Hydrological modification of subsurface drainage systems

by

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To my father who never doubted my abilities

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To my loving wife Miranda whose love and support is unceasing

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ABSTRACT

Controlled Drainage (CD), a subsurface drainage management system, has been researched in many regions. Previous research has reported CD to reduce subsurface drainage and as a result reduce nitrate loading. CD has been reported to have little effect on nitrate concentrations, so exploring alternative treatments to reduce these concentrations would be constructive. This research was intended to measure the effect of CD on surface runoff, crop yield, water table depth, and to document a biofilter's effect on nitrate concentrations. CD increased surface runoff ranging from 53% to 130%, increased corn yield by 14% over two years, and decreased nitrate loading with a range of 47% to 93%. The use of a biofilter decreased nitrate concentrations and loading by 35%. Water table measurements were also taken every five minutes on average over a two-year period and showed potential long-term water retention in a CD system.

CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

Subsurface drainage is one of the most important parts of Midwest crop production. Subsurface drainage is necessary, with certain soil types, because it allows for countless acres of land to be put into production that would otherwise be unfit for crop growth due to excess moisture conditions. However, subsurface drainage increases the release of nitrate into streams, rivers, and lake, and this nitrate export from the upper Midwest has been implicated as a major contributor to the hypoxic zone located in the Gulf of Mexico at the mouth of the Mississippi River (Rabalais et al., 1999; Sen Gupta et al., 1996; Turner and Rabalais, 1994). Nitrate concentrations have been shown to exceed the drinking water standard of 10 mg/L exiting subsurface drainage systems (Lalonde et al., 1996; Mejia et al., 1998; Ng et al., 2000; Ng et al., 2002).

Much of the drainage in the Midwest occurs during the months of April through June, and subsequently much of the nitrate loss through subsurface drainage is during the months of April through June (Randall and Vetch, 2005). If there was a system that allowed the drainage in these early months to be stored for the drier and hotter months of July and August it would be invaluable from a cost and nutrient retention standpoint. The concept of controlled drainage (CD) has been proposed as a system to accomplish this.

CD allows subsurface water to be held in the soil profile. A common practice in the Midwest for CD is to install a tile drainage structure that has a plate or many plates in the middle of the structure to close during the growing season, an example of this is shown in Figure 1.1. During the planting and harvesting season these plates are removed so that the drainage system represents conventional drainage to reduce compaction due to heavy machinery and allow timely field operations to promote early crop development. Then, during the growing season some of the plates are installed to allow the water table to reach a certain depth, possibly 60 cm below the soil surface, before it can be released through the drainage system. In many drainage systems, the tile lines are installed at 120 cm below the soil surface and 60 cm would be the midpoint. This allows water and nutrients to be stored in the soil profile for the crop to utilize during crucial times in the growth stage. In other words, the water and nutrients that would be lost in the early months would now be stored in the soil profile rather than exiting through the subsurface drainage system.

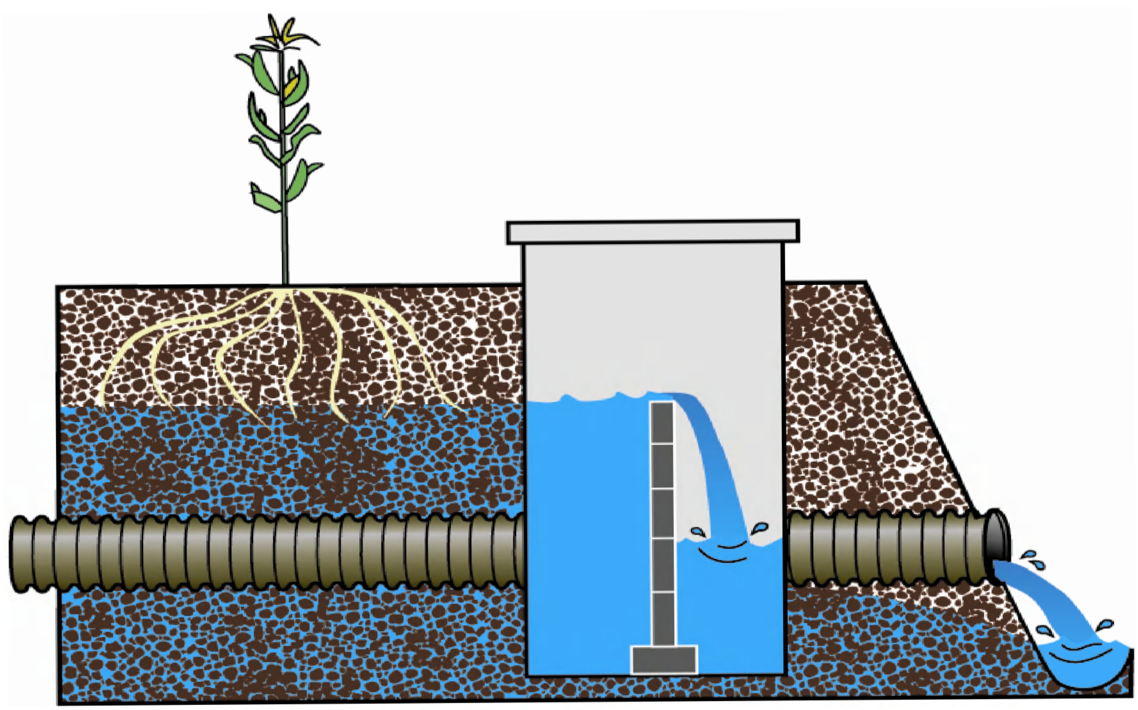

Figure 1.1. Depiction of controlled drainage in a field (Frankenberger et al., 2006).

It has been reported in previous research that CD can reduce the volume of subsurface drainage significantly. Percentage decrease of total subsurface drainage versus conventional free drainage is reported consistently between 10% to 40% (Amatya et al., 1998; Drury et al., 1997; Drury et al., 2001; Evans et al, 1995; Fouss et al., 1987; Gilliam and Skaggs, 1986; Skaggs et al., 1995a; Skaggs et al. 1995b; Tan et al., 1998). A reduction as high as 65% has been reported (Lalonde et al., 1996), but this amount of reduction has been rare in previous research. Nonetheless, CD has shown that it reduces subsurface drainage volumes with the potential to have other positive effects, such as reduced nitrate loading.

Under a conventional drainage system, excess water that cannot be absorbed into the soil profile is released through a drainage system and lost for the remainder of the season. Under CD, the same excess water is retained in the soil profile until a pre-set water table, such as 60 cm below the soil surface, is reached. Therefore, a portion of the nitrate and water that would be released in a conventional drainage system would remain in the soil profile under CD conditions. This has the potential to allow the nitrate to either be taken up by the crop or to be removed via denitrification given the anaerobic conditions in the soil due to saturated conditions. Total nitrate loss in research, expressed as kg/ha/yr, was reduced by a range of 11% to 60%, with 20% to 40% being common, when CD was implemented (Brevé et al. 1997; Brevé et al., 1998; Deal et al., 1986; Drury et al., 1996; Drury et al., 2001; Elmi et al., 2000; Evans et al., 1995; Gilliam and Skaggs, 1986; Ng et al., 2002; Skaggs and Gilliam, 1981; Skaggs et al., 1995a; Skaggs et al., 1995b; Tan et al., 1998).

The impact of CD on flow-weighted nitrate concentration has been a topic of past and present research. A portion of the previous research that had reduction in nitrate concentrations of 36% to 77% also had a subirrigation component to the research (Drury et al., 2001; Meija et al., 1998; Ng et al., 2000; Ng et al., 2002). This suggests that the added water for subirrigation may have been a factor in the concentration reduction. To further support this, Fausey (2005) showed, between three treatments, that subirrigated plots had 115% of the subsurface flow that was reported for the free drainage plots and the CD plots were 40% lower than the free drainage plots. Also, the nitrate concentration in the free and CD plots were similar but higher than that of the subirrigated plots. However, the nitrate loading for the subirrigated plots was 25% higher than the CD plots with the loading from CD being 45% lower than free drainage. Overall most research on CD has shown little impact on the nitrate concentrations. Nonetheless, CD without a subirrigation component has been reported on many occasions to decrease the overall nitrate loading, which is primarily due to decreased subsurface drainage volumes.

As discussed previously, the nitrate concentrations exiting subsurface drainage systems can exceed 10 mg/L. Exceeding this level is a problem due to "Blue Baby Syndrome." Nitrate concentrations above 10 mg/L leads to suffocation in small children when nitrate converts to nitrite in the blood stream and attaches to the hemoglobin instead of oxygen. As such there is a need for practices to reduce the nitrate concentrations or drainage volume. One such practice being researched is a biofilter. A biofilter, as discussed here, consists mostly of wood chips to act as a carbon source in a process that releases the nitrogen as a gas. A biofilter's nitrate concentration removal potential from tile drainage has been reported by van Driel et al. (2006). In this study, two different types of wood-based biofilters were used to remediate tile drainage water from two different sources. A lateral flow biofilter was used to remediate an agricultural drainage tile and an upflow biofilter was used at a golf course. The lateral flow biofilter achieved a 33% nitrate concentration reduction and the upflow biofilter achieved a 52% reduction.

The reduction in subsurface drainage volume and nitrate mass export through the use of CD is viewed as a positive, but there is a need for understanding the overall water balance of a system under CD. From this, additional studies are warranted before implementing CD as a standard practice. There is a potential for surface runoff to increase during a rainfall event as a result of a wetter soil profile because of the higher water table associated with CD. Some CD studies have documented impacts on surface water runoff. A 32% increase in surface runoff has been reported (Deal et al., 1986) and reports of increases of 46% and 53% have also been reported (Brevé et al., 1997; Drury et al., 2001). Furthermore, Skaggs et al. (1995b), in a modeling study, reported that controlled drainage increased surface runoff by an average of 68% and by an average of 164% if the controlled drainage is intensified. Intensified meant that the water level was allowed to rise up to 25 cm below the soil surface between September 15th and March 15th rather than 40 cm from November 1st to March 15th. Even though this research has shown that surface runoff can potentially increase with CD only a small portion of the CD, research has measured surface runoff or reported on potential surface runoff increases.

Another area of question, relative to CD, is the impact on crop yields, especially since there is a cost associated with CD implementation and management. In most research, differences in crop yield under CD versus conventional drainage have been inconsistent. For example, studies by Brevé et al., (1997) and Brevé et al., (1998) reported little increase or decrease in yields between the drainage treatments. Studies by Fisher et al., (1999) and Hunt et al., (1993) reported 10% to 20% increases in corn yield. This suggests that water retention improved crop yields. However, there have been reported yield decreases as well. Grigg et al. (2004) reports a small 3% decrease, but Kalita and Kanwar (1993) reported decreases in corn yield by 14% when the water table was at 60 cm below the soil surface during the growing season and a decrease in corn yield of 30% when the water table was at 30 cm below the soil surface during the growing season. This suggests that a higher water table may have impacts on root proliferation early in the season.

After reviewing the published literature on CD systems, it is apparent that there is a need for more research that includes a surface runoff component and the reporting of crop yield. If in most cases surface runoff increases by a significant amount, other problems may occur. Instead of nitrate loss with possible excessive drainage there could be increased erosion, phosphorus transport, and pesticide transport, common issues that are associated with increased surface runoff. In addition, if crop yields are shown to remain static or decrease, incentives, based on the environmental benefits of the practice, would be needed for producers to accept CD. Therefore, given this review of past research, which is summarized in Figure A.1, four objectives were identified for this research:

1. Determine the effects of CD on surface runoff volume
2. Further document the effect of CD on subsurface drainage volume
3. Determine the effect of CD on crop yield
4. Determine the effects of a biofilter on nitrate concentrations

These objectives were addressed using two different research sites. The first site was located in Ames, IA and consisted of six non-weighing lysimeters. A schematic of the lysimeters can be found in Figure 2.1. These lysimeters were monitored during the 2005 and 2006 growing seasons for subsurface drainage volume, surface runoff volume, and crop yield. Three of the six lysimeters were under free drainage conditions and three were under CD conditions. In addition, four separate rainfall simulations were conducted to help determine the water balance in a field during a rain event. The data collected from this site was used to develop conclusions for objectives one, two, and three.

The second research site was located in Pekin, IA and consisted of nine plots. There were three plots in each of the following treatments: free drainage, CD variable, and CD fixed. The CD fixed treatment used a control structure that was closed year round and the CD variable treatment had the plates open during planting and harvesting. The data collected at this site included depth of water in the CD structure and subsurface drainage volume recorded at five minute intervals. Flow-weighted water samples were also taken to measure the nitrate concentration of the subsurface drainage effluent. Two of the plots also had samples taken before and after a biofilter which was made up of a carbon source and an aggregate base, wood chips and gravel in this case. The data collected from this site was primarily used to help develop conclusions for objectives two and four.

1.2 Thesis Overview

This thesis has been organized with a general introduction followed by two articles, a general conclusion, appendices, acknowledgements, and biographical sketch. Each article contains its own abstract, introduction, materials and methods, results, and conclusion. First, Chapter 2 contains a paper entitled, "Water balance investigation of controlled drainage on a small scale." The research site near Ames that has six non-weighing lysimeters was used for this study. The main focus of this project was to determine the effect of CD on surface runoff. However, subsurface drainage was monitored during both and during the four sets of rainfall simulations that were conducted. In addition, crop yield was also collected. The paper presented in Chapter 2 will be submitted for publication in *Applied Engineering in Agriculture*.

Chapter 3 contains a paper entitled, "Controlled drainage and alternative treatments for subsurface drainage management." The Pekin site was used for this research to further document CD and its effect on nitrate loading and concentrations, and to further document CD and its effect on subsurface drainage volume. The main responsibilities at this research site were collecting drainage data, water level data, and managing the CD structures. The crops were managed through a partnership with Pekin Community Schools and the Pekin chapter of Future Farmers of America. A journal has not yet been selected for the paper presented in this chapter. Chapter 4 consists of general conclusions drawn from this research and recommendations for future work in this area. General conclusions are followed by sections containing appendices, acknowledgements, and a biographical sketch.

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CHAPTER 2. WATER BALANCE INVESTIGATION OF CONTROLLED DRAINAGE ON A SMALL SCALE

A paper to be submitted to *Applied Engineering in Agriculture*

Kyle D. Riley and Matthew J. Helmers

2.1 Abstract

Six non-weighting lysimeters with a depth of 120 cm were monitored over a two-year period under natural and simulated rainfall conditions. These procedures were performed to monitor the effects of controlled drainage (CD), established at 60 cm below the soil surface during the growing season and winter months, on surface runoff, subsurface drainage, and crop yield. The in-season data from natural rainfall showed that CD reduced subsurface drainage by 20% and increased corn yield by 14% when averaged over a two-year period. The simulated rainfall data showed CD increased surface runoff by 53% when the water table was 90 cm below the soil surface and 87% to 130 % when the water table was established 60 cm below the soil surface.

2.2 Introduction

Nitrate export from the upper Midwest has been implicated as a major contributor to the hypoxic zone in the Gulf of Mexico at the mouth of the Mississippi River (Rabalais et al., 1999; Sen Gupta et al., 1996; Turner and Rabalais, 1994). Taking this into account, researchers have been studying practices to reduce nitrate export. One practice under consideration is Controlled Drainage (CD). CD is a method of subsurface drainage water management that has shown positive impacts on reducing the volume of subsurface drainage.

CD allows subsurface water to be held in the soil profile during the growing season rather than be released from the system.

A typical value for subsurface drainage volume reduction by CD, compared to conventional Free Drainage (FD), is in the range of 10% to 40 % (Amatya et al., 1998; Drury et al., 1997; Drury et al., 2001; Evans et al, 1995; Fouss et al., 1987; Gilliam and Skaggs, 1986; Skaggs et al., 1995a; Skaggs et al. 1995b; Tan et al., 1998), although a reduction as high as 65% has been reported (Lalonde et al., 1996). A decrease in subsurface drainage volume, resulting in nitrate export reduction has also been reported. This is because nitrates move freely through the soil with water due to its solubility. In previous research there has been a wide range of nitrate loading reduction when CD is compared with FD. Common reductions were around 20% to 40% (Brevé et al. 1997; Brevé et al., 1998; Deal et al., 1986; Drury et al., 1996; Drury et al. 2001; Elmi et al., 2000; Evans et al., 1995; Gilliam and Skaggs, 1986; Ng et al., 2002; Skaggs and Gilliam, 1981; Skaggs et al., 1995a; Skaggs et al., 1995b; Tan et al., 1998).

Despite these positive results, there is still a need to further understand CD. In particular, investigating the pathways of water movement in a CD system. One concern is that higher surface runoff may occur when CD is implemented because of the wetter soil profile associated with the higher water table under a CD system. Logically, when surface runoff increases there is an increased risk of erosion, phosphorus transport, and pesticide transport. Reports that include a surface runoff component have shown that surface runoff increases with CD by 10% to 60% (Brevé et al., 1997; Deal et al., 1986; Drury et al., 2001; Evans et al., 1995; Grigg et al., 2004; Skaggs et al., 1995b). Furthermore, Skaggs et al. (1995b) reported, from DRAINMOD modeling simulations, increased surface runoff by 68%

with CD implementation and 164% when CD was intensified by bringing the water table up to 25 cm below the soil surface from September 15th to March 15th instead of 40 cm below the soil surface.

Another area of question, relative to CD, is the impact on crop yields, especially since there is a cost associated with CD implementation and management. In most research, differences in crop yield under CD versus conventional drainage have been inconsistent. For example, studies by Brevé et al., (1997) and Brevé et al., (1998) reported little increase or decrease in yields between the drainage treatments. Studies by Fisher et al., (1999) and Hunt et al., (1993) reported 10% to 20% increases in corn yield. This suggests that water retention improved crop yields. However, there have been reported yield decreases as well. Grigg et al. (2004) reports a small 3% decrease, but Kalita and Kanwar (1993) reported decreases in corn yield by 14% when the water table was at 60 cm below the soil surface during the growing season and a decrease in corn yield of 30% when the water table was at 30 cm below the soil surface during the growing season. This suggests that a higher water table may have impacts on root proliferation early in the season.

In the Midwest, much of the subsurface drainage occurs during the months of April through June (Randall and Vetch, 2005). This is due to the frozen conditions of the soil during the winter months of November through February, and increased rainfall during spring and summer. Therefore, most monitoring takes place between March through October.

Again, while previous research has shown that CD has potential to reduce subsurface drainage volume, there is still a need to understand the performance of the practice under varying conditions. While some information on surface runoff exists, there is a strong need to further document potential pathways of water movement under CD conditions. These pathways could include surface runoff, lateral seepage to surrounding areas, and deep percolation. The objectives for this research were to quantify surface water runoff, subsurface drainage, and crop yield under CD and FD conditions.

