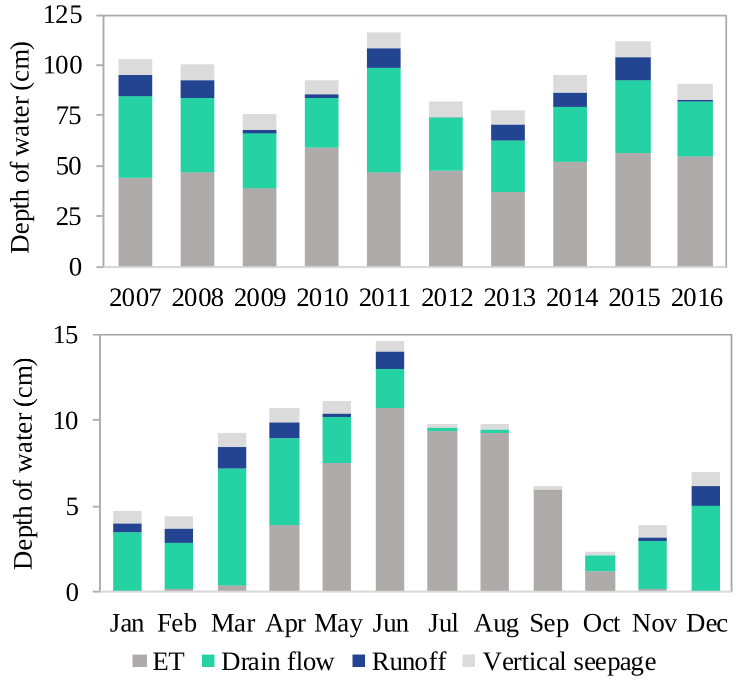

Figure 5-12. Estimated annual and monthly water balance with 4 major components: evapotranspiration (ET), drain flow, runoff, and vertical seepage.

The number of ponding and runoff events and total duration of ponding events simulated with DRAINMOD are listed in Table 5.12. The simulated ponding frequency ranged from 4 to 13 events per year and total ponding duration ranged from 4 to 34 days per year. Around 50% of all simulated ponding events produced surface runoff. When DRAINMOD predicted a ponding event, the simulated water table depth was zero, meaning that all of the DRAINMOD estimates of ponding were saturation excess ponding. The distribution of simulated ponding events over time varied at this site in each year, with 2-100% of ponding occurring during the cold season (Dec. – Mar.).

Table 5-12. DRAINMOD estimates of frequency and extent of ponding.

Year	No. of ponding events	No. of runoff events	Days of ponding	Ponding events in cold season* (%)
2007	12	6	30	67
2008	13	7	24	69
2009	6	3	12	33
2010	6	2	10	17
2011	13	8	34	23
2012	4	2	4	100
2013	7	4	13	43
2014	8	4	12	38
2015	8	4	13	2
2016	5	1	7	100

Cold season: December - March

5.5 Discussion

5.5.1 Comparison between three methods

The comparison between observed and simulated results indicated that DRAINMOD predicted fewer ponding events than what was observed in the field according to photos and water table depth measurements (Fig. 5.13). On average over 10 years (2007-2016), DRAINMOD predicted 8 ponding events per year (16 days total), while the water table depth (WTD) method estimated 18 ponding events (30 days total). Surface ponding was more frequent than runoff. Both observed and model results indicated that on average only 4 runoff events occurred per year. DRAINMOD under-predicted the frequency of ponding more than it under-predicted runoff. The under-prediction of ponding events in DRAINMOD could be due to the spatial variability in ponding generation and DRAINMOD's limitation on taking the spatial variability into account. DRAINMOD assumes that the field is completely flat, therefore, only predicted the extreme events that occurred over the entire field. While in reality, there was an approximately 2 m elevation change in the SW plot and water usually was accumulated in the corner of the field where timelapse camera was located and captured the ponding events. To determine the impact of elevation change on DRAINMOD ponding predictions, similar to the WTD method, the threshold of 35 cm was used instead of the ground surface for identifying saturated excess ponding events. Results indicated that DRAINMOD would predict around 13 ponding events per year, on average, which is higher than 8 ponding events predicted with the ground surface threshold used in DRAINMOD.