2.3 Materials and Methods

2.3.1 Research Site

The research site was comprised of six non-weighing lysimeters (Figure 2.1) that contain Clarion Loam (Fine-loamy, mixed, superactive, mesic, Typic Hapludolls) soil and have been under continuous corn, at a simulated 24,000 plants per acre, since their installation in 1993. The site was located about 10 kilometers west of Ames, IA. This research took place during the 2005 and 2006 growing seasons, growing corn in both periods. In 2005, 168 kg/ha of nitrogen was applied, and in 2006, 224 kg/ha of nitrogen was applied. The rate was increased in 2006 to insure nitrogen was not a limiting factor for crop growth. The nitrogen source was urea ammonium nitrate fertilizer and it was applied in the spring before both growing seasons. Spring tillage was implemented using a garden rotary tiller in the 2005 growing season and fall tillage was implemented in the fall of 2005 for the 2006 growing season.

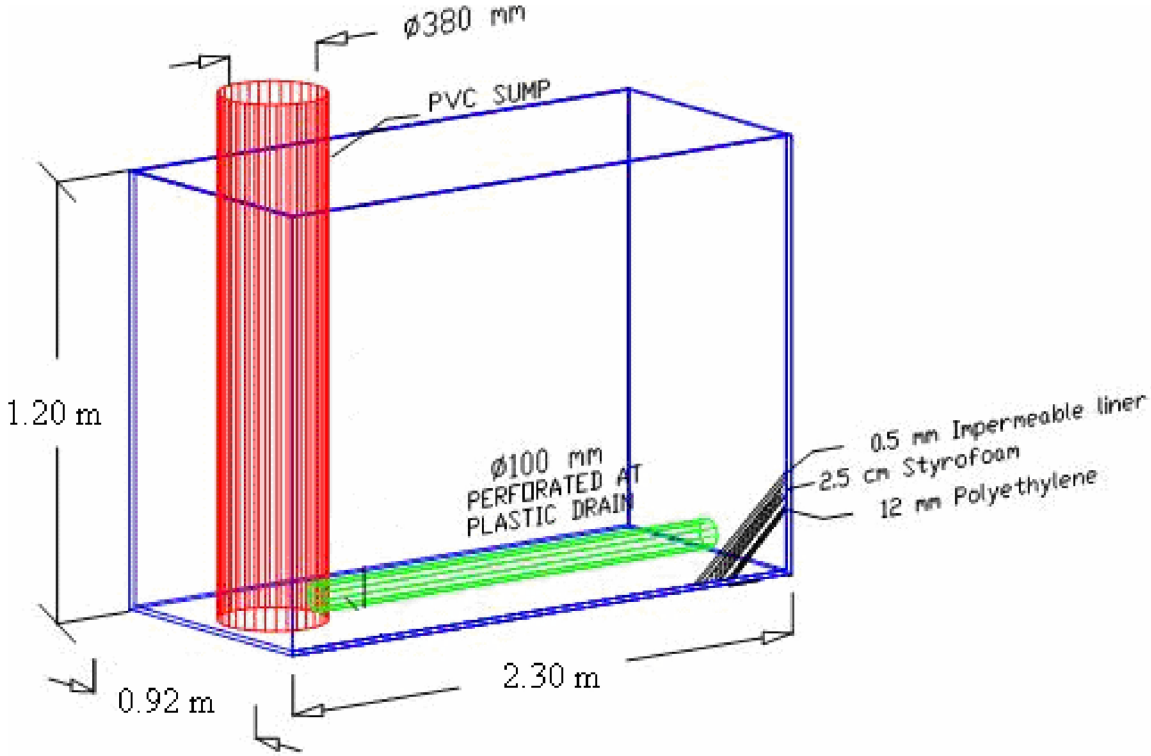

Figure 2.1. Schematic of a non-weighing lysimeter.

2.3.2 Treatments

The six lysimeters that make up the research site were divided into two different treatments using a completely random design. Three lysimeters were used for both treatments. All six lysimeters were monitored during the drainage season of 2005 and 2006. The lysimeters under FD conditions drained as a simulated conventional tile drained system with the drain open during the entire year. The drain depth for the FD plots was 120 cm. The lysimeters under CD conditions drained similar to FD during planting and harvesting and then during the growing season and during winter the water level was allowed to reach 60 cm below the soil surface before draining. However, the time period that the lysimeters were in FD or CD depended on that particular growing season based on environmental conditions. In 2005, the CD lysimeters began CD conditions on June 13th and were under FD conditions from Sept. 20th to Oct. 6th for harvest. In 2006, the CD lysimeters began CD conditions on June 1st and were under FD conditions from Sept. 29 to Oct. 13th for harvest (Table 2.1).

Table 2.1. Dates for the controlled drainage system.

Year	Structures Open	Structures Closed
2005	4/15 - 6/13 9/20 - 10/6	3/1 – 4/15 6/13 - 9/20 10/6 - 12/31
2006	4/1 - 6/1 9/29 - 10/13	3/1 - 4/1 6/1 - 9/29 10/13 - 12/31

2.3.3 Data Collection

Data was collected on average every seven days throughout the year. Subsurface drainage values were determined during the year and during the rainfall simulations. A PVC pipe in each lysimeter was used to pump water out and its volume measured via a container that was calibrated in two liter increments. This drainage season was between March and October. To collect surface runoff, a drain was cut in the side of the lysimeter to allow the runoff to drain into a catch container. When runoff occurred, the volume of water in the catch container was measured via the same calibrated bucket, except during the rainfall simulations. During rainfall simulations, time constraints lead to the use of a rotation of catch containers so that the incremental mass of the runoff could be determined separately using an on-site balance. The volume was then calculated using the measured mass.

In addition to monitoring surface runoff and subsurface drainage, surface soil moisture and crop yield were monitored. The surface soil moisture data was collected with a Theta Probe type ML2x, and it was used in conjunction with the field calibration curve developed for Des Moines Lobe soils reported in Kaleita et al. (2005). This device was attached to a Moisture Meter type HH2 to gather the moisture measurements. For yield data, the corn in both years was hand shelled and moisture was measured via a handheld electronic moisture meter. The mass of the corn was measured using a common mass balance.

2.3.4 Simulations

In addition to monitoring the lysimeters during the years of 2005 and 2006, four separate rainfall simulations (A, B, C, and D) were conducted at the research site to document surface runoff and subsurface drainage under representative rainfall amounts (Table 2.2). The rainfall simulations were conducted on each lysimeter individually and the simulator used was 2.5 m high and had an oscillating spray bar. Once activated, the spray bar provided a sweeping spray over the entire lysimeter every 5 seconds. To hinder unwanted water in or out of the lysimeters, each lysimeter was covered in between each simulation and pre-treatment. Residue cover during all simulations was perceived to be 10% to 20%, but was not formally measured.

Simulations A and B took place in the fall of 2005 with a pre-wetting treatment (25 mm/hr) applied by the simulator before the rainfall simulation, and each had a two-year, one-hour (45 mm/hr) simulation design storm. Simulations C and D took place in the spring of 2006 with a field saturation pre-treatment before the simulations. Simulation C had a six-month, one-hour (25 mm/hr) simulation design storm, and simulation D had the same two-yr, one-hour design storm as simulation A and B. A more frequent design storm was conducted in simulation C to determine it would have the same effects as in simulation A and B.

The pre-wetting treatment in the fall of 2005 consisted of a 25 mm/hr rainfall for four hours for a total of 100 mm. The lysimeter was then pumped out until there was no water freely draining from the soil, approximately three days, and at this point the simulation was conducted. Simulation A consisted of a 45 mm/hr rainfall for a period of one hour on each the six lysimeters. During the pre-wetting, and after simulation A, measurements showed the CD lysimeters were not at the CD level of 60 cm below the soil surface. Therefore, the CD lysimeters were pre-wet again at the 25 mm/hr rate until the CD level was reached in all three CD lysimeters, approximately 50 mm. After the CD level was reached simulation B was conducted using only the three CD lysimeters with a rainfall rate of 45 mm/hr.

The field saturation pre-treatment for simulations C and D consisted of pumping water from a nearby well into the sump of the lysimeter to completely saturate the lysimeter from the bottom to the top. This approach was used to reduce the air trapped in the soil and allow the lysimeter to reach as close to saturation as possible prior to draining. After saturating, the lysimeters were pumped out until there was no water freely draining, approximately three days. For the CD lysimeters, the water was pumped out to 60 cm below the soil surface. Simulation C, which consisted of a 25 mm/hr rate for one hour, was first conducted on the CD lysimeters. Since there was no surface runoff from these simulations, we did not continue with the FD lysimeters. Therefore, we proceeded to simulation D (45 mm/hr rainfall for one-hour) on all six lysimeters.

Table 2.2. Summary of rainfall simulation scenarios.

Date	Simulation	Simulation Rate (mm/hr)	Average Rainfall Measured (mm/hr)	Pre-Treatment	Lysimeters Involved
Fall 2005	A	45	44	Pre-Wet (100 mm)	ALL
Fall 2005	B	45	46	Pre-Wet (50 mm)	CD Lys.
Spring 2006	C	25	23	Saturation	CD Lys.
Spring 2006	D	45	46	Saturation	ALL

2.3.5 Statistical Analysis

Statistical analyses were conducted using Statistical Analysis System software (SAS, 2003). The general linear model (GLM) procedure was used to determine the statistical significance of treatment effects on simulation surface runoff, in-season subsurface drainage, and yield data. Differences among treatment means were determined to be significant at $p \leq 0.05$.

2.4 Results and Discussion

The in-season subsurface drainage flow for 2005 (Figure 2.2, Table 2.3) and for 2006 (Figure 2.3, Table 2.3) are similar. Total drainage in 2006 was lower than 2005 because of lower rainfall in the 2006 growing season when compared to the 2005 growing season. The rainfall in 2005 from March to October was 711 mm and 470 mm in 2006 (Figure 2.4) with 2005 being close to and 2006 being below March to October average of 735 mm for Ames, IA. The potential evapotranspiration over the same period was 110 cm and 107 cm in 2005 and 2006, respectively (Iowa State University 2006). The drainage results support previous research with CD having less subsurface drainage. The CD plots had a two-year subsurface drainage average of 20% less than the FD plots but the values were not significantly different.

Table 2.3. In-season subsurface drainage (mm).

Treatment	Controlled			
Year	1	2	4	Average
2005	299	269	232	267
2006	142	156	148	149
Treatment	Free			
Year	3	5	6	Average
2005	294	325	240	286
2006	206	197	265	223

Std Err = 13.52
Values were not significantly different

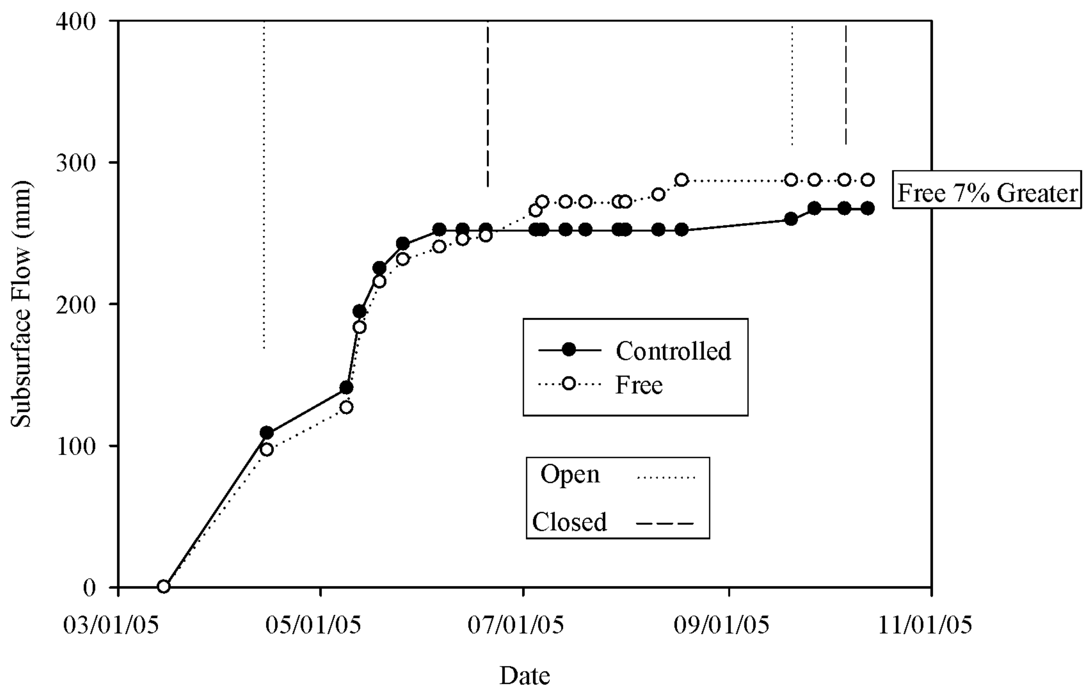

Figure 2.2. In-season subsurface flow measurements in 2005.

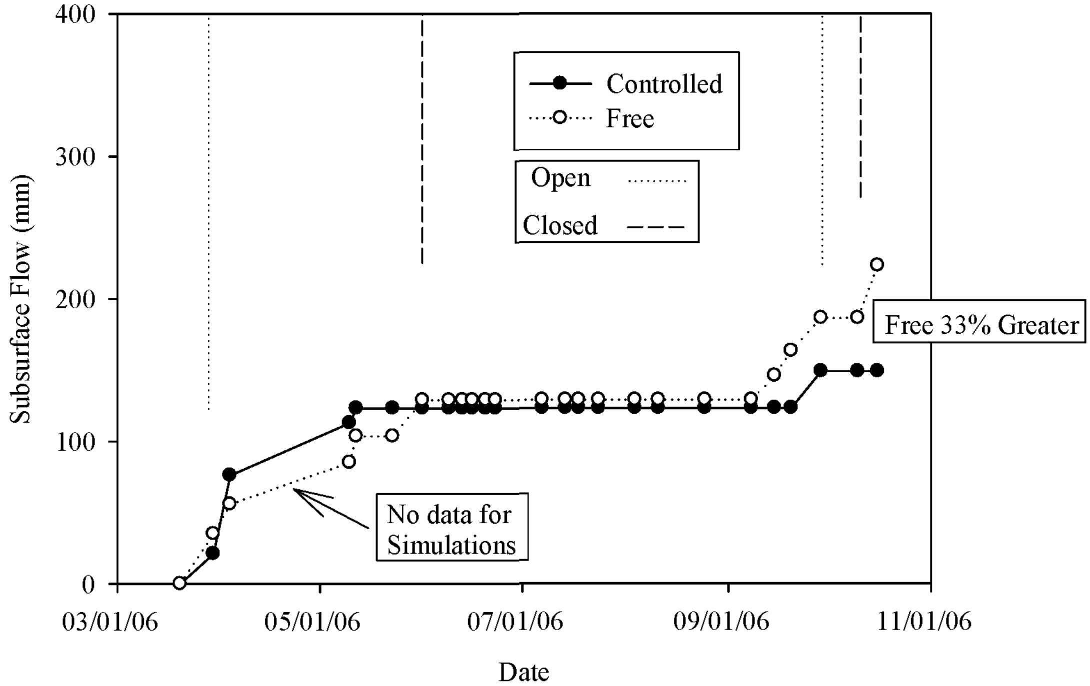

Figure 2.3. In-season subsurface flow measurements in 2006

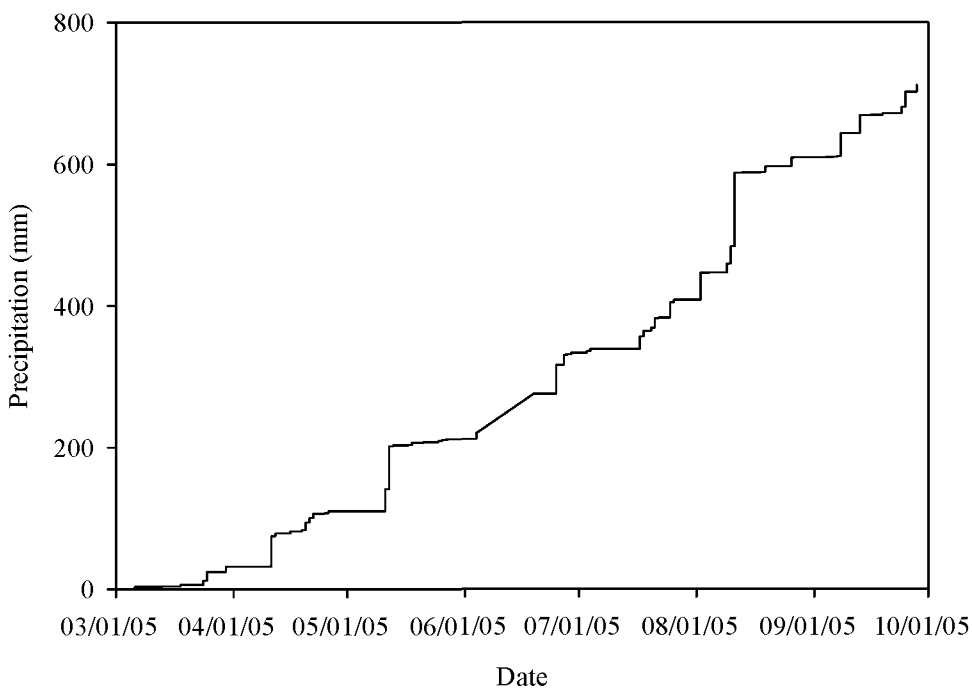

Figure 2.4. Precipitation for the 2005 drainage season.

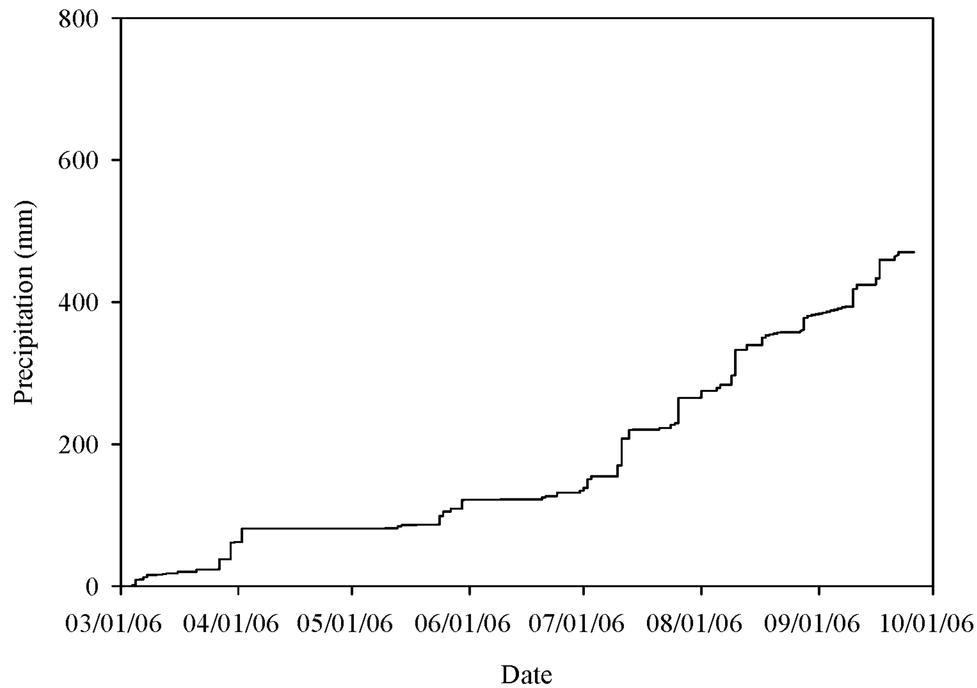

Figure 2.5. Precipitation for the 2006 drainage season.

The in-season monitoring period during 2005 had negligible surface runoff associated with both treatments. In 2006 there was surface runoff for both treatments, but overall there was little runoff due to lower than average rainfall. The surface runoff totaled 31 mm and 33 mm for the CD and FD plots, respectively.

In addition to subsurface drainage and surface runoff, surface moisture at zero to six centimeters and depth of water were taken in 2006 for the CD lysimeters (Figure 2.6, Figure 2.7). Corn yield data was measured in both seasons for both treatments (Table 2.4). Over the season, surface moisture varied greatly with the weather variations, but CD and the FD plots were similar at every measurement. Conversely, corn yield measurements showed CD consistently had a higher yield. The CD plots had a 20% greater yield in 2005 and 9% higher yield in 2006 for a two-year average that was 14% higher, but the increase was not significantly different. The depth of water measurements were particularly interesting because the water table fell steadily during the growing season and became higher after late summer rains before FD was established for harvest, which may suggest the retained water was being used for evapotranspiration. The periods of CD and FD were marked by lines in Figure 2.7 for perspective over the season.

Table 2.4 Corn yield data by plot and treatment (kg/ha).

Treatment	Controlled			Free			% Diff CD vs. FD
Year	1	2	4	3	5	6	
2005	8252	11136	12776	10139	5771	10858	20%
2006	12114	10796	12177	10482	10419	11298	9%
Average		**11208**			**9828**		**14%**

Std Err = 755

Values were not significantly different

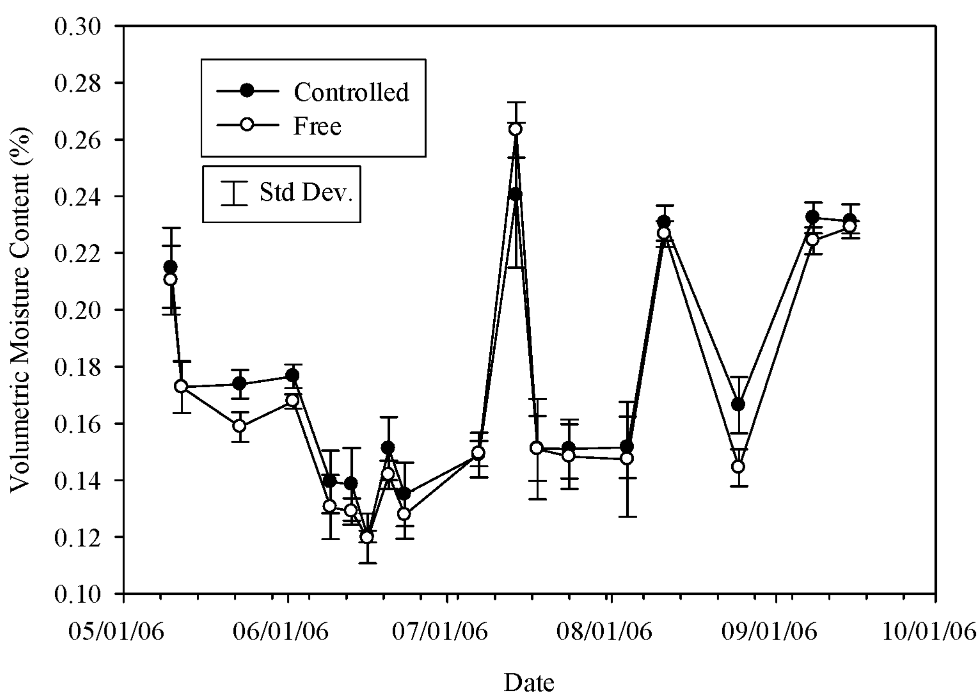

Figure 2.6. Surface moisture measurements for 2006.

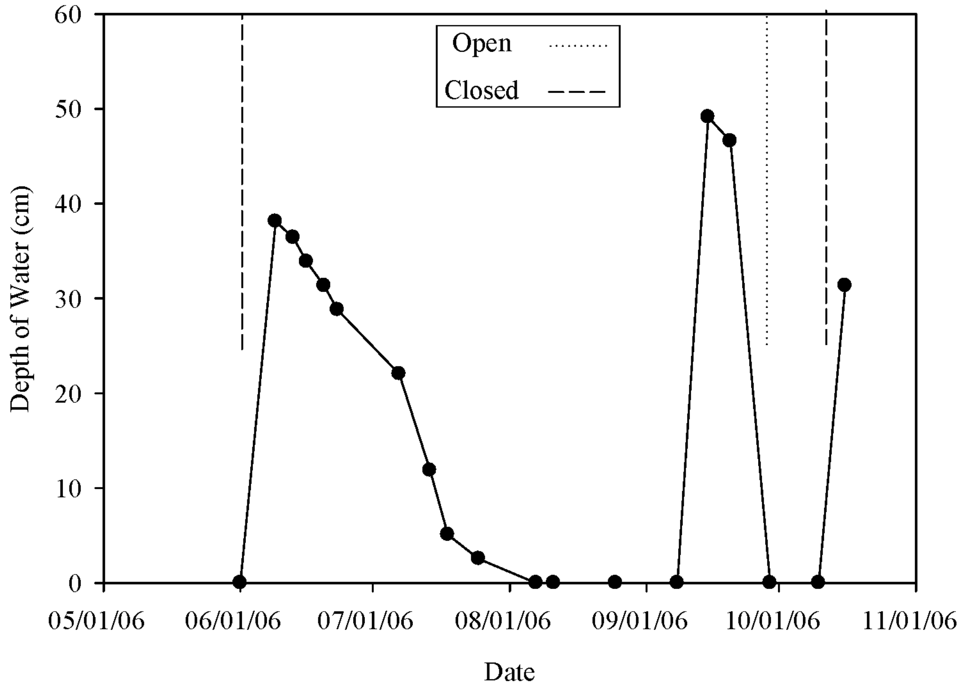

Figure 2.7. Depth of water for the 2006 growing season.

From simulation A (Figure 2.8, Table 2.5), surface runoff for CD was 20% of the total rainfall and was 13% of the total rainfall for FD. This shows that surface runoff increased 54% when CD was compared to FD, but was not significantly different. Simulation B (Figure 2.8, Table 2.5) shows surface runoff for CD to be 30% of the total rainfall, which is a 130% increase when compared to FD and was significantly different. The results for simulation D (Figure 2.9, Table 2.5) show that surface runoff for CD was 43% of the total rainfall and FD was 23% of the total rainfall. This was an 87% increase when CD was compared to FD, but was not significantly different. Although statistical significance was not exhibited in some of the simulation results, the increase in surface runoff is evident.

Table 2.5. Simulation runoff expressed as % total rainfall.

Treatment Comparisons	Sim	Reps			Average
CD	A	26	20	13	20
FD	A	22	11	5	13
CD	B	35	26	30	30*
FD	A	22	11	5	13*
CD	D	52	27	49	43
FD	D	30	38	2	23

Std Err = 5.01
* significantly different at $p \leq 0.05$
CD = Controlled Drainage
FD = Free Drainage

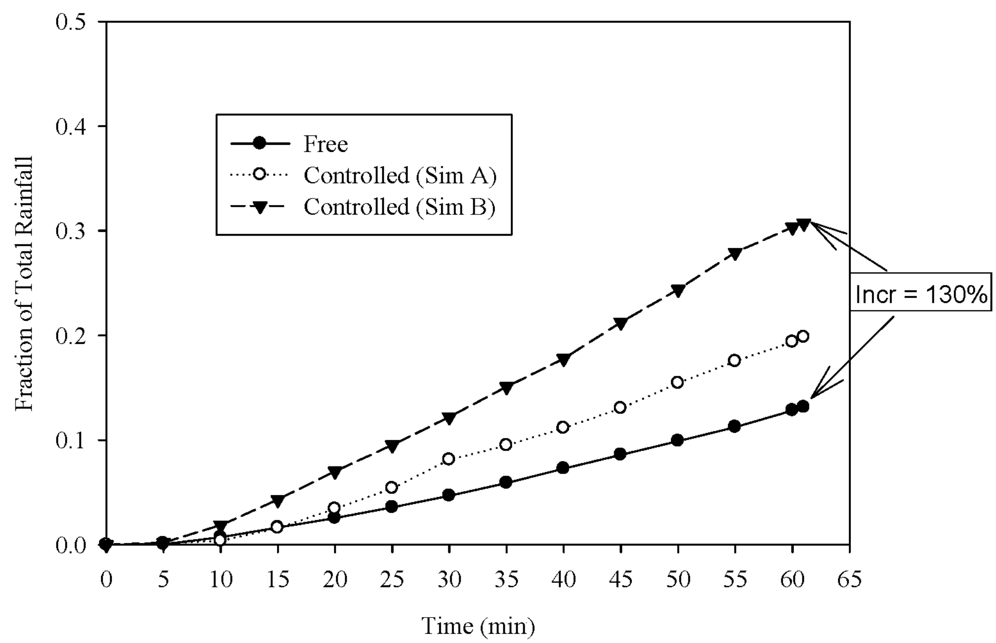

Figure 2.8. Surface runoff measurements for simulation A and B.

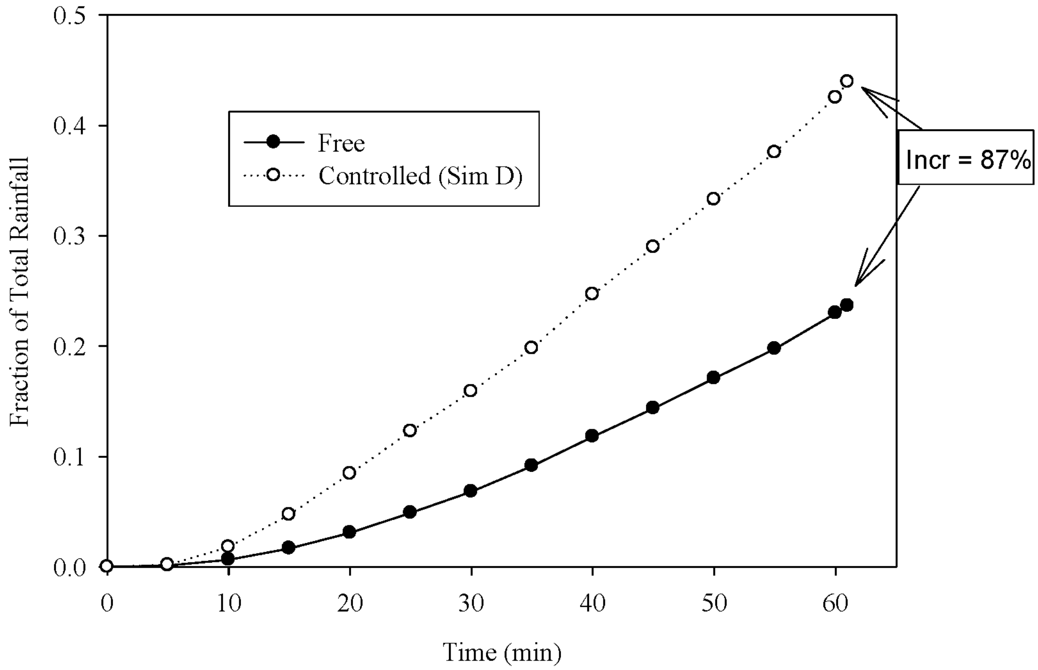

Figure 2.9. Surface runoff measurements for simulation D.

During simulation A the water table in the CD plots was approximately 90 cm below the soil surface, which is 30 cm lower than the intended 60 cm below the soil surface. However, a water table of 60 cm below the soil surface was then used in simulation B. Taking these conditions into consideration, the results in simulation A and B support the model findings in Skaggs et al. (1995b) that surface runoff increases as CD was intensified by raising the CD level from 90 cm below the soil surface in simulation A up to 60 cm below the soil surface in simulation B.

CD and FD surface runoff from simulation D (Figure 2.9) was greater than that of simulation A and B (Figure 2.8). Due to the saturation pre-treatment in simulation D more air was replaced by water in the soil pores when compared to the pre-wetting of simulations A and B. This left the soil in a state where it had a lower soil water storage capacity due to the higher amount of moisture in the soil. This lead to the surface runoff increasing for the

FD plots in simulation D by 77%, when compared to the FD plots in simulation A, and the CD surface runoff in simulation D increased by 115% and 43 % when compared to the CD plots in simulation A and B, respectively, and by 230% when compared to the FD in simulation A.

To further document the water balance, subsurface drainage data was also measured during the simulations. The subsurface drainage for simulation A and B can be found in Figure 2.10 and subsurface drainage for simulation D can be found in Figure 2.11 with CD having an average of 42% lower subsurface drainage from the simulations. In addition, a water balance summary considering runoff and drainage from the simulations can be found in Table 2.6. In simulation A, the CD plots only had 20% of total rainfall as surface runoff release from the system. The other 80% was held in the soil due to the 90 cm water table instead of the 60 cm water table during the simulation. The FD plots released 79% of the total rainfall when both the surface runoff and the subsurface drainage were considered from the same simulation. Furthermore, in simulation B, the CD plots only accounted for 53% of the total rainfall when both runoff and drainage were considered. Since 100% of the total rainfall was not accounted for by runoff or drainage in either simulation A or B it was determined that there was still water storage capacity in the lysimeters prior to simulations A and B being conducted.

A saturation pre-treatment was then developed because of the higher likelihood of minimizing water storage capacity in each lysimeter when the simulation occurred. It was then concluded following simulation D that there was minimal water storage capacity in each lysimeter when the simulation occurred. This was determined since the runoff and drainage accounted for 100% of the total rainfall in the FD plots and 97% in the CD plots in simulation D. Again, a summary of the water balance can be found in Table 2.6. Additionally, to supplement the water balance investigation through the rainfall simulations, the water that was pumped out after the saturation pre-treatment was measured, giving drained porosity measurements. These measurements concluded that the CD plots had an average of 31 mm less drained porosity than FD (Figure 2.12). The difference was due to the fact that a water table, established at 60 cm below the soil surface, was left in the CD plots.

Table 2.6. Rainfall simulation water balance summary.

	Controlled			Free		
Simulation	Runoff % total	Drainage % Total	Overall % Total	Runoff % total	Drainage % Total	Overall % Total
A	20	0	20	13	66	79
B	23	30	53	n/a	n/a	n/a
D	43	54	97	23	77	100

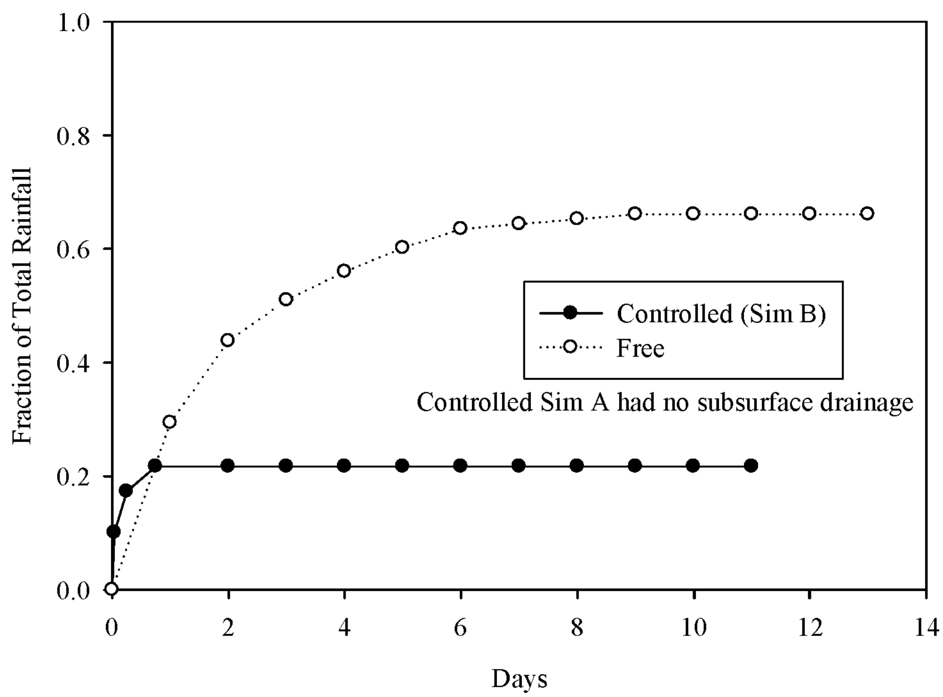

Figure 2.10. Subsurface drainage measurements for simulation A and B.

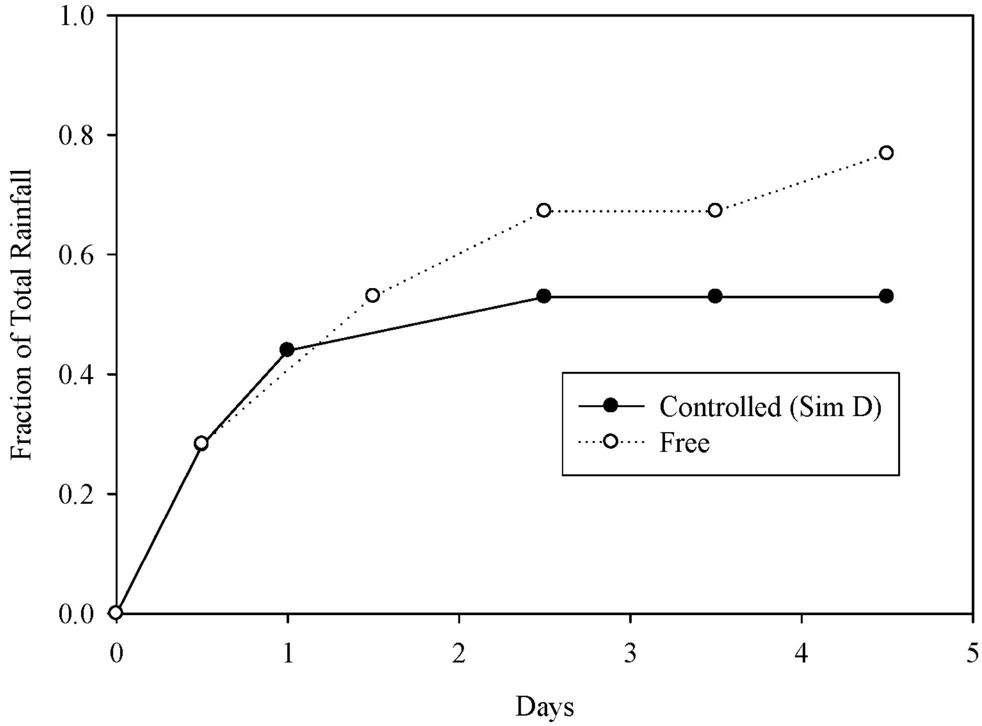

Figure 2.11. Subsurface drainage measurements for simulation D.