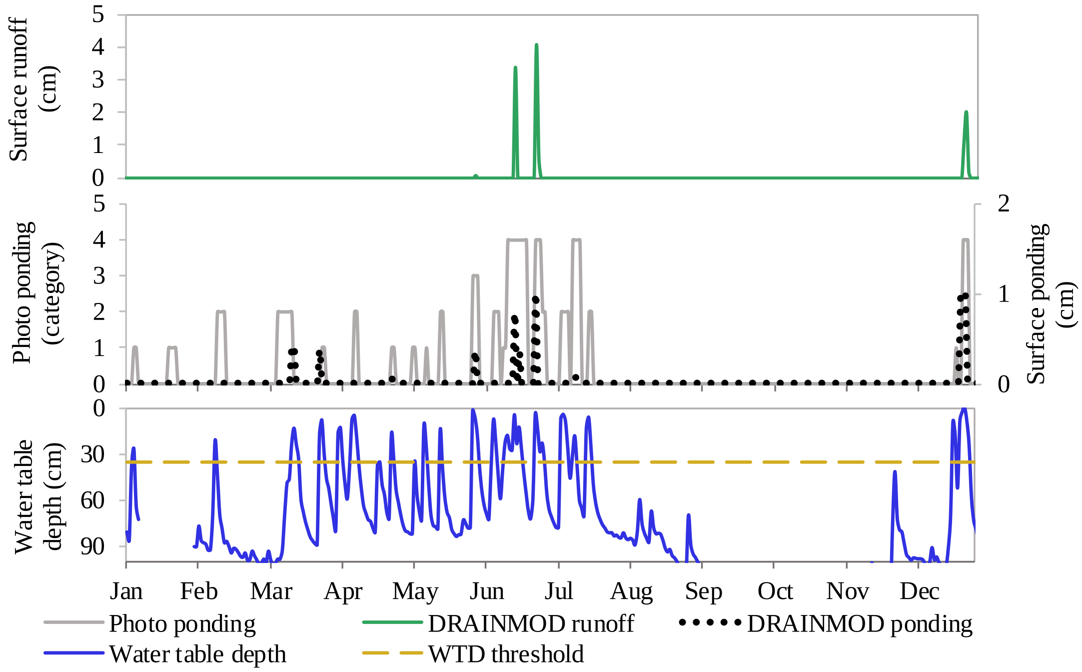

Figure 5-13. Water table depth measurements and photo estimates of ponding along with DRAINMOD simulations of ponding and runoff.

Both simulated and observed results indicated that all ponding events were due to saturation excess rather than infiltration excess, according to water table depth. Although simulating the infiltration excess ponding was sensitive to parameter selection for the infiltration equation in DRAINMOD (Green-Ampt), saturation excess ponding predicted with the model was comparable to the photo evidence of ponding which always occurred when WTD was below the threshold (35 cm). Additionally, the results found in this study were in agreement with Bou Lahdou et al. (2014) findings for the DPAC site. They found that when surface ponding occurred at the field (according to water table measurements), the average precipitation intensity was low, indicating that saturation excess was the driver of ponding generation rather than infiltration excess.

5.5.2 Limitations in simulating cold-season processes in DRAINMOD

Although a soil temperature component has been added to DRAINMOD and improved the model for cold climate (Luo et al., 2000), issues still partially remained with predictions during cold months for the DPAC site. Drain flow was over-predicted in March in some years due to the freeze/thaw processes and snowmelt impacts, however, it was mainly under-predicted in cold months, likely due to soil freezing impacts.

Frozen soil limits infiltration, so soil temperature plays a key role in simulating infiltration and drain flow. In DRAINMOD, soil surface temperature is set equal to air temperature except for the winter months when the snowpack on the ground insulates the soil and lowers the heat losses from the soil surface. However, DRAINMOD was not able to predict the snow accumulation and melt accurately for parts of the cold season (Fig. 5.14a), partly because of using the average air temperature as a basis for dividing snow and rain, while there were frequent changes in hourly air temperatures in Indiana. Additionally, DRAINMOD possibly did not simulate insulation of the soil surface due to snow sufficiently. Therefore, the surface temperature boundary condition tended to be too low during periods of observed snow cover, resulting in under-prediction of soil temperatures throughout the soil column (shown for the 10 cm depth in Fig. 5.14b). Excessively cold simulated soil temperature has led to a reduction in infiltration and drain flow estimations (Fig. 5.14c) and it increased the water storage in the soil profile. By reducing infiltration and slowing drain flow, the simulated frozen soil can also contribute to generating ponding and runoff or add to the existing conditions under which ponding is generated to increase the depth and extent of ponding and runoff. During the times when the soil was not frozen (March-April) drain flow was very well predicted in that year.

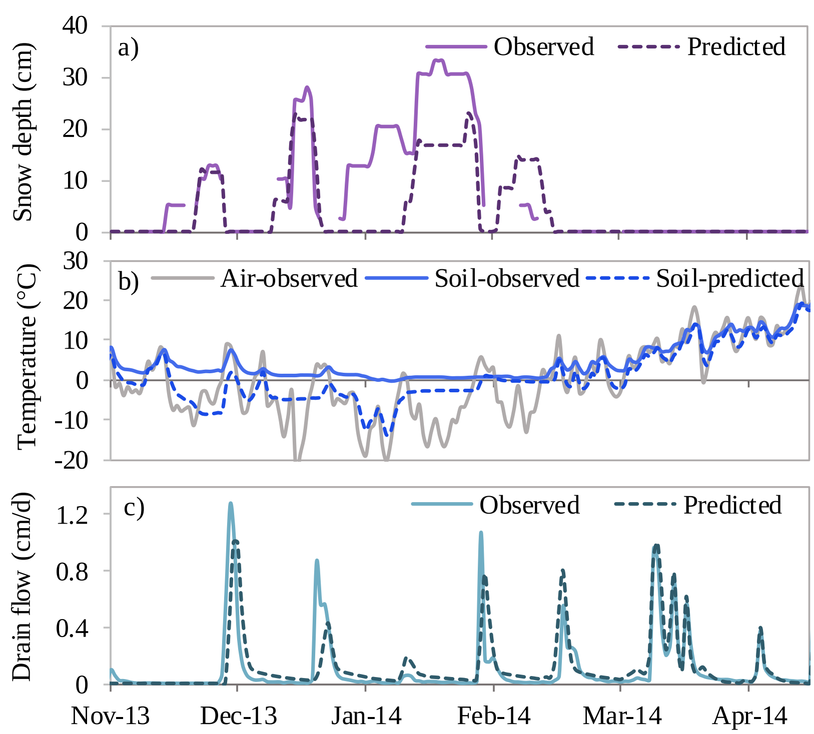

Figure 5-14. a) Observed and DRAINMOD simulated snow depth; b) observed average daily air temperature, observed soil temperature at 10 cm depth and simulated soil temperature at depth of 13 cm; c) observed and simulated drain flow.