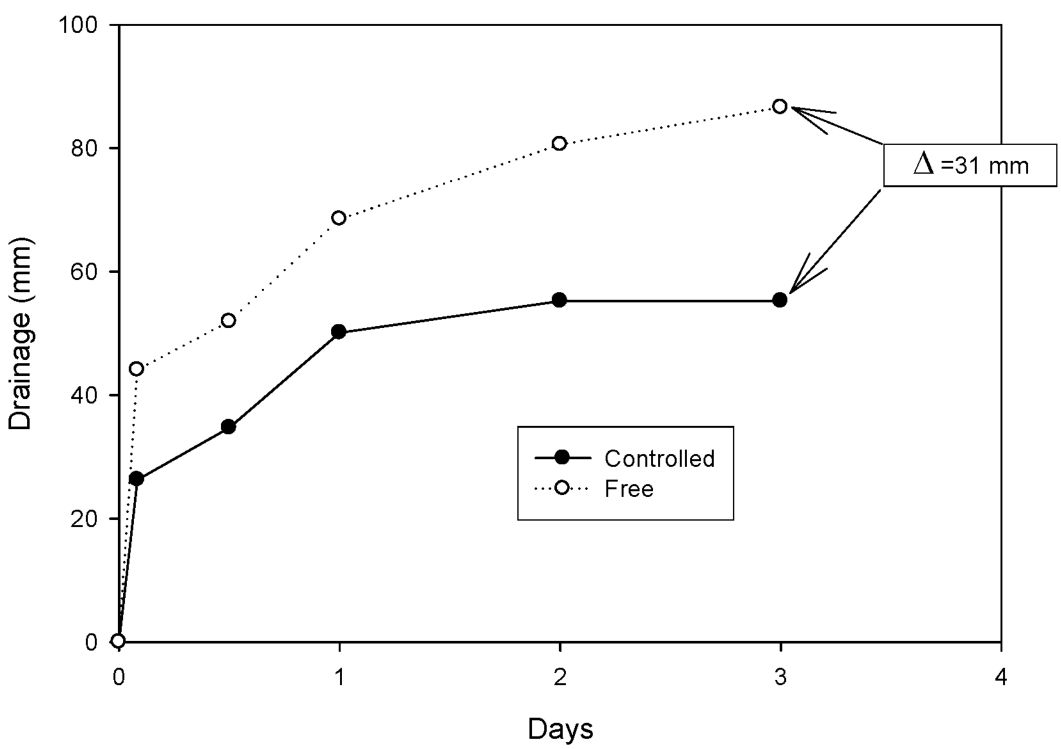

Figure 2.12. Drained porosity summary by treatment.

2.5 Conclusions

In this study, CD supported previous research both by the natural and simulated subsurface drainage data collected. The CD natural drainage was reduced by 20% over two years and falls well within the common range of previously reported values, but was not significantly different. Corn yield was greater by 14% over two years for CD, but was not significantly different. This increase was possibly because more water was available for the crop to use during the growing seasons. The rainfall simulations that were conducted in the fall of 2005 and the spring of 2006 also support the previously reported surface runoff data discussed earlier. In all simulation scenarios, surface runoff was greater in the CD plots when compared to the FD plots with the exception of simulation C. Surface runoff did not occur on the CD plots in simulation C with a six-month, one-year design storm and it was concluded not to continue with the FD. Taking into account the two-yr, one-hour design storm set for the other three simulations, this was cause for concern and may be a limitation associated with CD systems. At the very least, it is a reason to study the overall water balance, in particular surface runoff, in more depth on a larger scale.

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CHAPTER 3. CONTROLLED DRAINAGE AND ALTERNATIVE TREATMENTS FOR SUBSURFACE DRAINAGE MANAGEMENT

Journal not identified

Kyle D. Riley and Matthew J. Helmers

3.1 Abstract

Nine plots were monitored during a two-year period to determine the effects of Controlled Drainage (CD) on subsurface drainage, water table depth, and nitrate concentrations. Two CD conditions were implemented; Controlled Drainage Variable (CDV), that allows drainage during planting and harvesting and Controlled Drainage Fixed (CDF), which is closed year-round. A biofilter was also established in two of the nine plots to explore alternative treatments to reduce nitrate concentrations. CDV and CDF decreased subsurface drainage by 58% and 92%, respectively. Data collected also showed that a biofilter, consisting of wood chips as a carbon source, reduced nitrate concentrations by an average of 35% over two years. With these lower values, nitrate loading was reduced by 47% and 93% by the CDV and CDF, respectively, and by 35% with the use of the biofilter. Water table depth was measured every five minutes on average over the same two-year period and showed potential water retention in a CD system.

3.2 Introduction

The hypoxic zone, caused by excess nutrients, in the Gulf of Mexico is becoming a major problem for many different groups, whether it is associated with the recreation or fisheries industry. The Mississippi River is fed by the upper Midwestern states and the excess nutrient export from these states has been implicated as a major contributor to the hypoxic zone (Rabalais et al., 1999; Sen Gupta et al., 1996; Rabalais, 1994).

These implications act as a motivating factor to prevent excess nutrients, particularly nitrate-nitrogen, from reaching the rivers and lakes of the Midwest. One practice that has been investigated to thwart this excess nutrient export is Controlled Drainage (CD). CD is a method of subsurface drainage water management that has shown positive impacts on reducing the volume of subsurface drainage exiting an agricultural system. Whether as a tool to minimize the nitrate loading from an agricultural field or used to reduce the overall subsurface drainage, it has shown positive results.

Values for subsurface drainage volume reduction by CD fall in the range of 10% to 40 % (Amatya et al., 1998; Drury et al., 1997; Drury et al., 2001; Evans et al, 1995; Fouss et al., 1987; Gilliam and Skaggs, 1986; Skaggs et al., 1995a; Skaggs et al. 1995b; Tan et al., 1998). Although a reduction as high as 65% has been reported (Lalonde et al., 1996), this amount of reduction has been rare in previous research. Coinciding with the decrease in subsurface drainage volume, were reductions in nitrate export. In previous research there has been a wide range of nitrate loading reduction when CD is compared with Free Drainage (FD). Reductions were commonly reported around 20% to 40% (Brevé et al. 1997; Brevé et al., 1998; Deal et al., 1986; Drury et al., 1996; Drury et al. 2001; Elmi et al., 2000; Evans et al., 1995; Gilliam and Skaggs, 1986; Ng et al., 2002; Skaggs and Gilliam, 1981; Skaggs et al., 1995a; Skaggs et al., 1995b; Tan et al., 1998).

Despite these positive results, there is still a need to further understand CD systems. Even though CD has been reported to decrease nitrate loading, whether nitrate concentrations are reduced or not is still under debate, despite research on the subject (Deal et al., 1986;

Drury et al., 1996; Drury et al., 2001; Kalita and Kanwar, 1993; Lalonde et al. 1996; Mejia et al., 1998; Ng et al., 2000; Ng et al., 2002).

In other research, a biofilter was used to remediate nitrate release. Van Driel et al. (2006) showed a biofilter's nitrate concentration removal potential from tile drainage. In this study, two different types of wood-based biofilters were used to remediate tile drainage water from two different sources. The wood chips acted as a carbon source that eventually released nitrogen as a gas. A lateral flow biofilter was used to remediate an agricultural drainage tile and an upflow biofilter was used at a golf course. The lateral flow biofilter achieved 33% nitrate removal and the upflow biofilter achieved 52% removal.

Furthermore, understanding the water table dynamics of CD over a period of time would be valuable information for determining the full extent of a CD system. This is important because it can be determined if water is being retained in the soil with a CD treatment. If water is being retained in the soil, inferences can be made on the fate of the retained water. Inferences such as, lateral seepage, evapotranspiration, or deep percolation.

While previous research has shown that CD has potential to reduce subsurface drainage volume and nitrate loading, there is still a need to understand the performance of the practice under varying environmental conditions. Although some information on nitrate concentrations exists, there is a strong need to further document CD and other potential solutions to reduce nitrate concentrations exiting subsurface drainage systems. The objectives of this research were to quantify the nitrate concentrations under CD, FD, and before and after a biofilter; document water table depth in a CD structure over time; and further quantify subsurface drainage volumes under CD versus FD systems.

3.3 Materials and Methods

3.3.1 Research Site

The research site is comprised of nine plots under a corn and soybean rotation. The site consists of Taintor Silty Clay Loam (Fine, smectitic, mesic Vertic Argiquolls) soil (Table 3.1). The research plots are 140 m by 90 m and the drain depth and spacing is 1.2 m and 20 m, respectively. A schematic of the research site can be found in Figure 3.1. The slope seen in Figure 3.1 shows the predominately flat landscape. The site was established in late 2002 with the instrumentation installed in 2003 and it is located in southeast Iowa, near Pekin, IA. This research took place over the 2005 and 2006 growing seasons, and all plots included both corn and soybeans. In both years a split-plot rate of 140 and 196 kg/ha of nitrogen was applied to the corn in the spring with 90 kg/ha being applied before planting and the remainder applied as a spring side dress. The nitrogen source was urea ammonium nitrate fertilizer. Spring chisel plow with field cultivation was implemented in the both seasons.

Table 3.1. Plot averaged soil conditions

Depth (cm)	% Sand	% Silt	% Clay
0-15	13.44	48.67	37.78
15-30	13.56	48.78	37.56
30-60	13.11	47.33	39.44
60-90	12.56	47.78	39.44
90-120	12.56	56.00	31.11

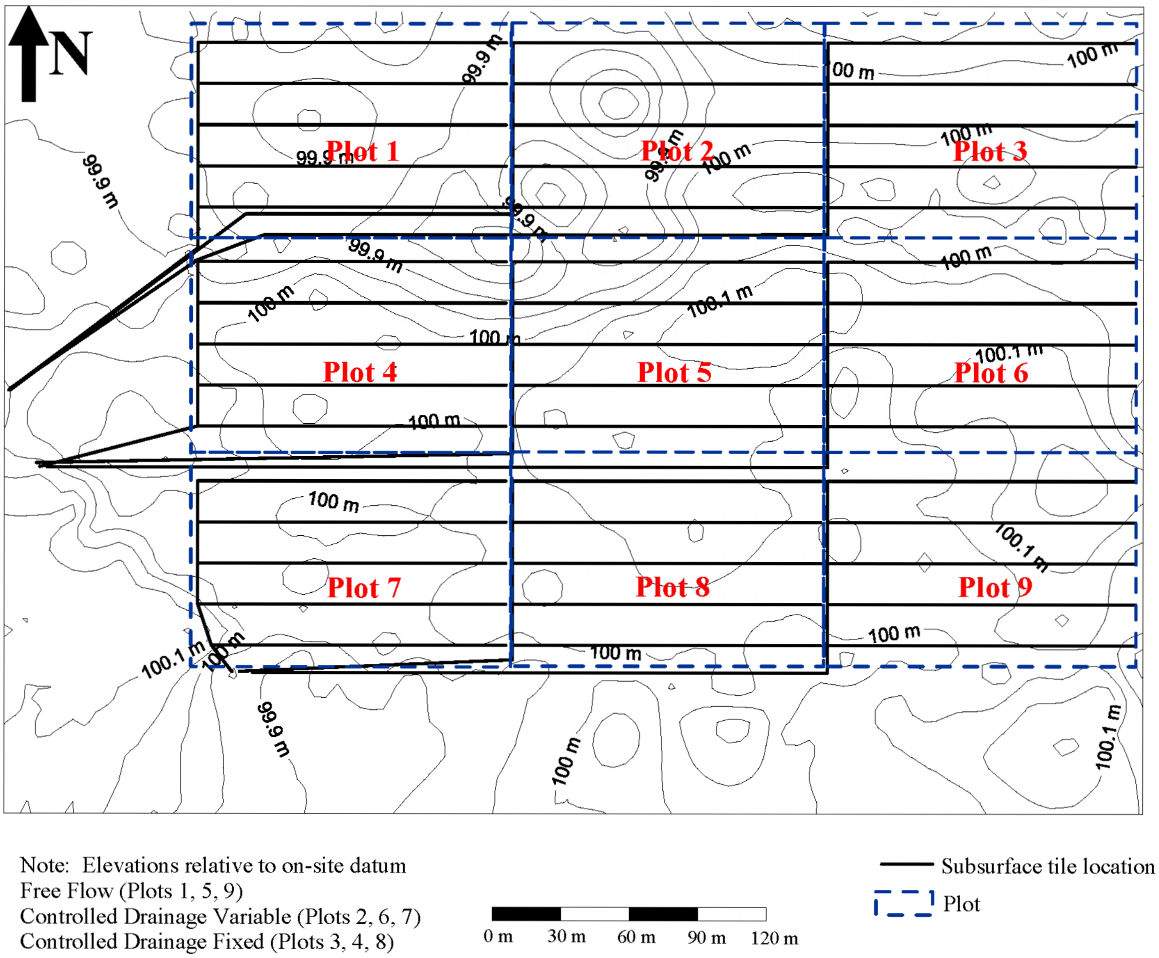

Figure 3.1. Pekin, IA research site schematic.

3.3.2 Treatments

The nine plots that make up the research site were divided into three different treatments using a Latin square design. Each treatment was established in three plots each. The three treatments were Free Drainage (FD), CD Variable (CDV), and CD Fixed (CDF). Biofilters were established in one FD plot and one CDF plot, which consist of a carbon source, wood chips in this case. The biofilter is 30 m long and 30 cm wide installed at the exit of the tile drain. The plots under FD conditions drain similar to a conventional tile drained system with the drain open during the entire year. The drain depth for the FD plots was 120 cm and the plots under CDV conditions drain similar to FD during planting and harvesting and then during the growing season and during winter the water level in the CDV plots was allowed to reach 60 cm below the soil surface before draining. The water level in the CDF plots was allowed to reach 60 cm below the soil surface before draining during the entire calendar year. However, the time period that the plots were under FD or CDV conditions was dependent on the particular growing season. In 2005, the CDV plots began CD conditions on June 14th and were under FD conditions from Sept. 8th to Nov. 17th for harvest. In 2006, the CDV plots began CD conditions on June 1st and were under FD conditions from Sept. 28th to Nov. 7th for harvest (Table 3.2).

Table 3.2. Dates for the controlled drainage variable system.

Year	Structures Open	Structures Closed
2005	4/14 – 6/14 9/8 - 11/17	1/1 - 4/14 6/14 - 9/8 11/17 - 12/31
2006	3/31 - 6/1 9/28 - 11/7	1/1 - 3/31 6/1 - 9/28 11/7 - 12/31

3.3.3 Data Collection

Data was collected throughout the year at various intervals. To gather subsurface drainage and precipitation data, a data logger recorded values every five minutes and the data logger was downloaded every two months. Drainage and precipitation data was also recorded manually to verify the electronic data collections. Water table data was collected using a capacitance level logger that recorded every five minutes. The data was downloaded every two months as well. Water samples were taken from each plot every five to seven days during high flow periods and less often during low flow periods and were analyzed at the Wetland Research Lab on the campus of Iowa State University to determine nitrate-nitrogen concentrations. All water samples were preserved by freezing at collection and acidification in the lab by adding sufficient concentrated sulfuric acid to yield a 0.1% sulfuric acid concentration. Acidified samples can be stored at room temperature. Nitrate analysis was done using a modified version of the second derivative UV spectroscopy method and analysis was carried out using a UV-Visible spectrophotometer.

3.3.4 Statistical Analysis

Statistical analyses were conducted using Statistical Analysis System software (SAS, 2003). The general linear model (GLM) procedure was used to determine the statistical significance of treatment effects on nitrate concentration and subsurface drainage. Differences among treatment means were determined to be significant at $p \leq 0.05$.

3.4 Results and Discussion

Subsurface drainage volume data that was collected during this study showed FD plots having an average of 91 mm of drainage in 2005 and 87 mm in 2006 (Figure 3.2, Figure 3.5, and Table 3.3). The CDV plots (Figure 3.3, Figure 3.6, and Table 3.2) had an average of 35 mm in 2005 and 29 mm in 2006 with all three plots showing drainage in both years. CDV plots showed a two-year average 64% lower than that of FD and were statistically different. CDF plots (Figure 3.4, Figure 3.7, and Table 3.2) carried a two-year average of 92% lower than that of FD with a significant difference. CDF drainage was 6 mm and 5 mm in 2005 and 2006, respectively, with all three plots in 2005 and only one plot in 2006 having drainage. However, due to the absence of drainage tiles installed at the borders of each plot, the differences in drainage may be inflated and this should be monitored in future research. Nonetheless, drainage in both years was lower than expected due to lower than average rainfall in both 2005 and 2006. Figures 3.8 and 3.9 show the precipitation received in 2005 and 2006. Both years were nearly 400 mm below the regional average.

As a result of the decreased drainage volume associated with CD, nitrate loading was also reduced by both CDV and CDF. Loading reductions of 47% and 93% were attained by the CDV and CDF treatments, respectively (Table 3.4).

Table 3.3. Subsurface drainage (mm).

Treatment Comparisons	Year	Reps			Average	Std. Dev.
FD	2005	120	131	22	91[a]	60
CDV	2005	47	28	29	35[b]	11
CDF	2005	6	4	9	6[c]	2.5
FD	2006	103	142	17	87[a]	64
CDV	2006	48	17	21	29[b]	17
CDF	2006	0	0	14	5[c]	8.1
FD	Both	112	137	20	89[a]	62
CDV	Both	48	23	25	32[b]	14
CDF	Both	3	2	12	6[c]	5.2

Different letters designate a significant difference at $p \leq 0.05$

Table 3.4. Nitrate loading summary (kg/ha/yr).