Other DRAINMOD users also reported similar difficulties in cold regions. For example, Yang et al. (2007) used DRAINMOD-N in Ontario Canada to simulate nitrate movement and concluded that the model had difficulty in simulating drain flow accurately when soils were frozen in winter and thawed in spring. In another study, Sands et al. (2003) used DRAINMOD to predict drain flow in Minnesota and concluded that the model over-estimated drain flow during snowmelt.

In order to overcome the impacts of excessively cold simulated soil temperatures on drain flow and runoff predictions, the freezing characteristic curve (SFC) was adjusted for temperatures below 0 °C, by assigning greater unfrozen water contents than what were obtained from the method described in Luo et al. (2000) (Table 5-6). In addition, the soil freezing curve needed to be defined down to -30 °C in order to achieve model stability (Lamya Negm, personal communication). Adjusting the SFC improved drain flow predictions by increasing the flow peaks and consequently, reduced surface runoff slightly (Fig. 5.15).

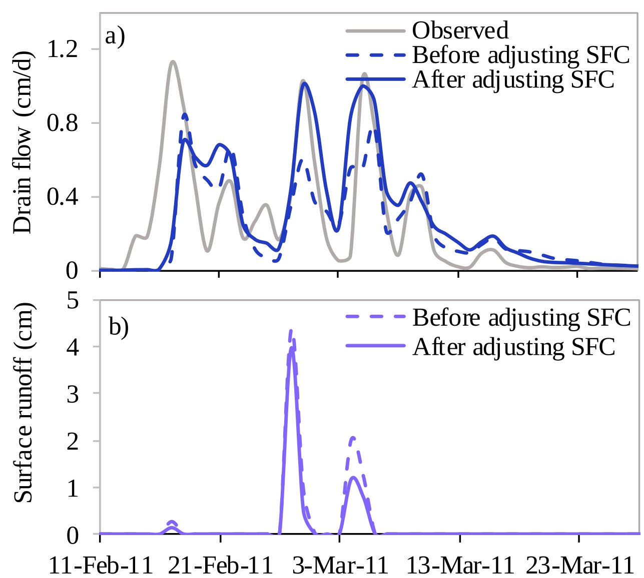

Figure 5-15. Predicted drain flow (a) and surface runoff (b) before and after adjusting SFC.

5.6 Conclusions

Surface ponding and runoff were estimated in a seasonally frozen drained agricultural field in eastern Indiana using three methods including field observations and model simulations. Using photo evidence of ponding together with the water table depth measurements, the potential of predicting surface ponding from water table depth measurements was examined. A 10-year simulation was conducted using DRAINMOD to predict surface ponding and runoff. The study resulted in the following conclusions:

- Multiple lines of evidence of surface ponding and runoff provided more information than just one. Photos provided direct evidence of ponding but only on a small portion of the field for parts of the study period. Water table depth method provided a simple alternate for saturation excess ponding. DRAINMOD predicted surface ponding and runoff over the whole field assuming it is flat, but it did not predict the spatial variability of ponding.
- Surface ponding was more frequent than runoff indicating not every ponding event leads to runoff.
- The estimated annual water balance indicated that only 7% of annual precipitation contributed to surface runoff, while 93% of the precipitation contributed to ET, subsurface drainage and vertical seepage.
- Results from both simulation and observation method indicated that all of the ponding events were generated as a result of saturation excess process rather than infiltration excess.
- The distribution of ponding events over time varied in different years but on average over 10 years the WTD method and DRAINMOD results both indicated that about 45% of ponding events occurred in the cold season (Dec. - Mar.).
- Adjusting the soil freezing characteristic curve (SFC) in DRAINMOD improved the simulation results in cold season with preventing under-prediction of drain flow and over-prediction of runoff.

The DRAINMOD model results together with field observations contribute to a better understanding of surface ponding and runoff generation in an agricultural drained field and is useful for developing management recommendations for water resources at the field or watershed scales.

5.7 Acknowledgements

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CHAPTER 6. CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

The goal of this study was to understand the hydrologic processes in a drained agricultural field in order to evaluate the hydrological and environmental impacts of controlled drainage (CD) to inform the possible improvement in the management of the system. In this study, rigorous statistical models were developed to evaluate the impacts of CD on water table recession rate, drain flow and nitrate and phosphorus loss through subsurface drainage. A method was developed for estimating drain flow using the water table depth measurements and a theoretical drainage equation. In addition to a digital photo time series and water table depth measurements, a hydrological model was used to simulate the hydrology of a free draining system in order to predict surface ponding and runoff in an agricultural drained field. Field W at Davis Purdue Agricultural Center (DPAC), a research farm located in eastern Indiana was used for the entire study.

Overall, nitrate transport through controlled drainage was lower than free drainage, indicating the drainage water quality benefits of CD, but water table remained at a higher level for longer when drainage was controlled. This can have negative impacts on crop yields, when water table is above a detrimental level, and can also increase the potential of nutrient transport through surface runoff since the saturation excess was the main reason for generating surface runoff at this field. The specific conclusions drawn from each objective are as follows:

1- In objective one, the potential impact of CD on water table recession rates was examined and the following research question was addressed:
   - ***How does CD affect the time of water table fall from the surface to a critical level to inform the possible improvement in the management of CD and reducing the potential negative impacts of CD on the yield?***

     Water table recession rate was used to calculate the amount of time the water table needs to recede from the surface to a level that could be detrimental to trafficability or crop yield, under both free and controlled drainage conditions. Results indicated that controlled drainage had a statistically significant effect on the rate of water table fall, and that a raised outlet (controlled drainage) increased the time of water table recession from the surface to 30 cm and 60 cm depth by an average of approximately 12 to 26 and 24 to 53 hours, respectively. Based on these results, it can be concluded that lowering the outlet before storm events would reduce the amount of time that the water table is at a detrimental level for either crop growth or trafficability. However, lowering the outlet during rainfall events does have costs in terms of the time required to manage the outlets. Whether the benefits of lowering the outlet outweighs the cost depends on the sensitivity of the crop and probability of a severe storm.