Treatment	Free	CDV	CDF	Biofilter
2005	3.27	2.36	0.31	1.99
2006	6.42	2.18	0.36	4.45
Average	4.85	2.27	0.34	3.22
Std Dev.	2.23	0.13	0.04	1.74

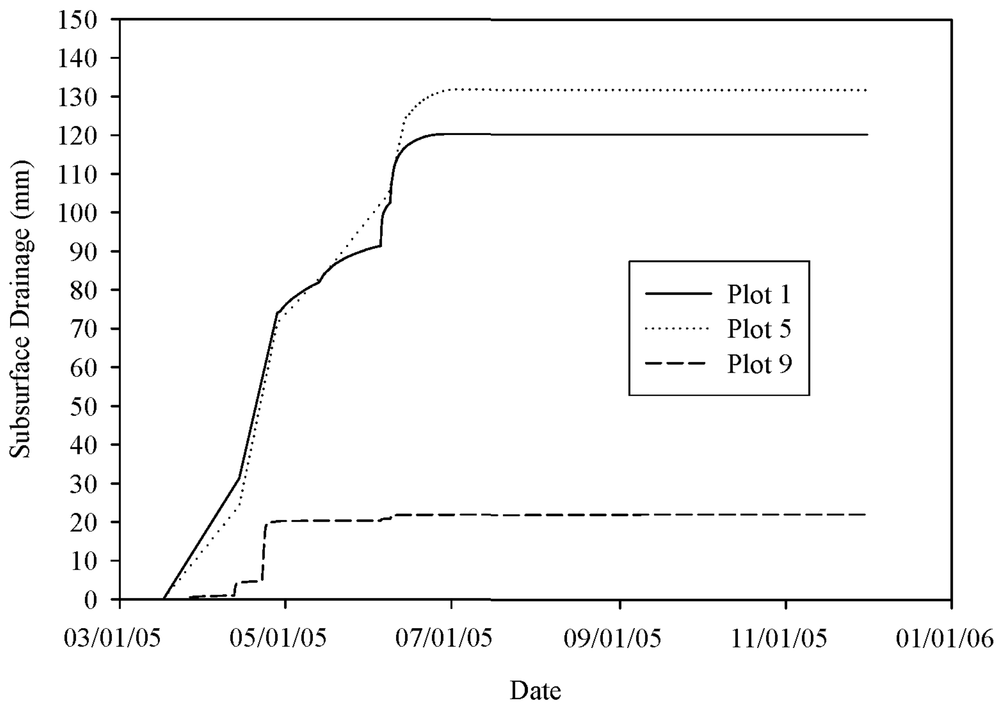

Figure 3.2. 2005 Subsurface drainage from FD plots.

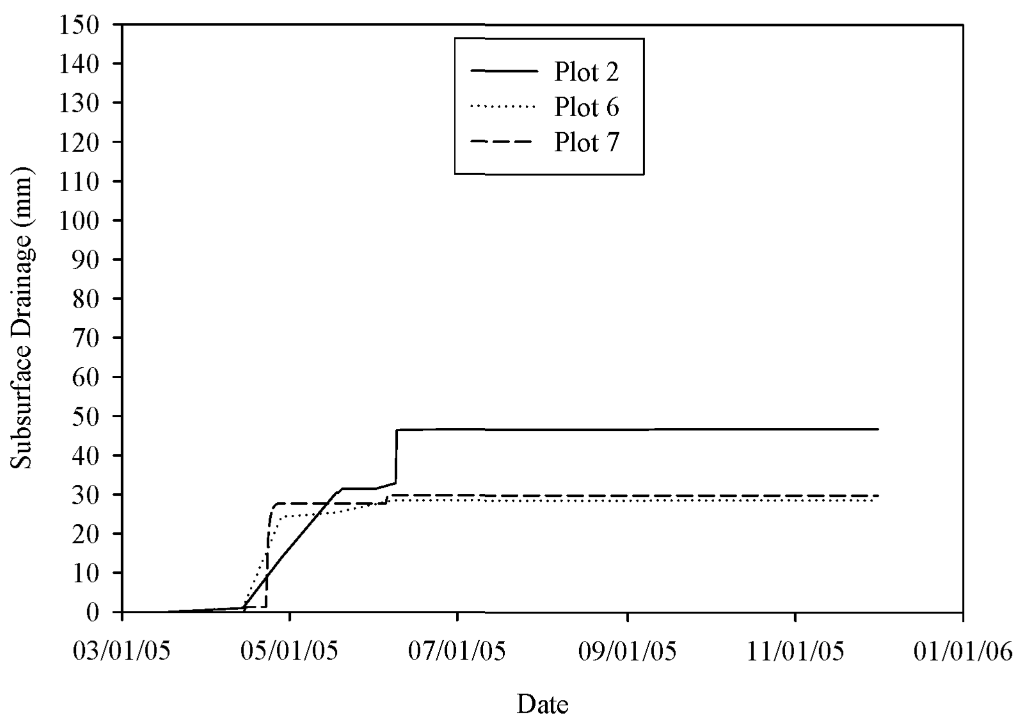

Figure 3.3. 2005 Subsurface drainage from CDV plots.

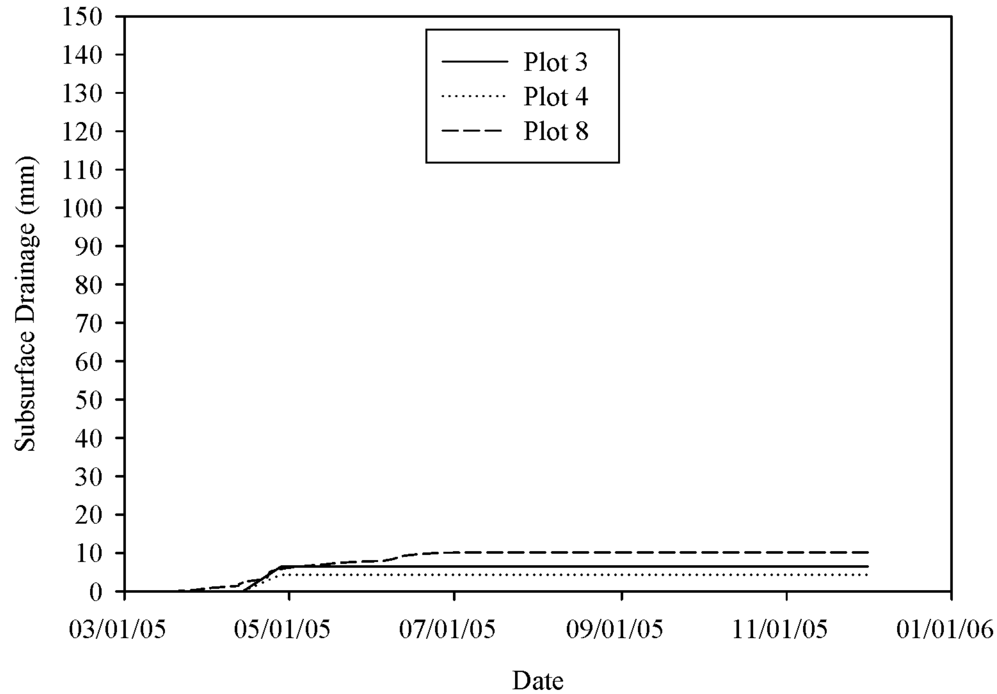

Figure 3.4. 2005 Subsurface drainage from CDF plots.

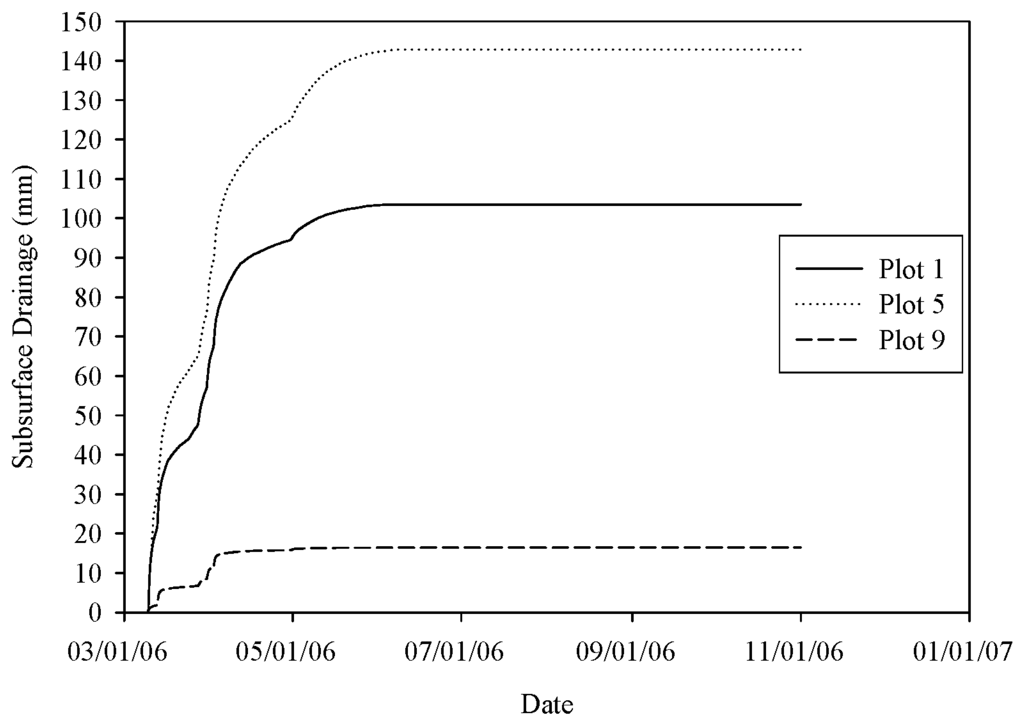

Figure 3.5. 2006 Subsurface drainage from FD plots.

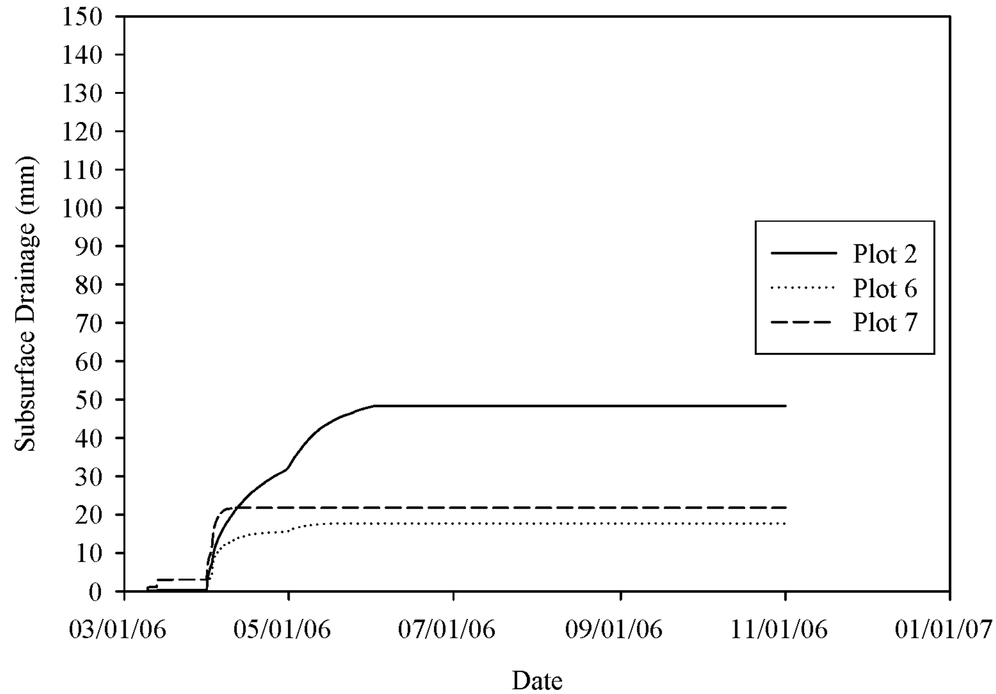

Figure 3.6. 2006 Subsurface drainage from CDV plots.

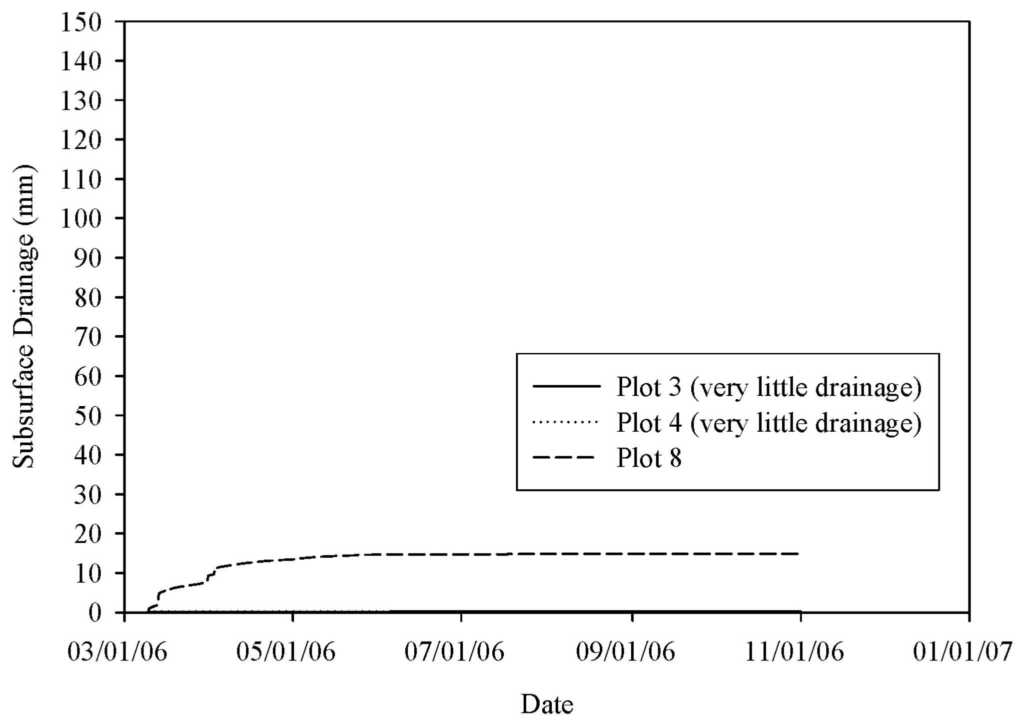

Figure 3.7. 2006 Subsurface drainage from CDF plots.

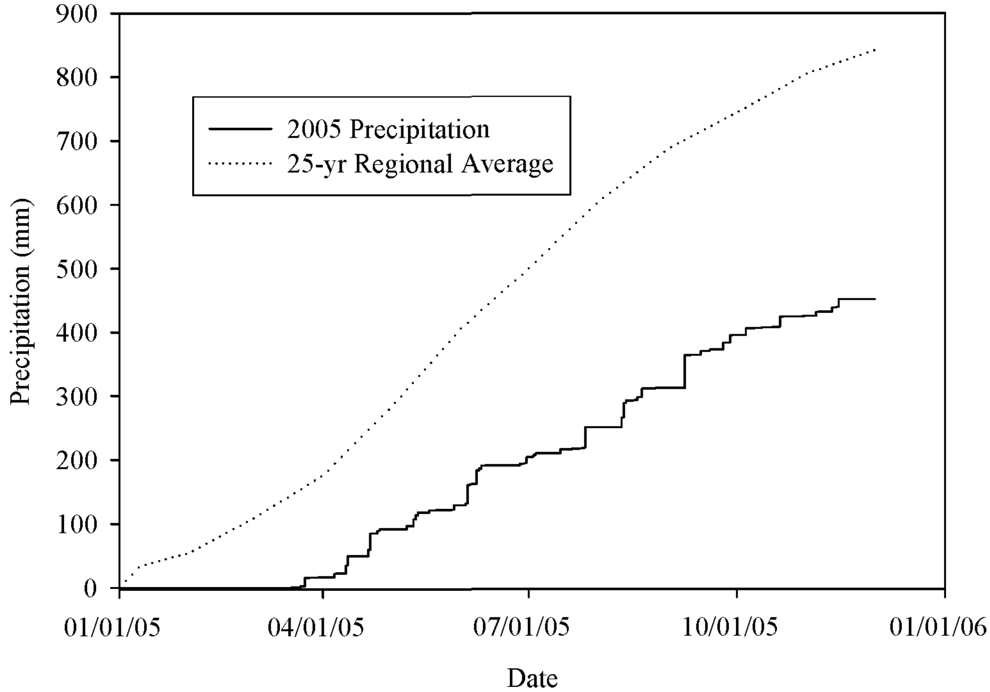

Figure 3.8. 2005 Precipitation compared to the regional average.

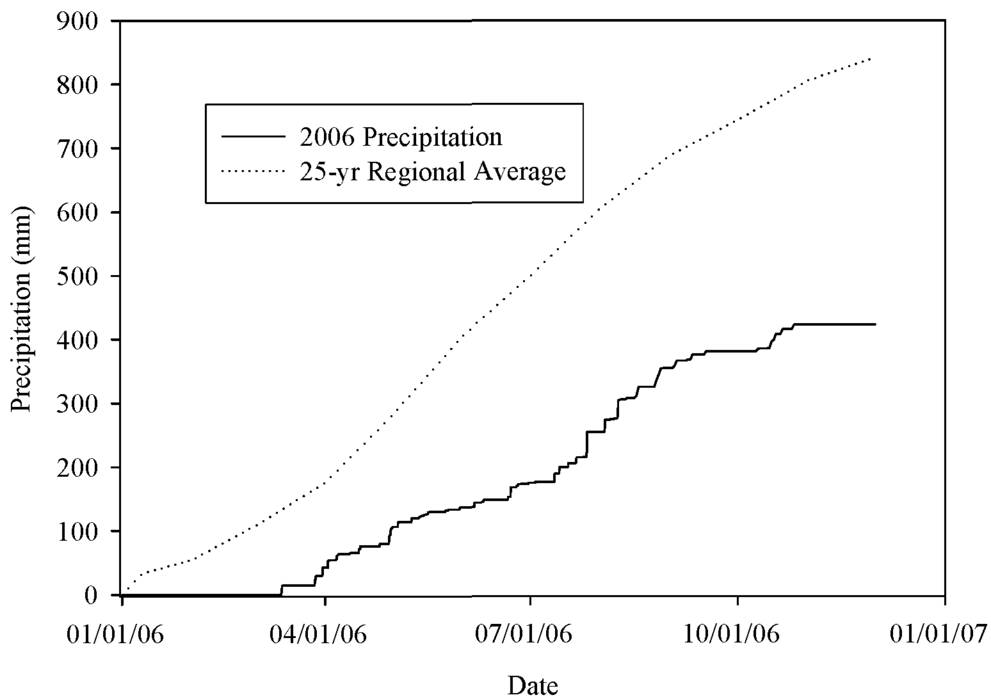

Figure 3.9. 2006 Precipitation compared to the regional average.

Water samples were taken primarily in April and May due to low flow conditions after May in both years. When nitrate data was compared across treatments, there was no direct correlation that CDV or CDF decreased concentrations (Figure 3.10 and Figure 3.11). In addition, the use of the wood-based biofilter decreased the concentrations being released from the FD treatment. This resulted in a two-year average of 35% reduction in nitrate concentrations (Table 3.4, Figures 3.12 and 3.13), which in turn decreased the loading by 35% as well (Table 3.3). With this in mind, the nitrate data post-biofilter was also compared to the CDV Plots. Post-biofilter was again consistently lower (Figure 3.14 and Figure 3.15). The nitrate concentration associated with FD and CDV were statistically the same for both years. Conversely, the post-biofilter measurements were significantly different from both the FD and CDV treatments. Flow-weighted nitrate concentrations were found by calculating total loading over the season and dividing it by the total drainage over the season and can be found in Table 3.5.

Table 3.5. Flow-weighted nitrate concentration (mg/L).

Treatment	Year	Average	Std. Dev.	Year	Average	Std. Dev.	Year	Average	Std. Dev.
FD	2005	6.71^{a}	1.16	2006	6.92^{a}	0.59	Both	6.82^{a}	0.88
CDV	2005	6.4^{a}	2.14	2006	7.2^{a}	1.44	Both	6.8^{a}	1.79
CDF	2005	4.57^{b}	2.49	2006	6.72^{a}	1.86	Both	5.65^{ab}	2.17
Biofilter	2005	4.08^{b}	1.06	2006	4.79^{b}	1.55	Both	4.44^{b}	1.30

Different letters designate a significant difference at $p \leq 0.05$

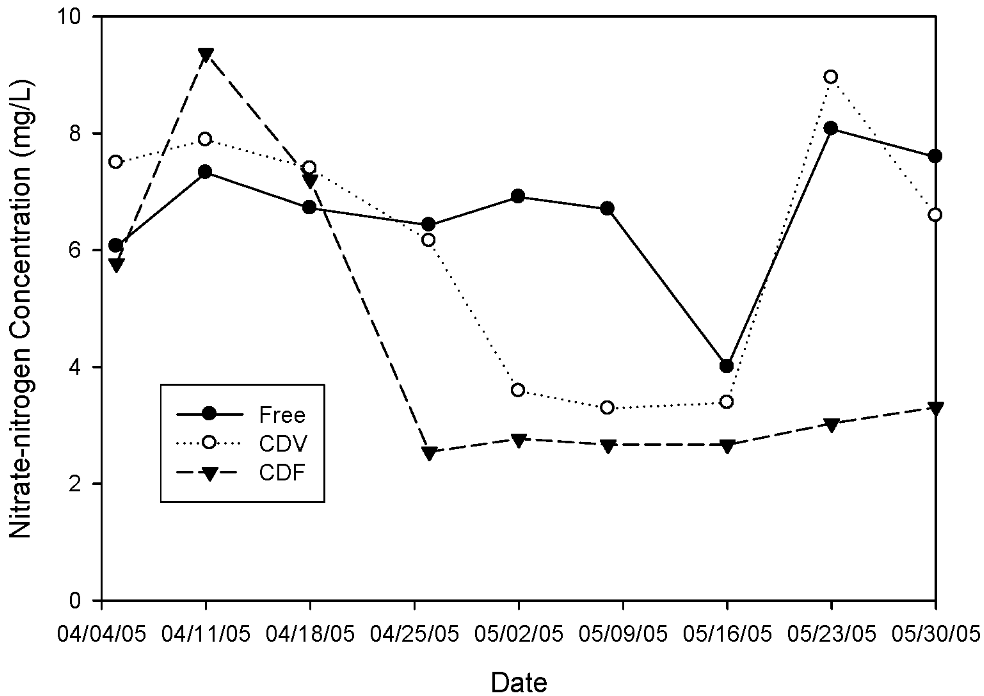

Figure 3.10. 2005 nitrate concentrations by treatment.

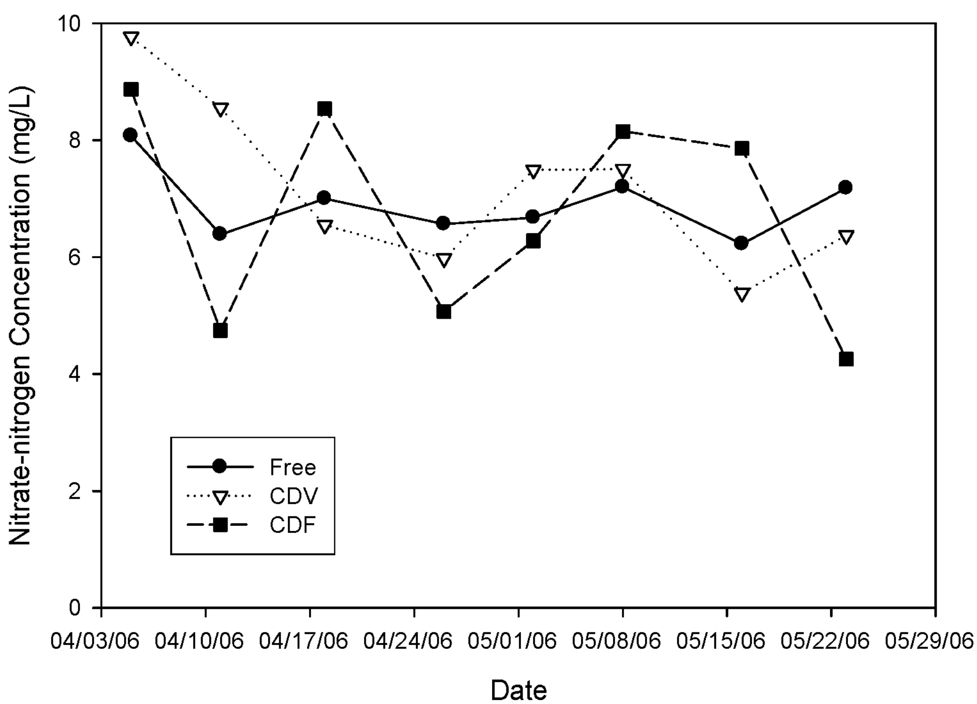

Figure 3.11. 2006 nitrate concentrations by treatment.

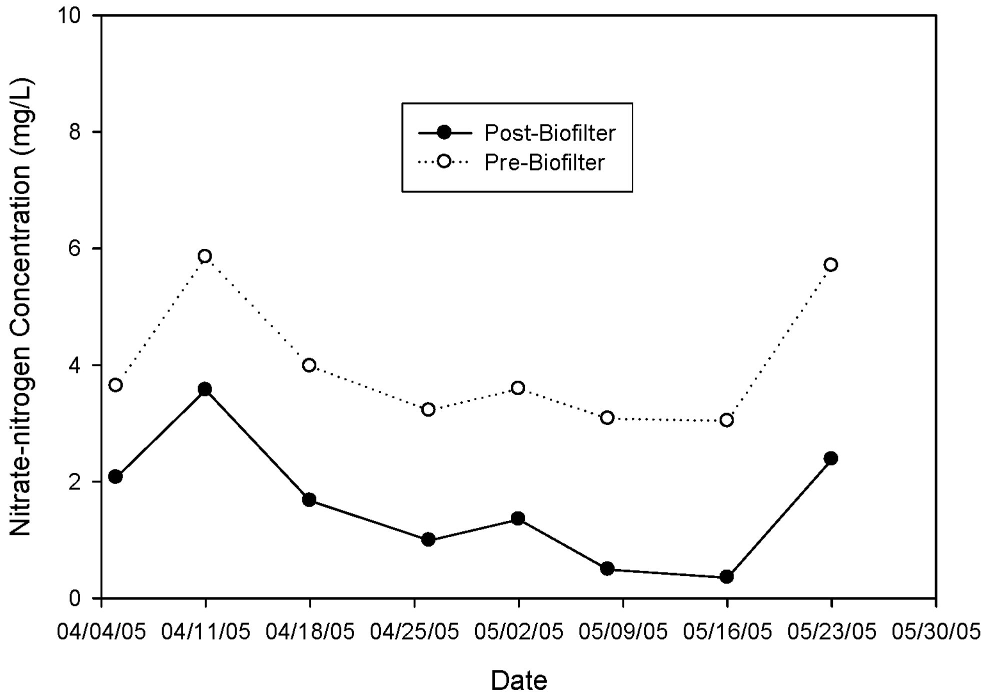

Figure 3.12. 2005 FD biofilter nitrate data.

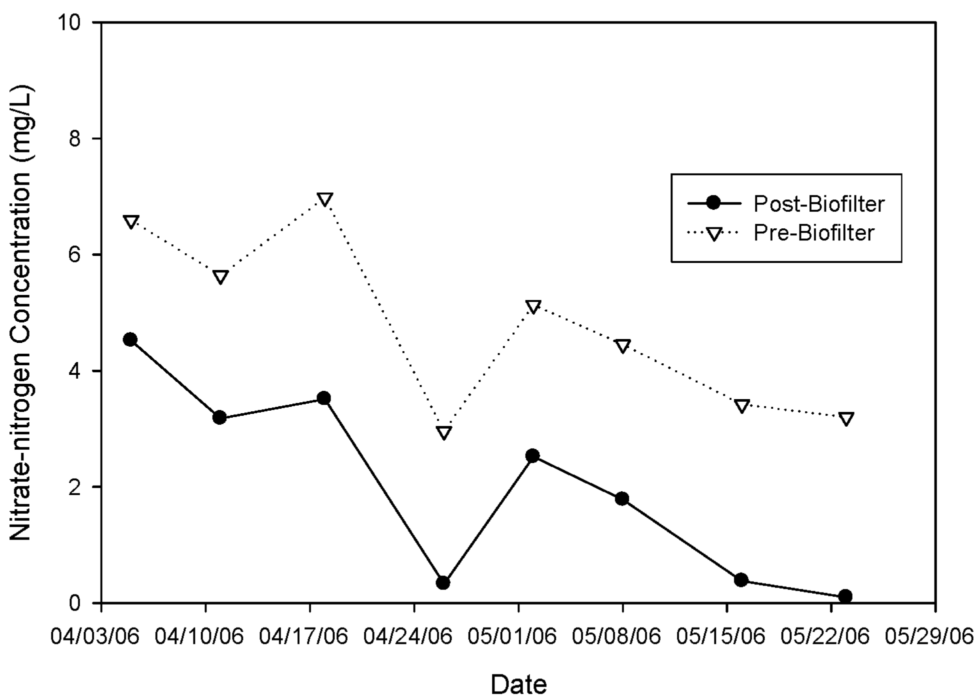

Figure 3.13. 2006 FD biofilter nitrate data.

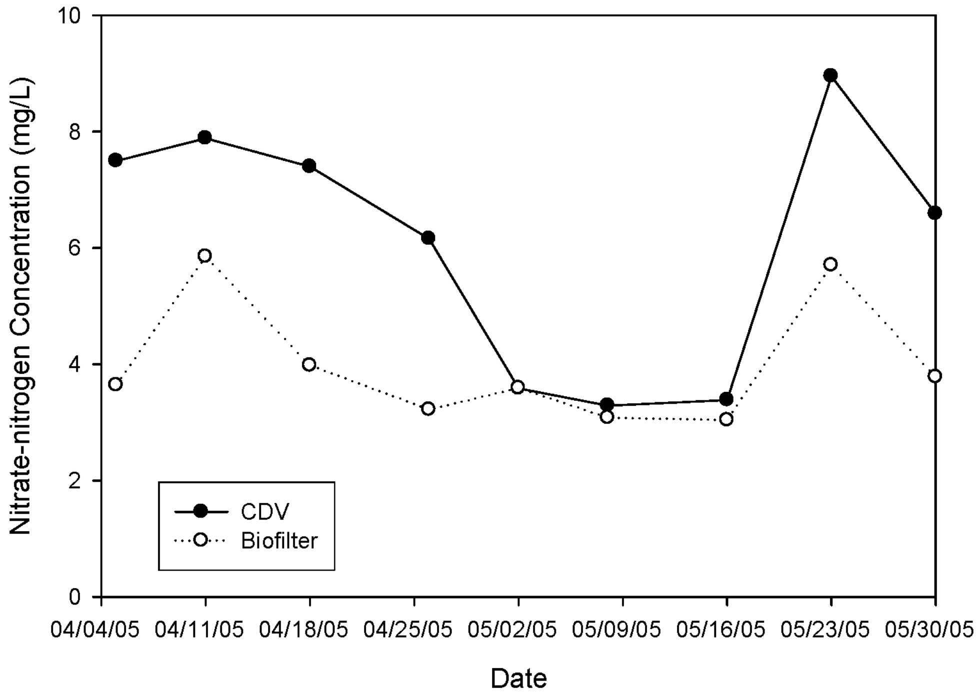

Figure 3.14. 2005 CDV vs. Biofilter nitrate data.

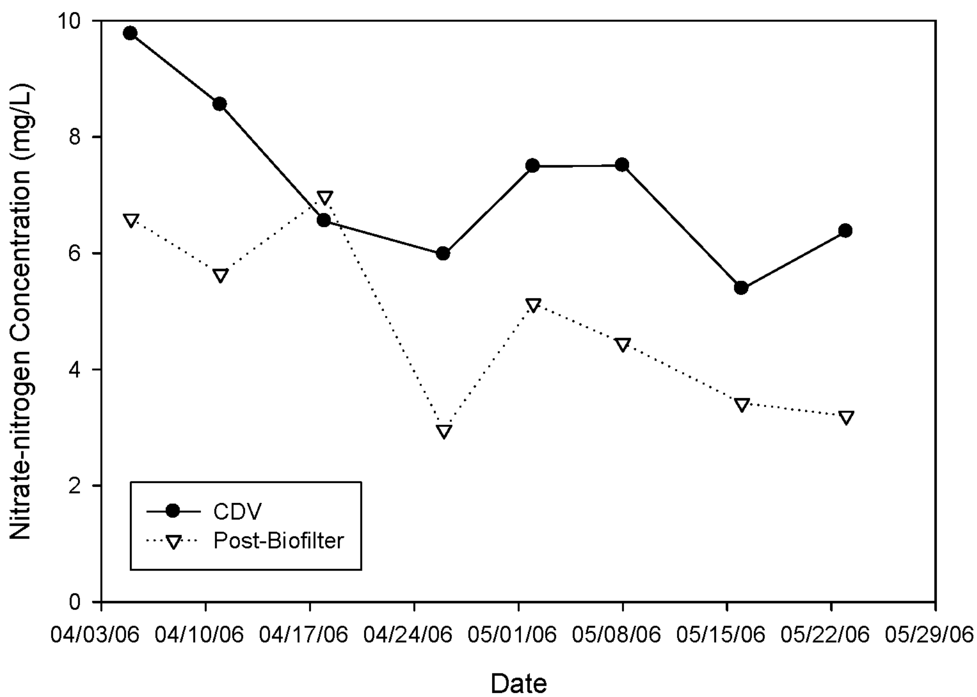

Figure 3.15. 2006 CDV vs. Biofilter nitrate data.

Water table data is being reported as depth of water from the drainage tile to the soil surface. Figure 3.16 through Figure 3.18 show the depth of water in the three CDV plots. All three graphs show the date CD structures were open and closed. This is important because the water table dramatically drops to zero at the open points (FD) and builds the water table back up during the closed sessions (CD). Also, the water table slowly declines during the growing season suggesting that the water is exiting the system via evapotranspiration.

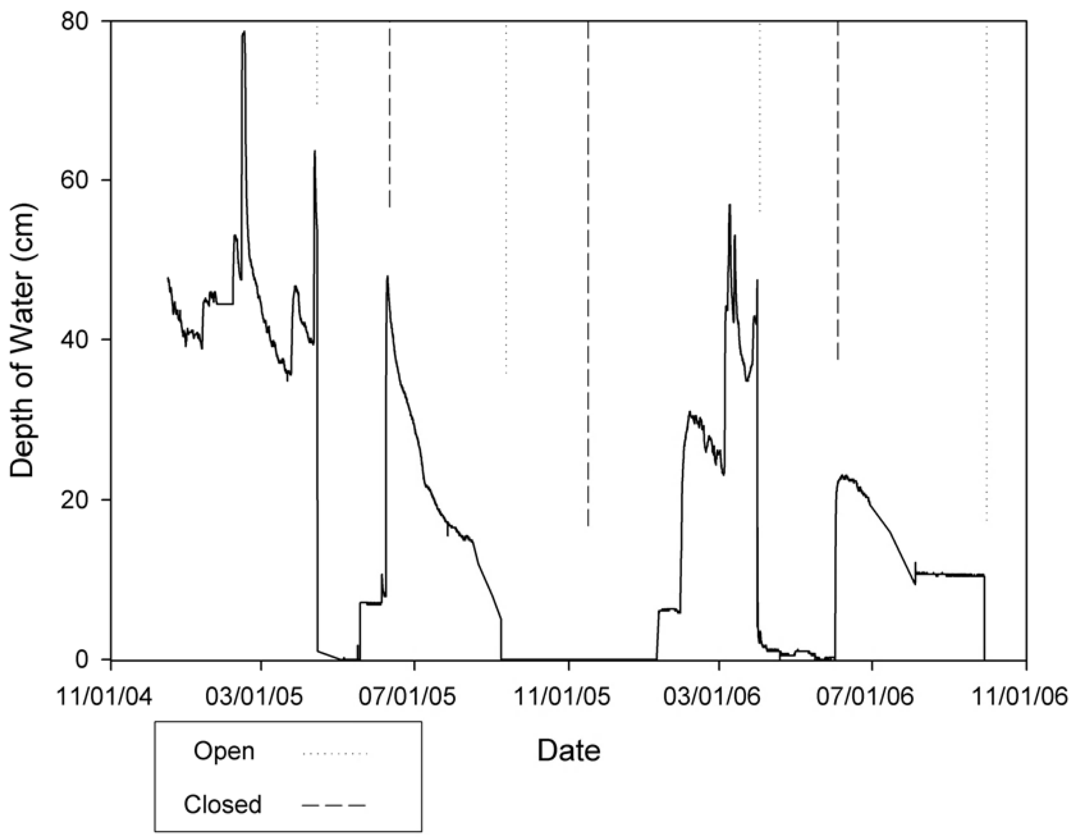

Figure 3.16. Depth of water in plot 2 (CDV).

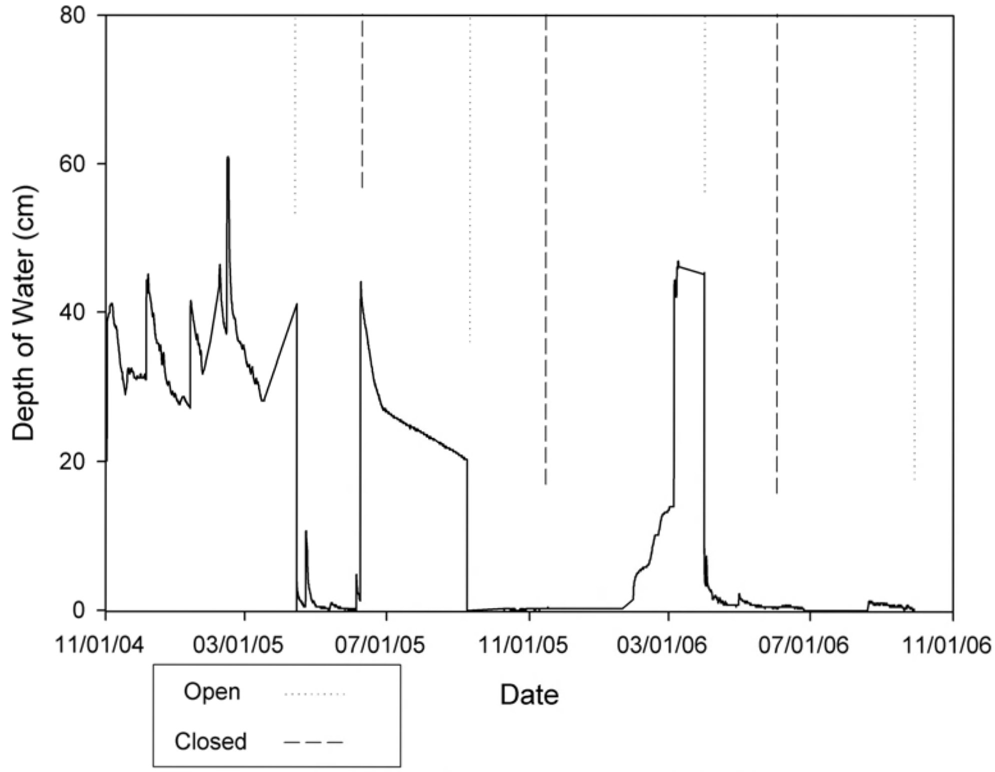

Figure 3.17. Depth of water in plot 6 (CDV).