2- In objective two, the potential of using water table observations for estimating drain flow was examined and the following specific research questions were addressed:

- ***What does the water table vs. drain flow relationship look like and how different hydraulic conductivity profiles impact the relationship between water table and drain flow in the Hooghoudt equation?***

  Examination of the shape of the water table height above drain and drain flow relationship under three different K profiles (constant, exponential, and layered) showed that the Hooghoudt equation can be linear or parabolic depending on the selected K profile. The constant K profile yielded an approximately linear relationship between water table height and drain flow. However, the relationship between water table height and drain flow is not always linear for all fields and the correct K profile should be recognized and used in the Hooghoudt equation.

- ***How well the Hooghoudt equation is able to predict drain flow using the observed water table depth measurements?***

  Among the three discussed K profiles, the layered K profile was chosen for prediction of drain flow. Drain flow estimated from water table height using the layered K profile and the Hooghoudt equation compared well to observed flow with Nash-Sutcliffe Efficiency values above 0.7 and 0.8 for calibration and validation periods, respectively, suggesting that this method could be used to fill in or extend the incomplete drain flow records when water table depth measurements are available.

- ***How much was the difference in drain flow volume between free and CD sites?***

  The incomplete drain flow records of four quadrants in field W were filled and extended using the estimations from the Hooghoudt equation, together with linear regression for the remaining gaps. These long-term drain flow records from free draining quadrants were compared to that in CD quadrants. In the controlled drainage quadrants, average annual flow was 14 - 49% lower than free drainage. The annual flow reductions ranged from 67 mm/year to 200 mm/year over the 11-year study period.

3. In the third objective, the long records (10 years: 2007-2016) of continuous drain flow obtained from field measurements combined with estimated values (from objective two) were used to evaluate the potential of CD for improving drainage water quality and to address the following research questions:
   - ***What are nitrate and P concentrations in the subsurface drain flow?***

     Nitrate-N concentration in drain flow ranged from 0.3 mg L^{-1} to 28.3 mg L^{-1} and phosphorus concentrations mostly ranged from 0.002 mg L^{-1} to 0.5 mg L^{-1} for SRP and from 0.004 mg L^{-1} to 1 mg L^{-1} for TP among four quadrants over 11 years (2006-2016).
   - ***What is the effect of CD on drain flow, nutrient concentrations and loads during periods of low outlet level control (summer) and high outlet level control (winter)?***

     Two different statistical methods with two sets of paired plots (eastern and western) were used to address this research question. The first method (Rank Sum test) was used to quantify the impact of CD on cumulative annual drain flow and nitrate-N and phosphorus loads. The second method (ANCOVA model) was used to evaluate the impact of CD on daily drain flow, nitrate-N, soluble reactive phosphorus (SRP) and total phosphorus (TP) concentrations and loads during the two different periods of control (low outlet level control and high outlet level control). The following conclusions drawn:
     - CD plots had a statistically significant (at 5% level) lower annual drain flow (eastern pair: 39%; western pair: 25%) and nitrate load (eastern pair: 43%; western pair: 26%) compared to free draining (FD) plots, while annual SRP and TP loads were not significantly different.
     - Nitrate concentrations were not significantly affected by CD, indicating that load reduction was mainly due to drain flow reduction.
     - The average percent reduction of daily drain flow was 68% in the eastern pair and 58% in the western pair during controlled drainage at the higher outlet level (winter) and 64% and 58% at the lower outlet level (summer) in the eastern and western pairs, respectively.

- P concentrations were not significantly different, except for a significant increase in SRP concentration with CD in one of the paired plots.
- The CD impacts on phosphorus (P) loads were more complex and inconsistent over years and across plots but overall during 5 years, CD decreased P loads.
- The higher level of outlet control during the non-growing season (winter) provided about 70% of annual water quality benefits while the lower level used during the growing season (summer) provided about 30%.
- At both control levels, the effectiveness of CD was greater when more drain flow or load was present in the field.

These results support the CD system as a reliable management practice for reducing nitrate loads from subsurface drains, mainly due to the reduction in flow. By quantifying the magnitude of the increased impact, this study clarifies the added drainage water quality benefit of controlling drainage at a higher level, especially during the non-growing season. However, controlled drainage impacts on surface runoff water quality were not investigated in this study. Controlled drainage has the potential to decrease water quality through increasing surface runoff that is difficult to quantify because of the large uncertainty in surface runoff and ponding.