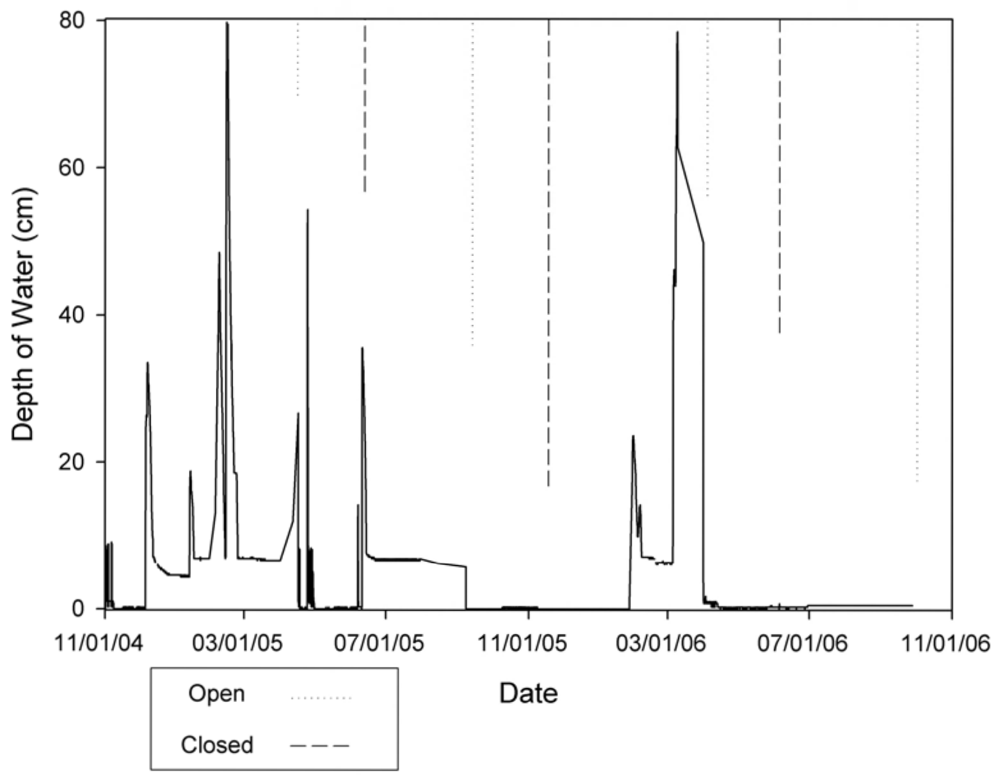

Figure 3.18. Depth of water in plot 7 (CDV).

Figure 3.19 through Figure 3.21 show the depth of water in the three CDF plots. These plots always have the CD structure closed, hence the reason why there is no open and closed sessions. The CDF plots had little drainage in both years and the figures show peaks that rise above the 60 cm mark, which means the water is spilling over the plates inside the control structure. The little drainage that did occur is shown by these peaks. The steady decrease in water table over the growing season is also seen in these graphs.

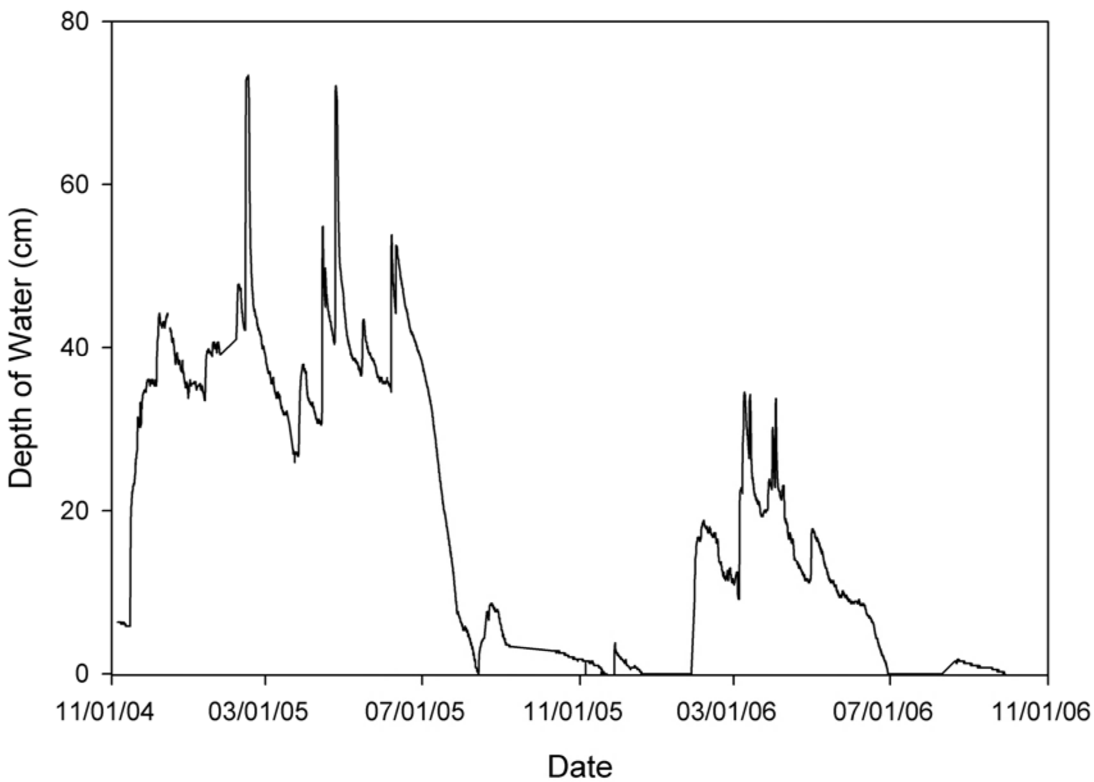

Figure 3.19. Depth of water in plot 3 (CDF).

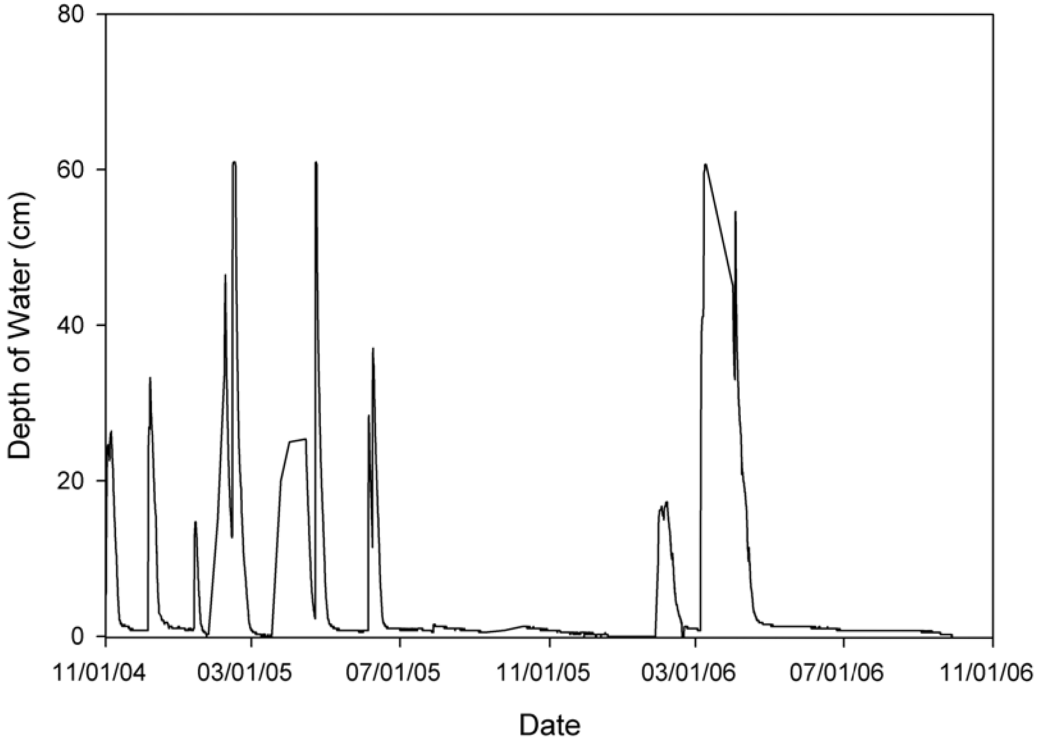

Figure 3.20. Depth of water in plot 4 (CDF).

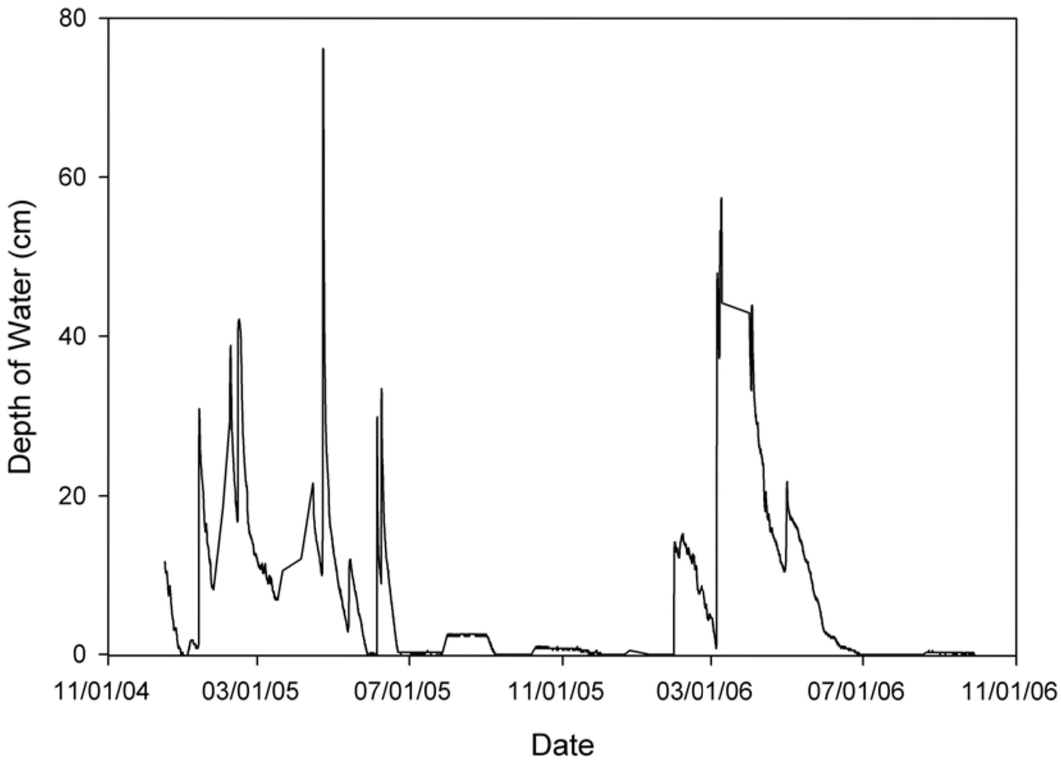

Figure 3.21. Depth of water in plot 8 (CDF).

3.5 Conclusions

In this study, a better understanding on how CD operates throughout the year was attained. Measuring water table depth over a two-year period showed that CD reduces subsurface drainage. Figures 3.16 through 3.21 show obvious instances over the period of study where water was held in the soil to be released via evapotranspiration or through seepage. In other instances, rapid spikes followed by rapid declines can be seen over the season (Figure 3.18 and 3.20). These spikes can be attributed to drier conditions in the soil coupled with flashy preferential flow patterns. After precipitation, in a drier soil, preferential flow will contribute to the rapid increase in the water table in the CD structure, initially, and over time the soil will absorb the water being held back in the structure leading to the rapid decrease in water table depth.

CD was shown to support previous research when CDV and CDF subsurface drainage data was compared with FD. The subsurface drainage was reduced by 58% and 93% over two years, respectively. Due to these decreases in drainage, nitrate loading was reduced substantially, which also follows previous reports. Furthermore, nitrate concentrations were similar between FD, CDV, and CDF treatments. A biofilter was studied as a part of this project and reduced the nitrate concentrations exiting the subsurface drainage system, which was statistically different from both the FD and CDV treatments. Taking these facts into account, it would be reasonable to conclude that CD combined with a biofilter in the same system has the potential to have a positive effect on nitrate management. In other words, the drainage and subsequent nitrate loading reduction of CD coupled with a biofilter could bring even lower nitrate loading while reaping the benefits of lower nitrate concentrations.

3.6 References

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CHAPTER 4. GENERAL CONCLUSIONS

4.1 Conclusions

This thesis has presented data from two projects that have advanced the understanding of CD and fulfilled the overall objectives set forth. The objectives were to:

1. Determine the effects of CD on surface runoff
2. Further document the effect of CD on subsurface drainage volumes
3. Determine the effect of CD on crop yield
4. Determine the effects of a biofilter on nitrate concentrations

CD was shown in Chapter 2 to have the potential to increase surface runoff under a design storm that would occur every two years when compared to free drainage. Considering the frequency of the design storm that caused increased runoff, this could be cause for concern. This provides motivation to concentrate further study on the water balance under CD conditions.

Previous research has shown on that CD reduces subsurface drainage and subsequently reduces nitrate loads released from a drainage system and the results in this thesis corresponded with previous results. In every case CD had less subsurface drainage when compared to free drainage, which also reduced the nitrate loading under CD conditions. Additionally, not only did a biofilter reduce nitrate concentrations, but due to the decrease in concentrations the nitrate loading was also decreased. Therefore, a system that couples the reduced drainage of CD and reduced concentrations associated with a wood-based biofilter could potentially have encouraging effects on nitrate management.

As for crop yield, CD has shown in the past to have inconsistent effects. It can be inferred, however, that the increased available water in the soil would have positive effects on crop yield under CD conditions. It is this implied scenario that is being put forth to explain the increased yield seen in this research. However, CD could have negative effects as well. The saturated conditions might not allow the crop roots to proliferate deep into the soil in the early months of the growing season. This would not allow the crop to reach the deep water late in season. It is this scenario that may have contributed to the inconsistent previous research.

4.2 Recommendations

Previous research reports subsurface drainage volume reduction and unaffected nitrate concentration associated with CD. These facts, integrated with the results from this thesis, reveal two recommendations for the future. A small amount of research, including the results presented in this thesis, has reported that a wood-based biofilter reduces nitrate concentrations released from subsurface drainage. If this technology was added to the reduced drainage and loading of CD the system has the potential to obtain the benefits of both simultaneously. It is for this reason research investigating the effects of a system that joins CD and a wood-based biofilter in the same system would be beneficial.

On the other hand, the positive effects of CD could obstruct the vision to see potential problems that may be associated with CD. The research presented in this thesis supports previous research showing increased surface runoff when CD was compared to free drainage. Yet, surface runoff reports are rather rare and not given as much importance as other factors in CD studies. This is why more research that has a focus on the effect of CD on surface runoff is needed, rather than have surface runoff be a small component of a larger study. If CD is impulsively adopted due to its positive attributes, the potential negative effects could emerge in the future as an even greater problem than the ones we are using CD to remediate.