4. Objective 4 examined the generation of ponding and runoff using field observations and DRAINMOD model simulations in a free draining field. Three different methods were used to determine the generation process of surface ponding and runoff and the frequency of incidence. Surface ponding was monitored with a timelapse camera at the edge of the field for three years. Using photo evidence of ponding together with the water table depth measurements, the potential of predicting surface ponding from water table depth measurements was examined. A 10-year simulation was conducted using DRAINMOD to predict surface ponding and runoff. The model was calibrated and validated by comparing model predictions of subsurface drainage and water table depth with field observations. The following research questions were addressed in this objective:
    - ***How can alternative datasets (photo time series and water table depth) be used to better evaluate the frequency and generation process of surface ponding and runoff at the field scale?***

Multiple lines of evidence of surface ponding and runoff provided more information than just one. Digital photos provided direct evidence of ponding but only on a small portion of the field for parts of the study period. Water table depth method provided a simple alternate for saturation excess ponding. The generation of ponding at this field was only observed above a water table threshold of 35 cm. Therefore, in the absence of direct evidence of ponding, water table depth measurements above the defined threshold provided a simple alternate for saturation excess ponding events.

- ***What is the frequency of occurrence of ponding and surface runoff?***

On average over 10 years (2007-2016), DRAINMOD predicted 8 ponding events per year (16 days total), and the water table depth (WTD) method estimated 18 ponding events (30 days total).The simulated annual water balance indicated that only 7% of annual precipitation contributed to surface runoff, while 93% of the precipitation contributed to ET, subsurface drainage and vertical seepage.

- ***How much ponded water actually leaves the field as surface runoff?***

Surface ponding was more frequent than runoff indicating not every ponding event leads to runoff. Both observed and model results indicated that on average only 4 runoff events occurred per year.

- ***What are the processes that generate surface ponding and runoff?***

Results from both simulations and observations indicated that all of the ponding events were generated as a result of the saturation excess process rather than infiltration excess.

- ***What is the influence of freeze/thaw processes on simulated surface ponding and runoff in DRAINMOD?***

The distribution of ponding events over time varied in different years but on average about 45% of ponding events occurred in the cold season (Dec. - Mar.) indicating the importance of soil freeze/thaw condition and snow accumulation. However, DRAINMOD was not able to predict the snow accumulation and melt accurately during parts of the cold season, and possibly did not simulate insulation of the soil surface due to snow sufficiently resulting in drain flow underprediction and runoff overprediction. However, adjusting the soil freezing characteristic curve (SFC) in DRAINMOD improved the simulation results in cold season with preventing under-prediction of drain flow and over-prediction of runoff.

The DRAINMOD model results together with field observations contributed to a better understanding of surface ponding and runoff generation in an agricultural drained field and provided useful information for developing management recommendations for water resources at the field or watershed scales.

6.2 Recommendations for future research

1- In order to make strong conclusions about the drainage water quality benefits of controlled drainage the following suggestions are made for future research:
   - Different experimental setting, such as creating buffer between free and CD fields, that limits lateral seepage from controlled drainage (CD) fields to the neighboring free draining fields, can help to better quantify the drainage water quality benefits of CD.
   - Storm discharge can significantly affect the phosphorus (P) transport through subsurface drainage, therefore more frequent concentration measurements are required, especially during storm events. Future research can investigate phosphorus impacts through event-based sampling.

2- Despite the reduction found in drain flow with controlled drainage, the question of the fate of the retained water and nitrate remains unresolved. Future research that quantifies the effect of CD on other potential flow paths such as surface runoff and lateral seepage, denitrification occurring in these pathways and the potential for increasing nitrous oxide emissions, would enable a more complete characterization of the impact of CD.

3- The question of whether the nitrate reduction at the outlet of the subsurface drainage system extends to the watershed scale needs further investigation.

4- Active management of controlled drainage would reduce the amount of time that the water table is at a detrimental level for either crop growth or trafficability but it involves costs in terms of the time required to manage the outlets. Future studies can examine the cost and benefit trade-off of active management of controlled drainage systems.

5- In this study the frequency of ponding was quantified for a free draining field. The distribution of ponding in the growing and non-growing seasons can be further investigated. This could be helpful for evaluating the potential negative impacts of surface ponding on crop yields.

6- This study indicated spatial variability in ponding generation across the field using photo evidence of ponding. Water table depth (WTD) above the ground surface could be an indication of surface ponding in the field. However, the measurements only represent the water table level at the observation well location. When agricultural fields are not flat, water table depth measurements from one location are not representative of the whole field since water table level can vary across the field. Measuring water table depth at different locations across the experimental field would provide useful information and future research can investigate spatial variability in ponding generation using water table depth measurements at several locations.

APPENDIX

Table A-1. Timing, extend and duration of ponding events from timelapse cameras in the SW quadrant.

Event no.	Start date & time	Hours of ponding	End date & time	Photo category
1	1/4/2015 12:00	27	1/5/2015 15:00	1
2	1/19/2015 8:00	74	1/22/2015 10:00	1
3	2/9/2015 8:00	80	2/12/2015 16:00	2
4	3/7/2015 13:00	66	3/10/2015 7:00	2
5	3/11/2015 11:00	44	3/13/2015 7:00	2
6	3/26/2015 8:00	28	3/27/2015 12:00	1
7	4/9/2015 12:00	25	4/10/2015 13:00	2
8	4/25/2015 15:00	24	4/26/2015 15:00	1
9	5/4/2015 12:00	22	5/5/2015 10:00	1
10	5/10/2015 6:00	12	5/10/2015 18:00	1
11	5/16/2015 18:00	20	5/17/2015 14:00	2
12	5/30/2015 16:00	51	6/1/2015 19:00	3
13	6/8/2015 6:00	54	6/10/2015 12:00	2
14	6/12/2015 14:00	24	6/13/2015 14:00	1
15	6/13/2015 17:00	208	6/22/2015 9:00	4
16	6/25/2015 7:00	5	6/25/2015 12:00	1
17	6/26/2015 15:00	50	6/28/2015 17:00	4
18	6/29/2015 6:00	37	6/30/2015 19:00	2
19	7/7/2015 15:00	76	7/10/2015 19:00	2
20	7/12/2015 6:00	78	7/15/2015 12:00	4
21	7/19/2015 19:00	15	7/20/2015 10:00	2
22	12/24/2015 7:00	5	12/24/2015 12:00	1
23	12/27/2015 6:00	60	12/29/2015 18:00	4
24	2/3/2016 6:00	12	2/3/2016 18:00	1
25	2/24/2016 8:00	14	2/24/2016 22:00	3
26	3/10/2016 17:00	22	3/11/2016 15:00	1
27	3/13/2016 6:00	54	3/15/2016 12:00	3
28	3/24/2016 13:00	6	3/24/2016 19:00	1
29	3/28/2016 6:00	14	3/28/2016 20:00	2
30	3/31/2016 6:00	38	4/1/2016 20:00	1
31	4/11/2016 6:00	33	4/12/2016 15:00	3
32	4/30/2016 6:00	29	5/1/2016 11:00	1