APPENDIX

Reference	Location of Study	Water Table Management Protocol	Length of Study (years)
Amatya, D.M., et al. (J. of Environ. Qual. vol. 27), 1998	Carteret County, NC	free, fixed, var. 0.4(mar-jun)/0.8(jun-nov.)	2.5
Borin, M. et al. (J. of Environ. Qual. vol. 30), 2001	Padova Univ. NE Italy	Free, Fixed, var.(fall to 100cm add to raise to 60cm)	3
Breve, M.A., et al. (Ag. Water Manag. Vol. 35), 1998	Plymouth, North Carolina	Controlled Drainage Fixed	20
Breve, M.A., et al. (Trans. of ASAE vol. 40(4)), 1997	Plymouth, North Carolina	2 Conv., 2 Control Fixed, 2 Cont. Subirr.	1
Deal, S.C. et al. (Agriculture, Ecosystems and Environment vol. 18), 1986	North Carolina	Dec. - Mar. 0.3, Mar. - Jun. 1.0, Jun. - Sept. 0.45. Sept. - Dec. 1.0	20
Drury, C.F. et al. (J. of Environ. Qual. vol. 25), 1996	Ontario, Canada	0.3m except 1mo. Before plant at harvest	3
Drury, C.F. et al. (TheScientificWorld vol. 1(S2)), 2001	Ontario, Canada	0.3m in growing season, 0.6 during plant and harvest	8
Drury, C.F. et al. (Soil Sci Soc. Am. J. vol. 25), 1997	Ontario, Canada	fixed	1 growing
Dukes, M.D. et al. (J. of Irrig. & Drain. Eng. Vol.129(2)), 2003	Goldsboro, North Carolina	30-46cm year-round (it seems), Free	2
El-Sadek, A. et al. (Journal of Enivronmental Eng. Vol. 128(4)), 2002	North Carolina	Not Specified, It just states CD and nothing else	14
Elmi, A.A. et al. (Ag., Ecosystems & Env. Vol. 79), 2000	Coteau Du Lac, Quebec	Subirrigation at 0.6m	2
Elmi, A.A. et al. (Water, Air, and Soil Pollution vol. 151), 2004	Coteau Du Lac, Quebec	Subirrigation at 0.6m	2
Evans, R.O. et al. (J. of Irrig. & Drain. Eng. Vol.121(4)), 1995	North Carolina	Year round fixed (it seems)	N/A
Fausey, N.R. et al. (J. of Irrigation & Drainage vol. 121(4)), 1995	This is a paper stating that there is opportunity to do more research with controlled drainage and subirrigation in general		
Fisher, M.J., et al. (Soil Sci. Soc. Am. J. vol. 63), 1999	Pike County, Columbus, Ohio	Subirrigation in growing season, Controlled in Winter	3
Fouss, J.L., et al. (Trans. of ASAE vol. 30(6)), 1987	New Orleans, Louisiana	conv., fixed weir, two stage weir (not very spec.)	5, 20
Gilliam, J.W. et al. (J. of Irrig. & Drain. Eng. vol. 8(1)), 1979	North Carolina	30cm March to January	3
Gilliam, J.W. et al. (J. of Irrig. & Drain. Eng. vol. 112(3)), 1986	Belhaven, North Carolina	30cm Dec.-Mar., 100cm Mar.-Jun., 45cm Jun.-Dec.	20
Grigg, B.C. et al. (Trans. of the ASAE vol. 47(2)), 2004	Louisiana	1.1m year round ?	?
Hunt, P.G. et al. (Journal of Soil and Water Cons. Vol. 48(6)), 1993	North Carolina	0.61, 0.76, 0.91, 1.07, 1.22	2
Kalita, P.K., et al. (Trans. of ASAE vol. 36(2)), 1993	Ames and Ankeny, Iowa	controlled 50 days after plant to harvest	3
Khan, G.D. et al. (Irrigation & Drainage vol. 52), 2003	Pakistan (Swat River)	controlled during May & June (peak crop water requirement)	2
Kliewer, B.A., et al. (Soil Sci. Soc. Am. J. vol. 59), 1995	Raleigh, NC	control fixed	2
Lalonde, V. et al. (Ag. Water Manag. Vol. 29), 1996	Bainsville, Ontario, Canada	0.25m & 0.5m Controlled fixed except in Fall	2
Liaghat, A. et al. (Canadian Water Resources Journal vol. 22(3)), 1997	Quebec, Canada	40cm below the soil surface	1
Mejia, M.N. et al. (J. of Irrig. & Drain. Eng. Vol.124(2)), 1998	Bainsville, Ontario, Canada	50cm, 75cm, Free (Subirr. To maintain WT)	2
Ng, H.Y.F. et al. (Ag. Water Manag. Vol. 43), 2000	Ontario, Canada	Controlled/Subirr.	1
Ng, H.Y.F. et al. (Ag., Ecosystems & Env. Vol. 90), 2002	Ontario, Canada	Controlled/Subirr.	1
Paasonen-Kivekäs, M.P. et al. (Water Science and Technology vol. 33(4-5)), 1996	Finland	Not Specified	2
Parsons, J.E. et al. (Agricultural Water Management vol. 18), 1990	Conetoe, North Carolina	0.4m from day 100-230, 1.2m from day 231-99	5
Shirmohammadi, A. et al. (J. of Irrig. & Drain. Eng. Vol.121(4)), 1995	This is a Drainage History Article with Research Recommendations		
Skaggs, R.W. et al. (European Journal of Agronomy vol. 4(4)), 1995	North Carolina	Winter 0.4m, Summer 0.5m	44
Skaggs, R.W. et al (Irrigation & Drainage Systems Vol. 9), 1995	North Carolina	40cm Nov.-Mar, 50cm May-Aug.	20
Skaggs, R.W. et al (Trans. Of the ASAE vol. 24), 1981	North Carolina	50cm (Apr. 15 - Aug. 15), 15cm (Oct. 15 - March 15)	5
Stone, K.C. et al. (J. of Soil and Water Conservation vol. 47), 1992	This is a paper explaining how drainage and controlled drainage is used in the eastern coastal plane of the US with reference		
Tan, C.S. et al. (2004 ASAE International Meeting, Ottawa, Canada) Paper #042241	Southwestern Ontario	During growing season at 40cm below soil surface(off for plant and harvest)	3
Tan, C.S. et al. (Water Science Technology vol. 38(4-5)), 1998	Ontario, Canada	controlled drainage only disengaged during plant and harvest	2
Thomas, D.L. et al. (J. of Irrig. & Drain. Eng. vol. 117(1)), 1991	Pierce County, GA	Not Specified	3
Thomas, D.L. et al. (J. of Soil and Water Consveration vol. 47), 1992	This is a paper explaining the importance of controlled drainage in the SE US with references to certain research papers		
Wahba, M.A.S. et al. (Irrigation & Drainage vol. 50), 2001	Alexandria City, Egypt	0.6m fixed during growing season	2
Wesstrom, I. et al. (Ag. Water Manag. Vol. 47), 2001	Southwest Sweden	0.6m fixed year 1, 0.3m fixed year 2	2
Wesstrom, I. et al. (Hydrological Processes Vol. 17), 2003	Manstrop, Sweden	0.6-0.7m in year 1, 0.2-0.4m in years 2 & 3	3
Wright, J.A. et al. (Trans. of ASAE Vol. 35(3)), 1992	Baton Rouge, LA	30cm during fallow season, 60cm for growing season	8
Zhou, X. et al. (European Journal of Agronomy vol. 12), 2000	Quebec, Canada	maintained with SI at 0.7m and 0.8m	2

Figure A.1. Controlled drainage literature review.

Cropping Practices	Soil	Drain Depth (m)	Drain Spacing (m)	Application Rate of Nitrogen (kg/ha)	Timing of Nitrogen Application	Formulation of Nitrogen Fertilizer	Volume of Subsurface Drainage from Conventional Conditions (cm)
Forest	Deloss fine sandy loam	1,0.6,0.4-0.8	100	unknown	20,13, 5 yrs before study	unknown	60
corn, sugarbeet, reed grass	Fulvi-Calcaric Cambisol Soil	flood, 0.6, 1	N/A	600 start, crop needs	plant	poultry, urea	27.2
Corn	Portsmouth sandy loam	1	10-100	150	Pre-plant & Sidedress	N/A	N/A
wheat-soybean	Portsmouth sandy loam	1.25	23	16.3, 145.6	Nov. '91, Feb. '92	N/A	37
corn?	6 Different soils	1	10 to 20	N/A	N/A	N/A	23.8
corn-ryegrass intercrop	Brookston Clay Loam	0.6	7.5	167	plant	urea	76.6
cont. corn/corn-soybean	Brookston Clay Loam	0.6	7.5	132, 115	only on corn, pre-plant, six-leaf stand	Starter, Urea	147.3
corn	Fox Sandy Loam	0.3,0.6,0.8	N/A	0,45,90,135	Plant	unknown	0.71
Riparian buffer, ??	Wickman loamy sand	0.3-0.46, ?	N/A	N/A	N/A	N/A	N/A
Not Specified	Not Specified	1	25 - 300	275	May 6, May 14	N/A	39 to 32
Corn	Soulanges fine sandy loam	1, 0.6	N/A	120-200	Pre-plant & Sidedress	Ammonium nitrate	N/A
Corn	Soulanges fine sandy loam	1	15	120, 200 + manure	Pre-plant & sidress	DAP, AN, Manure	Totals not reported, but
N/A	N/A	N/A	N/A	N/A	N/A	N/A	34
corn-soybean	Omulga silt loam	0.75	5	30, 120	plant, July	Urea	N/A
none	Commerce silt loam	0.6	16, 20	N/A	N/A	N/A	(131,160)(158,249)
N/A	Cape fear & Portsmouth	N/A	N/A	N/A	N/A	N/A	23.5
Corn	Portsmouth, Wasda	0.3, 0.45, 1	15	N/A	N/A	N/A	14.5, 12.5
Corn	Commerce silt loam	1.25	15	224	25%pre, 50%@30d, 25% June	Liquid (NH_3NO_3)	N/A
Peanuts	Portsmouth sandy loam	N/A	N/A	NONE	NONE	NONE	N/A
cont. corn	Nicollet loam, silt loam	0.3, 0.9	N/A	200	plant	urea	N/A
Wheat	Unknown	sporadic	350-450	unknown	Unknown	unknown	N/A
Wheat	Cape Fear Loam	(15,30,45)cm	N/A	56	May	urea	N/A
corn-soybean	Bainesville silt loam	1	18.3	211	sidedress & July	Liquid N	22.2
Grass	St. Amable sand	1	N/A	N/A	N/A	N/A	0.625 m^3
Corn-Soybean	N/A	0.5, 0.75, 1	18.3	130, 140	Sidedress (corn only)	ammounium nitrate	18.5
Corn	Brookston Clay Loam	0.6	7.5	55 + Prev. Alfalfa	sidedress	Urea	N/A
Corn	Sandy Loam	0.6	6.1	204	Pre-Plant	Anhydrous	32
Wheat, Barley	fine to loamy sand	1.1	14	120	N/A	N/A	N/A
Corn	Rains sandy loam	1.2	100	N/A	N/A	N/A	8.29
Corn	Portsmouth sandy loam	1	10-100	100 + 50	Apr. 15-May 22	N/A	61 to 38
Corn	Portsmouth sandy loam	0.4,0.5,1	20-100	150	Apr. 15-May 22	N/A	58.2 - 34.4
Corn	Typic Umbraqualt	1	22.5	60 + 120 sidedress	Pre-plant & Sidedress	N/A	N/A
s to certain research papers							
Tomato, corn	Berrian Sandy Loam	0.6	6	78 + 56 sideress (202 Corn)	Pre-plant & Sidedress (sidedress)	N/A, (anhydrous)	42.5
Soybean	Brookston Clay Loam	0.65	9.3	185(no till)- 224(till)	Plant, Fall	Starter	24.9
Bluberries Primarily	Pelham, Leefield	1	15.3	avg. of 80	N/A	ammounium nitrate	N/A
Wheat, Corn	Sandy silt loam-clay loam	0.6, 1.2	32	100-130	Pre-plant	Ammonium nitrate	50
potato (barley intercrop)	N/A	1	10	N/A	N/A	N/A	17.2(1), 23.9(2)
N/A	Structured loamy sand	1	10	N/A	N/A	N/A	28.7
Corn	Commerce clay loam	1	20	216	Pre-plant & Sidedress	N/A	N/A
Corn (ryegrass intercrop)	Typic Humaquept	1	N/A	270	Pre-plant	N/A	N/A

Figure A.1. (Continued)

Volume of Subsurface Drainage from Managed Condition (cm)	% Change in the Volume of Subsurface Drainage	Volume of Surface Runoff for Conventional Conditions (cm)	Volume of Runoff from Managed Condition (cm)	% Change in Surface Runoff	Flow-weighted NO_3-N Concentration from Conventional Drainage (mg/L)	Flow-weighted NO_3-N Concentration from Managed Drainage (mg/L)	% Change in the NO_3-N Concentration	NO_3-N Loss from Conventional Drainage (kg/ha)	NO_3-N Loss from Managed Drainage (kg/ha)
35, 41	42%, 32%	N/A	N/A	N/A	N/A	N/A	N/A	2.49	0.91,0.77
74,87,69	(-172,-219,-153)%	N/A	N/A	N/A	41	5.54,6.89,0.97	(86,83,97)%	111	41,60,6.75
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	37.7-5.9	16.4-4.5
32, 30	13.5%, 19.0%	8.00	15	-46	N/A	N/A	N/A	8.35	7.45, 3.85
18	24%	12.33	16.2	-32%	6	4.2	30%	17.9	12.52
57	26%	N/A	N/A	N/A	10.58	7.9	25%	77.3	43.7
99.9	32%	65.10	99.8	-53%	9.35 (8-yr avg)	5.5 (8yr avg.)	41%	134.8	54.6
2.46, 1.27	(-246,-78)%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	N/A	N/A	7.5	1.9	75%	N/A	N/A
38 to 28	2.56% - 12.5%	0 to 3	0 to 3	0%	N/A	N/A	N/A	39 to 19	38 to 18
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
percentage reduction of 15%-45% was reporte		N/A	N/A	N/A	6.1	1.4	77%	12.8 (3 yr tot)	4.4 (3 yr tot)
23.1	32%	30.20	22.4	26%	N/A	N/A	N/A	31.1	17.3
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
(94,119)(119,155)	(28,26)%(24,38)%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2.5	89.36%	N/A	N/A	N/A	N/A	N/A	N/A	32	4
10.3, 9.6	29%, 24%	1.7, 2.1	4.5, 3.9	(-164, -85.7)%	N/A	N/A	N/A	39.1, 27.8	26.4,19.1
52.9	N/A	42.20	46.3	-9.70%	N/A	N/A	N/A	N/A	9.2
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	N/A	N/A	3yr. Avg. 14.69	3yr. Avg. 10.43	29%	N/A	N/A
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Denitrification 0.44/day	Denitrification 4.23/day
9.1, 7.7	59%-65%	N/A	N/A	N/A	16.5	8.76, 13.36	47%-19%	32.9	7.92, 10.24
0.6 m^3	4%	N/A	N/A	N/A	30	18.8	37%	55% of initial	69% of initial
33.5, 49	(-81, -165)%	N/A	N/A	N/A	11.05	3.1, 4	72%, 64%	17	3, 11.5
N/A	N/A	N/A	N/A	N/A	12.5	6.7	46.40%	N/A	N/A
29	9.40%	N/A	N/A	N/A	14.5	8.5	41%	58	37
N/A	N/A	N/A	N/A	N/A	2.2 (SI)	5.9 (No SI)	-140%	N/A	N/A
0.535	93.50%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
55 to 30	9.8% - 21%	3 to 6	5 to 15	(-40, (-60))%	N/A	N/A	N/A	37 to 6	15 to 4
50.3-24.6	14%-28%	N/A	N/A	N/A	N/A	N/A	N/A	31.6-5.2	13.3-3.7
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	20	12.2
30	29.40%	N/A	N/A	N/A	12.65	8.1	36%	50.9	25.9
18.8	24.50%	N/A	N/A	N/A	Report as not significant, but no values given			32.8	25.9
N/A	N/A	N/A	N/A	N/A	N/A	2.55	N/A	N/A	N/A
30	40%	N/A	N/A	N/A	1.22	1.03	16%	5.5	3.1
3.67(1), 1.42(2)	79%-94%	N/A	N/A	N/A	20.4(1), 12.7(2)	19.6(1), 10.9(2)	4%-14%	37.65(1), 30.80(2)	8.15(1), 1.8(2)
6	79%	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
-15.8	-149%	N/A	58.7	121%	N/A	N/A	N/A	N/A	3.8
N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Figure A.1. (Continued)

% Change in the NO_3-N Load	Crop Yield Conventional (kg/ha)	Crop Yield Controlled (kg/ha)	% Change in Yield	Additional Notes
64%, 69%	N/A	N/A	N/A	Under Forest Conditions
(63,46,94)%	N/A	N/A	N/A	Lysimeter Study, Water added to maintain WTD
56%-24%	8100-4220	8360-3590	((-3.2%)-15%)	Drain Spacing has a huge effect on yield and nitrate loss benefits
11%,54%	W4950, S2850	W4900-5150, S3050-2900	1-(-4), (-7-(-1.7))	Field testing DRAINMOD-N
30%	N/A	N/A	N/A	DRAINMOD, all numbers are averaged over soil type and drainage practice
44%	N/A	N/A	N/A	Average over 3-yr flows and tillage practices
59%	N/A	N/A	N/A	Subirrigation (only recoreded outflow however), '91-'94 cont. corn/'95-'99 corn-soybean
N/A	lowest (g/plant)	0.6m Highest, 0.3m Mid	N/A	soil column study that does not seem representative
N/A	N/A	N/A	N/A	Riparian/Controlled Drainage study, Reported stage depth in stream
2.56% - 5.26%	N/A	N/A	N/A	DRAINMOD, 4 diff. drain depths but picked one and varied spacing, Good surface Storage
25-59%	N/A	N/A	N/A	This journal reported soil nitrate not nitrates in the drainage
12.50%	N/A	N/A	N/A	Subirrigation
44.40%	N/A	N/A	N/A	Sporadic Data
N/A	C4529, S1753	C5444, S3017	(-C17, -S72)%	Nitrate expressed as micrograms/g of soil
N/A	N/A	N/A	N/A	DRAINMOD
87.50%	N/A	N/A	N/A	Sporadic Data
32%, 31%	N/A	N/A	N/A	DRAINMOD Study-assuming no deep percolation
N/A	5900	5700	-3.39%	Surface Drainage is included for each treatment/focused on normal or drought cond.
N/A	4300	4750	10.50%	Focused on N accumulation in the peanut and peanut plant
N/A	9400	6614	-30%	Lysimeter/Open Field study, suction tube sampling
N/A	N/A	4.61	N/A	Not very infomative data
Den. 861%/day	N/A	N/A	N/A	Soil core study = Not very representative it seems
76%-69%	N/A	N/A	N/A	
14%	N/A	N/A	N/A	Lysimeters were used and water was applied over a 55 day period with a known nitrate condition
83%, 32%	N/A	N/A	N/A	Drainage is inflated due to Subirrigation to maintain water level
N/A	N/A	N/A	N/A	
36%	N/A	N/A	N/A	Subirrigation inflated the Controlled Drainage
N/A	N/A	N/A	N/A	Subirrigation, VERY incomplete data reporting
N/A	38.50%	45.70%	7.20%	(Drainage ditches were used), (avg. over 5 yrs. And 4 K's), (yields are percent of 100 avg. of dry/wet years)
60% - 33%	N/A	N/A	N/A	DRAINMOD
58%-29%	N/A	N/A	N/A	DRAINMOD, 20m spacing - 100m spacing
39%	N/A	N/A	N/A	DRAINMOD
49%	58400, 6700	64900, 11000	(-11.1%, -64%)	Farm scale/Plot scale, Subirrigation
21%	3.06?	3.1?	?-1.31%	Used CD with conventional and no tillage
N/A	N/A	N/A	N/A	very incomplete data reporting for this article
44%	N/A	N/A	N/A	
78%-94%	N/A	N/A	N/A	
N/A	N/A	N/A	N/A	Stated that initial storage for Controlled Drainage is less than Conventional Drainage
393%	N/A	N/A	N/A	Subirrigation with the use of CREAMS
N/A	8700	8625	-0.86%	Study focused more on Biomass accumulation and N accumulation in Biomass

Figure A.1. (Continued)

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BIOGRAPHICAL SKETCH

Kyle Dean Riley was born and raised on the southside of Des Moines, Iowa, USA. He was born on May 15, 1983 at Des Moines General Hospital. He is the younger of two children and has an older sister named Tami. His father was born in Des Moines and is self-employed as a logistics director. He currently resides in Denver, Iowa. His mother was born in Salt Lake City, Utah and works as a dietician at Mercy Hospital in Des Moines where she currently resides.

While in high school a man named Ace Hendricks opened Kyle's eyes to the area of environmental sciences and Ace urged him to continue in this field during his college career. So, after graduating from Abraham Lincoln High School in Des Moines in May 2001, Kyle enrolled at Iowa State University in the Agricultural & Biosystems Engineering department at Iowa State University for fall 2001. While working toward his B.S. degree in Agricultural Engineering, he gained valuable experience as a research assistant with Dr. Steven Mickelson in the summer of 2002. Then, in the summer of 2004 he worked for the Iowa Department of Natural Resources Pollution Prevention program and was assigned to Sara Lee Foods in Storm Lake, Iowa. His B.S. degree was then acquired in May 2005.

Having a general interest in research, Kyle enrolled in graduate school at Iowa State University and became a graduate assistant under the direction of Dr. Matthew Helmers after his undergraduate career. While in graduate school, he was fortunate enough to marry his wife Miranda and to travel to the Republic of Georgia on two occasions to work with Georgian Technical University on the country's water related environmental issues. His research, while in graduate school, is encompassed in this thesis and he received his M.S. degree, co-majoring in Agricultural Engineering and Civil Engineering, in December 2006.