Table A-1. continued

Event no.	Start date & time	Hours of ponding	End date & time	Photo category
33	5/12/2016 18:00	19	5/13/2016 13:00	2
34	5/14/2016 6:00	11	5/14/2016 17:00	1
35	12/23/2016 9:00	5	12/23/2016 14:00	1
36	1/3/2017 18:00	21	1/4/2017 15:00	1
37	3/28/2017 6:00	26	3/29/2017 8:00	2
38	3/31/2017 7:00	12	3/31/2017 19:00	2
39	4/4/2017 6:00	13	4/4/2017 19:00	2
40	4/5/2017 16:00	39	4/7/2017 7:00	2
41	4/10/2017 18:00	14	4/11/2017 8:00	1
42	4/29/2017 6:00	76	5/2/2017 10:00	3
43	5/4/2017 6:00	77	5/7/2017 11:00	4
44	5/24/2017 15:00	44	5/26/2017 11:00	3
45	5/27/2017 6:00	31	5/28/2017 13:00	2
46	6/23/2017 6:00	30	6/24/2017 12:00	4
47	6/29/2017 6:00	61	7/1/2017 19:00	2
48	7/7/2017 16:00	19	7/8/2017 11:00	2

Photos are missing from Jul. 19, 2015 to Oct. 21, 2015 due to the camera angle
Photos are missing from Jul. 2016 to Dec. 21, 2016 due to the camera angle
Photos are missing from Jan. 2017 to Mar. 21, 2017 due to the camera angle
Photos are missing from Aug. 2017 to Oct. 2017 due to SD card error

Table A-2. Timing, extend and duration of ponding events from timelapse cameras in the NW quadrant.

Event no.	Start date & time	Hours of ponding	End date & time	Photo category
1	1/3/2015 16:00	25	1/4/2015 17:00	1
2	2/8/2015 8:00	81	2/11/2015 17:00	1
3	3/8/2015 14:00	237	3/18/2015 11:00	3
4	3/25/2015 8:00	126	3/30/2015 14:00	3
5	4/2/2015 19:00	45	4/4/2015 16:00	1
6	4/8/2015 11:00	104	4/12/2015 19:00	3
7	4/20/2015 7:00	10	4/20/2015 17:00	1
8	4/25/2015 16:00	48	4/27/2015 16:00	2
9	5/5/2015 7:00	8	5/5/2015 15:00	1
10	5/10/2015 6:00	50	5/12/2015 8:00	2
11	5/16/2015 18:00	64	5/19/2015 10:00	1
12	5/30/2015 16:00	96	6/3/2015 16:00	4
13	6/8/2015 6:00	81	6/11/2015 15:00	4
14	6/12/2015 14:00	268	6/23/2015 18:00	4
15	6/25/2015 7:00	180	7/2/2015 19:00	4
16	7/7/2015 15:00	100	7/11/2015 19:00	4
17	7/12/2015 6:00	85	7/15/2015 19:00	4
18	7/19/2015 6:00	61	7/21/2015 19:00	4
19	8/10/2015 7:00	29	8/11/2015 12:00	1
20	8/15/2015 7:00	10	8/15/2015 17:00	1
21	8/31/2015 19:00	11	9/1/2015 6:00	1
22	9/1/2015 13:00	25	9/2/2015 14:00	1
23	9/19/2015 7:00	8	9/19/2015 15:00	1
24	10/28/2015 9:00	26	10/29/2015 11:00	1
25	12/1/2015 8:00	10	12/1/2015 18:00	1
26	12/2/2015 12:00	23	12/3/2015 11:00	1
27	12/22/2015 8:00	272	1/2/2016 16:00	3
28	1/8/2016 8:00	34	1/9/2016 18:00	1
29	1/15/2016 13:00	21	1/16/2016 10:00	2
30	2/3/2016 8:00	78	2/6/2016 14:00	1
31	2/7/2016 14:00	19	2/8/2016 9:00	1
32	2/24/2016 8:00	35	2/25/2016 19:00	3
33	3/1/2016 12:00	31	3/2/2016 19:00	1
34	3/9/2016 8:00	199	3/17/2016 15:00	3
35	3/24/2016 13:00	72	3/27/2016 13:00	1
36	3/28/2016 7:00	177	4/4/2016 16:00	3
37	4/7/2016 7:00	203	4/15/2016 18:00	3
38	4/30/2016 14:00	28	5/1/2016 18:00	1

Table A-2. Continued

Event no.	Start date & time	Hours of ponding	End date & time	Photo category
39	5/2/2016 7:00	60	5/4/2016 19:00	1
40	5/12/2016 18:00	71	5/15/2016 17:00	2
41	5/21/2016 6:00	8	5/21/2016 14:00	1
42	6/4/2016 18:00	16	6/5/2016 10:00	1
43	1/3/2017 9:00	34	1/4/2017 19:00	1
44	1/10/2017 9:00	6	1/10/2017 15:00	1
45	1/12/2017 9:00	97	1/16/2017 10:00	2
46	1/17/2017 8:00	11	1/17/2017 19:00	1
47	1/20/2017 8:00	32	1/21/2017 16:00	2
48	4/29/2017 9:00	72	5/2/2017 9:00	1
49	5/4/2017 9:00	48	5/6/2017 9:00	3
50	5/25/2017 6:00	6	5/25/2017 12:00	1
51	6/15/2017 6:00	7	6/15/2017 13:00	1
52	6/18/2017 17:00	2	6/18/2017 19:00	1
53	6/23/2017 7:00	60	6/25/2017 19:00	4
54	6/30/2017 6:00	78	7/3/2017 12:00	4
55	7/6/2017 12:00	5	7/6/2017 17:00	1
56	7/7/2017 12:00	49	7/9/2017 13:00	4
57	7/21/2017 7:00	53	7/23/2017 12:00	4

Photos are missing from Oct. 3, 2016 to Dec. 21 2016 due to the camera angle

Table A-3. Timing, extend and duration of ponding events from timelapse cameras in the NE quadrant.

Event no.	Start date & time	Hours of ponding	End date & time	Photo category
1	1/3/2015 12:00	28	1/4/2015 16:00	1
2	1/17/2015 12:00	95	1/21/2015 11:00	1
3	2/7/2015 15:00	70	2/10/2015 13:00	1
4	3/7/2015 16:00	190	3/15/2015 14:00	2
5	3/25/2015 8:00	6	3/25/2015 14:00	1
6	3/26/2015 8:00	30	3/27/2015 14:00	1
7	4/2/2015 19:00	19	4/3/2015 14:00	1
8	4/3/2015 17:00	14	4/4/2015 7:00	1
9	4/8/2015 11:00	55	4/10/2015 18:00	2
10	4/19/2015 14:00	26	4/20/2015 16:00	1
11	4/25/2015 13:00	21	4/26/2015 10:00	1
12	5/5/2015 7:00	9	5/5/2015 16:00	1
13	5/10/2015 7:00	12	5/10/2015 19:00	2
14	5/16/2015 11:00	6	5/16/2015 17:00	1
15	5/16/2015 18:00	23	5/17/2015 17:00	2
16	5/26/2015 16:00	2	5/26/2015 18:00	1
17	5/30/2015 16:00	69	6/2/2015 13:00	2
18	6/8/2015 6:00	54	6/10/2015 12:00	2
19	6/12/2015 14:00	26	6/13/2015 16:00	1
20	6/13/2015 17:00	213	6/22/2015 14:00	4
21	6/25/2015 7:00	25	6/26/2015 8:00	2
22	6/26/2015 15:00	118	7/1/2015 13:00	4
23	7/7/2015 15:00	93	7/11/2015 12:00	2
24	7/12/2015 6:00	80	7/15/2015 14:00	4
25	7/19/2015 6:00	58	7/21/2015 16:00	2
26	8/10/2015 7:00	4	8/10/2015 11:00	2
27	8/15/2015 7:00	3	8/15/2015 10:00	1
28	2/3/2016 8:00	24	2/4/2016 8:00	1
29	2/24/2016 8:00	34	2/25/2016 18:00	2
30	3/1/2016 12:00	28	3/2/2016 16:00	1
31	3/9/2016 18:00	68	3/12/2016 14:00	2
32	3/13/2016 7:00	75	3/16/2016 10:00	2
33	3/24/2016 13:00	18	3/25/2016 7:00	1
34	3/28/2016 7:00	36	3/29/2016 19:00	2
35	3/31/2016 7:00	55	4/2/2016 14:00	2
36	4/11/2016 7:00	36	4/12/2016 19:00	2
37	4/30/2016 14:00	19	5/1/2016 9:00	1
38	5/2/2016 6:00	24	5/3/2016 6:00	1

Table A-3. Continued

Event no.	Start date & time	Hours of ponding	End date & time	Photo category
39	5/12/2016 18:00	20	5/13/2016 14:00	2
40	5/14/2016 6:00	24	5/15/2016 6:00	1
41	6/4/2016 18:00	12	6/5/2016 6:00	1
42	10/20/2016 7:00	57	10/22/2016 16:00	2
43	12/26/2016 8:00	30	12/27/2016 14:00	1
44	1/3/2017 8:00	48	1/5/2017 8:00	2
45	1/11/2017 14:00	172	1/18/2017 18:00	2
46	1/20/2017 8:00	50	1/22/2017 10:00	2
47	3/7/2017 8:00	11	3/7/2017 19:00	1
48	3/20/2017 8:00	35	3/21/2017 19:00	1
49	3/28/2017 7:00	30	3/29/2017 13:00	1
50	3/30/2017 8:00	56	4/1/2017 16:00	1
51	4/4/2017 7:00	31	4/5/2017 14:00	1
52	4/5/2017 15:00	50	4/7/2017 17:00	1
53	4/29/2017 6:00	80	5/2/2017 14:00	2
54	5/4/2017 6:00	78	5/7/2017 12:00	2
55	5/24/2017 15:00	49	5/26/2017 16:00	2
56	5/27/2017 6:00	25	5/28/2017 7:00	2
57	6/14/2017 11:00	1	6/14/2017 12:00	1
58	6/18/2017 17:00	2	6/18/2017 19:00	1
59	6/23/2017 7:00	33	6/24/2017 16:00	4
60	6/30/2017 6:00	9	6/30/2017 15:00	1
61	6/30/2017 18:00	25	7/1/2017 19:00	1
62	7/7/2017 15:00	17	7/8/2017 8:00	1
63	7/21/2017 6:00	48	7/23/2017 6:00	2

Photos are missing from Sep. 15, 2015 to Jan. 21, 2016

Table A-4. Timing, extend and duration of ponding events from timelapse cameras in the SE quadrant.

Event no.	Start date & time	Hours of ponding	End date & time	Photo category
1	1/3/2015 12:00	28	1/4/2015 16:00	3
2	1/17/2015 16:00	95	1/21/2015 15:00	2
3	2/7/2015 16:00	70	2/10/2015 14:00	3
4	3/1/2015 8:00	203	3/9/2015 19:00	3
5	3/10/2015 12:00	43	3/12/2015 7:00	2
6	3/25/2015 7:00	11	3/25/2015 18:00	2
7	3/26/2015 7:00	29	3/27/2015 12:00	2
8	4/2/2015 19:00	18	4/3/2015 13:00	1
9	4/3/2015 17:00	15	4/4/2015 8:00	1
10	4/7/2015 7:00	79	4/10/2015 14:00	2
11	4/19/2015 14:00	17	4/20/2015 7:00	1
12	4/20/2015 8:00	4	4/20/2015 12:00	1
13	4/25/2015 13:00	18	4/26/2015 7:00	2
14	5/10/2015 7:00	3	5/10/2015 10:00	1
15	5/16/2015 11:00	3	5/16/2015 14:00	1
16	5/16/2015 18:00	13	5/17/2015 7:00	3
17	5/30/2015 16:00	39	6/1/2015 7:00	3
18	6/8/2015 7:00	11	6/8/2015 18:00	2
19	6/9/2015 7:00	7	6/9/2015 14:00	1
20	6/13/2015 17:00	14	6/14/2015 7:00	1
21	6/14/2015 19:00	21	6/15/2015 16:00	2
22	6/16/2015 7:00	12	6/16/2015 19:00	3
23	6/17/2015 7:00	36	6/18/2015 19:00	4
24	6/19/2015 7:00	30	6/20/2015 13:00	4
25	6/25/2015 9:00	3	6/25/2015 12:00	1
26	6/26/2015 15:00	41	6/28/2015 8:00	4
27	6/29/2015 7:00	25	6/30/2015 8:00	2
28	7/7/2015 14:00	19	7/8/2015 9:00	2
29	7/8/2015 14:00	41	7/10/2015 7:00	4
30	7/12/2015 7:00	11	7/12/2015 18:00	3
31	7/13/2015 12:00	24	7/14/2015 12:00	4
32	7/19/2015 7:00	5	7/19/2015 12:00	1
33	7/19/2015 19:00	16	7/20/2015 11:00	1
34	12/24/2015 9:00	5	12/24/2015 14:00	1
35	12/27/2015 8:00	72	12/30/2015 8:00	4
36	1/15/2016 17:00	17	1/16/2016 10:00	1
37	2/3/2016 9:00	10	2/3/2016 19:00	2
38	2/24/2016 9:00	34	2/25/2016 19:00	4

Table A-4. continued

Event no.	Start date & time	Hours of ponding	End date & time	Photo category
39	3/10/2016 15:00	22	3/11/2016 13:00	4
40	3/13/2016 8:00	48	3/15/2016 8:00	3
41	3/24/2016 13:00	20	3/25/2016 9:00	3
42	3/28/2016 8:00	24	3/29/2016 8:00	4
43	3/31/2016 8:00	25	4/1/2016 9:00	3
44	4/11/2016 8:00	23	4/12/2016 7:00	4
45	4/30/2016 12:00	5	4/30/2016 17:00	1
46	5/12/2016 18:00	13	5/13/2016 7:00	1
47	1/3/2017 9:00	48	1/5/2017 9:00	2
48	1/12/2017 9:00	80	1/15/2017 17:00	2
49	1/17/2017 9:00	24	1/18/2017 9:00	2
50	1/20/2017 9:00	28	1/21/2017 13:00	2
51	3/7/2017 9:00	23	3/8/2017 8:00	2
52	3/20/2017 10:00	27	3/21/2017 13:00	2
53	3/28/2017 7:00	24	3/29/2017 7:00	2
54	3/31/2017 7:00	11	3/31/2017 18:00	2
55	4/4/2017 7:00	7	4/4/2017 14:00	2
56	4/6/2017 7:00	24	4/7/2017 7:00	2
57	4/29/2017 7:00	32	4/30/2017 15:00	4
58	4/30/2017 16:00	22	5/1/2017 14:00	4
59	5/4/2017 7:00	57	5/6/2017 16:00	4
60	5/24/2017 15:00	40	5/26/2017 7:00	2
61	5/27/2017 7:00	5	5/27/2017 12:00	1
62	6/23/2017 8:00	23	6/24/2017 7:00	4
63	6/30/2017 19:00	14	7/1/2017 9:00	1
64	7/7/2017 18:00	14	7/8/2017 8:00	1

Photos are missing from Oct. 2016 to Dec. 2016 due to the camera angle